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Development of the traction system structure of a shunting diesel locomotive with a hybrid power supply scheme

In this work, the structure of the traction system of a shunting diesel locomotive with hybrid power, which performs both shunting work at the station and hauling work, is proposed. In order to develop the structure of the traction system, which will work effectively in both modes of operation of the shunting diesel locomotive, an analysis of the structures of the traction systems of diesel locomotives with hybrid power, produced by the world's leading companies, is carried out. In order to choose the optimal type of storage device, an analysis of the advantages and disadvantages of supercapacitor batteries and lithium-ion batteries is carried out. On the basis of the analysis of the structures of traction systems of diesel locomotives with hybrid power of leading companies and the advantages and disadvantages of supercapacitor batteries and lithium-ion batteries, the structure of the traction system of a shunting diesel locomotive with hybrid power, which performs both shunting work at the station and hauling work, is developed. In the proposed traction system structure, each traction motor receives power from a separate traction converter. The power for powering the traction motors during shunting work is transmitted from supercapacitor batteries, when carrying out hauling work - from lithium-ion batteries. This study can be used in the design of the traction system of a new and in the modernization of an existing shunting diesel locomotive.

Keywords: *hybrid power supply, supercapacitor, lithium-ion battery, shunting diesel locomotive, traction system.*

Introduction. Railway transport is the main transport artery of Ukraine. About 46...60% of all cargo transportation was carried out by railway in 2009-2023 [1]. The wear and tear of rolling stock, in particular locomotives, has a negative impact on the process of rail transport. Most of the locomotives in the stock of JSC "Ukrzaliznytsia" are obsolete. Their technical characteristics are worse than those of modern locomotives, which leads to an increase in operating costs and maintenance and repair costs. Solving this problem can be implemented in two ways, namely: purchase of new locomotives, or modernization of existing ones.

Execution of shunting operations is an integral part of the organization of railway transportation. There are more than 1,200 diesel locomotives of the ChME3 series in the inventory of JSC "Ukrzaliznytsia". Their wear is 100%. This leads not only to an increase in maintenance and repair costs, but also to an increase in fuel and lubricant costs. In this regard, the priority task is the restoration of shunting diesel locomotives through major repairs and modernization of individual units. The advantages of this option are relatively small capital investments and the presence of a developed repair and technological base. It should be noted that during overhaul it is impossible to restore the passport characteristics of diesel locomotives. This factor leads to significant costs for ongoing maintenance of locomotives. At the same time, the low quality of repairs will lead to an increase in unscheduled repairs.

Complex modernization with remotorization is an alternative for updating the fleet of shunting diesel locomotives. This will improve the traction and energy characteristics of diesel locomotives, reduce the costs of maintenance, repairs and fuel and lubricants. This will ensure a decrease in the cost of rail transportation.

Analysis of recent research and problem statement. At JSC "Ukrzaliznytsia" diesel locomotives of the ChME3 series are used for both shunting and haulage work [2]. Despite the fact that the wear and tear of these diesel locomotives is 100%, for some diesel locomotives of this series, the service life of the load-bearing structures has been extended to 15 years. Deep modernization is used on such diesel locomotives, namely: replacing the diesel unit with a more modern one, replacing the existing direct current power transmission with alternating current power transmission, improving the drive of auxiliary machines, introducing a microprocessor control system, etc. [3]. Depending on the nature of operation, fuel savings on modernized electric locomotives is 30...45%.

The analysis of the results presented in the study [4] shows that the duration of operation of a shunting diesel locomotive in idle mode is at least 50% of the total operating time. The change in power of the traction generator is within 50...250 kW when maneuvering works at the station. In addition, work [4] states that the execution of maneuvering operations is characterized by large and rapid changes in power in the traction system.

When starting from a standstill, accelerating and moving uphill, the required diesel locomotive must work at rated power. However, the duration of such regimes is insignificant [5]. In connection with this fact, the use of a diesel engine of lower power on a modernized diesel locomotive is impractical, since in this case the dynamics of the movement of such a diesel locomotive will be unsatisfactory. The solution to this problem during modernization can be the use of a traction system of a diesel locomotive with parameters that most closely correspond to the modes of operation of the diesel locomotive. In the paper [6], the authors proposed to modernize the traction system of a diesel locomotive by using several diesel engines. Another way to modernize the traction system is to use the traction system of a diesel locomotive with hybrid power [7, 8]. In these works, the authors proposed and substantiated the feasibility of using a hybrid power system in the traction system of diesel locomotives performing shunting work at the station. This will lead to a decrease in fuel consumption and a decrease in harmful emissions into the atmosphere.

In works [9, 10], the authors proposed and substantiated the feasibility of using a hybrid power system in the traction system of diesel locomotives performing export work. In these studies, the authors note that, unlike the shunting operation at the station, in this mode of operation of the diesel locomotive, there are no large and rapid changes in power in the traction system. However, when organizing a hybrid power system, one should take into account the fact that for this mode of operation of the diesel locomotive, the on-board batteries must have a large capacity to ensure long-term energy storage.

In the study [11], the authors analyzed the operation of the ChME3 diesel locomotive when carrying out hauling work on a specific site. In this work, the authors analyze the traction characteristics of the diesel locomotive on the specified section. Based on the analysis of the traction characteristics for the production diesel locomotive of the ChME3 series, for the diesel locomotive with a modern diesel engine and for the diesel locomotive with a hybrid power system, as a result of simulation modeling, it was established:

- a locomotive with a modern diesel engine consumes 18...22% less fuel than a conventional locomotive;

- for a diesel locomotive with a hybrid power system, fuel consumption can be both lower and higher compared to a diesel locomotive with a modern diesel engine. But the use of a hybrid power system allows to accumulate energy during electrodynamic braking and use it in traction modes, which helps reduce fuel consumption.

Since shunting diesel locomotives are used both for shunting and hauling work, the task of developing the traction system structure of a shunting diesel locomotive that would work effectively in both modes is urgent.

The purpose and tasks of the study. The purpose of the study is to develop the structure of the traction system of the shunting diesel locomotive, which would work effectively both when performing shunting work at the station and when performing hauling work.

To achieve the purpose in the work, the following tasks were completed:

- an analysis of the structures of traction systems of diesel locomotives produced by leading global companies was carried out;
- the choice of the type of batteries for the implementation of the traction system of a shunting diesel locomotive, which works both when performing shunting work at the station and when performing hauling work, is substantiated;
- the structure of the traction system of the shunting diesel locomotive has been developed, which will work effectively both when performing shunting work at the station and when performing hauling work.

Analysis of the structures of locomotive traction systems produced by leading global companies. Vehicles with a hybrid power system include locomotives and diesel trains with energy batteries based on electric or hydropneumatic energy batteries, locomotives capable of using different types of fuel. The development of technologies in the field of storage devices has made it possible to significantly improve their mass-dimensional indicators. As a result, it became possible to use several storage devices of different types on one locomotive.

Since induction traction motors are used on diesel locomotives of world manufacturers, the structures of traction systems are made taking this fact into account. Diesel locomotives of the ChME3 series use manifold engines as traction. But the approach to building the implementation of energy exchange in traction systems of diesel locomotives with both induction and collector traction motors is the same. Therefore, the analysis of the structures of traction systems of diesel locomotives with hybrid power is expedient for developing on their basis the structure of the traction system with hybrid power of a shunting diesel locomotive, which works both when performing shunting work at the station and when performing hauling work.

Hybrid shunting locomotives HD 300, HDB800 and DB CARGO HELMS by Toshiba

HD 300 diesel locomotives [12] are in operation on Japanese railways, and DB CARGO HELMS are in the design stage at the request of DB Cargo [13]. The first is a hybrid diesel locomotive with an electric transmission, the second is a modernized diesel locomotive equipped with a mechanical transmission.

In accordance with the accepted classification, hybrid locomotive power schemes belong to the fourth type (electric locomotives with a different type of energy storage (compared to the main engine).

The basis of the DB CARGO HELMS locomotive drive is a series-parallel hybrid scheme, in which a planetary gearbox serves as a device that coordinates power transmission from the diesel unit to the generator, wheel pairs and SCiB battery. The considered locomotives are obtained as a result of conversion of typical German diesel locomotives BR 294 (V90). The design of the latter included ballast, which increases the towed weight, so it was possible to place the battery and the hybrid drive without increasing the weight and axial load. In the course of modernization, the hydraulic transmission is replaced by a mechanical cable with planetary gearboxes, a battery pack, traction motors and a generator. The battery unit is similar to the one installed on the HD 300 hybrid diesel locomotive of

Japanese railways, which was produced earlier, but has a higher energy capacity: up to 150 kWh.

The electrical scheme of the DB CARGO HELMS hybrid locomotive provides for the installation of a storage device in the direct current link. Thus, the hybrid drive can work both in series and in parallel (Fig. 1).

It should be noted that DB CARGO HELMS diesel locomotives have the ability to transmit torque directly from the diesel engine to the wheel pairs. Since this paper considers only the electrical circuits of diesel locomotives, in fig. 1 torque transmission directly from the diesel engine to the wheel pairs is not shown.

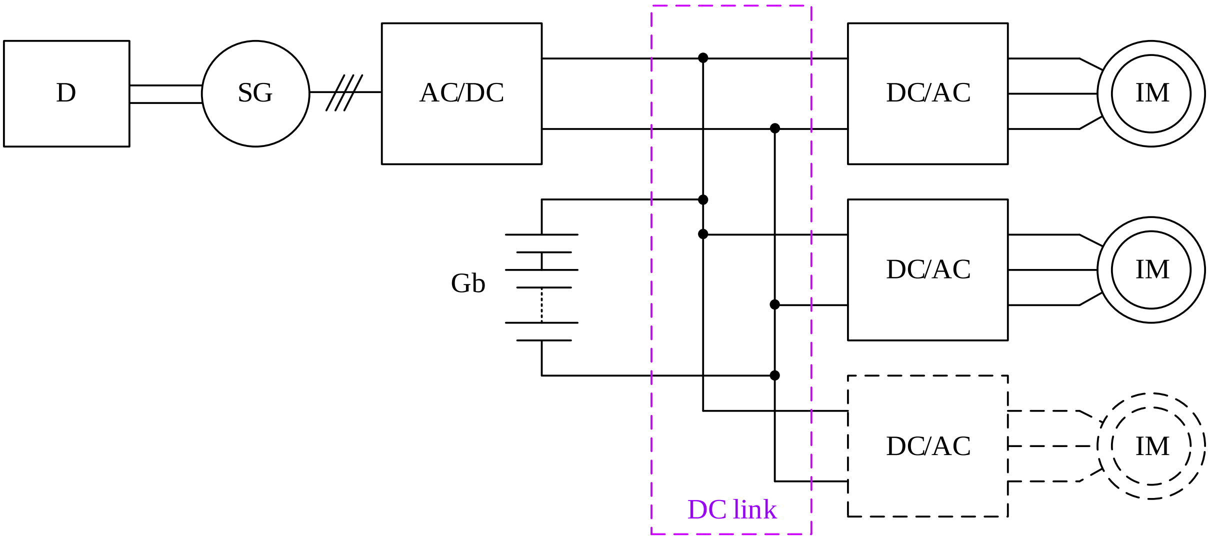

Рис. 1. **Scheme of the Toshiba CARGO HELMS hybrid electric drive: D – diesel; SG - generator; AC/DC - rectifier; DC/AC - autonomous voltage inverter; IM - induction traction electric motor**

Traction characteristics of the hybrid diesel locomotive CARGO HELMS of the Toshiba company are shown in fig. 2. When moving from a place, the traction force is 300 kN. The transition to the hyperbolic part (calculated mode) of the characteristic occurs at a speed of about 10 km/h, which is considered normal for a shunting machine.

The traction electric drive based on induction electric motors ensures a constant power of 750 kW in the entire range of speed values. Thus, the locomotive will be able to perform shunting work with warehouses weighing up to a thousand tons or train work with light-weight trains.

ALSTOM hybrid locomotives

In recent years, the Alstom company has established the production of a series of hybrid locomotives, primarily diesel locomotives with batteries based on battery batteries. The company produces a series of hybrid locomotives of the PRIMA H3 family [14] with different technical characteristics and schemes. Now more than 20 locomotives are in operation. The line includes a battery car (battery electric locomotive), a two-diesel version and the most powerful diesel-battery hybrid with a diesel engine up to 1000 kW. A nickel-cadmium battery is used on locomotives. Locomotives are produced in three-axle design (axle formula A_0-A_0-A_0).

The structural diagram of the PRIMA H3 hybrid diesel locomotive is shown in Fig. 3.

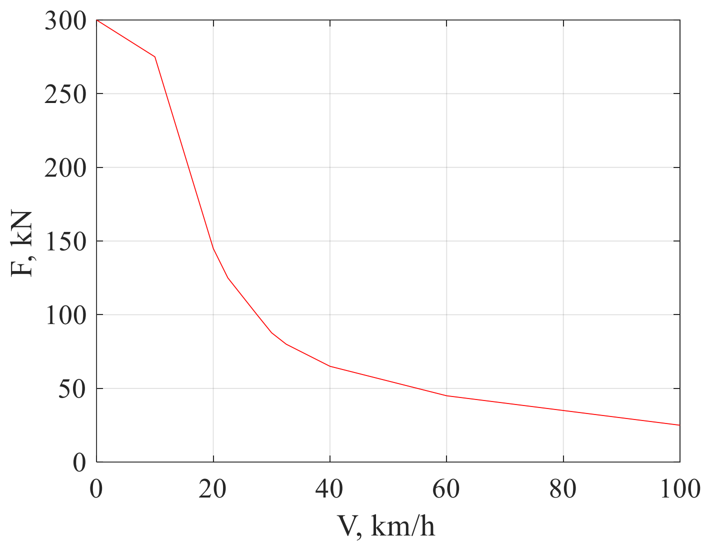

Fig. 2. **Traction characteristics of the Toshiba CARGO HELMS hybrid locomotive**

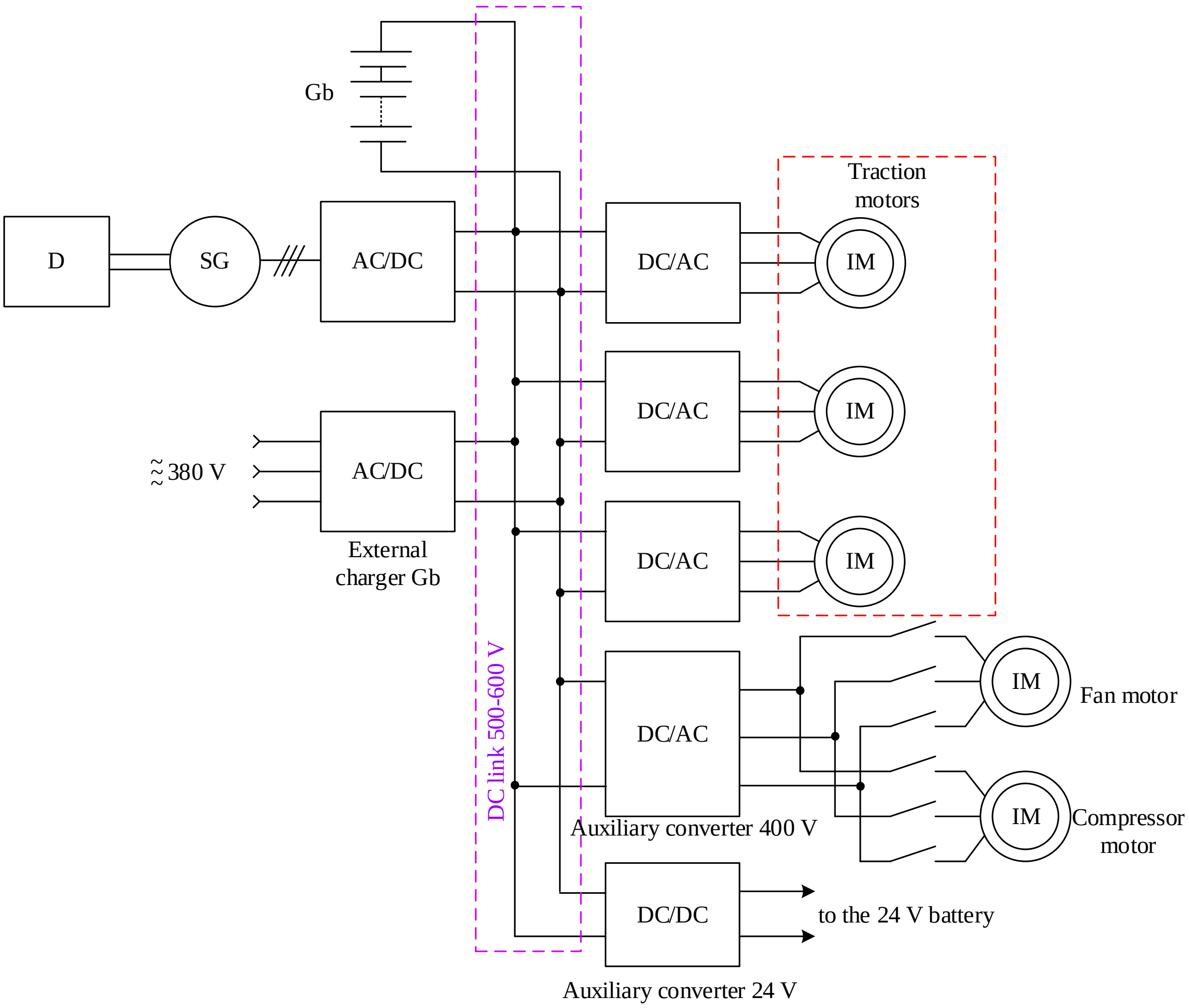

Рис. 3. **Схема гібридного тепловозу PRIMA H3**

As in the considered Toshiba hybrid scheme, induction traction motors are powered by individual inverters, the battery is connected in parallel to the direct current link. The scheme of the hybrid diesel locomotive includes a battery charger, which makes it possible to use the diesel without operation.

HSL 700 Hybrid diesel locomotive

The hybrid diesel locomotive was obtained as a result of a significant modernization of the DE 11000 shunting diesel locomotive (carriages and power elements of the body remained from the original design). The structure was developed in cooperation between TCCD (Turkey State Railways), TULOMSAS (locomotive construction company) and ASELSAN (manufacturer of electronic equipment in the field of armaments).

For the hybrid locomotive, ASELSAN developed a high-voltage battery unit based on lithium-titanate batteries. The structural diagram of the diesel locomotive is significantly different from the previously considered ones (Fig. 4).

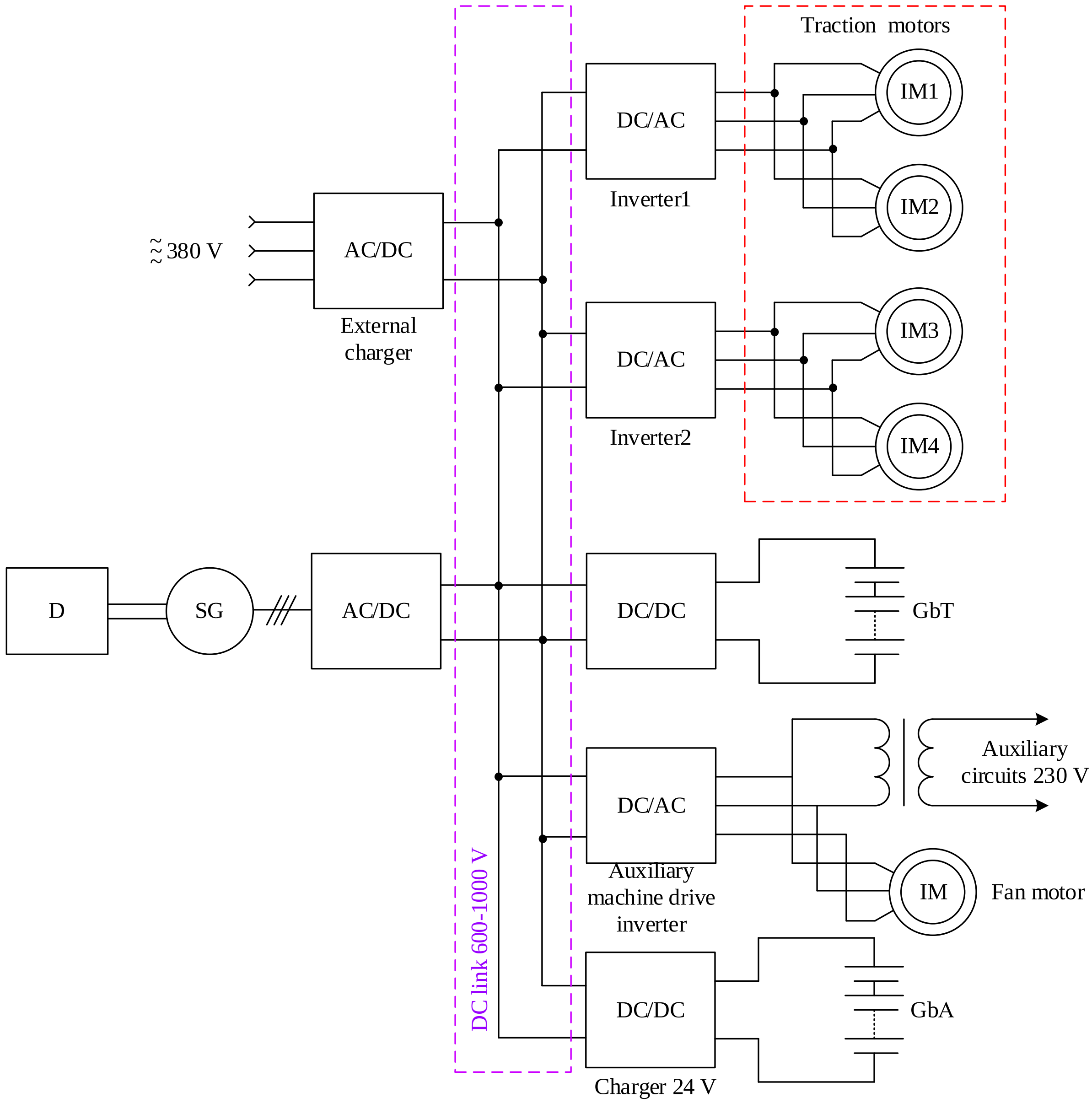

Fig. 4. **Scheme of the HSL-700 hybrid diesel locomotive**

The traction battery (GbT) is connected to the link via a step-up DC/DC converter that provides battery charge and reverse power. This makes it possible to improve battery operation and stabilize the voltage. Traction motors are powered by inverters based on silicon oxide IGBTs (DC/AC). The continuous power (total) is 400 kW with a short-term increase to 700 kW. The converter is designed for an input voltage of 600-1000 V and a current of up to 700 A. A rectifier (AC/DC) is used to charge the battery from an external source, which can provide pulse width modulation (PWM) operation. The auxiliary converter (DC/AC) is fed from the intermediate link and has output channels with three-phase and single-phase alternating voltage for power of 5, 125 and 10 kW. There is a charger for the auxiliary battery (GbA) with a voltage of 24 V.

The converter (DC/DC) has a modular design and a liquid cooling system. The traction battery consists of (GbT) cells, each of which contains four lithium-titanate batteries connected in parallel. Such a battery provides power to consumers with a large current with a significant number of charge-discharge cycles.

Development of the structure of the traction system of the ChME3 electric locomotive with a hybrid power system. The most common way to modernize diesel locomotives is to replace the power plant while retaining the traction electric drive based on collector electric motors. This significantly reduces capital costs. However, there is no significant increase in traction properties of the diesel locomotive, since outdated traction electric motors are used. For such a case, the traction system shown in Fig. 5.

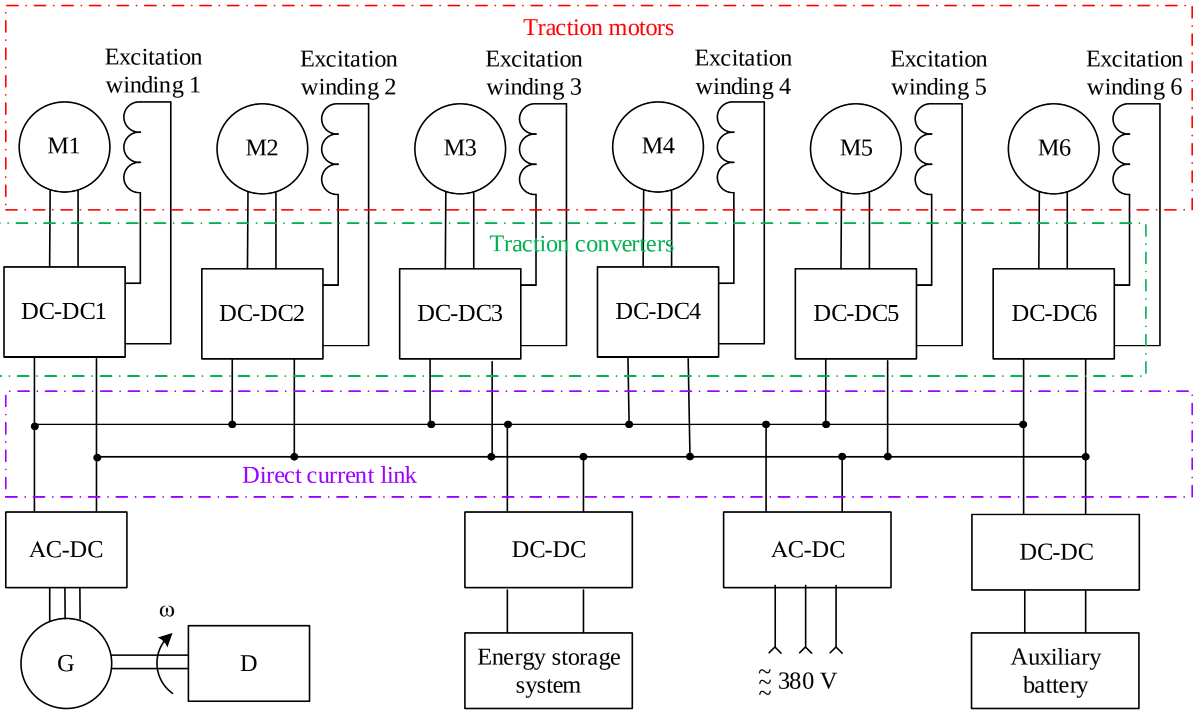

Fig. 5. **Modernized traction system of the ChME3 diesel locomotive with hydrogen power**

The hybrid power plant consists of a modern diesel engine and an alternating current generator, which is connected to the intermediate circuit through a semiconductor converter. The energy storage system through matching converters is also connected to the intermediate circuit. Since the ChME3 diesel locomotive has six traction motors - direct current electric machines with series excitation (M), in the modernized traction system, six controlled constant voltage (DC/DC) converters, which receive power from the intermediate circuit, are used as traction converters. Auxiliary converters are also connected to the intermediate circuit for powering consumers of the locomotive's own needs.

The ChME3 diesel locomotive is used both for shunting and haulage work. When carrying out hauling work, it is possible to move a diesel locomotive as part of a heavy train along a section of the road with long climbs. In this case, movement is carried out with all traction motors. When moving in reserve or with small trains on horizontal sections of the diesel locomotive, a large tractive force is not required. Therefore, movement can be carried out with several turned off electric traction motors. Potentially, this will help reduce energy consumption and, accordingly, fuel.

The following algorithm of power plant operation is proposed. When performing maneuvering operations, the traction electric drive is powered by the energy storage system. This is possible because maneuvers are performed with limited power. If necessary, power is supplied from a diesel generator

During export operation, the power supply of the traction system is provided by a diesel generator, and, if necessary, by an energy storage system that works together.

Charging of the energy storage system is carried out from the external power grid, a diesel generator and during electrodynamic braking.

Justification of the structure of the energy storage system. At present, inertial energy batteries [15], supercapacitors [16] and various types of lithium batteries [16] are used as energy storage schemes in the construction of on-board energy storage for railway rolling stock. There are well-known technical solutions for the construction of on-board energy storage systems that combine supercapacitors and lithium batteries [16]. In addition, lead batteries of various types are used on electric locomotives [17]. It follows from what has been said that when building an energy storage system, a different element base can be used. Determining the parameters of the energy storage system is a complex technical and economic problem [16], when solving which, in order to identify the priority parameters, a preliminary assessment of the options for building an on-board energy storage system should be performed.

Many studies are devoted to the analysis of the properties of various types of energy storage [16]. When choosing an element base for creating an on-board energy storage system for a specific locomotive, the following aspects are taken into account:

1. Inertial energy storage is a complex system that combines electrical, mechanical, aerodynamic subsystems and is created for a specific project taking into account operating conditions. The final appearance of such an inertial energy storage device is difficult to predict, as it requires a detailed study of the engineering and technological solutions necessary for its creation. Capital costs for the creation of an inertial energy store are included in the cost of the locomotive.

2. Compared to other energy storage devices, supercapacitors have the highest specific power values (5-10 kW/kg), but have a low specific energy capacity (5-10 W·h/kg) and the highest specific cost (5000-10000 USD/ kWh) [16]. Therefore, the cost of the energy storage system, which is built on supercapacitors, is high and is included in the cost of the locomotive.

3. In order to analyze the efficiency of application, table 1 shows the parameters of some types of modern lithium batteries [16]. It should be noted that lithium batteries can be optimized for both energy and power.

Table 1. **Parameters of lithium batteries**

Parameter	Battery type		
	NMC	LFP	LTO
Nominal voltage, V	3.6-3.7	3.2-3.3	2.2
C-rate	1	1…10	1…20
Number of charge/discharge cycles	1000…2000	1000…2000	10000…20000
Specific energy capacity, Wh/kg	150…220	90…120	70…205
Specific power, W/kg	-	-	500
Specific value, USD/kWh	100	100	500

From the analysis of the data given in the table 1, it follows that the specific energy cost of lithium batteries is at least an order of magnitude lower than the specific energy cost of supercapacitors. However, it will be necessary to replace the lithium batteries in the energy storage system several times during the entire life of the diesel locomotive. According to the data presented in the study [18], the total cost of lithium batteries, which will be used throughout the life of the diesel locomotive, is close to the cost of supercapacitors. However, the advantages of using lithium batteries when creating an on-board energy storage system are the following factors:

- lower initial cost of the diesel locomotive;
- constant improvement of lithium batteries, which leads both to the improvement of their parameters and to the reduction of their cost;
- other types of lithium batteries appear that can be used in the energy storage system;
- change of modes of operation of the diesel locomotive.

Thus, replacing the elements of the energy storage system after a certain period of time will allow to optimize its parameters taking into account the new operating conditions of the diesel locomotive. Taking into account the above, the most effective element base in the creation of on-board energy storage units of diesel locomotives is the use of lithium batteries.

The structure of the energy storage system requires a separate analysis. The traditional way of performing maneuvering operations is intensive acceleration followed by inertial movement. During acceleration, traction electric motors can work with currents that exceed the nominal by more than 40%. Accordingly, the same level of current overload must be ensured in the energy storage system. This can be done either through cell parameters or by creating a combined storage device from cells of different types.

Conclusions. The paper proposes the structure of the traction system of a shunting diesel locomotive with hybrid power on the example of a ChME3 diesel locomotive, which can perform shunting work at the station and hauling work. The following results were obtained in the work:

- an analysis of the structures of traction systems of diesel locomotives produced by leading global companies was carried out, as a result of which it was established that the most effective scheme is traction power from a separate traction converter;
- the structure of the traction system of a shunting diesel locomotive was developed, where each traction engine receives power from a separate traction converter. Traction engines will be powered from the energy storage system during shunting work, and from the diesel generator or jointly from the energy storage system and the diesel generator during hauling work. Such a traction system will work effectively both when performing shunting work at the station and when performing hauling work.

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Розробка структури тягової системи маневрового тепловозу з гібридною схемою живлення

В цій роботі запропоновано структуру тягової системи маневрового тепловозу з гібридним живленням, що виконує як маневрову роботу на станції, так і вивізну роботу. Для розробки структури тягової системи, що буде ефективно працювати в обох режимах роботи маневрового тепловозу проведено аналіз структур тягових систем тепловозів з гібридним живленням, що випускаються провідними світовими компаніями. З метою вибору оптимального типу накопичувача проведено аналіз переваг та недоліків суперконденсаторних батарей та літій-іонних акумуляторів. На основі проведеного аналізу структур тягових систем тепловозів *з гібридним живленням провідних компаній та переваг і недоліків суперконденсаторних батарей та літій-іонних акумуляторів, розроблено структуру тягової системи маневрового тепловозу з гібридним живленням, що виконує як маневрову роботу на станції, так і вивізну роботу. В запропонованій структурі тягової системи кожен тяговий двигун отримує живлення від окремого тягового перетворювача. Потужність для живлення тягових двигунів при виконанні маневрової роботи передається від суперконденсаторних батарей, при виконанні вивізної роботи – від літій-іонних акумуляторів. Дане дослідження може бути використане при проектування тягової системи нового та при модернізації існуючого маневрового тепловозу.*

Ключові слова: *гібридне живлення, суперконденсатор, літій-іонний акумулятор, маневровий тепловоз, тягова система.*