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Relay Protection Using Inductive Coils: A Resource-Saving Approach

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Abstract: This paper presents the development and principle of operation of resource-saving overcurrent protection, which is an alternative to traditional current protections. The experiments were used to study the electromagnetic field for the protection of electrical installations connected to the cells of complete switchgears, voltage 6–10 kV, without the use of conventional protections with metal-core current transformers. As is known, such current transformers (CTs) have significant weight and dimensional parameters and high price costs. The method of research is comparison of the developed protection with traditional current protections made using traditional measuring current transformers. The scientific novelty of this work consists of the developmental theory of the construction of protection for inductive coils based on the measurement of electromotive force values in different modes and points in the simulation of a three-phase short circuit inside the cell of the complete switchgear. The dependence of magnetic induction on the position of the inductive coil inside the cell has been found. It has been shown that the simplest formula of the Biot–Savart–Laplace law can be used to calculate them. This paper presents and describes the conducted experiments with their methodology. As a result of the industrial application of such protections, the act of implementation of the patent for the invention of an industrial enterprise is presented. The selection of settings of resource-saving protection is presented, as well as a feasibility study of the presented protection in comparison with conventional protection. This paper consists of the following sections: The Materials and Methods section describes the methodology used to achieve the purpose of the research. The Experiments section describes all the experiments conducted to achieve the purpose of the research. The Results section presents the results of the conducted experiments, an evaluation of the use of inductive coils in relay protection, an example of calculating the selection of the settings of parameters of resource-saving protection, a presentation of the patent for the invention, and a presentation of the feasibility study of the effectiveness of the considered resource-saving protection on inductive coils. The Conclusions section presents the result of this work, which is the creation of resource-saving protection on inductance coils. The References section presents a list of the sources used.

Keywords: inductive coil; current; induction; resource-saving; complete switchgear

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1. Introduction

The problem of resource-saving in the electric power industry is constantly raised at meetings of the International Council on Large High Voltage Electrical Systems (CIGRE) and remains relevant at present. This includes the development of relay resource-saving short-circuit protection of various electrical installations. Resource-saving can be achieved by refusing to use expensive metal-intensive current-measuring transformers and current relays with metal cores, characterised by high cost, significant weight and dimensional parameters [1,2]. The purpose of this work is to develop resource-saving protection for various electrical installations connected to the distribution device cell. To improve the reliability of traditional current protection devices, including electromechanical, semiconductor and microprocessor varieties, it is recommended to use alternative current protection devices instead of traditional ones. As it is known, traditional protections receive information from current-measuring transformers, which also have inherent errors [3–6]. As an alternative to current-measuring transformers and corresponding protections based on them, one can consider protections based on the various magnetosensitive elements, such as Hall sensors [7], magnetoresistors [7,8], magnetodiodes [9], magnetotransistors [9], Rogowski coils [10] and reed switches [11,12]. The development of resource-saving protection devices not requiring the above-mentioned current transformers—for example, those based on reed switches—has been carried out since the 1960s [12]. As a promising direction for the development of alternative relay protection devices not depending on the above-mentioned current transformers, the authors chose inductance coils from an intermediate relay, type KL-25 [13,14]. Their choice was conditioned by their comparative advantages over other magnetosensitive elements, which have the possibility to simultaneously perform the functions of analogue-sampling and converter measurement, as well as measuring the organ of protection. In addition, they are characterised by cost-effectiveness, light weight and compact dimensions. At this present moment, a number of current protection devices based on various elements, including inductance coils, have been developed [15–27]. Below, we consider brief characteristics of protections based on various elements, which are alternatives to traditional protections and can be used as backup protections to the main protections of electrical installations. Each of the considered protections has its own features, which limit their wide application.

Execution of protection with current sensors made on magnetic current transformer (MCT). When using MCTs to provide relay protection with a current proportional to the current flowing in one of the phases—for example, in a transmission line in a network with isolated neutral—it is necessary to take into account the influence of the currents on the neighbouring phases. The following disadvantages are inherent in MCT protections: core saturation at significant current multiplicity and low output power. It is not possible to position the sensor in such a way as to exclude the influence of currents flowing through the wires of neighbouring phases, which affect the current regulation of a given phase and create additional noise in the sensor coil. These limitations have led to the limited application of MCTs for relay protection.

Execution of protections with current sensors made with Rogowski coils. These coils consist of a wire wound around a non-magnetic core placed around a conductor to measure the current flowing through it. The signal from Rogowski coils has a minimum voltage value. Compared to conventional current transformers, the weight and size parameters of the coil are much smaller and the current range is significant. Coils are not subject to saturation and have the disadvantage of low measurement accuracy.

Execution of protections on magnetoresistors. The main characteristic of a magnetoresistor is its dependence on induction, where the resistance is inversely proportional to the magnetic flux density (R = f(B)). The introduction of a semiconductor in a magnetic field with current flowing through it leads to a change in resistance. The lack of widespread use of magnetoresistors for current measurement is largely due to their inherent inability to respond to the modulus of the magnetic field, which significantly limits the scope of their application.

Execution of protections on magnetodiodes and magnetotransistors. The magnetodiode effect is a well-known phenomenon that occurs when a semiconductor with non-equilibrium conductivity is placed in a magnetic field. One of the disadvantages of magnetodiodes in measuring currents is their inherent nonlinearity, which limits their use in relay protection. Magnetotransistors are characterised by their stability with respect to temperature, linearity and wide frequency range. The output of a magnetotransistor is proportional to the instantaneous value of the magnetic field induction. The use of magnetotransistors is advantageous in situations where significant output power is not required. However, there are a number of limitations: a current source is required, which may not always be available; magnetotransistors are sensitive to interference, which affects the accuracy of measurements; a large number of sensors are required, which increases the complexity of the system; and measurements are affected by the modulus of the magnetic field as well as changes in ambient temperature.

Execution of Hall sensor protections. Applying a magnetic field to a current flowing through a semiconductor results in the Hall effect. The main feature of a Hall sensor is its ability to generate an electromotive force (EMF) when in a magnetic field, which depends on the current flowing through it. The disadvantages include the fact that the measuring circuits are complex, have residual voltage, require a stable supply of their circuits, are affected by the currents of neighbouring phases of the electrical installation and require compensation for the effect of temperature.

Execution of protection on inductance coils. For power transformers and branches from power lines in networks with voltage Unom = 220 kV or more, the use of traditional current transformers leads to a significant increase in the cost of installations. In this connection, a scheme of remote current measurement using induction coils was proposed. With these sensors, currents can be measured using a symmetrical component filter. This three-sensor filter is placed above or below the current paths. An EMF is induced in each three-phase current loop, which is used in this design. If the influence of external magnetic fields must be considered when measuring currents and if there are other lines nearby, the frames are shielded. In general, it can be said that inductance coils are subject to the influence of neighbouring lines, depend on the parameters of the primary circuit, are not fully damped inductances by the filter itself and also vary in frequency, which are their significant disadvantages.

Execution of reed switch protection. When a reed switch is exposed to an external magnetic field created by a conductive busbar, permanent magnet or control coil, the ends of the reed switch contact and are magnetised differently; their ends bend, attracting and closing the electric circuit. Advantages of the reed switch include that it can simultaneously fulfil the functions of a current relay and a current transformer; the control signal is transmitted through control circuits, not through measuring circuits; and it has a long service life. If a reed switch is equipped with a control winding and a start button is included in its circuit, it is possible to obtain a protection device with test diagnostics of faults. The information value is the EMF occurring at the leads of the control winding of the reed switch.

A comparison of the proposed protection and microprocessor-based protection also shows that the latter, like other protections, has its disadvantages [28], which include (1) economic factors, as microprocessor protection is expensive, and a (2) narrow operating temperature range. Further, there is a risk of software failure.

From the above, the following can be said. It is necessary that the protection of each individual feeder includes at least two mutually redundant and fully independent protections operating on different principles. This is necessary to ensure that in case of the failure of one protection system, the other will trip and protect the installation. This article presents an attempt to solve the problem of the realisation of an alternative, resource-saving protection system based on inductive coils. This coil installed in a cell of a complete switchgear reacts to the sum of electromagnetic fluxes, both from the current of its current-carrying busbar, opposite to which it is installed, and from the currents of current-carrying busbars of neighbouring phases. Laboratory studies of the electromagnetic field in the place of its installation were carried out for the purpose of further development of resource-saving protection [14]. The research method is a comparative analysis of the proposed overcurrent protection device and traditional current-protection devices.

2. Materials and Methods

The receiving organ of the presented protection is the inductance coils of the intermediate relay, type “KL-25”. The KL-25 intermediate relay with an operating voltage of 220 V is a widely used component in protection, telemechanics and automation schemes operating on alternating voltage [14]. The time of relay operation from supplying nominal alternating voltage to the coil to contact closure is less than 0.06 s. Based on this, it can be assumed that the time required for the appearance of an electromotive force on the relay coil and its subsequent detection on its contacts is 0.02 s. This time is sufficient for triggering other elements of this protection.

The inductive coil of the intermediate relay KL-25 is capable of withstanding the nominal voltage of 1.1 Unom for a long time. Its arrangement in the cell of the switchgear protects from the effects of water splashes, oils, emulsions and other liquids. In the proposed protection, the inductive coil performs a dual function, acting as a current sensor and a magnetic field measurement unit created by the currents in the phases of the protected electrical installation. In order to enable the inductance coil to react to the magnetic field, it is mounted in close proximity to the current-carrying busbars, in accordance with the minimum permissible distance specified in the relevant standards [14,29,30]. The fundamental principles of electrical engineering and relay protection, the essential tenets of electromagnetic transient processes and the design of mechanisms and machines, together with laboratory experiments, were employed to achieve the objective of this work. This work was conducted in accordance with the scientific guidelines of the Research Committee B5 “Relay Protection and Automation” of the International Council on Large Electric Systems (CIGRE), which unites scientists and specialists in the field of electrical power systems throughout Europe and the CIS countries. In this work, the method of mathematical modelling (Section 4.2), specifically, the approximation method, is employed to determine the tripping of the current protection of inductive coils against short-circuit currents.

The protection presented is a further development of resource-saving protection, which shows significant savings in copper, steel, high-voltage insulation, initial capital costs for design and installation and minimal annual operating costs by completely eliminating the use of traditional current-measuring transformers that contain all these components in quantities tens and hundreds of times higher than the proposed alternative protection. The objective of this experimental study is to develop resource-saving protection based on inductive coils, which do not require the use of traditional current-measuring transformers with metal cores to protect electrical installations connected to 6–10 kV switchgears. The choice for this protection is based on the fact that traditional protections are based on expensive, bulky and metal-intensive current-measuring transformers. To achieve this, experiments with a switchgear cell must be carried out. The effectiveness of the proposed resource-saving protection is substantiated by calculating the protection response settings, assessing its sensitivity coefficient and its technical and economic comparisons with traditional protection.

3. Experiments with a Switchgear Cell

3.1. Experimental Setup

The components of the setup used in our experiments are listed in Table 1 and shown in Figure 1.

Table 1. Components of the experimental setup.

№	Component	Quantity
1	Cell	1
2	First wall	1
3	Second wall	1
4, 11	Current-carrying busbars (4) and (11)	2
5	Circuit breaker	1
6,8	Cable	2
7	Three-phase load transformer	1
9	First current-measuring transformers	3

10	High-voltage switch	1
12, 15	Wires	2
13	Current recorders	3
14	Inductance coils	3
16	EMF recorders	3
17	Plate	1
18	Frame	1
19	Second current-measuring transformers	2

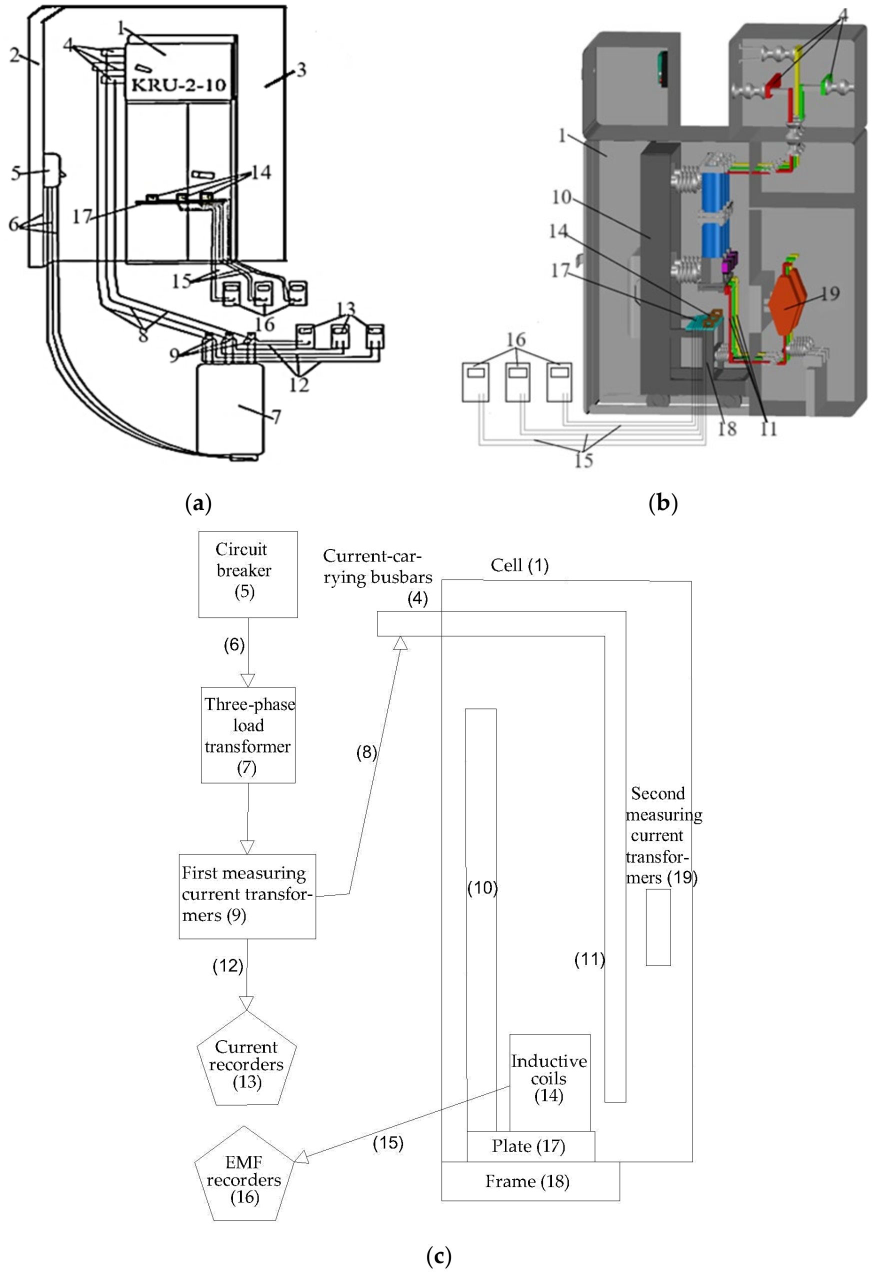


Figure 1. Experimental scheme for measuring the magnitude of the electromagnetic field: (**a**) front view of the cell—location of inductance coils in the cell; (**b**) side view of the cell with determination of the electromotive force in it; (**c**) functional block diagram of the experimental setup.

In order to determine the values of the electromotive force, field experiments were carried out inside cell 1, series "KRU-2-10" (Figures 1 and 2) [29]. Cell 1 was located in a room corresponding to the climatic conditions—moderately cold climate, category 3—on a concrete floor, and its width was 90 cm. On the left side of the cell was the first wall 2, and at the back was the second wall 3. An alternating current was supplied to the busbar 4 of cell 1. In order to carry out the experiments, its layout was assembled (Figure 1a), containing a circuit breaker 5, type VA57-35, with a rated current of 100 A, to which a three-phase load transformer 7, type "VDM-506", was connected on the primary winding by means of cable 6. Its secondary winding was connected to the first current-carrying busbar 4 by means of power cable 8 passed through the windows of the first current-measuring transformer 9 (type TTE-125 with a transformation ratio equal to KI = 4000/5). From the first current-carrying busbar 4, the current passed through the closed contacts of the high-voltage switch 10 to the second current-carrying busbar 11; the centre of its axis, with respect to cell 1, was as follows: 68 cm-phase A; 45 cm-phase B and 22 cm-phase C. The three-phase transformer 7 was installed opposite the front side of cell 1, and power cable 8 was laid on its left side. Current recorder 13 was connected to the secondary windings of current transformer 9 by wire 12. The electromagnetic field sensors were three identical inductance coils (ICs) (14) of the intermediate relay KL-25 without a metal core, connected to the electromotive force recorder 16 by means of wire 15 [14].

Figure 2. Photograph of the experimental setup.

To record the current 13 and the electromotive force 16, we used verified and certified multimeters, such as the Fluke 87 V. The inductance coil 14 inside cell 1 was installed and fixed on plate 17 using ordinary plasticine. Plate 17 was made of dielectric material, measuring 90*18*0.5 cm, with a scale of one centimetre. The distance from the plane of the location of the second current-carrying busbar 11 to the points of the location of inductance coil 14 on plate 17 was 12 cm, 18 cm and 24 cm, respectively. There are twenty-one points on plate 17 where the values of the electromotive force were measured, starting from the right to the left walls of cell 1, in three rows at the horizontal (zero) position of plate 17 and with a distance between these rows equal to 6 cm, and then at the same points and on the same rows, only already at the vertical position of the same plate 17.

The preparation for the experiments was as follows: plate 17 with inductance coil 14 placed on it using plasticine was mounted on frame 18 of switch trolley 10 inside cell 1. Plate 17 had three height positions relative to frame 18: the first was 0 cm (zero position on frame 18), the second was 6 cm and the third was 12 cm above it. The measured distance at which inductance coil 14 was mounted on plate 17 is counted from the right wall of cell 1 to its left wall. The inputs L1 of the primary windings of the second current-measuring transformer 19, type TOL-10-800, were connected to the second current-carrying busbar 11 of cell 1 [31]. The L2 leads of the primary windings of the current-measuring transformers have been short-circuited as a three-phase short-circuit. The secondary windings of CT 19 were shorted together. For safety reasons, load transformer 7 used in the experiments and the case of cell 1 were grounded.

3.2. Experiment: Current Flow Through Three Busbars (Three-Phase Short Circuit)

To determine the values of the electromagnetic field strength inside cell 1, circuit breaker 5 was included in all the experiments carried out (Figure 2). After the first current-carrying busbar 4 of cell 1, the three-phase load transformer 7 supplied alternating current through power cable 8. Current recorder 13 regulates the strength of the current flowing through the first current-carrying busbar 4 in accordance with the indications.

The three-phase short circuit was carried out by passing the current through the first and second of the three live busbars, 4 and 11. The value of the current flowing through them started with a current value equal to I = 100 A. At the same time, the EMF values of the inductance coil 14 placed on plate 17 were recorded by recorder 16. The current was applied to the first busbar 4 of cell 1. The inductance coil 14 was moved from the initial point of 0 cm to the final point of 90 cm, recording the EMF values at each measured point. By increasing the current value at each measurement point by 100 A, the EMF measurements were repeated up to 600 A—the maximum current that can be delivered by the three-phase load transformer 7 (Figure 1a). In addition, it was necessary to obtain EMF values at high current values. An approximation in the Excel program was used for this purpose. When current is applied to the first current-carrying busbar 4, the minimum safe distance for electrical installations with a rated voltage of 10 kV, according to the “Rules for the design of electrical installations”, is 12 cm (first row) from the plane of the second current-carrying busbar 11 [30] for all points where the inductance coil 14 is located. Furthermore, the electromotive force values are measured and recorded at the same points only at distances (h) equal to 18 and 24 cm (second and third rows of plate 17) from the same plane of location of busbar 11 at the first, second and third positions of plate 17 with inductance coil 14, both with and without the presence of the right wall of cell 1. The experiments were carried out on the switchgear cell in two variants: (1) with all cell walls and (2) without one side wall of the cell [29]. The purpose of these experiments was to find out to what extent the presence or absence of one of the walls of the switchgear cell affects the total resultant value of the magnetic field when determining the location of the inductance coil as the receptor of the alternative protection.

4. Experimental Results

4.1. Experiment with a Three-Phase Short Circuit in the Cell

The results were obtained using a real experimental setup. The experiments were carried out in the scientific laboratory of the Department of “Electric Power Engineering” of the non-commercial joint-stock company “Toraighyrov University”. From the analysis of the conducted experiments, that is, when passing the current through the three first 4 and second 11 current-carrying busbars (nominal mode of operation of the electrical installation connected to cell 1) the maximum values of EMF inside cell 1 were found for the three rows where the inductance coil 14 on plate 17 with the presence of its right wall, revealed in the following points: 22, 47 and 68 cm for the distance equal to h = 12 cm; 22, 47 and 74 cm for h = 18 cm; and 16, 47 and 74 cm for h = 24 cm.

At the same first position of plate 17 with inductance coil 14, the maximum values of EMF were found inside cell 1 for three rows, but without the presence of its right wall, they were found at the following points: 22, 45 and 68 cm for the distance equal to h = 12 cm; 22, 45 and 74 cm for h = 18 cm; 22, 50 and 86 cm for h = 24 cm, respectively, from the second conductor busbar 11 of cell 1.

Regarding the right wall, with the second (6 cm high from frame 18) and third (12 cm high from frame 18) positions on plate 17 with inductance coil 14, the maximum EMF values for the three rows were obtained at the following points: 0, 23, 45 and 68 cm for the first row; 0, 24, 45 and 70 cm for the second row; and 0, 24, 47 and 64 cm for the third row.

The arrival of the maximum value of induction with a deviation of 2 cm (point 47 cm) from the centre (45 cm) of the axis of the second current-carrying busbar 11 of phase “B” at a distance equal to h = 12 cm is due to the internal distribution of the magnetic field.

However, in percentage terms, it does not exceed five percent (5%). The difference in the results of the electromotive force values in the second and third positions of plate 17 with inductance coil 14 compared to its first position is that they are numerically greater, especially at the third position. This is explained by the fact that in these positions, inductance coil 14 is as close as possible to the internal metal structures of cell 1, namely to the structures of switch actuator 10 and to the door of cell 1, which in turn creates additional magnetic fields (interference).

The lowest values of EMF for all three rows and without the presence of the right wall of cell 1 fall on the points 34 and 57 cm, which corresponds to almost half (½) of the distance between the centres of two current-carrying busbars of phases AB and BC and equal to AB = 33.5 cm; BC = 56.5 cm. Electromagnetic fields when passing a current through three current-carrying busbars 4 and 11, concentrated in the right wall (if available) of cell 1 are superimposed on the magnetic fields created by currents from the first busbar 4 and the second current-carrying busbar 11 and increase the value of the total EMF in all measured points by 1.7–4.6 %.

On the basis of the experiments carried out and the comparison of the values of the EMF measured in this case, both with and without the right wall of cell 1, the percentages obtained do not exceed the value of five percent (5%). In this case, it can be considered that the presence or absence of the right wall of cell 1 of the complete switchgear does not affect the resulting value of the EMF and can be neglected.

The analysis of the experiments we performed has shown that when the first plate 18 is at the first position, the EMF is maximal at the following points:

- 22, 47 and 68 cm at a distance of 12 cm from the current-carrying busbars;
- 22, 47 and 74 cm at a distance of 18 cm;
- 16, 47 and 74 cm at a distance of 24 cm from busbar 11.

When the first plate 18 is at the second and third positions, the EMF is maximal at the following points:

- 1, 23, 45 and 68 cm at a distance of 12 cm;
- 1, 24, 45 and 70 cm at a distance of 18 cm;
- 1, 24, 47 and 64 cm at a distance of 24 cm from busbar 11. respectively.

In consideration of the tests conducted on all types of short circuits, which facilitate the identification of the points at which the EMF is at its maximum, it has been determined that it is advisable to mount the actuators of the proposed protection, which are reed switches, at the first position of the first plate (17). The optimal position for the actuators is found to be opposite the centre of the axes (due to the concentration of the magnetic induction maximum) of the live busbar 11 of cell 1, at a distance of 12 cm from them, where the EMF is higher than at the other two distances of 18 and 24 cm. Given the difficulty of detuning the overcurrent protection, it is also inadvisable to place the inductance coils at the second and third positions of the first plate 17 due to the significant influence of the metal structures of cell 1, which generates additional interference.

4.2. Triggering of Current Protection Made on Inductive Coils Against Short Circuit

Based on the results of the experiments, let us consider the operation of current protection in the event of a three-phase short circuit in the protected electrical installation of cell 1 when an inductance coil is mounted—for example, at point 22 cm. Let us derive the dependence of the magnetic induction B on the current I at the distance h = 12 cm from the lower terminal of the busbar 11 of the breaker of cell 1. When a three-phase current I = 600 A is applied to busbar 4 of cell 1, B = 468 μT at this point. Figure 3 shows this dependence for h = 12 cm. The straight line in the centre is the dependence of the magnetic induction on the current, calculated by Equation (1).

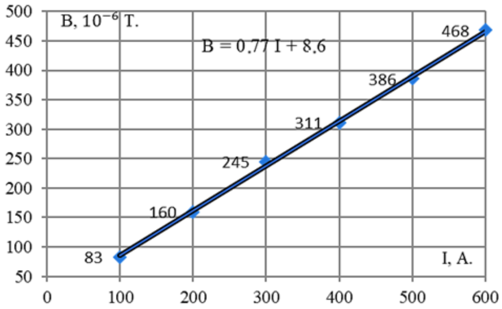


Figure 3. Magnetic induction as a function of three-phase current at a distance of 12 cm from the terminal of busbar 11.

We can approximate the dependence of the magnetic induction on the current and the distance between a current-carrying busbar and an inductance coil $B = f(I, h)$ as:

$$B = 0.77 * I + 8.6 \quad (1)$$

When working in the Excel program, when a trend line is selected, its format is selected. In the opened window, an equation pops up, which shows the more accurate reliability of the constructed diagram. And the higher the value tending to "1" in this equation, the better the points of the diagram of the given dependence are built. In this equation, the value of 0.77 is multiplied by the current value and summed with the value of 8.6.

Using Equation (1), we calculate B under the SC current $I_{SC} = 15$ kA at the terminal of busbar 11: $B_{15\ kA}$ = 11,550 μT. Based on the rated values of the actuating magnetomotive force (MMF) fact of the inductance coil and its length l_C, we calculate the magnetic induction *Bact*, under which the inductance coil actuates, that is, when EMF appears at its terminals. For example, for inductance coils from an intermediate relay, type "KL-25" with F_{act} = 302 A [14]:

$$Bact = \frac{F_{act}\mu_0}{l_{coils}} \quad (2)$$

where $l_{coils} = 7,2$ cm is the length of the factory inductance coil; μ_0 = 4π × 10^{-7} H/m is the magnetic constant. Hence,

$$Bact = \frac{\mu_0 \times F_{act}}{l_{coils}} = \frac{\mu_0 \times 302}{0.072} = 5418\ \mu\text{T}.$$

Finally, since $B_{15} > B_{act}$ at $I_{SC} = 15$ kA (11,550 μT > 5418 μT), an inductance coil of this type can be used for alternative resource-saving current protection.

4.3. Selection of Tripping Settings for Alternative Maximum Current Protection Using Inductive Coils

Based on the results of the research, a selection of tripping settings for alternative maximum current protection using inductive coils was compiled. The sensitivity coefficient of a traditional overcurrent protection is calculated by Equation [4]:

$$K_{sens} = \frac{I_{SCmin}}{I_{pt}} \quad (3)$$

where I_{SCmin} is the minimal SC current; I_{pt} is the protection operation current.

As is known, an inductance coil operates under the action of magnetic induction, i.e., after the occurence of EMF at its terminals. Therefore, we can write:

$$K_{sens} = \frac{B_{SCmin}}{B_{op}} \quad (4)$$

where B_{SCmin} is the magnetic induction induced by minimal SC current flowing through current-carrying busbar 11 at the point where the inductance coil is mounted; B_{op} is the induction under which EMF occurs at the terminals of the inductance coil.

$$Bop = \frac{\mu_0 * F_{ICop}}{l_{IC}} \quad (5)$$

where μ_0 is the permeability of air 4π × 10^{-7}H/m; F_{ICop} is the magnetomotive force of the inductance coil; l_{IC} is the IC length.

Calculation of alternative overcurrent protection. Let us calculate the protection operation induction B_{pt} for the voltage-blocking protection of a TM-2500/10 power transformer with a Y/Y-0 winding connection and a low voltage of 0.4 kV [32]. When selecting the protection operation current, we set the electric motor self-starting coefficient $K_{selfstart}$ = 5 and the protection offset coefficient K_{off} = 1.3.

$$I_{op\ max} = \frac{S_{nom}}{\sqrt{3}\ U_{nom}}, \quad (6)$$

where S_{nom} is the nominal power of the power transformer, kVa; U_{nom} is the nominal voltage of the high-voltage side of the power transformer.

$$I_{op\ max} = \frac{S_{nom}}{\sqrt{3}\ U_{nom}} = \frac{2.5}{1.73 \times 10} = 145\ \text{A}.$$

Let us mount an IC at the distance, e.g., h = 12 cm from the centre of the current-carrying busbar 11, at point 68 cm. In this case, the protection operation induction is calculated as:

$$Bpt = \mu_0\, \frac{K_{off}K_{selfstart}I_{ptmax}}{2\pi h} = \mu_0\, (\frac{1.3 \times 5 \times 145}{2 \times \pi \times 0.12}) = 1.2\ \mu\text{T},$$

With the neglect of interference because the protection is voltage blocking, let us mount a KL-25 inductance coil with the magnetomotive force F_{ICop} = 302 A [14,33], as well as the length l_{IC} = 0.072 m (from the reference data). Then,

$$Bop = \frac{\mu_0\ F_{ICop}}{l_{IC}} = \frac{\mu_0 \times 302}{0.072} = 5418\ \mu\text{T}.$$

According to our calculations, $Bop > Bpt$. This means that the selected IC satisfies the protection conditions. Let us check the sensitivity of the overcurrent protection by calculating its sensitivity coefficient K_{sens}.

For a TM-2500/10 power transformer, the maximal operation current $I_{op\ max}$ = 145 A. The cable length l = 1 km. Based on the reference data [32], we take an ASB cable 3 × 70 with I_{rated} = 185 A. The resistance of the power transformer X_{trans} = 2.6 Ω and the total resistance X_{Σ} = 2.6 kΩ. Let the minimal SC current be I_{SCmin} = 15 kA. Following Section 4.2, the induction of the magnetic field produced by minimal SC current flowing through current-carrying busbar 11 of cell 1, near which the IC is mounted,

$$B_{SCmin} = 11{,}550\ \mu\text{T}.$$

Substituting B_{op} and B_{SCmin} in Equation (4), we find the sensitivity coefficient of the overcurrent protection:

$$K_{sens} = \frac{B_{SCmin}}{K_{err} \times B_{op}} = \frac{11550}{1.1 \times 5418} = 2.13,$$

where K_{err} = 1.1 is the safety factor, which characterises the error of IC mounting.

Since the found sensitivity coefficient K_{sens} = 2.13 > 1.5, i.e., it meets the protection requirements, the maximum current protection based on inductance coils can be used as an alternative to the traditional maximum current protection.

In the event that the maximum current protection is deemed sufficient to satisfy the requisite sensitivity requirements, it is duly installed. In the absence of such satisfaction, however, the inductance coil is relocated in closer proximity to the current-carrying busbar 11, and the aforementioned calculations are then repeated.

4.4. Algorithm of Operation of the Current Protection Based on Inductance Coils

Based on the results of the experiments, we can propose the following algorithm for the operation of the current protection based on inductance coils. The operational principle of the proposed current protection, as well as that of any other current protection based on inductance coils, in the event of a short circuit in a protected electrical installation connected to a switchgear cell, is based on the effect of the magnetic flux *F* generated by the current in a busbar on an IC opposite to which it is mounted (at a safe distance according to the regulations for electrical installations) and at the point where the magnetic flux is at its maximum. In the event of a short circuit in the protected electrical installation, an increase in current in a busbar of cell 1 is observed, which is then reacted to by the inductance coil in response to the change in the magnetic field. Consequently, the voltage across the terminals of the inductance coil is increased. Given that the initial voltage is relatively low, approximately 2 V, it is subsequently elevated to 220 V by a voltage booster before being applied, for instance, to the winding of the time relay. Consequently, the time relay is triggered with a certain delay. The signal from the aforementioned time relay is then conveyed to the winding of the intermediate relay, which in turn initiates and transmits a signal to the trip coil of the circuit breaker within the cubicle via the signalling relay. Consequently, the circuit breaker is triggered, resulting in the disconnection of the protected electrical installation from the main electrical network.

During normal operation of the electrical installation connected to the cubicle, the parameters of the voltage amplifier are set in such a way that it trips only when a voltage of 2 V appears on it. If the voltage is lower, the current protection does not operate. The construction elements of the current protection based on inductance coils are made of easily accessible and inexpensive materials.

5. Patents

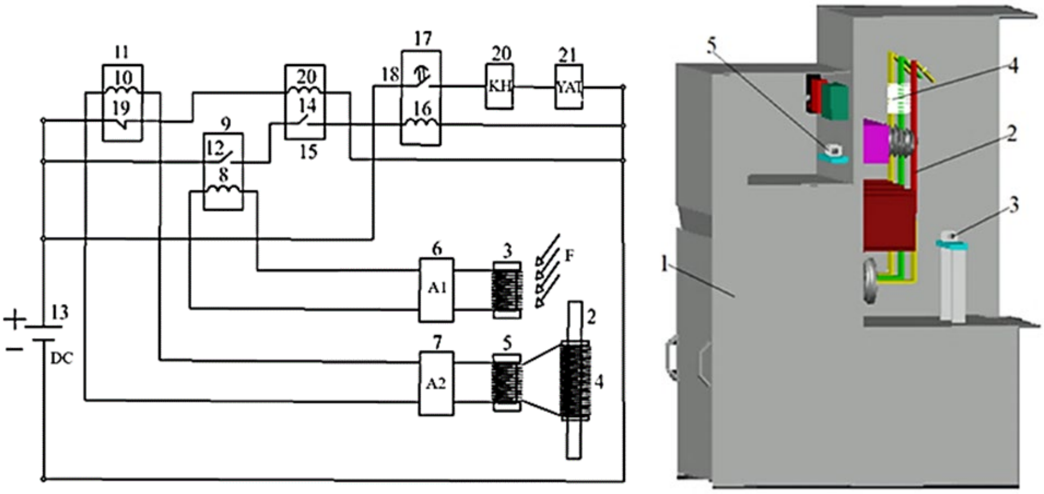
In order to understand the operating principle of the protections implemented in inductive coils, a patent for the invention "Maximum current protection with minimum blocking voltage" is presented. This protection is implemented on inductive coils and is an alternative to traditional current protection.

5.1. Maximum Current Protection Design with Minimum Voltage Blocking

Operating principle [34]. Considering the short-circuit mode on the protected electrical installation connected to the K-63 series cell 1 complete switchgear, it should be said that the main factor is the effect of the magnetic flux F (indicated by arrows) generated by the current of busbar 2 on the first 3 and second 4 inductance coils, the second 4 coil having primary and secondary windings wound on busbar 2 and performing the function of a measuring voltage transformer, analogous to the usual conventional protection [34,35]. At the same time, the secondary voltage is removed from the secondary winding of the second coil 4 and fed to the third inductance coil 5 (Figure 4a). This device is a protection set, which can be installed in the cells of a complete switchgear, closed switchgear or in closed current conduits, and can also be mounted as a separate set for each phase. The first inductance coil 3 is installed opposite current-carrying busbar 2 and in the place where there is a maximum value of magnetic flux (Figure 4b). The first 3 and the third 5 inductance coils are installed on a dielectric base in cell 1, series K-63, with the first coil 3 in the cable compartment and the second coil 5 in the relay cabinet of the cell. In the event of a short circuit in the protected electrical installation, the current in its current-carrying busbar 2 increases, and the first 3 and second 4 inductance coils react to changes in the magnetic field, whereby the first inductive coil 3 is installed at a safe distance equal to 12 cm from the given busbar 2 according to the Rules for Electrical Installations [30]. As a result, an electromotive force is induced in the first inductive coil 3 and on the secondary winding of the second inductance coil 4, which is fed to the third inductance coil 5 (Figure 4a,b).

Due to the fact that the values of the removed electromotive force from the terminals of the first 3 and second 4 inductance coils have small values, of the order of 3 and 1 V, they are increased by means of the first voltage amplifier (A1) 6 to 220 V, and by means of the second voltage amplifier (A2) 7 to a value equal to U = 100 V. After that, these voltage values from the first voltage amplifier 6 are fed to the winding 8 of the first intermediate relay 9, and from the second amplifier 7 to the winding 10 of the minimum voltage relay

11 (Figure 4a). As a result, the first intermediate relay 9 triggers the closing contact 12, sending the potential "+" coming from DC source 13 to the closing contact 14 of the second intermediate relay 15, from which this potential "+" comes to the winding 16 of the time relay 17.



(**a**) (**b**)

Figure 4. Maximum current protection design with minimum voltage: (**a**) structural diagram; (**b**) placement of its elements in the cell of a complete switchgear cubicle.

The positive potential of the "+" pole of DC source 13 is then applied to the delayed closing contact 18 of time relay 17. In this case, at the same time as the first intermediate relay 9, the minimum voltage relay 11 is actuated, whereupon contact 19 opens, causing the winding 20 of the second intermediate relay 15 to be deenergised and this relay to be actuated. From the time-delayed closing contact 18 of the time relay, the positive potential "+" of DC source 13 goes to signal relay (KH) 20, which sends the potential "+" to the first wire of the trip coil (YAT) 21 of the circuit-breaker of the electrical installation. As a result, the protected electrical installation is disconnected (Figure 4a). The second output: winding 20 of the second intermediate relay 15, the winding 16 of the time relay 17 and the trip coil (YAT) 21 are connected to the "−" pole of the DC source 13 (Figure 4a).

In normal operations, connected to cell 1 of the entire electrical installation of the switchgear, the parameters of the first 6 and second 7 voltage amplifiers are set in such a way that they are only triggered when the voltage at their terminals is 3 and 1 V, and at lower voltage values, the alternative maximum current protection for disconnecting the electrical installation is not triggered.

Advantages of the device. The absence of the use of current and voltage-measuring transformers with metal cores, which contain expensive steel, copper and high-voltage insulation, as well as significant weight and dimensional parameters, in this protection meets the actual problem of relay protection—resource-saving of the materials used—and is one of the alternative ways of realising the maximum current protection, performed with the use of inductive coils.

The proof of the results of the conducted experiments is the Act of Introduction into pilot operation of this patent for invention, received from the Republic of Kazakhstan, at one of the industrial enterprises. Below is the Act of Introduction into Experimental Operation and its translation in English.

ACT of Introducing into Production the Results of Scientific Work—A Patent for an Invention

We, undersigned, associate professor Isabekov D.D., professor Markovsky V.P. and technical director of "El-Nur-Service" LLP Temirkhanov E.U. have made the present act that the patent for invention of the Republic of Kazakhstan "Design of maximum current protection with minimum voltage blocking" has been put into trial operation in "El-Nur Service" LLP located in Pavlodar city, Pavlodar region, Republic of Kazakhstan.

The following results were obtained on the basis of the research and development work performed under this invention patent:

1. This invention made it possible to refuse the use of expensive and bulky current and voltage-measuring transformers in terms of weight and dimensional parameters;
2. Fully meets the actual issue of relay protection—resource-saving of used materials and represents a completely new approach to the realisation of maximum current protection, performed with the use of inductive coils;
3. Has lightened the weight and overall dimensions of the 6–10 kV switchgear cell since traditional current and voltage transformers are not used—in this case, there is also a possibility of complete abandonment of the use of the switchgear cell, where a voltage transformer is usually installed.

The above-mentioned scientific results are used in the protection of high-voltage electric motor sewage pump of the canteen and shower room of the enterprise, which purposefully allowed for the reduction in the cost of material resources required for the layout of protection, as well as setting the settings of operation of current protections of high-voltage electric motor.

5.2. Technical and Economic Justification for the Effectiveness of the Design of Maximum Current Protection with Minimum Voltage Blocking

In light of the findings from the magnetic field parameter measurements, we may consider this developed device, constructed with inductive coils [34], as an illustrative example. In order to ascertain the economic viability of utilisation, namely the impact of material resource conservation, a comparative technical and economic analysis will be conducted using the developed alternative maximum current protection system as a case study, in comparison to the traditional maximum current protection system, which is constructed on a microprocessor, semiconductor and electromechanical basis. The national currency of the Republic of Kazakhstan is the tenge (KZT); consequently, all calculations will be made in tenge. To facilitate understanding, it is noted that the average exchange rate of one US dollar (USD) to the tenge was approximately KZT 452 as of 5 March 2024. (https://nationalbank.kz/ru/exchangerates/ezhednevnye-oficialnye-rynochnye-kursy-valyut/report?beginDate=04.03.2024&endDate=05.03.2024&rates%5B%5D=5, accessed on 5 March 2024).

The cost of the development "Maximum current protection design with minimum voltage blocking" consists of the costs of its components, which include an inductance coil from the intermediate relay "KL–25" [14] with the cost of KZT 5000.

- Accessories for the inductive coil mounting block: clamp (150 g of plastic, "PLA" type)—KZT 1370;
- As well as the support stand (200 g of plastic "PLA")—KZT 1826;

(1) Olflex classic cables: Section 3 × 1.5 mm^2, connecting the first inductance coil with the first voltage amplifier—KZT 216 × 3 m = KZT 648 [14,36];
(2) Section 3 × 1.5 mm^2, connecting the second inductance coil with the third inductance coil—KZT 216 × 4 m = KZT 864;

- Section 3 × 1.5 mm^2, connecting the first voltage amplifier with the first intermediate relay—KZT 216 × 1 m = KZT 216; section 3 × 1.5 mm^2, connecting the second voltage amplifier with the second intermediate relay—KZT 216 × 1 m = KZT 216;
- The cost of the current relay, type "KA-40/10", is KZT 25,000 [14];

- The cost of the first and second intermediate relays, type "KL-25", is KZT 21,500 × 2 = KZT 43,000 [14];
- The cost of the minimum voltage relay, type "KV-54", is KZT 21,000 [14];
- The cost of the first and second voltage amplifier is KZT 12,000 × 2 = KZT 24,000 [36];
- The cost of time relay, type "ST3PR", is KZT 6440 [37]; the cost of index relay, type "KH-21", is KZT 13,116 [14].

The inductance coil is inserted into the clamp, which is fixed on the support stand. At the same time, their cost is KZT 8196.

Let us add to this sum the cost of connecting cables, brand Olflex classic: KZT 648 + 864 + 216 + 216 + 216 = KZT 1944; the cost of two intermediate relays, type "KL-25", is KZT 43,000.

- The cost of the time relay, type "ST3PR"—KZT 6440; the cost of the minimum voltage relay, type "KV-54"—KZT 21,000;
- The cost of two voltage amplifiers—KZT 24,000; the cost of the indicating relay, type "KH-21"—KZT 13,116. The cost of the used elements of this protection for one phase is KZT 117,696. Let us take into account the cost of protection elements for three phases of the switchgear cell: 3 × KZT 117,696 = KZT 353,088.

An adjustment with the manufacturing of this device will cost an amount equal to KZT 5000. The total cost of this device will be KZT 358,088. Also, the cost of the device includes travel expenses for trips to substations of industrial enterprises (within the region and the country), equal to the amount of KZT 50,000, and then we obtain the cost of the product, which is about KZT 408,088.

Due to the fact that at the substations of industrial enterprises, in addition to the widespread microprocessor relay protection devices (produced near and far), still successfully operate relay protection devices on the semiconductor and electromechanical basis, then the technical and economic comparison will be carried out with this in mind. For example, the average cost of current transformers with a metal core, type TOL-10, with a transformation ratio equal to Ki = 800/5 is KZT 100,000 [31]. Accordingly, we must factor in the cost of the following: Schneider Electric's "MiCOM P121" microprocessor terminal [38]—KAZT 700,000 + 100,000 × 3 = KZT 1,000,000; semiconductor current relay: KZT 37,000 × 3 = KZT 111,000 + 100,000 × 3 = KZT 411,000. Here, we will also take into account the cost of six intermediate relays, type "KL-25"—KZT 129,000; the cost of the time relay, type "ST3PR"—KZT 19,320; the cost of the minimum voltage relay, type "KV-54"—KZT 63,000; and the cost of the index relay, type "KH-21"—KZT 39,348.

Then, the cost of such protection will be KZT 661,668. The following must also be taken into account: the electromechanical current relay, type "KA-40/10": KZT 25,000 × 3 = KZT 75,000 + 100,000 × 3 = KZT 375,000; the six intermediate relays, type "KL-25"—KZT 129,000; the cost of the three time relays, type "ST3PR"—KZT 19,320; the cost of the six relays of minimum voltage, type "KV-54"—KZT 63,000; and the cost of three indicating relays, type "KH-21"—KZT 39,348. The total cost will be KZT 5,956,668.

The adjustment of traditional protection devices will cost KZT 5000. The total cost of production for the microprocessor terminal "MiCOM P121" will be KZT 1,005,000;

- For semiconductor current relays: KZT 664,670;
- For the electromechanical relay: KZT 598,670.

Taking into account travel expenses for trips to substations of industrial enterprises (within the region and the country) to install traditional protection devices, equal to KZT 50,000, then the cost of protection components for the microprocessor terminal "MiCOM P121" will be KZT 1,055,000; for the semiconductor current relay, it will be KZT 714,670; and for the electromechanical relay, it will be KZT 648,670.

The technical and economic comparison of any two variants of protection devices and the remaining present costs can be determined by the following formula [39]:

$$Z_i = I_i + U_i + K_i \times P_N \tag{7}$$

where Zi—present costs for realisation of the I-th variant for one year of operation; Ii—annual operating costs for the I-th variant for one year of operation; Ui—average damage caused by the unreliability of power supply per year for the I-th variant; Pn—normative coefficient (for payback period T (payback time) = 8 years, we take $Pn = 0.125$). To calculate the present value of costs for the u-thaw protection device, we use the following formula [40]:

$$Z_p = I_{\sum n} + U_n + P_N \times C_n = min \tag{8}$$

where $I_{\sum n}$ is the cost of operation of the u-thaw protection device per year; Un is, without taking into account its unreliability, the annual average damage in case of repeated recognition of modes of the protective device; Cn is the price of the u-th relay protection device (Cn—price of the proposed u-th alternative maximum current protection device).

In the event of a failure in the maximum current protection system, the enterprise will suffer damage. The following costs are taken into account: the cost of replacing the failed equipment; the cost of post-emergency repair or damage associated with sudden failure; the cost of underproduction due to the failure of electrical installations connected to the cells of complete switchgears. It can be reasonably assumed that the average damage per year during the operation of the proposed alternative maximum current protection device and traditional sets of maximum current protection will be approximately equal: $Un = Upr$.

They, in turn, are dependent on the reliability of tripping (non-tripping), and only with sufficient operating experience will it be possible to correctly determine the failure rate of the proposed alternative overcurrent protection device in comparison with conventional ones. The costs of U and the normative coefficients will be considered equal since there is no reason to consider them unequal, i.e.,: $Pn = Ppr$. Taking into account the above-presented economic effect when using the proposed device of alternative maximum current protection (at cost difference $Zpr = Zp$, where Zpr is the present cost of operation of the proposed device), it will be equal to:

$$E = \left(Z_{pr} - Z_p\right) \times n = (I_i + U_i + P_N \times C_n) \times n - (I + U + P_N \times C_{nm}) \times n = P_N(C_n - C_{nm}) \times n \tag{9}$$

where n—the number of proposed new devices of alternative maximum current protections to be implemented.

Given that the value of the microprocessor device Cn is KZT 1,055,000, the proposed device Cnm = KZT 408,088 and $Pn = 0.125$, for n = 1, we get $E_1 = (1{,}055{,}000 - 408{,}088) \times 0.125 \times 1$ = KZT 80,864 per year. For complete switchgears, the voltage is 6–10 kV. With the number of connections—for example, n—equal to 20, the economic effect is equal to E_{20} = KZT 1,617,280.

From the comparison of the developed device—alternative maximum current protection—with a traditional one, the following can be established:

- The first surpasses them due to the fact that it is cheaper than, for example, the microprocessor device "MiCOM P121" by 2.6 times (economic efficiency at n = 1 will be E_1 = KZT 80,864 per year). The semiconductor and electromechanical bases are 1.8 and 1.6 times cheaper. The economic effect is E_2 = KZT 38,323 and E_3 = KZT 30,073 per year, respectively.

6. Conclusions

Based on the experimentally determined maximum EMF values, places are determined for the installation of inductive coil 14 inside cell 1 to implement resource-saving overcurrent protection. In connection with all of the above, we consider it expedient to install measuring devices, i.e., inductive coils, for implementation in the first position of plate 17, opposite the centre of the axes of the second conductive busbar 11 and at a distance of h = 12 cm from it. Given the complexity of setting up the parameters of this type of protection, it is impractical to install these measuring devices in the second and third positions of plate 17 due to the increased influence of the internal metal structures of cell 1, which cause interference. Experimental studies have shown that the values of electromagnetic fields in the form of EMF, created by currents flowing through the busbars of the switchgear cell during a short circuit, are sufficient to detect these EMF using inductive coils.

Recommendations for the creation of a current protection device for electrical installations connected to the cells of the complete switchgear. EMF measurements based on the experiments showed the possibility of creating a new alternative resource-saving protection device on inductive coils, which will meet the requirements of relay protection and at the same time have the effect of resource-saving. The developed device "Maximum current protection design with minimum voltage blocking" has proven its effectiveness due to the fact that the protection reacts to all types of short circuits that occur in electrical installations connected to the cells of complete switchgears. Taking into account the results of the tests carried out on the implementation of alternative protection, it is recommended to install the developer device for the protection of electrical installations with a voltage of $Unom$ = 6, 10, 35, 110 or 220 kV, connected to the cells of complete switchgears with a voltage of 6–10 kV, as well as to closed switchgears with a voltage of 35, 110 and 220 kV. The presented technical and economic comparison of the developed alternative protection device once again confirms the effectiveness of its use compared to other similar traditional protection devices. Resource-saving protection devices made on inductive coils are small in size, light in weight, low in cost, and assembled from available materials and elements. These statements are confirmed by the choice of settings for resource-saving protection and the assessment of its sensitivity coefficient. This new protection device can be mounted directly on the breaker frame, opposite or at least at a safe distance from the centre of the tire axles without touching the metal walls of the cell. When choosing protection settings, special attention should be paid to the influence of adjacent cell phases. Such resource-saving devices also have an environmental effect of saving both non-ferrous and ferrous metals. As a result, there is a simultaneous reduction in the load on power plants and a reduction in the cost of non-ferrous and ferrous metals used in the production of traditional current transformers. This solves the problems of environmental protection, reducing harmful emissions in the atmosphere from production and reducing or even eliminating energy consumption for the production of traditional current transformers due to the lack of their use of relay protection. Inductive coils, first proposed as a new element base in relay protection, are an innovative solution and represent an excellent prospect for the further development of relay protection. This protection is connected in parallel with a traditional one, both in existing and newly introduced electrical installations, and in the event of a failure of the traditional protection, it disables the connected electrical installation.

The scientific and economic impact of this work is presented as follows:

- Resource-saving protection acts as a discrete analogue and measuring converter, as well as a protective body, providing significant savings in resources, helping to minimise initial material costs and having minimal annual costs for their operation;
- Developing competitiveness, since alternative protection protects the future and reduces the cost of producing it—in particular, electricity produced at power plants and consumed at enterprise substations—increasing labor productivity by reducing the time spent on manufacturing this alternative protection compared to the time spent on traditional protection.

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Supervision: V.P.M.; Project Administration: V.Y.M. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

$\mathrm{B}_{\mathrm{SCmin}}$	magnetic induction induced by the minimum short circuit current
$\mathrm{F}_{\mathrm{act}}$	magnetomotive force (MMF) of the inductance coil
$I_{\sum n}$	cost of operation of the u-thaw protection device per year
$\mathrm{I}_{\mathrm{op\ max}}$	operational maximum working current
B_{SC}	magnetic field induction produced by minimal short-circuit current
I_{pt}	protection operation current
SC	short circuit
I_{SC}	short-circuit current
$\mathrm{I}_{\mathrm{SCmin}}$	minimal SC current
$\mathrm{K}_{\mathrm{err}}$	safety factor
$\mathrm{K}_{\mathrm{selfstart}}$	self-starting coefficient
l_{coils}	inductance coil length
$\mathrm{S}_{\mathrm{nom}}$	nominal power of the power transformer
$\mathrm{U}_{\mathrm{nom}}$	nominal voltage of the high-voltage side of the power transformer
μ_0	magnetic constant, $\mu_0 = 4\pi \times 10^{-7}$ H/m
$\mathrm{K}_{\mathrm{sens}}$	sensitivity coefficient
B	magnetic induction
Bact	magnetic induction when EMF occurs at the terminals of the inductor coil
B_{op}	induction at which EMF occurs at the terminals of the inductive coil
Bpt	protection tripping induction
Cn	price of the u-th relay protection device
E	electromotive force (EMF)
E_1	economic effect
F	magnetic flux
h	distance from the axis of a current-carrying busbar to the centre of gravity of a reed switch
I	electric current
IC	inductance coil
Ii	annual operating costs for the I-th variant for one year of operation
$\mathrm{K}_{\mathrm{off}}$	protection offset coefficient
Pn	normative coefficient
Ui	average damage caused by the unreliability of power supply per year for the *i*-th variant
Un	without taking into account its unreliability the annual average damage in case of repeated recognition of modes of the protective device
Zi	present costs for realisation of the I-th variant for one year of operation
Zpr	present cost of operation of the proposed device

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