Numerical simulation of the efficiency of magnetic energy conversion in linear electromagnetic converters

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Abstract. Based on the representation of the magnetic field as an energy exchange medium, numerical simulation of the efficiency of magnetic energy conversion in linear electromagnetic converters is proposed. The dependence of the energy efficiency conversion in the magnetic field of the linear electromagnetic converters on the charge voltage of the capacitor feeding the motor, the capacitance of the capacitor, the active resistance of the magnetic field excitation winding, the moving mass and the counteracting force applied to the mass is analyzed. The results of the numerical simulation made it possible to reveal the features of the influence of the design and operating parameters of a linear electromagnetic converter on the energy conversion efficiency. The simulation model is verified with the dependence of the converter efficiency on the operating and design parameters. The ratios of these parameters are established. The research results are useful for a wide range of scientists engaged in improving the energy efficiency of reciprocating linear electromagnetic converters.

1. Introduction

The magnetic field, as one of the types of matter, should be considered as an energy exchange medium in which electrical energy is converted into the energy of mechanical motion of the moving element of the converter [1–5]. A clear example of the use of a magnetic field is a linear electromagnetic converter (LEC), where the ponderomotive force driving the moving element is determined by the proportional dependence of the magnetic energy change during movement [6–13]. At the same time, the features of the energy at the input and output of the magnetic subsystem of the converter significantly influence on the power and dynamic characteristics of the LEC [14–19]. In this paper, the numeric simulation shows the utilization efficiency of the magnetic field energy in electromagnetic converters. The features of the design and operating parameters of the LEC are established for the LEC model verification by the numeric simulation.
2. Energy conversion description for numeric simulation

The characteristic of the magnetic field as the energy exchange medium should be determined from
the analysis of the generalized force acting on the boundary of the energy exchange medium. The
boundary of the energy exchange medium is the design element, where a generalized force that
characterizes the process of energy transfer is registered:

\[ F = M \frac{d^2 X}{dt^2}, \]  

(1)

where \( M \) is the constructive coefficient (inertia coefficient), which determines the ratio between the
generalized force \( F \) and the acceleration of the generalized coordinate \( X \), so that the power of energy
conversion through the considered boundary of the energy exchange medium is determined according
to the expression:

\[ P = F \frac{dX}{dt}. \]  

(2)

From (1), the speed is defined as:

\[ \frac{dX}{dt} = \frac{t_2}{t_1} \frac{F}{M}, \]  

(3)

where \( t_1, t_2 \) are the time points, respectively, of the beginning and end of the energy conversion
process through the energy exchange medium. Substituting (3) into (2) gives the expression of the
power of energy conversion across the boundary of the energy exchange medium:

\[ P = F \frac{t_2}{t_1} \frac{F}{M}. \]  

(4)

Based on the expression (4), the energy \( W \) passing through the boundary of the energy exchange
medium during the conversion is defined as:

\[ W = \left( \int_{t_1}^{t_2} \frac{F_1}{M_1} \right) dt = \left( \int_{t_1}^{t_2} \frac{F_2}{M_2} \right) dt = \text{const}, \]  

(5)

where \( F_1, M_1 \) are the force and the coefficient of inertia, respectively, of the energy exchange medium
from which the energy flow is transmitted; \( F_2, M_2 \) are the force and the coefficient of inertia,
respectively, of the energy exchange medium into which the energy flow is transmitted; \( t_1, t_2 \) are the
time points of the beginning and completion, respectively, of the energy transfer process through the
energy exchange medium; \( t_{11}, t_{12} \) are the time points of the beginning and completion, respectively, of
the energy release in the "primary" energy exchange medium, that is, the one from which the power
transfer occurs; \( t_{21}, t_{22} \) are the time points of the beginning and end, respectively, of the energy
accumulation in the "secondary" energy exchange environment, that is, the one into which the power
is transferred.

Equation (5) generally describes the calculation of the energy values observed in interacting energy
exchange media. The equality signs in (5) express the law of conservation of energy. Depending on
the relationship between the moments of time \( t_{11}, t_{12}, t_{21}, t_{22} \) different modes of energy exchange can
be observed:

a) linear energy exchange media, without energy accumulation, will be characterized by the
following relations:

\[ t_{11} = t_{12}; t_{21} = t_{22}, \]  

(6)

from which it follows that, in the process of power conversion, the changes in both interacting media
are equal, that is, the ratio is fulfilled:
\[ \int_{t_1}^{t_2} \frac{F_1}{M_1} dt = \int_{t_1}^{t_2} \frac{F_2}{M_2} dt, \quad (7) \]

according to which, in turn, there is a proportional change in the integrable parameters:

\[ \frac{F_1}{M_1} = \frac{F_2}{M_2}, \quad (8) \]

what is observed, for example, during the operation of the lever; The following relations:

\[ F_1 = F_2; \quad M_1 = M_2, \quad (9) \]

are observed, either when the arm lengths of the lever are equal, or when energy is transferred by means of an absolutely rigid mechanical connection;

b) nonlinear energy exchange environments in which energy accumulation is observed during its transmission will be characterized by the following relations:

\[ \Delta t_1 = t_{21} - t_1 > t_{22} - t_2 = \Delta t_2, \quad (10) \]

- for systems with preliminary energy storage, in which the interaction energy is accumulated in the primary energy exchange environment for a period of time \( \Delta t_1 \) greater than the period of time \( \Delta t_2 \) during which the energy flows into the secondary energy exchange environment;

\[ \Delta t_2 = t_{21} - t_1 < t_{22} - t_2 = \Delta t_2, \quad (11) \]

- similarly, for systems with subsequent energy storage (recovery).

The possibility of reversible energy conversion, according to expression (5), is determined by the possibility of swapping the "primary" and "secondary" energy exchange environments, and depends on the physical and structural limitations of the boundary between the energy exchange environments.

In electric machines and apparatuses, the energy exchange medium is a magnetic field. For the LEC powered by a capacitive storage device, the expression (5) can be written as:

\[ W_{out} = \int_{t_1^L}^{t_2^L} \left( i_{out} \int_{t_1}^{t_2} \frac{d\psi_{out}}{L} dt - \frac{1}{L} \int_{t_1}^{t_2} \frac{d\psi_{out}}{L} dt \right) dt = \int_{t_1^L}^{t_2^L} \left( F_{x} \int_{t_1}^{t_2} \frac{F_{x}}{m} dt \right) dt + \frac{F_{x}}{m} dx = \text{const}, \quad (12) \]

where \( W_{out} \) is the amount of energy converted into mechanical form (the amount of useful energy); \( i_{out} \) is the electric current flowing in the LEC magnetic field excitation winding; \( C \) is the capacity of the supply capacitor; \( \psi_{out} \) is the flow coupling of the LEC magnetic field excitation winding; \( L \) is the self-inductance of the LEC winding; \( m \) is the mass of the moving parts of the LEC; \( x \) is the spatial displacement of the LEC from the initial location \( x_0 \) to the final one \( x_0 \); \( F_{x} \) is the total mechanical force, equal to the geometric sum of the electromagnetic force \( F_{el.m} \) and the forces of resistance to movement \( F_{res} \):

\[ F_{x} = F_{el.m} - F_{res}. \quad (13) \]

Given that in addition to the useful energy in the process of energy conversion, there will be energy losses, as well as residual energy in the magnetic form and useful mechanical energy performed (energy losses for hysteresis and eddy currents are neglected), the expression (12) should be supplemented:

\[ W_{m} = \int_{t_1}^{t_2} \left( i_{out} + i_{b} \right) \frac{i_{out} + i_{b}}{C} dt + R \int_{t_1}^{t_2} \left( i_{out} + i_{b} \right)^2 dt = \]

\[ = \int_{t_1}^{t_2} \left( \frac{d\psi_{out}}{dt} + \frac{d\psi_{b}}{dt} \right)^2 \left( \frac{1}{L} \frac{d\psi_{out}}{dt} + \frac{d\psi_{b}}{dt} \right) dt = \int_{t_1}^{t_2} \left( F_{x} \int_{t_1}^{t_2} \frac{F_{x}}{m} dt \right) dt + \frac{F_{x}}{m} dx = \text{const}, \quad (14) \]

where \( i_{b} \) is the component of the electric current of the capacitor discharge that forms the residual energy in the magnetic field of the LEC at the end of the energy conversion process:
\[
W_{\text{mag},b} = \frac{L_i^2}{2}; \quad (15)
\]

\[
\frac{d\varphi}{dt} \text{ is the component of the derivative of the flow coupling, which forms the residual value of the magnetic energy at the time of completion of the energy conversion process:}
\]

\[
W_{\text{mag},b} = \int_{t_1}^{t_2} \frac{1}{L} \left( \frac{d\varphi_{\text{out}}}{dt} + \frac{d\varphi}{dt} \right) dt.
\]

Expressing mechanical power in terms of the product of current and mechanical counter-EMF \[ \frac{d\varphi_{\text{mex}}}{dt} \]

\[ [20, 21]: \]

\[
F_k \int_{t_1}^{t_2} \frac{F_k}{m} dt = \left( i_{\text{out}} + i_b \right) \frac{d\varphi_{\text{mex}}}{dt}, \quad (17)
\]

let's determine the current value from this expression \[ i_b \]:

\[
i_b = \frac{F_k}{m} \frac{d\varphi_{\text{mex}}}{dt} - i_{\text{out}}; \quad (18)
\]

Substituting (18) into (15), we obtain the expression of the residual magnetic energy in terms of the operating parameters of the mechanical subsystem of the converter:

\[
W_{\text{mag},b} = L \left( \frac{F_k}{m} \int_{t_1}^{t_2} \frac{F_k}{m} dt \right)^2 - i_{\text{out}}; \quad (19)
\]

Based on the expressions (15), (18) and (19), we can write an equation describing the energy exchange medium (magnetic energy) as an energy storage device:

\[
W_{\text{mag},b} = \frac{L_i^2}{2} \int_{t_1}^{t_2} \frac{1}{L} \left( \frac{d\varphi_{\text{out}}}{dt} + \frac{d\varphi}{dt} \right) dt = \left( \frac{F_k}{m} \int_{t_1}^{t_2} \frac{F_k}{m} dt \right)^2 - i_{\text{out}}; \quad (20)
\]

The efficiency of the energy exchange medium should be evaluated based on the following expression of the efficiency of the energy exchange medium:

\[
\eta_s = \left( 1 - \frac{W_{\text{mag},b}}{W_{\text{mex}}} \right) \left( 1 - \frac{W_Q}{W_{\text{mex}}} \right) \frac{W_{\text{out}}}{W_{\text{in}}}, \quad (21)
\]

where \[ W_Q \] is the value of the loss energy observed during the energy conversion through the energy exchange medium. Under the accepted assumptions, energy losses are observed in the active resistance of the field windings of the LEC:

\[
W_Q = R \int_{t_1}^{t_2} \left( i_{\text{out}} + i_b \right)^2 dt; \quad (22)
\]
The coefficient $\eta_s$ is equal to one in the absence of energy losses and the absence of residual magnetic energy accumulated in the energy exchange medium (magnetic energy), to the end of the energy conversion process. The coefficient $\eta_s$ is zero when the output energy ($W_{\text{out}} = 0$) is zero.

Figure 1 shows the dependence of the efficiency of the energy exchange medium on the following values: the counteracting force (determined by the stiffness of the return spring); the active resistance of the magnetic field excitation winding of the LEC; the electric capacity of the capacitor feeding the LEC and its primary charge voltage; the mass of the movable parts. All calculations were performed using numerical simulation in MATLAB Simulink [22–24].

![Figure 1. Results of the numeric simulation of the magnetic energy conversion](image)

The dependences are built for the LEC parameters taken from [21].

3. Conclusion

The numeric simulation results show the efficiency of the magnetic energy conversion in LEC.

The LEC model verification helps to get the optimal ratio of the considered parameters which is determined by the equality of the internal resistances of the capacitive and the magnetic energy storage medium.

The representation of the magnetic field as the energy exchange medium gives possibility to determine the features of the energy conversion mode and obtain the maximum LEC efficiency.

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