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HIGH FORCE HEAVY DUTY DIRECT CURRENT ACTUATOR

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Key words: Linear direct current actuator, Nd-Fe-B permanent magnets, High force, High holding force, High air gap, Ferromagnetic circuit, Numerical analysis, Specially designed coils.

This paper presents the design, simulation and experimental validation of a direct current linear actuator. The proposed actuator is similar in design with an electromagnet, but it uses Nd-Fe-B permanent magnets for producing a high holding force when it is in closed position. From this point of view, the main purpose of this paper is to analyze the working principle of the actuator and to explain the advantages obtained by using a special geometry of the magnetic circuit. Such a linear actuator can be used in electrical equipment, like high voltage vacuum circuit breakers. The proposed linear actuator ensures high force during closing, which is produced by a coil specially designed for this maneuver, and also a high force when the air gap is minimum, produced by Nd-Fe-B permanent magnets. The magnetic problem was solved using FEMM package, which has a specially designed LUA script incorporated in it. Mechanical parameters were determined with MATLAB program, by implementing numerical integration.

1. INTRODUCTION

Electromagnets have a wide range of applications in many technical domains. They can be used for lifting heavy iron objects and also, for producing high forces when needed. This type of devices is widely used in electrical equipment, like contactors, relays and circuit breakers [1,2,9,14]. The main advantage of an electromagnet over a permanent magnet is that it can be controlled by changing the magnetic field produced by the coils. By changing the voltage applied on the coils, the electric current will modify. In accordance with Ampère's Circuital Law, the magnetomotive force is proportional with the electric current which flows through the coils. This way, it's possible to modify the flux density in the air gap, which will lead to a different force. However, one problem that occurs in electrical systems is represented by the possibility of energy power failure, which leads to the interruption of the force produced by the actuator and thus to the shutdown of the system in which it is integrated [13]. However, there is a solution to bypass this problem, and this refers to the use of permanent magnets in order to maintain the electromagnet in closed position. An advantage of this constructive solution is that the electromagnet does not consume energy during the period when it is closed, respectively when its air gap is minimum. Electromagnets with permanent magnets are often found in high voltage vacuum circuit breakers, because a property of this equipment is that it does not consume energy when it is closed [10,11,16].

The article is organized as follows: in Section 2 it is presented the proposed linear actuator design and how it works; in Section 3 are presented the influences of electromagnetic and geometric parameters, while computation of mechanical parameters are given in Section 4; in Section 5 is presented the experimental model and finally, a brief conclusion and future work in Section 6.

2. PROPOSED ACTUATOR DESIGN AND WORKING PRINCIPLE

The proposed electromagnetic actuator has the following main components: the magnetic circuit, the excitation coils and the permanent magnets. The excitation coils, together with the permanent magnets, have the role of producing the magnetic field for the proper working of the actuator. The excitation coils produce a magnetic field necessary to close the electromagnet and to reduce the air gap, respectively. The permanent magnets produce a magnetic field necessary to maintain the actuator in closed position. In order to open the electromagnet, the excitation coils must produce a magnetic field which has an opposed direction from the one produced by the magnets. By summing the two magnetic fields, which have an equal value, but an opposite direction, the resultant magnetic field leads to a low force developed by the actuator. Regarding this, the force is not enough to keep the device in closed position. The magnetic circuit is made of a fixed armature, on which are placed the rest of the components and the mobile armature. Its role is to guide the magnetic field produced by permanent magnets and excitation coils. The proposed actuator's design is presented in Fig. 1.

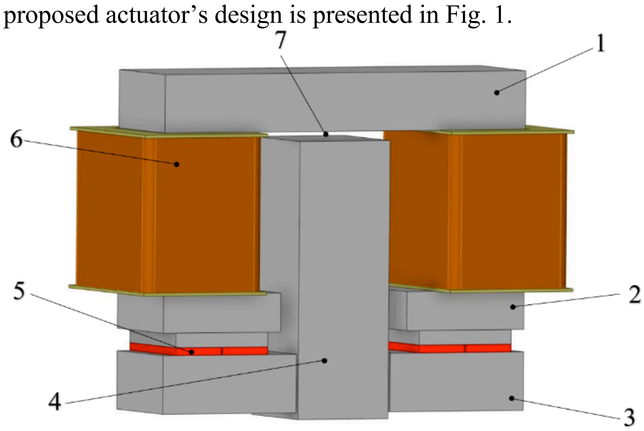

Fig. 1 – Design of the proposed actuator.

As shown in Fig. 1, the linear direct current actuator has the following main components:

1 – Upper plate magnetic core;
2 – Middle plate magnetic core;
3 – Lower plate magnetic core;
4 – Mobile magnetic core;
5 – Nd-Fe-B permanent magnets;
6 – Excitation coils;
7 – Air gap.

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The linear actuator must meet the following technical specifications, in order to perform its function, as a component in a high voltage vacuum circuit breaker:

- Minimum closing force: 6500 ± 500 N;
- Minimum holding force: 9000 ± 500 N;
- Stroke length: 60 mm;
- Minimum air gap: 0.1 mm;
- Rated coil voltage: 230 Vdc.

Preliminary calculations provide an estimative magnetomotive force for each coil of 60000 At, 60 Amps rated current intensity, and a number of 1000 of turns. Considering that the electromagnet has two coils, the total magnetomotive force is 120000 At. To determine the force produced by the actuator, the Weighted Stress Tensor is used. Every electromagnetic parameter of interest will be determined by using a finite element program.

3. NUMERICAL COMPUTATION OF THE PROPOSED LINEAR ACTUATOR

The proposed linear actuator can be analyzed using different approaches [15]. The actuator can be simulated using a 2D model. To determine the kinetic energy and the speed gained by the mobile armature, the force must be computed for every position along its path. Considering this, the numerical solution was computed using FEMM package, in which a LUA script was introduced. The problem described in the program is a planar type one, the frequency is 0 Hz and the depth is 120 mm. The actuator can be simulated using a mesh grid with a high number of elements and by doing so, the error decreases. The depth of the problem is equal with the thickness of the ferromagnetic circuit. The current in the coils is set at 60 Amps, and the number of turns for each coil is 1000. Considering this, both coils produce a magnetomotive force of 120000 At. The magnetic circuit is made of steel, and the coils are made of copper wire with a diameter of 2 mm. For the boundary of the domain, Dirichlet condition was implemented, in which the magnetic vector potential is considered to be zero. In order to verify the symmetry of the magnetic field, the entire actuator was simulated.

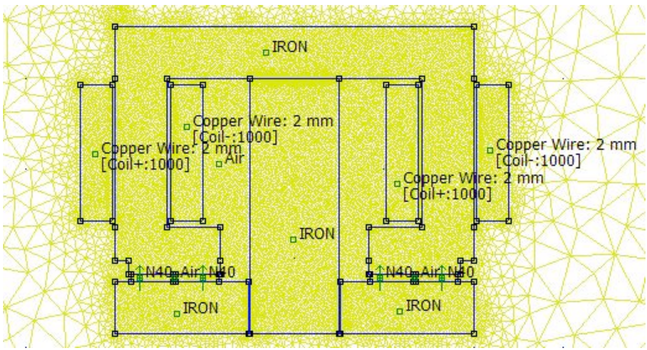

Fig. 2 – Numerical simulation of the direct current actuator.

The ferromagnetic circuit towards the air gap directs the magnetic field produced by the coils. The magnetic field flows through the path which has a minimal reluctance, and as a result, the force produced by the actuator tends to decrease the air gap. By reducing the air gap, the total reluctance decreases, and the magnetic flux increases. The maximum force obtained by the actuator corresponds with the minimum air gap, as seen in Fig. 2.

When the air gap has the highest value (60 mm, respectively), the force has a minimum value. The magnetic flux passes through the magnetic core and the air gap, as shown in Fig. 3.

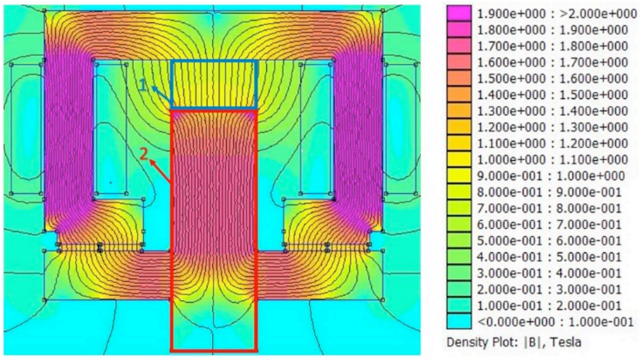

Fig. 3 – Direct current actuator in open position:
1 – maximum air gap, 2 – mobile magnetic core.

The magnetomotive force produced by the coils has a constant value for each position of the mobile core during closing operation. As the air gap becomes lower, its reluctance decreases and thus the magnetic flux increases. As a result, the force produced by the actuator increases with the distance travelled by the mobile core, as shown in Fig. 4.

When the air gap has a minimum value, the current through the coils is zero, and the magnetic flux needed to maintain the actuator in closed position is produced by the permanent magnets.

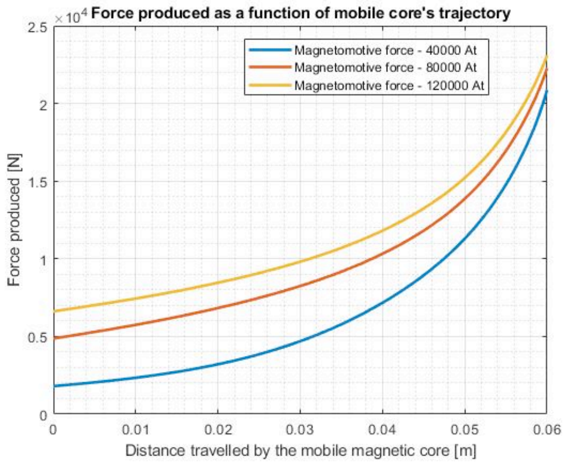

Fig. 4 – Force as a function of mobile core trajectory / travelled distance.

Higher energy density of the permanent magnets will lead to higher force produced by the actuator, as shown in Table 1.

Table 1

Computed force produced by the actuator in closed position for different permanent magnets

Permanent magnet type	Mechanical force [N]
Nd-Fe-B N35	12165
Nd-Fe-B N40	12715
Nd-Fe-B N48	13368
Nd-Fe-B N55	13789

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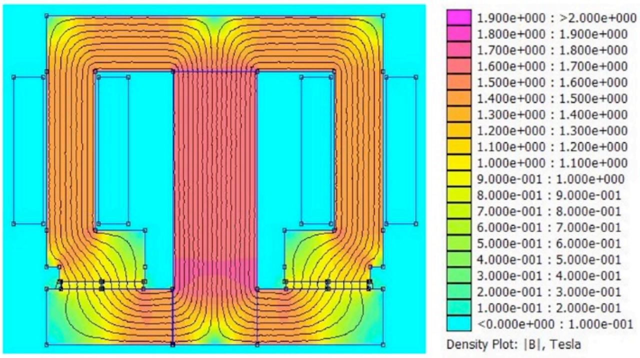

Fig. 5 – Direct current actuator in closed position.

However, the influence of the permanent magnets is important only if the distance between the mobile core and the fixed core has a low value. When there is no current through excitation coils, the force exercised by the actuator is the result of the magnetic field produced by the permanent magnets, as shown in Fig. 6.

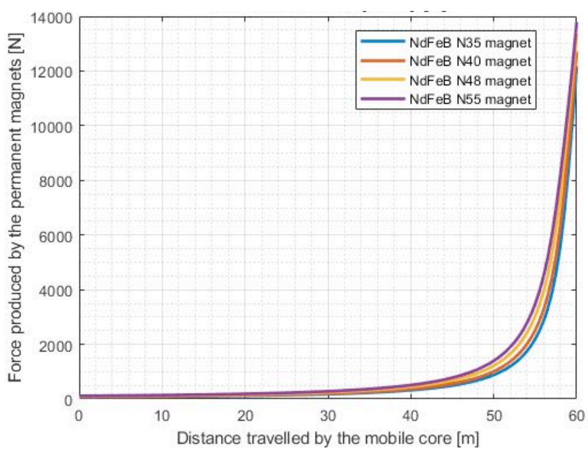

Fig. 6 – Force developed by the direct current actuator when the magnetic field is produced only by permanent magnets.

Comparing the results obtained in Fig. 4 and Fig. 6, the force produced by the permanent magnets is much lower than the force produced by the excitation coils. This leads to the fact that the most part of the magnetic field is in fact produced by the coils, and only a small portion of it is produced by the permanent magnets. However, the permanent magnets produce a force in closed position that is sufficiently high for the application in which the actuator is implemented, and the excitation of the coils is not necessary.

When the actuator opens, the magnetic field in the ferromagnetic circuit and in the air gap decreases, and thus the force produced is also decreasing. In order to do that, the excitation coils produce a magnetic field that has an opposite direction from that produced by the permanent magnets [4, 5]. In Fig. 7 is presented the force produced by the actuator in close position, computed for different values of the current that flows through the excitation coils.

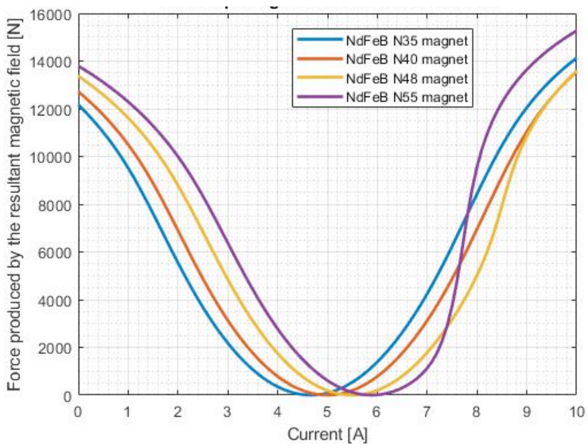

Fig. 7 – Force developed by the direct current actuator in closed position as a function of demagnetizing current for different types of permanent magnets.

For one value of the current that flows in the coils, the magnetic field produced by them is equal to that produced by the permanent magnets, but of opposite direction. Thus, the resultant magnetic field has a low value, and the force produced by the actuator is negligible. If the current exceeds a certain value, the resultant magnetic field leads to a force that can maintain the actuator in closed position. For different energy densities of the permanent magnets, the current at which the force has a minimum value is also different. A larger value of the energy density leads to a larger value of the current, in order to cancel the magnetic field produced by permanent magnets.

4. NUMERICAL COMPUTATION OF MECHANICAL PARAMETERS

In this section are presented the mechanical parameters of the direct current actuator. The most important parameters that can be computed are the acceleration and speed of the mobile magnetic core, as well as the work (or kinetic energy) produced by it [6, 8]. The mechanical parameters were computed using MATLAB, by implementing numerical integration. The first parameter that can be computed is the acceleration, which is proportional with the force produced by the actuator, as stated by Newton's Second Law:

$$\mathbf{a} = \frac{\mathbf{F}}{m} = \frac{\mathbf{F}_{elmg} - m \cdot \mathbf{g}}{m}, \qquad (1)$$

where: $\mathbf{a}$ [m/s^2] is the acceleration, $\mathbf{F}_{elmg}$ [N] is the force produced by the actuator, m [kg] is the mass of the mobile core and $\mathbf{g}$ [m/s^2] is the free fall acceleration. Preliminary calculations provide a mass of 24 kg for the mobile core, considering the fact that it is made of magnetic steel, which has a density of 7800 kg/m^3. The electromagnetic force produced by the actuator as a function of the position of the mobile magnetic core was determined earlier using FEMM package and a special LUA script [12].

As seen in Fig. 8, the acceleration of the mobile magnetic core for the closing sequence is presented, when the excitation coil produces the magnetic field necessary for this operation.

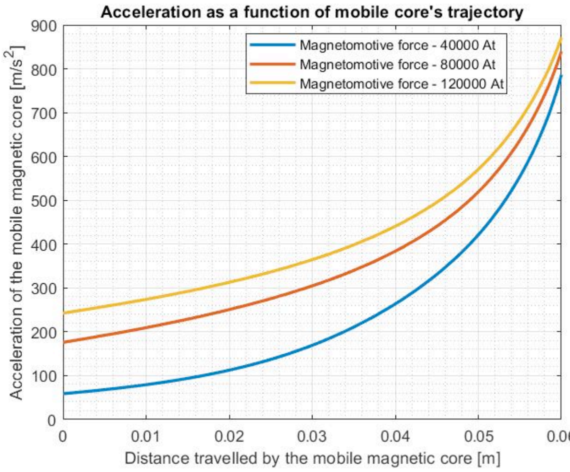

Fig. 8 – Acceleration of the mobile magnetic core as a function of trajectory.

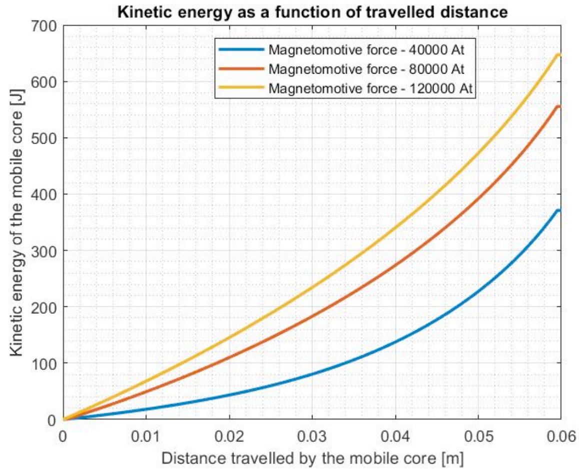

Fig. 9 – Kinetic energy gained by the mobile core as a function of travelled distance.

As seen in Fig. 8, the mobile core has a maximum acceleration at the end of the stroke, when the air gap is minimum, and the force has the highest value. The minimum acceleration of the mobile magnetic core is obtained at the beginning of the stroke, when the air gap has the maximum value. In any case, for the closing sequence, the acceleration is always positive, which leads to the fact that the speed is always increasing.

For computing the speed of the mobile core, the kinetic energy obtained by it must be determined.

The work produced by the actuator can be computed by integrating the electromagnetic force, which is a function of travelled distance:

$$W = \int_{\Gamma} F_{elmg}\,\mathrm{d}l = \int_{d_0}^{d_1} F_{elmg}\,\mathrm{d}l\,. \quad (2)$$

where: F_{elmg} [N] is the force produced by the actuator, d_0 is the initial position of the mobile magnetic core, d_1 is the final position and Γ is the trajectory from d_0 to d_1.

The kinetic energy can be computed using the following formula:

$$E_{d_1} = \frac{m \cdot v_{d_1}^2}{2} = \int_{d_0}^{d_1} F_{elmg}\,\mathrm{d}l - m \cdot g\,. \quad (3)$$

where: E_{d_1} [J] is the kinetic energy of the mobile core obtained when it travelled the distance between d_0 and d_1, F_{elmg} [N] is the force produced by the actuator, $m{\cdot}g$ [N] is the weight and v_{d_1} [m/s] is the gained speed.

The kinetic energy gained by the mobile core as a function of travelled distance is presented in Fig. 9.

To compute the speed gained by the mobile core, the previous equation can be written as follows:

$$v_{d_1} = \sqrt{\frac{2}{m}} \cdot \sqrt{\int_{d_0}^{d_1} F_{elmg}\,\mathrm{d}l - m \cdot g}\,. \quad (4)$$

The speed has the following characteristic, as it can be seen in Fig. 10.

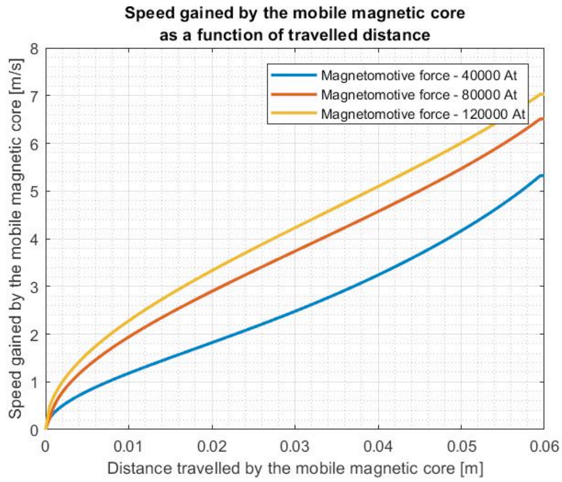

Fig. 10 – Speed gained by the mobile core as a function of travelled distance.

The computation of mechanical parameters did not took into account the friction forces that can occur during closing maneuver.

5. EXPERIMENTAL MODEL

In order to validate the working principle of the actuator simulated with the FEMM package, an experimental model was created. The device's dimensions are equal with those of the simulated model. The ferromagnetic circuit of the experimental model was made of solid steel S235JR, and every component was coated with a thin layer of zinc, in order to protect it from rust. The excitation coils were made of copper wire, with a diameter of 2 mm. Each of the coils have 1000 turns, and the current which flows through them is 60 Amps.

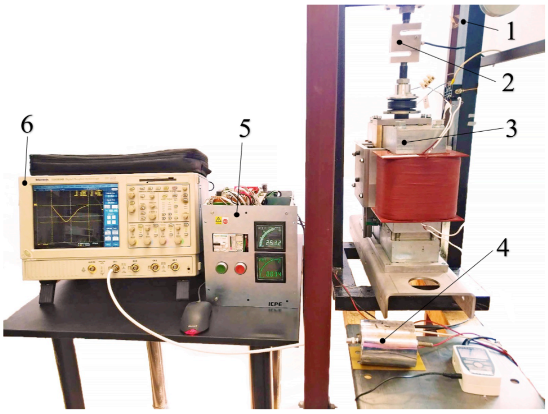

Fig. 11 – Physical model of the direct current actuator.

For measuring the force developed by the actuator and to validate computerized results, it was used the experimental setup presented in Fig. 11. As seen in the previous figure, the actuator (3) was placed on a stainless-steel support (1) to maintain the device in a fixed position. The force produced by the actuator was measured using a digital force gauge, type Mark-10 (2), which is also observed in the figure. In order to execute the closing sequence, a direct current electronic driver (5) was used. Also, with a Tektronix digital oscilloscope (6) in combination with a coaxial shunt (4), it was possible to measure and visualize the current which flows through the actuator's excitation coils [7].

The electrical and mechanical parameters are presented in the following table:

Table 2

Proposed actuator electrical and mechanical parameters

Direct current actuator parameters	
U_{coil} [V] (Series Coils)	310
R_{coil} [Ω] (Series Coils)	5.2
I [A] Current through coils	60
$\Theta = N \cdot I$ [At] Magnetomotive force produced by both coils	120000
$F_{holding}$ [N] Holding force (Measured)	9500
$F_{holding}$ [N] Holding force (Computed)	12715

The most important parameter of the direct current actuator is the holding force in closed position. As seen in the previous table, the computed force is 12715 N and the obtained result using the experimental model is 9500 N. The actuator can perform its function, considering the fact that the minimum holding force needed for the high voltage circuit breaker is 9000 N.

6. **CONCLUSIONS**

In this paper, a novel solution for a direct current actuator was presented. By using a special geometry of the magnetic circuit, along with a proper choice of the permanent magnets, the actuator is capable of producing high force at the beginning of the stroke, as well as in close position. The force produced in close position by permanent magnets without a power source is considered to be the most important advantage of the actuator. This paper focused on presenting the working principle of the actuator, and also the electromagnetic and mechanical parameters specific for this device. In a future work, the authors are looking to improve the existing model and to develop new solutions.

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