Numerical simulation of the energy conversion processes in an electromagnetic motor with preliminary accumulation of magnetic energy

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Abstract. The paper discusses the solution of the urgent problem of increasing the specific energy intensity indicators of electromagnetic motors using numerical simulation methods. The object of research is a linear electromagnetic motor powered from a DC voltage source. The purpose of the research is to numerically simulate energy conversion processes in a linear electromagnetic motor with preliminary accumulation of magnetic energy in an induction coil. The theoretical substantiation of energy conversion processes for a new method of controlling an electromagnetic motor based on the implementation of the energy balance is proved. It is shown that the accumulation time of magnetic energy should not exceed five time constants of the induction coil supply circuit.

1. Introduction
One of the main disadvantages of equipment based on linear electromagnetic motors is its lower energy intensity indicators in comparison with pneumatic and hydraulic impact machines [1-5].

The value of the specific impact energy for most electromagnetic machines does not exceed 5 J/kg [6].

One of the effective ways for increasing the specific impact energy is the method of accumulating magnetic energy in the induction coil of an electromagnetic motor at the stage of movement [7].

The implementation of the methods of accumulating magnetic energy in inductances is ensured by holding the movable striker of the electromagnetic motor by the opposing force at the moment of the start of movement.

In the known control methods, the striker working mode is performed when voltage is applied to the induction coil of the electromagnetic motor. The striker is returned to its original position under the action of the mechanical forces of the return spring when the induction coil is de-energized [8-10].

For the known control method the movement of the striker begins at the minimum induction coil current and the minimum initial value of magnetic energy. The time of movement of the striker can be several times longer than the time of its starting.

The disadvantages of this method of controlling the operation of the electromagnetic motor include the low value of the impact energy and the efficiency of the motor. This is due to the fact that the movement of the striker is performed at a low average current value. This does not allow the striker to accelerate until high speed by the electromagnetic forces of the induction coil at the end of
the movement. This control method is characterized by low energy values at the end of the movement.

To eliminate the disadvantages of the known control method, another control method is proposed that simultaneously admits of increasing the final speed of the striker and the impact energy up to 4 times and the efficiency up to 2 times.

The practical implementation of the control method includes holding the striker of the electromagnetic motor by external forces at the initial stage of movement. The control method is in the fact when voltage is applied to the motor induction coil, the striker is held by external forces until the end of the transient process caused by an increase of the current in the inductance. When the current in the induction coil is close to the certain value, the striker is released and moves rapidly. At the end of the movement of the striker, the induction coil is disconnected, and the striker, under the action of the mechanical forces of the spring, returns to its initial position. When the voltage pulse is reapplied, the operating cycle of the electromagnetic motor with the striker holding is repeated.

The aim of the research is to analyze the processes of the electromechanical energy conversion in a linear electromagnetic motor with the holding striker.

2. Materials and Methods

The process of energy conversion with the accumulation of magnetic energy in the inductance coil of the electromagnetic motor is carried out in two stages.

The first stage is the preparation stage. The stage of energy conversion is characterized by the conversion of the electrical energy of the source with a motionless striker into the energy of the magnetic field of the induction coil and into the heat loss energy in the active resistance of the induction coil. The duration of the stage is determined by the duration of the transient process associated with the increase of the coil current during the transient process to a steady-state value. At the first stage, the striker of the electromagnetic motor is held by external forces and is at rest. Useful mechanical work is not performed at this stage; the striker does not receive acceleration. The electromagnetic force acting on the striker increases as the current in the induction coil increases. The mechanical system maintains its balance due to the external opposing force applied to the striker, which exceeds the electromagnetic force of the induction coil. In this mode of operation, the electromagnetic motor converts the electrical energy of the source into magnetic energy, which is stored in the induction coil. At this stage, the balance of elementary energies can be represented as

\[ dW_s = dQ + dW_m, \]

where \( dW_s \) is the elementary energy coming from the source; \( dW_m \) is the elementary magnetic energy stored in the inductance of the induction coil; \( dQ \) is the elementary heat loss energy in the active resistance of the induction coil.

The energy balance of the system in the state of accumulation of the magnetic energy can be represented as

\[ \int_{\psi_1}^{\psi_2} (U - i^2r)dt = \int_{\psi_1}^{\psi_2} id\psi, \]

where \( U \) is the constant voltage source; \( i \) is the induction coil current; \( \psi_1, \psi_2 \) are the initial and final flux linkage of the induction coil; \( r \) is the active resistance of the induction coil.

The electrical energy coming from the source is spent only on changing of the magnetic field energy and the heat loss energy in the induction coil.

The energy consumed from the power source during the starting time can be represented as

\[ W_s = \int_0^t Ud\tau = \int_0^t \frac{U^2}{r} \left(1 - e^{-\frac{\tau}{r}}\right)d\tau, \]
where \( L \) is the inductance of the induction coil with a fixed striker.

The heat loss energy during the transient process when the striker is held by external forces

\[
Q = \int_0^{t_f} i^2 r dt = \int_0^{t_f} \left( \frac{U^2}{r} \left(1 - e^{-\frac{t}{\tau}}\right)^2 \right) dt.
\]  

(4)

Taking into account the expressions for the energy (3), (4) and the equation of the balance of elementary energies (1), the energy accumulated in the magnetic field of the induction coil when the striker is held by external forces

\[
W_m = \int_0^{t_f} U idt - \int_0^{t_f} i^2 r dt.
\]  

(5)

According to expression (5), the magnetic energy stored in the induction coil is determined by the energy consumed from the power source minus the heat loss energy.

In order to evaluate the process of converting the electrical energy of the source into the magnetic energy and the heat loss energy, the following expressions are used to determine the relative magnetic energy and the relative heat loss energy:

\[
\frac{W_m}{W_s} = \frac{\int_0^{t_f} U idt - \int_0^{t_f} i^2 r dt}{\int_0^{t_f} U idt};
\]  

(6)

\[
\frac{Q}{W_s} = \frac{\int_0^{t_f} i^2 r dt}{\int_0^{t_f} U idt}.
\]  

(7)

Figure 1 shows the calculated dependences of the energy at the start-off stage for a motionless striker, constructed in accordance with expressions (3)–(5) over the time interval of the coil time constant. The induction coil time constant is defined as the ratio of the inductance to the active resistance of the induction coil \( \tau = \frac{L}{r} \). The energy calculation for the starting process is carried out for the following induction coil parameters: \( L = 0.1 \, H \), \( r = 5.0 \, Om \), \( U = 220 \, V \).

Figure 2 shows the dependences of change of the relative magnetic energy accumulated in the inductance during the transient process according to the expression (6) and the relative energy loss calculated according to the expression (7).

The beginning of the second stage of energy conversion coincides with the moment of the striker separation and accelerated movement under the influence of the electromagnetic forces of the induction coil.

In this case, useful mechanical work is realized in the form of impact pulse energy at the end of the striker movement:

\[
dW_s - dQ = dW_{em} + dA_{mech},
\]

where \( dA_{mech} \) is the elementary work for accelerating the striker by the electromagnetic forces of the induction coil.

The energy balance equation at the stage of movement of the striker with respect to the reserve of magnetic energy has the form:
where \( f_{en} \) is the electromagnetic force during the movement of the striker; \( v \) is the striker movement speed; \( \Delta W_m(x,i) \) is the increment of the energy of the magnetic field during the movement of the striker.

The component \( \int_{t_2}^{t_1} f_{en} v dt = A_{mech} \) reflects the work of the electromagnetic forces of the induction coil due to the striker movement.

\[ \int_{t_2}^{t_1} (U_i - i^2 r) dt = \int_{t_2}^{t_1} f_{en} v dt + \Delta W_m(x,i), \quad (8) \]

3. Results and Discussion
Formally, the energy balance equation (8) during the movement of the striker does not have external differences from the balance equation when the mode of the striker holding by external forces is absent. Only the intensity of the energy conversion process increases owing to the increase of current at the moment of movement. Moreover, the value of the average current of the induction coil during the movement and the magnitude of the electromagnetic force increases significantly. The energy conversion process can also take place with a decrease in magnetic energy at the end of the striker movement. In the case of a decrease of the magnetic energy in the induction coil, the useful work in the time interval \( t_2 \ldots t_3 \) is performed due to the energy from the source and the stored magnetic energy of the induction coil.

If the energy source is turned off before the end of the striker movement, the energy balance takes the form

\[ \int_{t_2}^{t_1} (U_i - i^2 r) dt + \Delta W_m(x,t) = \int_{t_2}^{t_1} f_{en} v dt. \quad (9) \]

According to the energy balance (9), the total energy from the source, minus the heat loss energy, is spent on performing useful mechanical work to move the striker.

The results obtained are confirmed by the results of numerical simulation of the electromagnetic motor with a preliminary accumulation of magnetic energy. The simulation model of the electromagnetic motor in Matlab Simulink [11, 12] is shown in Figure 3.
With respect to the final speed of the striker and the dependences presented in the Figures 4 and 5, it is possible to estimate the increase of energy during the preliminary accumulation of magnetic energy.

![Simulation model of the electromagnetic motor](image1)

**Figure 3.** Simulation model of the electromagnetic motor

![Graphs](image2)

**Figure 4.** The change of the striker speed on time without accumulating magnetic energy

**Figure 5.** The change of the striker speed on time with accumulating magnetic energy

As it can be seen, the final speed of the striker with a preliminary accumulation of magnetic energy is significantly higher than the final speed of the striker without accumulation of magnetic energy.

4. **Conclusion**

The possibility of increasing the impact energy of the electromagnetic motor using a preliminary accumulation of the magnetic energy has been proved by methods of numerical simulation.

On the basis of the energy balance in the electromechanical system of the electromagnetic motor, a theoretical justification of the processes arising in the mode of a preliminary accumulation of magnetic energy in the inductance of the induction coil has been proved.
From the dependencies in figure 1 and figure 2 it follows that the energy consumed from the source and the energy losses in the coil, when the starting time changes, increase. For magnetic energy, the accumulation process can be considered almost complete in a time equal to the transient process $t = 3\ldots5\,\tau$. The increasing of the striker holding time $t > 3\ldots5\,\tau$ (Figure 1) is useless, since the current does not change. The further process of energy consumption at $t > 3\ldots5\,\tau$ is associated only with the conversion of the electrical energy into the heat energy and the decrease of the efficiency of the electromagnetic motor.

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