

Reed-Switch-Based Relay Protection without Current Transformers

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Abstract—A protection device is proposed that combines the functions of current transformers and current relays. The device contains a reed switch, two capacitors, two miniature relays, and three resistors. Reed switches are attached near the tires of the electrical installation at a safe distance. Relay parameters are calculated based on the operator method. The relay meets the requirements of sensitivity and performance. Unlike similar ones, it does not activate unnecessarily when contacts stick and the short-term interference is present, it is equipped with test diagnostics and simple mounting structures that allow the parameters of the relay operation to be adjusted. An experimental test confirmed the operability of the device.

Keywords: current relay, reed switch, current transformers, experiment

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Overcurrent relays are the basis of most protection circuits in 6- to 110-kV power-supply systems. They receive control signals from the current transformers (CTs). Development of relay protection without using CTs addresses urgent problems of energy conservation in power engineering [1]. One way to solve them is a relay based on a reed switch, which is installed at a safe distance from the busbar of the electrical installation (EI) and can combine the functions of the current sensor and the perceiving body of the relay. A reed switch is miniature glass bulb I (Fig. 1a) with an inert gas and normally open or switchable contacts (plates 2, Fig. 1a). If a magnetic field (MF) with instantaneous induction B_1 sufficient to activate the reed switch is applied along the contacts, they close for time t_1 during each half-period of the ac current and reset to their initial state if the induction decreases to the value of B_2 (Fig. 1b). Therefore, during time t_1 , the reed switch outputs a signal and, at the time t_2 , there is no signal.

Based on this property of the reed switch, it is proposed [2] to determine the amplitude of the current creating a magnetic field with induction B_1 on the basis of duration t_1 or the time between the resets of the two reed switches. If the current amplitude exceeds the set point, the relay gives a signal about the abnormal mode. In [3, 4], it was proposed to install several reed switches at different distances from the current-carrying bus or cable and to connect them to the microprocessor unit. This block, on the basis of the number of triggered reed switches, determines the amplitude and

shape of the current [3] or only the amplitude [4] and, thus, determines the mode. In [5], in addition to the reed switch installed near the current conductor, it was proposed to use a reed switch with a control winding connected to a voltage transformer. Both reed switches are connected to a microprocessor, which, on the basis of duration t_1 , determines the amplitude and phase of the current that creates induction B_1 .

All these devices have sufficient speed and sensitivity, but the schemes of [2, 5] may not work with a sticking contact of the reed switch, since it does not return to its original position, or they may work incorrectly if the duration of interference (for example, caused by lightning near the protected installation) is more than 10 ms. The schemes of [3, 4] can work incorrectly both when the contacts are stuck and when they are exposed to interference; in the first case, this happens because, after switching on the electrical installation, the reed switch with stuck contacts continues to give a signal about the current exceeding the setting of the relay operation, while, in the second case, this occurs if the corresponding reed contacts close under the influence of interference.

A lack of attachment fixtures near the phases without which they are actually inoperable, as well as a lack of fault diagnostic tests, is a common disadvantage for all these relays. The paper proposes a relay that lacks these drawbacks [6].

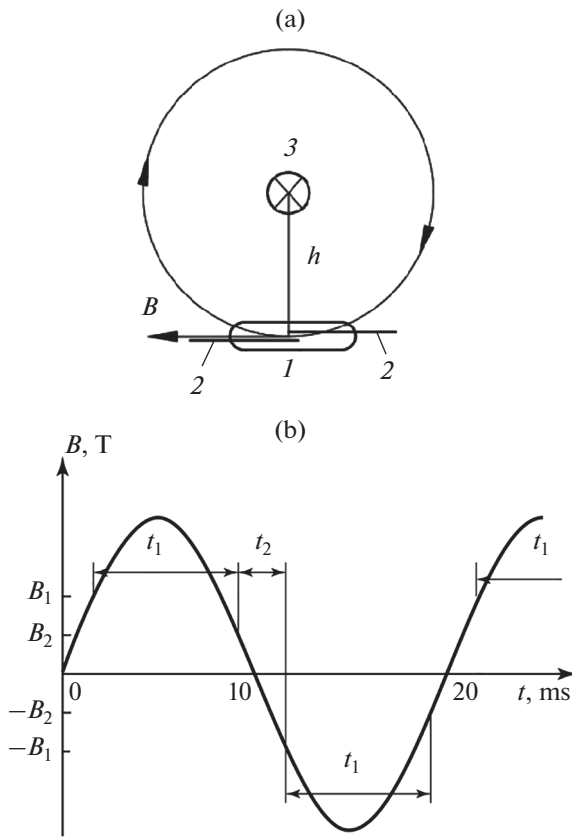


Fig. 1. (a) Location of the reed switch near the conductor. (b) Principle of its operation. (1) Reed-switch bulb, (2) plates (contacts), and (3) conductor.

SCHEMATIC AND PRINCIPLE OF OPERATION OF THE RELAY

A schematic diagram of the proposed current relay and the substitution diagram with closed and open contacts are shown in Fig. 2. In the load mode, the current in conductor 5 creates a magnetic field with an induction less than induction B_1 of operation of reed switch 1, and the relay is not switched on. At a short circuit in the EI, a field with an induction greater than B_1 is created, reed contacts 2 and 3 are closed, and contacts 3 and 4 are open for each half-period of the ac current. For the relay not to be triggered by a long interference with time t_i , it is desirable to delay the activation of relay 14 as long as possible (the definition of duration t_i is given below). Taking into account that modern current relays, including microprocessor-controlled ones, operate within 30–35 ms and the interval between the first and the fourth actuation of the reed switch is 30 ms (Fig. 1), as well as also taking into account the proper operation time of relay 14, we have to limit ourselves to three actuations of the reed switch. As calculations and experiments have shown, it is possible to choose the parameters of capacitor 17

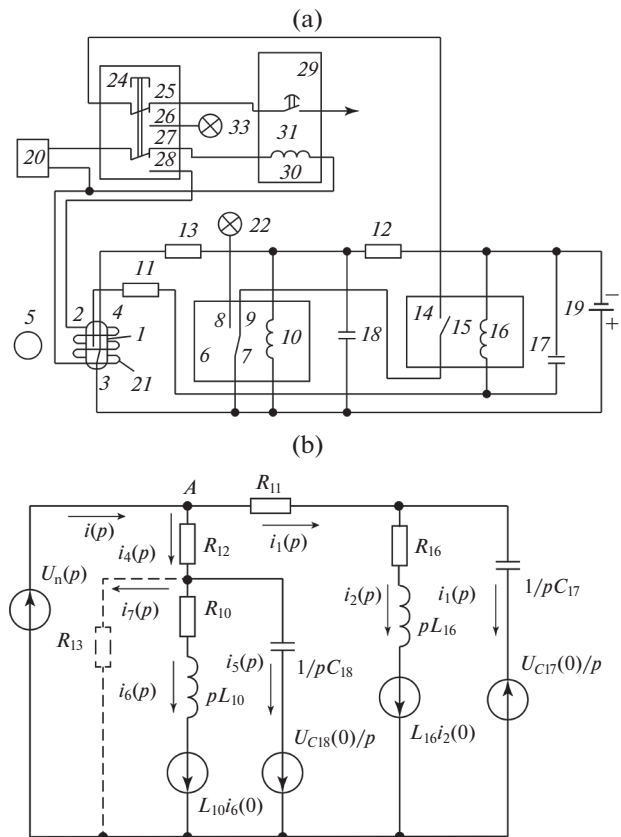


Fig. 2. (a) Schematic diagram of the current relay and (b) substitution diagram with closed and open contacts 2 and 3. (1) Reed switch with contacts 2–4; (5) conductor with current, (6, 14) relay with contacts 7–9 and winding 10 (16); (11–13) resistors; (17, 18) capacitors, (19, 20) source of dc (ac) voltage; (21) control winding; (22, 23) lamps; (24) contact key button 25–28; and (29) time relay

and resistor 11, which provide correct functioning at three actuations of the reed switch (we note that adjustment of the relay takes more time than adjustment of the relay with current transformers). At the third actuation of the reed switch (0.02 s after the first), capacitor 17 is recharged up to voltage U_{a14} actuating relay 14. The latter closes contacts 15 and sends a signal through closed contacts 25 and 31 to turn off the EI or to the logic part of the protection circuit. After turning off the EI, if contacts 2 and 3 are stuck, contacts 3 and 4 remain open, capacitor 18 is recharged, relay 6 opens contacts 7 and 9 and closes contacts 7 and 8, and lamp 22 signals that the contacts have been welded. Relay 14 gives no signal and the current relay does not trip incorrectly, for example, when the automatic reclosing device is active when the short circuit has eliminated itself. The charging time of capacitor 18 is longer than that of capacitor 17; otherwise, the protection will not trip.

DETERMINING THE PARAMETERS OF RELAY-CIRCUIT ELEMENTS

To ensure the functioning of the relay, it is necessary to do the following.

(1) Capacitor *17* should be charged to voltage U_{a14} after time $t_3 = 0.02 + t_4$, s. During 0.02 s it is charged twice (each time during time t_1 of closing of contacts 2 and 3) and discharged twice (during time t_2 of their open state); t_4 is the time needed to bring the voltage on capacitor *17* to $U_C \geq U_{a14}$ (after the third closure of contacts 2 and 3). For relay *14* used in the experiments, $t_4 = 0.5$ ms was taken. A further increase in the duration of t_2 is inexpedient, because it is desirable to have less than 30–35 ms to perform the function of cutoff protection.

(2) Capacitor *17* should be discharged through winding *16* down to voltage U_{r14} of relay *14* for $t_5 \leq 0.5$ s in order to prevent the false tripping of the automatic reclosing device after the EI switch turns off at the short circuit.

(3) Capacitor *18* should be charged up to voltage U_{a6} of the tripping of relay *6* for time $t_6 = t_a + t_{\text{off}}$ (where t_a is the protection activation time and t_{off} is the circuit breaker turnoff time). It should be allowed to discharge through resistor *13* to voltage U_{r6} of the reset of relay *6*.

Fulfillment of the first two requirements is ensured by a proper choice of resistor *11* and capacitor *17*, and the third requirement by choosing resistors *12* and *13* and capacitor *18*. Calculations have shown that the resistors must satisfy the following conditions.

$$\frac{U_n}{(0.5 \cdot I_{\text{reed}})} \leq R_{11} \leq \left(\frac{U_n}{U_{a14}} - 1 \right) R_{16}, \quad (1)$$

$$\frac{U_n (U_n - U_{r6})}{P_{\text{dis}}} \leq R_{12} \leq \left(\frac{U_n}{U_{a6}} - 1 \right) R_{10}, \quad (2)$$

$$R_{13} = \frac{R_{12} U_{r6} R_{10}}{[R_{10} U_n - U_{r6} (R_{10} + R_{12})]}, \quad (3)$$

where U_n is the nominal voltage of operational current source *19*, I_{reed} is the nominal transmitted current of the reed switch contacts, and P_{dis} is the dissipated power on resistors *11–13* and windings *10* and *16*.

Capacitors are initially defined by the expression

$$U_C(t) = U_n \left(1 - e^{-\frac{t}{RC}} \right), \quad (4)$$

where t is the capacitor-charging time (for capacitors *17* and *18*, $t = t_3$ and $t = t_6$) and R is the resistance of the resistor included in series with capacitance C .

Intervals t_3 and t_6 allow us to exclude complete charging of the capacitors at the first actuation of reed switch *I* and to set the initial data for calculation.

Specification of the capacitances and resistances of resistors *11–13* is carried out by the operator method. Schemes of substitution (Fig. 2b) and the equations according to Kirchhoff's laws are constructed for the modes when the contacts of reed switches 2 and 3 are closed and open. In the latter case, resistor R_{13} is added in the circuit of Fig. 2b and a break is made between point *A* and resistor R_{11} .

Using the Kirchhoff laws, we obtain the equations for the moment when pins 2 and 3 of reed switch *I* are closed:

$$\left\{ \begin{array}{l} i_1(p) = i_2(p) + i_3(p), \\ \frac{i_1(p)R_{11} + i_3(p)}{pC_{17}} = \frac{U_n}{p} - \frac{U_{C17}(0)}{p}, \\ \frac{i_2(p)(pL_{16} + R_{16}) - i_3(p)}{pC_{17}} = \frac{L_{16}i_2(0) + U_{C17}(0)}{p}, \\ i_4(p) = i_5(p) + i_6(p), \\ \frac{i_4(p)R_{12} + i_5(p)}{pC_{18}} = \frac{U_n}{p} - \frac{U_{C18}(0)}{p}, \\ i_4(p)R_{12} + i_6(p)(pL_{10} + R_{10}) = L_{10}i_6(0) + \frac{U_n}{p}, \end{array} \right. \quad (5)$$

where $U_{C17(0)}$, $U_{C18(0)}$ and $i_{2(0)}$, $i_{6(0)}$ are voltages on capacitors *17* and *18* and currents in windings *10* and *16* before closing contacts 2 and 3; U_n is the rated voltage of the operational current source; $i_1(p) - i_6(p)$ are currents in the circuit branches after closing contacts 2 and 3; R_{11} are R_{12} resistors *11* and *12*; R_{10} , R_{16} and L_{10} , L_{16} are active resistances and inductances of windings *10* and *16*; and C_{17} and C_{18} are capacitances of capacitors *17* and *18*.

Next, when considering relays *6* and *14* in question, U_{a6} and U_{r6} , U_{a14} and U_{r14} , and time t_{a6} and t_{a14} of their operation, as well as R_{10} , R_{16} and L_{10} , L_{16} are chosen based on experience. They are determined from time t_6 according to paragraph 3 and resistors R_{11} and R_{12} from the corresponding catalog, so that they satisfy conditions (1) and (2). Time t_1 is measured in the laboratory when the reed switch is exposed to a magnetic field with minimum induction amplitude B_{min} at which it should work (taking into account the sensitivity coefficient of the realized protection). Such a choice of time t_1 allows one to provide the required speed of the current relay at B_{min} and increase it when the reed switch is exposed to a higher induction. The fact is that, the greater the amplitude of the effective induction, the faster the value of B_1 is attained and the later the reset induction value of reed switch *I* is reached; in addition, its activation time t_{a1} decreases. Therefore, t_1

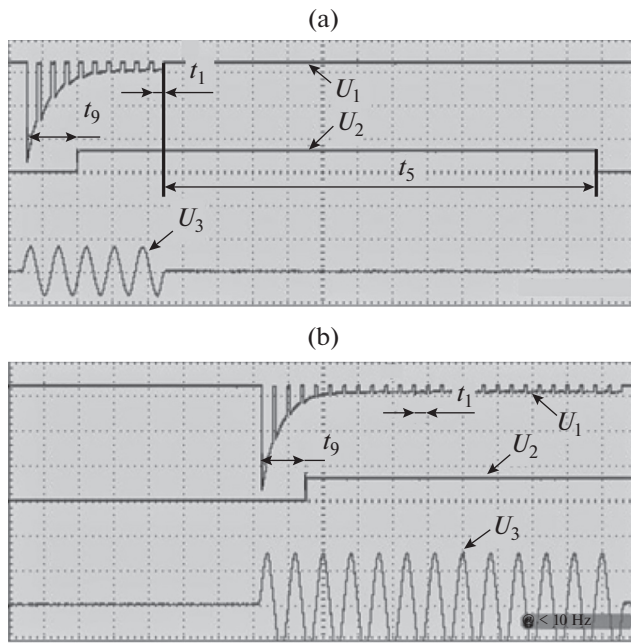


Fig. 3. Waveforms of voltages U_1 , U_2 , and U_3 across resistor 11, at the output of relay 14, and on winding 21: (a) under the influence of induction B_{\min} ($t_1 = 6.8$ ms, $t_5 = 311$ ms, $t_9 = 35$ ms); (b) under the influence of induction $2B_{\min}$ ($t_1 = 8.4$ ms, $t_9 = 32$ ms).

increases and t_2 decreases, capacitor 17 is charged faster, and the relay trips earlier. Capacitances C_{17} and C_{18} are then determined by (4) ($C_{17} < C_{18}$) and, by solving Eq. (5), voltages U_{17} and U_{18} on capacitors 17 and 18 and currents $i_2(p)$ and $i_6(p)$ in windings 10 and 16 after time t_3 are calculated.

Similarly to expression (5), the equations in the mode after opening of contacts 2 and 3 are derived. Obtained voltages U_{17} and U_{18} and currents $i_2(p)$ and $i_6(p)$ are taken as the initial conditions; using (3), resistance R_{13} is found and $t_2 = 0.01 - t_1$ is used instead of t_1 . Then, using MS Excel, voltages U_{17} and U_{18} and currents $i_2(p)$ and $i_6(p)$ are found after time t_2 . To determine U_{17} after $t_3 = 20.5$ ms, system (5) is solved three times (for each actuation of the reed switch), while it is done twice for opening of contacts 2 and 3. The values of voltages and currents obtained by solving each of the systems will be the initial values for the next system (as specified above). To determine voltage U_{18} after time t_6 at sticking of contacts 2 and 3, it is enough to solve Eq. (5) once using time t_6 instead of t_2 ; however, it is necessary to be sure that voltage U_{18} in t_6 will not reach a value of U_{a6} if contacts 2 and 3 do not stick. For this reason, Eq. (5) is solved t_6/t_7 times in which $t_7 = 10$ ms (the reed has time to be both turned on and off). If it turns out that, in $t_6 + 20.5$ ms, voltages U_{a6} and

U_{a14} will be applied to windings 10 and 16, respectively, and capacitor 17 discharges within 0.5 s, then the calculation stops. Otherwise, the resistors' capacitance changes and the calculations are performed over again.

After determining the parameters of the relay elements, one calculates duration t_n of the interference at which the relay will not trigger falsely. For this purpose, in (4), R and C are substituted with the obtained values of R_{11} and C_{17} and the time is calculated for which capacitor 17 will be charged to $0.9U_{a14}$ (accepted with allowance for measurement errors and deviations of nominal parameters of the elements from the actual values); this time is t_n . Note that time t_n is determined only for fast-acting protections, as the false operation of the relay induced by the interference does not lead to the activation of a protection circuit due to the presence of a time delay in the backup protection circuits.

The proposed device has a fault-diagnosis feature. For this purpose, switch button 24 is held in a pressed position for 1–2 s. At the same time, the ac voltage from source 20 is applied to winding 21, relay 29 turns off and opens contacts 31, and reed switch 1 closes contacts 2 and 3 followed by the protective action as described above. If all the elements are functioning properly, relay 14 closes contacts 15 and lamp 23 is lit, signaling that, upon the completion of diagnostics, contact 31 closes after a delay excluding false triggering of the relay due to the discharge of capacitor 17 through winding 16.

To check the ideas implemented in the design of the device and correctness of calculations, a device was constructed on the basis of a reed switch (with $I_{\text{reed}} = 1$ A, measured for time $t_1 = 6.8$ ms in the closed contacts state at B_{\min} after the switching), relays 6 and 14 with $R_{10} = R_{16} = 67$ k Ω , $L_{10} = L_{16} = 329$ H, $U_n = 220$ V, $U_{av} = 148$ V, and $U_r = 57$ V and response time of $t_{av6} = t_{av14} = 9$ ms at a voltage of 220 V applied to the relay. Capacitors and resistors were determined by the above technique.

The calculations yielded the following results.

(1) For the stated t_1 and relay parameters 14, its operation after the third closure of contacts 2 and 3 can be ensured by capacitance $C_{17} = 3.3$ μ F and resistance $R_{11} = 3.65$ k Ω , and, at this capacitance, the condition $t_5 \leq 0.5$ s is satisfied and the relay will not switch falsely at $t_i = 11.9$ ms. The time in which contacts 15 of relay 14 should close is $t_9 = t_3 + t_{av14} = 29.5$ ms, and that in which they should open is $t_5 = 0.28$ s.

(2) Triggering relay 6, for example, at $t_6 = 0.6$ s is provided with capacitor $C_{18} = 5.6$ μ F and resistor $R_{12} = 32$ k Ω and $R_{13} = 13$ k Ω . Closure of contacts 7 and 8

should occur after $t_8 = t_6 + t_{av6} = 0.609$ s. Other capacitors and resistors are selected for larger t_6 .

Testing of the relay showed the following.

(1) The proposed relay is not inferior to similar relays in terms of speed of operation. Thus, at voltage U_3 creating magnetic flux with induction $B_1 = B_{min}$, duration of closed state of contacts 2 and 3 $t_1 = 6.8$ ms and time t_9 (Fig. 3a) does not exceed 35 ms (Fig. 3) from the moment of their first closing (beginning of the first voltage pulse U_1) up to the moment of operation of relay 14 when its contacts 15 close and voltage U_2 appears, which is supplied into a cutoff circuit.

(2) When voltage U_3 is doubled, the induction acting on the reed increases to $2B_{min}$ (Fig. 3b), time t_1 increases from 6.8 to 8.4 ms (Figs. 3a, 3b), and the relay speed increases to $t_9 = 32$ ms.

(3) Time t_5 (Fig. 3a) of resetting of relay 14 after termination of voltage U_1 from contacts of a reed switch (in Fig. 3a, pulses U_1 terminate) does not exceed 0.31 s, which provides the possibility of triggering an automatic reconnection.

(4) Durations t_9 and t_5 exceed the calculated ones by no more than 17%, which satisfies the specification on the time to activation of relay 6 by 10%. These errors are caused by the fact that times t_{av6} and t_{av14} depend on the voltage applied to relays 6 and 14.

TRIGGERING OF THE RELAY

It is known that the tripping current of traditional relays I_a is determined by the type of protection implemented on its basis and the connection scheme of the current transformers. For example, in the current cutoff,

$$I_{av} = k_{dt} k_{ckt} I_{sc}, \quad (6)$$

where k_{dt} is the coefficient of detuning, k_{ckt} is the coefficient of the circuit, and I_{sc} is the maximum short-circuit current at the end of the line to be protected.

When determining a cutoff on the proposed relay, it is also necessary to detune from current I_{sc} ; however, without taking into account tuning factor k_{ckt} because there is no CT. In addition, it is necessary to take into account that the value of induction of the magnetic field acting along the longitudinal MO axis of the reed switch (Fig. 4) at point M of its installation is influenced by currents with phases A_1, B_1, C_1 and A_2, B_2, C_2 of the protected and the neighboring electrical installations, as well as by their case and shell (if any). To calculate the induction of B_{A1}, B_{B1}, B_{C1} and B_{A2}, B_{B2}, B_{C2} magnetic fields from these currents, one can use the Biot–Savart–Laplace formula [7]. Studies have shown, however, that, for this purpose, it is necessary to introduce coefficients into the formula: k_1 to

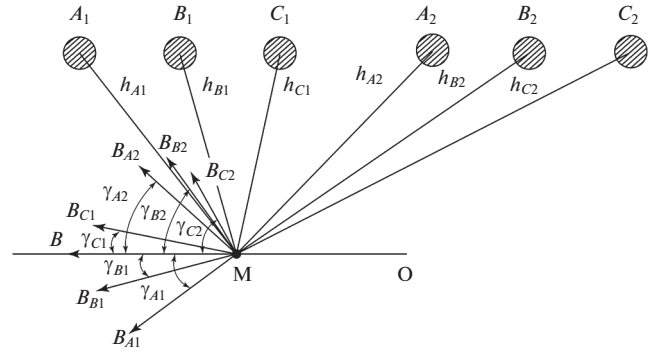


Fig. 4. Induction of magnetic fields acting along the reed axis.

account for the geometric dimensions of the current bus and the presence of magnetic materials near the reed switch (for example, metal parts of the structure of the EI housing), as well as the fact that the current is ac, not dc, and k_2 and k_3 , which take into account the shielding effect of the EI shells. In this case, the coefficients should be determined experimentally for each type of EI.

Based on the above, the expressions for calculating the inductions, for example, B_{A1} and B_{A2} due to currents I_{A1} and I_{A2} with phases A of the protected and adjacent EI will be as follows:

$$B_{A1} = \frac{\mu_0 I_{A1} \cos \gamma_{A1}}{2\pi h_{A1} k_1}, \quad (7)$$

$$B_{A2} = \frac{\mu_0 I_{A2} k_2 k_3 \cos \gamma_{A2}}{2\pi h_{A2} k_1},$$

where h_{A1} and h_{A2} are the distances from the axes of busbars of phases A of the protected and neighboring EI to point M, γ_{A1} and γ_{A2} are the angles between the MO axis and induction vectors B_{A1} and B_{A2} , and μ_0 is the magnetic constant.

Expressions for calculating inductions from currents in phases B and C are written similarly to (7) but with the substitution of indices A for B and C . Taking into account (6) and (7), the following condition for the reed switch induction should be fulfilled:

$$B_1 \geq k_{dt} (B_{A1} + B_{B1} + B_{C1} + B_{A2} + B_{B2} + B_{C2}). \quad (8)$$

It is possible to adjust the set point of operation of the relay by changing distances h_{A1}, h_{B1}, h_{C1} and h_{A2}, h_{B2}, h_{C2} and angles $\gamma_{A1}, \gamma_{B1}, \gamma_{C1}$ and $\gamma_{A2}, \gamma_{B2}, \gamma_{C2}$ (Fig. 4), as well as by selecting the reed switch with the necessary value of induction B_1 . In this case, in the first two variants, it will be necessary to recalculate the set point according to (8) every time the position of the reed switch is changed.

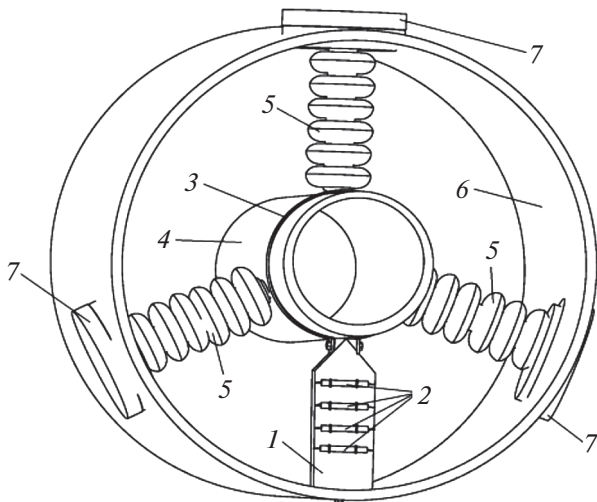


Fig. 5. Reed mounting in the complete busduct: (1) bar, (2) reed switches, (3) clamp, (4) busduct, (5) insulator, (6) shell, and (7) hatch.

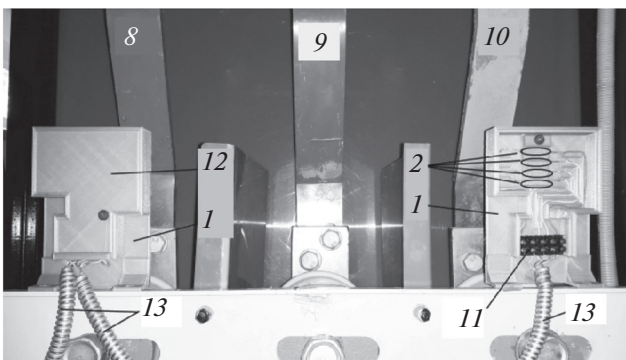


Fig. 6. Reed mounting in the complete distributing device: (1) bar, (2) reed switches, (8–10) bars, (11) terminal block, (12) cover, and (13) connecting wires.

SCHEMES FOR MOUNTING THE REED SWITCHES NEAR THE BUSBARS OF AN ELECTRICAL INSTALLATION

The reed-mounting design must ensure a safe distance from the live busbars of the installation to the relay's reed switches and the possibility of adjusting the settings. The basis of the proposed structures is

strip 1 with reed switches 2, which can be used independently, for example, to protect the connections connected to the closed busducts [7] (Fig. 5). The design contains strip 1 attached with clamp 3 to conductor 4 fixed on insulators 5 inside shell 6 with hatches 7. Reed switches 2 in an amount of from four to six are located on bar 1. Among them, the one with the induction B_1 closest to the calculated one for the current protection relay is selected.

Figure 6 shows the design for cells of complete distributing devices (CDDs) [7]. It is fixed inside near busbars 8–10. Reed switches 2 are attached to bar 1 and connected by connection wires 13 to the rest of the relay circuit located in the relay cabinet of the cell. Figure 6 also shows terminal block 11 and cover 12. Analysis of the design of CDDs and busducts showed that, in most cases, it is possible to install a reed switch or a whole relay near the busbars inside them. At the same time, for each of them, one has to develop a specific design for fixing the reed switch, which complicates the generalization of this approach.

ESTIMATED RESOURCE SAVING FROM THE USE OF THE PROPOSED RELAY

Table 1 shows the weight and dimensions of the proposed relay and the relay manufactured by ABB with three current transformers. For 110-kV installations, the total mass includes the weight of the remote insulators.

It follows from these data that the use of the traditional relays rather than those proposed in this work would require 23, 160, and 100 times more of copper, steel, and high-voltage insulation material for 10-kV installations; 55, 480, and 575 times more for 35-kV installations; and 216, 1250, and 1000 times more for 110-kV installations. Analysis of similar data for the relays of several other firms showed that the resulting ratios were close to those specified.

CONCLUSIONS

(1) The proposed current relay satisfies the requirements of speed and, in the vast majority of cases, the requirements of sensitivity. At short-term

Table 1

Voltage, kV	Mass, kg				Total occupied volume, m ³
	net	copper	steel	insulation	
10	80/0.8	7/0.3	32/0.2	31/0.3	0.024/0.001
35	390/1.1	22/0.4	120/0.26	230/0.4	1.9/0.0012
110	1500/1.6	130/0.6	500/0.4	600/0.6	8/0.0015

disturbances and sticking of reed contacts, the relay does not show false triggers.

(2) In comparison with relays using current transformers, the suggested relay allows reduction of the copper amount by approximately 20–200 times and of steel and insulating materials by 150–1200 times. At the same time, it is inferior to conventional current transformer relays in terms of unification capabilities and the time needed for determination and adjustment of its settings.

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