Review of Maglev train technologies

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Review of Maglev Train Technologies

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This paper reviews and summarizes Maglev train technologies from an electrical engineering point of view and assimilates the results of works over the past three decades carried out all over the world. Many researches and developments concerning the Maglev train have been accomplished; however, they are not always easy to understand. The purpose of this paper is to make the Maglev train technologies clear at a glance. Included are general understandings, technologies, and worldwide practical projects. Further research needs are also addressed.

***Index Terms*—EDS, EMS, Maglev train, magnetic guidance, magnetic levitation, magnetic propulsion.**

I. Introduction

ALONG with the increase of population and expansion in living zones, automobiles and air services cannot afford mass transit anymore. Accordingly, demands for innovative means of public transportation have increased. In order to appropriately serve the public, such a new-generation transportation system must meet certain requirements such as rapidity, reliability, and safety. In addition, it should be convenient, environment-friendly, low maintenance, compact, light-weight, unattained, and suited to mass-transportation. The magnetic levitation (Maglev) train is one of the best candidates to satisfy those requirements. While a conventional train drives forward by using friction between wheels and rails, the Maglev train replaces wheels by electromagnets and levitates on the guideway, producing propulsion force electromechanically without any contact.

The Maglev train can be reasonably dated from 1934 when Hermann Kemper of Germany patented it. Over the past few decades since then, development of the Maglev train went through the quickening period of the 1960s, the maturity of the 1970s–1980s, and the test period of the 1990s, finally accomplishing practical public service in 2003 in Shanghai, China [1]–[4].

Since the Maglev train looks to be a very promising solution for the near future, many researchers have developed technologies such as the modeling and analysis of linear electric machinery, superconductivity, permanent magnets, and so on [5]–[25].

The Maglev train offers numerous advantages over the conventional wheel-on-rail system: 1) elimination of wheel and track wear providing a consequent reduction in maintenance costs [26]; 2) distributed weight-load reduces the construction costs of the guideway; 3) owing to its guideway, a Maglev train will never be derailed [96]; 4) the absence of wheels removes much noise and vibration; 5) noncontact system prevents it from slipping and sliding in operation; 6) achieves higher grades and curves in a smaller radius; 7) accomplishes acceleration and deceleration quickly; 8) makes it possible to eliminate gear, coupling, axles, bearings, and so on; 9) it is less susceptible to weather conditions. However, because there is no contact between rails and wheels in the Maglev train, the traction motors must provide not only propulsion but also braking forces by direct electromagnetic interaction with the rails. Secondly, the more weight, the more electric power is required to support the levitation force, and it is not suitable for freight. Thirdly, owing to the structure of the guideway, switching or branching off is currently difficult. Fourthly, it cannot be overlooked that the magnetic field generated from the strong electromagnets for levitation and propulsion has effects on the passenger compartment. Without proper magnetic shielding, the magnetic field in the passenger compartment will reach 0.09 T at floor level and 0.04 T at seat level. Such fields are probably not harmful to human beings, but they may cause a certain amount of inconvenience. Shielding for passenger protection can be accomplished in several ways such as by putting iron between them, using the Halbach magnet array that has a self-shielding characteristic, and so on. [27], [79].

TABLE I
Comparison of Maglev and Wheel-on-Rail Systems

	Maglev System	Iron Wheel-on-Rail System
Vibration & Noise	No mechanical contact 60~65 [dB]	Contact between wheels and rails, 75~80 [dB]
Safety	No possibility of derailment	Derails from a minor defect
Guideway	Light vehicle & distributed load → light-weight	Heavy & concentrated load → Hardy structure
Maintenance	Very little	Periodic replacement of wheels, gear, rails, etc
Grade	About 80~100/1000	About 30~50/1000
Curve	In 30 [m] in radius	In 150 [m] in radius

Table I shows the comparison of Maglev and wheel-on-rail systems. In all aspects, Maglev is superior to a conventional train. Table II represents the comparison of characteristics of the mass transportation systems provided by the Ministry of Transportation in Japan. It is appreciable from the tables that the tendency of global transportation is toward the Maglev train. Accordingly, it is necessary to be concerned and understand all

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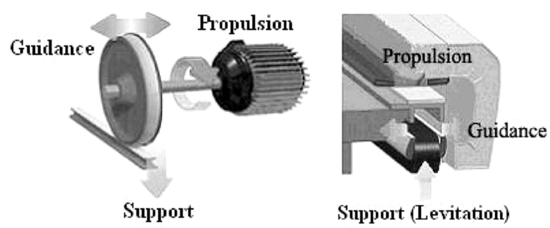
TABLE II
COMPARISON OF CHARACTERISTICS OF THE MASS TRANSPORTATION SYSTEMS

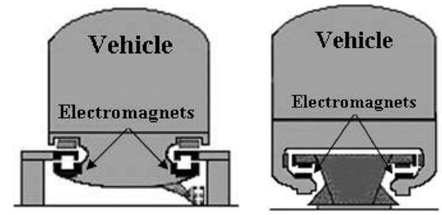
Type	Rapidity	Environment-friendly	Grade and Curve
Iron wheel-on-rail	○		○
Linear Motor Car (Iron wheel-on-rail)		○	◎
Maglev	◎	◎	◎
Rubbered tire			◎
Monorail		◎	◎

93' Ministry of Transportation, Japan
( ) average (○) good (◎) very good



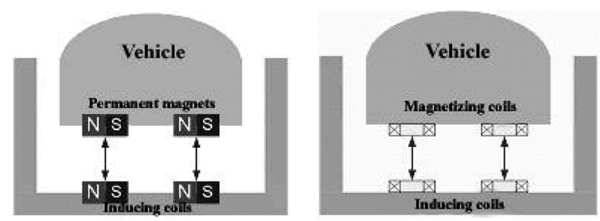
(a) (b)

Fig. 1. Comparison of support, guidance, and propulsion. (a) Wheel-on-rail system. (b) Maglev system.



(a) (b)

Fig. 2. Electromagnetic suspension. (a) Levitation and guidance integrated. (b) Levitation and guidance separated.



(a) (b)

Fig. 3. Electrodynamic suspension. (a) Using permanent magnets. (b) Using superconducting magnets.

technologies including magnetic levitation, guidance, propulsion, power supply, and so on.

II. TECHNOLOGY ASPECTS

State-of-the-art Maglev train technologies are investigated. Fig. 1 illustrates the difference between the conventional train and the Maglev train. While the conventional train uses a rotary motor for propulsion and depends on the rail for guidance and support, the Maglev train gets propulsion force from a linear motor and utilizes electromagnets for guidance and support.

A. Levitation

Typically, there are three types of levitation technologies: 1) electromagnetic suspension; 2) electrodynamic suspension; and 3) hybrid electromagnetic suspension.

1) Electromagnetic Suspension (EMS): The levitation is accomplished based on the magnetic attraction force between a guideway and electromagnets as shown in Fig. 2. This methodology is inherently unstable due to the characteristic of the magnetic circuit [28]. Therefore, precise air-gap control is indispensable in order to maintain the uniform air gap. Because EMS is usually used in small air gaps like ± 10 mm, as the speed becomes higher, maintaining control becomes difficult. However, EMS is easier than EDS technically (which will be mentioned in Section II) and it is able to levitate by itself in zero or low speeds (it is impossible with EDS type).

In EMS, there are two types of levitation technologies: 1) the levitation and guidance integrated type such as Korean UTM and Japanese HSST and 2) the levitation and guidance separated type such as German Transrapid. The latter is favorable for high-speed operation because levitation and guidance do not interfere with each other but the number of controllers increases. The former is favorable for low-cost and low-speed operation because the number of electromagnets and controllers is reduced and the guiding force is generated automatically by the difference of reluctance. The rating of electric power supply of the integrated type is smaller than that of the separated type, but as speed increases, the interference between levitation and guidance increases and it is difficult to control levitation and guidance simultaneously in the integrated type [29].

In general, EMS technology employs the use of electromagnets but nowadays, there are several reports concerning EMS technology using superconductivity, which is usually used for EDS technology [30]–[33]. Development of the high-temperature superconductor creates an economical and strong magnetic field as compared with the conventional electromagnets even though it has some problems such as with the cooling system.

2) Electrodynamic Suspension (EDS): While EMS uses attraction force, EDS uses repulsive force for the levitation [34]–[46]. When the magnets attached on board move forward on the inducing coils or conducting sheets located on the guideway, the induced currents flow through the coils or sheets and generate the magnetic field as shown in Fig. 3. The repulsive force between this magnetic field and the magnets levitates the vehicle. EDS is so stable magnetically that it is unnecessary to control the air gap, which is around 100 mm, and so is very reliable for the variation of the load. Therefore, EDS is highly suitable for high-speed operation and freight. However, this system needs sufficient speed to acquire enough induced currents for levitation and so, a wheel like a rubber tire is used below a certain speed (around 100 km/h).

By the magnets, this EDS may be divided into two types such as the permanent magnet (PM) type and the superconducting magnet (SCM) type. For the PM type, the structure is very simple because there is no need for electric power supply. The PM type is, however, used for small systems only because of

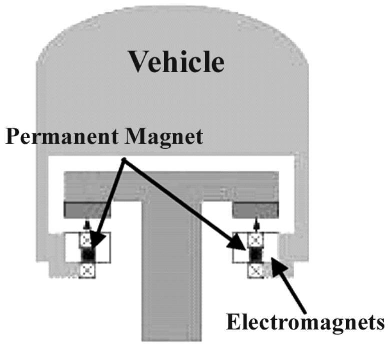


Fig. 4. Hybrid electromagnetic suspension.

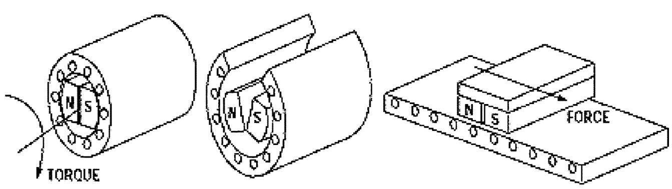


Fig. 5. Concept of the linear motor from the rotary motor.

the absence of high-powered PMs. Nowadays, a novel PM such as the Halbach Array, is introduced and considered for use in the Maglev train (Inductrack, USA). For the SCM type, the structure is complex, in addition, quenching and evaporation of liquid helium, which are caused from the generated heat of the induced currents, may cause problems during operation [49]–[60]. Hence, helium refrigerator is indispensable for making the SCM operate. Nevertheless, the SCM type holds the world record of 581 km/h in 2003 in Japan.

3) Hybrid Electromagnetic Suspension (HEMS): In order to reduce the electric power consumption in EMS, permanent magnets are partly used with electromagnets as illustrated in Fig. 4 [61]–[67]. In a certain steady-state air gap, the magnetic field from the PM is able to support the vehicle by itself and the electric power for the electromagnets that control the air gap can be almost zero. However, HEMS requires a much bigger variation of the current's amplitude as compared with EMS from the electromagnets' point of view because the PM has the same permeability as the air [68].

B. Propulsion

The Maglev train receives its propulsion force from a linear motor, which is different from a conventional rotary motor; it does not use the mechanical coupling for the rectilinear movement. Therefore, its structure is simple and robust as compared with the rotary motor [69]–[71]. Fig. 5 shows the concept of the linear motor derived from the rotary motor. It is a conventional rotary motor whose stator, rotor and windings have been cut open, flattened, and placed on the guideway. Even though the operating principle is exactly the same as the rotary motor, the linear motor has a finite length of a primary or secondary part and it causes "end effect." Moreover, the large air gap lowers the efficiency.

However, the linear motor is superior to the rotary motor in the case of rectilinear motion, because of the less significant amount of vibration and noise that are generated directly from the mechanical contact of components such as the screw, chain, and gearbox.

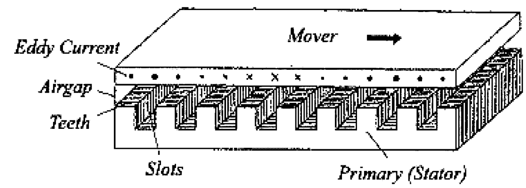


Fig. 6. Linear induction motor (LP type).

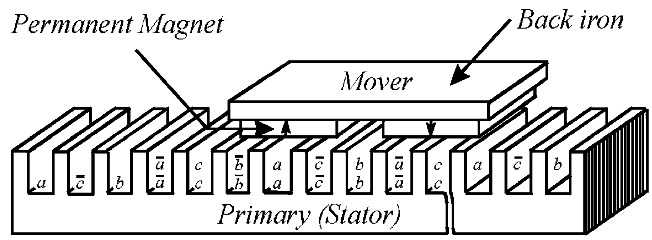


Fig. 7. Linear synchronous motor (LP type).

1) Linear Induction Motor (LIM): The operating principle of the LIM is identical to the induction motor. Space-time variant magnetic fields are generated by the primary part across the air gap and induce the electromotive force (EMF) in the secondary part, a conducting sheet. This EMF generates the eddy currents, which interact with the air-gap flux and so produce the thrust force known as Lorenz's force. There are two types as follows. 1) Short primary type (SP): stator coils are on board and conducting sheets are on the guideway. 2) Long primary type (LP): stator coils are on the guideway and conducting sheets are on board as shown in Fig. 6.

For the LP type, construction cost is much higher than SP type but it does not need any current collector for operation. In high speeds, the LP type is usually used because transfer of energy using a current collector is difficult.

In the case of the SP type, it is very easy to lay aluminum sheets on the guideway and thereby reduce construction costs. However, the SP type has low energy efficiency because of the drag force and leakage inductance caused from the end effect. Secondly, the SP type cannot exceed around 300 km/h on account of the current collector. Therefore, the SP type LIM is generally applied for the low–medium speed Maglev trains such as the Japanese HSST or Korean UTM.

2) Linear Synchronous Motor (LSM): Unlike the LIM, the LSM has a magnetic source within itself as shown in Fig. 7. Interaction between the magnetic field and armature currents produces the thrust force. The speed is controlled by the controller's frequency. According to the field location, there are two types equivalent to the LIM (LP and SP type).

Furthermore, there are another two types according to the magnetic field. One of them utilizes the electromagnets with iron-core (German Transrapid) and the other uses the superconducting magnets with air-core (Japanese MLX). High-speed Maglev trains prefer the LSM because it has a higher efficiency and power factor than the LIM. The economical efficiency of the electric power consumption is very important for high-speed operation.

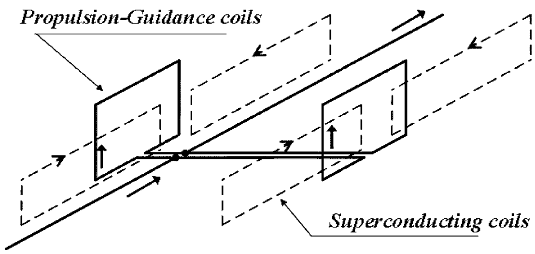


Fig. 8. Propulsion-guidance coils used in Japanese MLU-002.

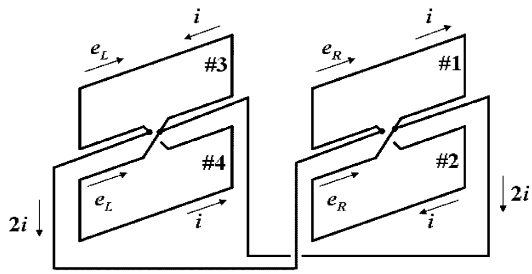


Fig. 9. Levitation-guidance coils used in Japanese MLX.

Neither the LSM nor the LIM requires sensor techniques for their operation, and they are much alike in reliability and controllability but, as mentioned above, either one can be chosen based on speed, construction costs, and so on.

C. Guidance

The Maglev train is a noncontact system that requires a guiding force for the prevention of lateral displacement. As in the case of levitation, the guidance is accomplished electromechanically by magnetic repulsive force or magnetic attraction force [72]–[75].

1) Using Magnetic Repulsive Force: As shown in Fig. 8, by setting the propulsion coils on the left and right sides of the guideway and connecting the coils, the induced electromotive force (EMF) cancels out each other when the train runs in the center of the guideway. However, once a train runs nearer to one sidewall, currents flow through the coils by the EMF induced by the distance difference. This produces the guiding force.

In the MLX, by connecting the corresponding levitation coils of both sidewalls as shown in Fig. 9, these coils work as a guide system. When a train displaces laterally, circulating currents between these two coils are induced and this produces the guiding force. In the case of the Transrapid, lateral guidance electromagnets are attached in the side of the vehicle and reaction rails are on both sides of the guideway. Interaction between them keeps the vehicle centered laterally as shown in Fig. 12.

2) Using Magnetic Attraction Force: As indicated in Fig. 14, magnetic attraction force is generated in the way to reduce the reluctance and increase the inductance when the vehicle displaces laterally. Because energy tends to flow toward small reluctance, this guides the vehicle centered laterally. Since guidance is integrated with levitation, the interference between them makes it difficult to run at high speeds. Therefore, guidance using attraction force is used for low–medium speed operation such as the HSST or UTM.

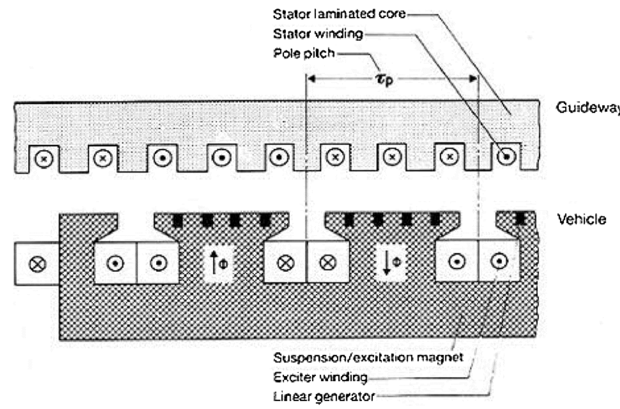


Fig. 10. LSM design of Transrapid. (Linear generator is inserted in the levitation electromagnets).

D. Transfer of Energy to Vehicle

Even though all Maglev trains have batteries on their vehicles, electric power supply from the ground side is necessary for levitation, propulsion, on-board electrical equipment, battery recharging, etc. The transfer of energy all along the track involves the use of a linear generator or a mechanical contact based on the operation speed.

1) Low–Medium Speed Operation: At low speeds up to 100 km/h, the Maglev train, generally, uses a mechanical contact such as a pantograph. As has been pointed out, this is the reason why the SP type-LIM Maglev train is used for low–medium speed.

2) High-Speed Operation: At high speeds, the Maglev train can no longer obtain power from the ground side by using a mechanical contact. Therefore, high-speed Maglev trains use their own way to deliver the power to the vehicle from the ground [76], [77]. The German Transrapid train employs the use of a linear generator that is integrated into the levitation electromagnets as demonstrated in Fig. 10. The linear generator derives power from the traveling electromagnetic field when the vehicle is in motion. The frequency of the generator windings is six times greater than the motor synchronous frequency. The linear generator is mechanically contact-free, as aspect that is very positive for high-speed operation. However, fluctuation of the induced voltage due to the unevenness of the airgap, and small magnitude of the induced voltage because of the miniaturized inducing coils can be a problem.

For MLX, beside a gas turbine generator, two linear generators are considered. The first one utilizes exclusive superconducting coils (500 kA) and generator coils at the upper and lower sides as shown in Fig. 11(a). The second one utilizes generator coils between superconducting coils and levitation-propulsion coils as shown in Fig. 11(b). Because the first one concentrates in the nose and tail of the vehicle, it is called the concentration-type. The second one is known as the distribution-type because it is distributed along the vehicle[101].

With speed, these coils generate a variable flux in the upper part of the levitation and guidance fixed coils. Consequently, the lower part (generator coils) sees a variable flux, which crosses the air gap. The variable flux is coupled with on board generator

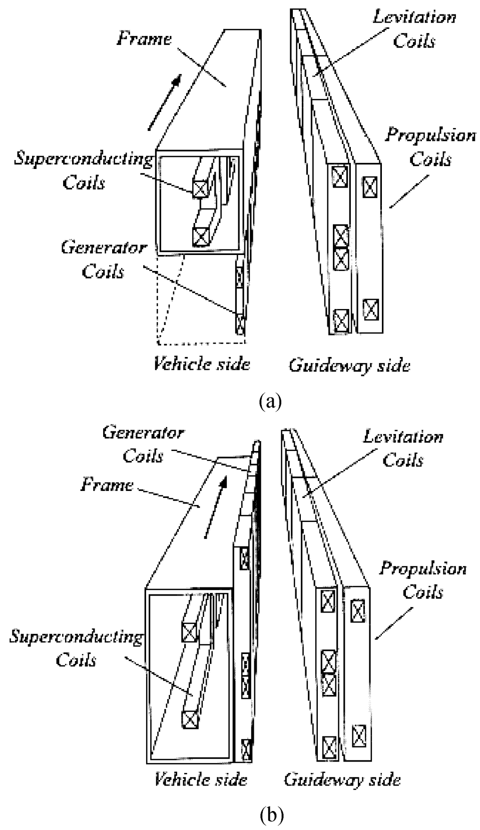


Fig. 11. Two types of the linear generators used in MLX. (a) Concentration-type. (b) Distribution-type.

coils. In other words, a dc flux created by the *on-board* superconducting coils is transformed in an ac flux, *on-board*, via a linear transformer [101].

III. Worldwide Maglev Train Projects

Since the Maglev train has been studied and developed from the 1960s, both German and Japanese Maglev trains have reached industrial levels and test tracks are experienced. In the 1990s, the USA *Inductrack*, the Swiss *Swissmetro*, and Korea's *UTM* have been intensively studied and some component prototypes have been built. The Transrapid in Shanghai, China and the HSST (High Speed Surface Transport) in Nagoya, Japan, have been in public service since December 2003 and March 2005, respectively. Some projects (Pittsburgh or Baltimore in USA, Seoul in Korea, London in England, and so on) are awaiting approval, and the Munich project in Germany was approved in September 2003 with public service possible from 2009 [78]–[114].

Tables III and IV represent the types and characteristics of the Maglev trains "in operation" and "in ready to use" states, respectively. The EDS levitation-type Maglev trains such as the MLU, MLX, and Inductrack, especially, need lateral and vertical wheel bogies to guide the vehicle at low speeds (below 100 km/h). There is one further thing that we cannot ignore. The MLX has higher maximum speed than the Transrapid. For the Transrapid, the maximum synchronous frequency is 300 Hz, which corresponds to limit of the power inverter. Such a limited frequency corresponds to a synchronous speed of around 500–550 km/h.

TABLE III
CLASSIFICATION OF THE MAGLEV TRAIN IN OPERATION

Type	Classification		
System	HSST (Japan)	Transrapid (Germany)	MLU, MLX (Japan)
Levitation	EMS	EMS	EDS
Propulsion	SP-LIM	LP-LSM	LP-LSM
Airgap	8~12[mm]	8~12[mm]	80~150[mm]
Maximum speed	100[km/h]	500[km/h]	581[km/h]
Service	Low-med. speed, Short distance Nagoya, Japan	High speed, Long distance Shanghai, China	High speed, Long distance -
Characteristic	Levitation/Guide integrated	Levitation/Guide separated	Cooling for SCM

TABLE IV
CLASSIFICATION OF THE MAGLEV TRAIN (READY TO USE)

Type	Classification		
System	UTM (Korea)	Swissmetro (Swiss)	Inductrack (USA)
Levitation	EMS	EMS	PM EDS
Propulsion	SP-LIM	LP or SP -LSM	LP-LSM
Airgap	8~12[mm]	18~22[mm]	80~150[mm]
Maximum speed	110[km/h]	500[km/h]	500[km/h]
Service	Low-med. speed, Short distance	High speed, Long distance	High speed, Long distance
Characteristic	Levitation/Guide integrated	Partial vacuum in tunnel	Halbach Magnet Array

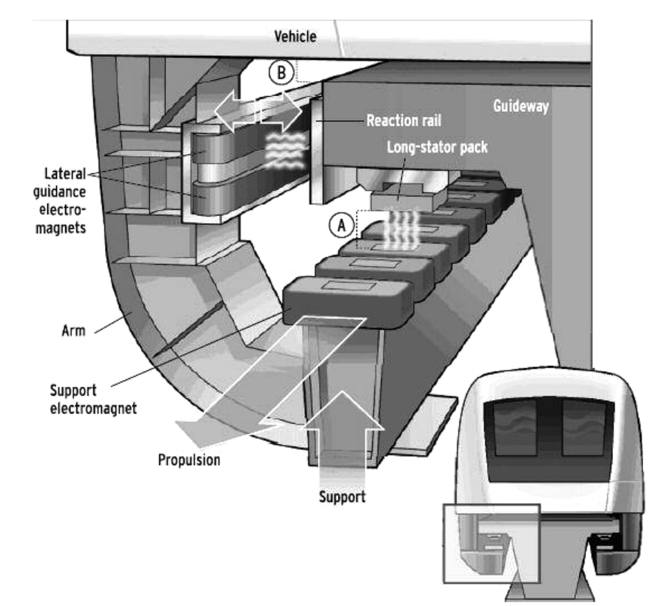


Fig. 12. Transrapid [107].

However, for the MLX, superconducting technology permits a higher pole pitch (1350 mm) than the Transrapid (258 mm) and

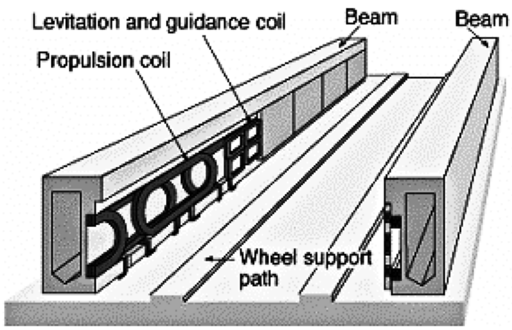


Fig. 13. Guideway of MLX [104].

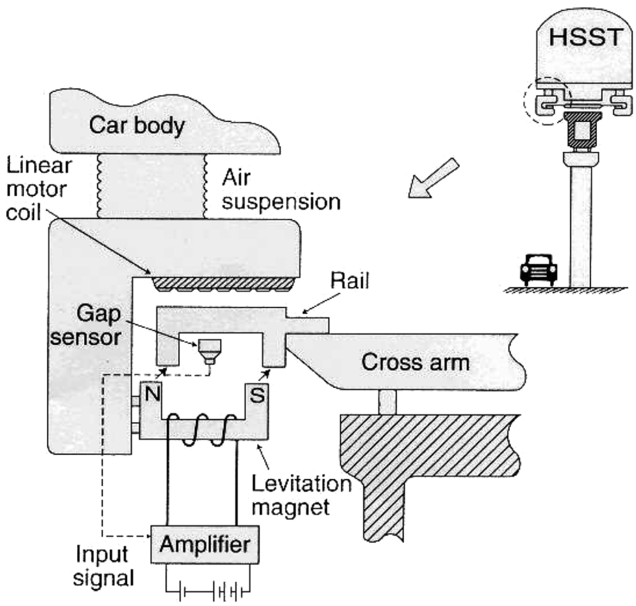


Fig. 14. HSST.

a corresponding lower synchronous frequency, 72 Hz can make 700 km/h, which is the speed goal of the Japanese train [101]. It is also notable that the low–medium speed Maglev train employs SP-LIM as its propulsion type.

Figs. 12–14 illustrate the Transrapid, infrastructure of the MLX, and the HSST system, respectively. Fig. 15 represents the diagram of the development of the global Maglev trains in chronological order.

IV. Conclusion

The Maglev train is considered for both urban transportation and intercity transportation systems. In the low–medium speed Maglev train, the operating routine is shorter than the high-speed train. Therefore, EMS technology and LIM is preferred from the construction cost viewpoint. However, in high-speed operation, EDS technology and LSM is preferred for controllability and reliability. In addition, as along with the development of the high temperature superconductor and new type of permanent magnets, stronger magnetic energy that is more cost effective will be used for the Maglev train. Authors are sure that this technology can be utilized for not only train application but also aircraft launching systems and spacecraft launching systems.

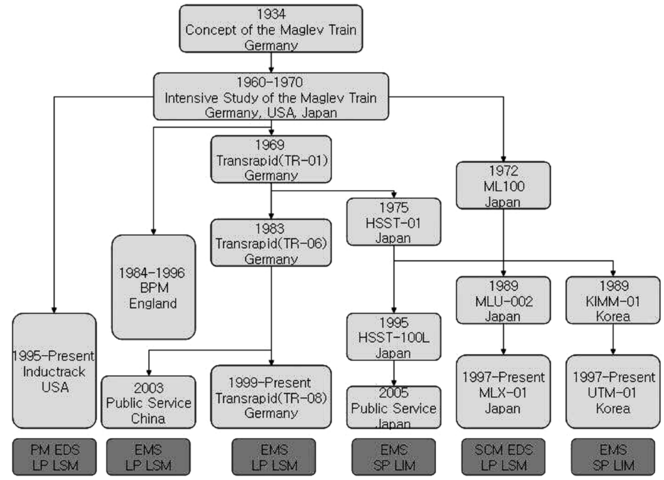


Fig. 15. Development diagram of the global Maglev train.

The need for a new and better transportation system has encouraged many countries to be interested in and attempt to develop the Maglev train. However, even though the Maglev train has been studied and developed for approximately half a century, only a few countries have the knowledge and expertise to do so. This review paper tried to describe the present complete system in detail and summarize foundational core technologies of the Maglev train from an electrical engineering point of view. It is certain that this review paper will be helpful for persons who are interested in this matter to assimilate the Maglev train technologies including magnetic levitation, propulsion, guidance, and power supply system.

It only remains to be said that besides core technologies, there is still the need to obtain a better understanding of how various factors may influence the system. For example, the dynamic behavior of the vehicle with the influence of the guideway may cause the mechanical dynamic resonance phenomena; air vibration rattles the windows of buildings near tunnel portals when a Maglev train enters or leaves a tunnel at high speed; the passenger safety issue is not considered fully; vehicle vibration generated from the rough guideway construction also remains. And furthermore, cost-effectiveness is still undecided.

Acknowledgment

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