Characteristics of Linear Generator with SC Coil Configuration to Reduce Leakage Flux

T. Murai, Y. Sakamoto, H. Hasegawa & T. Motoyoshi
Central Japan Railway Company, Tokyo, JAPAN

ABSTRACT: An improved configuration of superconducting (SC) coils, whose end coils have small size, is studied to reduce their leakage flux. This configuration can strengthen the magneto-motive force of SC coils, so it can enlarge the lateral gap between generator coils and cryostat of SC coils to increase output power of linear generator. This paper presents the basic configuration of this system and examines their characteristics by numerical examples.

1 INTRODUCTION

Vehicles of superconducting maglev system are suspended and driven by superconducting (SC) coils, which have a strong magnetic field, and their passenger cabins must be shielded from the leakage flux of the SC coils. Therefore, the passenger cabins keep away from the SC coils by concentrating them on articulated trucks, and magnetic shielding by industrial-pure steels and electromagnetic steels are also installed on the cabins. As a result, the maximum magnetic flux is less than the target value, though the magneto-motive force of SC coils can not be reinforced by the restriction of maximum flux. For this reason, we studied an improved configuration of SC coils to reduce their leakage flux. The improved configuration has end coils whose smaller length reduces the main leakage flux from the end coils. Due to the reduction of leakage flux, the improved configuration can reinforce their magneto-motive force and provide better performances for levitation and propulsion (Murai & Sasakawa 2004).

On the other hands an on-board power of superconducting maglev system is desired to be a non-contact apparatus and a linear generator is now being developed for the most realistic non-contact on-board power without environmental pollution such as noise and exhaust gas (Yamamoto et al. 2002). The linear generator utilizes harmonics of magnetic fields generated by ground coils so the generator coils are attached to the cryostat facing the ground coils. In this case, special attentions should be paid to eddy currents, which occur on the cryostat, caused by the magnetic fields of ground coils and generator coils and reduce the generator output. Therefore, the cryostat of SC coils for linear generator has through-holes within the racetrack-figure SC coils to increase the generator output, but the structure of cryostat and SC coils become complicated.

Since the improved SC coil configuration can reinforce their magneto-motive force, it can enlarge a lateral gap between SC coils and ground coils, which includes the gap between generator coils and cryostat. The enlargement of the gap between generator coils and cryostat reduces their mutual inductance, and the output power of linear generator can increase. The enlargement of the gap also doesn't need to complicate the structure of SC coils.

Thus, this paper studies the characteristics of linear generator with the improved SC coil configuration at strengthening the magneto-motive force. Using numerical examples, realistic specifications and their performances are clarified.

2 COMPOSITION AND PRINCIPLE

2.1 Improved configuration of SC coils to reduce leakage flux

Figure 1 shows the conventional configuration whose SC coils have a constant length. The magnetic fields by inner coils are canceled by the magnetic fields generated by the opposite poles placed in their vicinity. However, the end coils do not have neighboring opposite poles at any side. Therefore, they strengthen the leakage flux on the side without a neighboring coil. Thus, the magnetic fluxes spread at the end of articulated truck mounting the SC coils, and increase the weight of magnetic shielding on the

cabin, the magnetic field of crossing cars and that outside the guide-way.

In order to reduce this leakage flux, the improved configuration has end coils whose length is smaller than that of conventional configuration as shown in Figure 2. The improved configuration can reduce the far field on the cabins, crossing cars and outside the guide-way while keeping the closed field on the ground coil constant. Consequently, the improved configuration can also reinforce their magneto-motive force, which is restricted by the maximum value of magnetic flux in the cabins and outside.

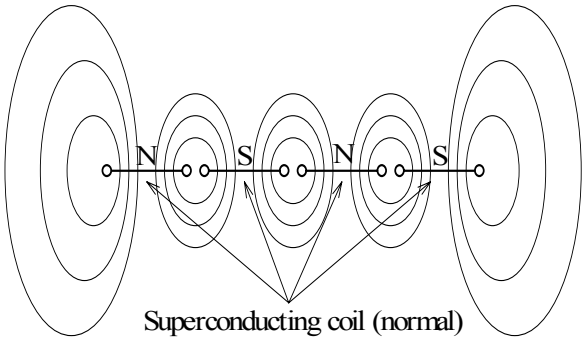


Figure 1: Conventional configuration of SC coils.

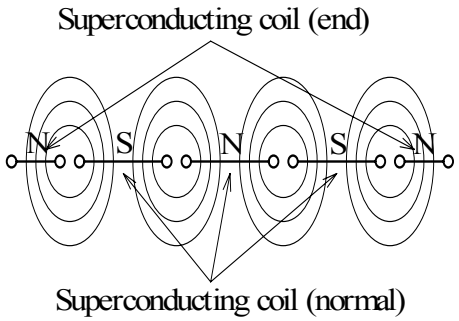


Figure 2: Configuration of SC coils to reduce leakage flux.

2.2 Linear generator

Figure 3 shows the basic composition of the linear generator, which is expected to be the most realistic on-board contact-less power source free from environmental pollution. The superconducting Maglev vehicles are suspended by magnetic forces between SC coils on board and fundamental magnetic fields generated by 8-figured coils for electro-dynamic suspension (EDS) on the ground. The linear generator utilizes the harmonics of these magnetic fields. This system is composed of the 8-figure generator coils, which are located on the surface of cryostat to face the ground coils, a power converter and battery on board.

However, since the eddy current, which occurs on the cryostat, reduce the induced voltage of generator coils and increase the joule loss of generator circuit, it is necessary that the mutual inductance between generator coils and cryostat have to decrease as much as possible. Therefore, the cryostat has through holes to reduce the facing area to generator coils, but it makes the structure of both cryostat and SC coils complicated. Consequently, this system has disadvantages to the cost, weight and reliability of SC coils.

On the other hands, the improved configuration to reduce the leakage flux can reinforce their magneto-motive force, so it can also enlarge the gap between generator coils and cryostat. Since the enlarging the gap between generator coils and cryostat reduce their mutual inductance, the output power of linear generator can increase without complicated structure of SC coils.

For realizing the linear generator, the generator coils should be more simplified and lose their weight. For this reason, we should also examine the generator coils which are without the lower coils.

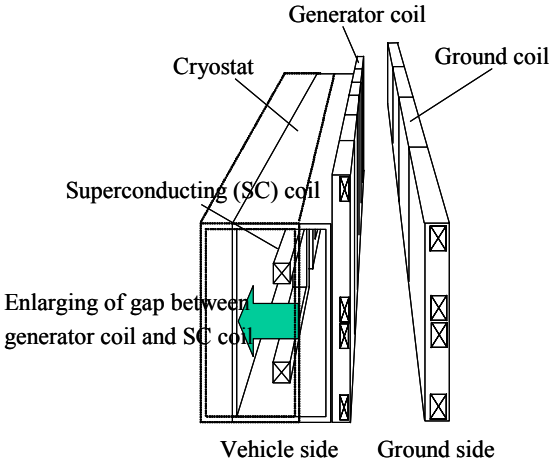


Figure 3: Composition of linear generator

2.3 Magnetic damper

The linear generator can generate not only power by using the harmonic magnetic field of ground coils but also magnetic damping by controlling zero-phase current of generator coils. Since the EDS has been known to provide only small magnitudes of magnetic damping, this system is effective to increase the magnetic damping and improve the vehicle dynamics (Murai & Sakamoto 2005).

Figure 4 shows the basic composition of linear generator with magnetic damper in the conventional SC coil configuration. The generator coil are located with 3-phase circuit for the harmonics in each pitch of SC coils and reversely connected with the SC coil pitch. Thus, the zero-phase current can provide fundamental magnetic fields with the same wavelength as the SC coils to induce larger currents on the ground coils, whose magnetic fields can generate larger magnetic forces on the SC coils. Consequently the magnetic damping can obtain by control-

ling zero-phase current in proportional to the vehicle vibration velocity.

Since each SC coil pitch of the improved SC coil configuration is different, each group of generator coils, which generates the same pole by zero-phase current, has different number of coils.

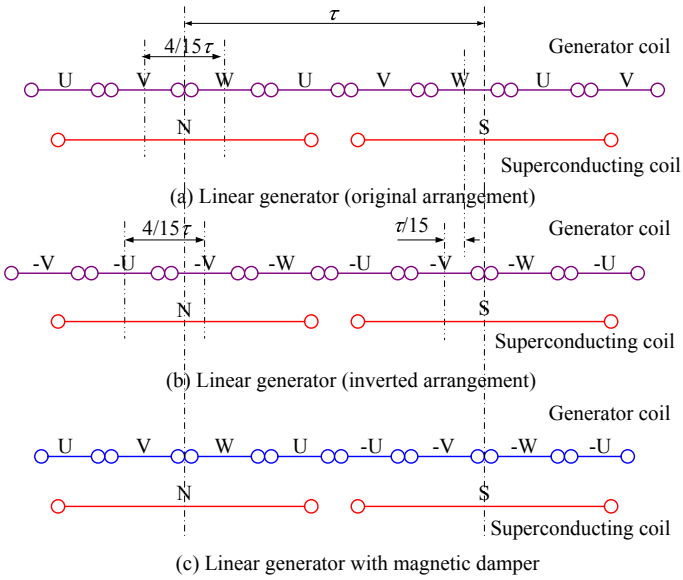


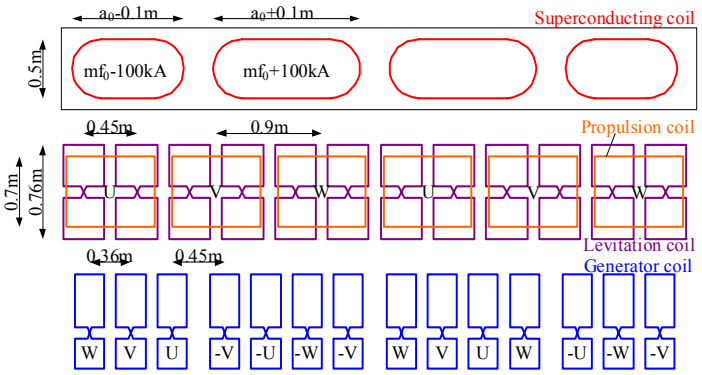
Figure 4: Composition and Principle of linear generator with magnetic damper

3 NUMERICAL EXAMPLE

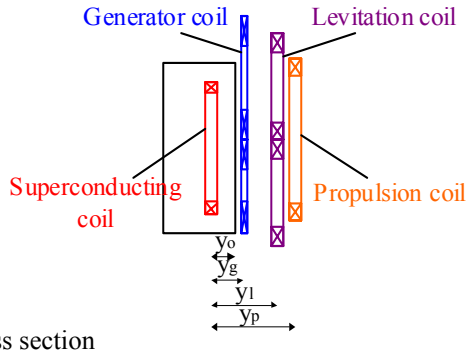
3.1 Analysis model

Figure 5 shows analytical models of SC coils, ground coils and generator coils. The SC coils consist of four coils with different coil pitches and different magneto-motive forces, whose averages are 50 kA larger than that of the conventional one. The levitation coils have 60-degree coil pitch and the propulsion coils, 120-degree coil pitch. The generator coils consist of 4 groups, which has 3, 4, 4 and 3 coils respectively and whose end coils have 60-degree larger coil pitch between neighboring groups.

Furthermore, the generator coils have different number of coils among three phases, for instance, U-phase has 4 coils, while each of V and W phases has 5 coils.



(a) Coil composition



(b) Cross section

Figure 5: Analysis model

3.2 Magnetic field of crossing cars

To represent the environmental magnetic field, we examine the magnetic field at a crossing car. Figure 6 shows the magnetic field distribution in the longitudinal direction of the conventional and improved configurations. The values of lateral and whole flux density are indicated By and B, respectively. The flux density at the end of the improved configuration is about half as large as that of conventional one.

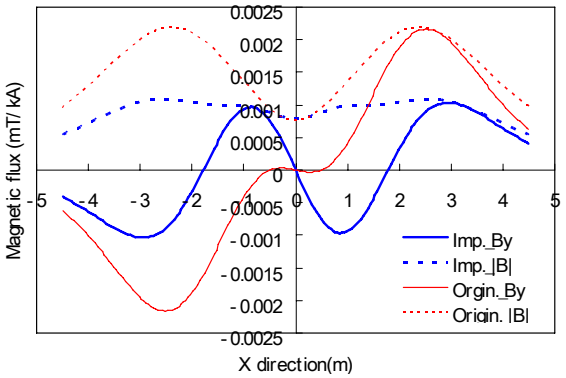


Figure 6: Magnetic field distribution

3.3 Enlarging gap between SC coils and ground coils

Figures 7-9 indicate the ratio of levitation force to drag force (drag ratio), equivalent guidance stiffness and propulsion force when the improved configura-

tion enlarge the lateral gap between SC coils and ground coils with strengthened magneto-motive force. These figures also show the values of conventional one without strengthened magneto-motive force.

Even if its gap extends by 20-30 mm, the improved configuration has almost the same performances as the conventional one due to strengthened magneto-motive force.

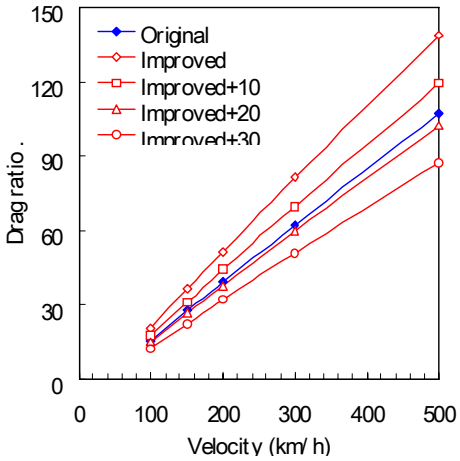


Figure 7: Drag ratio at enlarging lateral gap

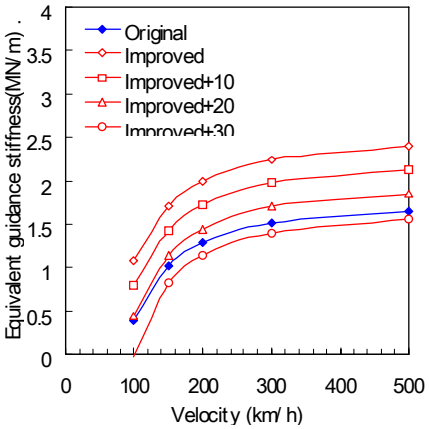


Figure 8: Equivalent guidance stiffness at enlarging lateral gap

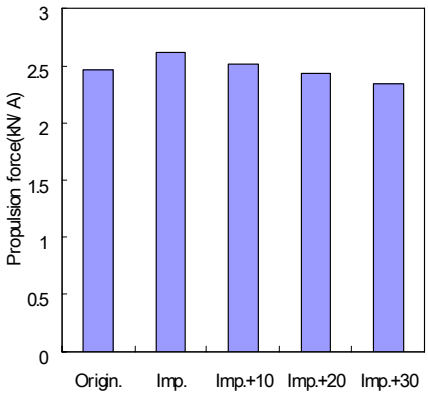


Figure 9: Propulsion force at enlarging lateral gap

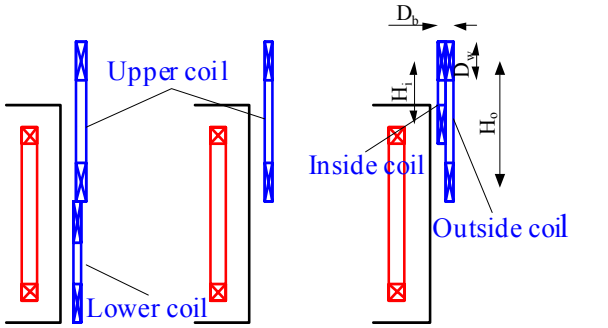
3.4 Optimized design of generator coil

We would design the dimensions of each generator coil figure, which are 8-figure coils, upper coils and improved upper coils as shown in Figure 10 and compare their performances. Thus, we utilize the coil design method by optimization program in reference (Murai & Fujiwara 1998). The assumptions of this method are as follows.

(1) Specifications of SC coil and ground coil are constant.

(2) The conductor volumes of generator coils are constant.

(3) The variables are dimensions of coils and cross sections of generator coils when they are arranged single layer with the constant coil pitch of 360 mm.



(a) 8-figure coil (b) Upper coil (c) Improved upper coil

Figure 10: Composition of generator coil

(4) The improved upper coil has inside and outside coils, which have different heights and whose upper sides set to the same position.

(5) The air gap is constant.

(6) Under the above-mentioned restrictions, the generator output is maximized at the velocity of 300 km/h.

Figure 11 shows the maximized output power of linear generator at each conductor volume of each coil figure. The upper coil has maximum output power at the conductor volume of about 40000cm^3. It is thought that the decreasing of lateral gap between generator coils and cryostat will reduce the induced voltage of generator coil and will increase the jule loss of generator circuit, while the increasing of conductor volume will reduce the resistance of generator coil, thus the output of linear generator will totally decrease.

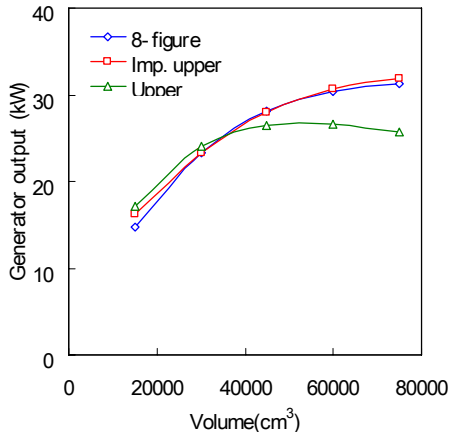


Figure 11: Generator output vs. conductor volume

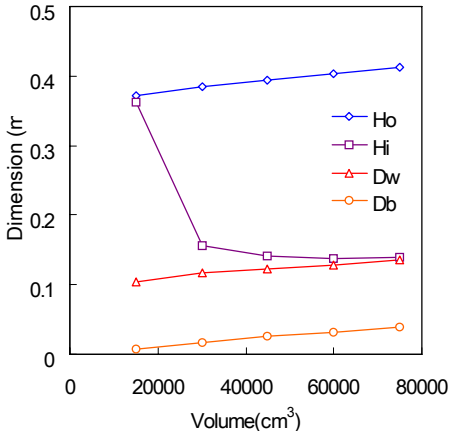


Figure 12: Specifications of improved upper coil

Figure 12 also shows examples of the optimized dimensions at each conductor volume of improved upper coil. The improved coils reduce the inside coil heights to concentrate on the top of cryostat at the conductor volume of about 30000 cm^3. This modification also suggests that it is important to avoid increasing of mutual inductance between generator coil and cryostat. Consequently, the improved upper coil can increase the generator output by increasing the conductor volume, thus it can gain the same output power as that of 8-figure generator coils. The improved upper coils are expected to be lighter weight and can moderate mechanical design because they remove the lower coils which are stressed out by larger magnetic force on their lower side and also need structural weight.

3.5 Concrete design of improved upper coil

After the optimization design, we concretely design the improved upper coil and examine their characteristics. Figures 13-16 show the induced voltage, equivalent resistance, equivalent inductance, which are influenced by eddy current on cryostat, and current of generator coils without load of passenger. The current indicates when the converter controls the output power to keep constant at the target power of 25 kW. Figure 17 shows the performance of generator output with no load and full load.

Since U-phase generator coils have different number of coils, their induce voltage, equivalent resistance and equivalent inductance differ from those of V and W phases. However, the currents of 3-phase is almost the same, so it is thought that the above-mentioned imbalances of 3-phase do not have bad influence.

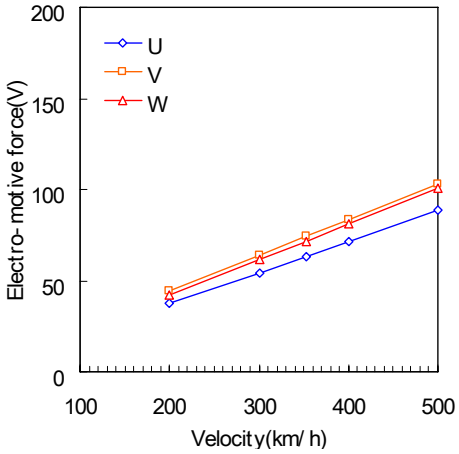


Figure 13: Induced voltage of improved upper coil

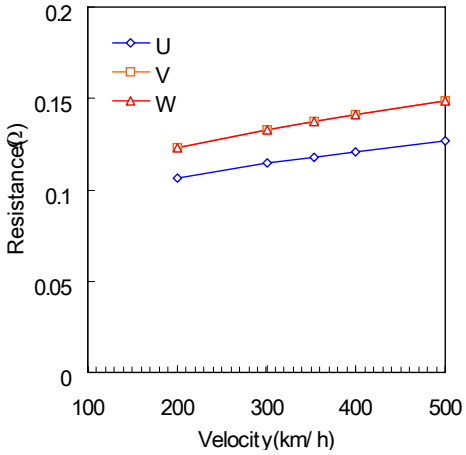


Figure 14: Equivalent resistance of improved upper coil

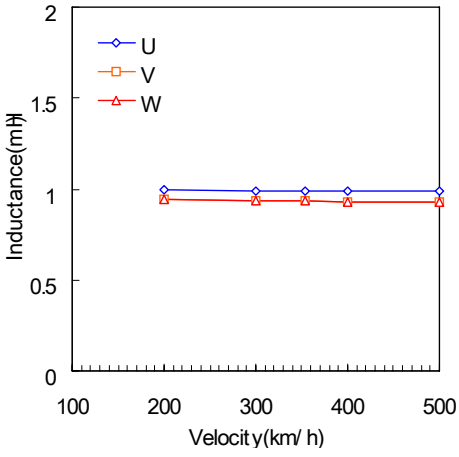


Figure 15: Equivalent inductance of improved upper coil

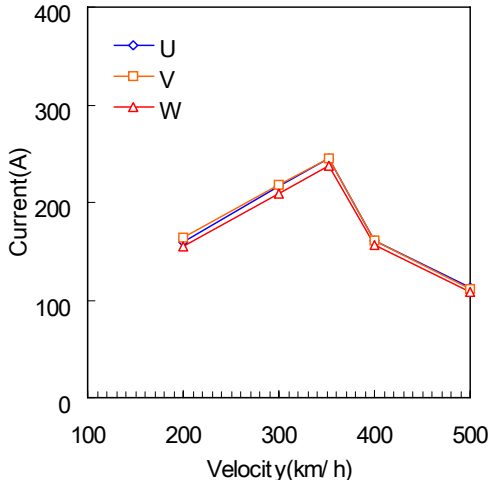


Figure 16: Current of improved upper coil

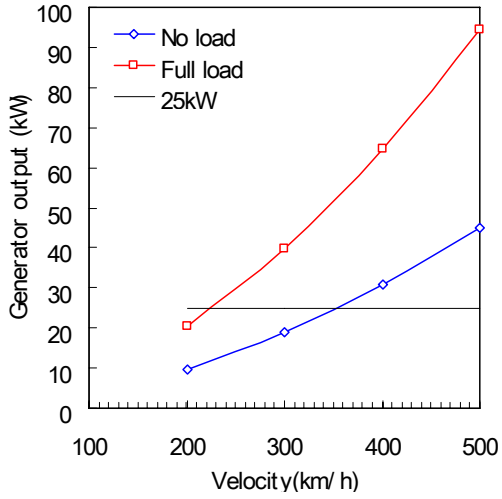


Figure 17: Generator output of improved upper coil

The generator output can reach the target power at the velocity of about 220 km/h with full load and at about 350 km/h with no load. The generator output depends on the vehicle weight because the magnetic fields, which consist of fundamental and harmonic magnetic fields caused by ground coil, are proportional to the vehicle weight. This figure also shows that the improved linear generator has better performance than that of the conventional one, which has 8-figure generator coils and conventional SC coils with through holes.

3.6 Magnetic damping

In order to examine the magnetic damping performance, the magnetic forces generated by zero-phase current are calculated in the upper and 8-figure coils. Figures 18 and 19 show the vertical and lateral forces by zero-phase current in the upper and 8-figure coils, respectively, when both coils have the almost same conductor volume. In these figures, Fz indicates the vertical force when the lateral coils have the same poles of zero-phase current and Fy the lateral force at the opposite ones as shown in Table 1.

The upper coil has the same vertical force, which will utilize vertical magnetic damping, and the opposite and smaller lateral force, which will utilize lateral magnetic damping in comparison with the 8-figure coil. Consequently, the upper coil can provide only vertical magnetic damping.

Table 1: Zero-phase current for magnetic damping

	Upper coil		8-figure coil			
	Right	Left	Right		Left	
			Upper	Lower	Upper	Lower
Fz	+	+	+	-	+	-
Fy	+	-	+	+	-	-

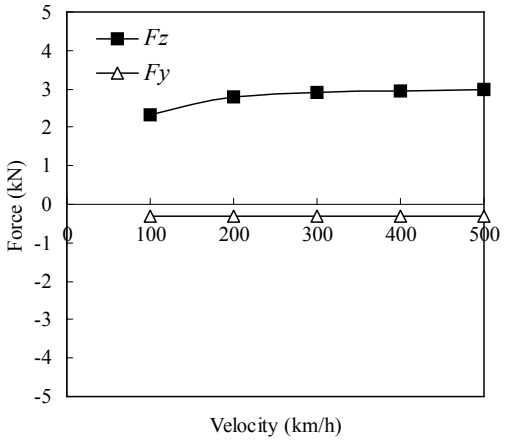


Figure 18: Magnetic force of upper coil

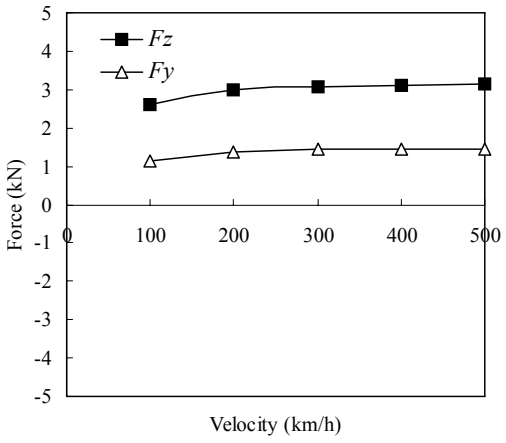


Figure 19: Magnetic force of 8-figure coil

4 CONCLUSION

This paper proposed a linear generator with SC coil configuration to reduce leakage flux with strengthened their magnet-motive force, which can enlarge the gap between generator coils and cryostat to in-

crease the generator output. By numerical examples, we revealed the following features.

First, the improved configuration has the same performances for levitation, guidance and propulsion at extending its gap.

Second, in order to increase the generator output, the improved upper generator coil is effective, and it can gain larger power than the conventional one.

Finally, the upper coil can provide the same vertical magnetic damping as the 8-figure coil.

REFERENCES

Murai, T. & Sasakawa, T. 2004. Characteristics of SC coil configuration for EDS Maglev to reduce leakage flux strengthened magneto-motive force, *Proc. maglev, conf., Shanghai, October 2004*: 966-972.

Yamamoto, T. et al. 2002. Development of distributed-type linear generator, *Proc. maglev, conf., Lausanne, September 2002*

Murai, T. & Sakamoto, Y. 2005. Sensor-less combined vertical and lateral magnetic damper by using linear generator for EDS maglev, *Proc. ldia, symp., Kobe-Awaji, September 2005*: 314-317.

Murai, T. & Fujiwara, S. 1998. Design of coil specifications in EDS maglev using an optimization program, *Proc. ldia, symp., Tokyo, April 1998*: 343-346.