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Ievgen Riabov[1*], Liliia Overianova[2], Liliia Kondratieva[3], Oleksandr Plyutin[4], Artem Overianov[5]

[1] Assistant professor, Department of Electric Transport and Locomotive Engineering, National Technical University «Kharkiv Polytechnic Institute», Kyrpychova str. 2, Kharkiv, 61002, Ukraine. ORCID: https://orcid.org/0000-0003-0753-514X.
[2] Assistant professor, Department of Electric Transport and Locomotive Engineering, National Technical University «Kharkiv Polytechnic Institute», Kyrpychova str. 2, Kharkiv, 61002, Ukraine. ORCID: https://orcid.org/0000-0002-4827-572X.
[3] Postgraduate student, Department of Electric Transport and Locomotive Engineering, National Technical University «Kharkiv Polytechnic Institute», Kyrpychova str. 2, Kharkiv, 61002, Ukraine. ORCID: https://orcid.org/0000-0002-2788-9116.
[4] Postgraduate student, Department of Electric Transport and Locomotive Engineering, National Technical University «Kharkiv Polytechnic Institute», Kyrpychova str. 2, Kharkiv, 61002, Ukraine. ORCID: https://orcid.org/0009-0009-5199-4344.
[5] National Technical University «Kharkiv Polytechnic Institute», Kyrpychova str. 2, Kharkiv, 61002, Ukraine ORCID: https://orcid.org/0009-0003-7367-2203.

***Corresponding author:** riabov.ievgen@gmail.com

Dual-mode powered locomotives for main routes

The development of railway transport in Ukraine is associated with the improvement of transportation along the routes of pan-European transport corridors, improving rail connections with the countries of the European Union and domestic transportation. This requires the renewal of traction rolling stock, the current technical condition of which does not meet modern indicators of fuel efficiency and environmental friendliness. An analysis of traction rolling stock from world manufacturers shows the interest of railway operators in locomotives with dual-mode power supply. Such locomotives are able receive power both from the contact network and a diesel generator. This provides a number of advantages, the key among which is a reduction in the cost and transportation duration. The designs of ALP-45DP locomotives manufactured by Bombardier Transportation, Vectron Dual Mode manufactured by Siemens Mobility, EURODUAL and Class 93 manufactured by Stadler are considered. It's demonstrated that locomotives with dual-mode power supply are based on the design and components of serial locomotives. This reduces the cost of the explored locomotives, simplifies maintenance and ensures high reliability. At the same time, the presence of dual-mode power supply has influenced the application of specific design and circuit solutions. Energy storage systems, including plug-in accumulators, are promising for use on locomotives with dual-mode power supply. The use of accumulators allows both to accumulate energy during braking and power the locomotive systems, and to store energy from low-cost sources. This reduces the cost of fuel and energy resources. Basing on the analysis fulfilled, the structure of the traction system for a domestic locomotive with dual-mode power supply, which can be created by modernizing existing locomotives, is proposed and substantiated.

Keywords: *locomotive, traction rolling stock, diesel, energy storage, plug-in hybrid power plant, traction system*

Introduction. Three international railway pan-European transport corridors No. 3, No. 5 and No. 9, the transport corridors Gdansk-Odesa (Baltic Sea Black Sea), Europe-Caucasus-Asia (TRACESA), Europe-Asia, also run through the river ports of Ukrainian railways tangent to the pan-European corridor No. 7, which runs along the Danube River [1]. In 2023, the agreement was reached on the creation of a 1520 mm gauge railway corridor between Ukraine and Lithuania [2]. In 2025, construction of a 1435 mm gauge standard from Chop to Uzhgorod [3] began, as well as preparations for the implementation of a project to build a 1435 mm Euro-gauge from the Romanian border to Chernivtsi and from Mostyska-1 station to Lviv. The development of railway connections along these routes is an important target that will accelerate European integration processes. In domestic transportation, the key tasks are the reorientation of freight transportation to rail transport, the renewal of rolling stock for passenger transportation, the replacement of carbon-emitting modes of transport, the advancing of "green" modes of transport, the development of high-speed rail traffic, etc. [4].

Analysis of recent research and problem statement. The development of domestic railway transport is not possible without updating the locomotive fleet. Currently, the main lines are electrified. At the same time, the volume of electrified sections is only 50% of the total length of Ukrainian railways, and many important routes have non-electrified sections. This requires the combined use of diesel locomotives and electric locomotives to drive trains on such routes. An alternative option is to use locomotives with dual-mode power supply, which can be powered both from the contact network and from the on-board power pack. Perhaps the first example of the use of such locomotives on trunk lines is the operation of the P32AC-DM locomotives manufactured by GE [5] and DM30AC manufactured by EMD [6]. Both locomotives are essentially diesel locomotives equipped with a current collection system from the "third rail". This is necessary for service on route sections where the application of diesel engines is impossible. In the 2000s, the BITRAC CC35600 locomotives manufactured by CAF Power [7], ALP45DP manufactured by Bombardier Transportation [8] were created. Recently, the locomotive line has been supplemented with the CLASS 88, CLASS 93, EURO9000, EURODUAL manufactured by Stadler [9], South African Class 38-000, Vectron Dual Mode and ALC-42E manufactured by Siemens [10], Euskotren TD2000 manufactured by CFD [11], Gama 111DE manufactured by PESA [12], locomotives of the BDD, EDD, EBB, BFC (Vossloh) series. and others. Dual-mode power supply technologies are used in the creation of Prima H4 (Alstom) shunting locomotives [13], HDB800 from Toshiba [14]. It is worth to note that energy storage systems are used on these locomotives, as a result of which manufacturers call them locomotives with tri-mode power supply. To a certain extent, locomotives with dual-mode power supply include electric locomotives equipped with power plants to implement the last mile function [15,16].

As can be seen from the experience in the EU and other countries, locomotives with dual-mode power supply are quite common in commercial operation, which confirms the feasibility of its use in rolling stock.

Currently, the locomotive fleet of Ukrainian railways requires significant renewal. A possible option is the application of locomotives with dual-mode power supply, since some important routes have electrified and non-electrified sections. The operation of locomotives with dual-mode power supply on such routes will ensure the improvement of rail transportation.

The exploitation of modern locomotives with dual-mode power supply compared to the technology of operating single-mode locomotives provides [17]:

– increasing the efficiency of locomotive operation due to the "coverage" of electrified and non-electrified sections by one locomotive;

– increasing traffic safety due to the presence of a dual traction system, which will ensure movement in the event of a power outage;

– simplifying the maintenance of routes on which there are electrified and non-electrified sections;

– flexibility of the system for organizing operational work due to the "universality" of the fleet in the case of freight and passenger locomotives;

– introducing alternative routes for freight and passenger trains, which in turn will lead to an increase in railway capacity and transportation efficiency;

– simplifying shunting operations when delivering target routes from door to door to ports and terminals, as well as changing the route;

– reducing harmful emissions into the environment;

– the possibility of reducing the noise level.

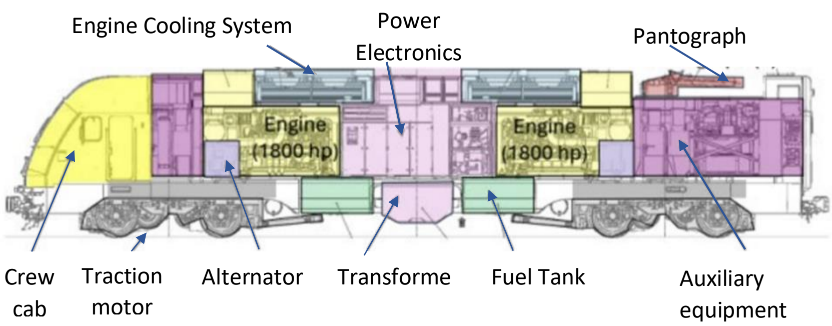
Thus, the use of locomotives with dual-mode power allows simplifying and accelerating rail transportation. This is important for the transport industry of Ukraine, for the development of which the growth of railway transportation is a priority.

The purpose and tasks of the research. The purpose of the article is to analyze the structures and traction systems of mainline locomotives with dual-mode power supply.

Research materials and methods. To date, foreign manufacturers have created several models of locomotives with dual-mode power supply. Below, the main characteristics of locomotives operated on main lines are considered and analyzed.

The ALP-45DP locomotive was developed and manufactured by Bombardier Transportation [8,18]. Fig. 1 shows a general view of the locomotive. The equipment layout is shown in Fig. 2. Table 1 lists the main technical parameters of the locomotive. The locomotives are putted into service on main lines in the USA and Canada.

a



b

Fig. 1. **Locomotive ALP-45DP (photo from the Internet)**
a – general view (photo from the Internet); b) – Equipment placement [8]:

The ALP-45DP locomotive is designed using technologies developed and used in the TRAXX family of locomotives and the ALP-46 electric locomotive [20]. The body is made with a single cab. To meet the requirements of the Association of American Railroads [21], the locomotive body has a reinforced structure. The reinforcement of the body structure was also caused by the use of equipment with a greater weight. To access the internal equipment, the locomotive body has been designed with a removable roof. The locomotive bogies have a reinforced frame structure due to the greater axial load. This also caused the strengthening of the spring suspension and hydraulic vibration dampers. The transmission of longitudinal traction and braking forces between the body and bogies is carried out through two longitudinal inclined pull rods connected to the body in the area of the fuel tanks. This provides high traction properties of the locomotive. The locomotive is equipped with disc and shoe brakes, which provides high braking efficiency.

To ensure high power in autonomous mode, the locomotive uses two high-speed 12-cylinder Caterpillar 3512C HD engines with a capacity of 1567 kW, each of which has a traction asynchronous generator. This solution provides a power plant capacity of over 3000 kW, and also allows movement in the event of a malfunction of one diesel engine.

The set of electrical equipment is similar to the ALP-46 electric locomotive. The main electrical equipment is located in the middle part of the body. The pantograph is situated on the roof in the rear part. A feature is the placement of the traction transformer under the locomotive body, between the fuel tanks.

Table 1. **Technical parameters of the ALP-45DP locomotive [19]**

Parameter	Value
Type of vehicle	Passenger locomotive
Track gauge	1435 mm
Clearance gauge	AMTRAK
Wheelset arrangement	B_0–B_0
Length over coupler, mm	21 800
Width, mm	3310
Virtual distance between bogie centers, mm	13 250
Axle base, mm	2800
Wheel diameter, mm	1118 (new)/ 1046 (fully worn)
Axle load, t	32.66
Total weight, t	130.64
Converter type	IGBT, water cooled
Traction converters	2 x MITRAC TC 3350
System voltage	25 kV/60 Hz, 12 kV/25 Hz
Head-end power (HEP) – train supply capability	1100 kVA, 3 x 480 V/60 Hz
Max. traction power «Electric mode», kW Max. traction power «Diesel mode», kW	4000 2x1567
Max. rheostatic braking power, kW	1200
Max. Starting tractive effort, kN	316
coefficient of adhesion	1:4.06
Max. Brake force (electric brake), kN	150
Brake resistor power, kW	1300
Fuel capacity (usable), l	6044…6800
Max. Service speed «Electric mode», km/h Max. Service speed «Diesel mode», km/h	201 160

Fig. 2 shows a diagram of the traction system of one trolley.

When operating from the contact network, the propulsion electric drive is powered from the traction transformer via four-quadrant converters (active rectifiers). When it powered from a diesel generator, three of the four phases are used, which are formed by two four-quadrant converters. Compared to synchronous generators of any type, this is a cost-effective solution, which, however, became possible and economically viable only thanks to the use of already existing four-quadrant converters. The diesel engines are started by an asynchronous generator, and the active converter is used at that as an inverter. For this purpose, the DC bus can be powered by a battery and one of the phases of the four-quadrant converter as a boost converter in a corresponding other bogie.

By operation under the contact network the energy is regenerated during electrodynamic braking. The rheostatic brake is as well available with a capacity of 2x650 kW.

The locomotive is equipped with a three-phase train power supply system with a capacity of 1100 kVA (1000 kW), regardless of the power mode.

The drive technology is designed in such a way that switching between modes can occur even while the train is moving, without any interruption in the train's power supply. For certain operators, the change can only occur when stopping at a station, to prevent the locomotive from running without power for the 100 seconds required for this.

The Vectron Dual Mode locomotive was developed by Siemens Mobility. Fig. 3 displays the general view (Fig. 3a) and the equipment layout (Fig. 3b). Table 2 consists the technical parameters of the locomotive.

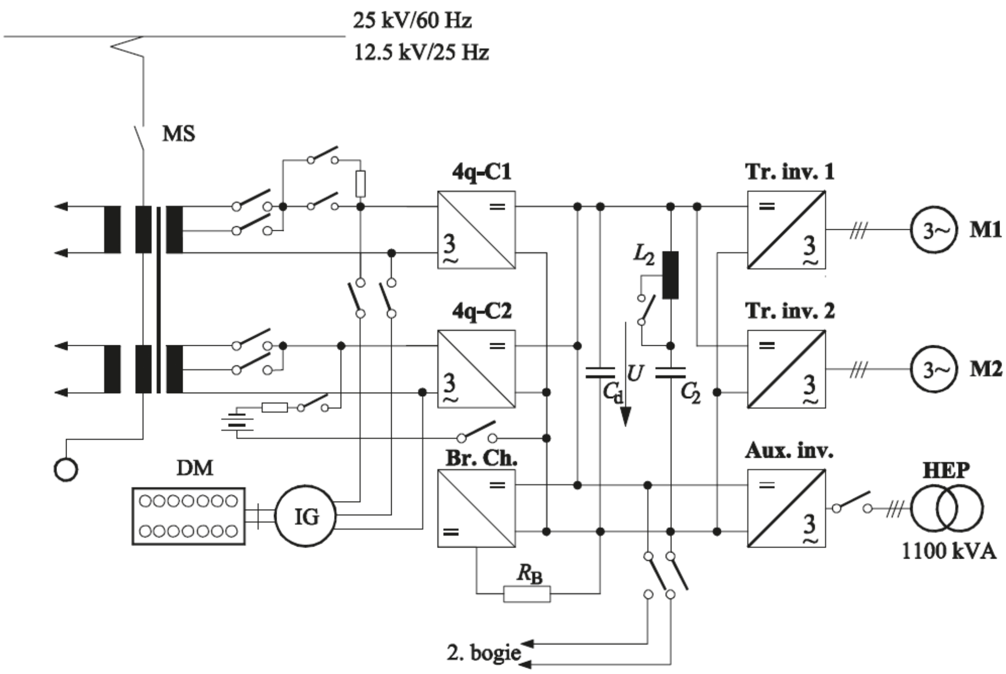


Fig. 2. **Diagram of the traction system of one trolley [19]**
MS – main switch; 4q-C1, 4q-C2 – four-quadrant converters; Br.Ch. – brake converter; R_B – braking resistor; C_d, C_2 – filter; L_2 – inductance; Tr.inv.1, Tr.inv.2 – traction inverters; Aux.inv. – auxiliary inverter; M1, M2 – traction motors; HEP – electric train supply; DM – diesel motor; IG – generator

The aim of the Vectron Dual Mode locomotive was to create a modern, environmentally friendly and powerful mainline locomotive that combines the advantages of diesel and electric traction [22]. This provided operators with the opportunity to make long trips with the same locomotive, which could overcome both electrified and non-electrified sections.

The Vectron Dual Mode locomotive is an evolution of the existing Vectron DE locomotive, to which appropriate equipment was added to ensure its operation from the catenary network. The traction properties of the locomotive in both modes are approximately the same, since the main area of application of the locomotive is driving trains moving under diesel traction. Fig. 4 represents the traction and braking characteristics of the Vectron Dual Mode.

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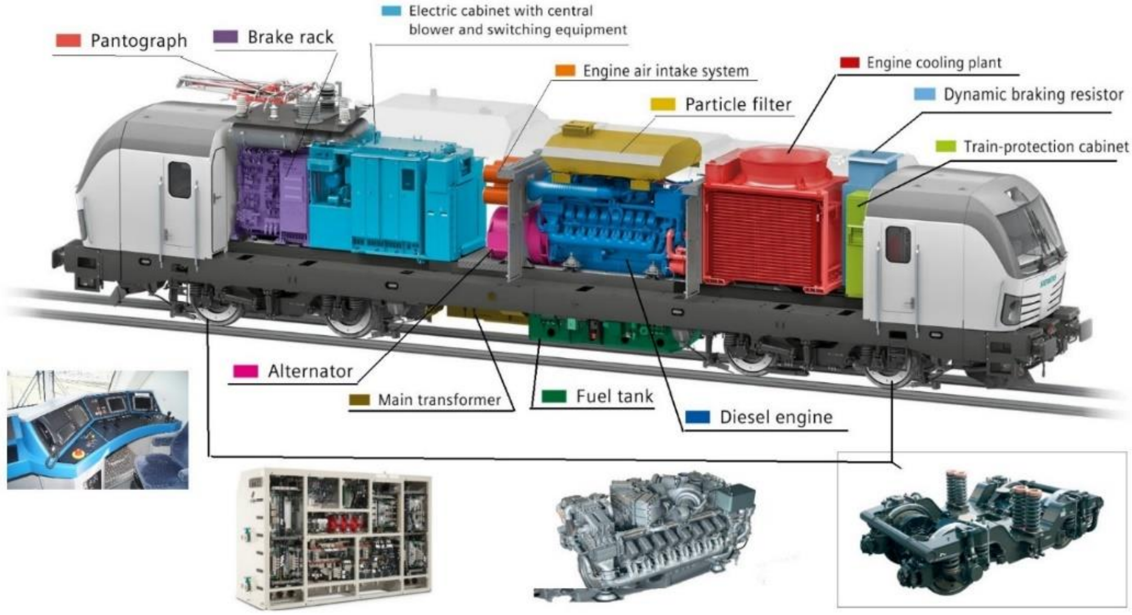


б

Fig. 3. **Vectron Dual Mode Locomotive**
a – general view (photo from the Internet); b – equipment placement [22]

The locomotive is designed as a mainline locomotive with two end cabs. The driver's cabs are identical to the Vectron E locomotive or the previous Vectron DE locomotive. The engine cabinet (Fig. 3b) is divided into three separate chambers by two partitions. The electrical chamber, located behind the driver's cab, contains the most important electrical functional components. These include the converter (with integrated equipment for switching between electric mode and diesel mode), the auxiliary system module, the pneumatic brake equipment and the air cleaning system for the diesel engine. In the middle of the locomotive is the diesel engine compartment, which is completely closed. This ensured its soundproofing. The diesel engine with an exhaust system and the preheating/heating support device for the diesel engine is located in the diesel compartment. Directly above the diesel engine is a particulate filter that acts as a silencer. Inside the particulate filter are individual replaceable filter elements. This arrangement of the particulate filter above the engine minimizes the number and length of exhaust pipes with high thermal load, as well as heat radiation to the engine compartment. A preheating/heating maintenance device with an installed thermal output of 35 kW ensures a smooth start of the diesel engine. The start itself is carried out using a starting system based on double-layer capacitors, so-called Ultra-Caps. Unlike conventional starter batteries, these energy storage devices are smaller and lighter, practically maintenance-free and have significantly better properties at low temperatures. Directly below the engine system is a 2,600-liter fuel tank, which can be filled from both sides, as well as a main transformer with a corresponding cooling system. The third segment of engine compartment contains the diesel cooling system, braking resistor and standard protection cubicle. All engine room components are located in the center.

Two through side passages provide good access for maintenance or changing direction. The essential feature of the less complex system is the usage of only one diesel engine and the intelligent combination of all components, fewer and easily replaceable individual modules. This results in a small number of interfaces, which in turn minimizes the number of possible electrical and mechanical sources of error, such as oil, coolant or fuel leaks.

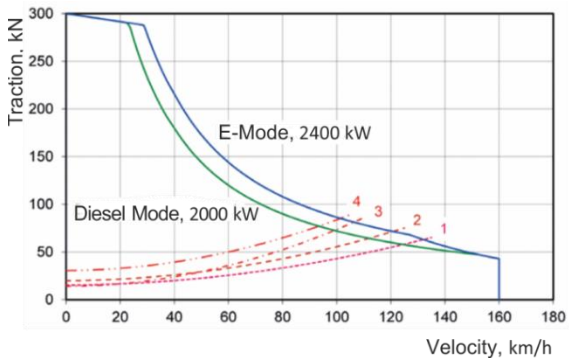
Table 2. **Technical parameters of the Vectron Dual Mode locomotive**

Parameter	Value
Area of application	Freight / Passenger
Wheelset arrangement	B_0-B_0
Vehicle length (length over buffers), mm	19975
Track gauge, mm	1435
Fuel tank volume (usable), l	2600
Wheel diameter. mm	1100 (new) / 1020 (worn)
Wheelset load, t	22.5
Weight (max.), t	90
Voltage system	AC 15 kV, 16.7 Hz
Diesel engine power (at the crankshaft), kW	2400
Traction power at the wheel rim, kW Electric mode (max.) Diesel mode	 2400 2000
Starting tractive effort, kN	300
Electric braking power at the wheel rim, kW Electric mode (max.) Diesel mode	 2100 1700
Electric braking effort, kN	150
Train protection	PZB, ready for ETCS
Traction gear type	Cog-wheel-hollow shaft
Gear ratio	1:5.1
Train power supply	1000 V, 22 Hz resp. 16.7 Hz; 480 kVA
Max. Speed, km/h	160
Double traction	Via WTB ÖBB: with same-type vehicles as well as Vectron E, Vectron DE, and ER20
Operation ambient temperature	-30°C….+40°C

The cooling system of the main transformer has three fans that can be switched on and off separately as required. The main transformer is characterized by a particularly compact design. The absorption circuit choke is also located in the transformer tank, which is filled with synthetic ester. This minimizes the noise level, especially at train stations. The side cooling tower system serves exclusively for cooling the diesel engine. The main features of the cooler are the infinitely variable cooling fan with hydrostatic drive and highly efficient aluminum radiators. The cooling system performance is designed for high loads, so the diesel engine does not experience any reduction in performance at outside temperatures of up to 35°C. For inspection and maintenance of the cooling system, access to the interior is possible at the same level via the end service door.

In contrast to purely electric locomotives, a locomotive with a powerful diesel engine requires a significantly higher air flow rate. The locomotive body is therefore specially adapted to the requirements of the diesel engine air supply. The combustion air is specially drawn in through an opening on the side of the electrical chamber. To meet the high air requirements for the diesel engine cooler and the brake resistor, large intake openings are locating in the cooler compartment.

The locomotive is powered by a 4000 series diesel engine from MTU Friedrichshafen, which is already used on the Vectron DE. The engine is a 16-cylinder V-engine. When idling, the engine control unit switches off the cylinders, meaning that in this operating mode the engine operates only with 8 cylinders at a time, which also minimizes fuel consumption in this operating mode. The engine is two-stage with turbocharging. The proportional reduction in exhaust emissions in the engine is achieved by recirculating the cooled exhaust gases. By choosing a large diesel engine that has been specially optimized for operation by railway, it can be perfectly tuned to the optimum maximum tractive effort with minimized fuel consumption, while adhering to the specified exhaust emission limits using the appropriate engine control parameters. The diesel engine used in the Vectron Dual Mode complies with the European Stage V emissions standard.



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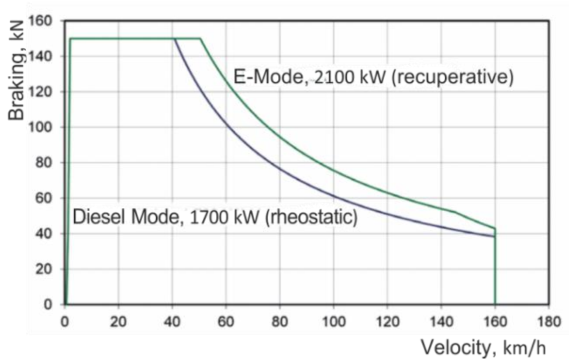


b

Fig. 4. **Traction and braking characteristics of the Vectron Dual Mode locomotive [22]**
a – traction characteristics; b – braking characteristics:
4 Vectron DM + loaded container train/block train 2,500 t hauled load on flat route;
3 Vectron DM + mixed freight train 1,200 t hauled load on flat route;
2 Vectron DM + loaded container train/block train 1,600 t hauled load on flat route;
1 Vectron DM + loaded container train/block train 1,200 t hauled load on flat route

The Vectron Dual Mode bogie is a further development of the long-proven SF3 Eurorunner ER20 bogie. It has been adapted to current standards and the maximum speed has been increased from 140 km/h to 160 km/h. This means that not only freight but also regional passenger traffic is fully covered. In addition, the maximum permissible axle load has been increased to 22.5 t. Since the locomotive is primarily intended for freight transport, the sand supply system has been designed in such a way that sand is supplied to the front wheels of both bogies in both directions of travel (8-fold sprinkling). In addition, the drive clutch control has been further improved to achieve the highest possible use of tractive force.

Fig. 5 displays a diagram of the traction system of the Vectron Dual Mode locomotive.

The propulsion system of the locomotive consists of a three-phase synchronous generator G with independent excitation, high-voltage equipment, a transformer, a power converter with IGBT power semiconductors and four three-phase asynchronous traction motors powered by the converter. The central converter unit, which was essentially borrowed from the Vectron DE, contains all the electrical equipment for the locomotive controlling. Two traction motors are powered by a pulse-controlled inverter from the DC intermediate circuit. The intermediate circuit is powered by a contactless three-phase synchronous generator via an uncontrolled rectifier bridge. The converter unit also contains an auxiliary power inverter that feeds an auxiliary network of 3x440 V, 60 Hz from the intermediate circuit to power internal consumers. The arrangement of the pulse inverters and auxiliary converters on a common intermediate circuit allows auxiliary systems to be powered by the regenerated braking energy during electrodynamic braking and thus ensures that the locomotive operates with optimized energy consumption. The roof segment above the power converter located a current collector, a main switch with an attached earthing conductor and two arresters for overvoltage protection. The design of the high-voltage equipment takes into account the possible option of a locomotive powered by a 25 kV network. The braking energy during electrodynamic braking is fed back into the energy overhead network during electric operation (regenerative braking). When operating on a diesel engine, excess braking energy that cannot be used to power the auxiliary systems is dissipated via the brake drive and the braking resistor (rheostatic braking). The braking resistor is designed in the form of a tower, as in the electric versions of the Vectron. This has allowed for an increase in power to 1,700 kW. This proven braking resistor was adopted from the Vectron DE without modification. The Vectron Dual Mode drive consists of the proven hollow shaft gear drive, which is already used as standard in all Siemens Eurorunner ER20 diesel locomotives. It differs from the drive of the Vectron electric locomotive variants in that the nominal power is adapted to the diesel engine. This results in weight savings, which is important for a dual-mode locomotive.

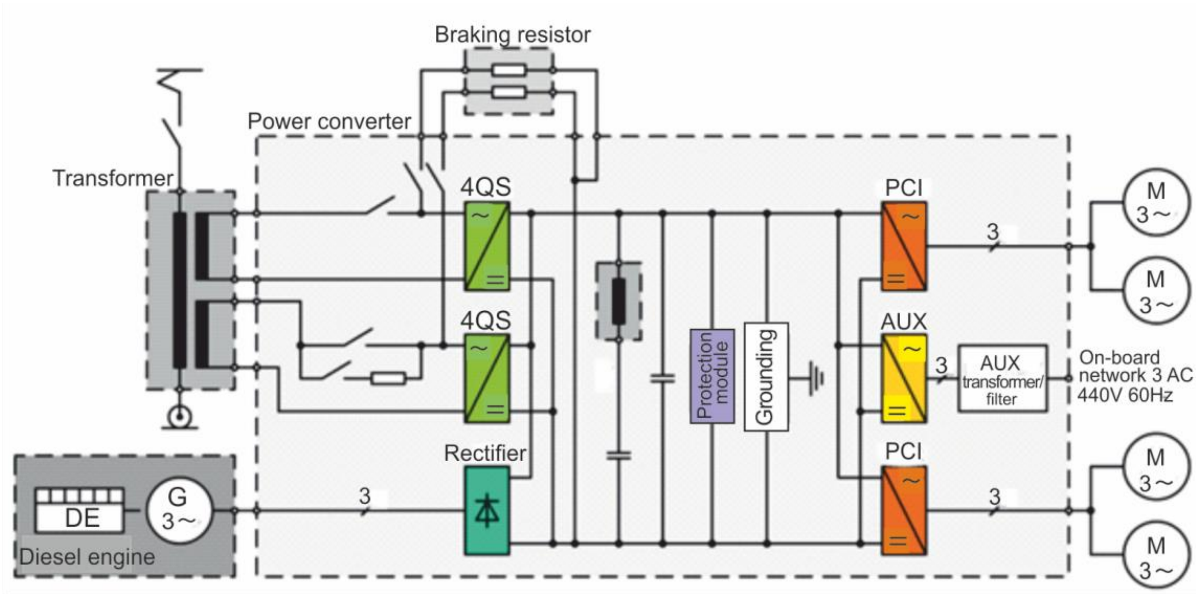


Fig. 5. **Diagram of the traction system of the Vectron Dual Mode locomotive [22]:**
4QS – four-quadrant converter; G – generator; PCI – pulse-controlled inverter;
AUX – auxiliary power inverter; M – traction motor

An important function of a dual-powered locomotive is the switching between electric and diesel operation. This switching is possible for the Vectron Dual Mode while in motion. The intermediate circuit remains charged and the auxiliary systems are continuously powered. The duration of the interruption of traction during the switch is minimal and amounts to a few seconds and therefore does not affect the movement. The switchover process is initiated by the train driver via the display and is largely automatic. Due to safety requirements, the driver must perform several operations/confirmations. For example, he must look after the lifting of the pantograph to ensure that the locomotive is under the contact wire. The corresponding preheating/heating maintenance concept ensures that the diesel engine is always ready to start with little wear.

As an evolution of the series is the Vectron Dual Mode Light locomotive with a less powerful diesel engine.

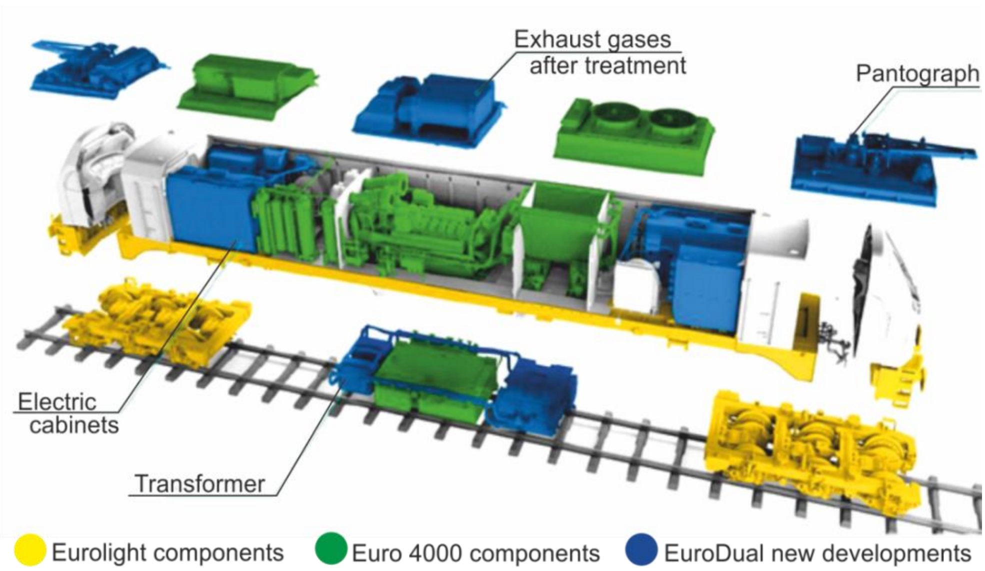
The EURODUAL locomotive was developed by Stadler. Fig. 6 shows the general view (Fig. 6a) and the design structure (Fig. 6b) of the EuroDual locomotive. Table 3 shows the technical parameters of the locomotive.

The EURODUAL locomotive is based on proven models such as EURO4000 and EUROLIGHT (Fig. 6b). The following advantages were achieved when creating the locomotive:

– multi-purpose locomotive for freight and passenger transportation;
– AC, DC or multi-system contact network;

– AC traction system with IGBT;
– for various engine powers up to 3000 kW;
– high starting tractive effort of 500 kN, both in diesel and electric modes(with each single axle control);
– high wheel-rail adhesion;
– remote radio control for effective shunting work;
– extremely low track forces due to the most modern design of the three-axle bogie with support-frame suspension of traction electric motors;
– equipped with the latest version of ETCS BL3.4.0 and all national class B systems;
– designed for (digital) automatic coupling;
– monocoque construction made of high-strength steel;
– multi-unit operation possibility;
– cross-border operations;
– reduced environmental impact.

a



b

Fig. 6. **EURODUAL locomotive:**
a – general view (photo from the Internet); b – locomotive design [23]

In autonomous operation, the power source is the CAT C175-16 ACERT TM diesel engine, which is derived from the successful Caterpillar C175 series, which is commonly used in diesel-generator sets and heavy earthmoving equipment. The C175-16 engine is a 16-cylinder V-cylinder four-stroke engine with a cylinder diameter of 175 mm and a stroke of 220 mm, a working volume of 84.7 liters and a power of 3755 h.p. (2800 kW) at 1740 rpm. It uses electronically controlled fuel injection, which allows for precise adjustment of the injection according to the requirements applied to the engine. The injection strategy, which is possible at this engine, can be changed depending on the load, speed, engine temperature, air temperature and fuel temperature. The engine is equipped with four turbochargers with two-stage cooling and weighs 11 tons. CAT engines meet European 2012 IIIB emission standards by replacing the muffler with a diesel particulate filter. Engine maintenance can be performed at intervals of 1,000 hours between minor maintenance (oil change) and of 18,000 hours between heavy work (overhaul).

Table 3. **Technical parameters of the EURODUAL locomotive**

Parameter	Value
Locomotive type	Dual-mode: Electric / Diesel-electric
Track gauge, mm	1435 (1520)
Axle arrangement	C_0-C_0
Length, m	23.02
Width, m	2.900
High,	4.290
Virtual distance between bogie centers, m	17.60
Wheel Base, m	3.60
Service weight, t	123
Friction weight, t	123
Axle load, t	20.5
Coefficient of adhesion	1:2.41
Electric power supply	DC (1500 V, 3000 V), AC (25 kV 50 Hz and 15 kV 16.7 Hz) Multisystem
Diesel engine	CAT C175-16, IIIB (Emission level according to EU standard EC 26/2004 Stage IIIB)
Engine power, kW	Up to 3000
Electric power at wheel rim, kW	Up to 7000
Starting tractive effort, kN	500
Fuel tank, l	Up to 4000
Transmission	AC/AC
Maximum speed, km/h	120
Brake system	Mechanic: Pneumatic Dynamic: Regenerative/ rheostatic 2 distributors, one per bogie Bail off functionality
Suspension	Primary: Coil springs Secondary: Rubber metal Vertical and horizontal dampers

Some components of the diesel generator are made of aluminum rather than steel to reduce weight. The ABB generator was specifically designed for use with the C175 engine and is attached directly to it. The engine/generator assembly uses a flexible five-point mounting system.

The traction system is built using ABB equipment. ABB’s Bordline CC1500 DE converter is a latest-generation device used in the Swiss manufacturer’s double-decker trains. It was therefore logical for Stadler to use it for its Euro Dual. The traction converter control must not only optimize the voltage waveforms supplied to the engines, but also ensure that the transmission is not a source of disturbances, oscillations or harmonic pollution for the power supply side. Using modern IGBT technology that controls each traction motor individually, the Bordline CC1500 DE generates a wave-like quasi-sinusoidal current, which reduces harmonic losses, acoustic noise and mechanical stress on the traction motor. On the EuroDual, the converter control must minimize generator waveform distortion to reduce wear and optimize fuel efficiency.

According to ABB, the secret to the compactness and power density of these ABB traction converters is basing on their internal liquid cooling, modular design and carefully manufactured aluminium or stainless steel housings. This has allowed two of them to be installed in the Euro Dual, one per bogie. Each channel has its own rectifier to create a DC intermediate power supply, a brake chopper and drive operation electronics (AC800 PEC) with manual control, two traction inverters and an auxiliary inverter.

The EURODUAL locomotive can operate in the following operating modes [24]:

– Last Mile operation;
– Diesel service with electrified stations;
– Dual operation on electrified and non-electrified lines;
– Diesel detour to avoid highly populated areas (e.g. cities) and stop time;
– Power-boost with diesel engine on electrified lines;

A further development of Stadler locomotives is the implementation of energy storage systems in the power plants of locomotives. For example, an energy storage system can be used on the EuroDual locomotive, which will provide a tangential power of 2400 kW [25]. The layout of the equipment of such a locomotive is provided in Fig. 7.

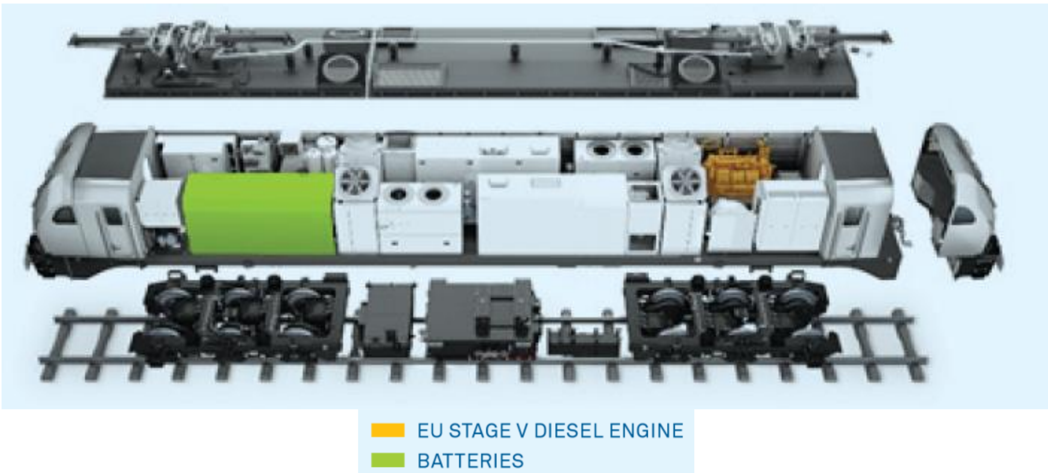


Fig. 7. **Design of a locomotive with an energy storage device [25]**

Energy storage devices in the traction system were used by creation of the *Class 93 locomotive* (Fig. 8).

Table 4 represents the main technical parameters of the locomotive. Fig. 9 displays a diagram of the traction system.

The locomotive is equipped with a Caterpillar C32 diesel engine, which has a power of 900 kW at 1800 rpm, and an energy storage system consisting of two traction batteries with a power of 200 kW each. A hybrid operation mode with a diesel engine and batteries is possible, which provides a combined power of 1300 kW.

Fig. 8. **General view of the Class 93 locomotive (photo from the Internet)**

Table 4. **Technical parameters of the Class 93 locomotive**

Parameter	Value
Axle arrangement	B_0-B_0
Weight, t	86
Track gauge, mm	1435
Maximum speed, km/h	180
Maximum tractive effort, kN	290
Continuous traction force, kN	229
Power in power supply mode from the catenary network 25 kV, 50 Hz	4000 кВт
Diesel engine power, kW	900
Power of the energy storage system, kW	2x200
Power in hybrid mode (diesel/battery), kW	900+400
Power in booster mode when powered from the catenary network, kW	4600
Fuel tank capacity, l	3600

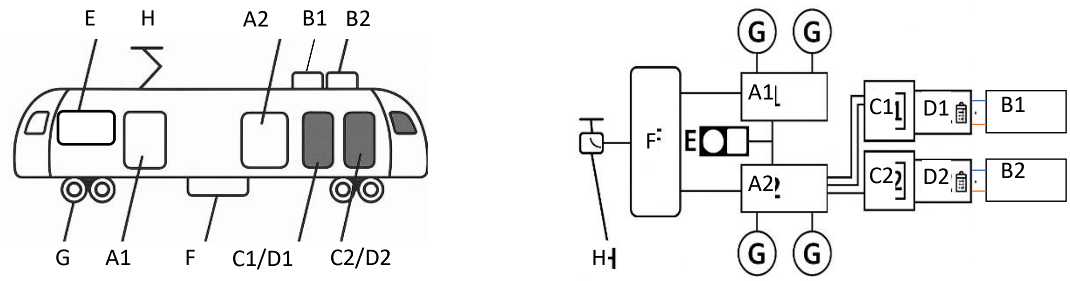


Fig. 9. **Diagram of the traction system of a Class 93 locomotive [26]**
A1, A2 – Compact converter; B1, B2 – Battery thermal management system; C1, C2 – Energy Storage System (ESS) filter; D1, D2 – Energy Storage System; E – Diesel generator unit; F – Transformer; G – Drive motors; H – Pantograph with main circuit breaker

The Caterpillar C32 diesel engine is a 12-cylinder, four-stroke, turbocharged engine with mechanical-electrical unit injection (MEUI) to meet Stage V emissions.

The traction batteries are an energy storage system (ESS) consisting of two lithium titanate oxide (LTO) traction batteries. These batteries can be charged from the overhead contact line or from the diesel engine. In ESS mode, the power is supplied as follows: energy from the batteries is supplied to a DC-DC converter, where the voltage is stepped up. The output current is fed into the DC link, and the current from the link is then inverted to AC by the traction and auxiliary inverters to power the traction motors and auxiliary loads respectively.

The Class 93 locomotive is equipped with four asynchronous AC traction motors. These motors are force-cooled and are individually controlled by four separate traction inverters. When operating at constant load, the motor has a rated power of 1050 kW at rotational frequency of 1281 rpm. This provides a rated electrical power of 4 MW when powered by the catenary, which can be increased to 4.6 MW in "Boost" mode.

Class 93 locomotives have an electrodynamic brake. When operating from the catenary, energy will be regenerated to the catenary. When the locomotive is operating in diesel or hybrid mode, the energy from the electrodynamic braking will be used to power the load of auxiliary systems and power the passenger cars or to charge the batteries.

Basing on the conducted analysis, two approaches can be distinguished to creating locomotives with dual-mode power supply for mainline operation. In the first case, the traction characteristics of the locomotive do not differ much when powered by the contact network and in diesel operation. Such locomotives are oriented for use on routes with predominantly non-electrified sections. In the second case, the power of the locomotive when powered by the contact network significantly exceeds the power when operating on diesel. Such locomotives are operated on routes with a predominant share of electrified sections. However, the power of the diesel is sufficient for movement on main lines. Another option is to use a diesel generator to provide the last mile function. In this case, the power of the diesel generator is sufficient for shunting operations with the train. An example is the TRAXX AC3 locomotive with a capacity of 5600 kW, where a diesel generator with a capacity of 240 kW is used. Thus, the option of a locomotive with dual-mode power supply is determined by the conditions of its operation.

For Ukrainian railways, it is considered as reasonable to use the above mentioned approaches, in which some of the locomotives will be diesel locomotives with the ability to be powered from the contact network, and some will be electric locomotives equipped with a sufficiently powerful diesel generator set or a low-power diesel engine to provide the last mile function. Given that Ukrainian railways are electrified with both alternating and direct current, it will be rational to provide power from these both power supply systems.

Usage of a plug-in energy storage device as part of a hybrid traction system will contribute to reducing costs for fuel and energy resources. This will occur, firstly, as a result of the accumulation of energy during electrodynamic braking and its subsequent use to power the traction system and auxiliary consumers. Secondly, since the plug-in storage device can be charged from a low-cost energy source, in autonomous driving mode, there is a possibility of longer-term power supply with low-cost energy.

Basing on the analysis of the designs of locomotives with dual-mode power supply, the following option for structure of traction system can be proposed (Fig. 10).

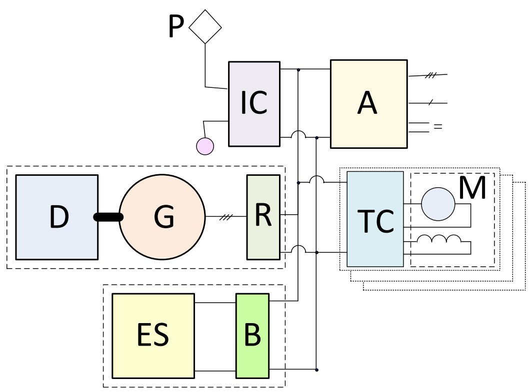


Fig. 10. **Plug-in hybrid traction system diagram using traction collector electric motors**
P – current collector; IC – input converter; A – auxiliary systems power supply; D – diesel; G – generator; R – rectifier; TC – traction converter; M – traction electric motor; ES – energy storage; B – matching converter

The scheme shown in Fig. 10 can be applied in the case of using a traction electric drive with AC electric motors. In this case, the traction converters are autonomous voltage inverters that power and control the traction electric motors. In the case of usage of high-voltage traction inverters operating at a voltage of 4000 V, it is reasonable to connect them directly to the contact network. In this case, a pulse voltage regulator is not used. The voltage of the intermediate circuit is chosen to be about 3000…4000 V.

It is foreseeing that a locomotive with a dual-mode power supply should be a freight-passenger one. In this case, single section is used in passenger operation mode, and for hauling of freight trains, locomotives are operated in a system of multiple units. In the case of locomotives application mainly with freight trains, it would be reasonable to create a specialized two-section locomotive.

Conclusions. Currently, the operation of dual-powered locomotives is advisable on routes with combination of electrified and non-electrified sections. The advantages of application of dual-powered locomotives are the reduction of costs by purchasing of such locomotive (one instead of at least two types of locomotives); reduction of travel time due to the elimination of locomotive changes; reduced track use fees, since you can move less on any tracks; reduced costs for diesel fuel, maintenance and repair of a diesel engine; decrease of harmful emissions.

Analysis of the designs of dual-mode locomotives demonstrated that when creating them, typical components from serial locomotives are kept in design. This reduces the cost of designing and manufacturing such locomotives. At the same time, the design of certain components and elements of the locomotive is adapted and optimized for operation from two power sources.

As further evolution of propulsion systems of dual-powered locomotives is the implementation of energy storage devices. This allows you to accumulate energy during electrodynamic braking and use it in traction mode. As a result, the consumption of fuel and energy resources and harmful emissions are reduced. When using a plug-in energy storage device, which can be charged with low-cost energy, the greatest reduction in the cost of fuel and energy resources is achieved.

The creation of a domestic locomotive with dual-mode power supply is possible by modernizing existing locomotives. The proposed generalized diagram of the traction system takes into account the possibility of powering of the locomotive from the AC and DC contact network and provides the application of a plug-in hybrid power plant.

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Євген Рябов[1*], Лілія Овер'янова[2], Лілія Кондратьєва[3], Олександр Плютін[4], Артем Овер'янов[5]

[1] Доцент, Кафедра електричного транспорту та тепловозобудування, Національний технічний університет «Харківський політехнічний інститут», вул. Кирпичова, 2, м. Харків, 61002, Україна. ORCID: https://orcid.org/0000-0003-0753-514X.

[2] Доцент, Кафедра електричного транспорту та тепловозобудування, Національний технічний університет «Харківський політехнічний інститут», вул. Кирпичова, 2, м. Харків, 61002, Україна. ORCID: https://orcid.org/0000-0002-4827-572X.

[3] Аспірантка, Кафедра електричного транспорту та тепловозобудування, Національний технічний університет «Харківський політехнічний інститут», вул. Кирпичова, 2, м. Харків, 61002, Україна. ORCID: https://orcid.org/0000-0002-2788-9116.

[4] Аспірант, Кафедра електричного транспорту та тепловозобудування, Національний технічний університет «Харківський політехнічний інститут», вул. Кирпичова, 2, м. Харків, 61002, Україна. ORCID: https://orcid.org/0009-0009-5199-4344.

[5] Національний технічний університет «Харківський політехнічний інститут», вул. Кирпичова, 2, м. Харків, 61002, Україна. ORCID: https://orcid.org/0009-0003-7367-2203.

***Автор,відповідальний за листування**: riabov.ievgen@gmail.com.

Локомотиви з дворежимним живленням для магістральних маршрутів

Розвиток залізничного транспорту України пов'язаний з удосконаленням перевезень маршрутами пан'європейських транспортних коридорів, покращенням залізничного сполучення з країнами Євросоюзу та внутрішніми перевезеннями. Це потребує оновлення тягового рухомого складу, поточний технічний стан якого не відповідає сучасним показникам паливної ефективності та екологічності. Аналіз тягового рухомого складу світових виробників показує зацікавленість залізничних операторів у локомотивах з дворежимним живленням. Такі локомотиви можуть отримувати живлення від контактної мережі та дизель-генератора. Це надає ряд переваг, ключовими серед яких є зниження вартості та тривалості перевезень. Розглянуто конструкції локомотивів ALP-45DP виробництва Bombardier Transportation, Vectron Dual Mode виробництва Siemens Mobility, EURODUAL та Class 93 виробництва Stadler. Показано, що локомотиви з дворежимним живленням базуються на конструкції і вузлах серійних локомотивів. Це зменшує вартість досліджуваних локомотивів, спрощує обслуговування та забезпечує високі показники надійності. Водночас наявність дворежимного живлення вплинула на використання специфічних конструктивних і схемотехнічних рішень. Перспективними для застосування на локомотивах з дворежимним живленням є системи накопичення енергії, у тому числі plug-in накопичувачі. Використання накопичувачів дозволяє як акумулювати енергію при гальмуванні і живити системи локомотиву, так і запасати енергію від джерел з низькою вартістю. Це зменшує вартість паливно-енергетичних ресурсів. На основі проведеного аналізу запропоновано і обґрунтовано структуру тягової системи для вітчизняного локомотиву з дворежимним живленням, який може бути створений шляхом модернізації наявних локомотивів.

***Ключові слова**: локомотив, тяговий рухомий склад, дизель, накопичувач енергії, plug-in гібридна енергетична установка, тягова система.*