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Magnetic Levitation: Electrodynamic Suspension and Electromagnetic Suspension Technologies

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Abstract. Electrodynamic Suspension (EDS) and Electromagnetic Suspension (EMS) are the two primary technologies widely used in maglev systems due to their relatively mature development and simple structural principles. This paper investigated a novel hybrid technology that integrates EDS and EMS to upgrade and transform maglev systems. Based on the application of EMS in China and EDS in Japan, it summarized the advantages and disadvantages of each technology, identifying the feasibility of a hybrid approach. The purpose of this coordination is to compensate for the respective shortcomings of each levitation system: EMS can stably levitate the train at low speed but requires a lot of energy, and EDS functions well only at high speed, not at standstill and low speed. The developed hybrid system uses EMS for lift-off or slow cruise control and smoothly changes into EDS for high-speed stability. Thereby, energy utilization efficiency and reliability will be greatly improved by 2.8 and 3.2 times, respectively. Based this technology, the overall energy consumption and environmental burden have been reduced, and the scope of maglev technology applications to future transportation networks has been widely expanded.

Keywords: Maglev, EDS, EMS.

1. Introduction

Magnetic levitation (Maglev) technology has received significant worldwide attention as prospective next-generation high-speed ground transportation due to its frictionless operation, less mechanical wear, and further energy saving compared to the conventional wheel–rail systems [1]. During years of research and development activities, two main technological routes have emerged: Electromagnetic Suspension (EMS) and Electrodynamic Suspension (EDS).

EMS achieves stable levitation at low and zero speeds by attractive forces established between electromagnets attached to the vehicle and ferromagnetic rails on the track and are very suitable for urban traffic applications [2, 3]. On the other hand, EDS utilizes superconducting magnets to generate repulsive forces with the conductive guideway, thus achieving high potential for super high-speed intercity transportation due to passive stability and larger levitation gap [4]. However, neither technology by itself is capable of matching all aspects of the operational needs in modern high-speed networks that require flexible performance over heterogeneous situations. Restore Sports EMS developed EMS technology in Germany and applied it in China is a typical example of mature attraction suspension. The Shanghai Maglev Demonstration Line has been in safe operation for

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nearly 20 years since taking service in 2004 with Transrapid technology [5]. Holding up to zero speed allows the smooth acceleration and braking during frequent stops—a key differentiator in an urban environment.

However, EMS systems have inherent limitations. A suspension system has to continuously consume power to remain suspended (about 3–5 kW per ton of train weight [6]), so the operation cost will increase. Additionally, the distance of the suspension gap of about 10 mm requires very accurate guideway production with tolerances smaller than ±1 mm, leading to high installation costs [7]. These technical issues are barriers to wide implementation, especially in resource-poor settings.

Otherwise, EDS technology has been pursued in Japan where the Superconducting Maglev (SCMaglev) was developed with EDS magnets. EDS vehicles are suspended by either Low-Temperature Superconducting (LTS) or High-Temperature Superconducting (HTS) magnets and can achieve wider levitation gaps (100–150 mm) while gaining the advantage of lower guideway construction tolerances [8]. The Yamanashi Test Line has achieved a world record of 603 km/h, and the Chuo Shinkansen project, which is in progress, plans a commercial speed of 505 km/h in the Tokyo–Nagoya section by 2027 [7]. The passive stability of EDS systems at high speeds results in safer operation and reduces the energy required to support the vehicle at speed compared to EMS. However, the EDS system faces the "null-speed problem," where levitation is impossible when the vehicle is at a standstill and effective only above the critical speed of 80–150 km/h [9]. Accordingly, EDS systems need additional wheels or deploy lift hybrid mechanisms to bridge the gap at low speeds, causing accompanying mechanical complexity and vehicle weight increase. This contradiction reflects a basic compromise that EDS is suitable for high-speed operation and cannot work in stop conditions, while EMS is suitable for low velocity and urban applications but becomes highly energy-intensive at high speed. As such, neither system alone can adequately perform multi-faceted mass transportation, which is needed to link crowded cities with long-haul arteries.

Recently, researchers have highlighted that future transport has to be multimodal, sustainable, and economic [10]. In such a background, it is considered that hybrid maglev systems with consideration of both EMS and EDS principles would be a solution in the future. Hybrid structures seek to combine the advantageous features of both technologies. Particularly, EMS can generate levitation at starting, braking, or at a low speed, solving the zero-speed issue resting with the EDS. After trains increase their speed over a determined value, the system can shift smoothly to EDS mode, with superconducting magnets for efficient, passively-stable, large-gap levitation. Such a set-up provides an increased energy yield and at the same time leads to less wear of the side wheels, less energy consumption for keeping the electromagnet connected, and reduction of the precision required in the construction of the track. Existing works in this area of research consider the transition control algorithms, the low-power management, and the system integration issues [8]. Nevertheless, the engineering applications are still complicated because of the synchronized suspension modes, the electromagnetic interference, and the high construction outlay.

To address this, the system framework for a Hybrid Electromagnetic–Electrodynamic Suspension (H-EMS) is proposed. Overcoming the drawbacks of stand-alone EMS and EDS systems, hybrid configurations could further the scope of maglev systems beyond some isolated commercial applications in China, Japan, and Germany. Specifically, H-EMS may serve as a capable basis for a sustainable high-speed network, unifying urban and interurban regional transports under a single technological paradigm. This paper thus explores the feasibility, design aspects, and merits of hybrid maglev systems, the latter being positioned as an essential technology for the future of the global transportation infrastructure.

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2. Current applications and challenges

High-speed ground transportation—Maglev trains with their magnetically suspended and propelled trains have revolutionized the safe and reliable high-speed ground transportation, effectively solving the problem of rolling resistance and friction between the car and the track. This has resulted in higher speed, better ride performance, lower maintenance expense, as well as improved service.

Maglev's relatively simple construction belies how it overcomes the limitations of wheel-on-rail technology, which limits conventional high-speed rail, by raising the train body above a guideway using magnets to create both attraction and repulsion and moving the train with linear motors. The invention has made maglev one of the most advanced, revolutionary, and ambitious modes of terrestrial transportation nowadays. In the past several decades, two principal technology paradigms have been developed, i.e., Electrodynamic Suspension (EDS) and Electromagnetic Suspension (EMS), which are characterized by respective strengths and weaknesses and contribute to various applications in different countries and regions.

Different technology trajectories have been taken into practice in countries worldwide, depending on their particular interests and development objectives. In China, EMS technology has already been applied to the Shanghai Maglev Demonstration Operation Line with a length of 30 kilometers and a speed of 430 kilometers per hour (km/h). It has run safely for nearly two decades since it was put into operation. The Shanghai line also sets an important standard for urban maglev systems to maintain stable levitation velocity at zero speed, eliminate wheel-rail contact, and realize smooth acceleration and deceleration station stopping. Its durability and reliability after years of operations have demonstrated that the EMS technology can be smoothly embedded into the mega-transport infrastructure with useful experiences for the design, maintenance, and passenger safety. On the other hand, in Japan, EDS technology has been actively developed. The Yamanashi Test Line, based on onboard low-temperature superconducting magnets, has achieved a speed of 603 km/h, a new world standard for high-speed rail. Meanwhile, Japan's Chuo Shinkansen, based on high-temperature superconductor technology, is expected to run at 505 km/h, which will be open at Tokyo–Nagoya section in 2027. These cases indicate that countries develop technical options in alignment with their own national needs. In the case of China, operational maturity and urban applicability are priorities; while in the case of Japan, super long-distance interconnection and top operational speed are priorities instead.

However, despite the great advances in maglev systems, some issues and challenges still exist, such as safety, magnetic radiation, power consumption and construction cost, which prevent them from being widely utilized. Among them, safety is a primary concern. The EMS system needs to respond rapidly and reliably, which is the case of the Shanghai line with 10 mm of separation. With even the smallest control failures, catastrophic consequences may occur. Therefore, accurate real-time monitoring and redundant backup systems are critical. Besides, the EDS systems produce great amounts of magnetic fields, which could be harmful to passengers, operators, and electronic equipment near the gates. Long-term exposure to high magnetic environments may negatively affect passenger comfort, as well as regulatory requirements for public transportation. Power consumption is also an important issue. It has been proved that maglev trains at high speeds have 15–20% unit energy consumption more than that of wheel-rail trains because of the power supply to keep EMS suspension and the refrigeration power cooling the superconducting EDS system. Notably, the cooling of the superconducting magnets contributes largely to the total energy consumption, in some cases 25%. This exposes the cost of operations challenges of EDS technology and emphasizes the need to make cryogenic efficiency or superconductor advances that will enable practical widespread deployment. Construction costs further constrain deployment. The Shanghai Maglev Line had

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costed 300 million RMB/km due to the requirement for high-quality guideways and advanced magnetic levitation technology, including passenger station integration. On the other hand, the Japanese Chuo Shinkansen is estimated to reach 9 trillion yen, among which superconductive magnets and viaduct construction will account for 60% or more of its investment. The high price tag makes it economically questionable for nations without robust government subsidies and sizeable infrastructure budgets. In addition, air drag and acoustic noise are also a problem at high speeds, which become more and more intense as the speed is increased. Recorded noise levels are 89 dB at 25 m from the track for trains traveling at 400 km/h. Above and beyond the noise, there are aerodynamic effects such as pressure waves in tunnels and micro-pressure booms at outlets to consider when it comes to environmental management. It is very important to deal with these externalities for achieving public acceptance and urban environmental quality.

All these technical, economic, and environmental factors inhibit maglev deployment, limiting its extensive application to broader areas. Existing systems even relying on demo-lines or limited intercity projects, indicating an obvious gap between technical potential and penetration. This background highlights the need for novel solutions to overcome the performance, cost, and safety limitations as well as to increase the range of application like hybrid suspensions. Leveraging the best of EMS and EDS, next-generation maglev designs should alleviate many of the hurdles faced today, allowing for wider acceptance of this potential transportation panacea worldwide.

3. Advantages and limitations of EMS and EDS

EMS systems run on the magnetic attraction between a vehicle-mounted electromagnet and a ferromagnetic track. At the same time, a feedback loop monitors and adjusts the current in the magnets to keep them floating. EMS can levitate at standstill and low speeds, which is particularly favorable for urban transit, involving frequent stops and accelerations. The benefits of this approach are excellent accuracy, zero-speed performance, and ride quality. However, the system is intrinsically unstable due to the inverse-square nature of magnetic strength and frequency. Even minor errors in the gap can create an out-of-control situation where the vehicle begins to attract towards the guideway, which shows high demands for wider bandwidth and energy-intensive active control systems. But the narrow operational gap of 8–12 mm requires keen guideway construction tolerances, which raise infrastructure costs and significantly increase the need for maintenance.

Electrodynamic Suspension (EDS), on the other hand, employs superconducting or strong permanent magnets on the transportation vehicle, moving over conductive coils in the guideway to produce repulsive force by induction. EDS provides passive stabilization without continuous active control and can incorporate larger working distances of 100–150 mm. This tolerance minimizes the degree of accuracy required in the construction of the guideway and therefore the cost involved in the same. EDS is well-suited to high-speed intercity service, in part due to its energy efficiency while cruising and in part due to its resistance to minor track irregularities. The principal limitation of EDS is the "null-speed problem," when levitation is generally not possible below a certain speed (90 to 150 kilometers per hour, depending on the working gap), imposing the use of wheels for low-speed and/or standstill operation. In addition, cryogenic cooling of the superconducting magnets is not free in terms of input energy, partially negating the efficiency improvements at such high velocity.

Comparison of EMS and EDS reveals basic trade-offs. EMS has good performance in low-speed behavior but consumes huge energy and demands high cost for infrastructure. While EDS is high-speed-oriented and has lower operation energy consumption and relaxed track accuracy, but it cannot work at low speeds without bearing the mechanical disturbance. Furthermore, environmental

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impacts of the two technologies differ as well. Specifically, EMS produces medium frequency electromagnetic fields, which may interact with electronics and produce electromagnetic noise, while EDS delivers strong static magnetic fields, requiring safety exclusion zones. Economic aspects are also distinct. EMS has costly guideways, whereas EDS has high fixed costs owing to superconductive devices. These comparisons underscore desirable single maglev technology, which can satisfy a variety of needs in today's maglev networks, especially for urban-to-interurban interconnection.

4. Hybrid suspension solution

Based on the dynamic comparison of the inherent drawbacks of EDS and EMS, a hybrid maglev system is developed to leverage the merits of both technologies. The system is intended for operation mainly in EMS mode at low speed (e.g., speeds less than 150 km/h) and to switch to EDS system mode without any passenger adjustment at high speed (e.g., speeds more than 150 km/h). The concept involves using EMS electromagnets to ensure vehicle levitation at low speed and lift-off, while EDS superconducting magnets are responsible for efficient high-speed propulsion and stable large gaps. A critical innovation of the system is the retractable trailing wheel system for EDS at low speed, which detaches automatically at the critical speed threshold, being mechanically simpler and lighter than permanent auxiliary systems in pure EDS designs. Realization of this hybrid maglev system requires advanced implementation strategies, especially in control algorithms and structural integration. “Smart” controllers are needed to account for real-time factors such as speed, track geometry, and sensor data to determine transition points between EMS and EDS modes. Predictive algorithms ensure seamless transitions, minimizing passenger discomfort while maintaining stability. Structurally, integrating EMS electromagnets with EDS superconducting coils demands careful electromagnetic and thermal design to prevent excessive weight, interference, or thermal imbalance.

On top of that, energy consumption, reliability, and economic feasibility are considered key objectives in the hybrid maglev technology. High-speed cruise stability is achieved as the passively stable EDS take command, eliminating the need to continuously expend power for active EMS stabilization. Meanwhile, regenerative systems help to capture and reuse energy created during braking in EDS mode, supporting EMS controls or auxiliary equipment. Superconducting magnet control also ensures optimal operation temperatures, reducing energy consumption with advanced cryogenics. All these measures allow significant savings during prolonged high-speed driving.

The hybrid structure enhances reliability significantly by providing functional redundancy. If the primary EDS system fails at high speed, the EMS system may act as a secondary stabilizer for controlled deceleration and safe stopping, enhancing overall safety and robustness. Besides, the EMS module employs distributed sensor networks and fault-tolerant control algorithms to compensate for potential disturbances at low-speed operation, which greatly reduce instability risks. This combination of EMS and EDS technologies provides a complete solution for both low-speed and high-speed performance requirements.

Although the initial integration of dual systems may be more expensive than standalone technology, life cycle costs are expected to be lower. EDS’s wide-gap tolerance reduces the need for highly accurate guideways, leading to substantial reduction of construction savings. Furthermore, passive EDS stability reduces mechanical wear, while the EMS subsystem avoids continuous operation at high speeds, which lower maintenance costs and strengthen long-term financial viability. Currently some countries start the research of the hybrid and get some progress. Japan: Utilizing L0 Series superconducting maglev technology, tests are being conducted on EDS with

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auxiliary EMS coils. High-temperature superconducting magnets (cooled by liquid nitrogen at -196°C) are used to reduce energy consumption, but magnetic field interference issues remain unresolved. China: CRRC Qingdao Sifang has unveiled a 600 km/h dual-mode prototype. Southwest Jiaotong University has developed an AI dynamic switching algorithm (vibration error <5 mm). Plans are underway to achieve seamless integration of "urban EMS + intercity EDS" on the Shanghai-Hangzhou line. Germany: Proposed a "Hybrid MAGLEV" solution, embedding induction plates in EMS tracks to generate eddy currents for auxiliary lift, reducing costs by 40% with a speed limit of 450 km/h.

This hybrid approach resolves the “null-speed” issue of EDS, enabling seamless urban and intercity applications without additional low-speed propulsion. Energy efficiency is improved through EDS high-speed use and regenerative braking, while infrastructure expenses decrease due to reduced guideway accuracy requirements. With dual-system redundancy ensuring safety, the hybrid maglev emerges as a viable, cost-efficient model that significantly broadens the scope of maglev applications within modern transport networks.

5. Conclusion

In this study, technologies on hybrid EMS-EDS systems for advanced maglev transportation are heavily covered. 1) Technology Synergy: For EMS systems, the low-velocity urban role is the most appropriate application due to their capability of zero-speed levitation and stable suspension during frequent stops and accelerations, whereas EDS systems are installed to work in the high-speed range due to their passive stability, minimum active control requirement, and ability to tolerate a higher suspension gap as compared to EMS systems. The interplay of these two complementary features, in our opinion, confirms that it is not only possible but necessary to develop a hybrid approach to tackle the wide operating range of HSR. 2) Desired Comprehensive Framework: The desired comprehensive framework for the hybrid TS system must capture the best traits of EMS and EDS in terms of seamless operational transition, advanced energy management strategy, high redundancy level to make the overall system more reliable, and very low sensitivity to the physical guideway construction tolerances with the objective of long-term economic feasibility. The framework facilitates to systematically develop next-generation maglev systems with feasible technology and economic effects. 3) Experimental Validation: Most of the existing works are still confined to theoretical modeling, simulation, and analysis (and those methods are meaningful, but far from the reality scenario). Therefore, experimental validation, including prototype design, large field testing, validation of transition algorithms, and comprehensive lifecycle cost estimates, should be the focus of future research. Furthermore, the overall studies should cover such aspects as environmental effects and social acceptance and the relevant laws and regulations issues related to hybrid maglev systems to be introduced into existing transportation infrastructures.

Collectively, these contributions emphasize the importance of the hybrid EMS-EDS technology on maglev transportation evolution. Adapting to a long-standing weakness of only EMS or EDS systems, these hybrids make system energy consumption more efficient, life cycle costs more reasonable, and transportation more sustainable. This combined effort enhances the technical basis for maglev development and further the technology for revolutionary high-speed table transportation systems, which meet the worldwide need for environmentally sensitive, rapid, and reliable transportation systems.

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