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Electrodynamic Contact Bounce Induced by Fault Current in Low-Voltage Relays

Andrzej Ksiazkiewicz, Grzegorz Dombek *, Karol Nowak and Jerzy Janiszewski

Institute of Electric Power Engineering, Poznan University of Technology, Piotrowo 3A, 60-965 Poznan, Poland; andrzej.ksiazkiewicz@put.poznan.pl (A.K.); karol.nowak@put.poznan.pl (K.N.); jerzy.janiszewski@put.poznan.pl (J.J.)

* Correspondence: grzegorz.dombek@put.poznan.pl; Tel.: +48-61-665-2192

Received: 13 August 2019; Accepted: 16 October 2019; Published: 16 October 2019

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Abstract: Due to fault currents occurring in electrical installations, high electromagnetic force values may be induced in current paths of low-voltage electromagnetic relays. This force may lead to an electromagnetic bounce that will further result in an electric arc ignition between contacts, and under some circumstances, it will result in contact welding. For the proper exploitation of relays, the threshold value of the maximum current, and thus the electrodynamic force, should be known. This force depends on several factors, including: contact materials, dimensions of relay current paths, relay electromagnetic coil, etc. This paper presents the results of calculations and an experiment on electromagnetic forces, which cover these factors. A static closing force, acting on the contacts, and the fault current were measured. As a result, values of the force and current threshold were obtained, which inform when an electrodynamic bounce may occur. The obtained result may be used in designing contact rivets and relay current paths together with the selection of adequate fault protection devices.

Keywords: relays; contact materials; contact bounce; electric arc; contact welding

1. Introduction

The flow of electric current in apparatus current paths, electric arc, or conductors located in a foreign magnetic field leads to the appearance of electrodynamic forces. These forces affect the flow of electrical charges, and consequently also on current paths, electric arc, or wires.

In electromagnetic relays, the flow of current of a considerable value can lead to the emergence of an electrodynamic force, affecting the contact system, and it can be large enough to cause a dynamic opening of the contacts. As a result, an electric arc will occur between the contacts, which may be welded [1–4] when the contacts close again. Welded contact will make the relay inoperable, which will necessitate its replacement or an exchange of the entire device within which it is incorporated. The electric arc will lead to the degradation of contact surface and may reduce the expected operating time of the relay [5–7].

Welding will depend on the type of contact material [8,9], arc burning time, arc energy [10–12] and the type of load [13,14]. It is important from the point of view of the design and exploitation of relays to determine the value of the current which may lead to the occurrence of an electrodynamic bounce. The knowledge of these values would allow the selection of the correct relay model for a given electric circuit, taking into account the peak current value of short-circuit. This is why the authors have decided to test the static contact force of an electromagnetic relay and test it with a fault current to determine the electrodynamic response. It has been proven that there is a correlation between the current value, static contact force, and electrodynamic bounce, and that it can be calculated with an acceptable level of accuracy.

Studies of electrodynamic forces that can act on electrical contacts have provided insight as to how these phenomena work. Both theoretical and experimental results are available that can, in some manner, describe these phenomena [15]. They describe the electrodynamic force generated by current flowing between contacts, but they do not link all force components. There are studies that utilize the contact force to describe the working principles of electrical equipment [16]. Many studies combine electrodynamic bounce of contacts with contact welding [1–3]. As shown in these studies there is a relation between contact bounce, contact welding, and electrodynamic force, however they do not focus on that subject. There is research concerning contact pressure, contact displacement, and contact bounces allowing the measurement of the dynamic characteristics of contactors [17]. Other ongoing research focuses on controlling the contact closing process by means of electromagnetic coil energy control [18,19]. Another approach is to use FEM methods for non-linear dynamic analysis of electrical machines in the time domain [20]. These studies are focused on controlling the electromagnetic coil and electrical contacts at make and do not address the topic of effects of electrodynamic bounce of contacts.

The experimental results presented in this paper provide information regarding the electrodynamic contact bounce related to the static contact force of the electromagnetic coil installed in a relay. These results can be useful in determining the electrodynamic bounce threshold solely on the dimensions of the relay current path and its rivet contact material. A theoretical analysis was conducted, taking into account three force components mentioned above, together with an experimental confirmation, which provided satisfactory consistency between theory and practice.

Research into the issue of electrodynamic bounce and electrodynamics in electrical contacts, focuses mainly on a single component of this force. It is focused mostly on the repulsion force between contacts [15] or force generated by electric arc [21]. Other studies attempt to describe these phenomena but only for very high currents, with a magnitude of kiloamperes [1,2,16]. Therefore, in this paper, the authors present results attempting to combine all force components induced during a fault current flow. The peak value of the current barely exceeds one kiloampere, as can be observed in typical, low voltage electrical installations. The spectrum of research presented in this paper is not covered by other studies.

The paper has been organized in the following way. The second chapter describes the main electrodynamic force components that have an impact on the electrodynamic bounce of contacts. In the third chapter the experimental setups and electromagnetic relays used in the research are presented and described. The results of the study were analyzed in the fourth chapter. The last and fifth chapter contains a summary and the final conclusions.

2. Analysis of Electrodynamic Contact Forces

In electric devices, the magnetic field is usually caused by the flow of electric current through the current paths of the same or another electrical circuit. The mutual forces of any pair of wires are proportional to the product of the values of currents flowing through these circuits and to the magnetic permeability of the environment in which these circuits are located. Electrodynamic forces and moments acting on conductive elements (rectilinear in particular) are calculated on the basis of Biot–Savart and Lorentz laws. The forces of dynamic interactions in electric circuits are distributed continuously. Assuming that the current path can be treated as a rigid body, elementary forces can be replaced by one cumulative force. In operating conditions, the continuous current flow should not lead to the appearance of significant forces and stresses in the current paths. However, such considerations should be taken into account in the case of flow of short-circuit currents through current paths.

When two wires L_1 and L_2 (Figure 1) are parallel and distant from each other by y, then there would be only one component of the electrodynamic force. When considering current paths with the same and finite length L placed opposite to each other and with a distance between them equal to a, the electrodynamic force can be calculated from the formula:

$$F_p = \frac{\mu_0}{2\pi} i_1 i_2 \frac{L}{a}\left[\sqrt{1+\frac{a^2}{L^2}} - \frac{a}{L}\right] \text{[N]}, \quad (1)$$

where: i_1, i_2—current flowing through the first and second current path (A), L—length of the current path (m), a—distance between the current paths (m).

Taking into account the construction of the tested relays (presented in Chapter 3), it can be concluded that such assumptions are justified due to the simple construction of the current path system.

Due to the step change of the contact surface, an additional electrodynamic force is created in the contact, which repels the contacts from each other. This force is caused by a change in the shape of the current path, and thus a change in the direction and density of current streams (Figure 2). For non-detachable contacts and for conducting operating currents, this force does not pose any hazards for the contacts. In the case of movable contacts, when a current of considerable value flows (fault current), this force may cause contact opening, appearance of the electric arc, and consequential contact damage [22]. Theoretical considerations assume that all contact geometry is symmetrical, and then the current conduction area on the contact surface is circular. In the case of axisymmetric contacts, repulsive force F_s is possible to be determined for any current density at the contact point [22].

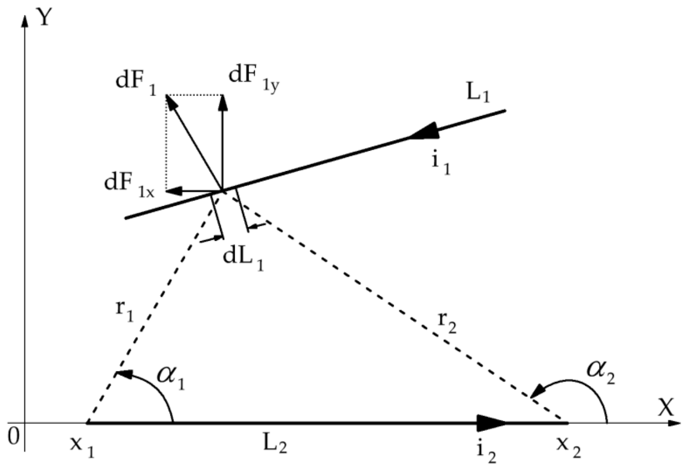

Figure 1. Determination of the electrodynamic interaction of one-dimensional wires of finite length with the currents i_1 and i_2, lying on the OXY plane, with one of the wires lying on the X axis [23].

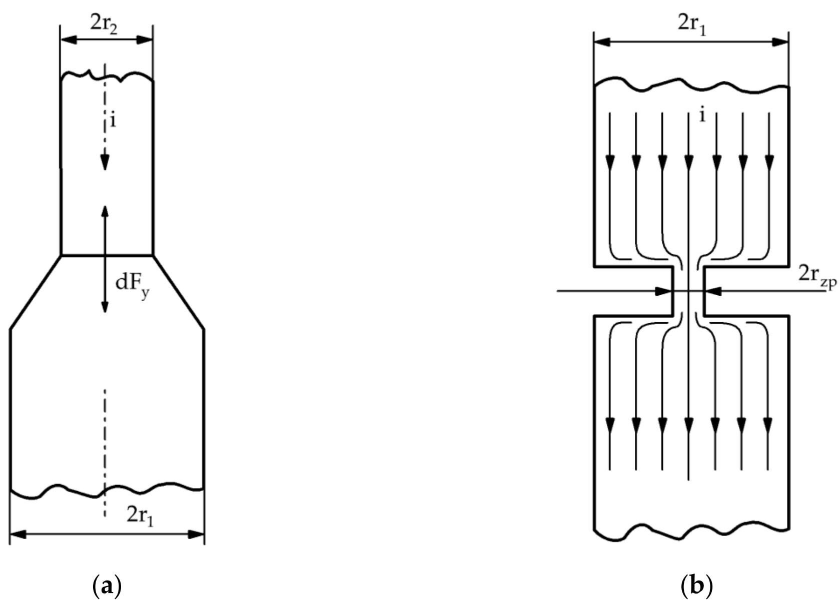

Figure 2. Sketches for the calculation of electrodynamic forces caused by: (**a**) the change in the cross-section of the conductor and, (**b**) in the point contact [24].

For a point contact, this force can be determined from the following dependence [23]:

$$F_S = \frac{\mu_0}{4\pi} i^2 ln \frac{r_1}{r_2} \text{ [N]}, \tag{2}$$

where: r_1—the radius of the apparent contact surface (m), r_2—the radius of the real contact surface (m).

In the real contact arrangement of the tested low voltage electromagnetic relays, there are forces coming from two parallel paths (current paths supplying electricity to the contact rivets), as well as from the narrowing of the contact area in the electrical contact. In order to analyze electrodynamic interactions in the case considered, the following assumptions were made:

- dynamic impacts are distributed continuously,
- the current path can be treated as a rigid body,
- the forces are parallel to each other.

The system of forces acting in the contact model under consideration and affecting the contact can be presented as sliding vectors and moved along the lines of their operation so that they are all hooked at one point, forming a convergent system of forces. Based on the above premises, it was assumed that the resultant force acting repulsively on the contactors can be determined as the sum of forces coming from two parallel wires F_P and narrowing in the contact area F_S:

$$F_1 = F_P + F_S. \tag{3}$$

During the flow of short-circuit current, in the extreme case, the forces generated may lead to the opening of the contacts. When the contacts are open, an electric arc is formed between them. This arc causes the occurrence of additional electrodynamic forces in the system of current paths. According to Reference [21], the value of this force was estimated at 22×10^{-5} (NA^{-1}). It is directed towards the current paths, which leads to their further mutual repulsion. Ultimately, the resultant force acting repulsively on the contactors is determined as the sum of the individual components, taking into account that F_A only occurs when the electric arc is present:

$$F_1 = F_P + F_S + F_A. \tag{4}$$

3. Results and Discussion

3.1. Used Materials

The following models of miniature relays were used to carry out the research experiments:

- RM85–2011–35–1012 (Relpol S.A., Poland) with contact material AgNi (Figure 3a),
- RM83–1011–25–1012 (Relpol S.A., Poland) with contact material AgCdO (Figure 3b).

The models used have a rated operating current of 16 A a.c., working voltage 250 V a.c., and coil operating voltage of 12 V d.c. The dimensions of contact springs, for two relay models, are shown in Figure 4. The dimensions of contact rivets and current paths are deliberately different in order to show the influence of relay construction on the resulting repulsion force.

The typical values of switching on and off times for RM85 and RM83 models are 7 ms and 3 ms, respectively. According to the manufacturer's data, the resistance of the contacts in each of the selected models is less than 100 mΩ.

Similar models of relays are manufactured by many companies worldwide, for example: Relpol (RELPOL S.A., Poland), Finder (Finder S.p.A. con unico socio, Italy), and Hongfa (Xiamen Hongfa Electroacoustic Co., Ltd., China). These relays have all utilized similar contact materials, both AgNi and AgCdO, and have almost identical dimensions. This can lead to the conclusion that the presented results can be applied to other types of relays, which are similar in design.

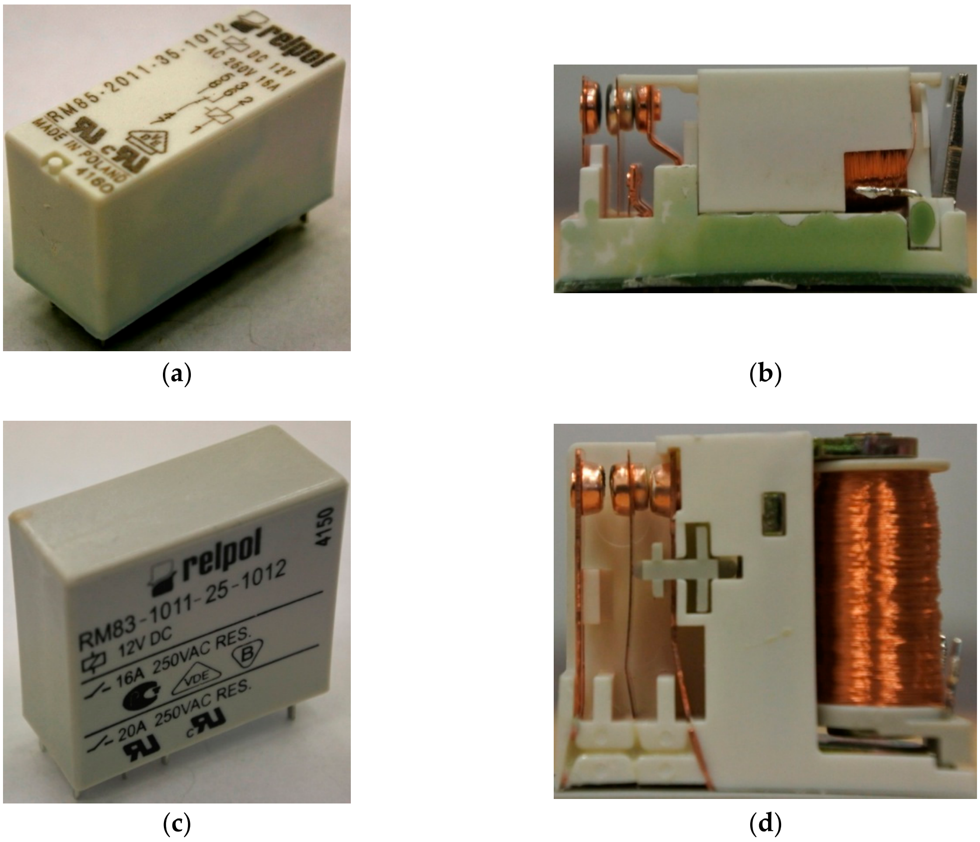

Figure 3. View of selected electromagnetic relays: (**a**) external view of RM85–2011–35–1012 relay, (**b**) internal view of RM85–2011–35–1012 with its contact positions, (**c**) external view of RM83–1011–25–1012 relay, (**d**) internal view of RM83–1011–25–1012 with its contact positions.

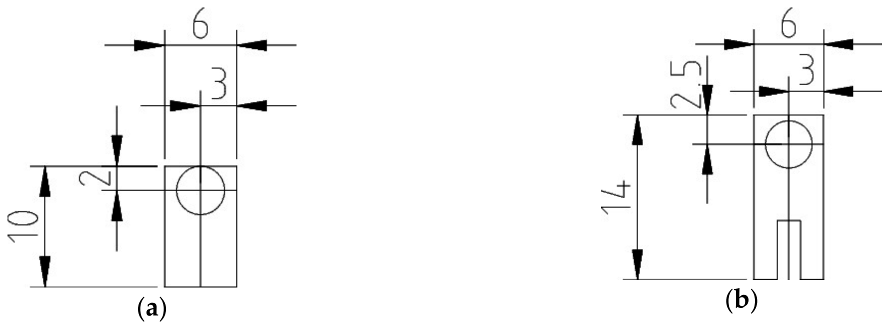

Figure 4. Dimensions (in millimeters) of moving contact springs for individual relay models: (**a**) RM85–2011–35–1012, (**b**) RM83–1011–25–1012.

3.2. Circuit Diagram

The circuit diagram for a testing circuit is presented in Figure 5 and the test bench in Figure 6. The circuit is supplied directly from the public power network of a low voltage of 230 V a.c. The peak current value is set by the value of limiting resistor R_{lim}. Voltage between contact relays and current flowing through them are recorded using an oscilloscope GW Instek GDS-3154 (GW Instek, Taiwan). The voltage was used to determine if the contacts are opened or closed and is not shown directly in any figure in this paper.

The circuit is protected against short circuits and overloads with an installation switch of rated operating current 16 A and characteristics B. The static contact force was measured using an FH–S (SAUTER GmbH, Germany) universal digital force gauge mounted on a dedicated TVL manual test bench for highly accurate tensile and compressive force measurement, equipped with length measurement. A single test was performed for each relay; at the beginning of the test, the contacts were in closed position. This situation simulates the occurrence of an unintentional short circuit during its normal exploitation.

Calculations of the electrodynamic force were based on theoretical principles presented in Chapter 2 and experimental results presented in Chapter 4, with the use of Scilab software (ESI Group, France) for numerical computation.

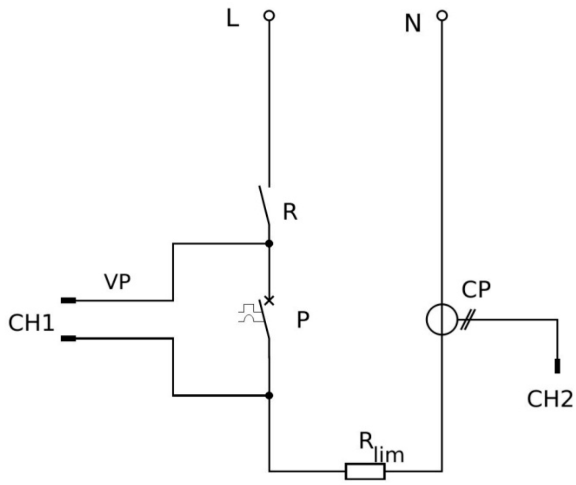

Figure 5. Testing circuit diagram: *R*—tested relay, *P*—protection of the circuit (installation switch), R_{lim}—limiting resistor, *CP*—current probe, *VP*—voltage probe, *CH*1, *CH*2—oscilloscope channels.

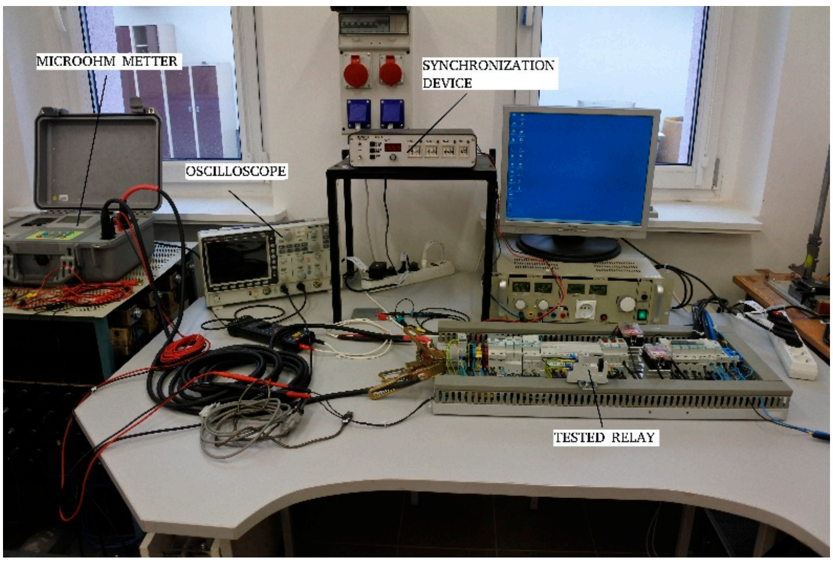

Figure 6. Photograph of the test bench used in the study.

3.3. Algorithm

To determine the values of individual components of the resultant electrodynamic force, i.e., F_S, F_P, and F_A, a calculation script for the Scilab program was created. This script algorithmized the mathematical equations presented in Chapter 2. The algorithm used is presented in Figure 7.

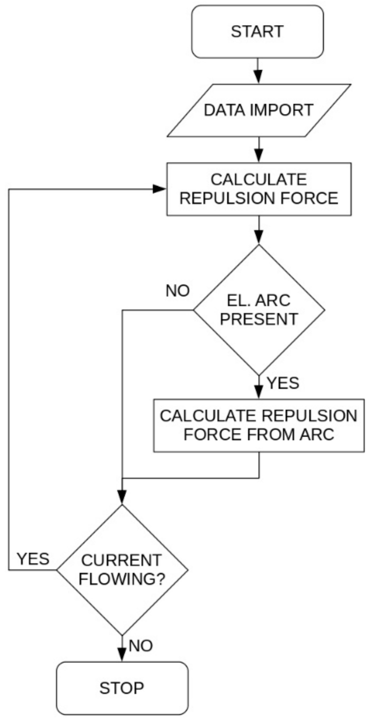

Figure 7. Algorithm of repulsion forces calculation.

4. Results and Discussion

Two cases of short-circuit fault current flow through relay contacts for which electrodynamic contact bounces were observed and analyzed. Two groups of previously presented relay models have been tested. Figures 8 and 9 show the time courses of the instantaneous current value and the calculated repulsive force F_1.

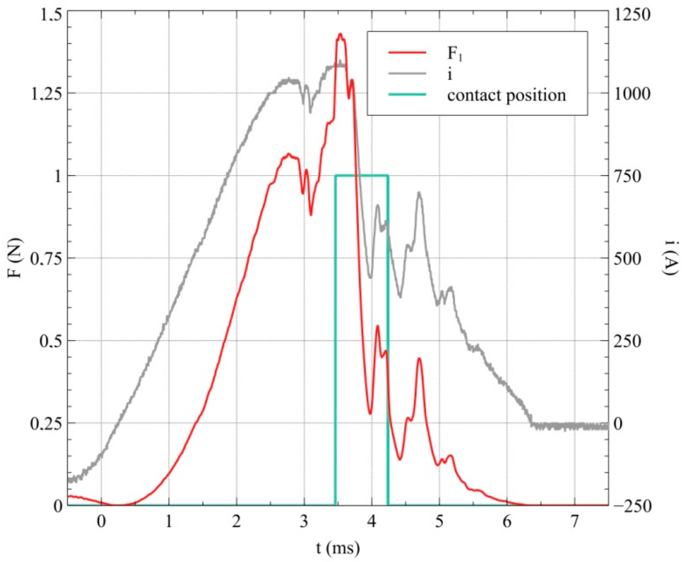

Figure 8. Dependence of repulsive force on the short-circuit current value; also marked is the moment of relay contact opening RM85–2011–35–1012: F_1—calculated repulsion force, i—current value, contact position—determines whether contacts were open or closed (high state—open contacts).

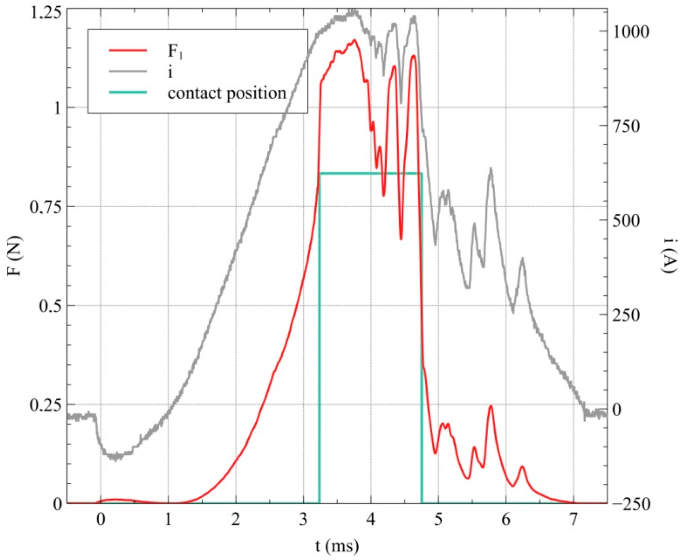

Figure 9. Dependence of repulsive force on the short-circuit current value; also marked is the moment of relay contact opening RM83–1011–25–1012: F_1—calculated repulsion force, *i*—current value, contact position—determines whether contacts were open or closed (high state—open contacts).

At the same time, time interval was marked during which the contacts remained open as a result of the electromagnetic bounce. Based on the analysis of the presented time series, the following conclusions can be made:

- the current is in phase with the source voltage,
- in the time when the contacts remain closed, force F_1 is proportional to the instantaneous current value,
- after the moment when the contacts are opened, there is a significant increase in force F_1 caused by the appearance of an additional component derived from the electrodynamic interaction of the F_A electric arc,
- at one point in time the circuit breaker starts to open its contacts, which results in a significant decrease of current value (which can be seen at time t = 3.7 ms in Figure 8),
- the resulting contact force is proportional to current value.

Figure 10 shows the electromagnetic blow-open process, during the fault current flow, for a single test of RM85–2011–35–1012 relay, with a visible eruption of molten contact material. Figure 10 shows four phases of the blow-open process: the ignition of electric arc between contacts, burning of electric arc phase, closing of electrical contacts with an eruption of heated, molten contact material, and welding of contacts phase.

For a full view of the phenomena occurring during the current flow, it is necessary to know the dynamics of the relay drive in order to try to determine the force that should arise in the current path with a greater value than that generated by the relay electromagnetic coil. Figures 11 and 12 show the dependence of the contact force of the movable contact versus the path of this contact in relation to the starting position. At the same time, the initial position should be understood as the closing state of the contacts when there is no electrical load and energy consumption by the relay coil is nominal. During the test, the values of coil current and supply voltage were measured. These values did not change with the increase of the force acting on the contacts (an increase of the displacement path). Additionally, one should take into account the force which is caused by the fixed contact, which in its closed position moves slightly in the direction of the drive. This force is for the RM83–1011–25–1012 19 cN model and for the RM85–2011–35–1012 22 cN. During the measurements of the closing force, the relay contacts were opened by the dynamometer until the contact current path was interrupted. With an increasing displacement, the force grew until the contacts opened, then rapidly diminished. It has been assumed that a force determined in this way will have to be achieved during the current flow in order for the contacts to be opened electrodynamically.

The maximum contact force of the movable contact in the RM83–1011–25–1012 model is 45 cN, and in RM85–2011–35–1012 it is 145.6 cN. The resultant value of the closing force which must be overcome to open the contacts due to the electrodynamic action is therefore 64 cN and 167.6 cN respectively. During the flow of nominal current, the calculated repulsion force is less than 0.03 cN.

The contact blow-open process is a complex one, dependent on the pre-open phenomena [25] and on electrodynamic forces [15,22,26,27]. The current thrusts of research are the effects of blow-open contact bounce on contact welding and the phenomena behind it [4,5,13,26]. Studies regarding the influence of electrodynamic forces [15,28] and high current [29,30] do not cover the electrodynamic action of the operating relay coil. Presented research shows the relationship between the electrodynamic blow-open of contacts under high fault currents and the static contact force trying to prevent the contacts from opening. The knowledge of how this process works can lead to both theoretical and experimental contamination of the peak current value which will not result in blow-open phenomena, thus lowering the chance of dynamic contact welding and increasing the relay life expectancy.

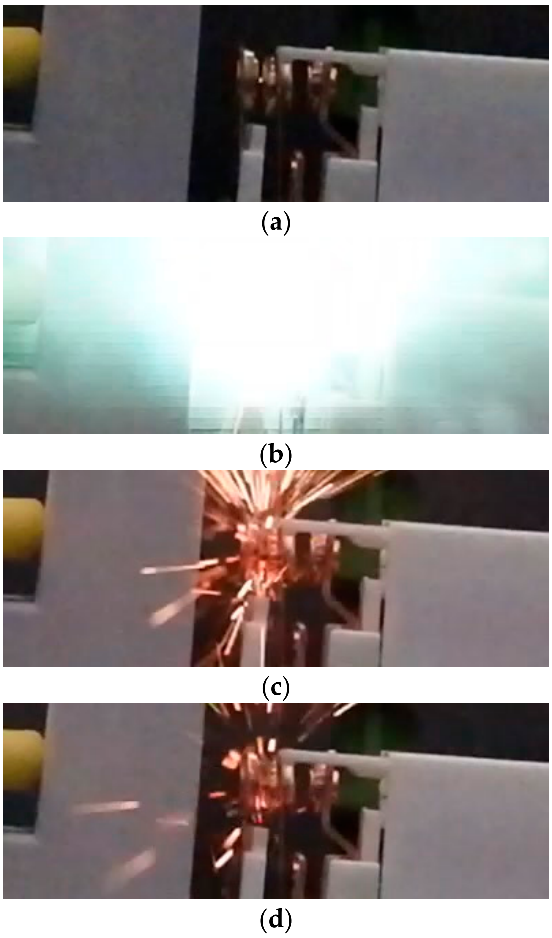

Figure 10. Photographs of the electromagnetic blow-open process for RM85–2011–35–1012 relay: (**a**) arc ignition during contact opening, (**b**) electric arc burning between the contacts, (**c**) closing of contacts with eruption of molten contact material, (**d**) closed (welded) contacts without current flow.

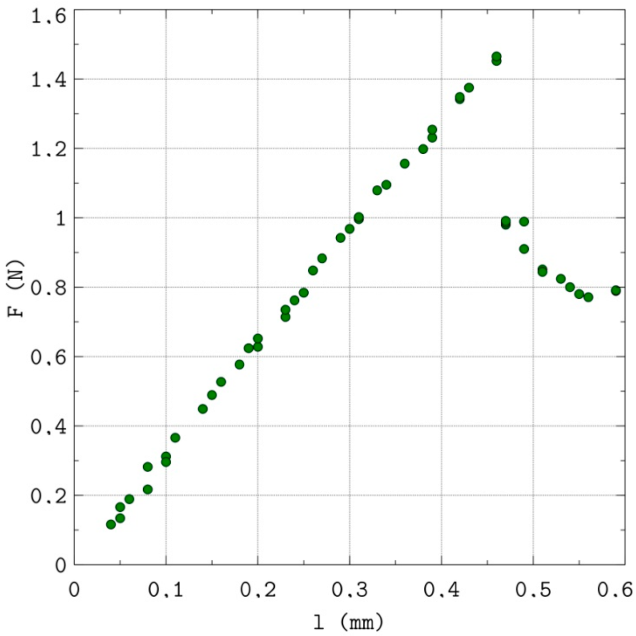

Figure 11. Dependence of the contact force of the movable contact on the path of this contact with respect to the starting position—relay RM85–2011–35–1012.

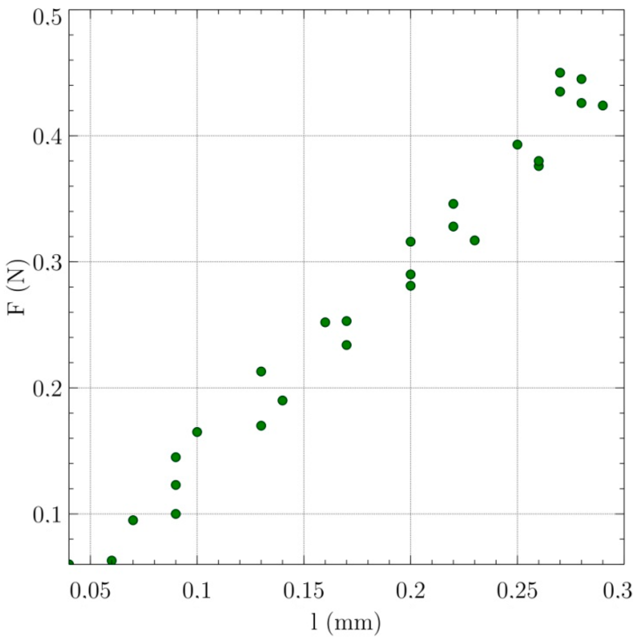

Figure 12. Dependence of the contact force of the movable contact on the path of this contact with respect to the starting position—relay RM83–1011–25–1012.

5. Conclusions

On the basis of the calculations carried out, the following theoretical values of the electrodynamic force were determined, with the corresponding moment of the relay contact opening time. These values are:

- 85.1 cN for the RM83–1011–25–1012 relay, which is 133% of the previously determined closing force,
- 122.1 cN for the RM85–2011–35–1012 relay, which is 72.9% of the previously determined closing force.

The relative error related to the closing force value is plus 33% for the model RM83–1011–25–1012, and minus 27.1% for RM85–2011–35–1012. On the basis of the results obtained, the following factors should be taken into account:

- relays are characterized by different construction of the drive coil,
- the force transmitting component of the drive is located at different heights of the current path; in the RM83–1011–25–1012 relay, it is below the contact, and in RM85–2011–35–1012 it is at the top,
- current paths have different lengths, widths, and densities, which affects their mechanical parameters, and in particular their elasticity,
- the formulas used to calculate the forces are simplified.

Despite the above-mentioned restrictions, it can be assumed that an error of 30% is acceptable with this type of estimated calculation. Thus, it can be considered that it is possible to determine approximately the value of the force and thus the instantaneous value of the current at which an electrodynamic contact bounce may occur. The opening of contacts in the real system occurred at current value of 1000 A in the RM83–1011–25–1012 model and at 1080 A in RM85–2011–35–1012. These values are similar, but due to the significant differences in the geometry of the contact system, they occur at different values of the electrodynamic force.

The presented results may be used by relay manufacturers to determine the peak current value which a specified relay model can conduct uninterruptedly under fault conditions. This may result in prolonging relay life expectancy by proposing a protection device (e.g., a fuse) that can limit the maximum value of fault current. Further studies may focus on other types of relays, with particular emphasis on different contact materials, and with a more accurate modeling of contact current paths. However, the new results should lead to a simplification of calculations that will allow engineers to use these studies in their work.

Author Contributions: Section 1 was prepared by A.K. and G.D. Section 2 was prepared by A.K., G.D., and K.N. Section 3 was prepared by A.K. and G.D. Section 4 was prepared by A.K., G.D., and J.J. Section 5 was prepared by A.K. and G.D. Conclusions were prepared jointly by all the authors.

Funding: This research was funded by the Ministry of Science and Higher Education, grant number 04/41/SBAD/4408.

Conflicts of Interest: The authors declare no conflict of interest.

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