Calculation of electromotive force induced by the slot harmonics and parameters of the linear generator

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Abstract: The linear generator used in magnetic levitation vehicle is investigated in this paper. Firstly, the principles of the linear generator are introduced, then the formulae of electromotive force (EMF) induced by the slot harmonics in the airgap and the formulae of armature resistance and inductance are deduced, and the design principles in which the phases of EMF are matched are presented. Finally, the EMF, armature resistance and inductance are calculated using those equations.

1. Introduction

Linear synchronous motor has been paid great attentions as one of new actuators in the magnetic levitation vehicle because of its high efficiency, energy saving and so on. When the velocity of the long stator linear synchronous motor used in magnetic levitation vehicle exceed some value, the linear generator can provide the excitation current of the linear synchronous motor.

The linear generator's armature windings are placed in the slots of the pole-shoes of the linear synchronous motor, as shown in Fig.1. When the magnet poles of the linear synchronous motor are moving, the slot harmonics from the field windings of the linear synchronous motor induce the alternating electromotive force into the linear generator's armature windings. The single-phase bridge rectifier to supply the excitation current can convert the alternating current into direct.

This paper proposed the basic knowledge of linear generator used in magnetic levitation vehicle.

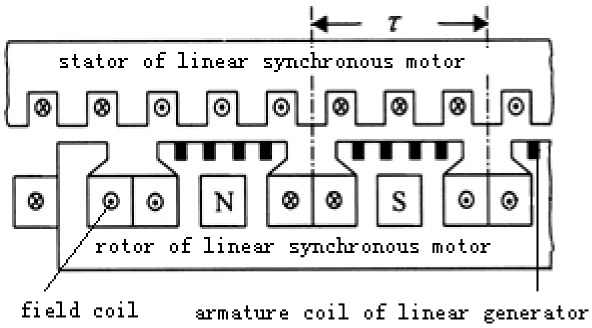

Fig.1 The principle of linear generator

On the first stage, the formulae of EMF in the armature windings of linear generator are deduced by theoretical investigation.

Then the design principles in which the phases of EMF are matched are obtained.

Finally, the formulae of armature resistance and inductance are presented for the armature windings of linear generator.

2. The electromotive force (EMF)

The type of stator windings of the linear synchronous motor is three-phase single- layer winding. If the three-phase symmetric currents in the windings of the linear synchronous motor are

$$i_A = \sqrt{2} I \cos \omega t$$
$$i_B = \sqrt{2} I \cos(\omega t - 120^0) \qquad (1)$$
$$i_C = \sqrt{2} I \cos(\omega t - 240^0)$$

Then the resulting the γ -harmonic component of magnetomotive force (MMF) in the airgap f_γ is

$$f_\gamma(x,t) = f_{A\gamma} + f_{B\gamma} + f_{C\gamma} = \pm F_\gamma \cos(\omega t + \gamma \frac{\pi}{\tau} x) \qquad (2)$$

where $f_{A\gamma}$、$f_{B\gamma}$、$f_{C\gamma}$ are the γ -harmonic component of MMF of the A、B、C phase respectively. The γ -harmonic amplitude of MMF equals to the fundamental MMF amplitude divides the number of harmonics (i.e. $F_\gamma = F_1 / \gamma$). Notice that, γ =5 or 7 and γ =11 or 13.

Fig.2 shows the location of conductors 1,2,3,4 in the field of 5th and 7th space harmonics when ψ_0=0 .

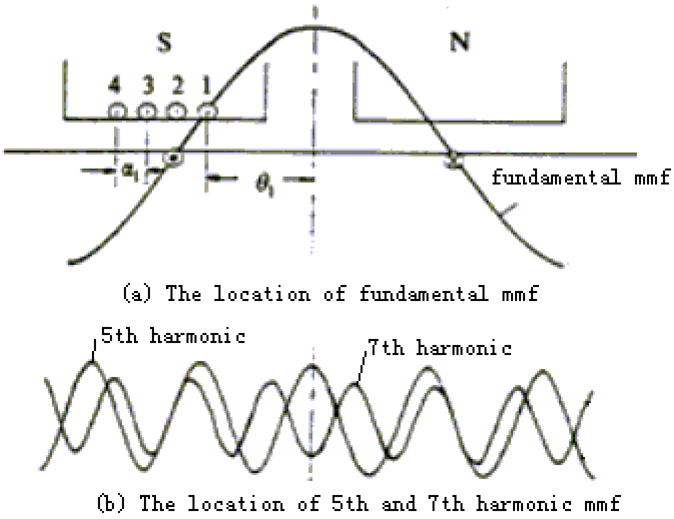

Fig.2 The location of conductors 1,2,3,4 in the field of 5th and 7th space harmonics when ψ_0=0

At this time, the EMF of phase A is maximum, as ψ_0=0, and the current of phase A is maximum. The peak of the fundamental MMF wave is located at the axis of phase A, and also is located at the q axis. The peak of 5th and 7th space harmonics MMF is located at the q axis.

Set the slot harmonics of γ =5 or 7 as an example. Assume that the angle(ψ_0) between $\dot{I}_0$ and

$\dot{E}_0$ of the linear synchronous motor not equals to zero, i.e. $\psi_0 \neq 0$. So the angle between the fundamental MMF and q axis is ψ_0 electrical degrees, and the angle between the total MMF of γ =5 or 7 and q axis is $\gamma\psi_0$ electrical degrees. As a result, the EMF induced by the γ =5 or 7 slot harmonics in the conductors 1,2,3,4 of the linear generator will be

$$\left.\begin{aligned} e_{1(\gamma)} &= \pm\sqrt{2}E_\gamma \cos(\omega_6 t + \gamma\psi_0 - \theta_{1(\gamma)}) \\ e_{2(\gamma)} &= \pm\sqrt{2}E_\gamma \cos(\omega_6 t + \gamma\psi_0 - \theta_{1(\gamma)} - \alpha_{(\gamma)}) \\ e_{3(\gamma)} &= \pm\sqrt{2}E_\gamma \cos(\omega_6 t + \gamma\psi_0 - \theta_{1(\gamma)} - 2\alpha_{(\gamma)}) \\ e_{4(\gamma)} &= \pm\sqrt{2}E_\gamma \cos(\omega_6 t + \gamma\psi_0 - \theta_{1(\gamma)} - 3\alpha_{(\gamma)}) \end{aligned}\right\} \quad (3)$$

The conductors are connected in (1→3)→(2→4) or in (1→2)→(3→4), the total EMF will be

$$e_\gamma = \pm 4\sqrt{2} n_c E_\gamma \left| k_{y\gamma} k_{q\gamma} \right| \cos(\omega_6 t + \varphi_\gamma) \quad (4)$$

where $\varphi_\gamma = \gamma\psi_0 + 90^0 - \theta_{1(\gamma)} - \frac{3}{2}\alpha_{(\gamma)}$.

When γ =5, equation (4) is positive. When γ =7, equation (4) is negative.

The EMF induced by the γ =11 or 13 slot harmonics can be obtained in the same way.

3. Condition of the phases of EMF are matched

Assume that the phase of the 5th harmonics EMF is matched with the phase of the 7th harmonics EMF, that is the sum of φ_5 and φ_7 must equal to 180 degree or the odd multiple of 180 degree, i.e.

$$\varphi_5 + \varphi_7 = (2k+1)180^0 \quad (5)$$

where k=0, 1, 2, 3, ….

If θ_1 represents the electrical degrees from the q axis to the conductor 1, α_1 represents the fundamental slot pitch of the linear generator, then $\theta_{1(5)} = 5\theta_1, \theta_{1(7)} = 7\theta_1$, $\alpha_{(5)} = 5\alpha_1, \alpha_{(7)} = 7\alpha_1$. The equation (5) can be expressed

$$2\psi_0 + 2\theta_1 + 3\alpha_1 = \frac{1}{3}k\pi \quad (6)$$

This formula describes the condition of the phases of EMF are matched.

The condition of the phase of the 11th harmonics EMF and the phase of the 13th harmonics EMF are matched can be obtained in the same way.

4. Parameters of the linear generator

The armature dc resistance per pole r_1 is

$$r_1 = \rho_t \frac{2Z_1 l_z}{N_1 S_a} \quad (7)$$

where ρ_t is the conductor's resistivity (ohm·m), Z_1 is turns per phase, l_Z is the average half length of one coil (m), N_1 is the parallel strands, S_a is the conductor cross-section area (m^2).

Consider the skin effect in the conductors with alternating current, the ac resistance equals to K_F times dc resistance, and the coefficient K_F is

$$K_F = 1 + (\frac{\mu_0 \pi f m n b}{3 \rho b_s})^2 a^4 \quad (8)$$

where a、b are thickness and width of the conductor respectively (m), b_s is the width of the slot bottom (m), m is number of the series conductors in the slot, n is the number of conductors in width, f is the frequency of the current (Hz), $\mu_0 = 4\pi \times 10^{-7}$ H/m.

If the conductors in slot have n_c turns, and the current flow in the conductors is i_c, then the armature inductance per pole L_a is

$$L_a = \frac{\Psi_1}{i_c} = \frac{2 n_c \Phi_1}{i_c} = 2 n_c^2 t_1 l_{ef} \mu_0 \frac{1}{k_c \delta} \quad (9)$$

where t_1 is the width between the slot and the teeth (m), l_{ef} is the effective length of rotor core (m), k_c is a coefficient, δ is the air gap length (m).

Consider the saturation of magnet circuit, the armature reactance per pole equals to the $2fK_s$ times the armature inductance, and the saturation coefficient K_s can be calculated using the finite element method.

The armature leakage inductance per pole L_s is

$$L_s = Q_1 L_{S1} = \mu_0 Z_1^2 \lambda_{s1} l_{ef} / Q_1 \quad (10)$$

where λ_{s1} is the slot leakage magnetic conductance coefficient, Q_1 is the per pole slot number.

Consider the skin effect, the effective armature leakage inductance per pole equals to K_x times L_s, and the coefficient K_x is

$$K_x = \frac{1}{m}(1 - \frac{8}{315}\xi^4) + \frac{m^2 - 1}{m^2}(1 - \frac{1}{30}\xi^4) \quad (11)$$

where $\xi = \alpha a$, $\alpha = \sqrt{\frac{b \pi f \mu_0}{b_s \rho_t}}$.

The armature end turns leakage inductance per pole L_e is

$$L_e = \mu_0 Z_1^2 \lambda_{e1} l_{ef} / Q_1 \quad (12)$$

where λ_{e1} is the end leakage magnetic conductance coefficient.

If define $l_E = \frac{\pi D_e \nu}{2p} y_m$, where y_m is average span space of the coil in slot number, D_e is the average diameter of the winding end, ν is end coefficient, p is the pole number, then the above equation will be

$$L_e = \frac{0.25}{2\pi p} \mu_0 Z_1^2 l_E = 0.5 Z_1^2 \frac{l_E}{p} \times 10^{-7} \quad (13)$$

Using the above equations (4), (7), (8), (9), (10), (11) and (13), the parameters of the linear generator can be calculated.

5 An example of calculation

The data of the linear synchronous motor are shown in table 1. The table 2 shows the per pole resulting electromotive force(emf) , armature resistance and inductance of the linear generator using the above equations, when the operation state of the linear synchronous motor is f= 215Hz，I=1200A.

Table 1 the data of the linear synchronous motor

pole pitch (mm)	258	Slot width of stator (mm)	20
per pole per phase slot number	1	Teeth width of stator (mm)	66
per phase turns	160	Effective length of rotor core (mm)	185×0.94
fundamental winding factor	1	Rotor core width (mm)	172
Pole number	320	Slot width of rotor (mm)	10
Air gap (mm)	10	Teeth width of rotor (mm)	12

Table 2 the calculation results

		(1→3)→(2→4)		(1→2)→(3→4)	
		γ =5 or 7	γ =11 or 13	γ =5 or 7	γ =11 or 13
EMF (rms)	$\psi_0=0^0$	4.405V	0.1029V	1.11331V	2.83823V
	$\psi_0=23.9^0$	4.108V	0.09536V	1.018363V	2.60389V
ac resistance (Ω)		0.07868		0.07868	
reactance (Ω)		0.003596		0.003596	
leakage reactance (Ω)		0.001239		0.001239	
end turns leakage reactance (Ω)		3.2629×10^{-5}		3.1811×10^{-5}	

6. Conclusion

Purpose of this paper is to propose the basic knowledge of the linear generator used in magnetic levitation vehicle. Theoretical investigations about the formulae of EMF in the armature windings of linear generator are deduced. The design principles in which the phases of EMF are matched are obtained. The formulae of armature resistance and inductance are presented for the armature windings of linear generator.

The calculation results show that (1) the5th and 7th space harmonics emf is larger than the11th and 13th space harmonics emf when the armature winding connected in (1→3)→(2→4) (2) the difference between the5th and 7th space harmonics emf and the11th and 13th space harmonics emf is small when the armature winding connected in (1→2)→(3→4), and the air field is balance, this will effect the levitation force of the magnetic levitation vehicle.

Reference

1. HuaqingLiu, ZhiyeLi, EngengRen. Magnetic levitation vehicle in Germany [M].Chendu, Electronic technical university press,1995.
2. YunqiuTang, NaiShi. Electrical machinery [M].Beijing, China machine press,2001.
3. ShikunChen. Design of Electrical machinery [M]. Beijing, China machine press,1989.
4. NongnianLi, BaolingWang, RuhuangZhou. Design of Electrical machinery [M]. Beijing, Tsinghua university press,1992.