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영구자석형 리니어 유도 동기모터의 동기화에 관한 실험적 검토

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Synchronizing Characteristics of the Linear Induction Synchronous Motor

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Abstract - In this paper, we describe the starting and synchronizing methods in the linear induction synchronous motor. The proposed motor consists of one pair of linear synchronous motors (LSMs) and an additional linear induction motor (LIM). The primary cores have a common ring winding, and solid conductors are arranged in both LIM and LSM. From the investigation by analysis and experiment, we verify that the proposed motor is effective for practical use.

1. INTRODUCTION

While the linear synchronous motor generally starts by the ramp input of frequency or the induction operation of secondary damper winding, we adopt two stages of supply frequencies based on the latter method. The feature of this method is that the supply frequency in the transient period between starting and synchronizing process is higher than that in steady-state drive [1]. The high frequency is effective for improving the induction thrust by damping effects.

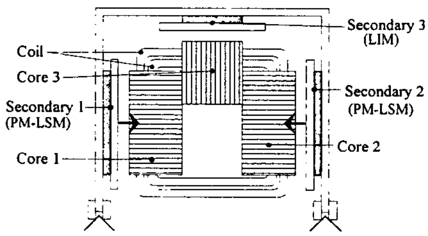
The proposed motor consists of a couple of LSM that disposed by back to back each other and a subsidiary linear induction motor. The primary-cores of the motor have a common ring winding of double-layer, and the secondary solid-conductor (i.e., damper winding) is arranged in both LIM and the interpole space of LSM [2]. From the past study of LSM with electromagnet, we verified that LIM action is useful not only for an accelerator at starting but also for a damper winding at the synchronizing process. The merit of our motor is that the vertical force between primary and secondary in LSM can offset by using the symmetrical double-sided construction and the secondary is capable of self-starting by induction operation.

We first investigate the physical phenomenon in our motor by the finite element method. Then, we verify that the motor is effective for practical use from the standpoint of the self-starting, the hunting oscillations, and the source efficiency. We also confirm that the stating by two stages of supply frequencies is superior to normal ones in view of the quick acceleration and synchronism. Finally, we describe the possible industry application of our proposed motor.

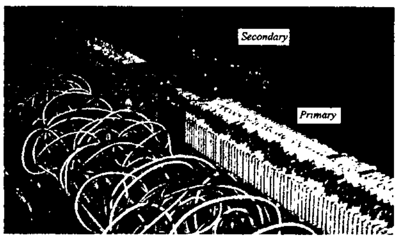
2. STRUCTURE

Figure 1 shows the structure of proposed motor, and table 1 the specifications. In the figure, the primary is composed by the one pair of right- and left-side cores for LSM and the upper core for LIM. The slot depth decides the width of core for LIM, which plays the role of damper winding. As for the polar arc in LSM, we adopt 80 percent of ferrite magnets per pole for eliminating the 5th space harmonic. The 3rd space harmonic is not produced in three phase connection of primary winding.

By applying such a double-sided construction to the primary, the magnetism between primary and secondary in LSM is offset. Furthermore, the source efficiency increases by adopting common ring winding, because three-fourths of primary winding contribute to the secondary movement [3].



(a) Front view



(b) Experimental machine.

Fig. 1. Structure of the proposed motor.

Table 1. Experimental specifications.

Item	Symbol	Value (Unit)
Primary length	L_p	2.160 (m)
Primary width (Cores 1 and 2)	W_1, W_2	0.044 (m)
Primary width (Core 3)	W_3	0.025 (m)
Pole pitch	τ	0.054 (m)
Slot width	W_s	0.006 (m)
Tooth width	W_t	0.003 (m)
Slot depth	d_s	0.027 (m)
Number of secondary pole	P_s	4
Number of turns	N	50 (turns)
Inside coil reactance	R_i	0.8 (Ω/coil)
Outside coil reactance	R_o	0.9 (Ω/coil)
Length of secondary	L_s	0.216 (m)
Thickness of secondary (LIM)		
Conductor	T_i	0.002 (m)
Back-iron	T_s	0.003 (m)
Frequency	f	50 (Hz)
Length of air-gap (LIM, LSM)	g	0.0035 (m)

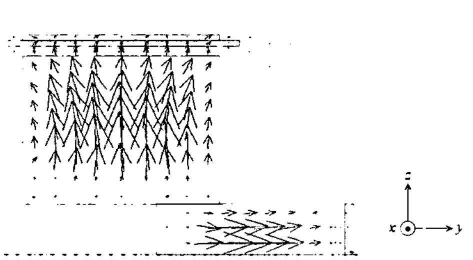
3. ANALYSIS

To investigate the performance of the proposed motor, we analyze the electromagnetic field by using three-dimensional finite element analysis. In case of nodal elements, we apply the Galerkin method to obtain,

$$\nabla\times\left(\frac{1}{\mu_0}\nabla\times A\right)=J_0-\sigma\left(\frac{\partial A}{\partial t}+\nabla\phi\right)+\frac{1}{\mu_0}\nabla\times M \tag{1}$$

$$\nabla\cdot\sigma\left(\frac{\partial A}{\partial t}+\nabla\phi\right)=0 \tag{2}$$

where A, J_0, ϕ, σ, and M mean the magnetic vector potential, the input current density, the electric scalar potential, the conductivity, and the magnetization, respectively. Figure 2 shows the configuration of the magnetic flux in y-z plane of the motor. As the boundary condition in x-y plane of the analysis model, we apply the symmetrical condition. In the figure, we can recognize that the leakage of magnetic flux among each unit motor is not existent.



$(A_x=A_y=\phi=0)$

Fig.2. Configuration of the magnetic flux.

4. RESULTS

4.1 Static characteristics

We first investigate the starting behavior of the motor driven by secondary conductor and back iron only, which make the secondary self-starting by induction operation. Figure 3 shows the characteristics of thrust versus slip-frequency at $I=2$[A], $f=50$[Hz] and Fig. 4 the secondary velocity versus time at $I=2$[A] under the different frequencies. Since the induction operation is influenced by the whole amounts of secondary conductor, we can confirm the higher thrust and acceleration. The thrust of subsidiary LIM becomes about 36 percent of whole thrust.

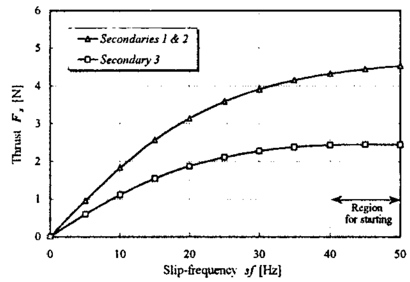


Fig. 3. Thrust versus slip-frequency (Analysis).

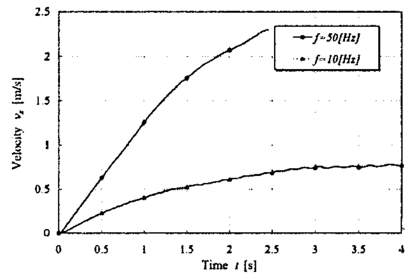


Fig. 4. Secondary velocity versus time (Experiment).

Figure 5 shows the distribution of magnetic flux density by secondary permanent magnets and Fig. 6 the thrust versus power angle. In Fig. 6, the result indicates that the maximum value of the synchronous thrust inclines to the center of the power angle.

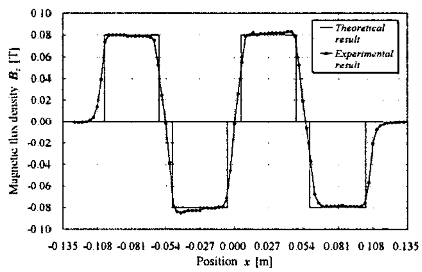


Fig. 5. Magnetic flux density by secondary magnets.

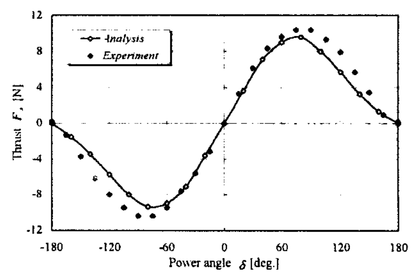
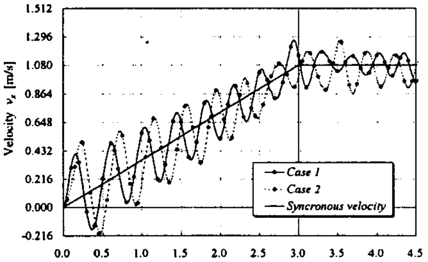


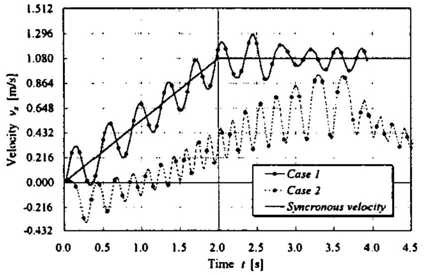
Fig. 6. Thrust characteristics versus power angle.

4.2 Transient Characteristics

Since the proposed motor has not the field winding, the starting and the reduction of hunting oscillations have to depend on the induction operation of secondary conductor. As for the former behavior, we investigate the characteristics in the transient period between starting and synchronous speed. Figure 7 shows the velocity characteristics in the synchronizing process by ramp input of frequencies and Fig. 8 the velocity in a single frequency.



(a) f=3.33[Hz] per second



(b) f=5.0[Hz] per second

Fig. 7. Starting by ramp input of frequency.

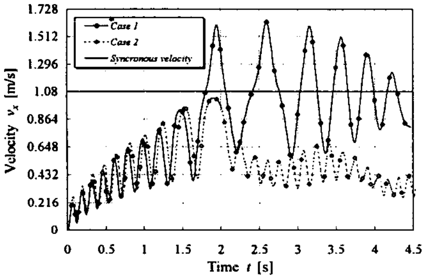


Fig. 8. Starting characteristics (f=10[Hz]).

Figure 7 indicates that the starting by ramp input is not suitable for quick acceleration, because the time period to synchronous speed is indispensable. From the result adopting a single frequency supply in Fig. 8, we can recognize that the secondary is underdamped, which always pull into synchronism from higher speed than synchronous one. These results show that the initial position between the traveling magnetic field of primary and the static fields by secondary magnet influence the synchronizing process.

While the most LSM is started by the above two methods, we propose a novel starting method in view of ease and efficiency for synchronism. The method is that the higher frequency than synchronizing one is supplied to the starting operation. Figure 9 shows the velocity characteristics by applying two stages of frequencies to the transient period. The result indicates that higher current provides the higher acceleration at both starting and the convergence of hunting oscillation.

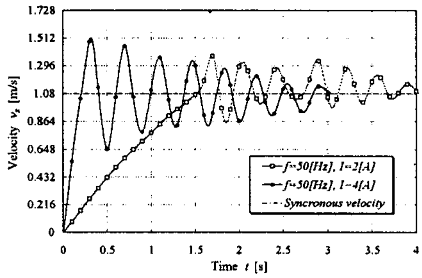


Fig. 9. Starting by two stages of frequencies.

5. CONCLUSION

The purpose of this paper is to develop a novel motor for the best possible use of both induction and synchronous operations. Two stages of supply frequencies are applied to our starting and synchronizing process. Comparing the proposed method with the normal ones by the ramp input of frequencies and the single frequency, we obtained the following results.

i) Adopting the proposed construction, we can achieve both the offset of magnetism between primary and secondary in LSM and the enhancement of damping effects by LIM action.

ii) Arranging the subsidiary LIM between LSMs, we can obtain the superior self-starting, the reduction of hunting oscillations, and the enhancement of source efficiency.

iii) Using two stages of supply frequencies, we can achieve the quick acceleration and synchronism of the secondary.

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