Design and Analysis of Long Primary Variable Pole Pitch Linear Induction Motor for Electromagnetic Aircraft Launch System

Mu Shujun, Chai Jianyun
Department of Electrical Engineering, Tsinghua University, Beijing 100084, China
chaijy@tsinghua.edu.cn

Abstract — The paper proposes the option of long primary variable pole pitch linear induction motor (VPPLIM) for the electromagnetic aircraft launch system (EMALS). Based on the method of combining the 2-D finite element analysis with the numerical solution of the secondary's motion equation, the paper analyzes the quasi-steady-state performance of the proposal under constant voltage constant frequency power source.

I. INTRODUCTION

Compared with the steam-driven catapult systems used on the aircraft carrier, the electromagnetic aircraft launch system (EMALS) has substantial improvements in areas of volume, weight, maintenance, efficiency, controllability and energy capability[1]. Generally, EMALS is consisted of four segments[2]: a linear launch motor, a power electronics systems, an energy storage system, and a control system.

The linear motor utilized in EMALS could be induction motor, permanent magnet, superconductor magnet synchronous motor or reluctance-synchronous motor [3] [4]. Conventionally, it's a long primary linear motor, winded to constant pole pitch (see Fig. 1), supplied by the electric power inverters to achieving the acceleration of the secondary by frequency control. As the power inverter's capacity reaches up to hundreds of megawatt, it becomes the bottleneck in the realization of EMALS for the desire of high reliability, not to mention the volume and cost.

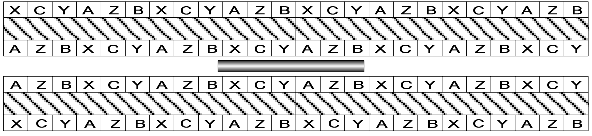

Fig. 1. Constant pole pitch structure linear motor

A new variable pole pitch speed control scheme will be discussed in this paper, in which, the secondary could be uniformly accelerated under a constant voltage constant frequency power source through properly increase the pole pitch of the long primary. Then, the using of huge electric power inverters could be effectively avoided, which would greatly increase the reliability of EMALS and decrease the cost of production and maintenance.

II. DESIGN

The basic structure of variable pole pitch linear induction motor (VPPLIM) is shown in fig.2, the pole pitch of the long primary gradually increases along the direction of the motion.

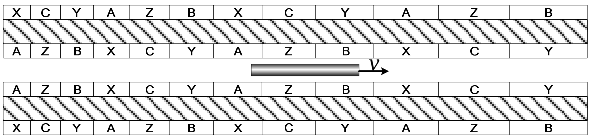

Fig. 2. Variable pole pitch structure linear induction motor

Design of the pole pitch, topology structure and circles turns of VPPLIM will be discussed in the following paragraph.

A. Pole Pitch

In a well designed linear induction motor, the velocity of the secondary mostly depends on the synchronous speed (the velocity of the transverse magnetic field generated by the primary) and the difference between the two could be limited to a little range. So, the design foundation of the pole pitch is matching the synchronous speed at various displacements to the requirement of the accelerating character of the secondary.

In order to achieve uniform acceleration of the secondary needed in EMALS, the increasing of the pole pitches in the motion direction is determined by gradually increasing the width of the phase-belt according to the following rules.

Supposing the width of the *i*-th phase-belt is w_i, the speed of the secondary at the entry end of the *i*-th phase-belt is v_{i-1} and at the exit end is v_i, according to the rules of uniform acceleration movement, we could get:

$$\begin{aligned} v_{i-1} &= \sqrt{2ax_{i-1}} \\ v_i &= \sqrt{2ax_i} = \sqrt{2a(x_{i-1}+w_i)} \end{aligned} \tag{1}$$

where, a is the rated acceleration.

So, the average synchronous speed at the *i*-th phase-belt should be:

$$v_{si} = \frac{v_{i-1}+v_i}{2} \tag{2}$$

Added with the time needed for the transverse magnetic field to sweep over the *i*-th phase-belt $1/(6f)$, there would be:

$$w_i = \frac{\sqrt{2ax_{i-1}}+\sqrt{2a(x_{i-1}+w_i)}}{2}\cdot\frac{1}{6f} \tag{3}$$

Solving (3), the width of *i*-th phase-belt could finally be given by:

$$w_i = \frac{12f\sqrt{2ax_{i-1}}+a}{72f^2} \tag{4}$$

In actual design progress, the value of the acceleration in (4) should be slightly bigger than the rated acceleration to compensate the effect of the slip.

B. Structure

The topology structure[5] of VPPLIM designed in this paper is shown in fig.3, for the purpose of reducing flux leakage and EMI in addition to saving copper.

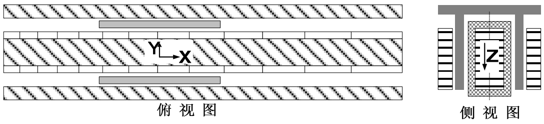

Fig. 3. The topology structure of VPPLIM

The primary is divided into several segments, each segment contains a certain even number of poles, which could yield the segment to be 1.2-1.5 times as long as the secondary. When the motor is on operation, the segments, in direction of the motion of the secondary, are power supplied successively. Concretely speaking, the three segments which are nearest to the secondary, with the circles of the same phase in series, are paralleled to the same power source.

C. *Circle Turns*

The design principle of the circle turns is that the VPPLIM could be able to produce a space fundamental flux density of an unchanged amplitude and an increasing space period, as shown in fig.4. It's obvious that the flux under each pole is in direct proportion to the pole pitch:

$$\Phi \propto \tau \tag{5}$$

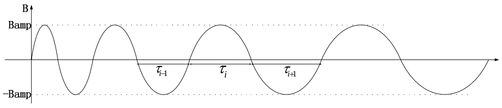

Fig. 4. The desirable distribution of flux density

Taking account of the electromotive force constrain of full-pitched coil $E = \sqrt{2}\pi fN\Phi$, the circle turns would be in inverse proportion to the pole pitch:

$$N \propto 1/\tau \tag{6}$$

As the circles of the same phase under various poles of the same segment being in serious, the turns should be equal to produce a magnetomotive force of the same amplitude which could then produce a flux density of an unchanged amplitude through almost the same magnetic reluctance.

Supposing the motor has j segments in total, and each segment has p_j pole pairs, then, the *emf* of the j-segment is:

$$E = 2\cdot\sum_{jk=1}^{p_j}\sqrt{2}\pi fN\Phi_{jk} \tag{7}$$

where $\Phi_{jk}$is the flux under the pole jk.

Solving (7), the circle turns of segment j could be got by:

$$N_j = \frac{E}{\sqrt{2}\cdot\pi\cdot f\cdot B_{avg}\cdot h\cdot l_j} \tag{8}$$

where, l_j is the length of the j-segment, h is the high of the VPPLIM.

The circles turns of the first segment should be increased properly to guarantee the uniform acceleration of the secondary for the slip in the start progress of the motor is comparatively bigger.

III. PERFORMANCE

Based on the theory discussed above, a model motor of 5.5 meters long, power supplied by 220V, 50Hz source, is designed and analyzed by 2-D finite element analysis. Fig.5 shows the space distribution of the flux density at one moment. It's could be seen that the space period is relatively larger when the displacement is comparatively bigger.

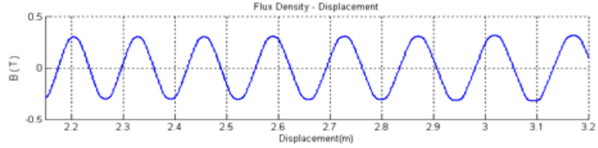

Fig. 5. Flux density distribution of VPPLIM

Combined with the motion equation of the secondary, we could get the acceleration characteristic of the model under 50kg rated loads, as shown in fig.6

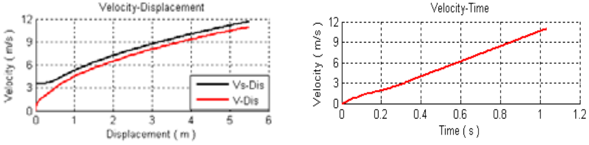

Fig. 6. Accelerating character of the model under 50kg rated loads

From fig.6 we could see that, as anticipation, the velocity of the secondary tightly follows the synchronous speed, and the model VPPLIM presents a good linear relationship between the velocity and time.

In order to facilitate computing the acceleration character of the model driving different loads, the paper provides a method of establishing a 3-D (displacement, slip, force) database which stores the mechanical properties of the motor at equidistant displacements that are enough to reflect the motor's property. Then, based on the database, combined with the motion equation, we could get the acceleration property of the motor with different loads through proper interpolation. Fig.8 shows the acceleration property of the model VPPLIM with loads of 20kg, 50kg and 80kg.

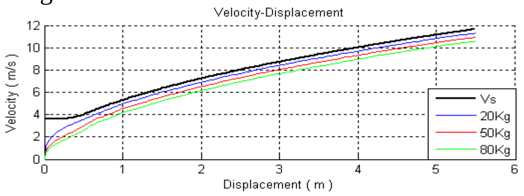

Fig. 8. Accelerating character of the model with loads of 20kg, 50kf, 80kg

IV. REFERENCES

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