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DETERMINATION OF THE INDUCTANCE OF STARTER RELAYS

L. NAGY, J. LÉNÁRT, E. JAKAB

University of Miskolc, Robert Bosch Department of Mechatronics, Miskolc-Egyetemváros, HUNGARY
E-mail: nagy.lajos@uni-miskolc.hu
E-mail: lenart.jozsef@uni-miksolc.hu
E-mail: jakab.endre@uni-miksolc.hu

This paper deals with the determination of the inductance of starter relays. The article proposes a method for the electro-mechanical determination of the self-inductance of the electromagnet and its derivative for various positions of the iron core. The results obtained at different current levels are given in tables and figures.

Keywords: starter relay, electromechanical model, inductance measurement

Introduction

The actuator of the pinion-engaging mechanism of the starter motor consists of concentric iron core coils [1]. The coils are excited by relatively high currents. The electro-dynamic modelling of the mechanism requires inductance of the relay and its derivative depending on the position of the iron core. The electromagnet has self-inductance, electrical resistance and mechanical force acting on the iron core. The inductance of an electromagnet is generally determined by purely electrical measurements, e.g. by current-voltage methods or bridge methods, by the resonance method, etc. [2, 3]. Relatively few methods are available for DC excited inductance measurements [4].

The inductance of a coil without an iron core can be determined by measurement or also by calculation with sufficient accuracy. It is particularly difficult to determine the inductance of a coil in the case of movable iron cores. The iron core has in general nonlinear magnetic properties, i.e. B-H characteristic curves are nonlinear or hysteresis also may occur [5].

In this work, the inductance function is determined in an indirect way, by measuring the electromagnetic force in the case of direct current excitation. It is assumed that the inductance depends on the position of the iron core and on the current. The time dependency and hysteresis are neglected. The measurement provides the derivative of the inductance function directly. The induction function sought is produced by integration when the inductance of the air core coil and the derived function of the iron core coil are known.

The measurement is repeated for three current values. The final objective of the measurement is to model electro-dynamically the pinion-engaging mechanism of the starter motor, which includes both the inductance function and its derivative.

The electromechanical model

Fig. 1 shows the cross-section of a typical starter relay [1]. The relay consists of a moving iron core – 1, a pull-in winding – 2 and a hold-in winding – 3, a fixed iron core – 4, a contact spring – 5, a switch contacts – 6, an electrical connection – 7, a switch contact – 8, an armature shaft – 9, and a return spring – 10.

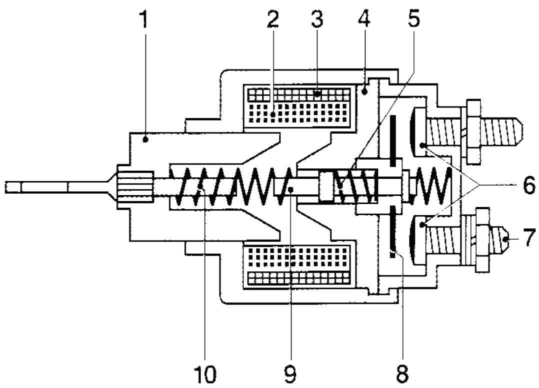

Figure 1: Cross-section of a starter relay

An experiment is designed to measure the inductance electromechanically, without springs.

The electromagnetic force is measured by a compact load cell in discrete positions of the iron core. Positioning is registered by a laser interferometer. The experiment is performed using a supply unit integrated into the measurement circuit. Apart from the phenomenon of switching on, the measurement is done with a constant current *i*.

The electromechanical model of the measurement relies on the following coupled differential equation system:

$$L(x,i)\frac{di}{dt} + L'(x,i)\,\dot{x}\,i + R\,i = U_0\,, \qquad (1)$$

$$m\,\ddot{x} - L'(x,i)\frac{i^2}{2} = F(x,t)\,, \qquad (2)$$

where $L(x,i)$ is the equivalent self-inductance of the relay depending on position x and current i, $L'(x,i)$ is the partial derivative of the self-inductance function by location, $\dot{x}$, $\ddot{x}$ are the velocity and acceleration of the iron core, respectively, R is the equivalent resistance of the relay, U_0 is the terminal voltage of the battery, m is the mass of the iron core and $F(x,t)$ is the force acting on the compact load cell.

Equations (1)-(2) are also suitable for describing the switch-on phenomenon. In a steady-state condition the time-derivative of the current as well as the velocity and acceleration of the iron core are zero. In this static state the following equations hold:

$$R\,i = U_0\,, \qquad (3)$$

$$-L'(x,i)\frac{i^2}{2} = F(x,t)\,, \qquad (4)$$

In the examination the current i and the force acting on the iron core are measured and equation (4) is used to determine the derivative inductance function:

$$L'(x,i) = -F(x,t)\frac{2}{i^2}\,, \qquad (5)$$

The self-inductance factor of an air core coil can be calculated using the parameters of the coil:

$$L_j = \frac{\mu\, N_j^{\,2}\, A_j}{l_j}\,,\ j\text{=1, 2, ...} \qquad (6)$$

where μ is air permeability, N is the number of turns of the coil, A is the coil diameter and l is coil length.

Mutual inductance is:

$$M = k\sqrt{L_1\,L_2}\,, \qquad (7)$$

where k is coupling factor.

The self-inductance of the air core coil can also be determined using an inductance meter.

In the present case the parallel connected two coils and the mutual inductance arising between the coils produce the equivalent inductance. The equivalent inductance is obtained by the following relation:

$$L_0 = \frac{(L_1 - M)(L_2 - M)}{L_1 + L_2 - 2\,M} + M\,, \qquad (8)$$

The inductance function sought can be produced by integration when the inductance of the air core coil and the derivative function of the iron core coil are known:

$$L(x,i) = L_0 + \int_0^x L'(s,i)\,ds\,, \qquad (9)$$

Measuring the inductance of the relay

In order to design the measurements firstly the original relay with springs mechanism is tested during normal operation. The measured current of the operating relay versus time function is shown in *Fig. 2*. It can be seen that during the whole period (t=0–0.025 s) the current is varying between 0 to 35 Amperes. The measurements are planned to perform at three different current levels, i.e. i = 8 A, 26 A, 32 A.

The set-up of the measurement is shown in *Fig. 3*. The instruments used for the measurements are given in *Table 1*.

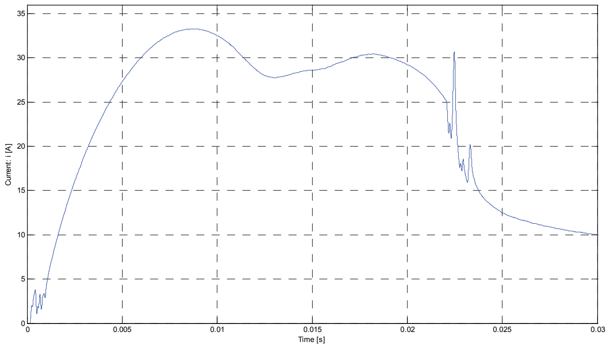

Figure 2: The exciting current of an operating relay

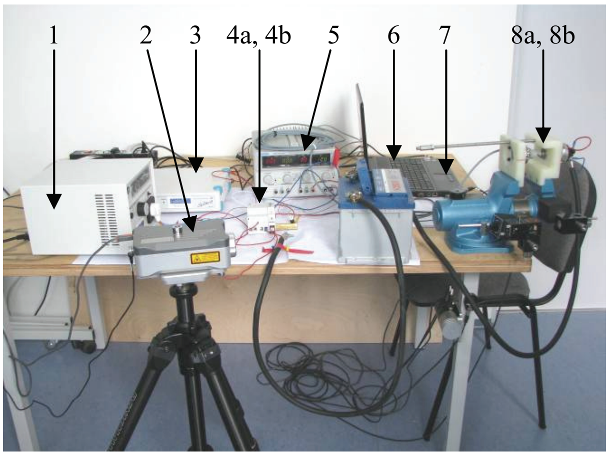

Figure 3: The measurement circuit used

Table 1: Elements of the measurement circuit

Nr.	Title	Type
1	AC power supply	EA-STT 2000 B-4.5 A 0–260 V AC
2	Laser interferometer	Renishaw XL-80
3	Data acquisition device	Spider 8 4,8 kHz/DC
4a	Relay	VS440-22 220–230 V AC
4b	Timer	CRM-91H
5	DC power supply	Matrix MPS-3005L-3 0–30 V
6	Battery	12V 544 402 440A (EN) 44 Ah
7	Laptop	
8a	Iron core actuator with compact load cell	GEFRAN TU-K1C (0–100 kg)
8b	The analyzed relay	

The measurements were done using a variety of supply units. In the first case a controlled unit supplies exciting current $i < 10$ A.

In the second case the supply unit is a starter battery, supplying current typical of operating conditions. In the latter case a magnetic switch and timer were built in the measurement circle as protection against heating.

Table 2 sums up the function values $L'_I(x,i)$, $L'_{II}(x,i)$ and $L'_{III}(x,i)$, obtained in the measurement series.

Table 2: Measurement results

x_I [mm]	$L'_I(x,i)$	x_{II} [mm]	$L'_{II}(x,i)$	x_{III} [mm]	$L'_{III}(x,i)$
0.00	0.0044	0.00	0.0596	0.00	0.07505
1.00	0.078	1.49	0.0894	1.68	0.0998
5.00	0.2343	4.39	0.1639	4.016	0.1628
7.1	0.2959	6.99	0.3309	5.95	0.2514
9.1	0.7078	8.5	0.4710	8.00	0.3913
9.95	1.1031	9.49	0.6255	10.00	0.5526
10.70	3.0653	10.44	0.7811	10.47	0.6039
10.95	5.025	11.01	0.9332	11.01	0.7583

The derivative functions are numerically integrated by the trapeze method. The inductance functions obtained at $i = 8$ A is approximated by an exponential function and the rest of them by five-degree polynomials. The coefficients of the functions are:

$$L_I = 0.5923 \cdot e^{0.1643x} + 1.528 \cdot 10^{-7} \cdot e^{1.515x}, \quad (10)$$

$$L_{II} = 2 \cdot 10^{-5} \cdot x^5 - 0.0003466 \cdot x^4 + 0.003742 \cdot x^3 - \\ - 0.005405 \cdot x^2 + 0.07921 \cdot x + 0.6738, \quad (11)$$

$$L_{III} = 7.338 \cdot 10^{-5} \cdot x^5 - 0.0001826 \cdot x^4 + \\ + 0.003192 \cdot x^3 - 0.005942 \cdot x^2 + \\ + 0.09194 \cdot x + 0.6742, \quad (12)$$

Figs 4 and *5* show the inductance functions and their derivatives obtained in the three measurement series.

On the basis of the results of the measurement series it can be established that if the displacement of the iron core is more than 8 mm, i.e. the iron core is located deep in the coils, dependence on current appears to be significant. This non-linear characteristic can be explained by the saturation of the iron core.

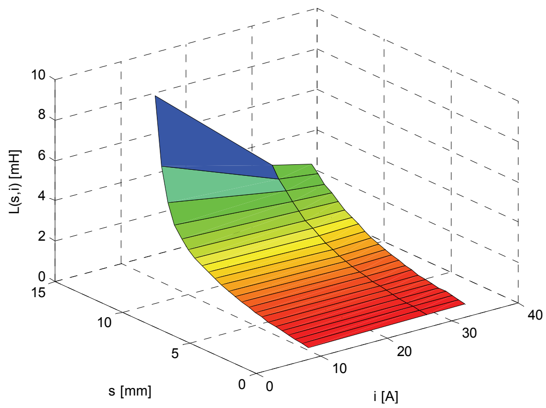

Figure 4: Inductance functions

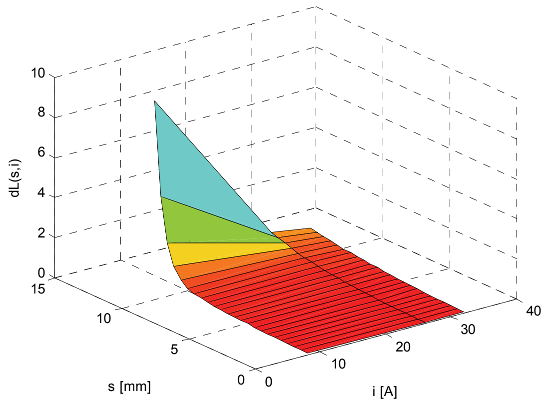

Figure 5: Derivative inductance

We note that the exciting current of the relay falls in the interval $i = 25$–35 A, where the inductance slightly depends on the variation of current.

Conclusion

The paper recommends an electro-mechanical method for determining the inductance function of starter relays. The inductance depends on the position of the iron core and on the current. The time dependency and hysteresis are neglected.

The method is based on the direct measurement of the inductance derivative with respect to the iron core position. The inductance is obtained by numerical integration. It is assumed that the inductance of the air core coil is given.

The current dependency is significant when the whole geometry of the iron core is situated in coils.

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