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POWER SYSTEMS AND POWER ELECTRONICS

Bistable relay – contribution of electromechanical design to global energy savings

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Abstract. Green energy transformation requires comprehensive strategies that include both innovations in energy production and more efficient energy use. This article investigates the potential for saving electrical energy in industrial automation systems by utilizing bistable switching/relay. Compared to traditional systems, these innovative solutions demonstrate significant reductions in energy consumption. A market analysis of available bistable relays, along with experimental determination of their control conditions, highlights their application potential and indicates the benefits of their implementation. The findings suggest that replacing classical relays with their bistable counterparts could significantly contribute to global sustainability efforts. The article presents the process of redesigning a standard industrial relay into a bistable design. Adding two additional elements achieved the intended bistable functionality. The article calls for increased research and investment in such technologies, emphasizing that the energy-saving potential offered by bistable switching/relay circuits should not be overlooked.

Keywords: energy efficiency; electromagnetic relays; bistable relays; magnetic circuits design; finite element method.

1. INTRODUCTION

Combating climate change requires transformation of energy production and more efficient energy consumption. Reducing energy consumption is a fundamental technical, economic and legal issue. By saving electricity, we reduce the consumption of fossil fuels, save money and save the environment. Energy saving has been introduced into the legislation of some countries. In the EU, Eco-Design requirements are currently in force, compelling the increase in energy efficiency of devices and technical facilities. Furthermore, the sale of equipment with an energy efficiency below the regulatory limits [1, 2] may be prohibited.

Typically, energy savings are sought in high-energy processes. Attention is paid to energy savings in car transportation [3–5]. Electric energy is generated in cogeneration, saving waste energy [6]. In industrial automation systems, energy saving is focused on the use of highly efficient drives [7, 8]. Energy is saved through advanced process control [9].

However, one must not forget about the small things such as connectors/relays [10]. Electromagnetic relays are commonly used to activate high-current circuits. The principle of operation of these switches has not changed over the years. However, due to their inherent characteristics, they are widely used in modern solutions eg. railway [11, 12] and marine transportation [13], quantum electrical metrology [14], aeronautics and military devices [15, 16], electrical vehicles [17] and many others [18]. Significant characteristics of electromechanical relays include:

- Natural galvanic isolation between control and working circuits [19].
- Insulating gap in the off state [20].
- Low resistance/impedance of working contacts in the on state [20].

Besides their advantages, these relays also have disadvantages. An electromechanical relay switches its state relatively slowly, which affects the maximum operating frequency and delay in action. To switch the relay, it is also necessary to provide a relatively large amount of power [19], which, depending on the type of relay, ranges from tens of milliwatts to a few watts. The main consumption of electrical energy in the relay occurs on the control side. It is necessary to supply current to the electromagnet in order to generate a magnetic field and the attractive force pulling the anchor (armature) and the relay contacts together.

A solution that allows for a significant reduction in electrical energy consumption in relays is the introduction of bistability function. The introduction of the bistability function requires using some latch, which will keep the state of the relay contacts in the selected position. For this reason, bistable relays are also called latching relays [21].

Classic relay consumes power all the time when it is turned on. On the other hand, the bistable relay consumes energy only for a change of its On/Off state. A graphical comparison of the power consumption characteristics is shown in Fig. 1. The power of the controlled load P_o is many times greater than power of the signal controlling the relay P_R. However, in a classic relay, power must be applied to the relay for the entire duration of the load operation. Whereas, for a bistable relay, the power P_{BR} is applied to the coil only when the relay states are changed. The energy consumed by the relay coil is equal to the area of the power consumption function – P_R for classical relay and P_{BR} for bistable one. As can be easily seen from Fig. 1, depending on the operating regime, bistable relays can significantly reduce energy. Typically, this energy saving exceeds 90%. For example, an estimation described in [12] regarding railway traffic control

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suggests that energy savings could reach up to 98% when replacing monostable relays with bistable ones. Unfortunately, such a replacement can only be considered in new applications because their control is more complicated than that of monostable relays.

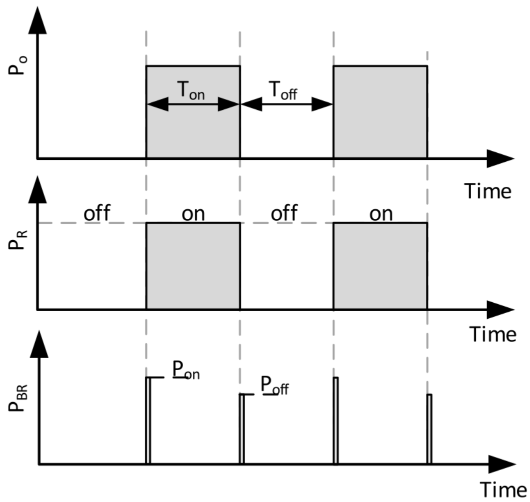

Fig. 1. The power consumption of the relay coil and load, P_o – power of the controlled load, P_R – power of the coil in monostable relay, P_{BR} – power of the coil in bistable relay

This article is dedicated to saving energy in relays by using bistable function. In the next section, based on market data, the volumes of energy consumed by relays will be estimated. As the analysis of Fig. 1 showed, most of this estimated energy can be saved by replacing classical relays with bistable relays.

Bistable relays are more complicated than classic relays, which is why bistable relays are typically much more expensive than classic relays [22].

In addition, the economy of scale is not applied yet to bistable relays as they are not as popular. However, with the potential of saving vast amounts of energy and in combination, with proper design and thus mass production, the costs will quickly become competitive. Section 3 will therefore show the design of a bistable relay. A distinctive feature is that the shown bistable relay is created by a minor modification of the popular R4N family relay. The modification involves adding two elements (a magnet and a L-shaped plate) to the existing relay. The base relay is a standard of industrial relays and is mass-produced by many companies worldwide. Therefore, achieving bistability is very simple and can be very cost-effective. Section 4 presents experimental research of the proposed solution confirming its utility. The last section presents a discussion of the obtained results.

2. THE IMPACT OF RELAYS ON GLOBAL ENERGY CONSUMPTION

Individual relays consume little energy. Therefore, the use of methods to reduce energy consumption was and often still is overlooked by designers. However, attention should be paid to the vast number of operating relays. Figure 2 shows the chart of annual sales of electromechanical relays from 2015 to 2019 [23]. The global market exceeds 400 million units annually (Fig. 2) and continues to grow, despite the development of alternative electronic switch technologies. Relays are mainly used in electrical devices, telecommunications, and car manufacturing.

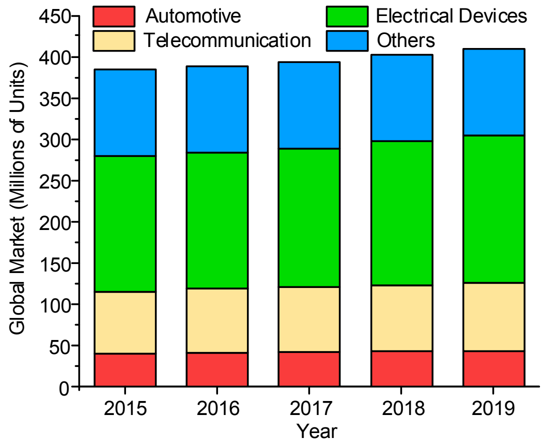

Fig. 2. Global annual sales of electromechanical relays

To estimate the energy consumption by relays, I used data from RELPOL S.A., a leading relay manufacturer in Poland. The company also holds 8% of the global market for miniature industrial relays. Table 1 presents the production profile of relays in the company. As can be seen in Table 1, relay control requires power ranging from several hundred milliwatts to a few watts.

Table 1
Profile of relay production at RELPOL S.A.

Relay family	Nominal power [mW]	[%] of production	Popular substitute
R4N	900 or 1200	23	CR-M230AC4 (ABB), 2903686 (PC)
RM84	480 or 720	23	6-1393243-8 (TE)
SOLAR	480	17	AZSR250 (Zettler)
R15	2800	7	MKS3P-5 (OMRON)
PI6	1600	5	G2RV-SR500 (OMRON)

Considering the production scale, one can make rough calculations showing the importance of the topic discussed in the article. Individual relays consume electrical power of the order of single watts. Assuming that the relay has a lifetime of 5 years and half the time the relay is on, the global average power demand of the relays can be calculated as:

$$P_G = \frac{5\ \text{years} \cdot 400\ \text{mln/year} \cdot 1\ \text{W}}{2} = 1000\ MW. \tag{1}$$

During the year, these relays would consume the following amount of energy:

$$\begin{aligned} E_G &= 24\ \text{h/day} \cdot 365\ \text{days/year} \cdot 1000\ \text{MW} \\ &= 8760\ \text{GWh/year}. \end{aligned} \tag{2}$$

Assuming 90% energy savings, it can be estimated that replacing classic relays with bistable ones would give 7884 GWh/year of savings.

The author knows that replacing classic relays with bistable ones will only sometimes be possible, and the presented calculations may need to be more precise. Nevertheless, the scale of possible savings is so large, that it is worth starting work on this topic. Therefore, the design of a bistable relay will be presented in the next section.

3. DESIGN OF A BISTABLE RELAY

Bistable relays remain in their switched state without taking external energy. The bistable function can be implemented using a mechanical or magnetic latch. The goal of the project is to build a bistable relay with as minimal interference as possible in the existing R4N family relay. The R4N relay standard (Finder type 55) is widely recognized around the world, and relays of this type are mass-produced by many manufacturers such as Finder, ABB, Relpol, Adeli. In the article [24], a detailed analysis of several relays from this standard can be found. Such an approach offers the chance for the mass application of bistable relays. Figure 3 shows a drawing of the R4N relay construction and a bistable relay based on this construction.

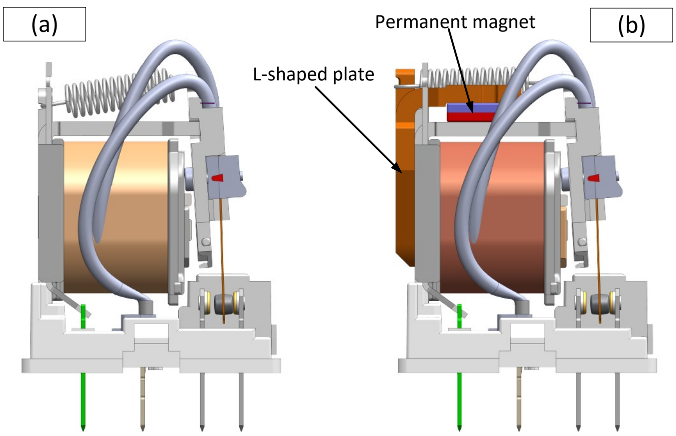

Fig. 3. Models of two relays: (a) classic relay of the R4N family, (b) proposed bistable relay

As one can notice, a bistable relay differs from a classical relay by two additional elements: a permanent magnet and an additional L-shaped plate. The design of the bistable relay is based on the patent application no P.439327 by the author of the article. The plate functionally serves as an additional yoke for the magnetic field. The aim of the project is to select the magnet and the thickness of the L-shaped plate. To consider the design of the bistable relay as good, it must be confronted with the requirements for the forces acting on the relay contacts.

3.1. Assumptions for the design

Before beginning the design process, essential assumptions were made based on the measured parameters of the R4N relay construction. Specifically, the return spring force and the contact forces were measured. Subsequently, safety coefficients were selected for the operating loads in the bistable version. The calculated torque set values required for the relay design are summarized in Table 2.

Table 2
Data provided in the project

Description	Symbol	Value
Free return spring length	l_0	12.4 mm
Loaded return spring length	l	19 mm
Return spring constant	c	40 cN/mm
Spring angle	α	9.6°
Return spring pretension	F_0	16 cN
Number of contact pairs	n	4
Distance between spring hook and centre of anchor rotation	r_s	4.1 mm
Distance between contact force and centre of anchor rotation	r_c	18.7 mm
The factor of safety – start	k_h	1.3
The factor of safety – hold	k_s	2
The factor of safety – reset	k_r	2.7

Figure 4 shows the forces acting on the relay contacts and anchor. Because the anchor movement is described by rotation angle, the most convenient approach is calculating torques instead of forces. In this study all the torques are referred to the anchor hinge axis. It is marked in Fig. 4 as ”O”. To introduce the bistable functionality, it is necessary to consider three specific values derived from the static equilibrium equations for the anchor in this design.

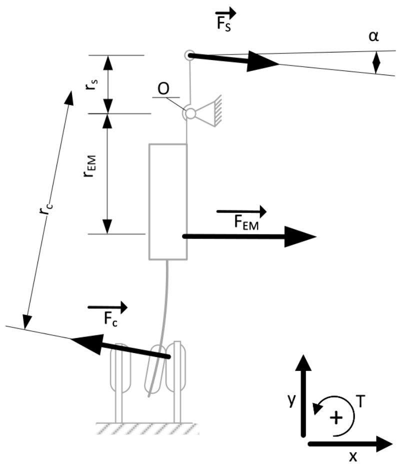

Fig. 4. The distribution of forces and torques in the relay contacts

The first is the torque needed to overcome the return spring force and drive the anchor, see equation (3)

$$T_s = k_s \cdot r_s \cdot \cos(\alpha) \cdot F_s\,. \tag{3}$$

The safety factor k_s found in formula (3) ensures the operation of the relay in different conditions (elevated temperatures decreasing the magnet force, vibrations, shock load, etc). The force F_s can be calculated from the equation:

$$F_s = F_0 + c \cdot (l - l_0). \tag{4}$$

The second value is the torque needed to hold the anchor in the closed position. The holding torque must be greater than the torque of the return spring force as well as the torques of the forces from the n contact springs guaranteeing the required contact force:

$$T_h = k_h \cdot (n \cdot r_c \cdot F_c + r_s \cdot \cos(\alpha) \cdot F_s). \tag{5}$$

The durability of the contact system depends on the contact force, which directly influences the holding torque obtained and the overall durability of the relay. In addition to the static force, which affects the contact resistance, the dynamics of the contact system also impact durability, as discussed in detail in [20, 25].

The last parameter is the reset torque T_r (6). To change the state from closed to open, the holding torque of the anchor must be smaller than the sum of the torques of forces coming from the contact springs and the return spring.

$$T_r = \frac{n \cdot r_c \cdot F_c + r_s \cdot \cos(\alpha) \cdot F_s}{k_r}. \tag{6}$$

The calculated values of the set torques are presented in Table 3.

Table 3
Torque set values for design relay

Description	Symbol	Value
Minimal start torque	T_s	14.7 Nmm
Minimal holding torque in closed state	T_h	46.6 Nmm
Maximal reset torque	T_r	8.6 Nmm

Having the requirements in terms of torques, one can approach the selection of two additional elements of the bistable relay: a permanent magnet and an additional yoke (an L-shaped plate). Since the parameters of both elements depend on each other, it was decided to select a permanent magnet from the market offer. For the chosen magnet, based on FEM simulations, the thickness and size of the additional yoke were selected. FEM simulations appear to be the only sensible method of force analysis. FEM simulations are widely used to describe and solve electrical engineering problems such as the design of magnetic devices [26], analysis of electric parameters [27], predicting control strategy [28]. In this case, significant nonlinearities of the magnetic systems and the complex geometry of the analyzed object are present. Utilizing FEM [29, 30] allows for an efficient solution.

3.2. FEM simulation of relay design

In this paper simulation is narrowed down to L-shaped plate thickness parameter. On the one hand, L-shaped plate must be thick enough to transfer sufficient magnetic flux. On the other hand increase in the cross-section area is correlated with the material consumption and the manufacturing costs. For this study magneto-static solver in ANSYS Maxwell software was used. Static solver can be used since the required forces and torques for equations (3)–(5) are defined for static states. Because there is one plane of symmetry in the relay, only half of the geometry may be considered. The next step is a definition of boundary conditions. In the mid-plane, the symmetry boundary condition is applied. After this step, material properties are applied to each geometry feature. Because B-H curves are nonlinear, it is essential to determine magnetic material properties with sufficient accuracy, especially in the knee region. Figure 5a shows Magnetic flux density B and magnetic field H for assumed magnetic material RFe80 (the data are taken from DIN 17405 standard). Other material non-linearity originates from the permanent magnet (PM). The PM material (N38H) parameters are presented in Fig. 5b (the data are taken from ANSYS database). Other materials such as copper and air, are linear and their parameters are also taken from ANSYS database.

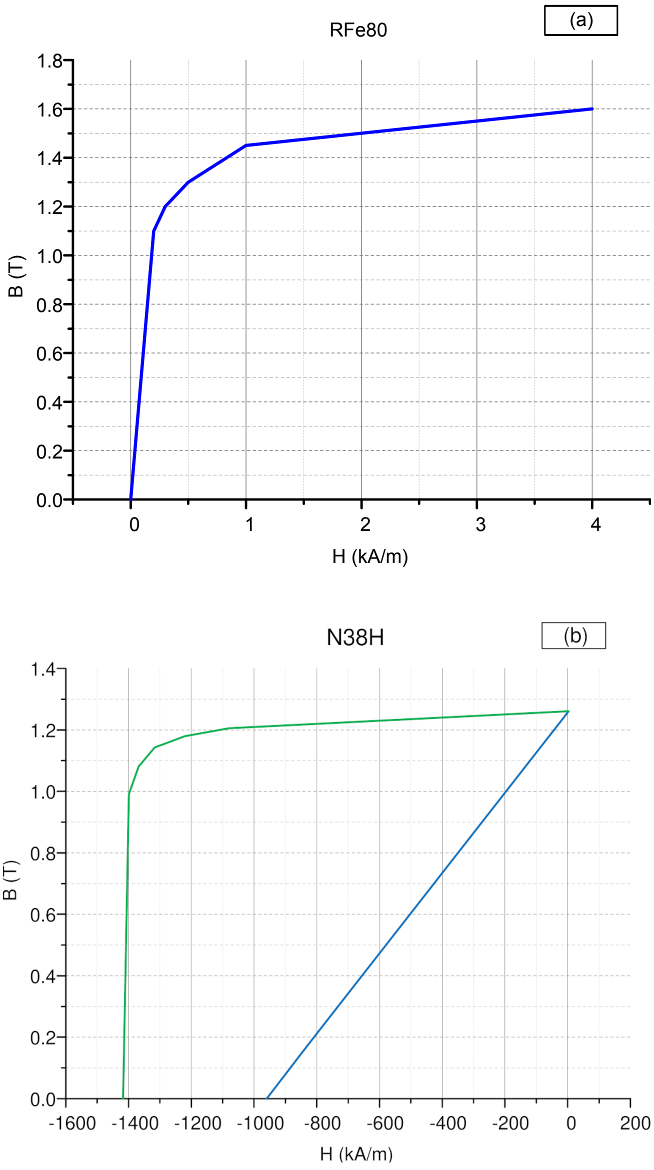

Fig. 5. (a) Magnetization – (B-H) curve of RFE 80 material, and (b) normal (blue) and intrinsic curve (green) of the N38H magnet

The next step is the definition of excitation. For this study, three states of the coil current are considered:

a) coil polarized on (MMF = 160 A · turns),
b) no current in the coil (MMF = 0 A · turns),
c) coil polarized off (MMF = 160 A · turns).

Selected magneto-motive force (MMF) is typical for R4N relay. The last thing is to set sweep parameters that are changing during simulation. This study must answer whether the L-shaped plate thickness is acceptable for specified requirements. Therefore, the torques acting in the relay were checked for L-shaped plate thickness from 0.5 to 3.5 mm with step 0.1 mm. Simulations were performed for the open and closed states of the relay. These states corresponded to the opening angle of the relay anchor. The anchor angle was assumed as 0° and 2.8° which are related for closed and opened state, respectively. Two states of anchor disconnection and three states of force application ultimately lead to six static states in which the relay can be. In the simulation, it is necessary to check if the torque requirements are met in each of these states. Use the FEM and 3D CAD, allowing for presenting the solution in 3D plot form. In this case, the magnetic flux density plot is particularly interesting since the torque acting on the anchor depends on its value. Example graphs of the magnetic flux density distribution in the core are presented in Fig. 6, for three coil power states. The analysis of the geometric distribution of magnetic induction allows for the identification of areas where saturation of the ferromagnetic material occurs. This provides intuition for potential changes in the design.

At this stage, the OPTIMETRIC tool in ANSYS software is used. It allows a simulation set with input variables: L-shaped plate thickness and magneto-motive force applied in the coil winding. Finally, simulations/calculations were performed for 279 different scenarios.

The output parameter in this study is the torque acting on the anchor generated by the electromagnetic field from PM and the energized coil. The torque is calculated, based on the spatial derivative of the magnetic field energy [31]. At this point, it is crucial to remember that only half of the geometrical model is calculated, and the software calculates only half of the torques. Therefore, the results presented below have been multiplied by two so that they can be directly compared with the requirements from Table 4.

Table 4
Comparison of holding torque from simulation and experiment

MMF applied AT	Torque (measured average) mNm	Torque simulation mNm	Criterion mNm
–160	0.81	0.45	< 8.6
0	53.5	51	> 46.6
160	125	121	> 46.6

3.3. Simulation results – selection of elements

Obtained by Optimetrics, results are presented in Figs. 7–9. On the presented characteristics, the limits, which result from the assumptions adopted in Table 3, are marked in red. For a coil energized with negative polarity, the torque should be lower than the limit. While for other cases, generated torque should be higher than the limit to fulfil the requirements. Figure 7 shows the torques acting on the relay anchor when the coil is energized with negative polarity. In this case, the coil magnetic flux counteracts PM magnetic flux, so the torque decreases significantly. If the L-shaped plate thickness is in the range from 1.3 mm to 3.5 mm, the resultant torque is below the holding torque limit and the anchor is open.

As shown in Fig. 7b, for anchor opened and off polarity, the torque requirements are met for all L-shaped plate thicknesses. This means that the relay remains open and does not close. If the torque exceeded the red line, it would mean that the relay could inadvertently close, failing to remain open as required.

Figure 8a presents the bistable state when the coil is not energized, and the anchor stays in position because of PM magnetic flux. The L-shaped plate should not be thicker than 1.8 mm in order to ensure the assumed holding torque T_h. Figure 8b shows the torque when the anchor is opened. The requirement is always fulfilled, because residual attraction torque is below T_s.

According to the results in Fig. 9a, the requirement is fulfilled for a L-shaped plate thickness above 1.7 mm, which means that after applying the magnetomotive force of 160 A·turns, the relay will close. Figure 9b presents torques for positive polarization of the coil. In this case, the resultant torque is much higher than the minimal holding torque T_h.

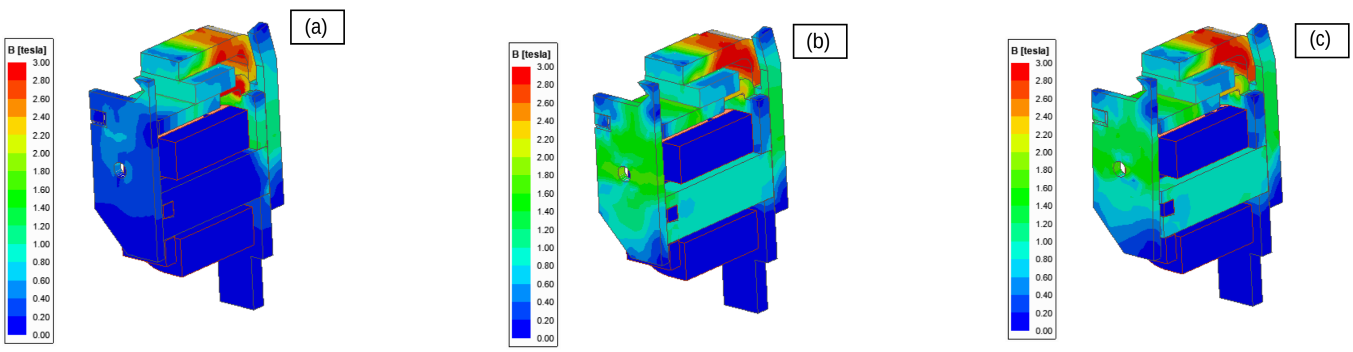

Fig. 6. Magnetic induction distribution in the relay, (a) contacts closed, polarization off, (b) contacts closed, no current, (c) contacts open, polarization on

Based on obtained results, it is reasonable to use a L-shaped plate on thickness from the range: 1.8–3.5 mm. The thickness of the material translates into the price, hence the choice is made of smaller thicknesses. Because of technology (ease of access), the final relay thickness of 2 mm will be used. A 2 mm sheet of material is easy to purchase, whereas other thicknesses (e.g. 1.8 mm) may result in special delivery conditions.

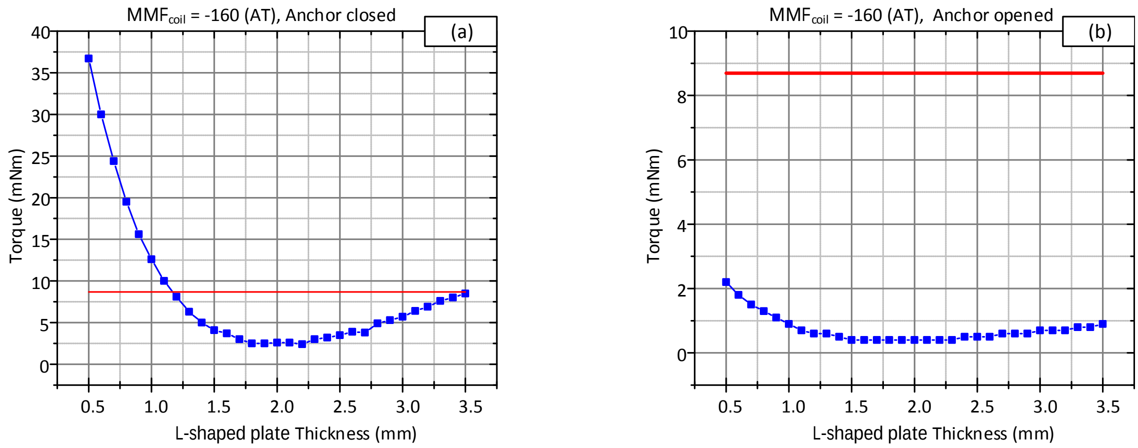

Fig. 7. Torque characteristics for coil energized with negative polarity: (a) Anchor closed, red line – maximal reset torque (T_r), (b) Anchor opened, red line – maximal reset torque

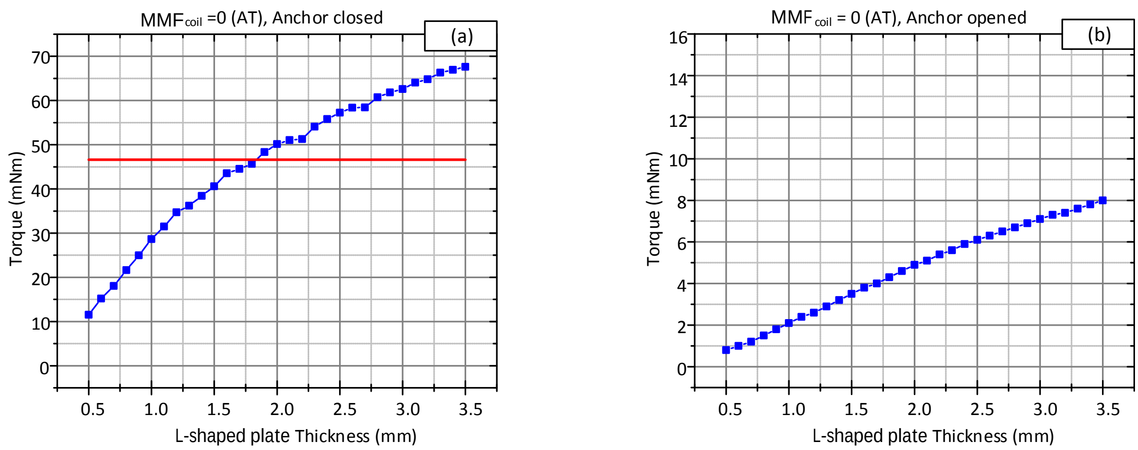

Fig. 8. Torque characteristics for coil without power: (a) Anchor closed, red line – minimal holding torque in closed state (T_h), (b) Anchor opened

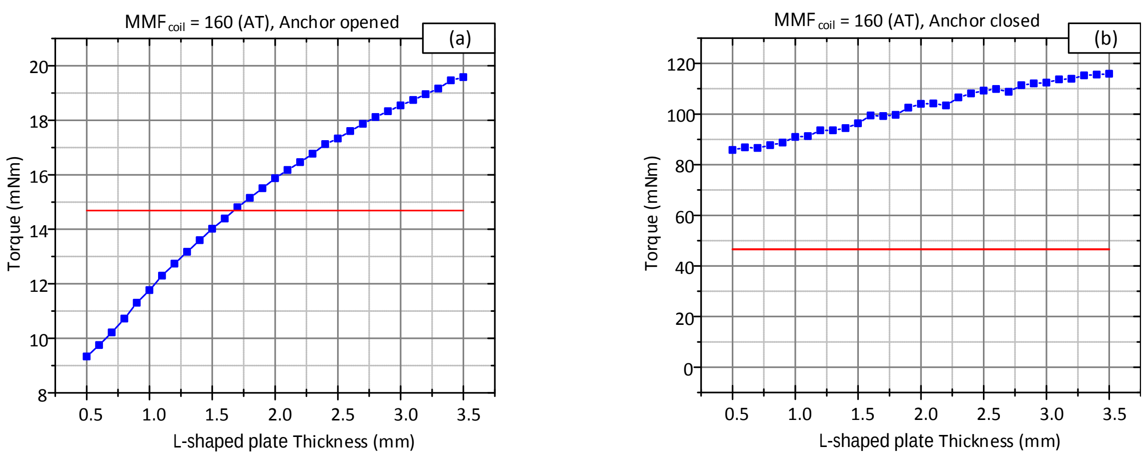

Fig. 9. Torque characteristics for coil in positive polarity: (a) Anchor opened, red line – minimal start Torque T_s, (b) Anchor closed, red line – minimal holding torque in closed state (T_h)

4. EXPERIMENTAL VERIFICATION

A prototype was made and tested experimentally to confirm the correctness of the adopted design of the relay. Complete tests of the relay before its introduction into production should be performed following the standard EN 61810-1. This standard contains several requirements regarding the activation voltage, resistance to external conditions, and safety parameters. Resistance to external factors and safety parameters are related mainly to the housing of the relay and the strength of the materials.

Standardization issues related to relays are discussed in more detail in [18], and testing is described in [32]. Bistable relays are covered by the same standards as monostable relays, with distinctions made for the specific parameters of the electromagnet.

Therefore, the paper presents only the results of measurements of the relay operating force for a given electromagnetic force. The measuring system, which allows the measurement of forces, is presented in Fig. 10.

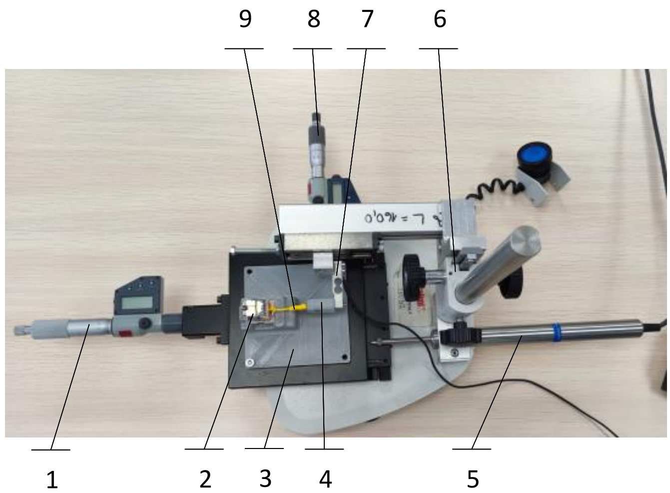

Fig. 10. Measuring system. 1 – Axis X adjustement, 2 – specimen, 3 – specimen fixture, 4 – eye for wire, 5 – displacement meter, 6 – Z (heigth) axis adjustement, 7 – strain sensor, 9 – wire connecting anchor set and strain sensor

The measuring system allows to adjust proper height (knob No. 6), symmetry (knob No. 8) and precise control displacement of X axis (knob No. 1). Force measurement is realized using Kistler maXYmos hardware. It utilizes strain gauge with the range up to 20 cN with accuracy +/– 0.1%. The strain gauge No. 7 is connected to the anchor by the wire. Joint between anchor and wire is designed to transfer only the axial force.

Measured is holding torque of the anchor when there are three different voltages applied to the coil defining the coil current and MMF. This part of study focuses on measurement of the force needed to switch the state of the relay. The measured force is perpendicularly applied to the anchor set. In this case only maximal force is taken into consideration (peak value). The measurement is performed for bare electromagnet (no contact set, no return spring). Obtained measured force is multiplied by $r = 12$ mm (taken from relay model) to calculate final holding torque. In this case five prototypes are measured and the average results are presented in Table 4. The FEM calculated torques and the measured torques are comparable. The simulation and experiment results meet the assumed criteria. Not all operating states could be verified experimentally on the stand shown. However, the convergence of the experimental results with the simulation results and the correct operation of the relay prototype justify the acceptance of the bistable relay design.

5. DISCUSSION

The article presents estimates of energy consumption in relays. Despite the low power consumption of a single relay, the global yearly energy consumption in relays is counted in GWh. This fact results from the scale of applications. It is therefore worth considering the possibilities of saving energy in relays.

Bistable relays are usually expensive, and their use requires changes to the application setup. This drawback can be eliminated through proper relay design. The article shows such a solution. The proposed solution is based on the classic industrial relay of the R4N family, and the bistable function can be implemented by adding two additional elements: a magnet and an L-shaped plate. After selecting a magnet from those available on the market, a method for determining the parameters of the additional plate serving as an extra yoke is presented. An additional yoke with a thickness of 2 mm, attached with a magnet to the classic relay design, transformed the relay from energy-consuming to energy-saving. The total cost of the new elements does not exceed 50% of the monostable relay production cost. Such conversion is especially recommended in industrial solutions, where relays are controlled by programmable controllers and industrial computers. In such a case, changing the control sequence, which ensures a reduction in energy consumption, can be achieved by changing the control program without additional hardware efforts.

PATENTS

The solution of a bistable relay with an additional yoke and a magnet placed perpendicular to the primary yoke has been granted a patent. The patent, titled "Bistable Relay with Magnetic Flux Stabilization," is registered under Patent No. PL245744B1 by the Patent Office of the Republic of Poland.

DECLARATIONS

The corresponding author states that there is no conflict of interest.

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