Effective energy in the volume of an electromagnetic motor with a given configuration of the magnetic circuit

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Abstract. The paper discusses the problem of generation of maximum energy in the volume of a linear electromagnetic motor with a given configuration of its magnetic circuit. It presents the relation between the energy generated in the motor volume and the linear motor dimensions, maximum induction in the operating air gap, constructive factor and the magnetic field forcing degree during the movement of the core. It is shown that the maximum energy in the motor volume significantly depends on the magnetic field induction and the magnetic field forcing degree. The example of calculation of the maximum energy in the volume of the electromagnetic motor with the moving core is considered for different degrees of the magnetic field forcing.

1. Introduction

The Drives often cause direct motion with linear electromagnetic motors [1–5]. Electromagnetic motors are preferable than other ones because of the simple construction, absence of intermediate gears, variety of thrust characteristics and other advantages. They are especially suitable for linear drives of impulse and impact machines and mechanisms [6–10].

Effectiveness of the application of the electromagnetic motor in impact machines drives means getting the maximum energy limited by the motor volume. The problem of obtaining maximum energy in the volume of a linear electromagnetic motor is studied in [11, 12]. For example, the author in [13] recommends finding the maximal energy in the motor volume from the expression:

\[ A_{em} = 8.2 \cdot 10^{-9} k_0 V_{em}^{4/3}, \]

where \( V_{em} \) is the electromagnetic motor volume, \( k_0 \) is the constructive factor depending on used construction materials properties. The energy \( A_{em} = 260 \text{ J} \) is obtained in the volume \( V_{em} = 1 \text{ m}^3 \) for the continuous duty of the motor.

Maximum energy values calculated by existing methods can be several times different. Unfortunately, the known design methods incompletely take into account the magnetic circuit configuration and the type of the electromagnetic motor [14–15].

The general principles of determination of conditions when it is possible to find maximum values of the useful energy concentrated in the motor volume are derived in the present paper for a given magnetic circuit configuration and motor type.
2. Analysis of the useful energy in the electromagnetic motor volume

It is assumed that the main part of the useful energy is concentrated in the volume of the operating air gap bounded by the coil length $L_c$ as it is shown in Figure 1. In contrast to previous investigations, the energy in the gaps limited by the pole length $h_p$ is accepted to be zero.

With respect to the uniform distribution of magnetic flux in the magnetic core the maximum volume $V_{\delta_{\text{max}}}$ of the operating air gap $\delta_{\text{max}}$ can be expressed through the total volume $V_{\text{em}}$ of the electromagnetic motor. It is supposed that the working travel of the moving core is limited by the coil linear dimensions $\delta_{\text{max}} = L_c$ (Figure 1).

![Figure 1. Linear electromagnetic motor](image)

The pole length $h_p$ is coupled with the diameter $d$ by the simple ratio:

$$h_p = \frac{d}{4}.\quad (1)$$

With respect to (1) the electromagnetic motor length $L$ and coil length $L_c$ are associated by the formula:

$$L = L_c + 2h_p.\quad (2)$$

With respect to (1) and (2) the maximum volume occupied by the operating air gap is expressed in terms of the electromagnetic motor volume as:

$$V_{\delta_{\text{max}}} = V_{\text{em}} \left(1 - \frac{d}{L} \frac{2d^2}{D^2}\right),\quad (3)$$

where $D$ is the external diameter of the electromagnetic motor.

Then the relative values $x = \frac{d}{D}$, $y = \frac{L}{D}$ are substituted into (3):

$$V_{\delta_{\text{max}}} = V_{\text{em}} \left(1 - \frac{x - 4x^2y}{2y}\right).\quad (4)$$

It is assumed that the induction $B$ in the operating air gap depends on the position of the moving core and the magnetic field forcing degree:
\[ B = B_{\text{max}} \left( \frac{\delta}{\delta_{\text{max}}} \right)^n, \]  

(5)

where \( B_{\text{max}} \) is the maximum induction in the operating air gap (\( B = 1.2\ldots2.0 \) T), \( n \) is the factor of the magnetic field forcing degree (\( 0 \leq n < 2 \)).

With respect to (4), (5) the energy-volume relation obtained in [11] has the form:

\[ A_{\text{em}} = V_{\text{em}} \left( 1 - \frac{x - 4x^2 y}{2y} \right) \frac{B_{\text{max}}^2}{2 \mu_0} \frac{(1 - k)^{2n+1}}{2n + 1}, \]  

(6)

where \( \mu_0 = 4\pi 10^{-7} \) H/m is the air magnetic permeability, \( k \) is the factor of core drawing into the coil.

It follows from (6) that the energy in the electromagnetic motor volume noticeably depends on the factor of drawing of the core into the coil. The core drawing level depends on the optimal size of the operating air gap, magnetic circuit configuration and electromagnetic motor type. According to figure 1 the initial core drawing into the coil is \( \delta_{\text{max}} k \).

The relation describes the drawing factor of the core and the operating air gap value:

\[ k = 1 - \frac{\delta}{L_c}. \]  

(7)

If \( L_c = \delta_{\text{max}} \) then, according to (7), \( k = 1 - \frac{\delta}{\delta_{\text{max}}} \).

The magnetic circuit configuration is mostly described by the constructive factor [14-15]:

\[ CF = \sqrt{\frac{F_{\text{em}}}{\delta_{\text{opt}}}}, \]  

(8)

where \( F_{\text{em}} = \frac{B^2 S_{\text{core}}}{2 \mu_0} \) is the electromagnetic force acting on the moving core, \( \delta_{\text{opt}} \) is the optimal size of the operating air gap, \( S_{\text{core}} = \frac{\pi d^2}{4} \) is the core cross-section.

According to (8) the optimal operating air gap is coupled with the constructive factor by the relation:

\[ \delta_{\text{opt}} = d \sqrt{\frac{B_{\text{opt}}^2 \mu_0}{CF^2 8 \mu_0}}, \]  

(9)

where \( B_{\text{opt}} \) is the optimal induction value corresponding to the minimum loss of the magnetizing force.

Recommended values of the induction are in the range \( B_{\text{opt}} = 0.7\ldots1.1 \) T [13]. The constructive factor depending on the magnetic circuit configuration and the motor type should be in the range \( CF = (0.012\ldots626) \cdot 10^3 \) N/m [14].

Substitution of (9) to (7) gives the expression of the drawing factor:

\[ k = 1 - \frac{d}{L_c} \sqrt{\frac{B_{\text{opt}}^2 \mu_0}{CF^2 8 \mu_0}}. \]  

(10)

Then (10) is reduced to the relative values:

\[ k = 1 - \frac{2x}{2y - x} \sqrt{\frac{B_{\text{opt}}^2 \mu_0}{CF^2 8 \mu_0}}. \]  

(11)

It follows from the comparison of (11) with (6) that the relative value of the initial operating air gap for the given form of the magnetic circuit is found from the relation:
\[1 - k = \frac{2x}{2y-x} \sqrt{\frac{B_{opt}^2 \pi}{CF^2 \mu_0}}. \tag{12}\]

Substitution of (12) into (6) gives the final expression for the energy in the given volume of the electromagnetic motor:

\[A_{em} = V_{em} \left(1 - \frac{x - 4x^2y}{2y} \right) \frac{B_{max}^2}{2\mu_0} \left(1 - k\right)^{2n+1} \left(\frac{2x}{2y-x} \sqrt{\frac{B_{opt}^2 \pi}{CF^2 \mu_0}}\right)^{2n+1}. \tag{13}\]

3. Results and Discussion

Substitution of \(CF = 219 \text{ N}^{0.5}/\text{m}, \ x = 0.4, \ y = 1.4, \ B_{opt} = 1.0 \text{ T}\) into (13) for the linear electromagnetic motor (Figure 1) gives:

\[A_{em} = V_{em} 374.12 \cdot 10^3 B_{max}^2 \frac{0.85^{2n+1}}{2n+1}. \tag{14}\]

If \(B_{max} = 1.2 \text{ T}\) and the induction linearly changes when the core moves in the magnetic field \((n = 1.0)\), the energy in the given volume of the electromagnetic motor is:

\[A_{em} = 110.28 \cdot 10^3 V_{em}. \tag{15}\]

Hence, if the electromagnetic motor has the volume \(V_{em} = 1 \text{ m}^3\) and the induction in the operating air gap changes linearly, the useful energy concentrated in this volume is \(A_{em} = 110.28 \cdot 10^3 \text{ J}\). It is simply to show that the specific energy in the volume of the linear electromagnetic motor (Figure 1) is \(a_{em} = 14.1 \text{ J/kg}\).

Figure 2 contains the curves family \(A_{em} = f \left(V_{em}, n\right)\) of the motor found from (14) for \(B_{max} = 1.2 \text{ T}\) and different forcing degrees \((n = 0...2.0)\). If \(n = 0\) then the magnetic field force is maximum.

\[A_{em} \cdot 10^3 \text{ J}\]

\[\begin{array}{c|c|c|c|c|c|c}
 \hline
 n & 0 & 0.1 & 0.4 & 0.5 & 1.0 & 2.0 \\
 \hline
 V_{em}, \text{ m}^3 & 500 & 300 & 200 & 100 & 0 & 0 \\
 \hline
\end{array}\]

**Figure 2.** Curves family \(A_{em} = f \left(V_{em}, n\right)\)

The analysis of the curves family in Figure 2 shows that the maximum energy in the electromagnetic motor volume noticeably depends on the magnetic field forcing degree. More energy levels can be achieved if a time constant of the coil circuit is significantly less than the time of the core
motion caused by the magnetic field generated by the coil.

4. Conclusion
The general expressions for the determination of the maximum energy concentrated in the electromagnetic motor volume with a given configuration of the magnetic circuit and motor construction type have been obtained. The useful energy dependence on the motor linear dimensions ratio, maximum induction in the operating air gap, constructive factor and the magnetic field forcing degree during the motion of the core has been studied. It has been shown that the maximum energy in the motor volume noticeably depends on the magnetic field induction and the magnetic field forcing degree. The example of calculation of the maximum energy concentrated in the linear electromagnetic motor volume for different magnetic field forcing degrees has been considered.

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