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IDENTIFICATION OF THE CHARACTERISTICS OF CONTROL SIGNAL GENERATION FOR IMPLEMENTING THE TRACTION MODE OF A PHYSICAL MODEL OF MAGNETIC LEVITATION TRANSPORT

The object of this research is the process of generating control signals for implementing the traction mode of a physical model of a magnetic levitation transport system.

The problem that was solved was the formation of control signals for implementing the traction mode of the physical model and the method of switching track coils.

In the experimental physical model, the traction mode is implemented by control signals formed on the basis of the angular values of the encoder corresponding to the position of the crew. Based on these signals, the traction modules of the stand are commutated to ensure the necessary polarity of the magnetic field, which creates traction force and ensures the movement of the crew past the section.

The implementation of the traction mode requires accurate determination of the position of the crew relative to the track structure. For this purpose, an encoder signal is used, the information from which is processed in the control unit of the track structure section. A schematic solution and an algorithm for the operation of this unit for a physical model are proposed.

The search for an element base for control boards requires performance verification. From several variations of boards, the one that implements the proposed algorithm with satisfactory process quality was selected.

The main research method is an experiment conducted on a physical model stand. A switching control unit for the traction section of the physical model stand has been developed and implemented, which includes: control boards, a motherboard and software on the Arduino platform. A board option with three DC-DC converters was selected, which ensured stable operation of the traction section.

The main characteristics of electrodynamic processes were obtained, namely: moments of polarity switching of modules, changes in voltage, current and power during the passage of the crew past the section. The switching range of the traction section is approximately five seconds.

The results obtained create the prerequisites for the development of experimental stands and models of maglev transport for further research into traction modes.

Keywords: magnetic levitation transport, traction module, physical model, control boards, electrodynamic processes, traction mode.

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1. Introduction

High-speed magnetic levitation transport (maglev) is a high-tech vehicle that uses the force of electromagnetic interaction between superconducting magnets on the crew and coils on the track structure. This interaction is necessary for levitation, creating traction and stabilizing the train of trains without mechanical contact with the rails. The high manufacturability of this type of transport is determined by the complexity of the design, the need for high-precision interaction between all components of ground control elements and the crew, which directly performs movement within the track structure [1].

The key element of the track structure of the magnetic levitation system are the track coils, which are mounted in the traction modules

and create a magnetic field for lifting the crew, as well as achieving its stable position within the track structure [2].

The work [3] presents the development of a physical model stand positioning system and research of the track module in the non-working mode. Using the angular values obtained from the encoder during the movement of the crew, it is possible to create an algorithm for controlling the traction module by transmitting signals through the RS422/TTL protocol data exchange module to Arduino.

There are many research works related to solving problems that may arise in high-speed maglev transport, especially with the switching of track coils to create and study traction force.

In the work [4], magnetic train technologies are considered from the point of view of electrical engineering, and a review of the results that

have been carried out over the past thirty years around the world in the field of maglev transport is also provided. General concepts, technologies and practical projects that are being developed and already implemented in the world are described. This work focuses on making magnetic train technologies more understandable, and also considers the needs for further research in the field of high-speed maglev transport.

In [5], a review of modern suspension systems for maglev transport was conducted, and the advantages and disadvantages were identified. As a result, a new hybrid suspension technology was investigated, which combines both suspension systems of maglev systems. The hybrid suspension system shown in this work uses an electromagnetic suspension system for takeoff, after which it switches to an electrodynamic one to ensure a consistently high speed. This hybrid suspension system increases energy efficiency and improves reliability by 2.8 and 3.2 times.

In [6], a review of the existing electromagnetic suspension system (EMS) was conducted for compliance with the requirements of ultra-high-speed operation in order to verify the electromagnetic characteristics of a linear motor for maglev trains. As a result, a model of the electromagnetic field of the EMS system was created, the authors concluded that the optimal shape of the magnetic field allows to minimize the pulsation of the traction force and increase the stability of the train movement. To further improve the electromagnetic performance of the linear motor, the Taguchi method was used. The conclusion confirms the effectiveness of the proposed optimal design using finite element analysis (FEA) modeling.

In [7], models and technologies for controlling magnetic levitation systems are summarized according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) criteria. This is due to the fact that a large amount of review material on magnetic levitation transport is outdated and no longer reflects the current state of research in this field. During the research, the authors considered the main methods for modeling magnetic systems. The principle of control methods and their effectiveness in magnetic systems are presented, and the method for controlling magnetic systems under various conditions is described. The conclusion describes the main issues related to the future direction of development in the field of controlling magnetic systems. In [8], a method for combined levitation and motion control in magnetic levitation systems/Hyperloop by selectively applying alternating and direct current operating modes to a group of asymmetric double-sided linear induction motors (ADSLIM) is presented. The concept of a new combined control method is studied using two-dimensional electromagnetic finite element (FE) simulations and compared with the Inductrack permanent magnet (PM) passive magnetic levitation system. By combining AC and DC modes, simultaneous control of the thrust and lift forces of ADSLIM is realized with high efficiency under various operating conditions.

In [9], a conceptual prototype of a maglev train is presented, which is economically advantageous for high-speed transportation. The dynamic characteristics of this prototype were determined using an experimental stand. The results of this research show that this technology is a promising alternative for magnetic levitation vehicles, heavy trains, metros and similar linear power plants. The basis of this work is the use of a system that combines traction and stabilization, which improves the efficiency of the system and reduces operating costs.

The analysis of the work [10] showed that maglev technologies can be integrated with current technologies, such as artificial intelligence (AI) and machine learning (ML). This is due to the fact that maglev transport is high-speed and requires high-speed control systems and certain dynamics of the traction system. However, despite the development of technologies, the practical modernization of maglev systems remains at a limited level. This article is necessary to understand the prospects for the development of modeling algorithms for high-speed transport systems.

In the work [11], the concept of a hybrid dual-mode traction-levitation module is demonstrated, which combines the functions of generating traction for rolling stock and stabilizing the suspension in

one unit. If to compare it with traditional maglev systems, which are divided into systems with an electrodynamic suspension system (EDS) and an electromagnetic suspension system (EMS), this concept is closer to the electromagnetic one.

The implementation of the proposed hybrid dual-mode traction-levitation module occurs due to the change in the polarity of the magnetic flux and interaction with superconducting elements.

Considering modern sources, it can be concluded that effective control of high-speed maglev transport is impossible without an integrated approach, which must take into account many factors simultaneously.

To study high-speed maglev transport, there is a need to develop and create a physical model. Since the task has a complex meaning, for convenience it can be divided into two components that are directly related to each other, namely: the traction and levitation system [3].

Unlike traditional maglev systems, where the traction and levitation modes are implemented separately. The physical model makes it possible to combine these two systems, simultaneously providing both the traction system and the crew levitation. This allows to study the traction mode of the physical model as a set of interaction of electromagnetic and electrodynamic processes.

No less important is the fact that existing maglev systems have long sections, which complicates control, creates design difficulties, and there are also serious requirements for the power supply of such systems.

This physical model offers an alternative implementation of the maglev traction drive, namely, instead of long sections, use short ones. This will significantly simplify the control systems, i. e. they will be turned on only when the rolling stock passes the section, due to which it will significantly reduce energy costs and also significantly simplify the implementation of this system.

Studies [1, 12] demonstrate that separate control of subsystems greatly limits the stability and accuracy of the system's movement, especially at the stages of acceleration and braking of the rolling stock. Everything emphasizes the importance and relevance of further research for the development of magnetic levitation technologies.

A promising direction for the development of high-speed transport systems is to improve its energy efficiency and the use of renewable energy. Analysis of the state of solar energy [12] demonstrates the potential of Ukraine, which can be applied to transport networks of a new type. Increasing the efficiency of renewable energy sources in the future will integrate them into the general infrastructure of maglev transport.

The model for energy consumption of maglev transport is given in [13]. The result of this work is the development of a model of the movement of maglev transport and its dependence on energy consumption. The authors showed that taking into account the dynamics of the linear motor allows to estimate energy consumption and increase the efficiency of operating modes (acceleration, braking). This article is important because it shows the need to analyze the movement mode and energy consumption in maglev systems.

In work [14], it was determined that in order to reduce the energy consumption of magnetically suspended transport, it is necessary to optimize the movement speed. The significance of the results of this work demonstrates that the optimization of movement modes is necessary to reduce energy consumption and can be used in the development of algorithms for controlling the movement of maglev transport.

The object of research is the process of forming control signals for implementing the traction mode of a physical model of maglev transport.

Therefore, *the aim of research* is to experimentally confirm the feasibility of the selected hardware and software solution for implementing the traction mode of a physical model of a high-speed maglev transport.

The objectives of research are as follows:

1. Create a switching unit for controlling the traction section.
2. Develop a control algorithm.
3. Obtain the time dependences of the voltage and current changes in the traction section of the physical model.

2. Materials and Methods

The main methods of the research are an analytical review of previous studies and an experiment conducted in laboratory conditions on a special physical model stand that simulates a magnetic levitation system: a crew-track structure. Control and registration of electrical parameters was carried out using digital oscilloscopes RIGOL DS1104B (RIGOL Technologies, China), as well as INSTRUSTAR ISDS205A (Instrustar Electronic Co., Ltd., China). Processing of the obtained results was carried out using standard software on a personal computer. The development of the hardware part of the switching control unit was carried out in the EasyEDA system based on a microprocessor kit of the Arduino MEGA 2560 R3 CH340 type (Arduino S.r.l., Italy). The software of the hardware-software complex was created using the Arduino IDE system. Visualization and processing of the obtained results was carried out using standard software packages.

3. Results and Discussion

3.1. Creation of a switching control unit

The switching unit includes: control boards, a microprocessor element and a motherboard and two independent power supplies.

The microprocessor element receives angular values from the encoder, processes them and creates control pulses. The motherboard performs the function of switching the traction section.

During the development of the control boards, several variations were created that have the same principle of operation, but differ slightly in the element base. Their main difference is that in the first variation 3 DC-DC converters were used, and in the other instead of one DC-DC converter the CJ812 chip was installed as an alternative option.

The basis for the development of the control boards was the principle of the H-bridge operation, which will provide a change in the direction of the current in the system. This means that at the required moment it is possible to obtain the required polarity of the magnetic field in the track coils installed in the traction modules depending on the position of the rolling stock at the point.

It is important to note that the control elements, i. e. the Arduino single-board computer, receives angular values from the encoder via the RS422/TTL protocol data exchange module, processes them and sends signals to the traction modules. One traction module is switched by two control boards due to the fact that one board switches two track coils connected in parallel. The switching

keys VT1-VT4 are responsible for switching. The use of an opto-driver in the control boards can not only provide complete galvanic isolation between the control elements and the power part, but also provide a stable and energy-sufficient control signal to the transistors. In addition, optodrivers eliminate the problem associated with the "floating" potential on the upper keys of the H-bridge. The power supply of the VD1-VD4 drivers is provided by DC-DC converters PW1-PW3 (in the first variation of the circuit), which receive 12 V, which in turn convert them into the 15 V required to power the drivers. For convenient connection to the motherboard and for quick replacement of the boards, the PLD-10R inter-board connector marked H1 is used.

The use of exactly three converters instead of four is due to the fact that the upper keys of the H-bridge have so-called "floating" sources, due to which the potential relative to the ground can change. Unlike the upper keys, the lower pair has a constant potential and does not affect the stable operation of the system. That is why one converter is used for the lower keys, which reduces the cost of the element base, and also reduces the dimensions of one control board. The schemes of variations of the control boards are presented in Fig. 1, 2.

To choose the desired one from the two control board variations, it is necessary to conduct a preliminary performance check by obtaining time characteristics using the RIGOL DS1104B oscilloscope (RIGOL Technologies, China).

It should be noted that unlike other types of drivers, such as: IR2184, EG3112, IR2104, in this case the dead time parameter is not implemented in the selected FOD3120 driver. Dead time is a short delay between turning off one transistor and turning on the other in one arm of the H-bridge, which prevents both transistors from turning on simultaneously and their failure. One of the options for implementing dead time is to set it manually in the Arduino program code.

The obtained time characteristics of the H-bridge-based boards are presented in Fig. 3, 4.

As a result of testing the operability of two variations of control boards, it is possible to conclude that, unlike the second sample, the board with 3 DC-DC converters operates stably, clearly formed pulses, as well as alternate switching on of pairs of transistors. The dead time parameter was taken into account, the voltage at each switching is stable and equal to 12 V, which is very different compared to other characteristics. According to the results, it is possible to choose a variation of the control board using 3 DC-DC converters. The selected control board is presented in Fig. 5.

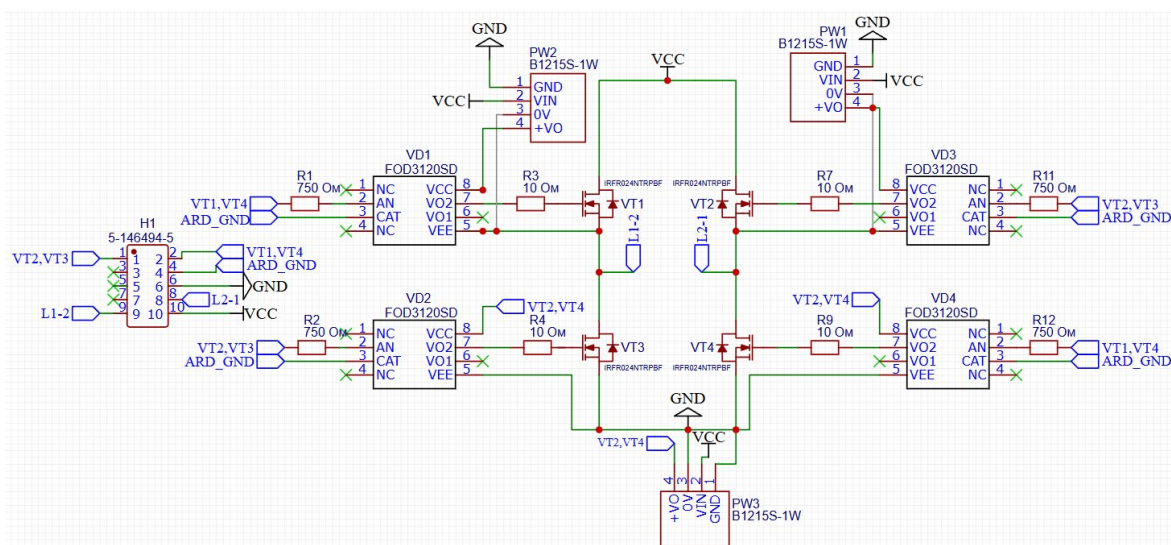


Fig. 1. Control board diagram with 3 DC-DC converters

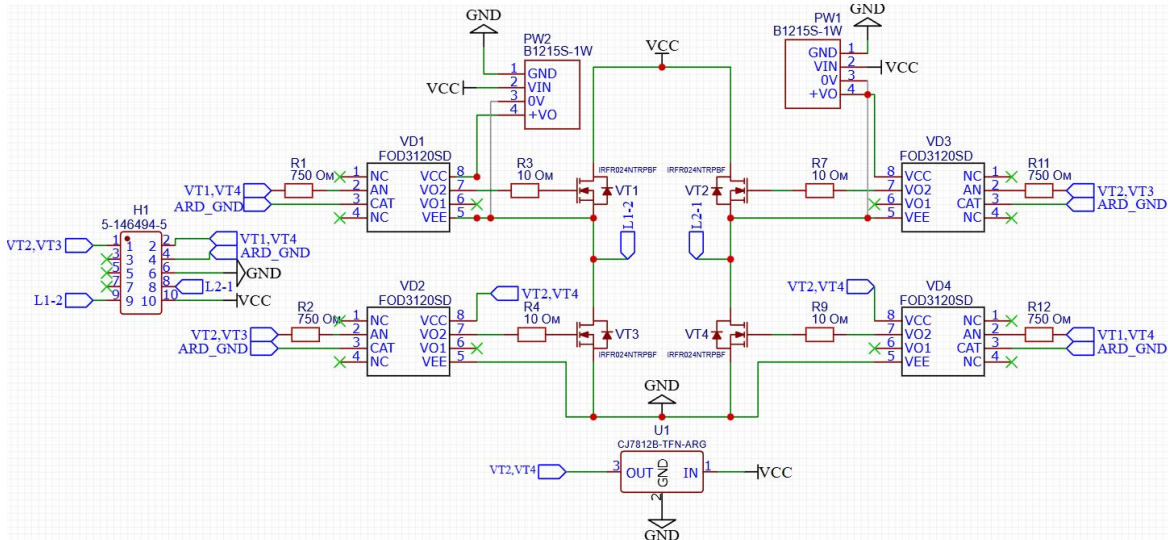


Fig. 2. Control board diagram with 2 DC-DC converters and CJ812 chip



Fig. 3. The result obtained by the control board with 3 DC-DC converters

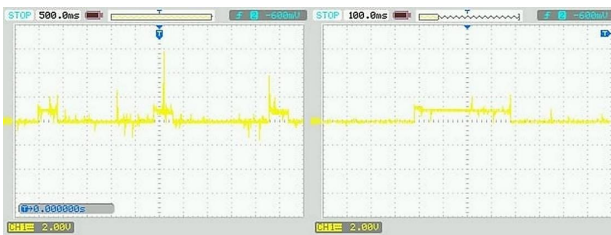


Fig. 4. The result obtained by the control board with 2 DC-DC converters and a roll

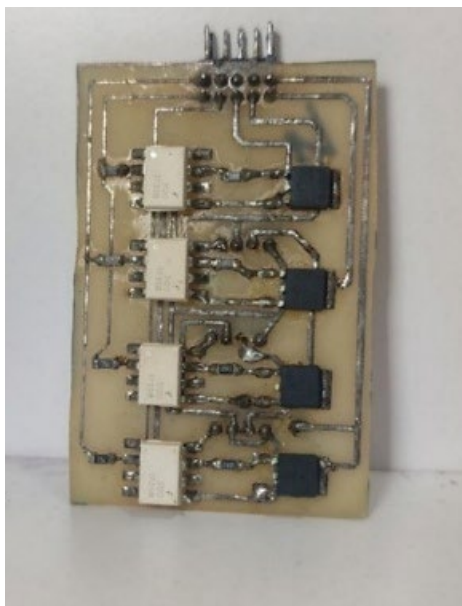


Fig. 5. Control board

The next step is to create a control motherboard. It is designed to combine control boards that switch track coils, creating traction, as well as implement a control system for one section. The traction section includes: 5 traction modules, 20 track coils, 4 in each module. The section view is shown in Fig. 6.



a



b

Fig. 6. View of the implementation of the physical model stand section:
a – external side; b – internal side

The control motherboard diagram is shown in Fig. 7.

The motherboard diagram allows to understand how the integration of individual control boards, which perform the function of switching the track coils of traction modules into one system, is implemented. It demonstrates how the distribution of control signals looks like throughout the section, as well as separate power sources for the control and power parts. A fully implemented switching unit in the form of a modular system is presented in Fig. 8.

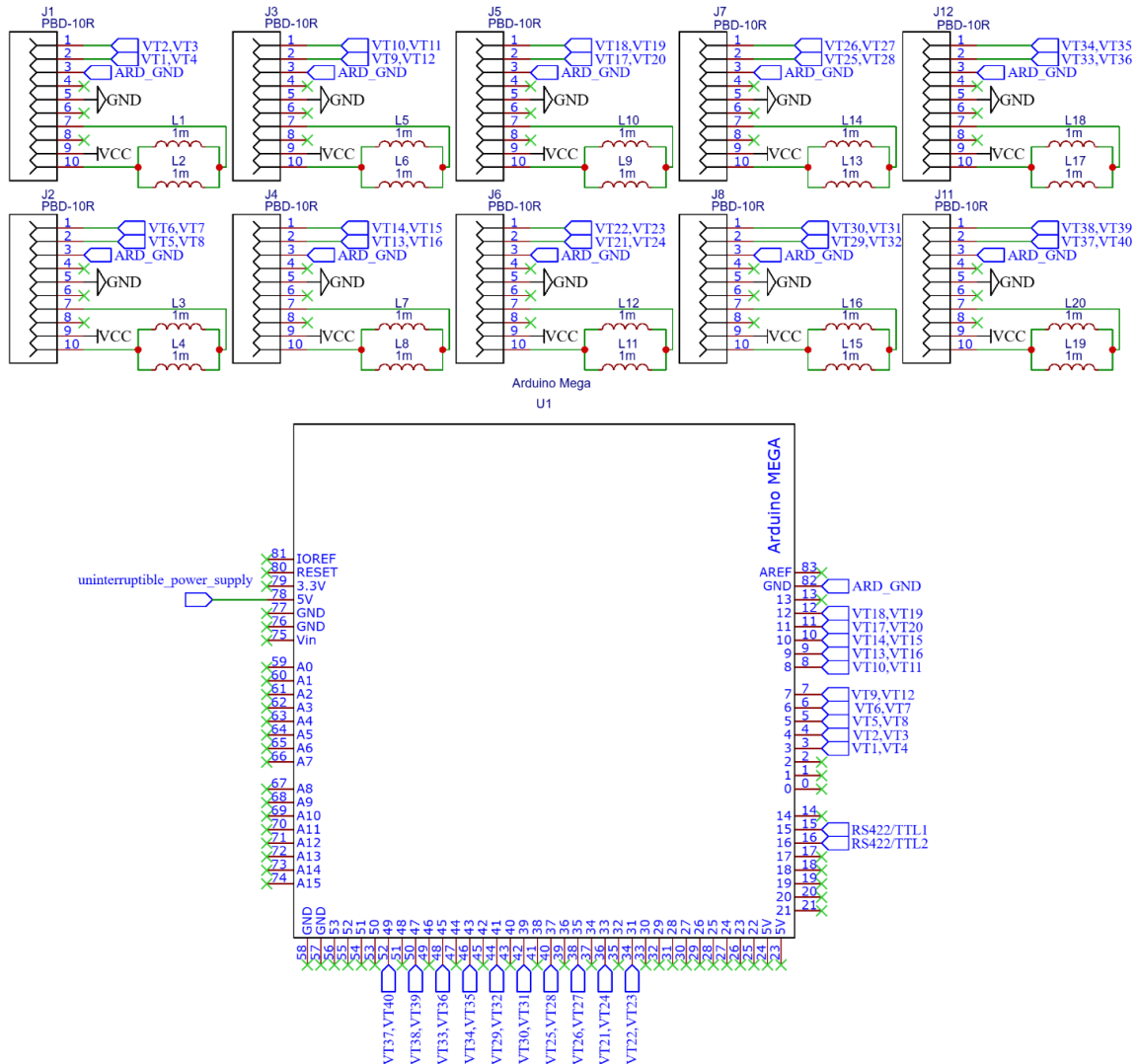


Fig. 7. Control motherboard diagram

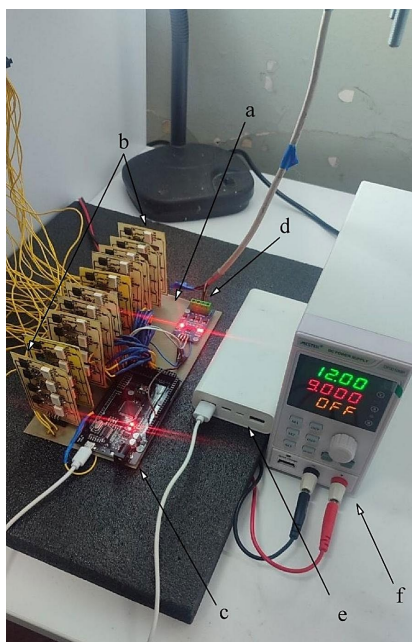


Fig. 8. Switching unit in the form of a modular system: *a* – motherboard; *b* – control boards; *c* – Arduino MEGA; *d* – RS422/TTL module; *e* – Arduino power supply; *f* – motherboard system power supply

3.2. Development of control algorithm

The control principle is based on the supply of signals from Arduino. When the crew passes certain angular values, a control signal is supplied to the board corresponding to a specific track module. The program code defines the sequence of transmission of control signals to a specific board with the required polarity of the magnetic field, thereby creating interaction between the traction modules and on-board magnets moving forward along the section.

The use of Arduino MEGA is due to its advantage among other models in the number of digital and analog outputs, which simplifies the implementation of the traction module control system. Considering that there are three pairs of magnets on the crew sides, one module must work 4 times. The complete passage of the crew through the section with a change in the polarity of the magnetic field in the track coils is schematically presented in Fig. 9.

However, it should be noted that in order for the rolling stock to pass one or another section, it is necessary to clearly implement the switching moment based on the obtained angular values. Fig. 10 shows that one section is 45 degrees, and therefore there are 9 for each module. The traction module does not work only at the moment when each pair of on-board magnets passes the center of the track coils or when the last pair of on-board magnets has gone beyond the boundaries of a certain module. This is due to the fact that at the moment when the centers of the magnet coincide with the track coil, the traction force will be zero.

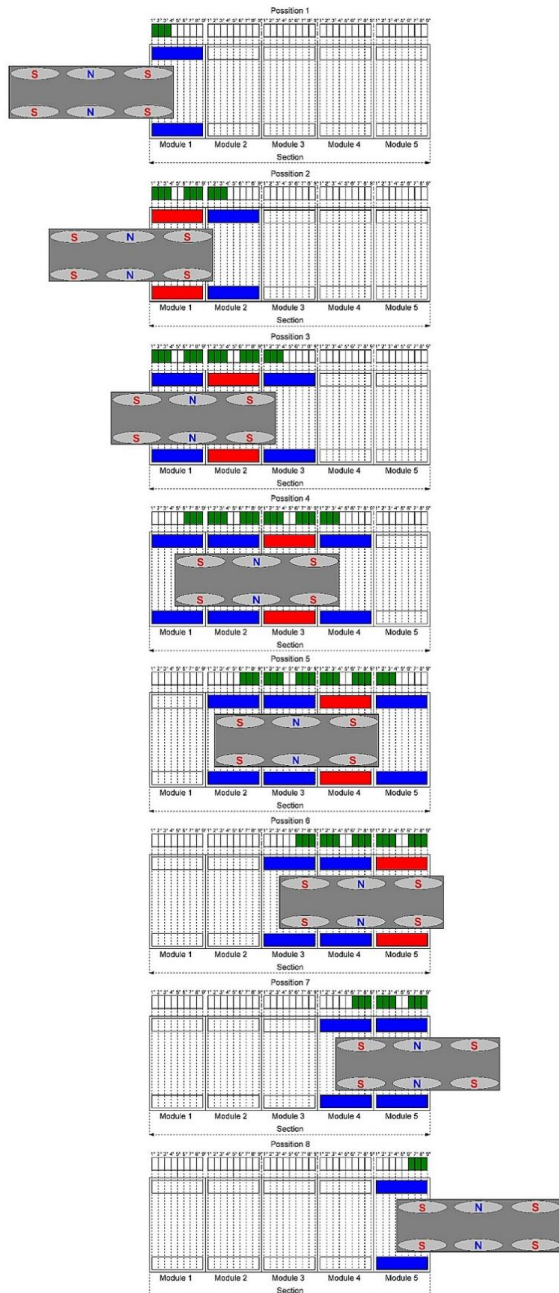


Fig. 9. Schematically depicted complete passage of one section by the crew

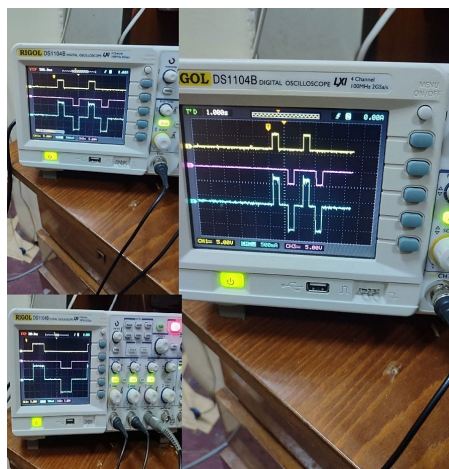


Fig. 10. Example of traction mode characteristics of one module

Based on this, before studying the traction mode of the physical model and analyzing electrodynamic processes, it is necessary to perform experimental calibration of the control algorithm to prevent false inclusions, etc.

3.3. Time dependences of voltage and current changes in the traction section of the physical model

The assessment of the traction mode includes obtaining the characteristics of electrodynamic processes during the passage of the crew through the section. An example of ideal operation of one module is presented in Fig. 10.

The characteristics of the traction mode were obtained using an INSTRUSTAR ISDS205A oscilloscope. The use of another oscilloscope is due to the fact that this oscilloscope has a wider frequency range compared to the previous one. The experimentally obtained characteristics of the traction mode of one section are presented in Fig. 11.

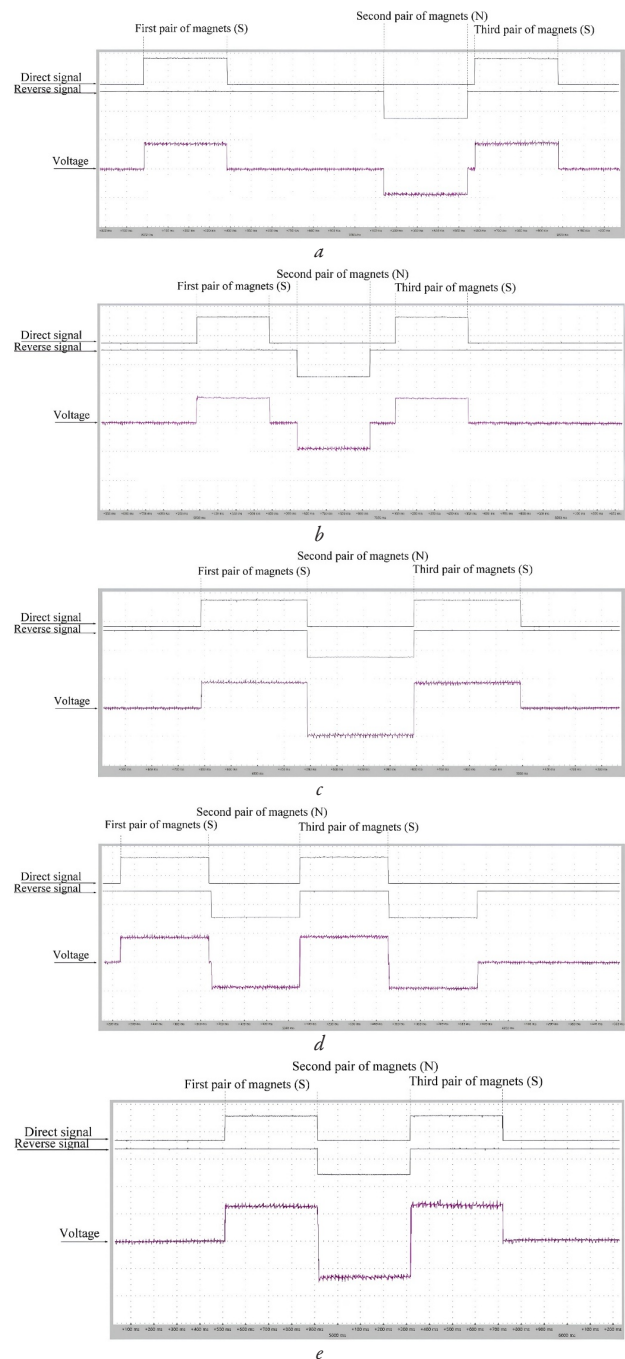


Fig. 11. Characteristics of the traction mode of the section: *a* – first module; *b* – second module; *c* – third module; *d* – fourth module; *e* – fifth module

As a result of experimental research of the traction mode of a physical model of a high-speed maglev transport, it is observed that the real operation of the traction section differs from the ideal one. This is due to the fact that during the operation of the section, the force created in the system provides a high speed of the crew and does not require the involvement of all traction modules. The time characteristic of the power source current during the passage of the crew past the section is presented in Fig. 12.

After obtaining the time characteristic of the current change, the next step is to determine the power. Given that the voltage during the entire experiment is stable and equal to 12 V, the power will be determined by the formula

$$P(t) = U \cdot I(t), \text{ W} \quad (1)$$

where U – the voltage of the power source, V; $I(t)$ – the current of the power source consumed at time t , A.

The obtained time characteristic of the power is shown in Fig. 13.

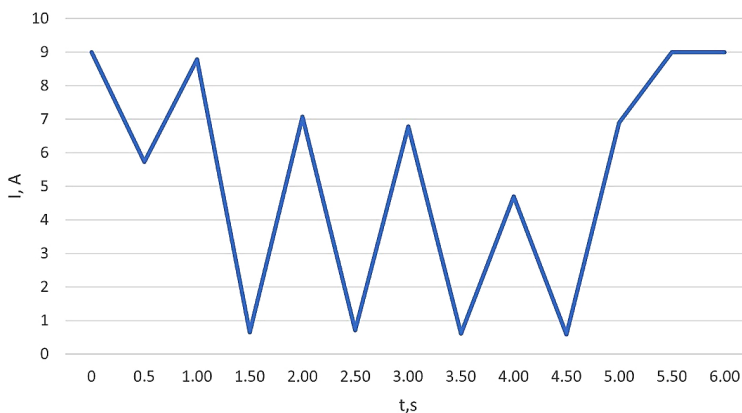


Fig. 12. Time characteristic of the power source current

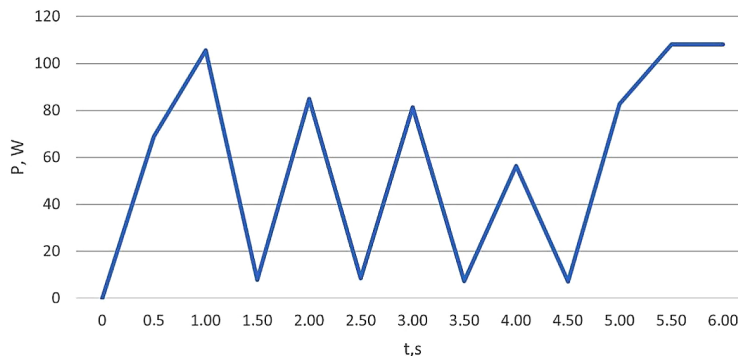


Fig. 13. Time characteristic of power

The obtained time characteristic of power allows to evaluate the operation of the traction section of a physical model of a high-speed maglev transport in operating conditions. Analysis of the obtained results showed that due to the fact that the voltage was stable throughout the time, the power almost repeats the current-time characteristic and has a pulsed nature. This is due to the algorithm of switching traction modules and the interaction between on-board magnets and track coils.

3.4. Discussion

The traction mode was studied experimentally on the stand of a physical model. A switching unit for controlling the traction section was developed and created, which includes: control boards, a motherboard that connects all boards, and a single-

board computer Arduino MEGA 2560 R3CH340 (Arduino S.r.l., Italy), which generates control signals based on the angular values obtained from the ARS-B-50 encoder (ATEK Sensor Technologies, Turkey).

The use of a microprocessor unit allowed to implement the traction mode of a physical model. The main characteristics of electrodynamic processes were obtained, including:

- moments of polarity switching in traction modules,
- changes in voltage, current and power during the passage of the crew through the section, determined using an oscilloscope INSTRUSTAR ISDS205A (Instrustar Electronic Co., Ltd., China), as well as in the form of graphic images.

The practical significance of the results obtained is the creation of a switching unit for implementing the traction mode of a physical model of high-speed maglev transport.

Based on the analysis of the obtained time dependences of voltage and current changes in traction mode, the adequacy of the proposed system and its operability are confirmed.

To implement the obtained results in practice in maglev systems, it is necessary to take into account a large number of factors, namely:

1. Thermal mode limitations – with increasing power, the track coils will emit a greater amount of heat, which can lead to its overheating.
2. When scaling this system to real dimensions, the electrodynamic characteristics may differ from those expected, which will require additional research.
3. The real prototype will have larger dimensions, mass, and higher speeds, which will require additional experimental research in operating conditions.

In the future, when creating a real hardware-software switching unit for each traction section of a real system, performance evaluation is possible only in real operation conditions.

The results obtained create the prerequisites for increasing the efficiency of magnetic levitation transport control, simplifying the implementation of traction effort, as well as future improvements in the field of high-speed magnetic levitation transport.

The practical significance lies in obtaining experimental results of the traction mode of the physical model and assessing the performance of the switching unit controlling the section.

Thus, it is possible to conclude that the experimental research of the traction mode of the physical model do not contradict the known provisions of electrical engineering and electrodynamics, which confirms the adequacy of the obtained results, and also demonstrates the stable performance of the system.

4. Conclusions

1. A traction section control switching unit was developed and created, which combines into one system separate control boards for switching the track coils of traction modules, distribution of control signals throughout the section, as well as separate power sources for the control and power parts.

2. The traction mode of the physical model was implemented using control signals that are formed on the basis of the angular values obtained from the encoder, which correspond to the positions of the crew. The result showed the adequacy of the operation of the traction section control algorithm of the physical model. The range of traction section switching is approximately 5 s.

3. As a result of an experimental research of the traction mode of the physical model of magnetic levitation transport, the time characteristics of the moment of switching the polarity of the modules, changes in voltage, current and power during the passage of the crew past the section were obtained. Analysis of time characteristics showed that at the initial stage of movement, i. e. the first traction module, an increased current value is observed, which is due to the need to form a traction force. During further movement along the section, the current gradually decreases, which characterizes the stabilization of movement and a decrease in the load on the traction system. The time characteristics of the moment of switching the polarity of the modules, voltage, current and power were obtained experimentally, and also correspond to the nature of transient processes in electrical circuits with an inductive load present in them.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship or other nature, which could affect the research and its results presented in this article.

Financing

The research was conducted without financial support.

Data availability

The manuscript has no related data.

Use of artificial intelligence

The authors confirm that they used artificial intelligence technologies:

- The artificial intelligence model used is GPT-3.
- To increase the quality of the figures (section 3), search for literary sources for the last 5 years (section 1), design a list of literature (section References).
- All of the above was checked for the truthfulness and reliability of the displayed information.
- The results of the experimental research of the traction mode of the physical model (diagrams, oscillograms, etc.) were not obtained using AI and did not affect the conclusions of this work.

Authors' contributions

Yehor Chupryna: Methodology, Software, Validation, Investigation, Writing – original draft; **Andrii Mukha:** Supervision, Project administration, Conceptualization, Data curation, Funding acquisition; **Serhii Plaksin:** Supervision, Project administration, Conceptualization; **Dmytro Ustymenko:** Writing – original draft, Conceptualization; **Oleg Bondar:** Formal analysis, Writing – original draft, Writing – review and editing; **Oksana Marenych:** Formal analysis, Visualization; **Oleksandr Holota:** Methodology, Software, Investigation; **Andrii Antoniuk:** Resources, Funding acquisition, Investigation.

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