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## MODERNIZATION OF ADVANCED TRANSPORT TECHNOLOGIES TO ENSURE SUSTAINABLE SOCIETAL DEVELOPMENT

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**Introduction.** Contemporary trends in transport development emphasize increasing energy efficiency while simultaneously reducing adverse environmental impacts.

**Problem Statement.** Existing magnetic levitation (maglev) systems retain a number of legacy (“historical”) design features that constrain their energy efficiency and limit the precision of traction linear motor control, etc.

**Purpose.** This study aims to develop an inertia-free control system for the traction–levitation system of a maglev vehicle that integrates the advantages of both electromagnetic and electrodynamic suspension methods and operates using an environmentally sustainable energy supply.

**Material and Methods.** The study draws upon theories and methods from electric traction, electrical machines, electrical engineering, power electronics, and automatic control theory. These approaches are applied to redesign the architecture and parameters of the power supply system, traction linear motor, levitation subsystem, and control strategies governing traction and suspension.

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**Results.** *The findings have demonstrated that substantial improvements in maglev technology can be achieved through the coordinated integration of electromagnetic and electrodynamic levitation methods within a fundamentally new system architecture. Specifically, the conventional “long-stator” track design with continuous three-phase windings is replaced by discrete modular units capable of dynamic electronic reconfiguration. This approach enables flexible reconfiguration of the operating modes of module coils according to a specified control algorithm, with energy supplied exclusively to those coils aligned with the projection of the maglev vehicle onto the guideway. The system’s energy efficiency is enhanced through localized power supply to standardized modules from a distributed network of photovoltaic converters.*

**Conclusions.** *The study has substantiated a second-generation traction–levitation system concept based on the synchronized application of electromagnetic and electrodynamic levitation principles. The proposed approach enables the generation of both lift and propulsion forces using standardized modular units operating in different modes under coordinated control.*

*Keywords: magnetolevitative vehicle, electromagnetic levitation, electrodynamic levitation, traction-levitation system, coil, photoelectric converter.*

The advancement of transport and energy technologies in the twenty-first century must adhere to the principles of sustainable development. This implies, on the one hand, reducing the energy consumption of transport systems while simultaneously minimizing their negative impact on regional ecosystems, and, on the other hand, meeting societal needs for reduced travel time for both passengers and goods. Achieving these objectives within the framework of conventional transport and energy technologies appears increasingly problematic. Transport systems account for more than one-third of total energy consumption, while air transport — the fastest mode — remains one of the leading sources of atmospheric pollution.

One of the most promising approaches to addressing these challenges is the integration of renewable energy technologies with magnetic levitation (maglev) transport within a unified system. Such integration has the potential to generate a positive synergistic effect, enhancing both energy efficiency and environmental performance.

Magnetic levitation transport is widely regarded as the most перспективный (promising) form of high-speed ground transportation [1–3]. Its advantages are particularly evident when it operates in conjunction with environmentally sustainable energy systems, as recommended by the European Union’s Framework Programmes for Research and Innovation [4]. Scholars and philosophers in leading countries emphasize that adherence to these

principles is essential for achieving sustained progress in line with the concept of sustainable societal development [5–6].

All existing maglev systems are based on two principal methods of levitation — electrodynamic and electromagnetic — and a single method of propulsion, namely the linear motor, which is deployed (“unfolded”) along the guideway [1].

The first method of levitation is implemented in electromagnetic suspension (EMS) systems, such as those used in the Transrapid trains (Germany). In this type of suspension, no mechanical support systems are engaged during motion, as the vehicle remains continuously in a state of levitation. Propulsion is provided by a linear motor with a “long stator,” whose windings are embedded in specially designed slots within the guideway structure. The interaction between the magnetic field of the stator and the magnetic field of the onboard magnets generates the traction force. To ensure lateral stability during operation, additional stabilizing magnets are incorporated into the lower part of the maglev vehicle, arranged transversely relative to the track.

The principal advantages of transport systems based on electromagnetic suspension include the high responsiveness of magnetic interaction, operational efficiency when using ferromagnetic materials, and smooth ride quality. At the same time, this type of suspension has several limitations, including the complexity of the control system and

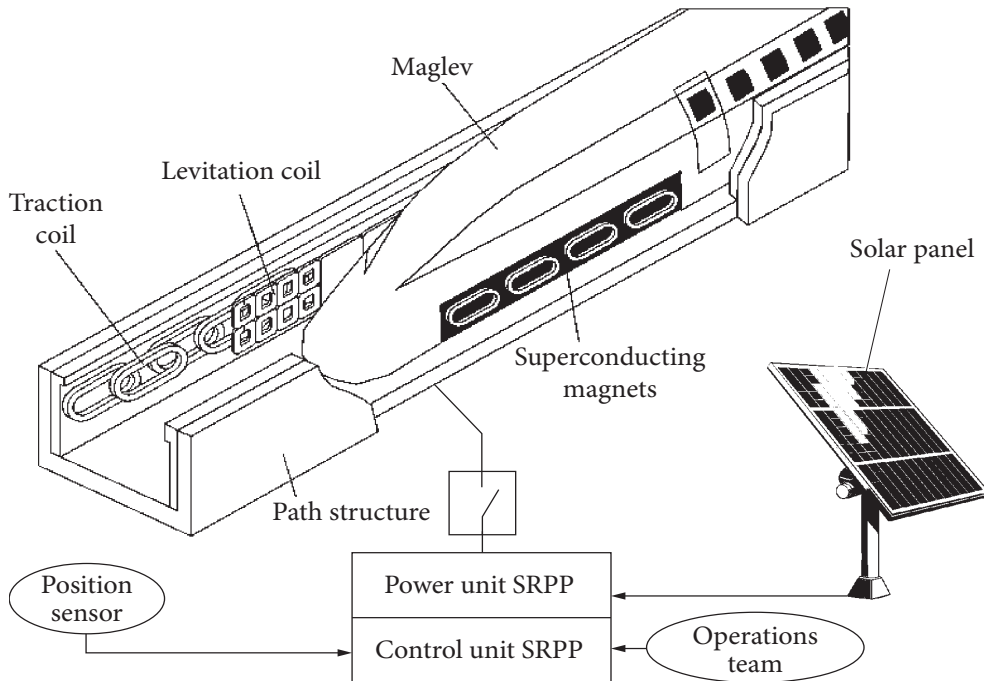


Fig. 1. Power unit control system Maglev

the small air gap between the vehicle and the guideway (approximately 10 mm), which imposes stringent requirements on the precision of guideway construction, installation, and maintenance.

The second type of suspension — electrodynamic suspension (EDS) — is employed in the Japanese JR-Maglev system. The distinguishing feature of this approach is that the constant magnetic flux generated by superconducting magnets onboard the maglev vehicle intersects with the coils embedded in the guideway, inducing an electromotive force and generating a secondary magnetic field. The interaction between these magnetic fields produces the levitation force [7]. Consequently, levitation occurs only during motion, and operational experience indicates that a minimum speed of approximately 120 km/h is required. For this reason, trains equipped with EDS systems incorporate auxiliary support mechanisms (bogies or wheels), which maintain the vehicle in a stable position during acceleration and deceleration phases. Another key feature of this suspension type is the use of superconducting magnets capable of generating ext-

remely strong magnetic fields, enabling high travel speeds and overall system energy efficiency.

The linear propulsion motor constitutes the common component of existing maglev transport systems, regardless of the suspension type. The active windings of the three-phase linear traction motor are grouped into traction sections whose length significantly exceeds that of the maglev vehicle; these are often referred to as “long stator” windings. These sections are installed along the guideway within specialized slots and are powered by dedicated substations via multi-kilometer high-voltage cable lines.

The control of maglev train motion is essentially reduced to the timely supply of electrical power of the required frequency to the appropriate sections of the linear traction motor, in accordance with the well-established method of frequency control of torque and speed in electric machines. This control approach is well developed and is considered sufficiently reliable for passenger transportation.

Nevertheless, it should be noted that the current implementation of control systems largely repre-

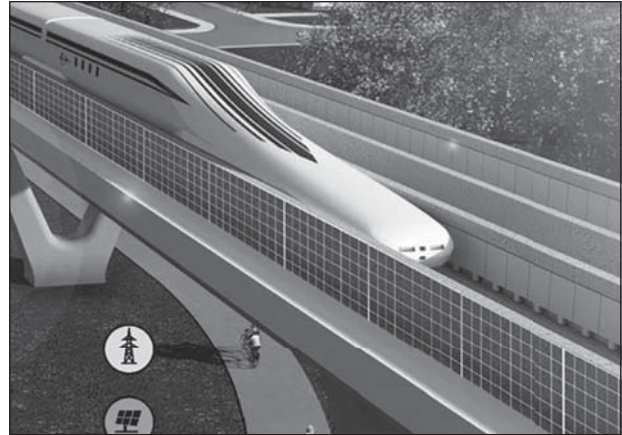
sents incrementally modernized versions of classical approaches that were already available in the 1970s. As a result, these systems retain certain “legacy” characteristics. These include the need to supply high currents (on the order of hundreds of amperes) to traction sections due to losses in long cable lines; limited control precision associated with the switching speed of power thyristors in cycloconverters; and the technical complexity of bringing the linear traction motor into synchronous operation during the initial phase of motion, among others.

The stator windings of the traction motor described above are responsible solely for train propulsion, whereas a separate subsystem of windings is required to provide suspension (levitation). In the JR-Maglev system, which is the focus of this study, train levitation is achieved using a secondary system of short-circuited coils — levitation coils (Fig. 1) — which are installed in the sidewalls of the guideway structure alongside the traction coils (traction sections).

All of these features impose a number of reliability constraints on such a complex, multi-level cyber-physical system as the motion control system of a maglev vehicle. At the same time, advances in microelectronics, radio navigation, and renewable energy over recent decades have created a foundation for the development of a new generation of control systems. In parallel, there has been a growing interest in organizing transport operations at hypersonic speeds within evacuated guideways [8]. Accordingly, the development of a novel inertia-free control system for the traction–levitation system (TLS) of a maglev vehicle — one that integrates the advantages of both electromagnetic and electrodynamic levitation — represents a highly relevant research objective.

### HIGH-SPEED GROUND TRANSPORT BASED ON AN ENVIRONMENTALLY SUSTAINABLE ENERGY SYSTEM

The solution to the aforementioned problem is structured into several stages. At the first stage, it is proposed to integrate two technologies — mag-

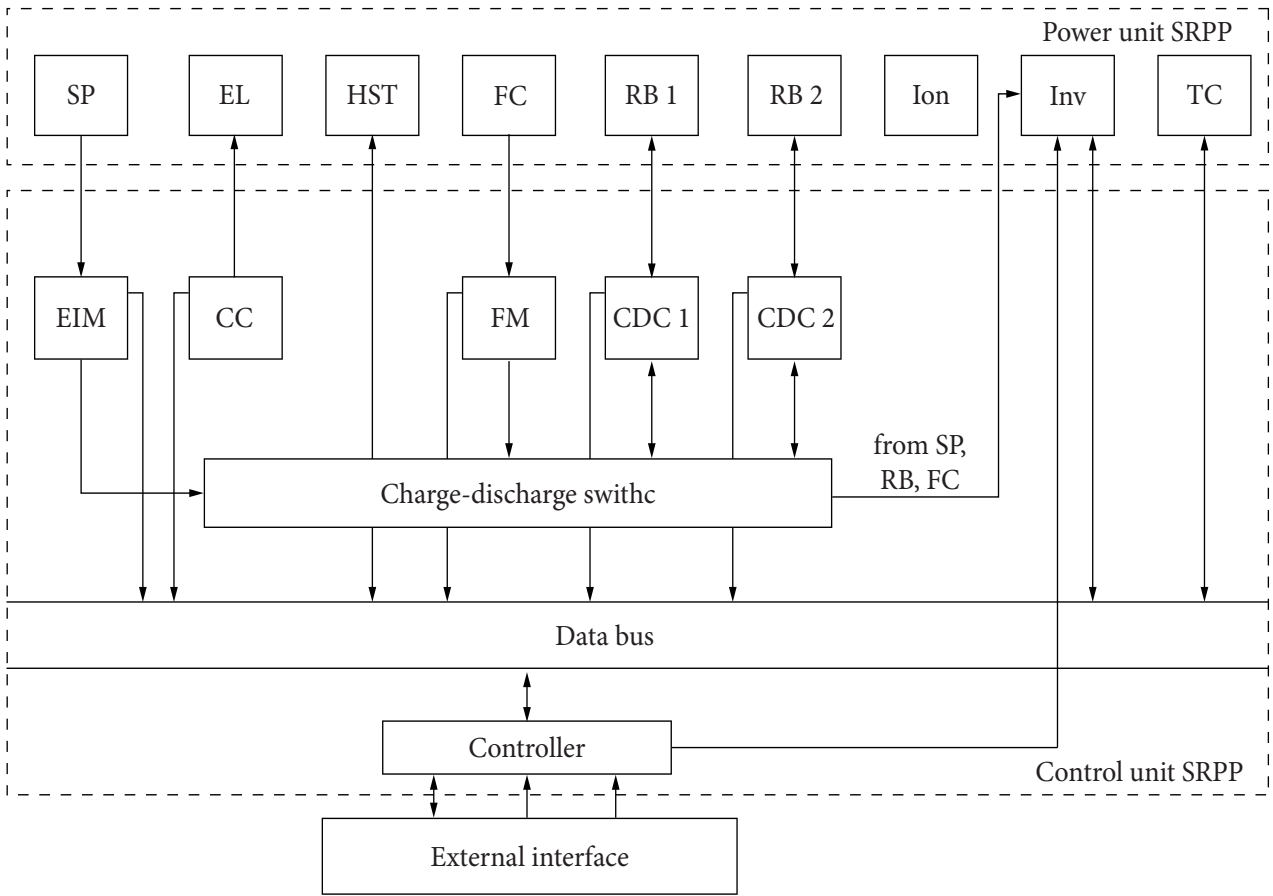


**Fig. 2.** Integration of a magneto-levitation highway and a distributed solar power plant

netic levitation and photovoltaic energy conversion — into a unified transport and energy system [9]. This approach предусматривает (envision) the placement of photovoltaic converters (solar panels) based on amorphous silicon along the entire external surface of the sidewalls of the guideway (Fig. 2).

As a result of this integrated interaction between the two subsystems, it becomes possible to fundamentally transform the structure of the linear traction motor. Under this approach, the traditional “long” motor sections are replaced by “short” sections (approximately 2 meters in length) in the form of solar road power plants (SRPPs). In such units, the traction coil (TC) of the motor serves as the load, to which electrical energy is supplied at specific time intervals via an inverter (Inv). This energy is generated by solar panels (SP) and temporarily stored in rechargeable batteries (RB), which are also part of the SRPP system [10, 11]. The structure of the solar track power plant is illustrated in Fig. 3.

An analysis of average statistical data on solar energy input across the territory of Ukraine indicates that the annual total solar radiation per square meter ranges from approximately 1,070 kWh/m<sup>2</sup> in the northern regions to nearly 1,400 kWh/m<sup>2</sup> in the southern regions [12]. In practical applications, taking into account panel orientation



**Fig. 3.** Structural diagram of the solar track power plant: SP — solar panel; EL — electrolyzer; HST — hydrogen storage tank; FC — fuel cell; RB — rechargeable battery; Ion — ionistor; Inv — inverter; TC — traction coil; IEM — incoming energy meter; CC — charge counter; FM — flow meter; CDC — charge-discharge counter

and conversion efficiency, the effective usable energy can be estimated at an average level of approximately 50 kWh/m<sup>2</sup>. A key advantage of solar energy is its near-universal availability, which enables energy generation directly at the point of consumption without the need for long-distance transmission. This characteristic supports the design of distributed energy systems, which underpins the structure of the SRPP presented in Fig. 3.

These modifications enable a transition to renewable energy sources and fundamentally alter the control algorithm for maglev vehicle motion. In this configuration, the traction sections are powered not by a centralized three-phase alterna-

ting current generator, but by discrete direct current sources distributed along the guideway. This allows each “short” traction section of the linear motor to be controlled independently, significantly improving control precision. However, this approach requires highly accurate spatial positioning of the maglev vehicle, given that its speed may reach 500 km/h or higher. This challenge is addressed through the development of a microwave radio navigation system [13], the integration of which into the combined maglev-photovoltaic system completes the first stage in the development of a high-speed ground transportation system based on an environmentally sustainable energy framework.

## SECOND-GENERATION CONTROL SYSTEM FOR THE TRACTION-LEVITATION SYSTEM

Whereas earlier maglev systems required two separate and independent windings — one for propulsion and another for suspension — installed in the sidewalls of the guideway (Fig. 1), the proposed approach enables the development of a traction–levitation system composed of standardized, unified modules (Fig. 3). These modules are capable of performing both levitation and propulsion functions, depending on control signals generated by a specially programmed microprocessor.

It is well established that, in electrodynamic suspension (EDS) systems, the levitation effect is achieved through short-circuited loops (Fig. 1, levitation coils), in which current is induced by a superconducting magnet moving relative to them. The induced current generates a secondary magnetic field which, through interaction with the magnetic field of the superconducting magnet, produces the levitation force required to suspend the maglev vehicle [14].

The guideway suspension winding sections consist of two individual coils arranged vertically and connected in series (Fig. 4, *a*), forming an “8-shaped” configuration. When the superconducting magnet (Fig. 4, *b*) moves along the guideway such that its longitudinal axis of symmetry does not coincide with the longitudinal axis of symmetry of the coil sections — i.e., when a vertical displacement occurs — an electric current is induced in the suspension circuit windings. The magnitude of this current is proportional to the displacement. As a result, a levitation force  $F_L$  is generated, which supports the maglev vehicle.

In addition, the suspension circuit coils located on both sides of the vehicle are connected in opposition, forming a null-flux loop that compensates for lateral displacement of the maglev vehicle, thereby enhancing stability during motion.

It is well known that a key limitation of the electrodynamic suspension (EDS) method is the insufficient magnitude of the levitation force  $F_L$  at low vehicle speeds (below approximately 100–150 km/h).

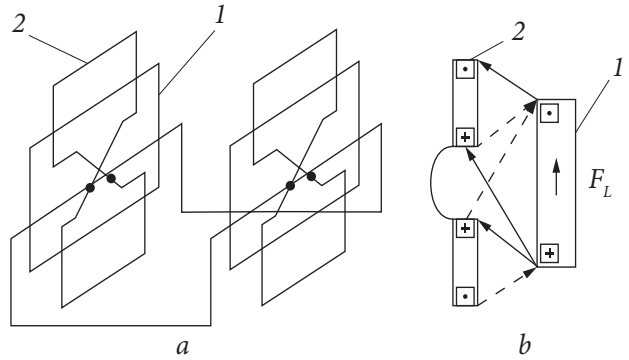


Fig. 4. Levitation system with discrete circuits: *a* — general view; *b* — currents and suspension force; 1 — superconducting magnet; 2 — suspension track circuit

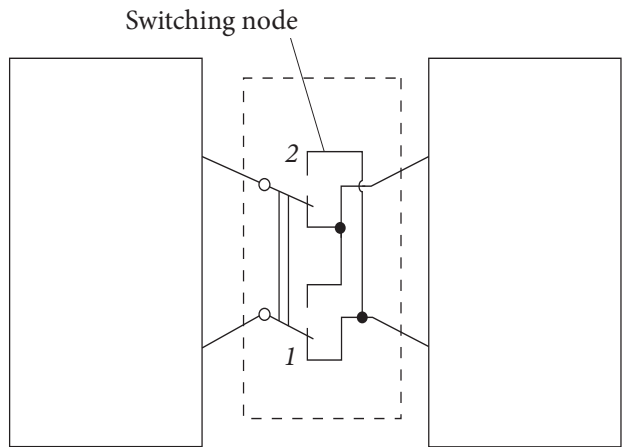
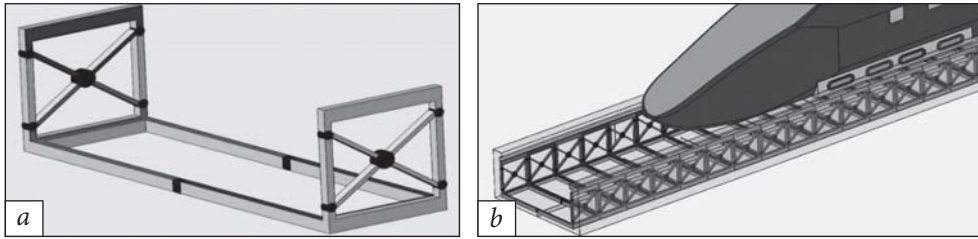


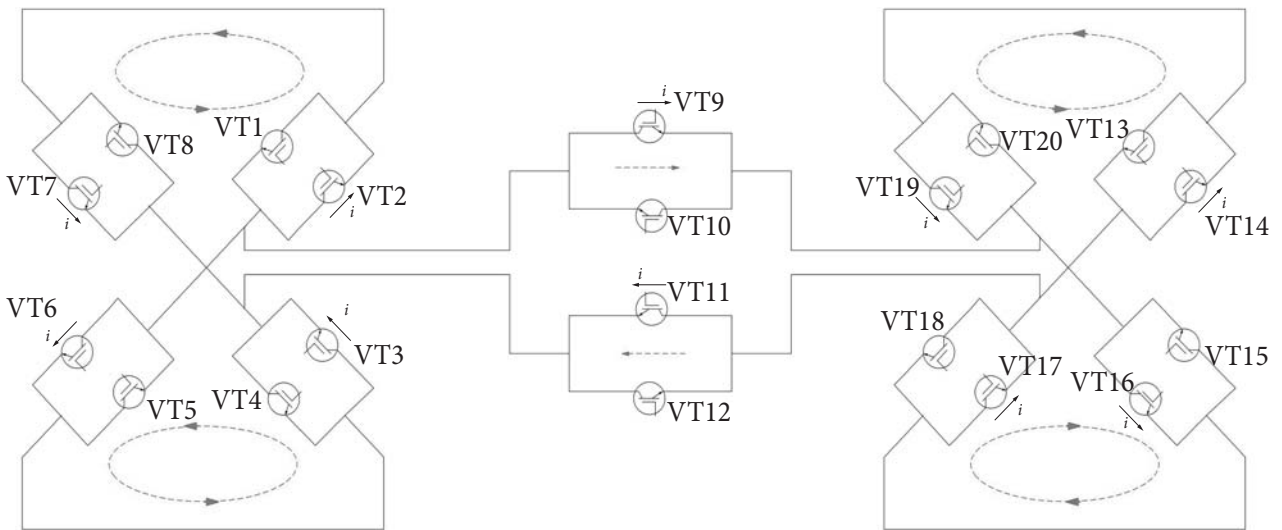
Fig. 5. Schematic representation of the implementation of a section with coil switching: 1 — traction mode; 2 — suspension mode

However, the proposed power supply architecture for the “short” sections of the linear traction motor, based on standardized SRPP modules, enables the implementation of an electromagnetic suspension mode in the low-speed range (from 0 to 100–150 km/h). This is achieved by supplying electrical power to the guideway winding sections of the accelerating vehicle. In this way, the first function of the second-generation traction–levitation system is realized.

The second function consists in enabling, using the same hardware components — including the traction motor section — the propulsion (traction)



**Fig. 6.** Basic module of the road structure: *a* — module; *b* — mutual arrangement of modules and vehicle



**Fig. 7.** Electrical diagram of the coils of the basic track structure module

operating mode. To achieve this, a high-speed switching unit is installed between the upper and lower coils of each section (Fig. 5), providing two operating configurations:

- ◆ In the first switch position, the section operates in traction mode; the resulting configuration resembles a “0”-shaped loop.
- ◆ In the second switch position, the section operates in levitation mode, corresponding to a 8-shaped configuration.

The guideway structure of the maglev track comprises two lateral sidewalls, between which the maglev vehicle travels. Two “short” sections, each consisting of a pair of coils and a high-speed switching unit, are electrically interconnected and mounted on opposite sidewalls of the guideway, thereby

forming a fundamental module of the guideway structure (Fig. 6) [15].

The switching unit, in response to control system commands, transitions the section between traction and levitation operating modes, depending on the state of the transport system and the requirements of the operating schedule.

Figure 7 illustrates one possible implementation of the electrical circuit for connecting the coils of the basic guideway module. High-speed switching elements are realized using IGBT transistors (VT1—VT20, Fig. 7). Although this configuration increases the complexity of the control system, it is technically justified, as it ensures the required control algorithm for regulating the direction of current in the coils.

## COMBINED SYSTEM FOR SYNCHRONIZED CONTROL OF MAGLEV MOTION AND SUSPENSION

The construction of the linear traction motor using such discrete modules enables the transition to the final stage of solving the stated problem. This dual-function module makes it possible to implement a fundamentally new hybrid control system that simultaneously governs both the motion and suspension of the maglev vehicle, thereby fulfilling the primary objective of this study. The concept of hybrid control for the traction–levitation system (TLS) is based on the following principles.

At the initial moment, when the maglev vehicle is located at the starting point of the route, direct current of sufficient magnitude is supplied to all guideway coils within the length of the vehicle that are configured in the “0” mode. This generates a levitation effect, raising the vehicle above the guideway surface by a small clearance (approximately 5–10 mm). The levitation force arises from the repulsive interaction between the magnetic fields of the guideway coils and those of the onboard superconducting magnets.

At any given time, only the guideway coils located within the interaction zone of the maglev vehicle are active. This active region (referred to as the “activity zone”), with a length slightly exceeding that of the vehicle, moves along the guideway at the same speed as the vehicle. Relative to the maglev vehicle itself, this “activity zone” exhibits a quasi-static structure, as the guideway modules forming it are rapidly switched between operating modes in strict accordance with the movement schedule.

Simultaneously with supplying the guideway coils with direct current, the coils located near the front section of the vehicle at a given moment (two on each side) are additionally fed with a low-amplitude, low-frequency three-phase voltage (not exceeding several tens of hertz), which is sufficient to initiate the motion of the maglev vehicle. This three-phase voltage is generated by a pulse-width modulation (PWM) inverter incorporated into the guideway module, using the DC voltage provided by the onboard energy storage system [13].

The analysis of the operating modes of the guideway coils, the calculation of their design parameters, and the corresponding current values were carried out using a simulation model based on the concept of a locally commutated synchronous linear motor (LCSLM) as described in [16]. The results indicate that, by the end of the first time interval, the vehicle advances a distance equal to the length of one traction coil. At the same time, the guideway coils located near the front and rear sections of the vehicle are switched to opposite operating modes. Specifically, the coil positioned near the front of the vehicle is switched to traction mode, while the adjacent coil in the direction of motion (previously inactive) is switched to levitation mode. The operating modes of the remaining coils remain unchanged.

At this stage, the vehicle speed is still insufficient for transitioning to electrodynamic levitation, as the Lorentz force has not yet reached the required magnitude. However, it is already sufficient to enable, by the end of the next time interval, the activation of 12 coils in traction mode instead of 4, as in the previous interval. Correspondingly, the number of coils operating in static levitation mode decreases from 16 to 12. The calculations assume that along a vehicle of standard length (approximately 40 m), there are 20 traction coils on each side, each with a length of about 2 m. This coil length is derived from the condition of maximum energy efficiency [11].

During the subsequent time interval, the speed remains insufficient for a full transition to electrodynamic levitation; however, it is already adequate to switch 20 coils to traction mode while leaving only 8 in levitation mode. As the speed increases further, a point is reached at which it becomes sufficient to achieve full electrodynamic levitation of the maglev vehicle. At this stage, all coils forming the moving “activity zone” are switched to traction mode, and none remain in static levitation mode. Thereafter, the vehicle continues to accelerate to the target speed defined by the operational schedule for the given route segment.

The “long stator” sections used in systems such as *Transrapid* (Germany, China) and *SC Maglev*

(Japan) limit traction motor control to force and speed components only. In such systems, all inductors and guideway coils operate in identical modes along the entire section; that is, while the vehicle remains within a given section, the motor operates under a uniform regime. An exception occurs when the maglev vehicle passes the junction between adjacent sections, where the supplied power must be decreased in one section and increased in the other during the transition.

The concept proposed by the authors enables arbitrary reconfiguration of the operating modes of individual guideway coils according to a specified control algorithm. This allows electrical ener-

gy to be supplied exclusively to the coils covered by the projection of the maglev vehicle onto the guideway structure, with operating modes assigned only along the vehicle length through dynamic electronic reconfiguration.

The results of the study have substantiated the development of a control system for maglev motion and suspension, which integrates the advantages of both levitation methods: electromagnetic levitation (at zero speed during start and stop) and electrodynamic levitation at high speeds, with a large clearance between the guideway and the vehicle, achieved through the use of superconducting magnets.

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## МОДЕРНІЗАЦІЯ ПЕРЕДОВИХ ТРАНСПОРТНИХ ТЕХНОЛОГІЙ ДЛЯ ЗАБЕЗПЕЧЕННЯ СТАЛОГО РОЗВИТКУ СУСПІЛЬСТВА

**Вступ.** Сучасними трендами у розвитку транспорту є підвищення його енергоефективності з одночасним зменшенням негативного впливу на екосистеми.

**Проблематика.** Діючим магнітолевітаційним системам притаманні «історичні» особливості, що суттєво обмежують їхню енергоефективність, точність управління режимами роботи тягового лінійного двигуна тощо.

**Мета.** Створення безінерційної системи управління тягово-левітаційною системою магнітоплану, що поєднує в собі переваги електромагнітного і електродинамічного способів підвішування та отримує живлення від екологічно раціональної енергетичної системи.

**Матеріали й методи.** Використано теорії та методики електричної тяги, електричних машин, електротехніки, електроніки та теорії автоматичного управління для модифікації структури та параметрів системи електропостачання, тягового лінійного приводу, системи підвішування та способів управління тягово-левітаційною системою магнітоплану.

**Результати.** Значного поліпшення магнітолевітаційної технології можливо досягти завдяки взаємоузгодженій комбінації двох способів магнітної левітації — електромагнітної та електродинамічної, шляхом використання принципово іншої архітектури побудови маглев-траси — не з «довгих» секцій з трифазними силовими обмотками, а з дискретних базових модулів, що мають можливість електронного реконфігурування їхньої структури та режиму роботи. Це дозволяє змінювати режими роботи котушок модулів у будь-якому порядку за заданим алгоритмом та подавати енергію тільки в ті котушки, що покриваються проєкцією магнітоплану на шляхову структуру. Енергоефективність такої системи досягається локальним живленням однотипних модулів від розподіленої мережі фотоелектричних перетворювачів.

**Висновки.** Обґрунтовано концепцію тягово-левітаційної системи другого покоління на основі синхронізованого використання електродинамічного і електромагнітного способів левітації, суть якої у створенні підйомної та тягової сил однотипними дискретними модулями, що працюють у різних режимах завдяки відповідному управлінню.

**Ключові слова:** магнітолевітаційний транспортний засіб, електромагнітна левітація, електродинамічна левітація, тягово-левітаційна система, котушка, фотоелектричний перетворювач.