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REDUCTION OF FORCE RIPPLES IN LINEAR MOTORS

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Abstract: The influence of higher field harmonics of permanent magnets, and asymmetry of flux linkages according to the phase shift on the value of force ripples in linear motors is studied. The solution to this problem is based on a higher field harmonics analysis in the active zone of a two-phase permanent-magnet cylindrical linear motor. The laws of gate current variation due to the position of the slider, which allows the compensation of these ripples, are established.

Key words: flux harmonics, force ripple, linear motor.

1. Introduction

The value of output force ripple is an important metrological characteristic of linear motors (LM) in the load system of a pilot simulator. Therefore, the study of its causes and ways of its reduction have become the object of numerous publications.

The cause of output force ripple in LM is the presence of higher harmonics in the flux linkage formed by permanent magnets, as well as by asymmetry of flux linkages according to the phase shift that might occur due to technological errors or motor design.

For pragmatic reasons, LM are mostly designed as two-phase and not three-phase, because this helps to reduce the number of LM coils, PWM converters of power supply, etc. Therefore, in this article, our research is restricted to two-phase systems of electromechanical transducers.

It is known that the initial force of a linear motor for its m-phase implementation is $F = \sum_{i=1}^{m} \Psi_i \cdot i_i$,

where Ψ_i is the flux linkage of phase windings; i_i is the m-phase currents system specially formed depending on the position of the motor slider.

Given the symmetry of harmonic flux linkages and currents of a single amplitude phase, the output force of a two-phase LM is

$$F_{AB} = \Psi_A \cdot i_A + \Psi_B \cdot i_B = \sin\gamma \cdot \sin\gamma + \cos\gamma \cdot \cos\gamma = 1 \quad (1)$$

where γ is the linear slider position, expressed in electrical degrees.

It is clear that for symmetrical m-phase structures force is constant, and the force ripples equals zero. In the case of asymmetry in phase linkages or their non-harmonic character, there appears a variable component of the force which is referred to as ripple. It is known [1, 2, 3] that the force ripples can be compensated by a specially elaborated law of phase current variation due to the slider position.

The objectives of this investigation are to determine the effect of higher field harmonics and asymmetry of flux linkages according to the phase shift on the force ripple value, and to establish the law of variation of phase control currents due to the position of LM slider, which allows the compensation of these ripples.

The object of this research constitutes power characteristics, including the value and output force ripple in the linear motor of ЛД/СЗТ-45-2 type, designed at Research Laboratory 68 of Special Design Bureau of Electro-Mechanical Systems at Lviv Polytechnic University, City of Lviv, Ukraine (Fig. 1).

Fig. 1. Design of a permanent-magnets linear motor.

2. Theoretical fundamentals

If one of the harmonic components of the phase flux linkages (the most vivid is usually the third one) is present, a mathematical expression of LM force has the following form

$$F_{AB\nu} = (\sin\gamma + K_\nu \sin\nu\gamma)\sin\gamma +$$
$$+(\cos\gamma + K_\nu \cos\nu\gamma)\cos\gamma = 1 + K_\nu \cdot \cos\frac{\nu+1}{2}\gamma. \quad (2)$$

As it can be seen, there are force ripples caused by ν-th harmonic with the relative amplitude K_ν, the frequency of which is increased by $\frac{\nu+1}{2}$ times.

Equation (2) is transformed into

$$F_{AB\nu} = 1 + \sum_{\nu=3}^{\infty} K_\nu \cdot \cos\frac{\nu+1}{2}\gamma \quad (3)$$

for several higher harmonics of the field.

The LM force ripple caused by any higher harmonic of the flux linkage can be compensated by the introduction of a higher order component to the harmonic law of the gate currents variation [3], the component which is equal to the higher harmonics by relative amplitude, and is opposite by phase

$$F_{AB\nu} = (\sin\gamma + K_\nu \sin\nu\gamma)\cdot(\sin\gamma - K_\nu \sin\nu\gamma) + \\ + (\cos\gamma + K_\nu \cos\nu\gamma)\cdot(\cos\gamma - K_\nu \cos\nu\gamma) = \\ = 1 - K_\nu^2 . \quad (4)$$

As shown in (4), the relative value of the force has only constant components (no ripple) and is less than K_ν^2 .

A wish to similarly eliminate the influence of other harmonics gives the following result

$$F_{AB\nu} = \left(\sin\gamma + \sum_{\nu=3}^{\infty} K_\nu \sin\nu\gamma \cdot\right)\cdot \\ \cdot\left(\sin\gamma - \sum_{\nu=3}^{\infty} K_\nu \sin\nu\gamma\right) = \\ = 1 - \sum_{\nu=3}^{\infty} K_\nu^2 - 2\cdot \sum_{\substack{\nu,n=3 \\ n\neq\nu}}^{\infty} K_\nu \cdot K_n \cdot \cos\frac{\nu - n}{2}\gamma , \quad (5)$$

where ν and n are the odd numbers of higher harmonics of the field; K_ν and K_n are their relative amplitudes.

Thus, for example, for the 3rd, 5th and 7th harmonics, an expression for the force is as follows

$$F_{AB} = 1 - K_3^2 - K_5^2 - K_7^2 - \\ -2K_3K_5\cos\gamma - 2K_5K_7\cos\gamma \\ -2K_3K_7\cos 2\gamma . \quad (6)$$

Thus, when trying to simultaneously eliminate the influence of two or more higher field harmonics, in the expression of, there appear small components varying depending on the slider position in LM. The methods of elimination of these components may become the object of further research. However, the previous analysis of the amplitude of these variable components shows that the force ripple in the case of several higher harmonics' compensation is by order of magnitude lower than the force ripple of LM without compensation of any of these harmonics.

3. The conducted research

The second focus of this research is to determine the effect of flux linkage asymmetry due to the phase shift on the value of force pulsations that may occur because of technical errors, or design peculiarities of a linear motor.

These features include, for example, increasing the amount of copper by expanding the coils in order to boost the energy performance of the upgraded LM [3].

Such modernization of the structure of the active zone in a two-phase LM is shown in Fig. 2.

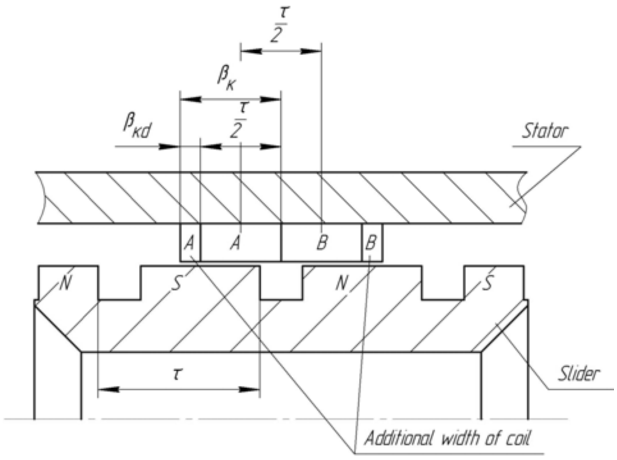

Fig. 2. The structure of the active zone of a cylindrical linear motor.

The distance between the axes of coils of the phases A and B in this case varies from $\frac{\tau}{2} = 90$ electrical degrees to $\frac{\tau}{2} + \beta_{\kappa d} = \beta_\kappa$, where $\beta_{\kappa d}$ and β_κ are the additional and full width of the coil respectively, expressed in electrical degrees.

Therefore, the phase linkage for the basic field harmonics will be sinusoids, shifted relating to each other not by $\frac{\tau}{2}$, but by β_κ , that under condition of symmetric currents power of a single amplitude $i_A = \sin\gamma$, $i_B = \cos\gamma$ would result in significant pulsations that vary according to the sinusoidal law with a double frequency. An expression for relative value of pushing in this case will be

$$F'_{AB} = \sin(\gamma + \varepsilon)\cdot\sin\gamma + \cos(\gamma - \varepsilon)\cdot\cos\gamma = \\ = \frac{1}{2}\left[2\cos\varepsilon + \cos(2\gamma + \varepsilon) - \cos(2\gamma - \varepsilon)\right] = \\ = \cos\varepsilon - \sin\varepsilon\cdot\sin 2\gamma , \quad (7)$$

where $\varepsilon = \frac{\beta_{\kappa d}}{2}$.

The amplitude of force pulsations equals sin ε. Certainly, the level of the force (DC component in (1) and (2)) will decrease from 1 to cos ε.

The mathematical studies have shown that such pulsations can be avoided by creating a certain asymmetry in phase currents (changing an angle of switching) that for unit amplitude are as follows

$$i_A = \sin(\gamma - \varepsilon), \quad i_B = \cos(\gamma + \varepsilon).$$

Then the relative value of the two-phase LM force in the position function γ for a certain ε is

$$F''_{AB} = \sin(\gamma+\varepsilon)\cdot\sin(\gamma-\varepsilon)+\cos(\gamma-\varepsilon)\cdot\cos(\gamma+\varepsilon) = \\ = \cos 2\varepsilon = \text{const},$$

and is devoid of the pulsations regardless of the position of the slider.

Thus, the increase in the coil width, on the one hand, leads to the increase in the flux linkage and, therefore, the force, however, not linearly, because of the decrease in the distribution coefficient K_p of the coil turns (for the basic variant $\beta = \frac{\tau}{2} = 90$ electrical degrees – equals $K_{pb} = \frac{\sin \tau/4}{\frac{\tau}{4}\cdot\frac{\pi}{180}} = 0.9$). In addition, force ripple compensation by changing an angle of phase commutation also reduces an average level of the force, as shown in Fig. 3.

The relative value of the force provided electromagnetic loads are invariable taking into account the change of the distribution coefficient in the function ε

$$F^*_{AB} = \left(1+\frac{2\varepsilon}{\tau/2}\right)\cdot K'_p\cdot\cos 2\varepsilon = \\ = \left(1+\frac{\varepsilon}{45}\right)^2\cdot(\cos\varepsilon-\sin\varepsilon),$$

where $K'_p = \frac{K_p}{K_{pb}} = \frac{\cos\varepsilon+\sin\varepsilon}{1+\frac{\varepsilon}{45}}$ is converted to the base value of the distribution coefficient.

The analysis of this function indicates the existence of an extremum at a certain value of $\varepsilon = \frac{\arcsin 1/3}{2} = 9.74$ electrical degrees.

Thus, the increase in the coil width is justified only to a certain value of $\beta_{\kappa d\,\max} = 19.47$, electrical degrees, since its further increase causes a sharp fall in the distribution coefficient. In this case, the force increases by 8.87% provided electromagnetic loads are invariable.

Fig. 4 shows experimentally determined flux linkages Ψ_A, Ψ_B for a linear motor of ЛД/СЗТ-45-2 type, phase shifted currents i_A, i_B with an additional third harmonic introduced, and the total force of the modified engine in the relative units F_{AB}, that is 9% greater than the force of the baseline variant. For comparison, here are the LM force F''_{AB} to supply a symmetrical current that varies according to the harmonic law. The currents and force are computer simulated.

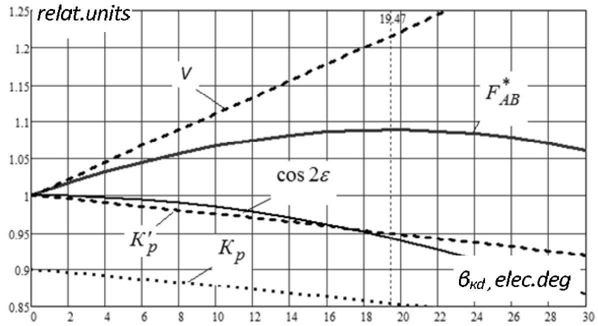

Fig. 3. Dependence of motor parameters on extra width of the coil $\beta_{\kappa d}$ *:*
V is the volume of copper in the coil; K_p *is the absolute value of the distribution coefficient of coil turns;* K'_p *is PU (per unit)* $K_{pb} = 0{,}9$ *value of the distribution coefficient;* F^*_{AB} *denotes the relative value of the force ;* cos 2ε *represents the relative value of the force loss due to changes in the phase switching angle.*

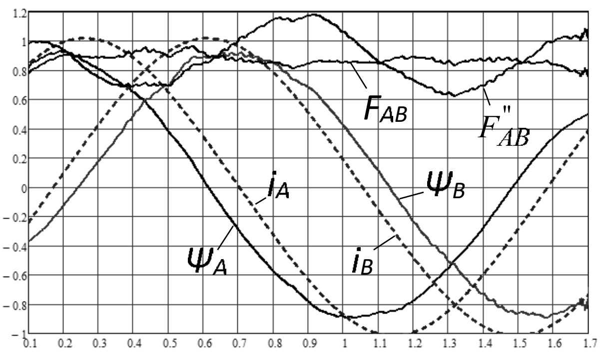

Fig. 4. Flux linkages, phase currents and summary linear motor force.

This confirms the above given research into the possibility of improving a two-phase linear motor with one-coil phases by widening its coils.

4. Conclusions

The performed mathematical analyses allow us to state that:

- the impact of the third (or any other) field harmonic on initial force of a linear motor can be completely eliminated by introducing a corresponding harmonic opposite in sign to the phase control current;
- a simultaneous introduction of several higher harmonics to gate currents of a linear motor can significantly reduce force ripple caused by the related field harmonics;
- within given dimensions of a two-phase linear motor, it is possible to increase the force at a given electromagnetic load by widening the coils by the angle $\beta_{\kappa d}$;
- force ripples arising from the asymmetry of phase linkages can be compensated by changing an angle

of phases commutation opposite to the phase asymmetry of flux linkages;

− it is possible by changing the law of control of linear motor to simultaneously compensate ripples generated both by higher field harmonics and by phase asymmetry of flux linkages.

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ЗМЕНШЕННЯ ПУЛЬСАЦІЙ ЗУСИЛЛЯ ЛІНІЙНОГО ДВИГУНА

Богдан Харчишин, Михайло Хай, Володимир Мороз

Досліджено вплив вищих гармонік поля постійних магнітів та несиметрії потокозчеплень за фазовим зсувом на величину пульсації зусилля лінійного двигуна. Вирішення цієї проблеми грунтується на аналізі вищих гармонік магнітного поля в активній зоні двофазного лінійного двигуна з постійними магнітами. Встановлено закони зміни струмів керування від положення повзуна, що дає змогу компенсувати ці пульсації.

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