Comparison between Short-stator and Long-stator Linear Drives of Maglev System for Regional Transport

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Abstract
Assuming applications for urban and regional transportation systems with the track length of one to several tens of km, the short stator and the long stator drives for the maglev system are studied and compared on the basis of existing data on HSST, Linear Metro, M-Bahn and Transrapid for a model case. Because of the limited length of route and rather high demand of the system, the maximum velocity of trains in operation should be chosen less than 300km/h. The distribution of demands along the track of these systems requires high train density under operation near the end station. The limit of drive characteristics of the short-stator linear induction motor in high velocity would be marginal against rather high investment costs of the long-stator system, considering the rather complex operation of the regional systems and the development of the demand in the region after the revenue service.

1 Introduction

The maglev transportation systems are going into practical operation in the field of the city center-airport and suburban area connection. The Transrapid airport connection in Shanghai is scheduled to provide commercial service at the beginning of 2004[1]. Nagoya East-hillside line will be utilized for transportation of guests for Expo'2005 at the first stage and then be integrated into the metro network of the city [2]. Furthermore, two projects with Transrapid are under the planning stage in Germany for an airport connection and a regional transportation system [3]. Short haul maglev systems are also studied for practical applications in United States [4]. These systems have the route length of ten to several tens of km as shown in Table 1.

Though the development of maglev transports has been mainly carried out for the high speed and long distance transportation, those projects shown in the Table are short and middle distance system utilized for the urban and regional transportation. As stated in the later section, the demand and operational requirements for regional transports are different from the high speed systems for inter-city operation. Because the scale of facilities for these applications is not so large, it is difficult to use the maglev with superconducting electro-dynamic suspension system (EDS) for them, unless the technology based on high temperature superconductors could be well established. The operational velocity of urban and regional transports is not high, so that the merit of the maglev with EMS system is enhanced with its burden to the neighboring and global environment less than conventional railways [5]. However, the urban and regional transportation network has been developed well. There are many alternatives exist for the construction of new lines.

Table 1. Urban and Regional Maglev Transport Projects

	Project	Length	Stations	System	passenger/year	Status
Japan	Nagoya East-hill Line	9km	9	HSST	11.7 M	Under Construction (2005 service)
Germany	Munich Main Station - Airport	36.8km	2	Transrapid	6.5 M	Planning
	Metrorapid Rhein-Ruhr	78.9km	7	Transrapid	24.6 M	Planning
United States	Baltimore-Washington	64km	3	Transrapid		Planning
	Pittsburgh-Greensburgh	76km	4	Transrapid		Planning

Then the selection of the drive system for the maglev transport becomes important to provide enough competitiveness in the flexible operation, inter-modality and system costs against alternative means. Two types of drive systems adopted for maglev transports, the short stator drive and the long stator drive, are discussed and compared in the following from these points of view.

2 Urban and Regional Maglev Transportation System

The Applications of maglev to urban and regional transportation are versatile from very low speed people movers to rather high speed point-to-point systems. Many demonstrations and studies have been carried out in those application fields in relation with the developments of a specific system. However, practical utilizations are realized for the urban to suburban connection and the regional system connecting neighboring cities in the first stage as shown in Table 1. The operational route length of systems is one to several tens of km. In order to study the applicability of different types drive systems, the basic requirements of urban and regional transportation systems are considered and analyzed in relation with their operational characteristics.

2.1 Urban and Regional Applications

The scope of urban and regional transportation systems with the route length of one to several tens of km covers the following applications.

- A point to point connection between a city center and an airport
- A point to point connection between a city center and a suburban development
- A connection between a metropolis and its satellite towns
- A regional system between neighboring cities
- A combined system stated above

They are simply illustrated in Fig.1. Because the maglev transport has not enough inter-modality, its application is mostly limited to a branch line from the existing railway or subway network. Otherwise it is completely independent from the network and forms a part of new system.

Three types of systems shown in Fig.1 have basically a similar structure from the operational point of view as a transportation system. Their characteristics can be analyzed with a unified regional system model, in which the features of a specific application are expressed by parameters such as the number of stops, route length, distances between stops, total demand and distribution of demand along the route.

2.2 Operational Characteristics of the Application System

If the route parameters shown above are assumed for a specific type of application, the operational characteristics of a transportation system applied to it can be calculated on the basis of the performances of transport mean. The adoption of maglev transport in a specific application should be rationalized on its operational characteristics in comparison with conventional railway systems, as well as the total cost of the system. In order to clarify the general features of maglev transport in operation as an urban or regional transportation system, its system characteristics are studied with a simplified model, in which the train is operated with a constant acceleration and de-acceleration and its running resistance is neglected, being combined with the route model stated above. The influences of practical conditions of route and transport mean are discussed in relation with the analytical results.

2.2.1 Scheduled Velocity

Generally the merit of maglev transport lies in its higher speed operation than conventional railways. The benefit of high velocity is limited by the route conditions of the system. In order to evaluate it against the route length and distance between stops, the scheduled velocity of an urban or regional transportation system is calculated under assumption that the distance between stops is uniform. Then the point-to-point system is expressed with a system having two stops. The difference between type b and c system in Fig.1 depends only on the distance between stops.

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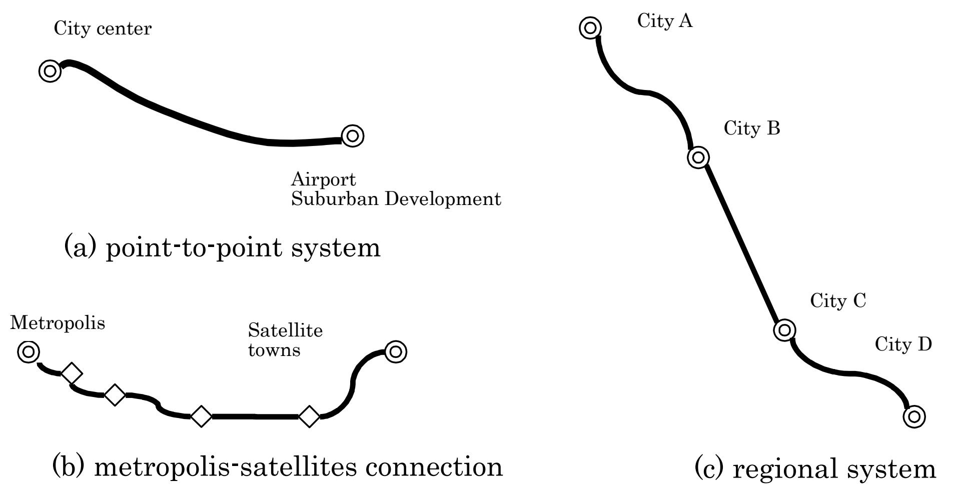

Fig.1 Images of Urban and Regional Applications

The point-to-point system can make the most use of the high speed operation with the maglev system. Even in this case, the off-brake operation requires around 2km and 8.5km of the route length to attain the top speed of 200km/h and 400km/h respectively. If 10% of time margin is supposed to recover the delay from the scheduled operation, the minimum route length of a point-to-point system is shown in Fig.2 against the maximum operational velocity under the condition that the scheduled velocity of the system is higher than 75% of the maximum velocity. The value of acceleration and de-acceleration is assumed to be 0.15g. It is a little higher than those of the systems shown in Table 1, but the flexible operation as an urban transportation system prefers the higher rate of acceleration and braking. If the acceleration is decreased, the needed track length is increased. As easily understood from Fig.2, even for the point-to-point system it is difficult to apply the high speed maglev system for the case other than the system with a large route length. Actual route includes lateral and vertical curves, which limit the operational velocity of the trains passing over them. It means that the schedule velocity of the system may decrease furthermore than the value given in Fig.2.

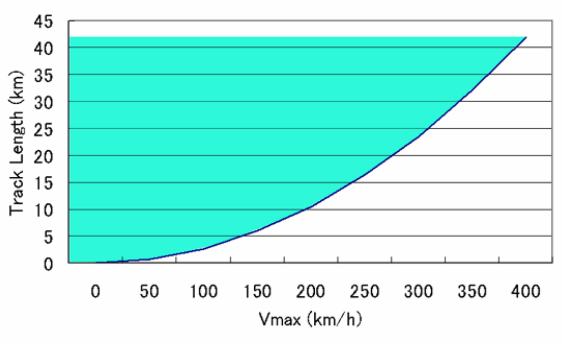

Fig.2 Length of Track needed to realize the schedule velocity more than 75% of the maximum operational velocity

For the system with more stops, the ratio of schedule velocity against the maximum operational velocity is calculated on the number of stops and shown in Fig.3. The total length of route is assumed to be 64km. The stopping time of the train at a stop is supposed to be 30seconds. These values are chosen on the basis of operations in existing urban and regional transportation systems. The acceleration is same with the case of the point-to-point system. Existing urban systems in Japan operate mostly with this ratio higher than 0.6. Considering real systems have different length between stops, velocity limits based on their route profile and the number of passengers getting on and off at each station is not uniform, the practical values of the ratio are reduced. It means that higher operational velocity than 300km/h can not be used fully in most of regional applications.

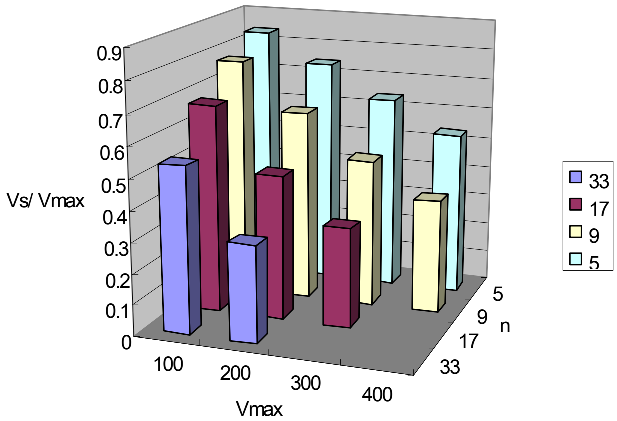

Fig.3 Ratio of Scheduled Velocity Vs against Maximum Operational Velocity Vmax with n Stops in Route

2.2.2 Density of Trains Distributed along Track

The number of trains operating in a specific part of the track relates the needed number of converter stations of the long-stator drive system. Even for the medium speed maglev systems, the track switch is the bending type. It is impossible to realize the crossing type. Then the approach of trains to platforms in the end station becomes complicated operation. The urban or regional transportation system usually operates very dense in the rush hour at its end station. If the duration of arriving trains at the terminal is 3 minutes, an additional power feeding converter station is required to cope with shuttle operation of trains.

In the application system connecting a metropolis to satellite towns, the distance between stops decreases with approach to the metropolitan center. Coupled with the reduction of scheduled velocity as shown in Fig.3 and with the shuttle operation at the terminal, the density of operating trains increases in the neighborhood of the metropolis. It is confirmed with making a model timetable for the Tsukuba Express line in Tokyo on the basis of calculation shown in Fig.3. Comparing with a case supposed a uniformly distribution of stops, the number of trains operating at a specific time on the total track is more than 50%.

3 General Characteristics of Drive Systems for Maglev Transport

3.1 The Short-stator Drives

The maglev vehicle with the short-stator drive is equipped with power converters and linear motors on board as shown in Fig.4. It is basically similar to the conventional railway train with the a.c. drive on its construction. The Linear Metro system, which is widely used in the underground railways in Japan [6], has the same type of drive system, but is supported by wheels. Such applications are considered to develop further [7]. Thus it means that this type of drive system has been practically utilized and can be accepted easily by system operators. However, the weight and volume of on-board drive units limit the operational characteristics of vehicles especially in high-speed.

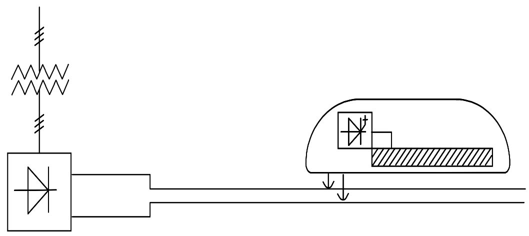

Fig.4 Short-stator Drive System

Two types of linear motors, the linear induction motor and the linear inductor motor, are applicable for this drive system. The linear inductor motor on board can be used both for propulsion and levitation. However, it is not useful to reduce the total weight of vehicle [8]. The structure of the reaction rail becomes complicated and increases the construction costs. Then it is not utilized for the maglev vehicle, though it is used for the linear drives in industrial machines. The double-sided linear induction motor drove maglev vehicles in its early stage of development [9], but had been replaced by the single-sided linear induction motor (SLIM), because of the simple structure of reaction plates.

The short-stator drive for the practical transport uses SLIM at present. Then the characteristics of the short-stator drive system are discussed on the SLIM propulsion system in the followings. The SLIM propulsive unit is inferior to the conventional asynchronous drive system because of rather large air gap length between the stator and the reaction plate, and its open asymmetrical structure of magnetic circuit. It has large leakage inductance and low energy efficiency. The normal and side forces between the stator and the back iron of propulsion rail may disturb the magnetic levitation system. If the slip frequency is chosen to suppress these forces, the propulsive force and the operating efficiency of motor are reduced. Though the well-known end effect of SLIM is not so influential in the velocity range up to 250km/h on the basis of theoretical analysis, the practical experiences obtained in the demonstration show that the thrust force is reduced even in lower velocity.

The control of propulsive force of SLIM is done by the on board inverter which regulates its output voltage and frequency as conventional railway vehicles. The input power to the inverter is supplied through the d.c. power feeder to avoid increase of the vehicle weight with the on board rectifier. Because the regenerative braking energy is utilized for the levitation system and fed back to the substation not so much, the capacity of equipment to absorb braking energy is not required to be large. It means another problem of rather poor energy efficiency of the system.

3.2 The Long-stator Drives

The active element of maglev system with the long-stator drive is equipped on the track. The linear synchronous motor (LSM) is adopted for the system, because the on board magnet can be utilized in common with the levitation system and can contribute to reduce the total weight of vehicle. Then it is favorable for the high-speed operation. For urban and regional transportation applications, LSM has the iron core and the magnets are conventional electromagnets due to the medium operational velocity. LSM itself has far higher energy efficiency to provide the propulsive force to the vehicle than SLIM.

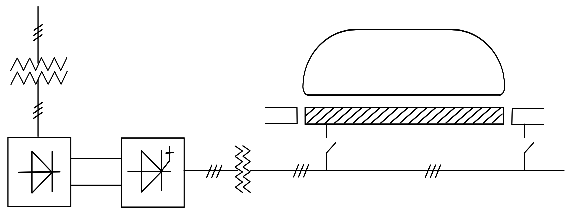

Fig. 5 Long-stator Drive System

The substation connected to the power grid is equipped with rectifiers and inverters. Each train on the track is driven by an inverter, which feed electric power to the LSM section at the position of the train and synchronizing with its velocity to give it the required thrust force. Then rather complicated control system should be installed, including the communication between the train and the substation as well as the sensing system of the exact position and velocity of the train [10]. The long stator of LSM is separated into sections, which are switched following the motion of the train in order to reduce the losses in the motor section and secure the stable operation. The length of section depends the operational velocity, the frequency of operation, the required acceleration and so on.

As stated above, the requirements of facilities of the long-stator drive depend strongly on the operational characteristics of trains. It is rather difficult to change its system performance following the growing of demand of the system.

4 Comparison of Two Types of Drives for Regional Maglev Transportation System

The applicability of the two types of drive systems for the regional maglev transport is studied on the basis of the general characteristics of the urban and regional transportation systems. General features of both types of drives are discussed for the unified model of the chapter 2 at first. Then they are compared with each other for two typical applications.

4.1 Short-stator Drive

The features of short-stator drive are appropriate for the urban and regional applications, because the drive system is quite similar with the a.c. drive of the conventional railways used in these fields. The success of linear metro system has proven it. This type of system is very flexible for the increase of demand and the change of route, which happen often in these applications. The construction of such transportation system makes the region more attractive for commuters to cities and metropolis. The development of the region requires extension of route. They are coped with introduction of more train sets and extension of track. They do not reduce system performances and need much more investments for the ground facilities.

SLIM characteristics worsen in high speed operation. With it the capacity of on-board inverter is enlarged. That lowers the performance of drive system and increases its weight. The experiences up to now are limited to the maximum velocity of 130km/h. As shown in Fig.3, it is desirable to realize a system operable up to 200km/h in order to advance into wider markets. The practical design study is needed for improvement of high speed characteristics and energy efficiency of SLIM. The combined motor structure with levitation magnets as the module of HSST makes it feasible to control the air gap length of motors accurate and improve motor performance.

The d.c. power feeding system is limited for its operational voltage and therefore the motor voltage. It reduces the efficiency of system. The short distance system with many stops in the neighborhood of a large city is appropriate application of this type of drive system from this point. The energy saving with the regenerative braking should be good implemented into the structure of power feeding system. Introduction of self-commutated converters in place of rectifiers like HVDC-light [11], deserves to further studies for this purpose.

Though the performance of the short-stator drive is inferior to that of the long-stator one, it is covered flexibly with the utilization of different types of trains over the same track. The system can cope with a part of demand to use a regional system as a point-to-point high speed service, introducing the express train designed for the purpose.

4.2 Long-stator Drive

The long stator drive system is very useful for a long distance regional transportation with rather limited number of stops or a point-to-point system as shown in Fig.2. If the planned system and route conditions are near to ideal, the scheduled velocity may attain at the level of 300km/h. If the fully reservation service is introduced to passengers, higher acceleration is feasible. The fully contact-less operation is preferable for the environment along the track because of reduction of aero-dynamic noise caused by power collecting system, though the electromagnetic noise from the long-stator should be cared. The energy consumption for a specific operation of a train is better than the case of SLIM drive. The long-stator can be operated with higher a.c. voltage than SLIM and contributes to reduce losses in power distribution.

The difficulty of the long-stator system lies in its high investments cost [3, 12], even if the costs for sensing and control system for vehicle operation are neglected. The problem is to find an adequate application system to satisfy the route conditions and to have enough demands corresponding to the costs. The type of application stated above is very similar with the case in the regional transportation solved by the express operation of conventional railways. Considering the maglev is an independent system from the railway network, its applicability depends strongly on the cost reduction in the long-stator system.

Even in the low speed application, the long-stator drive is assumed rather uniform system structure [13]. In the case that the long-stator drive is applied for a system with very non-uniform distribution of demand and distance between stops as happens in Asian area, the concept of power supply system structure might be reconsidered. Such possibilities as distribution of inverters along track side or intermittent operation of motors should be studied.

4.3 Comparison of Drives in relation with Specific Applications

Two types of applications as shown in Fig. 1 (b) and (c) are studied for the comparison between the short-stator drive and the long-stator drive on the basis of the practical data related to Tsukuba express in Japan for (b) [14] and Metrorapid Rhein-Ruhr for (c) [3]. The results are shown in Table 2.

Table 2. Comparison between Two Drives in Application Systems

Application System	Short-stator Drive	Long-stator Driver	Competitor	Further Developments
Connection of satellite cities to metropolis 58.3km, 20stops distance between stops: 1.4-6.8km 44,000p/hr/direction	Feasible: System performance: Maximum velocity : 150km/h Scheduled velocity : 100km/h (express) Minimum interval: 3 min * d.c. 3kV feeding should be studied. Power supply system near terminal is needed to integrate with other service loads.	Problematic: Even the system with the maximum speed of 200km/h, the scheduled velocity can not attain 100 km/h. The active track and regulation near terminal become so complicated and make number of inverters large.	Conventional railways: Merits: Trackside environments. Freedom in route profile. Points: Energy saving Track switch	<u>Short-stator Drive</u> Energy efficient SLIM design. 3kV power collector
Connection of cities in a region 78.9km, 7stops distance between stops: 8-18km 4,300p/hr/direction	Feasible: System performance: Maximum velocity: 200km/h Scheduled velocity: 150km/h Minimal interval: 10min * Energy efficiency is low and train becomes heavy. SLIM drive for high speed operation requires development.	Feasible: System performance: Maximum velocity: 300km/h Scheduled velocity: 180km/h Minimal interval: 10min * Cost reduction of the active track system is important.	Road Traffic (highway) Conventional railways Merits: Regional environments High speed Points: Costs Inter-modality Accessability	<u>Long-stator Drive</u> Low cost active track. Simplified structure of power substation

5 Conclusion

Because of the scale of investments and the sluggish economic situations, the practical application of the maglev transport has started from urban and regional transportation. It is expected that applications of the maglev transports would be extended with the successes of these early systems due to their friendliness to environments and attractiveness as a new type of transportation mean. During development processes of maglev systems, the performances of magnetic levitation system are mainly concerned. Then existing maglevs are reviewed on the drive system on the basis of simplified models. It is aimed to show a view for their applicability and to clarify items to be developed further needed for more attractive transportation system.

The short-stator drive is applicable to most of regional applications. The cost related to the drive system does not differ so much from that of conventional railways. If linear motors are used widely in industrial applications and standardized in design and production, its cost may be lower than rotational motors. For the performance of short-stator drives, the improvement of operational energy efficiency and high speed characteristics are essentially needed for the enlargement of regional applications. If they are solved, this type of maglev system can find new market in urban and regional transportation as a friendly system for environment. Inter-modality with the rubber-tire people mover makes benefit as an access system to large city center from suburban area.

The long-stator drive can realize a new type of regional transportation system as the high speed intercity operation of the conventional railway system. The unified power supply system with the drive unit can be a highly energy efficient system. The problem is the expensive drive system equipped over the whole length of track, in order to compete with the road traffic or the railway network servicing already for the region under rather limited demand. To extend its applicability into systems with lower scheduled velocity, the measures to increase its flexibility for operation and route conditions should be developed. Because this type of drive uses onboard magnets common with the electromagnetic suspension system of the vehicle, the development is needed to carry out in close cooperation with it.

The energy saving has become an important and urgent requirement to the modern society for the global environment. If we take notice of recent trend of increase, the energy saving in the transportation sector is required and taken measures with the highest priority. The maglev transport should contribute in this area too. For that purpose, more sophisticated drive systems are expected to be introduced into them.

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