

Electrical Components of Maglev Systems: Emerging Trends

Nisha Prasad¹ · Shailendra Jain¹ · Sushma Gupta¹

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Abstract Consistently rising environmental concerns and depleting petroleum resources have accentuated the need of sustainable, energy efficient and clean means of transport. This has provided the impetus to the research and development of clean alternatives for existing public transportation systems. Development of linear motor-propelled, contact-less maglev systems is considered a promising alternative to conventional on-wheel rail transport technology. Maglev technology primarily focuses on improving the performance, speed, fuel economy, driving range and operating cost of the transit system. These parameters vary with the design and efficiency of the electrical system used in maglev-based transportation systems. To present this study, firstly, a detailed survey of the important constituents of a maglev electrical system has been carried out with techno-economic perspectives. Contemporary maglev technologies have then explored along with their respective advantages and limitations. Electrical systems form the heart of maglev systems and, therefore, this paper presents the components of a standard electrical system together with the comparative analysis in terms of present trends, on-going technological advancements and future challenges.

Keywords On-wheel rail · Maglev · Propulsion · Linear motors · Guidance · Levitation

1 Introduction

Rapidly increasing urbanization has given rise to an aggravating transport crisis and deteriorating environmental conditions [1–3]. According to recent studies, road transport dominates the global transport industry with a percentage share of 35.1%. Road transport not only contributes around 72.6% of total CO₂ emission resulting from the transportation, but it also consumes 75.3% of total transport energy demand [3]. These facts emphasize the need for clean and efficient mass transit systems. Rail transportation industry has the capability to cope with the expanding transport network. However, on-wheel railways worldwide fulfil 60% of their total energy demand through petroleum products. This not only indicates the necessity of the electrification of railways, but it also emphasizes on the need of improvement in their technological performance [3]. This has motivated the researchers and manufacturers to foster the development of magnetic levitation (maglev)-based rail technology worldwide. Being a fully electrified system, a maglev system can assure future passenger transport. Electrification makes it fully congruous with the renewable energy resources without any technological modifications, which provides sustainability to the system [1–3].

In the last few decades, maglev technology has globally emerged as a sustainable and feasible alternative to conventional on-wheel rail technology. The purported maglev-based system involves specialization both in technical and non-technical aspects for its reliable operation. Technical facets include skilful integration of mechanical, civil and

✉ Nisha Prasad
nipr24@gmail.com
Shailendra Jain
sjain68@gmail.com
Sushma Gupta
sush_gupta@yahoo.com

¹ Department of Electrical Engineering, Maulana Azad National Institute of Technology (MANIT), Bhopal, India

electrical systems. Other than these technical aspects, well-planned signalling, control, operation, maintenance and monitoring ensure its predictability and sustainability. Non-technical aspects of the system involve matters related to finance, marketing, management, customers and legal issues. All these components contribute to the qualitative and quantitative improvement in the performance of the system [1, 2].

The electrical system in a maglev system constitutes components such as levitation, guidance, propulsion, input power transfer and control. This system generally derives power from linear motors for its propulsion and braking mechanism. Available literature and papers discretely deal with levitation, guidance, propulsion, linear motors, input power transfer and control. Still, it would benefit researchers to have access to a state-of-the-art review of the maglev technology in a unified and holistic manner. There is also a lack of literature presenting an overview of linear motor-based propulsion systems and associated components as well as their integration for transit systems. The objective of this paper is to present a state-of-the-art understanding of the various components of the electrical system used in maglev technology. In addition, this paper highlights the current techno-economic issues and future challenges.

The organization of the paper is as follows: Section 2 gives an overview of the existing rail technologies that include both on-wheel rail technology and maglev technology. It also discusses the distinctive features of these technologies. Section 3 highlights the components of maglev technology in detail. This section highlights the emerging trends in the levitation and propulsion systems used in rail transportation along with their types. It also includes brief discussion on linear motors generally used for such applications. This section also presents a review on guidance, power transfer and control technology used in such systems. Section 4 summarizes this review.

2 Classification of Rail Systems

Technological enhancement of rail transportation technology requires either up-grade of the on-wheel railway infrastructure or construction of dedicated corridors for running maglev-based systems [4, 5]. Figure 1 shows the classification of existing high-speed rail systems worldwide.

Figure 2a shows the basic block diagram of an on-wheel rail system. In this system, groundside supply energizes the catenary and contact wires comprising the overhead equipment (OHE). Mechanical contacts like pantographs then collect the supply from the OHE and transfer it to the rail locomotive converters. Converters then convert this

supply into a suitable form to energize the traction motor drive systems. These motors further propel the rail wheels, and adhesion between the tracks and wheels helps the vehicle to move forward. Remote sensing units monitor the whole operation of the system through an optical fibre cable-based signalling and monitoring system which sends signals to a semi-automatic centralized control unit and to track signalling control unit. This centralized unit not only controls the supply of the system, but it also monitors the operation and maintenance of the whole system [6].

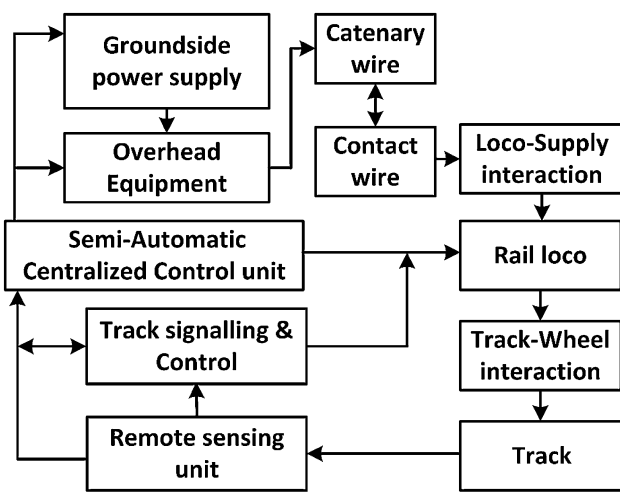
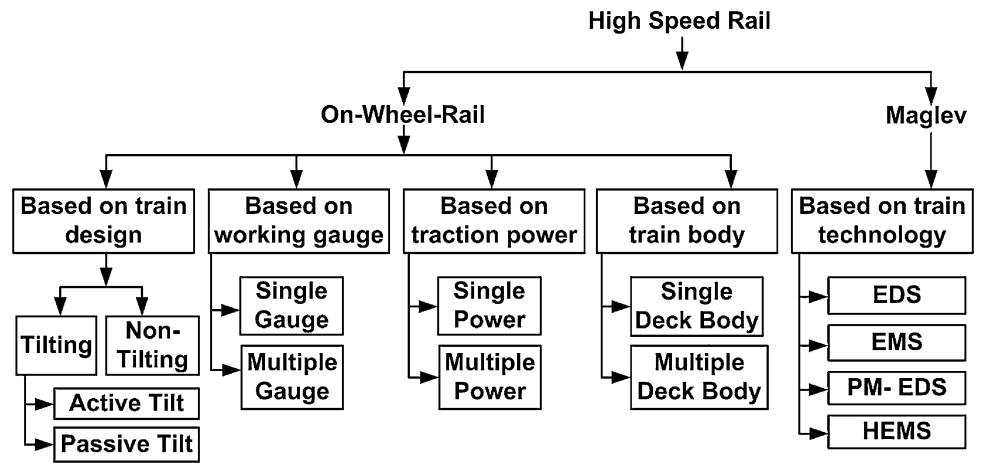
Modifications in rolling stock and infrastructure components of the on-wheel railways limit the maximum achievable speeds due to mechanical and adhesion constraints. However, some European countries have implemented modifications in aerodynamic structure and material of rolling stock along with the use of high-efficiency propulsion motors to achieve higher speeds. Nevertheless, for achieving higher speed with efficient performance, countries worldwide are adopting maglev-based rail transportation systems.

Figure 2b shows the general block diagram representation of a maglev-based rail system. Input power transfer is not feasible through mechanical contacts at speeds higher than 300 km/h [5–7]. Therefore, in maglev systems, ground supply either energizes the track coils or it supplies the on-board system through magnetic coupling between the track coils and rail car, whereas in on-wheel rail systems, mechanical contacts fulfil this task. Features like an automatic centralized control unit and in-cab signalling system differentiate the maglev systems from on-wheel rail systems [5–7]. Table 1 presents the basic differences between an on-wheel system and maglev-based system.

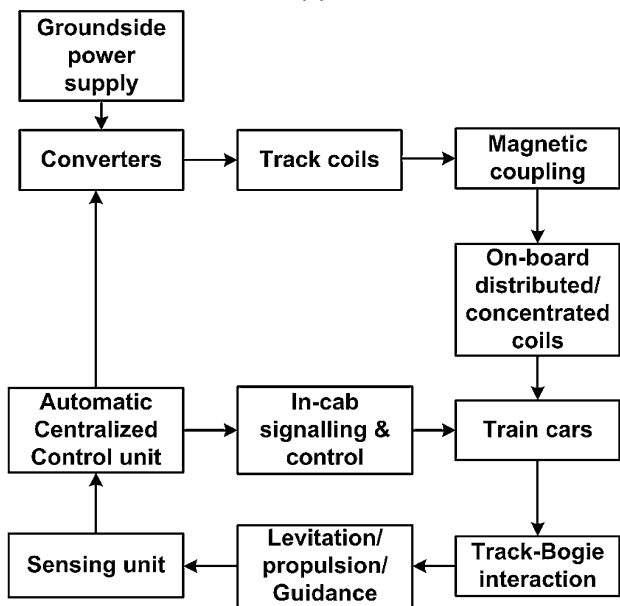
Regardless of efforts to improve and upgrade conventional rail systems, they are limited in achieving speeds of more than 350 km/h with desired efficiency. Maglev technology has emerged as a breakaway from the conventional wheel-based technology for achieving higher speeds with better performance [8]. Although the capital cost of establishing a maglev system is high, its maintenance and operating costs, however, are much lower than the on-wheel railways due to less mechanical contacts. Maglevs show much less specific energy consumption as compared to wheel-based rail systems for the same travel distance at the same operating speed [9]. Specific energy consumption, which is measured in watt-hour per seat per kilometre (Wh/pl/km), changes with the operating speed, travel distance, track profile, train length and train technology used. Still, maglev systems increase energy consumption by approximately 7% for an approximately 30% rise in speed, for the same track profile and distance.

On-wheel rail systems use adhesion between wheels and rails to move forward, while maglev systems use propulsion force generated by a linear electro-mechanical system,

Fig. 1 Classification of high-speed rail systems



(a)



(b)

Fig. 2 Block diagram, **a** on-wheel rail system, **b** maglev system

to move forward. This linear propulsion system replaces conventional rail wheels with electromagnets, by yielding sufficient force to levitate the train on the guideway [10]. This feature imparts a smooth ride to the vehicle along with increased speed. In some existing systems like Moscow monorails, linear motors are used to power the wheel-based rail systems. However, such systems are currently used at lower operating speeds of around 60–70 km/h. Therefore, in higher-speed systems, maglev technology is currently used. The following sections of this paper describe maglev technology in detail.

3 Components of a Maglev Electrical System

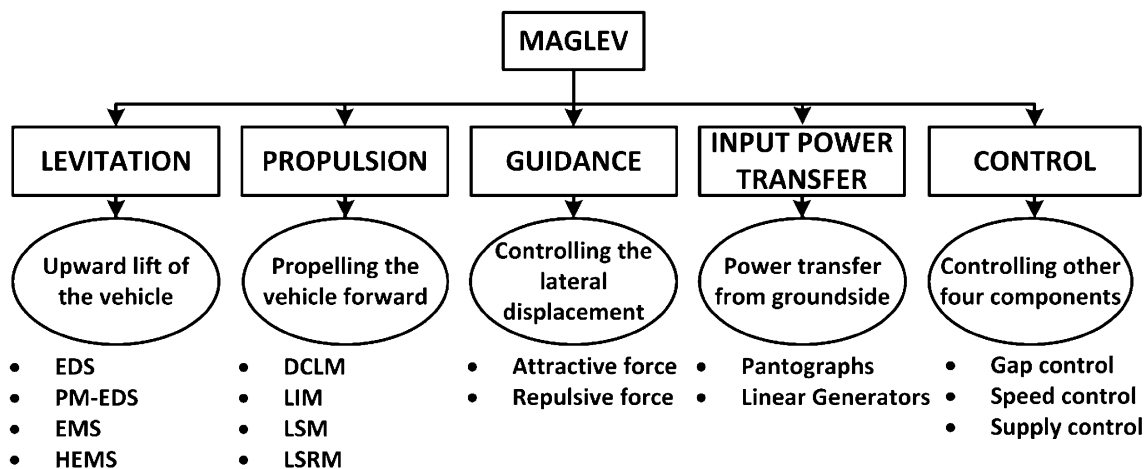
A maglev system comprises five major components, namely levitation, guidance, input power transfer, propulsion and control systems, as shown in Fig. 3. Levitation force provides the upward lift to the vehicle, whereas propulsion force is responsible for propelling the vehicle forward. Guidance force balances the lateral displacement of the vehicle to keep the vehicle centred on the guideway, as marked in Fig. 4a. Input power transfer deals with the mechanism of transferring power from the groundside. The control system is designed mainly to control the previously described components, as shown in Fig. 3. The following sub-sections include detailed discussions about these components [8–11].

3.1 Levitation

Levitation technology is an integral part of every maglev system that enables the vehicle to glide over an air cushion. The method used to accomplish levitation can be either a magnetic repulsion-based system or a magnetic attraction-based system [12, 13]. Based upon the method used for realizing levitation, maglev system can be classified as an

Table 1 Comparison between on-wheel and maglev systems

S. no	Parameter	On-wheel rail system	Maglev system
1	Levitation	No levitation	Levitating coils
2	Propulsion	Rotary motors	Linear motors
3	Forward motion	Rail and wheel adhesion	Linear motors
4	Braking	Various braking circuits	Linear motors
5	Guidance	Rail and wheel	Guidance coils
6	Vibration and noise	More due to rail-wheel contact	Less, as no mechanical contacts
7	Maintenance	Frequent replacements of parts	Less frequent replacements
8	Safety	Derails from minor defects	No possible derailment
9	Specific energy consumption (Wh/pl/km)	48.5–59	45–54

**Fig. 3** Components of a maglev system

electro-dynamic suspension (EDS) system, electro-magnetic suspension (EMS) system, a permanent magnet electro-dynamic suspension system (PM-EDS) or a hybrid electro-magnetic suspension system (HEMS).

3.1.1 Electro-Dynamic Suspension System (EDS)

This system employs magnetic repulsive force for accomplishing levitation, as shown in Fig. 4a [11, 12]. On-board magnets, when moving forward with the vehicle over the guideway consisting of inductive coils or conducting sheets, generate repulsive force due to interactions of on-board magnets with the currents induced in the guideway coils [13, 14].

This repulsive force provides the required levitation to the vehicle. This technique can achieve levitation up to 10 cm. However, the inherent pitfall of this system is the requirement of rubber tires on which the train must roll initially until it reaches a lift-off speed of about 100 km/h. In addition, this system uses superconducting magnets (SCMs) which are super-cooled at frigid temperatures

using a cryogenic system. These magnets not only raise the cost of the system, but the strong magnetic field generated by such magnets penetrates inside the train car even after shielding, making the travel uncomfortable for the passengers. However, the SCMs can conduct electricity during power failure. The Japanese MLX01 vehicle uses this levitation technology [15, 16].

3.1.2 Permanent Magnet Electro-Dynamic Suspension System (PM-EDS)

This system is a modified form of the conventional EDS system. It is a passive levitation system, also known as an inductrack system based on the principle of magnetic repulsion. It uses permanent magnets at room temperature, arranged in the form of a Halbach array, as shown in Fig. 4b [13, 14].

Unlike a conventional EDS system, this system does not require any super-cooled magnets, neutralizing any cryogenic requirements [15, 16]. However, the system requires auxiliary wheels to accelerate the vehicle until it acquires

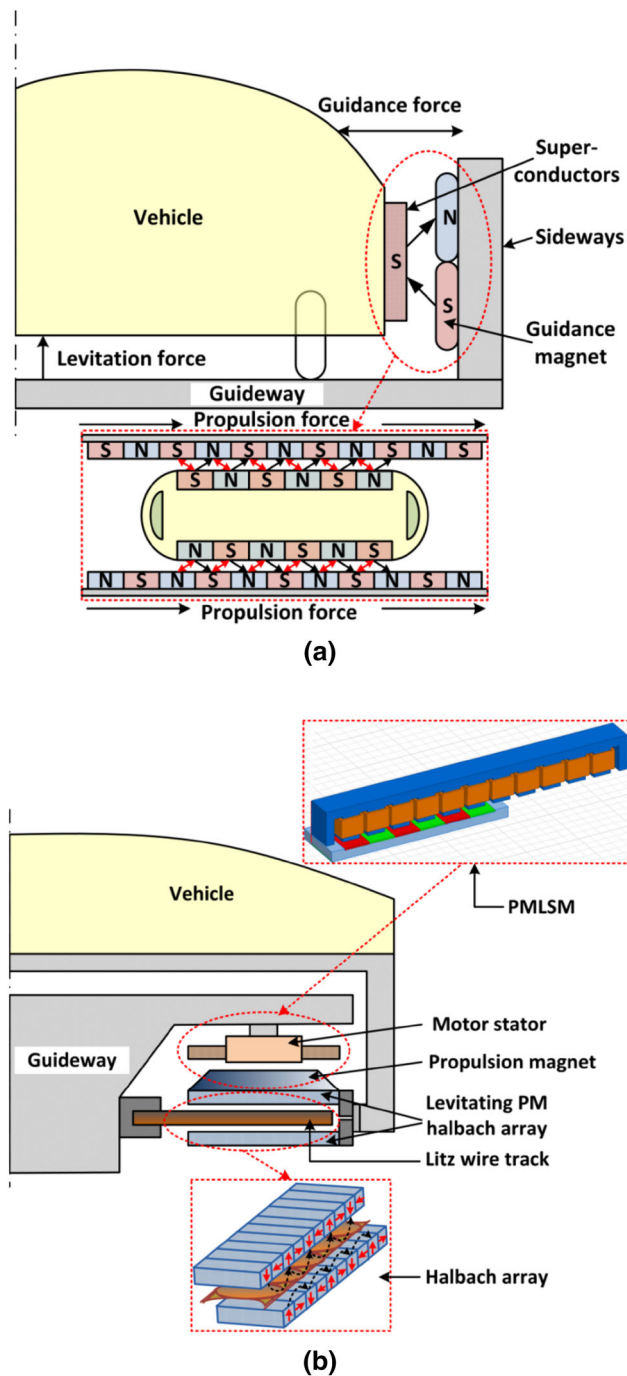


Fig. 5 **a** Electro-dynamic suspension system, **b** permanent magnet electro-dynamic suspension system

some initial take-off speed, after which it starts levitating. In case of power failure, the train can slow down and rest on its auxiliary wheels. The PM-EDS system employs a Halbach array formed with permanent magnets. This arrangement produces a sinusoidal magnetic field on the lower side of the array while cancelling it completely on its upper side. This magnetic field interacts with the insulated short-circuited coils forming the track to produce repulsive

levitating force [14]. As this design does not require any super-conductor, it is a low-cost design. Since an ideal Halbach array does not exist, the magnetic field produced by such an array is not purely sinusoidal [13]. Thus, for smaller levitation air gaps, irregularity in the magnetic field produces higher-order harmonics in the system [15]. These harmonics result in oscillations in the system even without external disturbances. This technology has been under trial by General Atomics, USA, with suspension magnets separated from propulsion magnets [13]. Other technology that uses super-conducting material levitating in a constant field of permanent magnets has also been under trial and research in Chengdu, China since 2002 [16].

3.1.3 Electromagnetic Suspension System (EMS)

This system uses magnetically attractive forces between the guideway and the on-board electromagnets installed below the guideway, for accomplishing levitation. This design produces levitation even at zero speed [17, 18]. Unlike the EDS system, EMS system uses standard electromagnets, which conduct in the presence of electric power supply only [19]. This results in magnetic fields of comparatively lower intensity inside the passenger compartment, making the travel more comfortable for the passengers.

However, lower intensity of magnetic field produces a levitation air gap of 1 cm. A small levitation air gap makes the continuous controlling of the gap imperative because of the inherent instability of the suspension systems. Nevertheless, controlling the smaller air gap becomes more and more inconvenient with the increase in speed. This makes it suitable for low- to medium-speed applications [8]. The Shanghai Maglev, Korean UTM and Japanese HSST use this system with the levitation and guidance circuits completely integrated [17–19], as shown in Fig. 5a. This design not only decreases the number of power controllers and electromagnets required, but it also decreases the power supply rating required for the circuit, making it an inexpensive design [6]. However, in this arrangement, the interference between the two circuits increases with the increase in speed. Therefore, this integration is suitable for low-speed applications [18]. The German Transrapid TR09 uses EMS technology with the levitation and guidance circuits completely separated, as shown in Fig. 5b, which makes it suitable for high-speed operation because of the absence of interference between the two circuits [19]. However, such arrangement increases the cost of the design due to the increase in number of power controllers used.

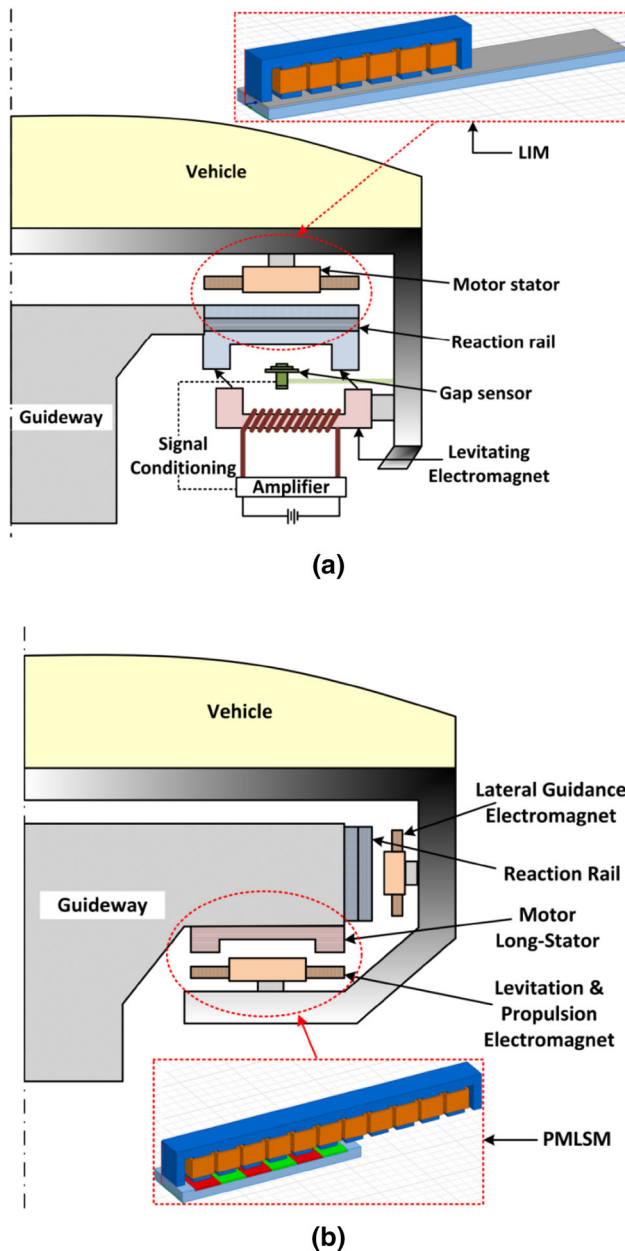


Fig. 5 Electro-magnetic suspension system, **a** with levitation and guidance circuits integrated, **b** with levitation and guidance circuits separated

3.1.4 Hybrid Electromagnetic Suspension System (HEMS)

This is a modified form of the conventional EMS system, as shown in Fig. 6. It uses permanent magnets along with electromagnets to reduce the electric power consumption of the conventional system and to achieve larger air gaps [20, 21]. At the start, the system uses both the electromagnets and permanent magnets (PMs) to accomplish levitation. However, after achieving a steady-state air gap, the PMs solely starts levitating the vehicle, nullifying the power of the electromagnets. The PMs generate a magnetic

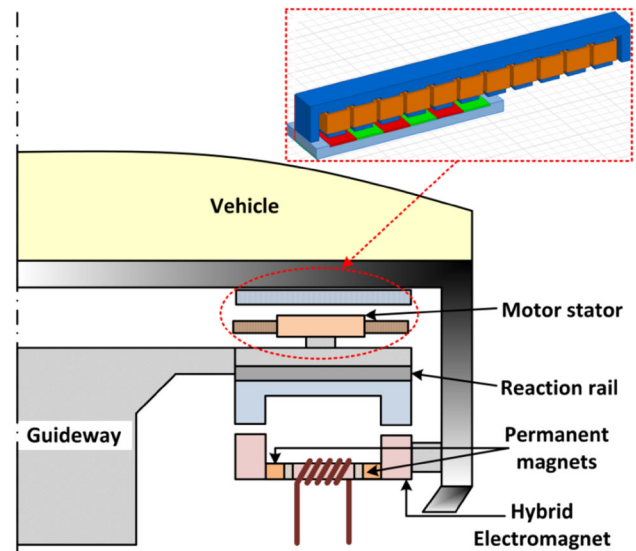


Fig. 6 Hybrid electro-magnetic suspension system

flux of constant magnitude. Therefore, in this system, adjustment of the electromagnet's excitation provides the necessary air gap control [20]. Thus, the requirement for a controllable input source having larger variation becomes imperative for exciting the electromagnets [21].

This system is currently used by an experimental maglev vehicle, CMS04, designed by the National University of Defense Technology (NUDT) in Tangshan City, China, for low to medium speed. Achieving stable suspension from hybrid magnets requires a complex control system.

Nevertheless, this technology is under research because of its robustness and high stability. This technology shows many future prospects in the field of high-speed contactless transport systems [21].

Based on the distinctive characteristics of maglev levitation systems, Table 2 gives the comparison of different levitation techniques, which summarizes this section based on the existing literature. However, it may vary with several factors such as type of magnets used, location and arrangement of magnets with respect to the vehicle and track.

3.2 Guidance

In order to keep the vehicle centred on the guideway, the maglev vehicle requires a precise guidance mechanism so that the lateral displacement of the maglev vehicle can be controlled [22]. Such a guidance mechanism generally uses either magnetic-repulsive force or magnetic-attractive force [6, 16].

In magnetic-repulsive guidance, the sideway track contains the guidance coils on both sides, as shown in Fig. 4a. Coils on either side of the guideway are connected together

Table 2 Comparison of various levitation technologies

S. no	Features	EDS	PM-EDS	EMS	HEMS
1	Air-gap (mm)	80–150	80–150	8–12	18–25
2	Speed (km/h)	> 500	500	100–500	500
3	Propulsion	LSM	LSM	LIM/LSM	LSM
4	Magnets	Super-cooled magnet	PM Halbach array	Electro-magnet	Hybrid magnet
5	Country using this technology	Japan	USA	Japan/Germany	China
6	Current status	In use	Under trial	In use	Under trial

in such a way that net electromotive force (emf) induced in the coils becomes zero, in case of null lateral displacement [23]. As soon as the train displaces laterally towards one side, the net magnitude of induced emf increases and engenders a repulsive force on the vehicle to centralize it on the guideway.

The Japanese MLX and MLU use such a technique. Japanese MLX technology integrates the guidance system with the levitation system, whereas Japanese MLU technology integrates the guidance system with the propulsion system. The German Transrapid also uses magnetic repulsive force between the on-board electromagnets and the side coils connected on either side of the train for accomplishing guidance. Nevertheless, in the German system, the levitation and propulsion systems remain separated from each other to shun any interference between the two systems at higher speeds.

In magnetic-attractive guidance, attractive force generated between the on-board electromagnets and reaction rail controls the lateral displacement, as shown in Fig. 5a [6]. A gap sensor senses the air gap between the electromagnets and reaction rail. As soon as the vehicle displaces laterally, the air gap increases which further increases the reluctance and decreases the inductance of the electromagnetic flux path. This impels the system to reduce the reluctance for maintaining stability. This further pushes the vehicle towards the centre of the guideway. The Japanese HSST system uses this guidance control with integrated guidance and levitation systems.

3.3 Input Power Transfer

In a maglev system, transfer of electricity from the groundside is crucial for powering the levitation and propulsion coils and other on-board accoutrements [24, 25]. For speeds up to 300 km/h, an instrument, like a pantograph, transfers the required power [14]. However, mechanical contacts become impractical for speeds more than 300 km/h [5–7]. For such applications, linear transformers and linear generators together form the contact-

less power delivery system. This system transfers the necessary power to the vehicle [23].

The power supply system of the Chinese Shanghai Maglev includes substations, feeder cable along with tracks, switch stations and other supply equipment. In this system, high-voltage alternating current (AC) supply is taken at 110 kV from the power grid which was stepped down to 20 kV and 1.5 kV using transformers. This stepped-down AC is converted into direct current (DC) using rectifiers, then into a variable-frequency AC supply of 0–300 Hz using inverters [24]. After stepping up, this supply excites the long stator windings of linear motors on the guideway.

The German Transrapid uses linear generators embodied with levitation electromagnets for power transfer. These linear generators procure power from the traversing electromagnetic field that travels with the vehicle and generates frequency six times larger than the motor synchronous frequency. Being mechanically contact-free, this transfer method is suitable for high-speed operation [23].

The Japanese MLX uses two linear generators of concentrated type and distributed type along with a gas turbine generator. On-board coils distributed along the vehicle form the coils of the distributed type of generator. These coils are fitted with on-board superconducting coils. In the concentrated type, generator coils are concentrated in the nose and tail part of the vehicle. Superconducting coils and generator coils form the upper and lower part of the on-board assembly, respectively. When the vehicle moves with speed, DC flux produced by superconducting coils varies and links with levitation and guidance coils forming the sideways of the track. This variable flux in turn links with the on-board generator coils. This converts the DC flux generated by the on-board superconducting coils into AC flux using on-board linear generators [24, 25].

Pulse width modulation (PWM)-controlled voltage source converter systems supply and control the propulsion motor windings. These converters use power semiconductor switches such as an insulated gate bipolar transistor (IGBT) or gate turn-off thyristor (GTO). Future applications may use silicon carbide (SiC), as it offers high

switching speed, lower losses and a wider gap [25]. Cooling and encasing the input supply circuit are key techniques in maglev systems. The French TGV uses concentrated power cars with the input circuit encased and concentrated under the floor of the locomotive. The Japanese Shinkansen uses distributed power cars with input circuit components fitted under the locomotive floor. A maglev train carries auxiliary power sources of several kilowatts for powering air-conditioning, lighting, cryogenic cooling and controlling systems [25].

3.4 Propulsion

Maglev systems need a contact-less propulsion mechanism to propel the vehicle body. For fulfilling this prerequisite, linear motors are the most fitting selection as they produce thrust without any mechanical conversion. Unlike rotary motors, thrust produced by linear motors is independent of any adhesion factor between rails and wheels. Therefore, these motors are required to produce necessary braking forces along with the propulsion forces for maglev systems. The use of linear DC motors and linear AC motors is common for such applications [26, 27]. Linear AC motors are either synchronous or asynchronous, as shown in Fig. 7. Linear induction motors and linear switched reluctance motors are the most popular asynchronous motors [26–29].

3.4.1 Linear DC Motor

Use of linear DC motors in maglev systems is still restricted to trial and research because of their inherent disadvantages. These motors can be either brushed type or brushless type [29].

A brushed DC motor uses commutator and brushes for current switching in the windings. As the polarity of the active part of the motor alternates with the motor translation, arcing takes place at the brushes connecting the active and passive part of the motor [27, 29]. This gives rise to

excessive wear and tear at the brush contacts, which makes it unsuitable for high-speed applications [29].

A brushless DC motor replaces mechanical switching with electronic switching [30]. It requires excitation of the stator windings to be precisely timed using position feedback. It utilizes PMs in the translator, which not only increases the cost of the motor, but it also demands a proper current-limiting circuit (CLC). The CLC prevents the adventitious demagnetization of PMs and overheating due to fast flux reversals.

Because of the large number of power stages and system components in this drive, its complexity increases, which may lead to improper controlling, short circuit and other such damage. Along with these drawbacks, this motor also possesses higher force ripples and low reliability. Because of such limitations, linear AC motors have always been the preferred choice for maglev applications [28–30].

3.4.2 Linear Induction Motor (LIM)

The LIM comprises a stator containing excitation windings and a translator composed of a metal conduction sheet laid over a ferromagnetic layer, as shown in Fig. 8 [31, 32]. The working principle of a LIM is similar to its rotary counterpart. Stator windings, when excited, produce a travelling magnetic field, which induces eddy currents in the translator. Interaction of magnetic fields produced by the stator currents and translator eddy currents produces necessary propulsion force [30].

Either the stator or translator can form the on-board moving part of the vehicle, leaving the other to form the stationary guideway [18]. The LIM-based propulsion systems are a mature and extensively accepted dominating candidate for maglev transit systems. This motor offers features such as simplicity, reliability, robustness, low maintenance and cost, wide speed range, low force ripple, advanced control techniques and ability to operate in adverse conditions. However, despite its rugged, cheap and simple construction, this motor suffers from high eddy current losses, which decreases the force density and overall efficiency of the machine [12]. These features have long influenced the research exploring various possibilities of using linear induction motors for traction applications [31, 32].

However, the LIM is generally not preferred as compared to the LSM for speeds more than 300 km/h, because of its lower efficiency, higher eddy current losses, lower propulsion force density and lower power factor [32, 33].

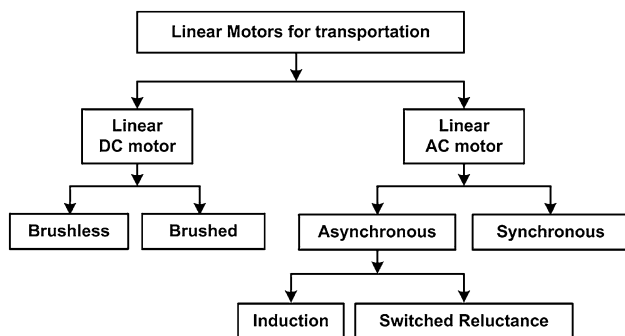
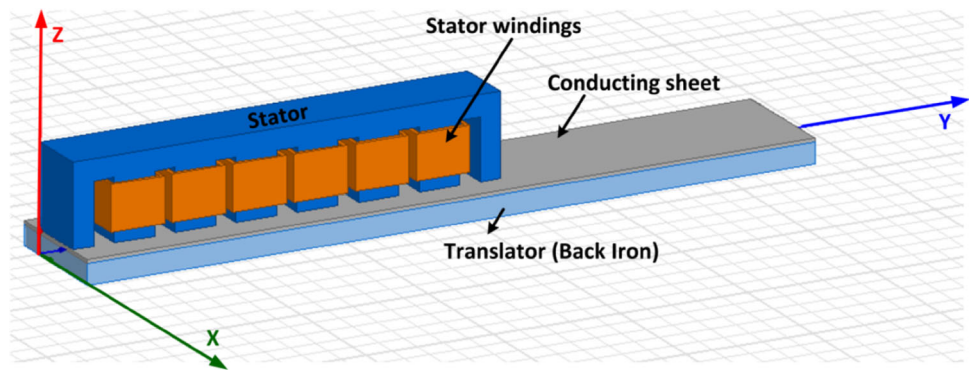


Fig. 7 Classification of linear motors used in transportation

Fig. 8 Linear induction motor



3.4.3 Permanent Magnet Linear Synchronous Motor (PMLSM)

Like a LIM, the LSM also comprises a stator and a translator, as shown in Fig. 9 [33]. The stator of the LSM resembles the stator of a LIM, but the translator embodies a DC magnetic source; therefore, the motor is doubly excited. In high-performance propulsion systems, DC excitation is preferably provided with PMs. In that case, the motor is termed as a PMLSM. However, some maglev systems use DC electromagnets also. Stator windings are excited using an alternating supply, which produces a travelling flux moving at synchronous speed. The translator, when energized with DC excitation, generates constant flux. Interaction between these two fluxes produces magnetic locking of the motor, which forces it to move at a synchronous speed [33–35].

Owing to its higher force density, higher efficiency and higher power factor, this motor has been the most preferred motor for maglev applications [35–39]. Researchers have suggested many topological modifications to enhance these features and to reduce the construction cost of the motor [33–39]. The LSM with stator coils forming the track is generally preferred for maglev systems [37–39]. This configuration is suitable for high-speed applications as no current collector is required. Ground switch stations supply

and control the stator. The LSM stator coils divided into different sections, form the guideway.

Different inverters energize each of these sections [39, 40]. Therefore, this configuration requires an additional control circuit to maintain the synchronism of the motor during the transition of the vehicle from one section to the other. Maglev trains such as the German Transrapid and Japanese MLX employ LSMs in their propulsion systems [40].

3.4.4 Linear Switched Reluctance Motor (LSRM)

Like other linear motors, the LSRM also comprises a stator and a translator, as shown in Fig. 10 [41, 42]. Either the stator or translator can carry windings. The motor can have for any number of phases depending upon the requirement. When a phase is excited, the motor moves to attain the minimum reluctance position. This process of achieving minimum reluctance position produces the required propulsion force [30].

This motor has been under research since its advent because of its inherent advantages. The LSRM possess advantageous features such as rugged and cheap construction because of having windings either on the stator or on the translator, capability of producing high propulsion force without using any PMs, more fault tolerance because of phase independence [41–49]. However, it also suffers

Fig. 9 Permanent magnet linear synchronous motor

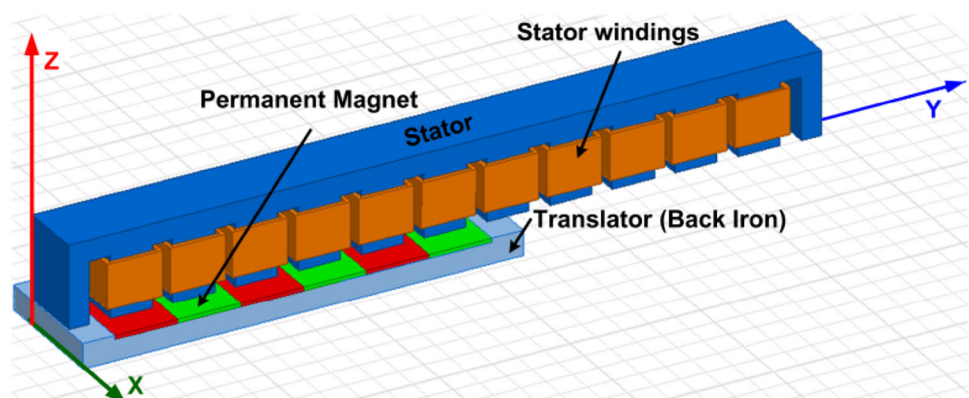
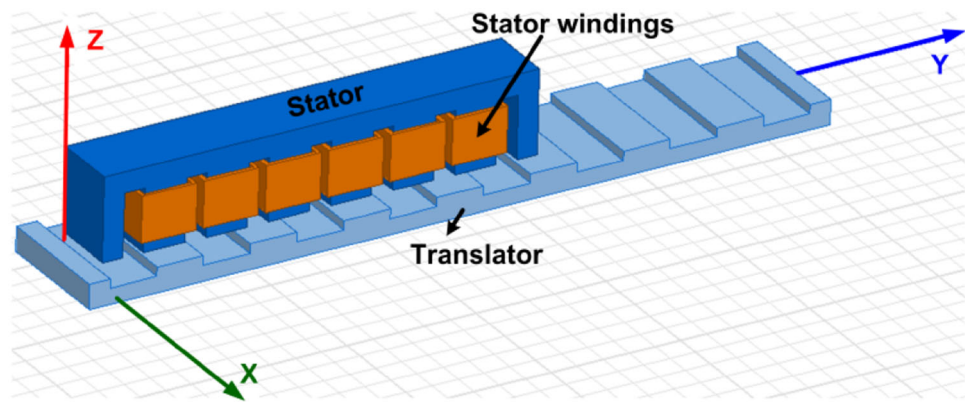


Fig. 10 Linear switched reluctance motor



from drawbacks of high force ripples, vibration, acoustic noise and complex control [46–49].

The researchers have suggested many topologies to overcome these disadvantages and to enhance its performance. This motor has shown its capability of being a cheap alternative to other AC motors for maglev applications, but it is still under research and trial [41–49].

Based on the desirable characteristics for maglev propulsion systems, Table 3 gives the comparative analysis of different linear motors used for such applications [50, 51]. The suitability of a particular motor is rated on the scale of 1–5 for a particular characteristic. Point 5 indicates the best response, whereas point 1 represents the worst. This comparison is based on the existing literature;

Table 3 Comparative analysis of linear motors

Feature	BLDC	LIM	LSM	LSRM
Power density	5	3.5	5	4
Efficiency	3.5	3	4	3.5
Reliability	3	4	3.5	5
Fault tolerance	5	4	4	5
Excitation arrangement	4	3	5	4
Cost	4	3	4	5
Translator copper loss	5	4	4	5
Cogging torque	5	4	4	5
Line start capability	3	5	3.5	3
Position control	3.5	5	3.5	3.5
Acoustic noise	4	4.5	4.5	3
Force ripples	3	5	5	3
Controllability	5	5	4	3
Robustness	3.5	5	4	4.5
Speed range	4	4	5	5
Life span	4	5	4	4.5
Force density	4	3.5	5	4
Technical maturity	4.5	5	4.5	3.5
Overload capability	3.5	4	4.5	4

however, it may vary with several factors such as operating speed, topology of the motor, power converters used and material used for magnets and the core. Comparative analysis highlights the capability of the LSRM to power the propulsion systems of future maglev systems.

3.5 Prevalent Maglev Control System

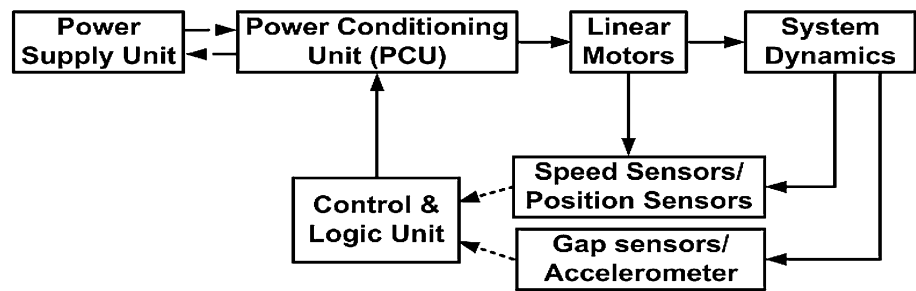
Reliable and safe operation of maglev systems requires continuous controlling and monitoring of the air gaps and coil excitations. Various gap sensors, speed sensors and position sensors perform this task. Generally, in such systems, regulating the levitation and guidance forces maintains the position of the vehicle steady with respect to the guideway [16, 18]. This helps in maintaining the air gap constant, which further helps in maintaining the ride comfort. Other than this, signals given by the accelerometers and position sensors control the excitation of the linear motor [38]. This further controls the speed, acceleration, deceleration and braking of the vehicle.

As shown in Fig. 11, sensors acknowledge the changes in the vehicle dynamics due to the external factors and pass the signal to a control and logic unit (CLU). This unit further compares the generated signal with the commanded value and transmits the error to the power-conditioning unit (PCU). The PCU then generates the supply of appropriate magnitude and frequency that further controls the winding excitations of the linear motors [24].

4 Conclusion

In view of growing transportation, its energy requirements and its impact on the global environment, maglev technology has emerged as a sustainable, faster and clean alternative. This paper has presented a bird's-eye view of the maglev technology with a special focus on components of its electrical system. Amongst the various levitation, guidance and propulsion technologies, each one has its own

Fig. 11 Block diagram of a maglev control system



capability and limitations in terms of cost, working air gap, efficiency, performance, complexity, control, safety and comfort. Out of these technologies, magnetic-repulsive force-based levitation and guidance are most suited for operation above 350 km/h. This magnetic-repulsive levitation technology is generally used in superconducting maglevs. Currently, the maglev systems based on this technology are the fastest trains available worldwide. However, the use of superconductors in maglev systems improves speed and drive performance tremendously, but the resulting cost constraints and ride discomfort have encouraged researchers to explore the use of permanent magnets and hybrid magnets in such applications. Hybrid excited magnets provide a suitable alternative to costly superconductor magnets to power future maglev systems. The integration of levitation, guidance and propulsion systems decreases the cost and size of the system, but it adds complexity in controls.

This paper has explored the possibility of using a linear switched reluctance motor as a propulsion motor in maglev systems by comparing it with other suitable linear motors. The input power mechanism depends upon the topology of the linear motor used and the operating speed of the system. Integrated design of levitation, guidance and propulsion with suitable control algorithms offers significant reduction in cost, weight and volume. The suitable integration and packaging of these components to achieve reliable operation of a maglev system is a challenging task that needs to be addressed so that significant improvement in durability, force-to-weight ratio and cost can be achieved without compromising the performance.

The sustainable development of maglev systems depends on electrical system and its components. This eclectic review of the electrical system indicates that the recent modifications and customization of its components due to technological advancement makes maglev capable of competing against conventional rail transport.

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