Development of Distributed-type Linear Generator

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Keywords:
auxiliary power system, improvement of ride comfort, linear generator, PWM converter

Abstract

The superconducting Maglev has a special feature that it has no contact with any ground object when it runs at high velocity. Therefore, we must develop a new auxiliary power system for Maglev, and have developed a distributed-type linear generator. This system has abilities not only to generate power but also to improve the ride comfort by generating damping force. We manufactured this system for the vehicle of Yamanashi Test Line. In this time, we introduce the construction of this generator, and the results of this system at the Yamanashi Test Line.

1 Introduction

The superconducting Maglev has a special feature that it has no contact with any ground object when it runs at high velocity. Therefore, we must develop a new auxiliary power system for Maglev to replace the conventional contacting power collecting system, and have developed a distributed-type linear generator for this purpose. We manufactured a system of this type for the vehicle of the Yamanashi Test Line.

By the way, the superconducting Maglev system suspended by an Electro-Dynamic Suspension (EDS) system intrinsically has a negative magnetic damping force[1)2)3)] . This factor degrades the ride comfort of the Maglev system. This distributed-type linear generator system has a possibility to improve the ride comfort. This method is realized by controlling the PWM converter in order to control the phase angle (or power factor) between the induced voltage and the currents in the linear generator coils for generating a damping force[4)5)].

This paper introduces the construction of this generator, and the running test results at the Yamanashi Test Line.

2 Structures and specification of the elements in the linear generator system

2.1 Structures and principles of distributed-type linear generator

Fig. 1 shows the structure of distributed-type linear generator. The linear generator coils are installed on the surface of outer vessel of superconducting magnet. Currents are induced in the levitation ground coils (shaped like a figure 8) when the Maglev vehicles run. Therefore, the Maglev vehicle can be levitated by the force between the alternating magnetic field generated by the currents in the levitation ground coils and the direct magnetic field of the superconducting magnet. Because the guideway is composed of discrete ground coils, we can observe a harmonic alternative magnetic field on the vehicle. Therefore, we can obtain currents induced by setting the linear generator coils (shaped like a figure 8, like the levitation ground coils) from that of the harmonic alternative magnetic field. We can utilize the power for the load on the vehicle by converting the induced alternative current into a direct current by the PWM converter.

The PWM converter can control the phase angle and the amplitude of the currents in linear generator coils by the method explained in the section 3. When the phase angle is $0°$ (or the power factor is unity), the vertical force is 0. When the phase angle is not $0°$, the reactive currents in the linear generator coils generate a vertical force. Consequently, we can use this force to reduce the bogie vibration by controlling the phase angle according to the signal of the bogie vibration velocity.

Our target generating power is 50 kW per bogie, but this time we manufactured this system for half (one side) of a bogie. Therefore, our target generating power is 25kW this time. The gap between the linear generator coil and the levitation ground coil is 80 mm.

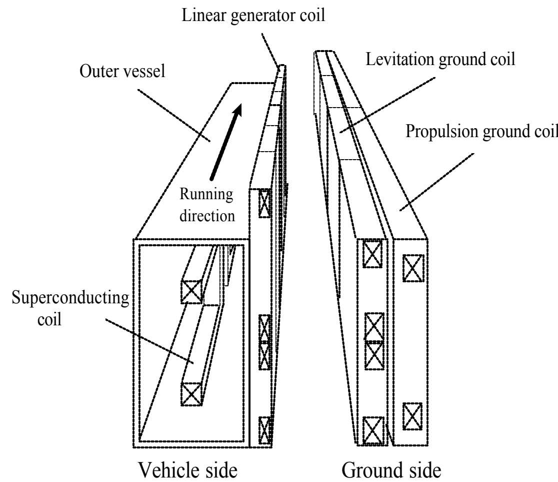

Fig. 1 Structure of distributed-type linear generator

2.2 Specification of the elements in the Distributed-type linear generator system

Fig. 2 shows the elements in the distributed-type linear generator system. A new bogie and superconducting magnet are needed to replace the conventional one. The PWM converter and linear generator coils are added. These new elements in this system are as follows:.

(1) Bogie
(2) Superconducting magnet
(3) Linear generator coils
(4) PWM converter

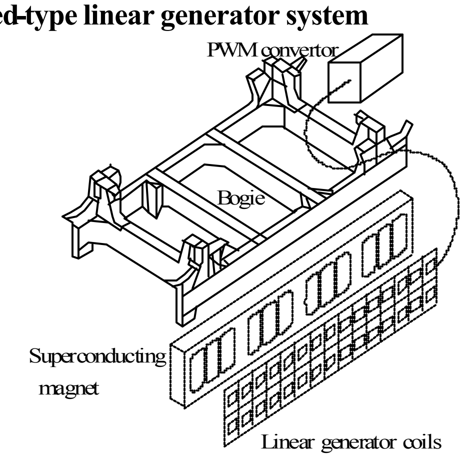

Fig. 2 Elements in the distributed-type linear generator system

2.2.1 Specification of the bogie

The width of the new superconducting magnet is larger than that of conventional one. Therefore, the width of this bogie is smaller. The conventional superconducting magnet is installed to the bogie from outside, and the new one is installed from inside, because the linear generator coils are installed on the surface of outer vessel of the new superconducting magnet. This bogie can be installed with either of them.

2.2.2 Specification of the superconducting magnet

Fig. 3 shows the outside drawing of the new superconducting magnet. It is required for the surface of this superconducting magnet facing the ground coils to keep a 20 mm space for the linear generator coils. So the distance between the cross sectional center of the superconducting coil and the surface of outer vessel has been reduced from that of the conventional magnet without changing the distance between the superconducting coil and the levitation coil. In order to improve the ability of generating power, any conductive materials should not be near the linear generator coils (an eddy current generated by the alternative magnetic field is induced in it to reduce the linkage flux of linear generator coils). The outer vessel of the superconducting magnet, on which the linear generator coils are installed, is made of aluminum. This superconducting magnet is designed as follows, in order to increase the ability of generating power.

(1) There are a number of hollows in the outer vessel.

(2) The upper and the surface (linear generator coil side) part of the outer vessel is cut to keep a distance from linear generator coils.

(3) The linear generator coils are higher than the outer vessel.

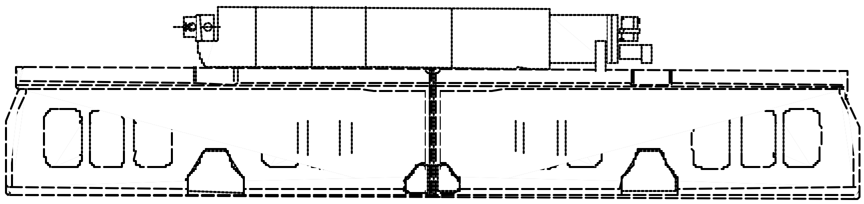

Fig. 3 Outside drawing of new superconducting magnet

2.2.3 Specification of the linear generator coils

There are fifteen linear generator coils on the outer vessel of the superconducting magnet. Fig. 4 shows the outside drawing of a linear generator coil. In order to increase the ability of generating power, the windings are arranged as near the coil surface as possible. And we use strand wires for the windings in order to avoid increasing of AC resistance. To reduce the weight, the back side of the linear generator coils facing the outer vessel of the superconducting magnet has a number of hollows (like a honeycomb structure). The linear generator coil positioned near the guidance wheel is lower than that in Fig. 4.

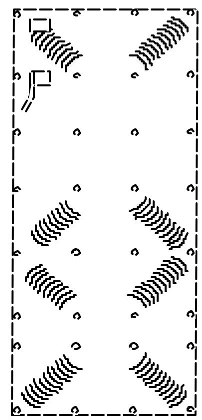

Fig. 4 Linear generator coil

2.2.4 The specification of the PWM converter

Table 1 shows the main feature of PWM converter. Fig. 5 shows an outline of PWM converter main circuit. There is a very large inductance in the linear generator coil. Then, it is not possible to change the alternative current induced in linear generator to a direct current by the conventional passive method. Therefor, it is required to develop a PWM converter for the active method. This PWM converter has six switching arms in total (three-phase, upper and under arms, like the conventional inverter). This PWM converter not only keeps the power factor as unity but also controls the phase angle. Now we develop a control method to improve the ride comfort of Maglev.

Table 1 Main feature of PWM converter

Size	1000 x 500 x 350 (mm)
Weight	90 kg
Capacity of output	30 kW
Input voltage	200 Vrms(max)
Input current	350 Arms(max)
Output voltage	410-660 V
Output current	50 A(max)
Cooling system	Fan-cooling

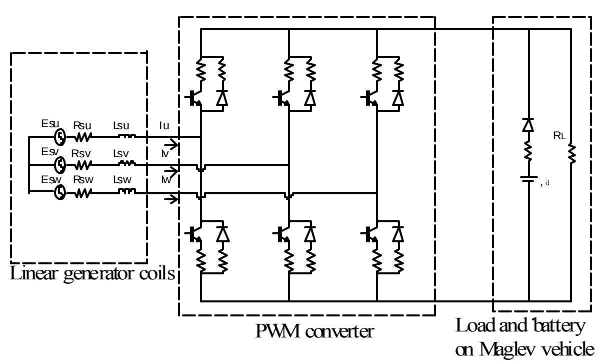

Fig. 5 Outline of PWM converter circuit

3 Operation principle of the rectification used by PWM converter

In terms of electrical characteristics, we can regard the linear generator coils as a power source - whos e induced voltage and frequency change according to the Maglev vehicle velocity -, resistance and inductance. This impedance of linear generator coil is assumed to be $Rs + jwLs$. A power converter is necessary to supply a power to the DC loads on the vehicle from AC power generated by linear generator coils. We use a PWM converter for this purpose. We regard the PWM converter and these loads as equivalent impedance $Rc - jwLc$. Fig. 6 shows a simplified equivalent single-phase circuit.

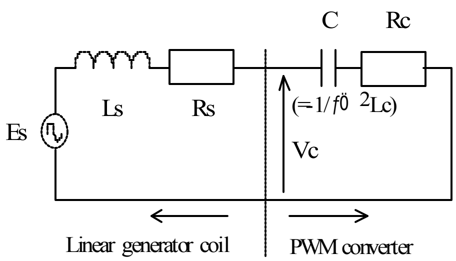

Fig. 6 Equivalent single-phase circuit

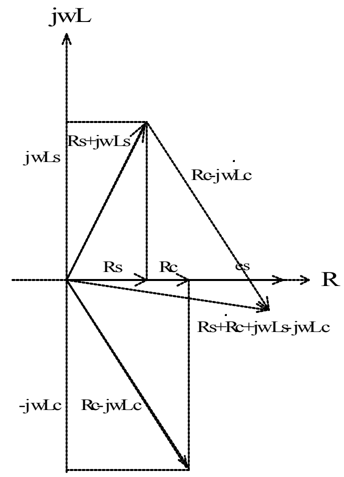

Fig. 7 Phase diagram

In order to obtain a maximum power condition, it is necessary to control the power factor to unity. It is realized when the following conditions are satisfied for the equivalent impedance of the PWM converter.

$Rc = Rs$ (maximum power condition)

$Lc = Ls$ (power factor unity condition)

If we put the equivalent impedance of the PWM converter as $Rc - jwLc$, the input voltage of PWM converter (Vc) is expressed by the equation (1).

$$Vc = (Rc - jwLc) \times Ic \qquad (1)$$

Ic: Input current of the PWM converter, w : Angular frequency

In the equation (1), " j " means a phase angle lead of $90°$, and we can quickly calculate " Vc " by using the same phase current and each of other phase currents[6]. This system can generate enough power when Maglev vehicles run at high velocity. In this case, the output voltage exceeds the allowable voltage if the power collection continues under the condition of maximum power with the power factor at unity. During this time, the output voltage must be controlled. The output power " P " is expressed by the following equation (2).

$$P = 3 \times \left(\frac{es}{Rs + Rc} \right)^2 \times Rc \times a \times \cos^2 q \quad ...$$

es: Induced voltage of linear generator coils, a : Efficiency, cos$q$: Power factor

Therefore, output voltage control is realized by adjusting the output power by controlling "Rc" in the equation (2).

In order to generate a damping force, it is necessary to control the phase angle between the induced voltage and the input current in the linear generator coils. The phase angle "q " satisfies the equation (3).

$$q = \tan^{-1} \frac{w(Lc - Ls)}{Rs + Rc} \qquad (3)$$

We can control the phase angle by adjusting "Lc" in the equation (3). Fig. 7 shows a phase diagram. We have examined these methods by the simulation using Micro Cap 6[7].

4 Results of experiment in Yamanashi test running

4.1 Results of generating power ability

Fig. 8 shows the results of power generating ability test. This generator can start to generate power at the velocity of 220 km/h after the Maglev vehicles start levitation running. The target power of 25 kW can be generated at the velocity of a little less than 400 km/h.

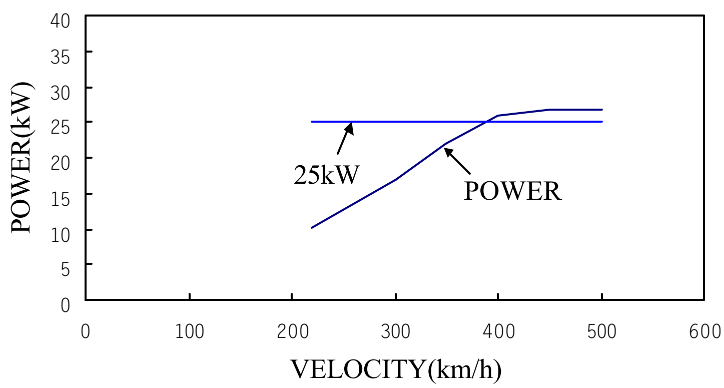

Fig. 8 Results of power generating ability test

4.2 Sample time charts of running test

Fig. 9 shows sample time charts of running test. At the velocity of about 200 km/h, the PWM converter starts to run. From that time, the power factor is controlled unity. At the velocity of a little less than 400 km/h, the target power of 25 kW is generated, and the power is controlled during the speed of over 400 km/h. In spite of changed the angular frequency and induced voltage, the control of PWM converter follows them very well.

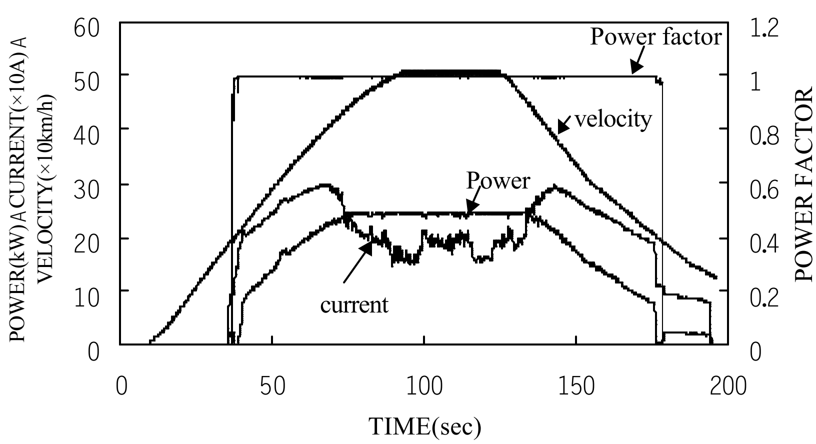

Fig. 9 Sample time chart of test running

4.3 Result of phase angle control

Fig.10 shows the result of phase angle control tests. This results is under the condition of 4 Hz and of keeping to generate the target power. This result of the phase angle control follows the demand very well.

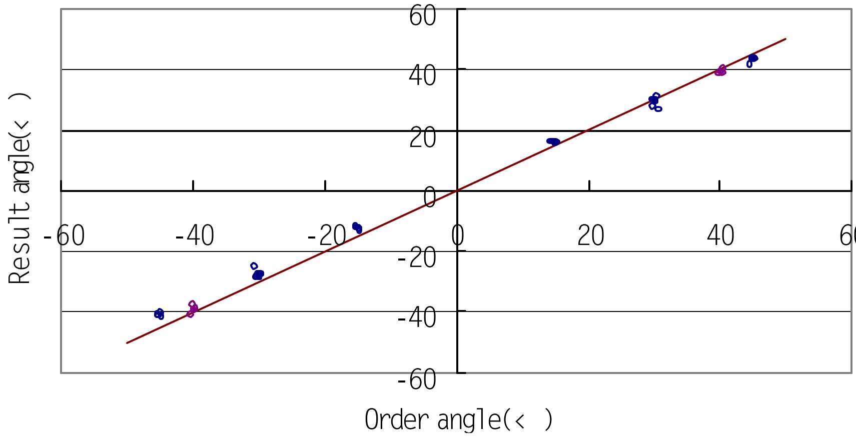

Fig.10 Results of phase angle control tests

5 Conclusions

We obtained the results of Yamanashi test line as follows:.

(1) We confirmed target power ability (25kW per half of bogie) at the speed of a little less than 400km/h.

(2) We confirmed that the power factor is controlled at unity and that the characteristic of the control follows up exactly in the velocity range of 0 to 500 km/h.

(3) We confirmed that the result of the phase angle satisfactorily catches up with the demand.

6 Future plan

Now we confirm that the system has the ability of generating power and phase angle control. Hereafter, we will confirm the method how the phase angle control should be used for damping control to improve the ride comfort of Maglev. After that we expected to introduce this system for the Yamanashi Test Line.

7 Acknowledgments

We express our gratitude for the members of Yamanashi Test Line and those of Yamanashi Linear Project for their assistance in Yamanashi test running. This development had been financially supported by a state subsidy of Japan.

Reference

1. Yamada, T., Iwamoto, M. and Ito, T.: "Magnetic Damping Force in Inductive Magnetic Levitation System for High Speed Train (in Japanese)," Trans. IEE of Japan, Vol.94-B, No.11, pp.49-54, 1974.1
2. Fujiwara, S. and Yamaguchi, H.: "Magnetic Damping of Electro-dynamic Levitation System (in Japanese)," Linear Drive Trans. IEE of Japan, LD-92-55, pp47-54, 1992.7
3. Higashi, K., Ohashi, S., Osaki, H. and Masada, E.: "Magnetic Damping of the Electrodynamic Suspension Type Superconducting Levitation System (in Japanese)," Trans. IEE of Japan, Vol.117-D, No.8, pp.1015-1023, 1997.8
4. Murai, T., Hasegawa, H. and Fujiwara, S.: "Improvement of Inductive Power Collection in Null-flux EDS Maglev (in Japanese)," Trans. IEE of Japan, Vol.117-D, No.1, pp.81-90, 1997.1
5. Fujiwara, S., Murai, T. and Hasegawa, H.: "Magnetic Damping Method of EDS System Using Power Collection Coil (in Japanese)," Trans. IEE of Japan, Vol.119-D, No.2, pp.254-259, 1999.2

6. Watanabe, T., Ueno, H., Takeuchi, N., Nagabuchi, S., Hayashi, H. and Saitou, Y.: "PWM Converter Using Instantaneous Current Detection For Linear Generator of Maglev Vehicle (in Japanese)," Trans. IEE of Japan, Vol.115-D, No.3, pp348-353, 1995.3
7. Yamamoto, T., Murai, T., Hasegawa, H., Yoshioka, H., Fujiwara, S., Hatsukade, S.: "Development of Distributed-type Linear Generator with Damping Control," Quarterly Report of RTRI, Vol.41, No.2, pp.83-88, 2000.1

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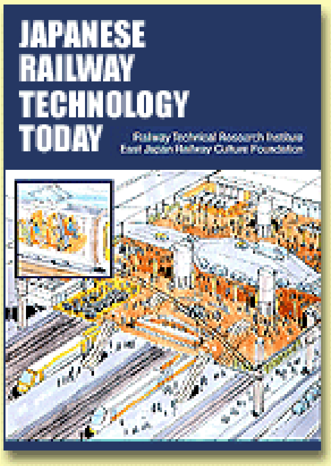

Joint edutors	Railway Technical Research Institute
	East Japan Railway Culture Foundation
Publisher	East Japan Railway Culture Foundation
Distributor	Transportation News Co., Ltd

- **WCRR'99 in Tokyo**

The Fourth World Congress on Railway Research (October 19-23, 1999, Tokyo, Japan)

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Last updated 2002. 2. 8