Journal of ELECTRICAL ENGINEERING, VOL. 52, NO. 3-4, 2001, 92–95

COMMUNICATIONS

DESIGN OF A CORRECTING CIRCUIT FOR AN ELECTROMAGNETIC ACTUATOR

Daniel Mayer — Jan Teplý *

The aim of the paper is the design of a correcting circuit that allows to increase the attraction force at the beginning of the armature travel of an electromagnetic actuator. The equations describing dynamic operational states of the actuator are defined and numerically solved.

K e y w o r d s: electromagnetic actuator, electromagnet, network synthesis

1 INTRODUCTION

Operating characteristics of an electromagnetic actuator have a rather problematic locus: at the beginning of the shift the attraction force is too small. The shape of the characteristic can be changed with the help of an electronic source but at the cost of higher expenses. At the small air gap it is possible to correct the shape of the characteristics with the shape of the core. In literature recommended (see *eg* [3]) correcting circuits consisting of elements R, L, C and in series to the winding of the actuator show to be little efficient. In this paper a device will be observed that allows a substantial increase in the rate of rise at the beginning of the armature travel. No changes will be made in the actuator itself but its winding should be divided into two or more sections that are connected with the actuator terminal board. These sections of winding will be connected with the correcting circuit that is simple, inexpensive and reliable.

Even though the electromagnetic actuator is among simple electric apparatuses, construction of a mathematical model is not a simple matter, if we want to describe exactly the distribution of the magnetic field (i.e. if we respect the non-linear character of the magnetic circuit and magnetic flux leakage). In our case the aim is not an exact investigation of the dynamic behaviour of the actuator but a comparison of its effect with or without a correcting circuit. That is why the equations for the dynamic state of the actuator are formulated under the common simplifying preconditions.

2 MATHEMATICAL MODEL OF LINEAR ELECTROMAGNETIC SYSTEM

In Fig. 1 the actuator is shown with winding divided into two coils. In Fig. 2 their connection to the correcting circuit, which consists of capacitor C and diode D, is presented.

Presuppose that a) permeability of the magnetic circuit $\mu = \text{const}$, b) magnetic flux leakage does not depend on the armature operating position and can be neglected. The force applied to the actuator armature is defined from the energy of the magnetic field

$$W_m = \frac{1}{2}L_1 i_1^2 + \frac{1}{2}L_2 i_2^2 + L_{12} i_1 i_2 \tag{1}$$

with self-inductances of coils L_1, L_2 and their mutual inductance L_{12}. We obtain them by the solution of the magnetic circuit. There is then

$$L_1 = G_m N_1^2\,, \quad L_2 = G_m N_2^2\,, \quad L_{12} = G_m N_1 N_2\,. \tag{2}$$

where G_m is magnetic conductivity. Magnetic reluctance is

$$R_m = \frac{1}{G_m} = R_{mo} + R_{mv}(x)\,. \tag{3}$$

Magnetic conductivity G_m is obtained from reluctance R_m, that consists of reluctance of those parts of the magnetic circuit that do not change with the armature travel R_{mo} and reluctance of variable of air gap $R_{mv}(x)$.

$$G_m = \frac{1}{R_m} = \frac{1}{R_{mo} + R_{mv}(x)}\,.$$

From the stated presumptions we obtain $R_{mv}(x) = kx$, where k is a constant. The force of the electromagnet is then

$$f_m = \frac{\partial W_m}{\partial x} = \frac{1}{2}\frac{\partial G_m}{\partial x}(N_1^2 i_1^2 + N_2^2 i_2^2 + 2N_1 N_2 i_1 i_2)\,. \tag{4}$$

After substitution from previous equations to equation (4) the following is obtained

$$f_m = -\frac{1}{2}\frac{k}{R_m^2}(N_1^2 i_1^2 + N_2^2 i_2^2 + 2N_1 N_2 i_1 i_2)\,. \tag{5}$$

* Department of Electrical Engineering Theory, University of West Bohemia, sady Pětatřicátníků 14, 306 14 Plzeň, Czech Republic, E-mail: mayer@kte.zcu.cz, teply4@kte.zcu.cz

ISSN 1335-3632

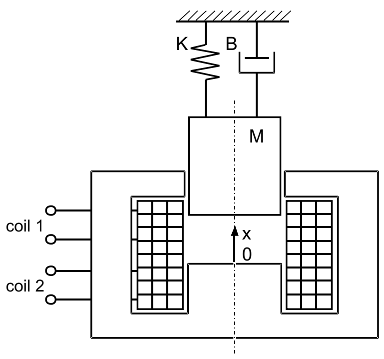

Fig. 1. Cross-section of the actuator

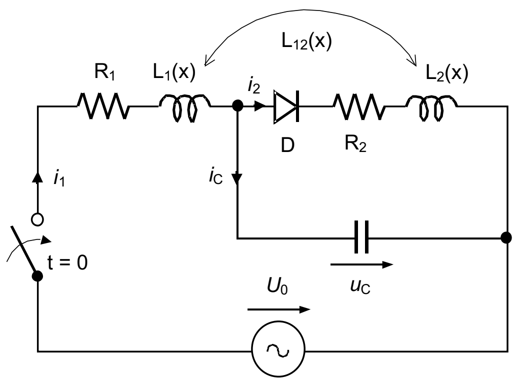

Fig. 2. Electric circuit of the actuator with correcting circuit

Table 1. Parameters of particular variants.

Variation	Parameters	
	actuator	correcting circuit
1.	$N = 2550\,,\ R = 16.5\,\Omega$	without correcting circuit
2a.	$N_1 = 128\,,\ R_1 = 0.83\,\Omega,\ N_2 = 2422\,,\ R_2 = 15.67\,\Omega$	$C = 100\,\mu$F
2b.	dtto.	$C = 500\,\mu$F
3a.	$N_1 = 384\,,\ R_1 = 2.48\,\Omega,\ N_2 = 2166\,,\ R_2 = 14.02\,\Omega$	$C = 100\,\mu$F
3b.	dtto.	$C = 500\,\mu$F

From the Newton law the following equation is valid

$$M\frac{\mathrm{d}^2x}{\mathrm{d}t^2} = f_m + B\frac{\mathrm{d}x}{\mathrm{d}t} + K(l - x) \tag{6}$$

where M is the mass of armature, B is the damp constant, K is the stiffness of the spring and l is the total displacement of the armature. From Kirchhoff's laws the equations for the electric circuit are obtained (Fig. 2):

$$\begin{aligned} R_1 i_1 + u_{L1} + u_C &= U_0 \\ -i_1 + i_2 + C\frac{\mathrm{d}u_C}{\mathrm{d}t} &= 0 \\ R_2 i_2 + R_D i_2 + u_{L2} - u_C &= 0 \end{aligned} \tag{7}$$

where the resistance of the diode is

$$R_D = \begin{cases} 0 & \text{if } i_2 \geq 0 \\ \infty & \text{if } i_2 < 0 \end{cases} \quad \textit{and} \quad u_{L1} = \frac{\mathrm{d}\Phi_{c1}}{\mathrm{d}t}.$$

As the entire magnetic flux linked with the first coil is

$$\Phi_{c1} = L_1 i_1 + L_{12} i_2\,,$$

the voltage on the inductance of the first coil is

$$u_{L1} = L_1(x)\frac{\mathrm{d}i_1}{\mathrm{d}t} + i_1\frac{\mathrm{d}L_1}{\mathrm{d}x}\frac{\mathrm{d}x}{\mathrm{d}t} + L_{12}(x)\frac{\mathrm{d}i_2}{\mathrm{d}t} + i_2\frac{\mathrm{d}L_{12}}{\mathrm{d}x}\frac{\mathrm{d}x}{\mathrm{d}t}\,. \tag{8}$$

Similarly the voltage on the inductance of the second coil is

$$u_{L2} = L_2(x)\frac{\mathrm{d}i_2}{\mathrm{d}t} + i_2\frac{\mathrm{d}L_2}{\mathrm{d}x}\frac{\mathrm{d}x}{\mathrm{d}t} + L_{21}(x)\frac{\mathrm{d}i_1}{\mathrm{d}t} + i_2\frac{\mathrm{d}L_{12}}{\mathrm{d}x}\frac{\mathrm{d}x}{\mathrm{d}t}\,. \tag{9}$$

The actuator is thus described by the system of non-linear equations (6) and (7). We introduce the velocity of the armature travel of the actuator

$$v = \frac{\mathrm{d}x}{\mathrm{d}t}\,.$$

The unknowns are quantities i_1, i_2, u_C, v and x. After modification, this system is expressed by the following matrix equation:

$$\begin{bmatrix} L_1(x) & L_{12}(x) & 0 & 0 & 0 \\ L_{12}(x) & L_2(x) & 0 & 0 & 0 \\ 0 & 0 & C & 0 & 0 \\ 0 & 0 & 0 & M & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \frac{\mathrm{d}}{\mathrm{d}t} \begin{bmatrix} i_1 \\ i_2 \\ u_C \\ v \\ x \end{bmatrix} +$$

$$+ \begin{bmatrix} R_1 i_1 + \frac{\mathrm{d}L_1(x)}{\mathrm{d}x} i_1 v + \frac{\mathrm{d}L_{12}(x)}{\mathrm{d}x} i_2 v + u_C \\ R_2 i_2 + R_D i_2 + \frac{\mathrm{d}L_2(x)}{\mathrm{d}x} i_2 v + \frac{\mathrm{d}L_{12}(x)}{\mathrm{d}x} i_1 v - u_C \\ -i_1 + i_2 \\ -f_m - Bv - K(l - x) \\ -v \end{bmatrix} =$$

$$= [U_0\,, 0\,, 0\,, 0\,, 0]^\top\,. \tag{10}$$

3 NUMERICAL EXAMPLE

Judgement of the influence of the correcting circuit on the working characteristics of the actuator is done in comparison with the characteristics of the actuator without the correcting circuit.

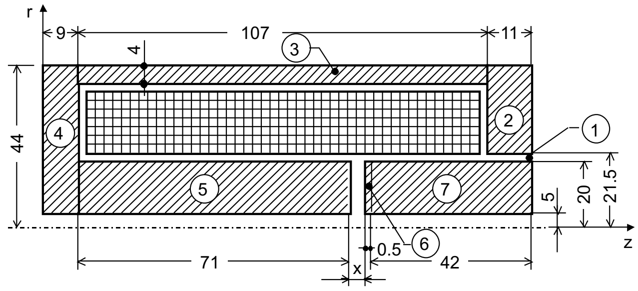

Fig. 3. Magnetic circuit of the actuator: 1 — constant armature gap, 2-5,7 — ferromagnetic material, 6 — non-ferromagnetic insert

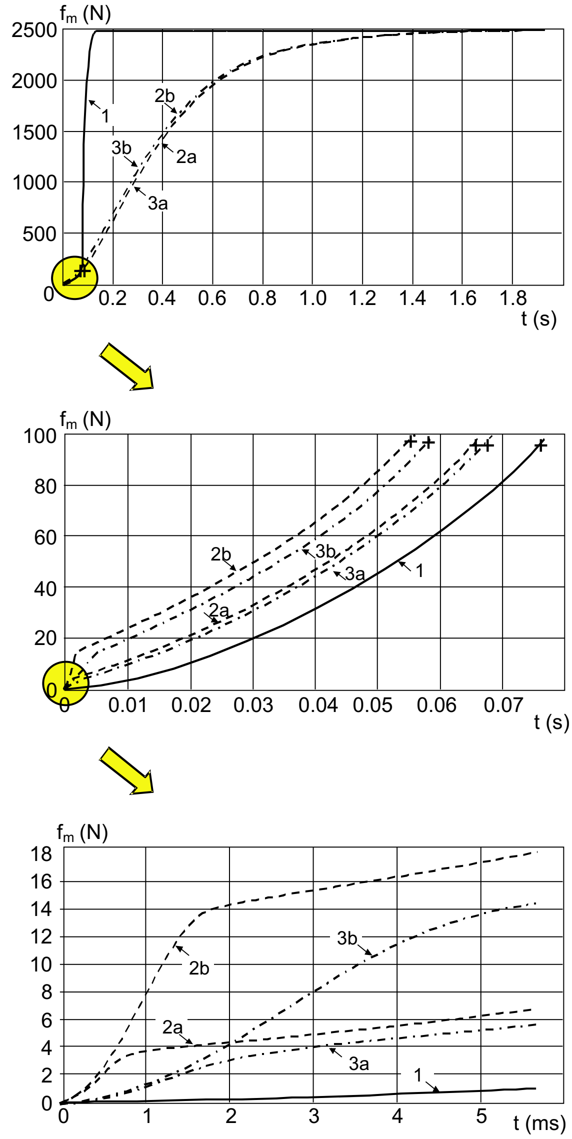

Fig. 4. The dependence of forces f_m of the actuator upon time with two magnified views

Calculation of the characteristics of the actuator is done for an actuator with supply voltage $U_o = 24$ V. Its *mechanical parameters* are: $M = 10$ kg, $B = 100\,\mathrm{Nsm}^{-1}$, $K = 1000\,\mathrm{Nm}^{-1}$ and travel $l = 4.5$ mm. For the calculation of the *magnetic parameters* the magnetic circuit is divided into eight parts, Fig. 3, and their reluctance is calculated. The total reluctance of parts independent of displacement of the core (in Fig. 3 these are parts 1 to 7), at permeability of ferromagnetic material $\mu_r = 1000$ is

$$R_{mo} = \sum_{k=1}^{7} R_{mk} = 1.366\;10^6 H^{-1}\,.$$

Reluctance variation with armature displacement is

$$R_{mv} = 6.755\;10^8 x\,.$$

Five variants of the calculation were done, see Table 1.

The system of non-linear differential equations (10) is solved numerically with the help of standardly constructed function ODE23s (modified Rosenbrock formula of order 2) in the universal calculating and programming environment MATLAB.

In Fig. 4 the time evolution of the force of electromagnet f_m is evident. The switch-in moment is marked by plus. It is evident that the initial slope is influenced by capacity C of the capacitor of correcting circuit and by the number of turns (N_1 *ie* inductance L_1) and resistor R_1.

In Fig. 5 there is a plot showing the displacement x of the electromagnet. Also here the accelerating effect of capacity C and inductance L_1 is evident.

In Fig. 6 there are the currents i_1 and i_2 for variant 2b. The correcting circuit increases the initial impulse of current i_1 after switch-on. Results is in a big rate of rise of the force of electromagnet. This current impulse cannot be neglected when dimensioning the winding of coil 1. Both currents i_1 and i_2 get for $t \to \infty$ the same value.

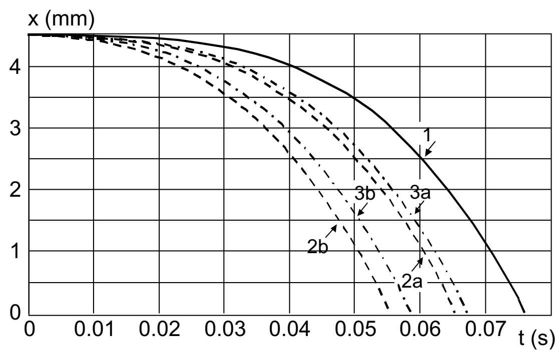

Fig. 5. The displacement x of the actuator armature with the time

4 CONCLUSIONS

In the presented work a simple way of allowing an increase of the attraction force of electromagnetic actuator, especially shortly after voltage supply, is investigated.

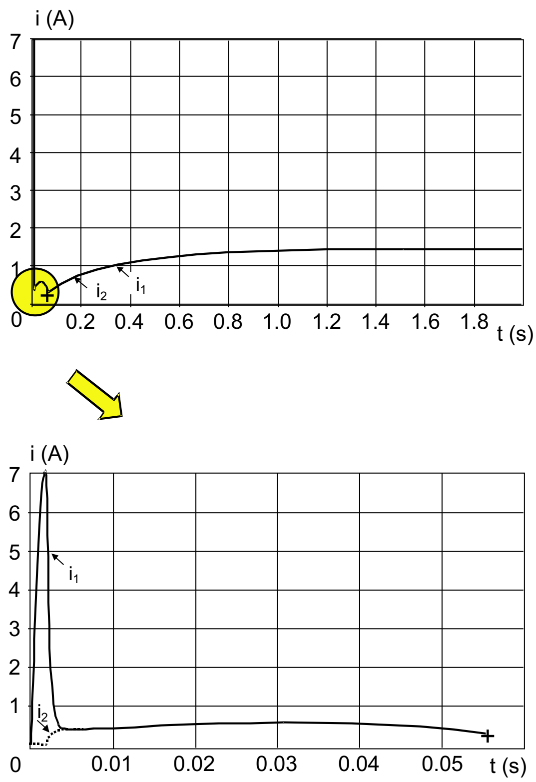

Fig. 6. Plot of the currents i_1 and i_2 of variant 2b versus time with one magnified view

At the calculation neither leakage nor non-linearities of magnetic circuit were respected, which influences the responses of the characteristics of the actuator, but in our case the focus was on comparison of characteristics of actuators with different parameters of the elements of the correcting circuit.

Acknowledgements

This work has been supported from the research project MSM No. 232200008.

References

[1] MAYER, D.—ULRYCH, B.: Analysis of Transient State on Nonlinear Electromagnetic Actuator with help of Professional Software, J. Electrical Engineering **49** No. 11-12 (1998), 326–330.

[2] MAYER, D.—ULRYCH, B.: Numerical Solution of Transient State of Electromagnetic Actuators, J. Electrical Engineering **47** No. 3-4 (1996), 62–66.

[3] PHILIPPOW, E.: Taschenbuch Elektrotechnik – Bd. 2., VEG Verlag Technik, Berlin, 1966.

Received 31 January 2001

Daniel Mayer (Prof, Ing, DrSc) was born in Pilsen (Czech Republic) in 1930. He received the degree of Ing, CSc (PhD) and DrSc in electrical engineering from the Technical University of Prague in 1952, 1958 and 1979 respectively. Since 1968 he has been Professor at the Department of Electrical Engineering Theory, University of West Bohemia in Pilsen. His major fields of interest are the theory of electromagnetic field in heavy current electrical engineering. He is a fellow of the Institution of Electrical Engineers (London).

Jan Teplý (Ing) was born in Teplice (Czech Republic) in 1976. He received the Ing degree in electrical engineering from the University of West Bohemia. His major fields of interest are the theory of optimisation of power transmission and genetic algorithms.