Development of Distributed-type Linear Generator with Damping Control

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The superconducting Maglev system suspended by EDS intrinsically has negative magnetic damping. In order to improve the magnetic damping, we used a linear generator by controlling the power factor of the current in the linear generator coils. We developed a PWM converter and a simulator (using Micro Cap VI) for this control. This paper describes how to control the PWM converter and subsequently the power factor and the result of confirmation of this control method through simulation and synthetic bench tests. We can now control the PWM converter and the power factor without affecting the output power.

Keywords : Auxiliary power supply, linear generator, PWM converter, controlling the power factor, improving the ride comfort

1. Introduction

The superconducting Maglev system suspended by Electro-Dynamic Suspension (EDS) intrinsically has negative magnetic damping^{1) 2) 3)}. This factor degrades the ride comfort of the Maglev system. Therefore, a method to use a linear generator is proposed to improve the negative damping of EDS⁴⁾. This method is to control the phase (power factor) between the induced voltage and the currents in the linear generator coils in order to generate a damping force⁵⁾. This method is realized by controlling the PWM converter of the linear generator to change the phase angle of the current in the linear generator coil in proportion to the signal of bogie vibration velocity.

However, the output generator power reduces when the phase angle is changed, because the power factor is reduced. Therefore, this method is effective when sufficient output power is generated. We have not yet confirmed if the power generated stably when controlling the phase and if the PWM converter follows properly the signal to control the phase.

This paper reports the calculation result of improving the ride comfort, result of simulation of PWM converter operation and result of this operation in bench tests of an experimental circuit.

2. Structure and principle of linear generator

2.1 Damping control method using linear generator

Fig.1 shows the structure of Distributed-type Linear Generator. The linear generator coils are installed on each surface of outer vessel of superconducting magnet. Currents are induced in the levitation ground coils shaped (like a figure 8) when the Maglev vehicle runs. So 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. So we can obtain currents induced by setting the linear generator coils (shaped like a figure 8, the same as the levitation ground coils) from that harmonic alternative magnetic field. We can utilize the power for the load on the vehicle by converting the induced current into direct current by the PWM converter.

The PWM converter can control the phase angle and the amplitude of the current in the linear generator coils by the method explained in section 2.4. When the phase angle is 0° (or the power factor is unity) , the vertical force by the current in the linear generator is 0. And when

Fig. 1 Structure of Distributed-type Linear Generator

the phase angle is $\pm 90^\circ$, the maximum absolute vertical force is generated.

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.

2.2 Superconducting magnet for Distributed-type Linear Generator

Fig. 2 shows the outside drawing of the superconducting magnet for Distributed-type Linear Generator.

Fig.2 Superconducting magnet for Distributed-type Linear Generator

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 a conventional magnet without changing the distance between the superconducting coil and levitation coil. To improve power collection, conductive materials should not be near the linear generator coil (an eddy current is induced in it to reduce the linkage flux of linear generator coils). Because the outer vessel of the superconductive magnet which installs the linear generator coils is made of aluminum, this superconducting magnet is designed as follows, in order to increase the power collection performance.

- (a) There are a lot of hollows in the outer vessel.
- (b) The upper and linear generator side of the outer vessel is cut.
- (c) The linear generator coils are higher than the outer vessel.

2.3 Distributed-type Linear Generator coils

There are fifteen linear generator coils on the superconducting magnet. Fig. 3 shows the outside drawing of the linear generator coils.

In order to make coils as light as possible, the windings are concentrated near the coil surface. And we use strand wires for the windings in order to avoid increase of AC resistance. To reduce the weight, the back side of the linear generator coils facing the superconducting magnet is composed of a honeycomb structure. The linear generator coil positioned near the guidance wheel is lower than that in Fig. 3.

2.4 Operation principle of PWM converter

Fig. 4 shows an outline of the main circuit of the Distributed-type Linear Generator.

In terms of electrical characteristics, we can regard the linear generator coils as a power source (whose induced voltage and frequency change with the Maglev vehicle velocity), resistance and inductance. This imped-

Fig. 3 Distributed-type Linear Generator coil

Fig. 4 Outline of the main circuit

ance of linear generator coil is assumed to be $R_s + j\omega L_s$. A power converter is necessary to supply 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 load as an equivalent impedance $R_c - j\omega L_c$.

Fig. 5 shows a simplified equivalent one-phase circuit.

Fig. 5 Equivalent one-phase circuit

To obtain the maximum power, it is necessary to make the power factor unified. It is realized when the following conditions for the equivalent impedance of the PWM converter are satisfied.

$$R_c = R_s \text{ (maximum power condition)}$$

$$L_c = L_s \text{ (power factor unity condition)}$$

If we put the equivalent impedance of the PWM converter as $R_c - j\omega L_c$, the input voltage of the PWM converter (V_c) is expressed by the equation (1).

$$V_c = (R_c - j\omega L_c) \times I_c \quad (1)$$

I_c : Input current of the PWM converter

Here, "j" means a phase angle lead of 90° , so we can quickly calculate " V_c " by using the same phase current and another phase current⁶⁾.

We can receive 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 and unified power factor. So the output voltage must be controlled. The output power " P " is expressed by the following equation (2).

$$P = 3 \times \left(\frac{es}{R_s + R_c} \right)^2 \times R_c \times \alpha \times \cos^2 \theta \quad (2)$$

es : Induced voltage of linear generator coils,

α : Efficiency, $\cos \theta$: Power factor

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

In order to generate a damping force, it is necessary to control the phase angle of the input current. The phase angle " θ " satisfies the next expression.

$$\theta = \tan^{-1} \frac{\omega(L_c - L_s)}{R_s + R_c} \quad (3)$$

ω : Angular frequency

We can control the phase angle by adjusting ' L_c ' in the equation (3). Fig. 6 shows a phase diagram, and Fig. 7 a flow chart of PWM converter control.

Fig. 6 Phase diagram

Fig. 7 Flow chart of the PWM converter control

2.5 Expected effect of damping control

The damping force is estimated to be about 2 kN at the linear generator coil current of 350 A, winding of 11 turns and controlling phase limit of $\pm 30^\circ$. We examined how we can improve the ride comfort by using this force. As a preliminary study, we used the following simple rule.

We use '-' maximum damping force at the vertical velocity of bogie > 0 .

We use '+' maximum damping force at the vertical velocity of bogie < 0 .

This rule is equal to the one when a friction force works between the bogie and absolute space.

We calculate the improvement effect of the ride-comfort level (the level which is calculated from the RMS acceleration wave-form multiplied by the ride-comfort filter). Fig. 8 shows the reducing effect. In this figure, the horizontal axis is the ride-comfort level without damping control. The reducing effect vs maximum control force is

shown in Fig. 9 (at the ride-comfort level of 90 dB without damping control).

We can see that an improvement of ride comfort, more than 1.5 dB, is expected under the 92dB in Fig. 8. And we can improve the ride comfort further if we can increase the damping control force in Fig. 9.

Fig. 8 Relation between the reducing effect and ride comfort level without damping control

Fig. 9 Relation between the reducing effect and maximum damping control force (at the ride-comfort level of 90 dB without damping control)

3. Confirmation by simulation of PWM converter operation

3.1 Simulation software

We used Micro Cap VI (Pspice series electric circuit simulator manufactured by Spectrum Co. in the US) for simulation of PWM converter operation. We can easily use this software, because it :

- (a) Can be used for mixed analog and digital circuit simulation.
- (b) Can output the consequence of transient analysis in text files.
- (c) Has a lot of device libraries.
- (d) Can be used for simulation by a personal computer (not a workstation).

Fig. 10 shows a sample of simulation circuit.

Fig. 10 Sample of simulation circuit

3.2 Results of the simulation

Fig. 11 shows the waveform of the induced voltage and the current in the linear generator coils simulated at about 500km/h, phase control of 15Hz, $\pm 30^\circ$ (sine wave).

Fig. 12 shows the consequence of phase control and the output power.

From these figures, we can see that the output power is obtained stably and the output phase angle is controlled satisfactorily. There is a small discrepancy on the + side between the consequence and the phase control command.

Fig. 11 Simulation of phase control (Induced voltage, current in the linear generator coils)

Fig. 12 Simulation of phase control (Phase, output power)

4. Results of the bench test

4.1 Construction of test equipment

We used an electro-magnetic vibration simulator (a magnetic field generating simulator with coils set to generate the sixth harmonic magnetic field) and an inverter to generate an alternate magnetic field which is generated when the Maglev train runs.

By arranging the linear generator coils to face these exciting ground coils, we generated an induced voltage which simulated the real induced voltage of Maglev train running. Fig. 13 shows the construction of the bench test circuit.

Table 1 shows the constant values of induced voltage, resistance, inductance of the linear generator coils. Table 2 shows the specification of the PWM converter.

This bench test used 48 cell series-connected 12V 30Ah lead storage batteries. The resistance to simulate the load was 15 Ω .

Fig. 13 Construction of bench test circuit

Table 1 Constant value of the linear generator coils (at 300Hz).

Resistance	0.0863 Ω
Inductance	0.373mH
Induced Voltage	83.75V _{rms} (at heavy condition)

Table 2 Main features of PWM converter

Size	1000×504×350 (mm)
Weight	90 kg
Capacity of output	30kW
Input Voltage	200V(max)
Input Current	300A(max)
Output Voltage	410~660 V
Output Current	50A(max)
Cooling system	Fan-cooling

4.2 Experiment results

Fig. 14 shows the characteristics of power supply capacity without damping control. The result at 300Hz is the value when the output voltage is controlled. We can see that the power factor is nearly 1 and power efficiency is about 0.9. We confirm that the frequency to give an output power above the prescribed 25kW is about 185Hz (velocity of 300km/h).

Fig. 15 shows the relation between frequency and the

Fig. 14 The characteristics of the output power

Fig. 15 Relation between frequency and the output voltage

output voltage at the command of output voltage of 660V. We can see that the value of output voltage doesn't exceed the commanded voltage after the output power reaches its rated output.

Fig. 16 shows the result of phase control at the velocity of 500km/h and the phase control command of $15\text{Hz} \pm 30^\circ$. In this condition, we can obtain sufficient collection power, and see that the output power is in stable agreement with the result of the simulation in spite of phase control command.

We can see that the response of phase is a little different when the phase control command is less than zero in the same way as in the simulation. The reason for this difference is explained as follows.

(a) There is a difference between the linear generator coil inductance L_s and set-up inductance of PWM converter L_c , so that there is a little phase difference to the "+" side when the control command of the phase angle is 0 degrees. In addition, the phase control command is limited to $\pm 32^\circ$.

(b) There is a dead-time ($3\mu\text{sec}$) which cases the phase difference, in order to avoid shortening the main circuit arms.

Fig. 16 The consequence of phase control experiment

5. Conclusions

Through simulation and bench tests of the phase control of PWM converter, we obtained the follow conclusions.

- We confirmed that the frequency to generate power over 25kW is about 185Hz (velocity of 300km/h).
- We obtained the same phase control result from the simulation which used MICRO CAP VI and bench test.
- We can see that the output voltage is properly limited by the command of output voltage when large output power is generated.

- In the bench test of phase control to obtain damping force, the PWM converter follows the command of phase control signals, and there is no large fluctuation in the output power.

In this study, we examined the operation of PWM converter of Distributed-type Linear Generator to obtain damping force in order to improve the ride comfort, and we confirmed that the PWM converter follows the command of phase control signal. At the next step, we will develop the logic and system on how to make the command of phase control signal from the vehicle dynamics information. And we examine the method to increase the damping force to improve ride comfort.

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