

# MODERNISING THE DS3 LOCOMOTIVE FOR AC/DC DUAL-SYSTEM OPERATION: CROSS-BORDER INTEROPERABILITY AT EU-UKRAINE INTERFACES

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**Abstract.** The analysed research question raises the problem of modernisation of technical specifications of the locomotive on electric traction. The authors of the scientific research consider the modernisation of the DS3 locomotive with the transition from a single-phase (25 kV 50 Hz AC) to a two-phase (25 kV 50 Hz AC/3 kV DC) power supply system, which aims to increase interoperability with neighbouring railway networks. A multi-level literature review has been carried out, transient and dynamic characteristics have been modelled in MATLAB, and the principles of control of traction converters and motors have been formulated. Ensuring stable operating modes when switching power systems is confirmed by optimal attenuation  $\zeta \approx 0.7$ , and the electromagnetic compatibility analysis has revealed characteristic interference of 500–3000 Hz, thus allowing us to propose filters in accordance with EN 50121. The radar graph of the comparative analysis provides an improvement in the main metrics (power, traction efforts, efficiency, and reaction time) in the context of an ideal 100% scale. A step-by-step roadmap for the functional compatibility of ERTMS / ETCS and GSM-R in the Siemens SIBAS 32 platform has been designed and technical conditions for

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certification according to TSI and EN standards have been formed. The modernisation of DS3 is recognised as technically feasible, cost-effective and compliant with international technical aspects, which ensures prospects for joint operation in Ukraine and the EU.

**Keywords:** dual-system locomotive (AC 25 kV 50 Hz; DC 3 kV), electromagnetic compatibility, interoperability, modular multilevel converter, pantograph, power supply, railway, rolling stock, SIBAS 32.

## Introduction

The technical condition and versatility of the locomotive fleet is one of the fundamental properties of a railway company. After all, it is important not only what kind of track is used or how the movement is regulated, but also what kind of locomotive is used when performing cargo and passenger logistics from point A to point B. Considering the current state of the locomotive fleet of electric locomotives of JSC “Ukrainian Railways” (UR), the total number of this type of machines is about 1630 units, of which wear is 94.4%, which is a fairly critical figure. The reasons for such a deplorable situation are a gap in the design of planning and conceptuality and a regular lack of economic support for investing in the purchase of new units (Buresh, 2021). One of the most functional and modern machines among the obsolete rolling stock of UZ is DS3. This equipment was manufactured by the Dnepropetrovsk Electric Locomotive Plant (mechanical and crew parts, assembly) in collaboration with the German conglomerate Siemens (traction converters and electronics) and the Smelyansky Electromechanical Plant (traction motor). The participation of several enterprises makes the locomotive under consideration unique, as it allowed demonstrating in real conditions the latest technological solutions of that time, including high-performance traction converters, asynchronous motors and microprocessor technology of motion coordination from Siemens. The first test copy was created in 2002, and mass production was carried out from 2005 to 2008. During three years of construction, only 18 copies were built, which was an insufficient production volume, given the operational characteristics and needs of the Ukrainian railway system. Such a number of sold DS3 is not enough for a full-scale renewal of the electric locomotive fleet. In addition to the problem of a shortage in the receipt of traction units, there is also a limited operational capability of the locomotive – single-phase and operation only with a voltage of 25 kV 50 Hz alternating current. Considering that in addition to this voltage standard, the Ukrainian railway system is also represented by 3 kV DC, this reduces the use of DS3 on all rail transport lines. Moreover, there is a functional inconsistency with the energy infrastructures of neighbouring countries, such as Poland and Slovakia, which also use 3 kV DC and reduce the import-export potential and interoperability of the Ukrainian railway systems with these countries. Based on the above arguments, it becomes urgent and strategically important to develop a two-system

modification of the DS3 locomotive, which would significantly improve the process of interoperability of railway systems and improve the operational flexibility of the rolling stock of JSC “Ukrainian Railways”. Similar technical concepts have been implemented earlier and are used in European countries. The same Siemens presented a two-phase locomotive Vectron MS, and the French giant Alstom showed its version of a two-phase traction unit – Traxx MS. The objective and evaluation criteria in this paper are to evaluate the feasibility of upgrading a single-system DS3 to a dual-system AC/DC mode. The feasibility is assessed by simulating the AC↔DC switching in the time and frequency domains, and by checking compliance with EN 50163/50367 (power supply and pantograph) and EN 50121 (electromagnetic compatibility).

## **1. Literature review on locomotive modernisation from single-phase to a two-phase power supply system**

This section covers scientific articles and works of other authors who have fully investigated the structure of the locomotive in a multi-faceted manner. In particular, all existing engineering solutions that will make the modernisation of the DS3 effective are analysed and systematised. In the initial phase of consideration, works that describe the technical re-equipment of the power supply system are considered. Since the basic characteristic of the DS3 is to work with voltages of 25 kV 50 Hz AC, it is necessary to pay attention to the improvement of this component. Chen et al. in their article consider a new modelling – a combined single-phase power supply system. The architecture of such a structure will consist of a single-phase multifunctional transformer and a single-system reversible converter, which is called power-factor correction (PFC). In the traction circuit, the transformer and PFC provide uninterrupted current with a standard frequency for the locomotive with the voltage value of the same phase; therefore, the neutral compartment at the output of the substation can be cancelled. The PFC itself consists of a converter, the frame of which is based on a four-bridge modular multilevel converter (MMC). Compared to the two-bridge component, the base voltage of the DC bus has the ability to decrease, and the stable voltage of the coordinating connection of the DC side capacitor is subject to elimination (Chen et al., 2018). Rageh et al., in their work, focused on minimising defects and deviations of electric power in the structure of traction power supply. The researchers propose a configuration consisting of a solar photovoltaic installation and two single-phase five-stage converter modules that are connected to a LeBlanc transformer. According to them, this design model performs the function of full correction of asymmetric loads, inductive power and current harmonics in a three-system network. The solar photovoltaic system is coupled in

the direction of direct current to transmit power supply or to provide excess power, which is not used in load processes. This type of design helps balance the current on the network side when secondary loads are not coordinated (Rageh et al., 2018). Cheng and Xiao analysed the latest type of automated phase separation unit. The device consists of a vacuum load disconnecter, an isolator switch, and a position sensor. The basic operation of this device is as follows: during the locomotive's movement from feeder A to feeder B, the vacuum disconnecter and the electronic switch are closed, and during the locomotive's entry into the neutral section, the voltage of phase A occurs in the same zone. The disconnection of the entire phase advance structure is coordinated by the control system, no secondary actions are needed on the locomotive, and the switch is in an inactive state when there are no passing trains and thus there is a possibility of providing automatic over phasing (Cheng & Xiao, 2021). Kuppa et al., in their article, focused on the implementation of pulse-width modulation (PWM) rectifiers for the locomotive. According to the authors, such technology will have an impact on the fundamental efficiency of the locomotive traction system. For example, PWM rectifiers provide the option of a recuperative mode of operation, an improved power indicator and reactive power control, including minimisation of harmonics at the input current. The element in question, together with traction converters, operates in a number of blocks on the megawatt power scale in order to implement increased energy capacity and increased frequency of mode changes. The supply of rectifier blocks is carried out from a single-phase traction transformer, in which there are various secondary windings with high-quality powerful leakage resistance, which provides for phase changes of the moments of conversion (Kuppa et al., 2007). As already noted, the peculiarity of DS3 is the power supply from 25 kV 50 Hz AC only. Possible solutions for the implementation of the functionality of working with a voltage of 3 kV DC is the implementation of an input four-square DC / DC converter. Sun et al. in their article analysed the integration of this component using the example of a bidirectional substation of the urban railway system. The authors state that the four-square converter is the basis of the feedback device of the metro energy infrastructure, which has the function of returning energy to the AC system during recuperative braking of the train. An additional quality of the four-square converter is traction rectification and reactive power compensation of the traction machine (Sun et al., 2020). The basic technical specification of the DS3 has two independent insulated-gate bipolar transistor (IGBT) converters that feed two AD-914 asynchronous motors, and to smoothly integrate the new type of current, it is necessary to modify the IGBT converters. Huang et al. in their article considered the upgrade of this component of the locomotive. It was determined that reverse-conducting (RC) IGBT could be used to replace conventional IGBT converters. The internal layout of the RC-IGBT differs from the basic IGBT in that the collector zone is not the entire n+ region, but only a built-in part of the n+ zone. The diodes are

defined as pin diodes, including n+ base region, n-epitaxial region and n+ short-circuit region. In the diode cycle of the RC-IGBT, during the negative applied gate voltage, the conduction voltage drop of the internal diode decreases (Huang et al., 2017). The cornerstone of each locomotive is the traction motor. An important advantage of the DS3 is the already built-in asynchronous traction motor AD-914 with microprocessor control from Siemens. The technical specification of this component is designed for a line voltage of about 1870 V or 1300 V phase. Such functionality provides rational use in a promising two-phase circuit without the need for replacement. The reason for this is that the voltage range on the inverters remains the same. The power component and the speed limit of the DS3 remain unchanged – hourly power  $4 \times 1200$  kW. If the DS3 motor environment is modernised, the changes affect only the input circuits, and the inverter + motor complex remains unchanged, but it is also worth reprogramming the control system (Traction motor and auxiliary electric machines, 2019). Investigating the microprocessor system DS3, the range of tasks performed is huge – coordination of traction converters, traction and recuperation regulation, and anti-skid protection. Given the task of modifying a single-phase to a two-phase locomotive, this element of the locomotive must be supplemented with an automatic current type detection module. Zeng & Dai, in their research paper, offer a solution based on advanced (reduced instruction set computer architecture, RISC) (ARM) processors. In the work, it was determined that the entire hardware architecture of the collector sampling was divided into three key parts. The first stage is responsible for rectification and interference elimination. The incoming AC pulse is converted into a continuing positive half-period sine wave. The second stage concerns isolating and sending the pulse using a linear optocoupler and standardising the grounding of the sampling signal and the A / D module. The third stage is an increase in signal amplitude. The incoming voltage increases to a practically filled A / D scale using an operational amplifier. At this point, the thread pulse is fed to the ARM chip's sample port (Zeng & Dai, 2011). In DS3, the implementation of the voltage sensor is possible at the input – at 25 kV 50 Hz AC, the working process is through a transformer, at 3 kV DC – connecting the direct power supply mode. When upgrading the locomotive, it is important to consider the mechanism for blocking the simultaneous connection of both systems and the control of the main switches. Bhatti et al., in their article, indicate that the ground return algorithm must adhere to the requirement for the return flow in the operating mode of AC and DC. Incorrect planning of the train system can lead to such obstacles as the circulation of the rails of the locomotive body, the electric potential of the traction machine body, and electrical corrosion of the bearings. High and potential currents through the locomotive body affect the operation of on-board systems and will reduce the electromagnetic environment of the rolling stock, and the damage to the bearing will directly affect the safety of the train control process (Bhatti et al., 2024). The DS3

protection systems (differential current protection, overvoltage, undervoltage protection) must comply with two modes. Taking into account that at 3 kV the currents are significantly higher, it is necessary to adjust the current protection settings and thermal models. The locomotive system must take into account the regulatory limits: at 3 kV DC, the current limitation according to the technical standard EN 50163 is up to 3600 V, surges at 25 kV 50 Hz – frequency  $50 \pm 0.4$  Hz and amplitudes up to 29 kV. With the predicted operating mode of DS3 on direct current, the key is the control of the reverse current through the traction motors during the recuperation process, so that there is no excess voltage of the contact network or uncoordinated energy return (Analysis of the determinative parameters for maintaining the technical and operational compatibility of the 1520 mm and 1435 mm gauge rail systems at the Commonwealth of Independent States (CIS)/European Union, 2010). In the process of modification, one of the most noticeable changes will be the implementation of another type of pantographs. DS3 in the basic specification is equipped with two single-lever similar pantographs for 25 kV 50 Hz AC. When working with 3 kV DC, pantographs with a wide runner head (1950 mm) are often used, and they are designed for high current (about 2–3 kA). Two-phase locomotives practically use a pantograph for each system, so in DS3 it is necessary to install a pantograph for working with a 3 kV system. Wu et al., in their scientific work, described the optimal design of the pantograph. This locomotive component consists of such elements as the head, frame, lower frame, and transmission mechanisms. The head is one of the cornerstones of this device. This part contains a sliding plate, a pantograph angle, and a pantograph head support unit. The sliding panel is a current collector element, which is fixed from above, by means of a bracket of a sliding plate, which is a replaceable part. The angle of the current collector is demonstrated by an arc part, which is implemented at both ends of the head of the current collector. The primary task is to smoothly overcome the current collector through the overhead transition of the power transmission line. Also, to prevent discharge, the pantograph angle must consist of materials that have high insulating properties. The details of the current collector head support are one of the important elements that affect the efficiency of the pantograph. The task of this element is to implement a smooth contact between the sliding plate and the contact wire, and this part is made of highly wear-resistant materials with a lightweight (Wu et al., 2022). Jia et al., in their research work, indicated the motion parameters that the pantograph must meet in the correct operating mode:

- the working height of the pantograph varies from 400 to 2350 mm;
- the discrepancy in the lateral deformation of the pantograph head is not less than 30 mm;
- the head of the locomotive pantograph presumably moves slowly, to reduce the deflection angle. This is necessary for constant placement in a horizontal

position, which will give the possibility of reducing the impact of the locomotive element on the power line and changing the contact pressure;

- the contact effect, which fluctuates in the range of 120 H + 10 H, between the pantograph and the overhead line is coordinated by the lifting spring of the pantograph (Jia et al., 2017).

Technical standards, regulations EN 50367 and TSI “Energy” define the order of interoperability of the pantograph and the contact network for different systems, mentioning the geometry of the runner and the nominal pressing force. In fulfilling these standards, it is necessary to make sure that at 25 kV the new pantographs will be insulative resistant (taking into account about 2.5 m between the frame and the runner), and when working at 3 kV AC, the current collectors can conduct the required current without overheating. Conversion between 25 kV 50 Hz AC and 3 kV DC systems is performed in neutral zones. The principle of such an operation is as follows: upon an approach signal, the crew lowers the active pantograph, DS3 will be de-energized for a short time. Then another pantograph rises, and power is restored from another system. For DS3, it will be important to install voltage sensors, which will allow the locomotive to lower the pantograph on its own if a voltage loss is detected in one system, and raise the other when voltage in another system appears. However, this requires synchronisation of actions with the coordinating circuits in order to make arcing and current surges impossible. Analysing the area of operation of the updated locomotive with the current coordination and safety systems, it must work normally with both systems, without causing abnormal situations in the signalling, centralisation, and blocking elements, as well as in the power system. There are no cardinal structural changes in the configuration of the automation and control systems of the traction machine – in Ukraine, the signalling systems are unified and DS3 will retain the current automatic blocking and radio communication devices. Midya and Thottappillil briefly described what the structure of ERTMS system. The system consists of the following components:

- European Vital Computer (EVC), an on-board computer for coordinating and monitoring all data;
- European Train Control System (ETCS), an algorithm that is the signalling infrastructure;
- Global System for Mobile Communications (GSM-R) protocol for communication between the train and the central control. This technology is coordinated by GSM-R antennas with a range of 876 to 915 MHz in the upper communication line and 921–960 MHz in the lower communication line for exchanging data;
- Radio Block Center (RBC) is the fundamental element of signal encoding;
- Eurobalise transponders, which can be either active or passive. This element is located between the rails and transmits data to the on-board balise transmitting unit at a frequency of 4.234 MHz;

- Euroloop is an autonomous communication system based on an inductive loop for serial-continuous communication mode, where line pulses are transmitted via a coaxial cable (Midya & Thottappillil, 2008).

To perform its functions in the EU countries, the locomotive in question must be integrated into ERTMS. The stages of ERTMS implementation in DS3 will be as follows:

- Stage 1. Design. Monitoring the current electrical and mechanical circuits of DS3, designation of available space and parameters for installing new components. Forecasting the prospects for interoperability of ERTMS with the microprocessor part of DS3 Siemens Bahn Automatisierungs System 32 (SIBAS 32) from Siemens. Formation of a technical base for the location and connection interfaces;
- Stage 2. Integration of on-board equipment. The fundamental ERTMS EVC module is implemented in the rack of the Siemens microprocessor architecture. The ballast channel blocks are mounted in the lower part of the locomotive body next to the bogies to perform correct scanning of the ballasts from the track. Track measurement systems are connected to the current locomotive speed measurement components, with the prospect of additionally completing the auxiliary sensors to increase accuracy. DMI (Driver Machine Interface) is placed in the crew cabin instead of or as an addition to the current one;
- Stage 3. GSM-R integration. Radio modules of this communication protocol are mounted next to the locomotive radio communication elements. Antennas are provided on the roof of the locomotive. Equipment of cable routes and connection to the ETCS and DMI control system;
- Stage 4. Software interoperability. Current coordination elements from Siemens must be reflashed for functional compatibility with the European Vital Computer (EVC) via a standard interface, for example, Multifunction Vehicle Bus (MVB). Configuration of interoperability with GSM-R and ETCS is performed using TSI standards (Subset-026) (ERTMS/ETCS..., 2023). Carrying out procedures for the operation of ETCS with DS3 safety elements;
- Stage 5. Trial run and certification. Carrying out static and dynamic testing of ETCS and GSM-R in the infrastructure where the necessary balises already exist. Testing safety options, automatic braking, and conversion between ERTMS levels 1 and 2. Carrying out certification processes according to TSI CCS standards and obtaining a positive decision from the European Union Agency for Railways (EURA) or JSC Ukrainian Railways.

In addition to the above conditions, electromagnetic compatibility must be observed for the modernised locomotive. This component is one of the main ones during locomotive modernisation, since DS3 has a multilayer microprocessor architecture (IGBT transistors, asynchronous motors). For the correct regulation of

electromagnetic compatibility in the locomotive, the following technical regulations and standards are used:

- EN 50121 (Railway Transport Applications). Standards EN 50121-2, 50121-3-1, 50121-3-2 imply general standards for EMC of rolling stock, rail transport infrastructure, and rolling stock components.

The consequences of poor electromagnetic compatibility are the following technical faults:

- Minimisation of locomotive equipment stability (regular failures and restart of the motion coordination system, and early failure of the digital equipment and DS3 sensors from the working condition);
- Deviation from the standard state in the operation of the railway infrastructure (recording errors in the operating condition of track circuits, occurrence of false abnormal situations in ERTMS);
- Increased maintenance costs (the need for regular maintenance due to frequent errors);
- Reduction in engineering stability (increased risk of emergency events due to abnormal operation of safety devices).

To eliminate the listed abnormal situations, the following solutions are proposed for the implementation of the DS3 electromagnetic compatibility process:

- Shielding and grounding of cables. This principle is based on using a metal winding for signal and power circuit cables. Rational arrangement of elements reduces stray currents and electromagnetic interference;
- Noise suppression. Implementation of EMC filters (chokes, capacitors, and LC filters) at the inputs of power converters. In addition, there is a need to use high-frequency filters to improve the stability of sensitive electronic components (SIBAS 32 and ERTMS);
- Distribution of power and signal circuits to counteract interference transmission. Complex arrangement of high-power device elements and vulnerable units.

In addition to analysing the key points for performing the DS3 modification, it is also necessary to take into account the experience of other countries and enterprises in the production of locomotives that operate on alternating and direct current. Some of the modern locomotives are Siemens Vectron MS and Alstom Traxx MS. First, we will analyse the German version of a dual-system traction machine. According to information on the Siemens Corporation website, this rolling stock can be used in both freight and passenger transportation. Voltage systems in which this locomotive can operate are not only 3 kV DC and 25 kV 50 Hz AC, but also 1.5 kV DC and 15 kV 16.67 Hz AC. The last two voltage systems operate on the railways of Austria, Germany, Switzerland, and the southern part of France (Avignon-Marseille section). In addition to universality in working with voltage systems, this locomotive has the option of working on such track widths as 1435,

1520 and 1668 mm. Manufacturers assure that Vectron MS provides full flexibility, allowing for future upgrades for any modular train protection that is used in various railway systems of the EU countries. This feature of the locomotive has become possible due to the modular configuration, which has the ability to be improved to maximum indicators and combines ETCS solutions for each European country. The authors of the current paper would also like to draw attention to the Vectron MS bogies. All Vectron series models are equipped with similar bogie platforms, which consist of a modular architecture and are based on a standard bogie frame. In the lower part of this element, it is possible to install all the provided antennas and sensors (Siemens Mobility, Vectron AC/DC/MS – the locomotive that's forging new paths, 2025). Considering the locomotive from Alstom Traxx MS, this machine represents a family of four-axle traction machines, which are widely used in Europe. The Traxx Hauler series is a locomotive for heavy freight transportation. Having an innovative design of the bogie and multi-level coordination of the Traxx Hauler clutch, it is possible to develop a traction force of up to 1400 KH. This locomotive has options with 6, 8 and 12 axles. Owing to the continuous improvement of the traction chain and energy recovery, these machines ensure the minimisation of energy consumption and optimisation of costs per kilometre of run. The peculiarity of the assembly of these locomotives is the localization of production. Alstom Corporation initiates factory infrastructure in the countries where the locomotives will be used. Thus, the Prima T8 KZ8A locomotives, which were intended for the Kazakh railways, were assembled in Astana, and the WAG-12 traction machines for the Indian railway system were designed at the plant in Madhepura (Alstom, 2025). In addition to considering examples of originally created two-phase locomotives, it is necessary to analyse cases where the technical specification of the traction machine was changed. One example is the process of “dualization” on Czech Railways of the locomotive, project 163 into 363.5 and 363.2. In particular, the ČD Cargo locomotive with the number 163 252 after the modification program in 2022 received a new onboard number 363 252. During the upgrade, a transformer and all the necessary equipment for operation from alternating current were added, while maintaining the option of operation from 3 kV. In addition, in technical terms, this modernisation provided a replacement of the rectifier-inverter equipment and the implementation of additional current collectors. However, the traction motors remained the same, but received the function of being powered by both rectified alternating current and direct current. After the modernisation of 18 locomotives, these machines were approved for operation in Poland, Slovakia, and partially in Poland (Sůra, 2023).

## **2. Aspects and requirements of interoperability in the modernisation of the locomotive taking into account the EU and Ukrainian standards**

Modernisation and further operation of a dual-system locomotive requires compliance with a number of technical regulations and standards currently in force in Ukraine and the EU. To begin with, it is important to analyse the standards for voltage and interaction with the contact network. The EU has implemented an approach to standardising the parameters of railway power systems based on the EN 50163 standard, which sets the ratings and tolerances for 25 kV 50 Hz AC and 3 kV DC. Referring to this standard, the voltage of 3 kV in the established mode can fluctuate from 2.7 kV to 3.3 kV and in the short-term period – from 2 kV to 3.6–4.0 kV. For a voltage of 25 kV 50 Hz AC, the range of values is from 17.5 kV to 29 kV. The specified ranges are necessary for rational operation – the locomotive and its internal components (insulation and protection parameters) are designed to comply. The TSI Energy document clearly states that the technical specification of the rolling stock must be prepared for operation in one or more systems that are standardised on the railway, and the limits within the technical standard EN 50163 have been observed (European Union Agency for Railways..., 2023). Also, the technical standard EN 50367 specifies the interaction of “pantograph-overhead contact system” to ensure interoperability between the locomotive and the railway infrastructure. EN 50367, together with TSI ENE, defines pantograph-overhead contact line compatibility classes. For a dual-system locomotive (3 kV DC/25 kV 50 Hz AC), the pantograph head must match the standard of the network on which it operates: typically, 1950 mm on 3 kV DC lines and 1600 mm (in some networks 1450 mm) on 25 kV AC lines. In the EU, the harmonised types are Type 5 (1600 mm) and Type 8 (1950 mm). Accordingly, the modernised DS3 should be equipped with two pantographs (a 1,950 mm DC head and a 1600/1450 mm AC head), or a single universal head only where it is listed in the compatibility registers of the relevant infrastructure managers. This selection ensures the required pantograph-OCL interoperability in accordance with EN 50367 and TSI ENE. In the EU countries, pantographs are standardised as follows: type 5 (gauge about 1600 mm), type 8 (gauge 1950 mm) and the modified locomotive must be equipped with the corresponding pantograph devices, without violating the above-mentioned standards. In Ukraine, the State Standards of Ukraine (DSTU) EN 50163:2016 is responsible for a similar area, which sets the same ranges for 3 kV and 25 kV voltage systems. Taking into account the above provisions, the modernised DS3 is subject to verification for compliance with the DSTU EN50163 standard in domestic Ukrainian use. This test should consist of withstanding a voltage dip of up to 2000 V in the operating mode of 3 kV DC and an overvoltage

of up to 3900 V. When testing in the operating mode of alternating current, it involves assessing compliance in operation with voltage and frequency deviations, which is regulated by the standard (SE “Ukrainian Research and Training Center for Standardization Problems”, 2016). Analysing technical regulations concerning interoperability and certification, the TSI “Rolling Stock – Locomotives and Passengers” and the already mentioned document “Energy” operate in the EU. These standards regulate, at the level of EU regulations, the fundamental criteria for the design and testing of dual-system locomotives. In particular, the TSI “Rolling Stock – Locomotives and Passengers” stipulates that a locomotive, the functionality of which is intended for operation in several voltage systems, should receive a positive result in all envisaged operating modes as a result of testing, and should not negatively affect the working processes of adjacent subsystems, such as signalling and communication. It is also important to note that in the EU countries, when certifying a dual-system locomotive, the switching time between systems, the absence of current surges during switching, the correct operation of protection in different ranges, the compliance of the locomotive with the mass and dimensions, the noise level, and electromagnetic compatibility are verified (Rolling Stock ..., 2025). In the period from 2022 to 2023, Ukraine, due to the harmonisation of national legislation with European technical standards, adopted and introduced more than 2000 EU standards in the status of DSTU (State Standards of Ukraine). In addition, work is underway to create Ukrainian technical standards that will be comparable to EU directives. For example, Resolution No. 1194 of the Cabinet of Ministers of Ukraine dated December 30, 2015 is the “Technical Regulation on the Safety of Rolling Stock of Railway Transport”, and it is a prototype of Directive 2008/57/EU on interoperability on railways (Cabinet of Ministers of Ukraine ..., 2015). The DS3 modification project provides for the need to develop new design documentation, which will schematically display changes in the internal structure of the locomotive. Taking into account Ukrainian standards, the large-scale update of the locomotive’s functionality is a recertification through Ukrainian expertise, which was accredited through the National Accreditation Agency of Ukraine. It has the authority to certify products for the needs of railway transport and assess the conformity of products with the requirements of technical regulations (Certification of products ..., 2025). In the European Union, when making such modifications to an already operating locomotive type, a new Type Approval “Applications for Vehicle (type) Authorisations (VAs)” certificate from the ERA must be obtained. The process of obtaining and issuing this certificate allows the regulator to obtain sufficient assurance that the applicant and other entities that participated in the modernization process have fulfilled their tasks to ensure that the locomotive or other unit complies with the legislation. The applicant for such a certificate can be either an individual or a legal entity – a railway company, an infrastructure regulator, a manufacturer of equipment, an owner, or a custodian (Applications for

Vehicle (type) Authorisations (VAs), 2025). Studying the operating rules, in Ukraine there is already a briefing for locomotive crews on the control of traction machines on electric traction, including transitions between different types of current. As cases demonstrate, two-phase locomotives do not require re-equipment – training of drivers is a sufficient measure to provide correct operation of the equipment. In the EU, similar moments are also provided – the driver must receive signals about approaching the neutral zone, according to TSI.

### **3. Methodology for studying the impact of locomotive modernisation on the interoperability of the railway system. Technical sustainability and efficiency of the DS3 locomotive modernisation**

The stages of the research methodology are based on the following hypotheses:

- DS3 (AD-914) traction motors and inverters have operating voltage properties, which allows maintaining the basic design when implementing AC/DC converters and updating IGBT-converters;
- The DS3 locomotive, which has undergone a two-system modernisation, ensures stability and operational versatility on all railway lines in Ukraine and in border areas with neighbouring countries (Poland, Slovakia, Hungary);
- The functional compatibility of ERTMS and GSM-R and the SIBAS 32 control system of the updated DS3 will greatly improve the integration process and make it possible to use the locomotive on European railway networks without a limit in the field of safety and communication.

To demonstrate dynamic processes, electromagnetic compatibility, energy efficiency of the optimisation and modernisation process of the DS3 locomotive, the triangulation principle of methods has been used (several research methods in a scientific article). The reasons for using such an algorithm are due to the following theses:

- Modernisation of the locomotive will require multiple studies of all the intricacies of the conversion of the traction machine from single-phase to two-phase;
- Detailed visualisation guarantees a comprehensive illustration of the planned modification process.

The research methods used to write the script are as follows:

- Method of mathematical modelling of dynamic systems. This tool models the dynamic properties of traction motors and transient processes from AC to DC. This method is also used to study the frequency characteristics of the engine

using Bode and Nyquist diagrams. Thus, the stability margin of the locomotive traction element has been determined;

- Method of transient characteristics. The current integrated approach has been chosen to consider the system response (first and second order) to a step input action, which gives the study of the dynamic behaviour of the motor and power supply coordination systems of the DS3;
- Fast Fourier transform (FFT). The considered technique has been chosen to analyse electromagnetic interference (EMI), which allows isolating frequency components, monitoring the interference that has arisen in the locomotive system;
- Optimisation method. This principle has been taken to optimise the PWM frequency with the inclusion of an artificial loss function. In addition, the approach of numerical analysis and optimisation with the analysis of various runs has been taken into account, the result of which is the determination of the optimal convergence point.

As already noted, in this article, the research rationale is to modernise the locomotive on electric traction DS3 from single-phase to two-phase operation mode and the basis for writing a script in MATLAB will be setting the parameters of the main parameters of the locomotive (see Figure 1).

The axle formula of the DS3 locomotive is  $Bo'Bo'$ , which according to the UIC classification means the following:

- B (the locomotive unit has two driving axles);
- o (each of the axles is driven by its own traction electric motor);
- The apostrophe between the groups indicates the division between the bogies.

```
%% 1. General DS3 Locomotive Parameters
axialFormula = 'Bo''Bo''';           % Axial formula (Bo'Bo')
power_total = 4800;                   % Total power, kW (4 x 1200 kW)
max_speed = 160;                      % Maximum speed, km/h (operational limit may be 80 km/h)
mass = 90e3;                          % Mass, kg (90 tons)
length_mm = 17000;                   % Length, mm
width_mm = 3000;                     % Width, mm
wheel_diameter = 1200;               % Wheel diameter, mm
min_curve_radius = 80;               % Minimum curve radius, m
frontal_area = 11;                   % Frontal area, m^2 (average of 10-12 m^2)
```

**Figure 1.** General DS3 locomotive parameters (Source: corresponding author' work in MATLAB)

This type of axle formula describes the locomotive as a traction machine with independent control of each axle in any of the present buggies. Thus, it improves the distribution of traction efforts and increases the dynamic characteristics of the train. The maximum power of the DS3 is equivalent to 4800 kW, where each of the

four traction motors AD-914 has a power of 1200 kW. The maximum design speed is up to 160 km/h, and the operating speed is considered to be 80 km/h. The mass of the locomotive is 90 tons, the length is 17 000 mm, and the width is 3000 mm. The diameter of the wheels is 1200 mm, and the minimum radius of curvature of the wheels is 80 m. The area of the frontal part is 11 m<sup>2</sup>. Figure 2 illustrates the power supply parameters of DS3.

```
%% 2. Power Supply System Parameters
% AC System
ac_nominal = 25000;           % Nominal AC voltage, V (25 kV)
ac_freq = 50;                % AC frequency, Hz
ac_range = [17500, 29000];   % AC voltage range (EN 50163), V

% DC System (after modernization)
dc_nominal = 3000;          % Nominal DC voltage, V (3 kV)
dc_range = [2000, 4000];    % DC voltage range, V

% Main Switch and Grounding
ac_main_switch_current = 10e3; % Main switch AC rating, A (8-10 kA)
dc_main_switch_current = 6e3;  % Main switch DC rating, A (4-6 kA)
% Automatic grounding switch assumed

% Converter Type: Four-quadrant DC/DC converter (to be integrated after modernization)
```

**Figure 2.** Power supply system parameters (Source: corresponding author' work in MATLAB)

As it is known, the basic locomotive operates only in the AC voltage system of 25 kV 50 Hz, and according to the EN 50163 standard, the AC voltage range fluctuates from 17.5 to 29 kV. Integrating a 3 kV voltage system into the locomotive, it is fixed in the range of such values from 2 kV to 4 kV. The main switch and grounding in the AC mode are designed for a voltage system of 8–10 kA, in direct current from 4 to 6 kA. The type of converting device that will be equipped after modernisation will be a four-quadrant DC / DC converter. The next step is to enter the parameters of the AD-914 traction motor; this metric is shown in Figure 3.

```
%% 3. Traction Motor Parameters (AD-914)
numMotors = 4;                % Number of traction motors
motor_power = 1200;           % Power per motor, kW
line_voltage = 1870;          % DC line voltage for motors, V
phase_voltage = 1300;         % Phase voltage, V
starting_force = 310;         % Starting traction force, kN
constant_force_63 = 270;      % Traction force at ~63 km/h, kN
constant_force = 161;         % Constant traction force, kN
```

**Figure 3.** Traction motor parameters (Source: corresponding author' work in MATLAB)

The *line\_voltage* variable specifies the voltage on the DC bus that is supplied to the traction motors, meaning that after the conversion and rectification of high voltage, an intermediate DC bus is created, in which the voltage of about 1870 V is

maintained. This figure is key for the correct operation of asynchronous motors of the type installed in the DS3, due to the dependence of the operating point and the efficiency of energy transformation. The *phase\_voltage* variable determines the voltage that is used directly to each phase of the asynchronous motor. Often, the voltage that is “visible” on individual motor windings turns out to be lower than the voltage on the entire bus. The value of 1300 V is the one at which the traction motor operates in the operating mode, providing the required torque. *Starting\_force* shows the traction force in kilonewtons that the locomotive can develop when starting from a standstill. The 310 kH indicator is important for ensuring rational acceleration of the rolling stock and overcoming resistance, which is associated with inertial and coupling algorithms. *Constant\_force\_63* is a physical quantity that indicates the traction force that DS3 can maintain at a speed of 63 km/h. This variable displays the dynamism of the traction machine when converting from the high starting current mode to an improved performance characteristic. The last parameter *constant\_force* shows the stable traction force that the locomotive implements in the operating mode at a high-speed mode. With a further increase in speed, taking into account the reduction in the influence of the magnetic field and the redistribution of power, the traction force indicators decrease to a value of 161 kH. This indicator is important for regulating a stable speed mode and extending the service life of the equipment. The next block of the script covers the parameters of the power electronics. As already defined, the DS3 has two autonomous IGBT converters that supply power to two of the four AD-914 asynchronous motors. Figure 4 shows the characteristics of the power electronic modules.

```

%% 4. Power Electronics Parameters
igbt_voltage = 6500;           % IGBT rating, V
igbt_current = 1000;          % IGBT rating, A
pwmFreq_range = [1e3, 8e3];  % PWM switching frequency range, Hz
conversion_eff = 0.85;        % Conversion system efficiency (85%)
nominal_motor_current = 450;  % Nominal current per motor, A
peak_motor_current = 600;     % Short-term peak currents, A

```

**Figure 4.** Power electronics parameters (Source: corresponding author' work in MATLAB)

The 6500 V value of the *igbt\_voltage* variable shows that the devices must withstand voltages up to 6.5 kV, which is an important functional requirement in high-voltage rail transport systems. In general, the identifier in question determines the rated operating voltage for the IGBT elements of the locomotive, which are included in the design of the DS3 traction converters. The *igbt\_current* variable shows the rated current that the IGBT module can conduct in normal mode. The value of 1000 A or 1 kA indicates the maximum permissible current load that the IGBT can withstand without overheating and breakdowns. *PWMFreq\_range* records

the range of the operating frequency of PWM communication, which is used in IGBT devices to coordinate the power of motors. Values from 1 to 8 kHz make it possible to select a rational frequency to minimise losses, ensure correct operation of the motor, and reduce the occurrence of electromagnetic interference. *Conversion\_eff* defines the efficiency of the energy conversion system, namely the fraction of incoming energy converted into useful power for the traction motors. The value of 0.85 illustrates that 15% of the energy is lost as heat and other unavoidable losses. The value of 450 A in *Nominal\_motor\_current* specifies the nominal current that each of the four AD-914 traction motors consumes in the optimal operating mode. This indicator is taken to calculate the operating characteristics of the system and interpret the conditions for optimising the control parameters. *Peak\_motor\_current* shows the maximum permissible short-term current peaks for the traction motor. Such features can occur during start-up or under high load conditions. The next line of the script sets the parameter of the DS3 electric brakes.

```
% 5. Electric Braking Parameters
brake_power = 3700; % Brake rheostat power, kW
```

**Figure 5.** Electric braking parameters (Source: corresponding author' work in MATLAB)

The *brake\_power* variable denotes the power of the brake rheostat, which is 3700 kW. The brake rheostat is a component of the electrodynamic brake, the function of which is to dissipate the energy obtained during braking, in the form of heat. This type of braking is often used when recuperation is impossible. The figure of 3700 kW indicates the maximum possible power that the brake rheostat can dissipate without damage or deterioration of the locomotive system characteristics. One of the important blocks in the script is about the parameters of the pantographs. Figure 6 will demonstrate these indicators.

```
% 6. Pantograph Parameters
pantograph_profile_AC = 1450; % Pantograph profile for 25 kV AC, mm
pantograph_profile_DC = 1950; % Pantograph profile for 3 kV DC, mm
max_pantograph_current = 3e3; % Maximum pantograph current for DC, A
numPantographs_AC = 2; % Number of pantographs for AC
numPantographs_DC = 2; % Number of pantographs for DC (after modernization)
```

**Figure 6.** Pantograph parameters (Source: corresponding author' work in MATLAB)

*Pantograph\_profile\_AC* is set to 1450 mm, which illustrates the pantograph head width used when working with 25 kV AC systems. *Pantograph\_profile\_DC* is set to 1950 mm, indicating that a pantograph with an increased head width is required for

working with DC systems. An increased head provides a high-quality contact cross-section and enables higher current to be passed, considering that the voltage may be lower and the current higher. The *max\_pantograph\_current* parameter describes the maximum current that can normally be transmitted through the pantograph during DC operation. The 3e3 value represents 3000 A, indicating that the pantograph must withstand high currents that occur when working with 3 kV. *NumPantographs\_AC* and *numPantographs\_DC* are equal to two, which indicates that after the upgrade, there will be four pantographs on the roof of the DS3, which will allow the traction machine to be used in two power supply systems. The next section of the script sets important values that describe the locomotive coordination and protection system, based on the Siemens SIBAS 32 platform.

```

%% 7. Control and Protection System (Siemens SIBAS 32)
control_system = 'Siemens SIBAS 32'; % Control system type
power_factor = 0.95; % Minimum power factor in vector control (>= 0.95)
protection_response = 1e-3; % Response time to emergency, sec (<1 ms)
% Communication interfaces: MVB. CAN Bus. Ethernet

```

**Figure 7.** Control and protection system Siemens SIBAS 32 (Source: corresponding author' work in MATLAB)

The *power\_factor* value specifies the minimum power factor that must be achieved in the vector control mode of traction units. The figure 0.95 shows that the system must operate with such a power factor without falling below this figure to provide highly efficient energy transportation and reduce losses in the system. The *protection\_response* value is set to 0.001 s. This figure is the maximum permissible amount of time for the protection system to respond to abnormal situations, which is necessary to ensure the safety of the traction machine. Sections 9 and 10 of the script cover electromagnetic compatibility and interoperability parameters of DS3 with ERTMS/ETCS systems.

```

%% 9. Electromagnetic Compatibility (EMC)
emc_standard = 'EN 50121'; % Compliance with EN 50121 (parts 2, 3-1, 3-2)
shielding_material = 'Copper/Aluminum'; % Cable shielding materials
% EMC filters: chokes, LC filters for high-frequency interference protection.

%% 10. ERTMS/ETCS Interoperability Parameters
gsmr_freq = [876 915; 921 960]; % GSM-R frequencies in MHz (uplink and downlink)
eurobalise_freq = 4.234; % Eurobalise operating frequency, MHz
control_unit = 'European Vital Computer (EVC)'; % Type of control unit

```

**Figure 8.** Electromagnetic compatibility (Source: corresponding author' work in MATLAB)

The following variables are specified in the electromagnetic compatibility block:

- `emc_standard` = EN 50121 (a parameter that forms the electromagnetic compatibility standard for the locomotive. The EN 50121 standard is a pan-European set of regulations describing the EMC requirements for rail transport. Compliance with this regulation guarantees that the components and devices of the modernised DS3 will operate normally in an electromagnetic environment and will not interfere with other systems;
- `shielding_material` = 'Cooper / Aluminium' (indicates that materials such as copper and aluminium are used to shield cables and vulnerable elements of the locomotive system. They have high electrical conductivity properties and are sufficiently shielded from external electromagnetic fields.

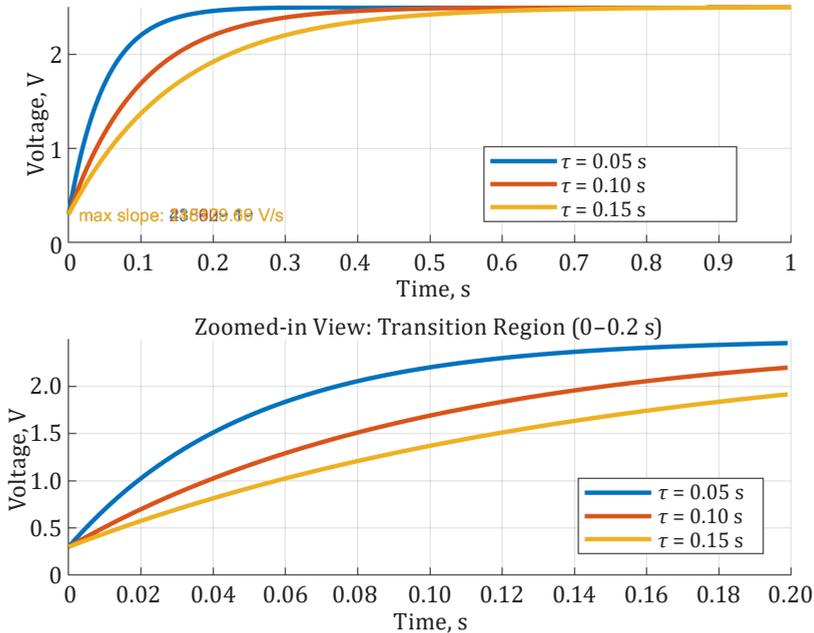
Section 10 on ERTMS/ECTS interoperability is based on the variables listed below:

- `gsmR_freq` = [876 915; 921 960] – an argument that specifies the frequency ranges for the communication protocol, such as GSM-R. The first line [876 915] detects the frequency range for transmitting data from the train. The second line [921 960] is the range of values for receiving data by the rolling stock;
- `eurobalise_freq` = 4.234 – informs about the operating frequency for the Eurobalise equipment;
- `control_unit` = 'European Vital Computer (EVC)' – denotes the type of coordinating unit, which is the fundamental component of the ERTMS/ETCS system. EVC regulates the processing of signals from the balises, the coordination of the speed mode, the operating algorithms of automatic braking, and provides the interoperability of the system with dispatchers.

The simulation scenarios in the script will be as follows:

- Transition from AC (25 kV) to DC (3 kV) – transient response;
- Engine operating modes: start, acceleration, constant traction;
- Regenerative braking: energy recovery and brake circuit analysis;
- Electromagnetic interference: analysis using FFT and spectrogram;
- Control system response: handling overloads, short circuits, and automatic switching.

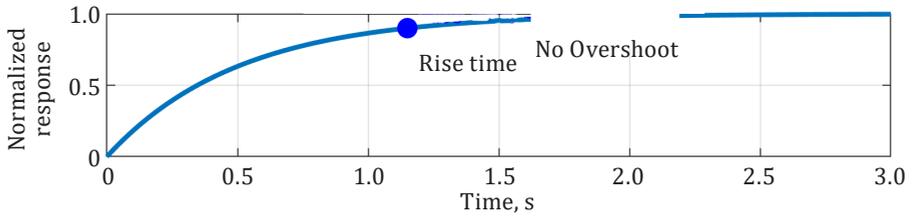
To form a comprehensive scientific discussion and conclusion of the study, it is necessary to visualise the obtained modelling results. The first graphical representation will be the first scenario (transient response from 25 kV AC to 3 kV DC).



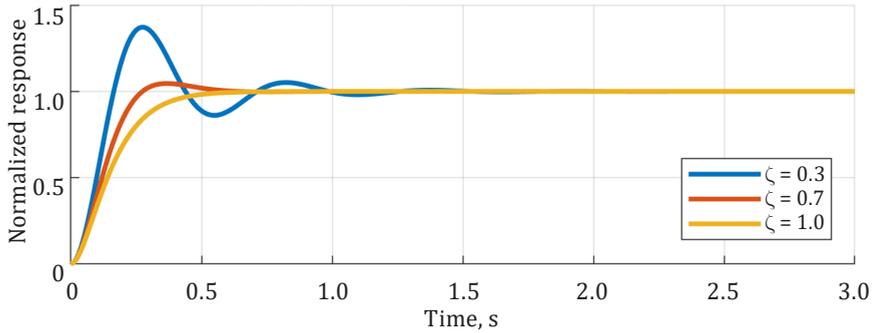
**Figure 9.** Transient voltage response (AC to DC Switching) (Source: corresponding author' work in MATLAB)

The figure below illustrates the dynamic process of switching from AC to DC voltage. Different constant switching time metrics ( $\tau = 0.05, 0.10,$  and  $0.15$  s) were used in the simulation to demonstrate how quickly the mode change occurs. Each curve in the image above is analogous to the difference in constant switching time. A small  $\tau$  value results in a fast and steep transition, while a larger  $\tau$  value provides a slow and smooth transition. In addition, it is also possible to notice how quickly the voltage starts to decrease from the nominal AC value and settles down to the nominal DC value. The graph below marks the point where the change in voltage per second ( $dV/dt$ ) is maximum, allowing us to analyse the rapid electrical stress during the switching. When zooming in on the first 0.2 s of the simulation, the lower graph displays the initial transient response. A practical application of this figure can be in optimising the mode change strategy to reduce the predicted damage while achieving the desired performance. The following figure shows the response of the motors to a step change, which was modelled as a first-order and second-order system with variable damping.

a) First-order model



b) Second-order models with varying damping



**Figure 10.** Step response: First and second-order models (Source: corresponding author' work in MATLAB)

The first-order model is a tool that describes the dynamics of a system where there is only one component for energy storage. The mathematical form of the first-order model is:

$$G(s) = \frac{K}{\tau s + 1}, \quad (1)$$

where:  $K$  – system gain coefficient;  $\tau$  – time constant that determines the reaction rate of the system;  $s$  – Laplace complex variable.

The mathematical form of the second-order model is:

$$G(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}, \quad (2)$$

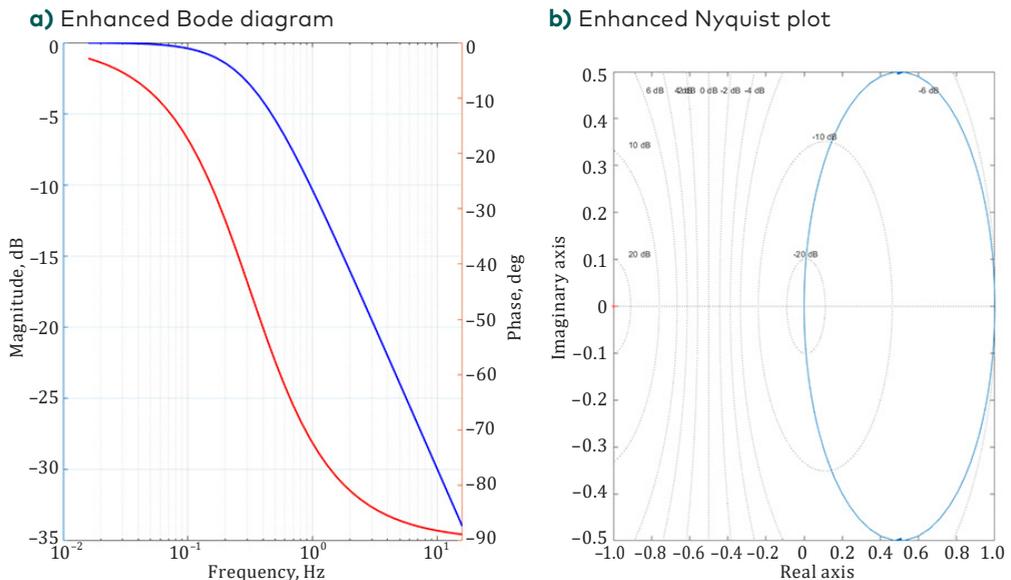
where:  $\omega_n$  – natural (undamped) frequency of oscillations;  $\zeta$  – damping coefficient.

The second-order model with variable damping is an algorithm that denotes a system with two energy storage elements. This variation of the model has the ability to exhibit complex behaviour (oscillation and overshoot). In the first case, the model is simple and provides an exponential response, which is typical of most systems with one dominant link, so the algorithm under consideration is effective for monitoring basic estimates of the response rate. The second-order formula provides

greater adaptability, due to the possibility of oscillatory behaviour, which is typical of architectures with inertial and elastic components. With changes in the damping coefficient values, it is possible to model a variety of operating states – from sharp oscillations to a uniform transition. Summarising the first- and second-order model plots, we can draw the following conclusions:

- the first-order model plot demonstrates the speed and stability of the engine’s dynamic response, which is important for tuning control characteristics and achieving fast but stable performance;
- the second-order model plot shows that low damping ( $\zeta = 0.3$ ) represents high overshoot and oscillatory behaviour, the ( $\zeta = 0.7$ ) parameter illustrates minimal overshoot, faster rise time and faster settling, which is normalized for most practical scenarios. The  $\zeta = 1.0$  parameter is considered critical damping – there is no overshoot, but a slower response when compared to the  $\zeta = 0.7$  parameter.

The next stage of visualisation demonstrates frequency analysis of stability and quality of operation of the locomotive control system. Two algorithms were chosen for the correct image – Bode diagram and Nyquist diagram.



**Figure 11.** Enhanced Bode Diagram and enhanced Nyquist plot (Source: corresponding author’s work in MATLAB)

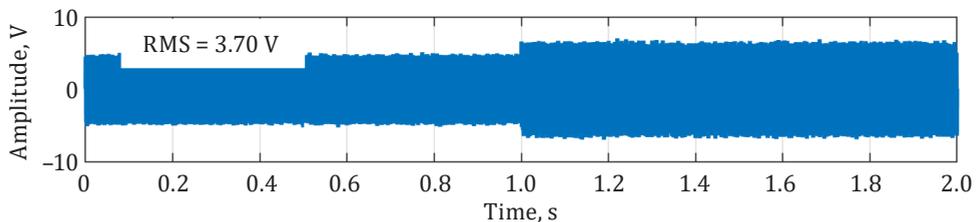
The Bode diagram is a graphical representation of the frequency response of the system in a logarithmic scale along the frequency axis. This algorithm helps find the stability reserves – Gain Margin, Phase Margin. Gain Margin shows how

many dB it is possible to increase the gain of the system before the circuit becomes unstable. Phase Margin is what additional angle the phase can shift at 0 dB before the system enters an unstable mode. The Nyquist diagram is the frequency response in the complex plane, where the real part of the transfer function is projected along the abscissa axis, and the minimum part of the locomotive is projected along the ordinate axis. Both of the presented diagrams are fundamental and complement each other in the evaluation and design of traction machine control systems. These illustrations show the following:

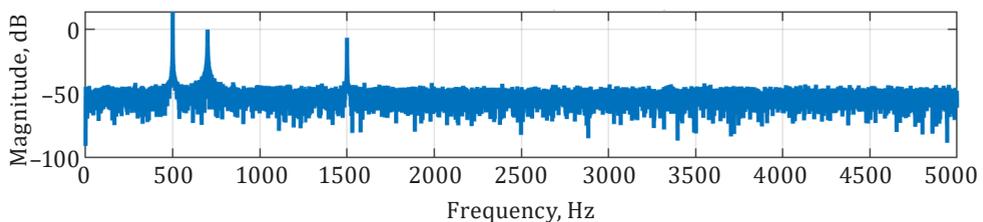
- detection of the frequency where the system can become unstable or have influential oscillations;
- identification of the degree of stability;
- obtaining results for coordinating locomotive regulators, such as a PID controller or system parameters, to improve the locomotive’s dynamic and reliable performance.

The results in the Bode diagram show a steep drop in the blue curve (Magnitude) with increasing frequency, which gives an understanding that the system weakens high-frequency signals. The red curve (Phase) decreases and can cross 180. The greater the phase “reserve” at  $\omega$ , where the amplitude is 0 dB, the more stable the system. The result in the Nyquist diagram screens that the curve does not cross or approach point  $-1.0$ . That is, if you develop a locomotive modification complex, this figure will give an understanding of the stability of the system. An important part of the locomotive modernisation is the arrangement of electromagnetic compatibility. This component will be the subject of the subsequent visualisations.

**a)** Simulated EMI voltage signal



**b)** FFT spectrum (dB scale)

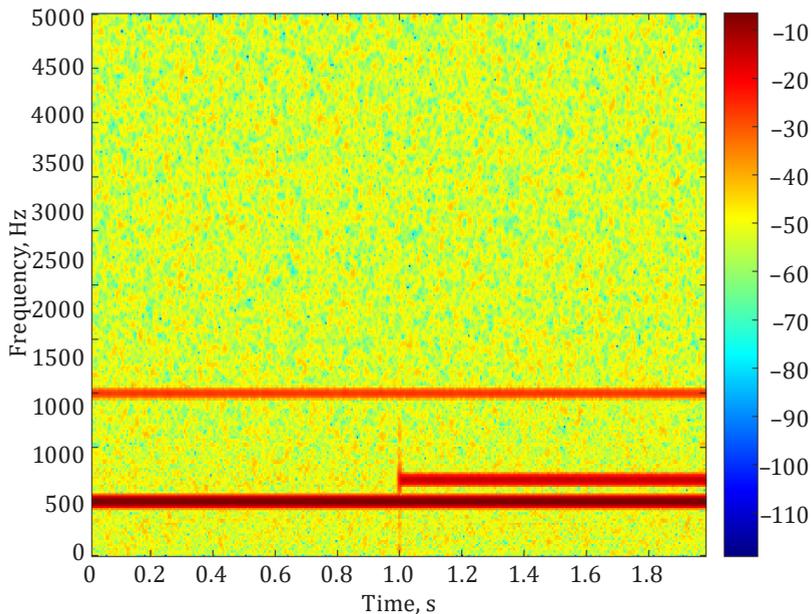


**Figure 12.** Simulated EMI voltage signal and FFT spectrum (dB scale)  
(Source: corresponding author’ work in MATLAB)

The upper subgraph shows the analysis of electromagnetic interference in the time domain. One can see the amplitude that fluctuates around some average noise level with periodic emissions. The RMS value of 3.70 V provides a rough estimate of the “power” of interference in the locomotive’s electrical network. The practical value of this subgraph is to assess the level of interference at present, diagnose the operation of electronic modules, and control risks for sensitive systems. The lower subgraph is the FFT interference spectrum in the range from 0 to 5000 Hz, where the ordinate axis is the level in dB. In this image, the peaks are noted in detail, which give an understanding of the dominant harmonic or disturbance frequency. The noise level, measured in dB, gives an understanding of how strong each frequency is in the energy component, if compared with another noise background. Thanks to this subgraph, it is possible to design and configure locomotive filters, monitor compliance with EMC standards, and search for sources of interference. Both visualisations will provide the engineers who will coordinate the DS3 upgrade with the following:

- optimisation of the DS3 electronics;
- improvement of the reliability and safety component;
- compliance with international technical standards.

The next visualisation about electromagnetic compatibility will be a spectrogram, which shows the time sweep of the frequency-amplitude analysis of the signal.



**Figure 13.** Enhanced spectrogram of EMI signal (Source: corresponding author’ work in MATLAB)

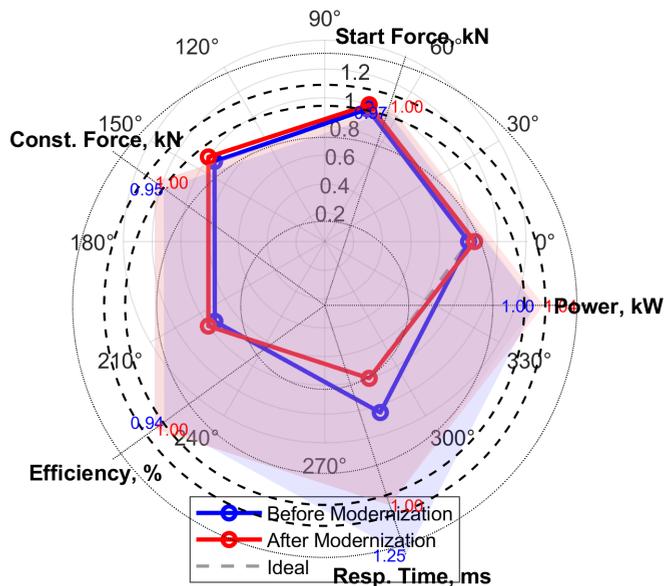
The horizontal axis in the figure shows time (from 0 to 2 s), and the vertical axis shows frequency (from 0 to 5000 Hz). The colour scheme on the right side reflects the signal power scale, especially the red and yellow tones, which characterise high signal levels. The graph shows how and when high levels of electromagnetic interference occur in the range from 0 to 5000 Hz. The aim of this graph is to:

- define the main interference frequencies and the time scales of their occurrence (the continuous presence of bright bands at a certain frequency indicates that this system generates a stable high interference);
- connection with various operating modes of the traction drive (when converting from AC to DC or switching traction and recuperation modes, the spectrum may change);
- design filters and shielding for the locomotive (the spectrogram allows you to compare the operating modes of the locomotive with interference peaks, so that you can turn on filters or adjust control parameters precisely in problematic time intervals);
- compliance with EMC technical standards according to EN 50121 (to achieve certification, it is necessary to ensure that interference does not exceed permissible levels in the specified frequency ranges).

In the context of the DS3 modernisation, this visualisation will provide a picture of:

- comparative analysis of different stages of locomotive operation (start, speed up, switching to DC, braking);
- protection of key nodes (the spectrogram allows you to plan the protection of GSM-R nodes, ERTMS/ETCS modules, making sure that at key moments high-frequency noise does not exceed acceptable levels);
- the ability to correctly configure filters, screens (engineering personnel can see the result of the modernisation on the graph in the experimental mode).

Below are three subgraphs that characterise the transient response of the traction motor DS3, the voltage transition (AC to DC), and the FFT spectrum of electromagnetic interference.



**Figure 14.** Comparison of the DS3 parameters before and after the upgrade (Source corresponding author' work in MATLAB)

The final visualisation in this section of the article will concern the comparison of the DS3 parameters before and after the upgrade.

The graph in question is a multi-level radar chart that compares five fundamental performance characteristics of the DS3 with their ideal target values. The chart shows the following values:

- engine power (kW);
- starting and constant force (kN);
- efficiency (%);
- response time (m/s).

All values are normalised to the sufficiently optimal value (1.0) and indicate full compliance with the target level. The chart consists of the following parameters:

- before modernisation (illustrated by a blue polygon and shows the locomotive's performance before the upgrade);
- after modernisation (shown as a red polygon, indicating improved performance after the modifications);
- ideal values (represented by a grey dotted circle and indicates the target level for each parameter, which is a benchmark for monitoring the results obtained).

The radar chart emphasises the locomotive's improvements after the modification. The

proximity of the red polygon to the ideal contour informs about the achievement of the set goals and the effectiveness of the study. It can also be noted that the parameters that have reached the target values and those that need further improvement are easily determined.

## 4. Scientific discussion

This section summarises the volume of research performed in this scientific article. The results obtained from the script modelling performed in MATLAB confirm that there is a feasibility of switching the DS3 locomotive from a single-phase to a two-phase power supply system. Analysing through the prism of interoperability of the Ukrainian railway system with a similar pan-European infrastructure, ensuring the functional compatibility of locomotives and cars is obvious. Such conclusions are determined with previously performed experiments and operating experience of such traction machines as Siemens Vectron MS and Alstom Traxx MS. For instance, Siemens Vectron MS locomotives, which are designed to operate on both AC and DC networks, have demonstrated superior energy efficiency, reduced operating costs, and enhanced flexibility in various European regions (Siemens Mobility. Vectron AC/DC/MS – the locomotive that's forging new paths, 2025). Similarly, Alstom's Traxx MS also shows significant advantages in energy recovery and minimising energy consumption per kilometre of travel (Alstom, 2025).

In this context, the proposed modernisation of the DS3, by modifying its traction system, offers several operational and economic benefits. Compared to purchasing a new traction unit, the DS3 modernisation involves minor modifications to the basic technical specifications while maintaining the key components of the power and mechanical parts, which minimises economic costs and shortens the implementation timeline for updates.

During the research process, the authors of the article have discovered important technical aspects. For example, during the analysis of conversion actions from 25 kV AC to 3 kV DC, the probability of coordination of the switching speed of voltage systems with minimal surges has been shown. It should be emphasised that with fast switching ( $\tau = 0.05$  s), abrupt voltage changes have been recorded, which can adversely affect the service life of the locomotive equipment. On the other hand, in smoother transitions ( $\tau = 0.15$  s), a gentle operating mode of electrical units is provided, but at the same time, there is a need for a comprehensive adjustment of the protection and control systems to exclude temporary downtime or loss of locomotive traction. Chen et al. (2018) also discuss the significance of controlling the speed of voltage switching and highlight the importance of voltage stability during dynamic transitions in traction systems. They explore the implementation of Power Conversion Technologies that could stabilise the power supply and ensure smoother transitions, which are crucial for the modernisation of DS3.

Studies of the dynamic characteristics of the AD-914 traction motor have confirmed the importance of selecting the damping coefficient  $\zeta = 0.7$  for the second-order model, which corresponds to the basic engineering recommendations for adjusting the engine control architecture. The obtained results, which have been presented using Bode and Nyquist diagrams, demonstrate the stability of the proposed coordination schemes. The visualisation data show the provision of the necessary stability margin and the existence of the probability of continuing the modernisation of the parameters of the regulators, which gives an understanding of the feasibility of the proposed solutions in technical terms.

One of the significant indicators obtained during the study is the results of the analysis of electromagnetic compatibility (EMC). The spectral analysis of electromagnetic interference has revealed the presence of high-frequency interference, which can negatively affect the operating efficiency of vulnerable internal elements of the locomotive (SIBAS 32, GSM-R, ERTMS/ETCS). The detected spectral peaks in the range from 500 to 3000 Hz provide for the implementation of effective filters and functionally justified shielding of the DS3 cable architecture, which is provided for by the European standard EN 50121. Wu et al. (2022) highlighted the challenges of maintaining electromagnetic interference levels within acceptable standards in high-speed rail systems, proposing specific solutions to shield vulnerable components effectively. A comparative analysis of the fundamental technical characteristics of the traction machine before and after the modernisation process, which is illustrated in the radar diagram, provides an indicative record of the practical benefits and prospects of the proposed options for the design implementation of solutions. The improvements in power efficiency, response time, and the minimisation of electromagnetic interference are evident, highlighting the feasibility of transitioning the DS3 locomotive to a two-phase system. Promising steps for subsequent research are a comprehensive study of the impact of the proposed solutions of the authors on the cost of operating a locomotive that has undergone modernisation, as well as field tests to analyse the operating period of DS3 under real operating conditions. Furthermore, further research into the economic side of the modernisation project, considering capital and operating costs, should be undertaken.

## Conclusion

As a result of the conducted research and scientific discussion, it is possible to draw comprehensive conclusions of the article:

- Scientific significance and novelty. For the first time, a multi-level study of the availability and conditions of modernisation of the DS3 locomotive for operation in a dual-system mode has been implemented and carried out,

which provides an area for development as a traction machine and application potential in a wider range of European rail traffic. The authors scientifically substantiated the principles and methods of technical implementation of the modernisation process for a dual-system mode of operation, based on international experience and modern engineering solutions;

- Technical feasibility and functional significance. The technical feasibility of modernising the DS3 with the preservation of the basic design components is documented: traction motors AD-914 and converters on IGBT transistors with minimal design modifications in the original locomotive circuit. In addition, in the presented simulation results and conformity checks, the conversion of the single-system DS3 system to a dual-system AC/DC system is technically feasible: the AC-DC switching transients remain within acceptable limits, the closed-loop stability margins are sufficient, the conducted emissions comply with the limits of EN 50121, and the supply/pantograph conditions comply with EN 50163/50367;
- Interoperability and compliance with technical standards. It is argued that the modernised DS3 meets the requirements of international standards EN 50163, EN 50367, and TSI technical specifications, which verifies the possibility of certification of the ERA traction machine. A roadmap for the functional compatibility of ERTMS/ETCS and GSM-R systems with the existing Siemens SIBAS 32 microprocessor control system is substantiated, including structurally outlined stages of implementation and certification;
- Predicted barriers and risks. The authors pointed out the essential condition for careful development of electromagnetic compatibility elements, due to the presence of a multilayer microelectronic architecture in the DS3, which is sensitive to interference and requires the implementation of modern means of protection, filtering, and shielding. It has been stated that a detailed approach to the issue of synchronisation of power supply mode changes is necessary, since abrupt transitions can lead to a reduction in the operational service life and potential failure of devices;
- Prospects for further research. The next priority step in the study should be a full-scale test of the modified DS3 to obtain field operational values, which will confirm the results of modelling and allow specifying the economic aspects of the proposed modernisation. There is a prospect in studying the economic side of the modernisation project, considering the calculation of capital and operating costs, as well as determining the economic efficiency compared to the purchase of new traction machines.

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