Electrical Power and Energy Systems 154 (2023) 109457

Contents lists available at ScienceDirect

International Journal of Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

# Reed switch protection of double-circuit lines without current and voltage transformers

M.Ya. Kletsel, B.E. Mashrapov *, R.M. Mashrapova

*Toraighyrov University, Lomov str., 64, Pavlodar 140008, Kazakhstan*

ARTICLE INFO

*Keywords:*
Protection of double-circuit lines
Sequence of actuation of the reed switches
Selection of operation parameters
Algorithm of operation
Determine the fastening point
Structure for fastening

ABSTRACT

Protection of 6–35 kV double-circuit lines from the supply side is suggested. It allows saving copper, steel, and high-voltage insulation in amounts unprecedented for relay protections. The protection is based on the control of sequence of actuation of reed switches fastened near the corresponding phases at a safe distance and of the time $\Delta t$ between their actuation. The effect of all possible errors on $\Delta t$ is studied and the number of reed switches required to be mounted near the phases of the lines is determined. The peculiarities of selection of $\Delta t$ and inductions for the protection operation, points of reed switch mounting, sensitivity estimates, and the fields of use of the protection are analyzed. An example of the selection is considered. The protection operation algorithm is formulated and written in the form of switching algebra functions with allowance for the protection operability in the case of reed switch failures. The correct operation of the protection is shown in all actual modes of operation of the lines (including the failure of one of reed switches). A construction for fastening reed switches at a safe distance from the line phases is presented.

## 1. Introduction

Transverse current differential protections with power direction relays have been used to protect double-circuit lines for almost a hundred years. It has several well-known disadvantages: low sensitivity in some cases (due to the need to offset from currents in fault-free phases and full-load currents), the use of voltage circuits, etc. Many improvements have been suggested for the protection, including such [1–3], where several disadvantages are simultaneously eliminated. However, to receive information about currents in the lines, current transformers (CTs) are still used. They contain high-quality steel, copper, and high-voltage insulation; saturate in transient conditions, during which relay protection devices incorrectly operate sometimes leading to major accidents. In view of these disadvantages, CIGRE conferences many times emphasized a need in creating protections [4,5] without CTs, and the problem of constructing them was called one of the fundamentally unsolved problems of the electric power industry. Changing CTs to small-size magnetically sensitive elements (Rogowski coil, Hall sensor, reed switch, etc.) would eliminate the consequences of their saturation and save resources [6]. Works in this direction have been carried out for a long time. There are works where these elements are suggested to be used as a basis for designing the overcurrent (including protection with filters of symmetrical components) [6–18], differential [19–21], centralized [22,23], and remote [24] protections for some electrical installations. However, no protections of double-circuit lines based on these elements have been suggested so far. In this paper, we try to fill this gap. We suggest using reed switches, since, unlike other magnetically sensitive elements, they can simultaneously function as current sensors, a current relays, and analog-to-digital converters and, which is very important in relay protection, transmit signals through control circuits, but not through measuring circuits.

## 2. Reed switch and some its properties

A reed switch (Fig. 1) is a sealed glass tube (GT) filled with an inert gas. Two or more metal plates (contacts) (PL) are fixed inside; they contact (close) if the magnetic induction $B_{lon} \geq B_{act}$ ($B_{act}$ is the reed switch actuation induction) acts along their longitudinal axis. This induction is calculated as

$$B_{act} = \mu_0 F_{act} / l_c$$

where $F_{act}$ is the magnetomotive force of the reed switch actuation; $l_c$ is the reed switch wrap length; $\mu_0$ is the permeability of vacuum.

Under the action of an alternating magnetic field (MF), the reed switch closes (actuates) and opens the contacts every half-wave with a

* Corresponding author.
*E-mail address:* bokamashrapov@mail.ru (B.E. Mashrapov).

https://doi.org/10.1016/j.ijepes.2023.109457
Received 27 January 2023; Received in revised form 16 June 2023; Accepted 18 August 2023

## Nomenclature

$B_{lon}$ induction acting along the longitudinal axis of a reed switch
$B_{act}$ reed switch actuation induction
$F_{act}$ magnetomotive force of the reed switch actuation
$l_c$ reed switch wrap length
$t_{act}$ action time of reed switch
$k$ $B_{lon}$ to $B_{act}$ ratio
$t_r$ rated time of reed switch actuation
$B_A$, $B_B$, $B_C$ inductions of magnetic fields produced by currents in the phases A, B, C
$I_A$, $I_B$, $I_C$ currents in the phases A, B, C
$\alpha_A$, $\alpha_B$, $\alpha_C$ angles between the longitudinal axis of the reed switch and the induction vectors $B_A$, $B_B$, $B_C$
$h_A$, $h_B$, $h_C$ distances between the axes of the phases $A$, $B$, $C$ and the center of gravity of the reed switch
$\Delta t$ time between actuation of reed switches fastened near the same phases of the lines
$I_1$, $I_2$ currents in the first ($L_1$) and second ($L_2$) lines
$B_1$, $B_2$ inductions of magnetic fields (MF) produced by currents $I_1$, $I_2$
$k_1$ ratio of the maximum to minimum short circuit current at the boundary of the cascade action zone
$\Delta t_{th}$ ($\Delta t_{th1}$) time between the instants of closing the contacts of reed switches 1 (3) and 2 (4) required for the protection operation
$\Delta t_{im}$ time imbalance
$\varepsilon_1$ error appears when a reed switch is mounted at the target point
$\varepsilon_2$ error is due to the difference between the reed switch actuation times
$\varepsilon_3$ error is due to the deviation of $B_{act}$ from the calculated value
$t$ time from the $B_{lon}$ zero-crossing time to the reed switch actuation
$B_{th1}$ induction under which reed switches 1, 2, 9, 10, 17, 18 should actuate
$k_2$ ratio of $B_{lon}$ to $B_{th1}$
$B_{th2}$ induction under which reed switches 3, 4, 11, 12, 19, 20 should actuate
$\Delta t_{im1}$ time imbalance under the action of a MF with $B_{lon} = B_{th2}$ on the reed switches
$B_{load.\max}$ induction amplitude of MF produced by the full-load current in a line
$l_{ca}$ section of the line, where $\Delta t < \Delta t_{th}$ under a SC
$B_{f1}$ induction amplitude of MF acting on a reed switch near the phase of a fault-free line under the current in a fault line after circuit breaker opening from the side of the receiving substation in the case of SC in $l_{ca}$
$B_{ca.r}$ ($B_{ca.\min}$) induction amplitude of MF which acts on a reed switch in the minimal mode of system operation in the case of a double phase short circuit (SC) at the boundary of cascade action zone before circuit breaker opening from the receiving side (at busbars of the receiving part in the case of double phase SC after the breaker opening)
$k_s$ sensitivity coefficient
$B_{f2}$ induction amplitude of MF produced by the double earth fault current in the phases of the lines after opening the fault line circuit breaker from the receiving side
$l$ line length
$X_{S.\max}$ maximal resistance of the power system
$X_L$ resistance of a line circuit
$B_{th3}$($B_{th4}$) induction under which reed switches 3, 4, 11, 12, 19, 20 (7, 8, 15, 16, 23,24) should actuate
$O_1$ ($O_2$) signals for opening breakers $Q_1$ ($Q_2$)
$G_1$–$G_{24}$ signals for actuation of reed switches 1–24
$R_1$–$R_4$, $R_9$–$R_{12}$, $R_{17}$–$R_{20}$ signals about reed switches 1–4, 9–12, and 17–20 have actuated the first
$Z_1$–$Z_{24}$ signals about non opening contacts of reed switches 1–24 for 0.01 s after the actuation
$T_1$, $T_2$, $T_3$, $T_4$, $T_5$, $T_6$ signals about exceed of the time between the actuation of reed switches 1 and 2, 3 and 4, 9 and 10, 11 and 12, 17 and 18, 19 and 20 over a value specified
$T_7$ ($T_8$) signal of expiration of 5 ms from the actuation of reed switch 5, 13, or 21 (6, 14, or 22)
$P^t$ memorization operator
$F_1$, $F_2$, $F_3$, $F_5$, $F_7$, $F_9$, $F_{10}$, $F_{17}$, $F_{18}$ the fault signals of reed switches 1, 2, 3, 5, 7, 9, 10, 17, 18
$T_9$ signal about expiration of 5 ms from actuation of reed switch 1
$u_{SC.\max}$ ($u_{SC.\min}$) maximal (minimal) short-circuit voltage of the transformer
$r_{spec}$ specific active resistance
$X_{spec}$ specific reactive resistance
$X_S$ system resistance before the transformer
$I_{load.r}$ rated load current amplitude
$X_{T.\max}$ maximal resistance of the transformer
$I_{SC.L1}$, $I_{SC.L2}$ maximum currents in $L_1$ (fault) and $L_2$ in the case of a SC at the boundary $l_{ca}$
$I_{1ca}$, $I_{2ca}$ currents in $L_1$ and $L_2$ in the case of a double phase SC at the boundary of $l_{ca}$ in the minimal operation mode of the power system
$I_{tr.L1}$ maximum current in $L_1$ with a short circuit at the boundary $l_{ca}$ (second line is broken)
$I_{ca.\min}$ minimum current in the event of a bus SC in the receiving substation, when one of the lines is broken
$I_{SC.ca}$ current of an earth fault at two points
$I_{SC}$ current of a double phase SC at the boundary $l_{ca}$
$B_{SC.L1}$, $B_{SC.L2}$ inductions of MFs produced by currents $I_{SC.L1}$ and $I_{SC.L2}$
$U_{DC}$ DC voltage across the induction coil under which the reed switch is actuated
$U_{AC}$ AC voltage across the induction coil proportional to $B_{lon}$
$U$ rated voltage of the lines
$k_3$ ratio of $B_{th2}$ to $B_{th1}$
$I_{SC.\min}$ current in one line circuit in the case of a double phase bus SC in the receiving substation in the minimal system operating mode when both lines are live
$B_{SC.\min}$ induction of a MF produced by the current $I_{SC.\min}$
$B_{ca1}$, $B_{ca2}$ inductions produced by the currents in the fault and fault-free lines in the maximal system operating mode
$\Delta t_{SC.\min}$ ($\Delta t_{SC.\max}$) time between actuation of reed switches 1 and 2 in the case of a SC at the boundary of $l_{ca}$ under the minimal (maximal) system operation modes
$U_i$ is the voltage applied to the microcontroller input when the contacts of the corresponding reed switch are closed (i = 1, 2, 3, 5, 6, 7, 10, 11, 13, 14, 18, 19, 21, 22)
$U_s$ is the voltage at which the microcontroller considers a signal to arrive at its input
$t_1$- $t_5$ are the times counted by timers $T1$–$T5$
$t_{et1}$ is the time required to detect that the contacts a reed switch have not broken in the same AC half-wave during which they have closed (10 ms)
$O_1^{'}$,$O_1^{''}$ the variables with values equal to the results of calculation of the 1st and 7th terms in (10)

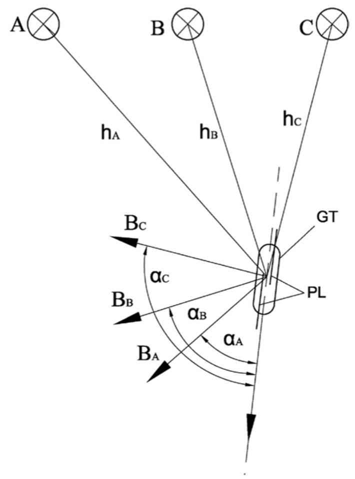



**Fig. 1.** Inductions of MFs which affect a reed switch (single column fitting image.).

frequency of 100 Hz and outputs signals in the form of rectangular pulses. Its action time $t_{act}$ decreases [25] with an increase in the ratio $k = B_{lon}/B_{act}$, and $t_{act} \leq t_r$ ($t_r$ is the rated time $t_{act}$) at $k \geq 1.5$. When a reed switch is located near a live conductor, the induction $B_{lon}$ is produced by the current in this conductor and can be calculated by the Biot–Savart law. In three-phase current mains, a reed switch is affected by the sum of MFs with the inductions $B_A$, $B_B$, and $B_C$. These MFs are produced by currents $I_A$, $I_B$, and $I_C$ in the phases $A$, $B$, and $C$ of an electrical installation (Fig. 1). In this case,

$$B_{lon} = B_A\cos\alpha_A + B_B\cos\alpha_B + B_C\cos\alpha_C = \frac{\mu_0}{2\pi}\left(\frac{\cos\alpha_A}{h_A}I_A + \frac{\cos\alpha_B}{h_B}I_B + \frac{\cos\alpha_C}{h_C}I_C\right) \quad (1)$$

where $\alpha_A$, $\alpha_B$, and $\alpha_C$ are the angles between the longitudinal axis of the reed switch and the induction vectors $B_A$, $B_B$, and $B_C$; $h_A$, $h_B$, and $h_C$ are the distances between the axes of the phases $A$, $B$, and $C$ and the center of gravity of the reed switch.

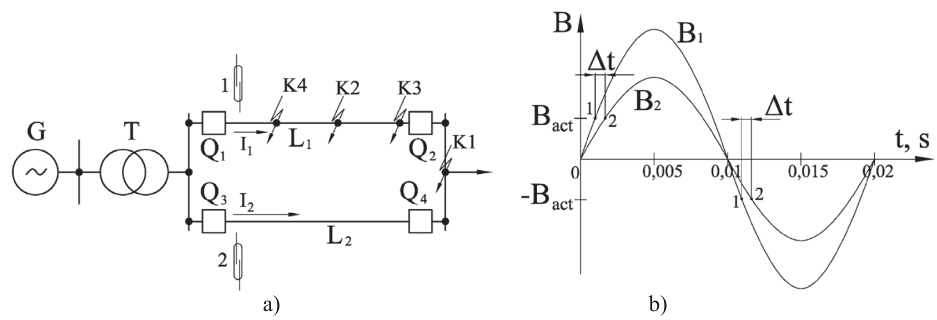



**Fig. 2.** (a) Circuit of a network section with double-circuit lines; (b) time of actuation of reed switches 1 and 2 in the case of a SC in the first line. (single column fitting image.).

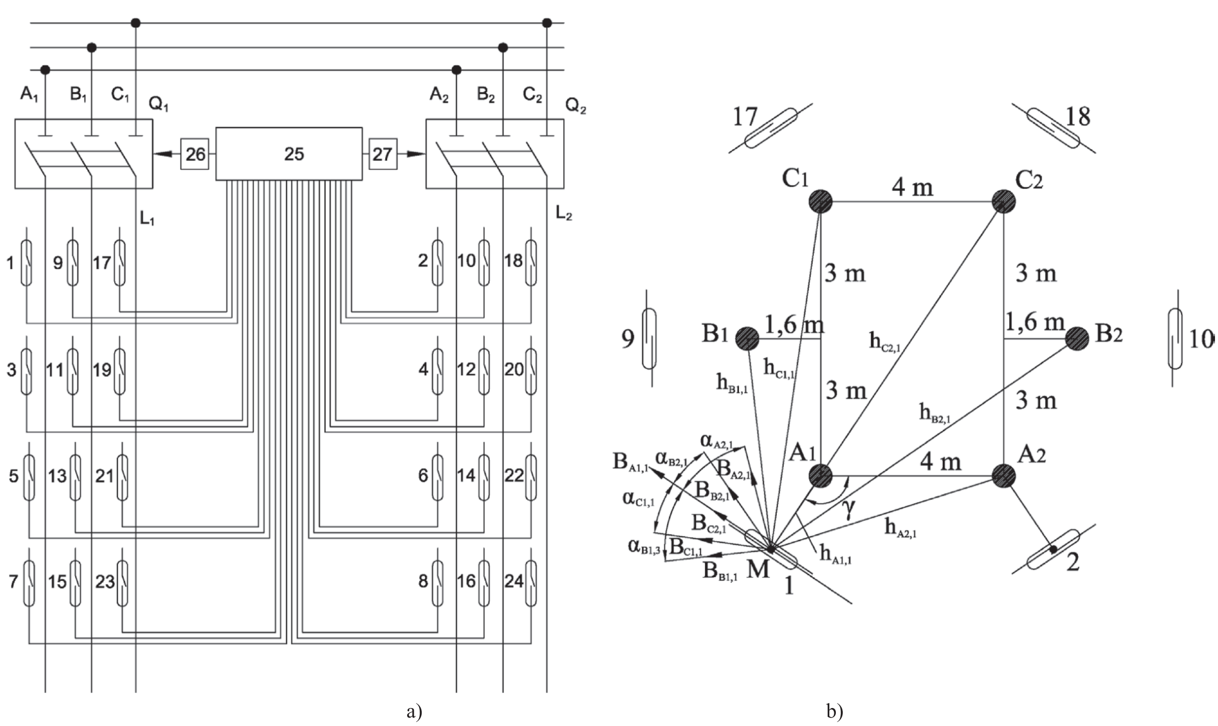



**Fig. 3.** (a) Protection device and (b) arrangement of the reed switches near the phases of the lines: reed switches (1–24); microcontroller (25); output elements (26 and 27). (single column fitting image.).

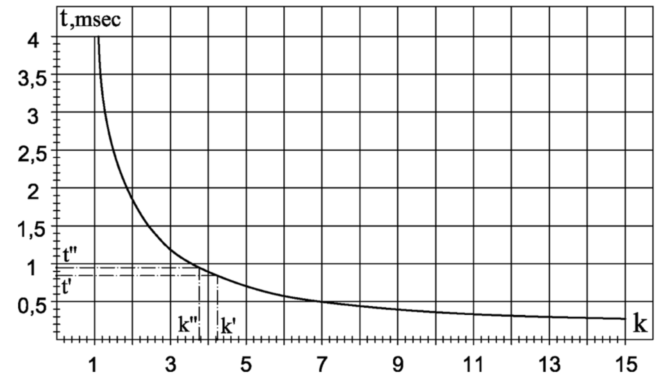



**Fig. 4.** Dependence of the time $t$ from the $B_{lon}$ zero-crossing time to the reed switch actuation on the ratio $B_{lon}/B_{act}$ (1.5-column fitting image.).

## 3. Principle of protection operation

Principle of protection operation is based on the control of the time $\Delta t$ between actuation of reed switches 1 and 2 fastened near the same phases of the lines (Fig. 2) and of the sequence of their actuation [26]. They are configured so as to actuate (close contacts) under the same currents in the lines. The time $\Delta t$ is a kind of analogue of the differential current in a transverse differential directional protection. The $\Delta t$ value determines whether a line short circuit (SC) occurs or not; and the sequence of actuation of the reed switches determines a fault line.

If reed switch 1 (2) actuates first, then a short circuit is in line $L_1$ ($L_2$). Let us show this. In the case of an external fault (point $K1$ in Fig. 2a), the currents $I_1$ and $I_2$ in the lines are equal (measurement and calculation errors are not taken into account for a while), and MFs with the same inductions $B_1$ and $B_2$ act on the reed switches. Therefore, they close the contacts at the same time, $\Delta t = 0$, and the protection does not operate. In the case of SC, for example, in line $L_1$ (point $K2$), $I_1 > I_2$ and $B_1 > B_2$ (Fig. 2b). Reed switch 1 actuates the first (point 1 in Fig. 2b) and signals, thus starting the time $\Delta t$ reading until reed switch 2 actuation (point 2 in Fig. 2b). The time $\Delta t$ is determined after its actuation. Since $\Delta t > 0$ and there is a signal from reed switch 1, then an opening signal is applied to breaker $Q_1$ of line $L_1$.

## 4. Discriminating elements of the protection

These are reed switches fixed at a safe distance from phases: reed switches 1, 3, 5, 7 for the phase $A$ of line $L_1$, and reed switches 2, 4, 6, 8, of line $L_2$ (Fig. 3a); the same is for the phases $B$ and $C$. Reed switches 1 and 2 are used to detect a fault line and measure the time $\Delta t$ at $k_1 \leq 1.5$ ($k_1$ is the ratio of the maximum to minimum SC current at the boundary of the cascade action zone), while reed switches 3 and 4, at $1.5 < k_1 \leq 2$. Reed switches 5 and 6 (7 and 8) are used to block the protection under certain conditions, considered below. Any of the reed switches is affected by the sum of MFs produced by the currents in the phases $A$, $B$, and $C$ of the first and second lines.

For reed switches 1 and 2, 3 and 4, 5 and 6, and 7, 8 to operate under the same currents in the lines, they are fasted symmetrical about the support (Fig. 3b) and should be of the same type. One of the simple ways to determine the point for fastening a reed switch is to fasten it tangentially to a circle (with the radius equal to the minimum allowable safety distance) circumscribed about the phase axis. In this case, it is affected by the maximal induction from the current in this phase, and we need only to find the point $M$ (Fig. 3b) on this circle, where the total induction $B^n_{lon}$, which affects a reed switch, produced by the currents in the remaining five phases is minimal. The induction $B^n_{lon}$ is calculated by Eq. (1), but five terms are used, which correspond to the phases where the currents interfere. The reed switch is mounted at this point.

## 5. Selection of the protection operation parameters

### 5.1. Selection of the time $\Delta t_{th}$ between the instants of closing the contacts of reed switches 1 and 2 required for the protection operation

We mention above that $\Delta t = 0$ in the case of an external fault when errors are ignored. However, actually, $\Delta t = \Delta t_{im}$ ($\Delta t_{im}$ is the time imbalance, by analogy with the imbalance current of differential protection) due to errors. The error $\varepsilon_1$ appears when a reed switch is mounted at the target point, the error $\varepsilon_2$ is due to the difference between the reed switch actuation times; and the error $\varepsilon_3$ is due to the deviation of $B_{act}$ from the calculated value. Therefore, the protection should operate at the setting $\Delta t_{th} > \Delta t_{im}$.

To determine $\Delta t_{im}$, it is necessary to determine the dependence of the time $t$ from the $B_{lon}$ zero-crossing time to the reed switch actuation on the ratio $k = B_{lon}/B_{act}$. It is experimentally determined for each reed switch, for example, as shown in Appendix A. Fig. 4 shows this dependence for HSA-12126 reed switches with the rated action time $t_r = 0.3$ ms. We determine $\Delta t_{im}$ when using them in the both lines.

Let $\varepsilon_1 = \pm 0.03$ [21], $\varepsilon_2 = \pm 0.1$, $t_r = 0.3$ ms [27], $\varepsilon_3 = \pm 0.03$; $k_2 = B_{lon}/B_{th1} = 4$ ($B_{th1}$ is the induction under which reed switches 1 and 2 should actuate) in the case of a SC at point $K1$. Due to the error $\varepsilon_1$, reed switches 1 and 2 can be affected by the inductions $B^{'}_{lon} = 1.03B_{lon}$ and $B^{''}_{lon} = 0.97B_{lon}$. Since $\varepsilon_3 = 0.03$, one reed switch can actuate under $B^{'}_{act} = 0.97B_{th1}$, and another, under $B^{''}_{act} = 1.03B_{th1}$ in the worst case. The ratio $k$ is $k^{'} = B^{'}_{lon}/B^{'}_{act} = 1.03B_{lon}/0.97B_{th1} = 4.24$ and $k^{''} = B^{''}_{lon}/B^{''}_{act} = 3.76$. Using Fig. 4, we find the times $t^{'} = 0.85$ ms and $t^{''} = 0.5$ ms corresponding to $k'$ and $k${\Prime}. As a result, we find

$$\Delta t_{im} = t^{''} - t^{'} + 0.2t_r = 0.95 - 0.85 + 0.2 \cdot 0.3 = 0.16 \text{ ms}$$

The time $\Delta t_{im}$ is determined in the same way with other values of $k_2$ in the case of an external fault (point $K1$); $\Delta t_{im}$ increases with a decrease in $k_2$. Therefore, if an SC occurs in the end of the line outgoing from busbars of a receiving substation, $\Delta t_{im}$ can be larger than in the case of a busbar SC. To avoid the offset from this $\Delta t_{im}$, the protection is blocked if reed switches 5 and 6, which close contacts at $B_{th2} > B_{th1}$, does not actuate. Then,

$$\Delta t_{th} \geq 1.3\Delta t_{im1} \quad (2)$$

where $\Delta t_{im1}$ is determined in the same way as $\Delta t_{im}$, but under the action of a MF with $B_{lon} = B_{th2}$ on reed switches 1 and 2; the offset coefficient 1.3 is responsible for the calculation and experimental errors, as is common in the relay protection.

### 5.2. Induction $B_{th1}$ and $B_{th2}$ under which reed switches 1, 2 and 5, 6 should actuate

As is shown in Appendixes B and C, the inductions $B_{th1}$ and $B_{th2}$ should satisfy the following conditions:

$$B_{th1} \leq B_{th2}/1.5 \quad (3)$$

$$B_{th1} \geq 1.3\left(B_{load.\max} + B_{f1}\right) \quad (4)$$

$$B_{th1} \geq 1.3B_{f2} \quad (5)$$

$$B_{th2} \leq B_{ca.r}/1.5 \quad (6)$$

$$B_{th2} \leq B_{ca.\min}/1.5 \quad (7)$$

where $B_{ca.r}$ ($B_{ca.\min}$) is the induction amplitude of MF which acts on a reed switch in the minimal mode of system operation in the case of a double phase SC at the boundary of cascade action zone (section $l_{ca}$ of the line from its opposite side, where $\Delta t < \Delta t_{th}$ under a SC) before circuit breaker opening from the receiving side (at busbars of the receiving part in the case of double phase SC after the breaker opening); the required protection sensitivity factor $k_s = 1.5$ in case of SC in $l_{ca}$, like in traditional protections [28]; $B_{load.\max}$ is the induction amplitude of MF produced by the full-load current in a line; $B_{f1}$ is the induction amplitude of MF acting on a reed switch near the phase of a fault-free line under the current in a fault line after circuit breaker opening from the side of the receiving substation in the case of SC in $l_{ca}$ (calculated for a three-phase SC at the $l_{ca}$ boundary in the maximal mode of system operation); $B_{f2}$ is the induction amplitude of MF produced by the double earth fault current in the phases of the lines after opening the fault line circuit breaker from the receiving side.

Condition (3) ensures $\Delta t > \Delta t_{th}$ in the case of a SC at the $l_{ca}$ boundary ($l_{ca} \leq 0.25\ l$ [28], $l$ is the line length); conditions (4) and (5) ensure failure of the protection to break a fault-free line in the case of a SC near the busbars of the power supply substation and in the cascade zone, as well as in the case of a ground SC at two points of the network, one in the zone $l_{ca}$ in the phase of the line protected and the other in the phase of the connection outgoing from the busbars of the receiving substation. Conditions (6) and (7) ensure the sensitivity of reed switches 5 and 6 to short circuit in $l_{ca}$, when $X_{S.\max} > 0.4X_L$ and $X_{S.\max} \leq 0.4X_L$, respectively ($X_{S.\max}$ is the maximal resistance of the system before the busbars the considered lines are connected to; $X_L$ is the resistance of a line).

*5.3 Time $\Delta t_{th1}$ between the instants of closing contacts of reed switches 3 and 4, required for the detection of line SC and inductions $B_{th3}$ and $B_{th4}$ under which reed switches 3, 4 and 7, 8 should actuate*

These reed switches and elements connected to them form an auxiliary part of the protection used to detect SCs in the lines protected before $l_{ca}$ at $1.5 < k_1 \leq 2$. To avoid $\Delta t_{th1}$ offset from the maximal $\Delta t_{im}$, this part is blocked if reed switches 7 and 8 do not actuate (like in the case of reed switches 1, 2 and 5, 6). In this case, for $\Delta t_{th1} = \Delta t_{th}$, it is convenient to take $B_{th4}/B_{th3} = B_{th2}/B_{th1}$. The $B_{th4}$ value is limited by the need to ensure $k_s \geq 1.5$ at $B_{lon} > 1.5B_{ca.r}$, since reed switches 7 and 8 should actuate only when $k_1 > 1.5$. Hence,

$$B_{th3} \leq B_{th4}/1.5 \tag{8}$$

$$B_{th4} \leq B_{ca.r} \tag{9}$$

When $X_{S.\max} > 0.4X_L$, one can avoid mounting reed switches 3 and 4 and measure $\Delta t$ between actuation of reed switches 5 and 6, because $B_{th2}$ is selected from condition (6) and is equal to $B_{th3}$. Let us note that the required protection operation can be ensured (see justification in Appendix B), if $X_{S.\max} \geq 0.15X_L$, $\varepsilon_3 \leq 0{,}03$, and $t_r \leq 0.3$ ms for all the reed switches used for $\Delta t$ measurement.

## 6. Protection circuit and algorithm of operation

Fig. 3a shows the line protection circuit, where $1.5 \leq k_1 \leq 2$. It includes reed switches 1–24, microcontroller 25, and output elements 26 and 27. Reed switches 1, 2, 9, 10, 17, and 18 actuate under $B_{th1}$; reed switches 3, 4, 11, 12, 19, and 20, under $B_{th3}$; reed switches 5, 6, 13, 14, 21, and 22, under $B_{th2}$, and reed switches 7, 8, 15, 16, 23, and 24, under $B_{th4}$.

Since many reed switches are used, we construct the protection so as it correctly operates if any of them fails. Malfunctions include: failure to operate, closed reed switch contacts for 10 ms after its actuation (the duration of the closed state of the contacts of a good reed switch is always less than 10 ms). Let us formulate the protection operation conditions in the case of SC on line L1 in terms of the boolean algebra. We will use boolean operators AND, OR, and NOT and the following designations: $O_1$ and $O_2$ for the trip signals to breakers $Q_1$ and $Q_2$ (Fig. 3a); $G_i$ for the reed switch actuation signal; $F_i$ for the operation failure signal; $Z_i$ for the signal that the reed switch contacts remain closed for 10 ms after its actuation (i is the reed switch number in Fig. 3a); $R_1$ ($R_2$), $R_3$ ($R_4$), $R_9$ ($R_{10}$), $R_{11}$ ($R_{12}$), $R_{17}$ ($R_{18}$), and $R_{19}$ ($R_{20}$) for the signals about actuation of reed switches 1 (2), 3 (4), 9 (10), 11 (12), 17 (18), and 19 (20) before reed switches 2 (1), 4 (3), 10 (9), 12 (11), 18 (17), and 20 (19), respectively; $T_1$, $T_2$, $T_3$, $T_4$, $T_5$, and $T_6$ for the signals that the time between the actuations of reed switches 1 and 2, 3 and 4, 9 and 10, 11 and 12, 17 and 18, and 19 and 20 attains $\Delta t_{po}$ (2); T7 (T8) for the signal that 5 ms has elapsed since the actuation of reed switches 5, 13, or 21 (6, 14, or 22) (a good reed switch actuates before the induction attains the amplitude value, which takes 5 ms). All signals are boolean variables. If there is a signal, then the corresponding variable asserts, else deasserts (for the sake of brevity, we will omit the words "signal", "logical zero", and "logical unit", but keep this in mind).

The first mode is a short circuit in section L1 before the cascade action zone $l_{ca}$. In this case, the currents on L1 are greater than the currents in L2; $B_{po2}$ acts on the reed switches near L1, $B_{po1}$ acts on the reed switches near L2, and $B_{po2} > B_{po1}$. Signal O1 is produced, if phase A is damaged and there are G1 AND G2 AND G5 AND there are R1 (reed switch 1 has actuated before reed switch 2) AND T1 ($\Delta$t between the actuations of reed switches 1 and 2 attains $\Delta$tpo (2)), which are stored for a time of 5 ms (time of 5 ms is taken with a margin based on the fact that all reed switches operate until the induction attains its amplitude value, which occurs in 5 ms after it passes through zero), AND there are no $Z_1$ AND $Z_5$ (prevent false tripping of L1 under an external fault, see explanations in Appendix D). Memorization (operator $P^t$) of signals $R_1$ and $T_1$ ensures the protection operation in the case of a short circuit on L1, otherwise it is impossible to determine the sequence of actuations of reed switches 1 and 2 and measure the time $\Delta$t, since reed switch 5 actuates after reed switches 1 and 2 ($B_{po2} > B_{po1}$), and signals from reed switches 1 and 2 simultaneously arrive at the time of closing the contacts of reed switch 5.

The second mode is a short circuit in the section L1 before $l_{ca}$, when the reed switches are affected by MFs with inductions $B_{po4}$ near L1 and with inductions $B_{po3}$ and near L2. Signal $O_1$ is produced if there are $G_3$ AND $G_4$ AND $G_7$ AND there are $R_3$ (reed switch 3 has actuated before reed switch 4) AND $T_2$ (the time between their actuations attains $\Delta t_{po}$ (2)), which are stored for 5 ms, AND there are no $Z_3$ AND $Z_7$ (perform the same role as $Z_1$ and $Z_5$). The conditions for the protection operation of in these modes in the case of damage in phase B or C of line L1 are similarly formulated.

The third mode is a short circuit in the cascade action zone $l_{ca}$. Signal $O_1$ is produced if there is $G_5$ AND there is no $Z_5$ OR there is $G_{13}$ AND there is no $Z_{13}$ OR there is $G_{21}$ AND there is no $Z_{21}$ AND there is $T_7$ (5 ms has passed after the actuation of any of the reed switches 5, 13, or 21; 5 ms is sufficient to failure of actuation of reed switches 2, 10, and 18) AND, OR there are no $G_2$ AND $G_{10}$ AND $G_{18}$ AND $F_2$ AND $F_{10}$ AND $F_{18}$ OR there are no $G_2$ AND $G_{10}$ AND $G_{18}$ AND $G_6$ AND there is $F_2$, OR there are no $G_2$ AND $G_{10}$ AND $G_{18}$ AND $G_{14}$ AND there is $F_{10}$ OR there are no $G_2$ AND $G_{10}$ AND $G_{18}$ AND $G_{22}$ AND there is $F_{18}$ OR there are no $G_{10}$ AND $G_{18}$ AND $G_6$ AND there is $G_2$ AND $Z_2$ OR there is no $G_2$ AND $G_{18}$ AND $G_{14}$ AND there is $G_{10}$ AND $Z_{10}$ OR there are no $G_2$ AND $G_{10}$ AND $G_{22}$ AND there are $G_{18}$ AND $Z_{18}$. Here, the signals $Z_2$, $Z_{10}$, $Z_{18}$ and $F_2$, $F_{10}$, $F_{18}$ are needed to avoid failure in the protection operation in this mode, and $F_2$, $F_{10}$, and $F_{18}$ are also required to avoid a false L1 tripping signal in the case of a ground fault at two points, where one point is located on L2 in $l_{ca}$ zone, and the second point is on the connection branching off from the busbars of the receiving substation; $Z_5$, $Z_{13}$, and $Z_{21}$ are required to prevent tripping of L1 in the load mode after clearance of the external fault. The same condition is used to detect a short circuit on L1, when the currents in L2 produce an MF with the inductions less than $B_{po1}$. The protection operation conditions for opening circuit breaker Q2 (signal O2) in the above modes are similarly formulated.

Let us write the protection operation conditions in the analytical form according to the above formulations (the signs "+" and "·" denote boolean addition and multiplication, and the sign "–" above a symbol denotes boolean negation):

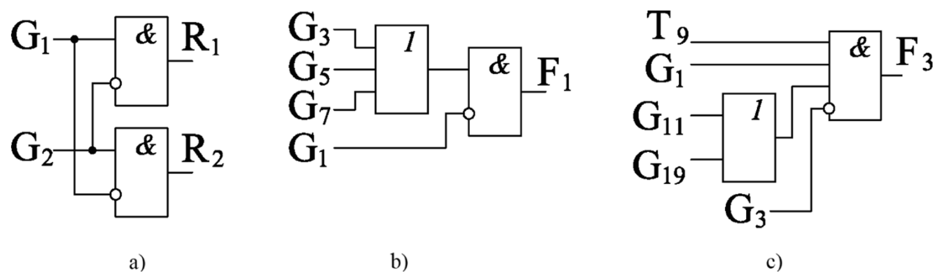



**Fig. 5.** Signal generation logic for $R_1$, $R_2$, $F_1$ and $F_3$.

$$\begin{aligned}O_1 = {} & G_1 \cdot G_2 \cdot G_5 \cdot (T_1 \cdot R_1)P^t \cdot \overline{Z}_1 \cdot \overline{Z}_5 + G_3 \cdot G_4 \cdot G_7 \cdot (T_2 \cdot R_3)P^t \cdot \overline{Z}_3 \cdot \overline{Z}_7 + \\ & + G_9 \cdot G_{10} \cdot G_{13} \cdot (T_3 \cdot R_9)P^t \cdot \overline{Z}_9 \cdot \overline{Z}_{13} + G_{11} \cdot G_{12} \cdot G_{15} \cdot (T_4 \cdot R_{11})P^t \cdot \overline{Z}_{11} \cdot \overline{Z}_{15} + \\ & + G_{17} \cdot G_{18} \cdot G_{21} \cdot (T_5 \cdot R_{17})P^t \cdot \overline{Z}_{17} \cdot \overline{Z}_{21} + G_{19} \cdot G_{20} \cdot G_{23} \cdot (T_6 \cdot R_{19})P^t \cdot \overline{Z}_{19} \cdot \overline{Z}_{23} + \\ & + (G_5 \cdot \overline{Z}_5 + G_{13} \cdot \overline{Z}_{13} + G_{21} \cdot \overline{Z}_{21}) \cdot T_7 \cdot (\overline{G}_2 \cdot \overline{F}_2 \cdot \overline{G}_{10} \cdot \overline{F}_{10} \cdot \overline{G}_{18} \cdot \overline{F}_{18} + \\ & + \overline{G}_2 \cdot \overline{G}_{10} \cdot \overline{G}_{18} \cdot \overline{G}_6 \cdot F_2 + \overline{G}_2 \cdot \overline{G}_{10} \cdot \overline{G}_{18} \cdot \overline{G}_{14} \cdot F_{10} + \overline{G}_2 \cdot \overline{G}_{10} \cdot \overline{G}_{18} \cdot \overline{G}_{22} \cdot F_{18} + \\ & + \overline{G}_{10} \cdot \overline{G}_{18} \cdot \overline{G}_6 \cdot G_2 \cdot Z_2 + \overline{G}_2 \cdot \overline{G}_{18} \cdot \overline{G}_{14} \cdot Z_{10} \cdot G_{10} + \overline{G}_2 \cdot \overline{G}_{10} \cdot \overline{G}_{22} \cdot Z_{18} \cdot G_{18})\end{aligned} \tag{10}$$

$$\begin{aligned}O_2 = {} & G_1 \cdot G_2 \cdot G_6 \cdot (T_1 \cdot R_2)P^t \cdot \overline{Z}_2 \cdot \overline{Z}_6 + G_3 \cdot G_4 \cdot G_8 \cdot (T_2 \cdot R_4)P^t \cdot \overline{Z}_4 \cdot \overline{Z}_8 + \\ & + G_9 \cdot G_{10} \cdot G_{14} \cdot (T_3 \cdot R_{10})P^t \cdot \overline{Z}_{10} \cdot \overline{Z}_{14} + G_{11} \cdot G_{12} \cdot G_{16} \cdot (T_4 \cdot R_{12})P^t \cdot \overline{Z}_{12} \cdot \overline{Z}_{16} + \\ & + G_{17} \cdot G_{18} \cdot G_{22} \cdot (T_5 \cdot R_{18})P^t \cdot \overline{Z}_{18} \cdot \overline{Z}_{22} + G_{19} \cdot G_{20} \cdot G_{24} \cdot (T_6 \cdot R_{20})P^t \cdot \overline{Z}_{20} \cdot \overline{Z}_{24} + \\ & + (G_6 \cdot \overline{Z}_6 + G_{14} \cdot \overline{Z}_{14} + G_{22} \cdot \overline{Z}_{22}) \cdot T_8 \cdot (\overline{G}_1 \cdot \overline{F}_1 \cdot \overline{G}_9 \cdot \overline{F}_9 \cdot \overline{G}_{17} \cdot \overline{F}_{17} + \\ & + \overline{G}_1 \cdot \overline{G}_9 \cdot \overline{G}_{17} \cdot \overline{G}_5 \cdot F_1 + \overline{G}_1 \cdot \overline{G}_9 \cdot \overline{G}_{17} \cdot \overline{G}_{13} \cdot F_9 + \overline{G}_1 \cdot \overline{G}_9 \cdot \overline{G}_{17} \cdot \overline{G}_{21} \cdot F_{17} + \\ & + \overline{G}_9 \cdot \overline{G}_{17} \cdot \overline{G}_5 \cdot G_1 \cdot Z_1 + \overline{G}_1 \cdot \overline{G}_{17} \cdot \overline{G}_{13} \cdot Z_9 \cdot G_9 + \overline{G}_1 \cdot \overline{G}_9 \cdot \overline{G}_{21} \cdot Z_{17} \cdot G_{17})\end{aligned} \tag{11}$$

There are no the 2nd, 4th, and 6th terms in (10) and (11) for lines where $k_1 \leq 1.5$. Signals about the failure of reed switches 3–8, 11–16, and 19–4 to operate are not used as well in (10) and (11), since they do not impact the correct operation of the protection when reed switches 1, 2, 9, 10, 17, and 18 are healthy. All signals, except for $G_1$–$G_{24}$, are generated inside microcontroller 25. For example, signals $T_1$–$T_8$ are produced by timers; signals $R_1$ and $R_2$, by the logic circuit (Fig. 5a, where 1, 2, 3, 5, 7, 11, 13, 15, 19, 21, and 23 are the contacts of the corresponding reed switches). Signals $R_3$, $R_4$, $R_9$–$R_{12}$, and $R_{17}$–$R_{20}$ are generated in the same way as $R_1$ and $R_2$. Block diagrams of algorithms that implement the 1st (terms 2–6 are similar to the first one) and the 7th terms from (10) in microcontroller 25 are presented in Appendix E.

## 7. Reliability of the protection reed switches

The conditions for detection of reed switch failed to operated, e.g., 1, 3, 5, and 7, are formulates as follows. Signal F1 about the failure of reed switch 1 to operate is produced if there is no signal $G_1$ from this reed switch AND there is $G_3$ OR $G_5$ OR $G_7$. Signal $F_3$ about the failure of reed switch 3 to operate is produced if there is no $G_3$ AND there are $G_1$ AND $T_9$ (5 ms have passed since the actuation of reed switch 1) AND there is $G_{11}$ OR $G_{19}$. Signal $F_5$ about the failure of reed switch 5 to operate is generated if there is no $G_5$ AND there is $G_1$ OR $G_3$ AND there is $T_9$ AND there is $G_{13}$ OR $G_{21}$. Signal $F_7$ about the failure of reed switch 7 to operate is generated if there is no $G_7$ AND there is $G_1$ OR $G_3$ OR $G_5$ AND there is $T_9$ AND there is $G_{15}$ OR $G_{23}$.

These conditions can be analytically written as

$$F_1 = \overline{G}_1 \cdot (G_3 + G_5 + G_7); \tag{12}$$

$$F_3 = (G_1 + G_5) \cdot \overline{G}_3 \cdot T_9 \cdot (G_{11} + G_{19}) \tag{13}$$

$$F_5 = G_1 \cdot \overline{G}_5 \cdot T_9 \cdot (G_{13} + G_{21}) \tag{14}$$

$$F_7 = (G_1 + G_3 + G_5) \cdot \overline{G}_7 \cdot T_9 \cdot (G_{15} + G_{23}) \tag{15}$$

Signals $F_1$, $F_3$, $F_5$, and $F_7$ are generated in microcontroller 25 according to the logic diagrams in Fig. 5b and 5c. The block diagram of algorithms (12) and (13) is given in Appendix E. The failures of the remaining reed switches to operate are detected in the same way, but also only in SC modes when they operate.

## 8. Protection operation in different modes

Let a three-phase SC occurs on busbars of the receiving substation, and SC currents in lines produce MFs with the inductions $B_{po4}$. If reed switches 1–24 (Fig. 3a) are good, then signals $G_1$–$G_{24}$ about their actuation arrive to the inputs of microcontroller 25. Due to the errors, signals from reed switches 1 and 2, 3 and 4, 9 and 10, 11 and 12, 17 and 18, and 19 and 20 fixed near the same phases of lines L1 and L2 arrive at different times. But the time between their actuations $\Delta t < \Delta t_{po}$ (2); therefore no signals $T_1$–$T_6$. As a result, the first six terms in (10) and (11) are equal to zero. The 7th is also zero, since in contains inverted variables. As a result, $O_1 = O_2 = 0$ and the protection does not operate.

Let, in the case of a three-phase short circuit in the L1 section before $l_{ca}$, the currents in it and in line L2 produce MFs with the inductions $B_{po4}$ and $B_{po3}$, respectively. Reed switches 3, 4, 11, 12, 19, and 20 actuates and produce signals $G_3$, $G_4$, $G_{11}$, $G_{12}$, $G_{19}$, and $G_{20}$. Since the currents in L1 are greater than the currents in L2, reed switches 3, 11, and 19 close contacts earlier than reed switches 4, 12, and 20, and signals $R_3$, $R_{11}$, and $R_{19}$ are generated. The time between the actuations of reed switches 3 and 4, 11 and 12, and 19 and 20 attains $\Delta t_{po}$, and signals $T_2$, $T_4$, and $T_6$ are generated, respectively. The both groups of signals are memorized for 5 ms ($P^t$ operator indicates this in (10)). Reed switches 7, 15, and 23 also actuate, but no>5 ms later than reed switches 3, 4, 11, 12, 19, and 20, since they react to the high induction value. Therefore, there are $G_7$, $G_{15}$, and $G_{23}$. There are no $Z_3$, $Z_7$, $Z_{11}$, $Z_{15}$, $Z_{19}$, and $Z_{23}$, since 10 ms has not elapsed after the actuation of reed switches 3, 7, 11, 15, 19, and 23. Therefore, the 2nd, 4th, and 6th terms in (10) are equal to 1, and $O_1 = 1$. Line L1 is tripped. In case of failure of, e.g., reed switch 15 to operate, the 4th term in (10) is equal to zero, since there is no $G_7$. But the 2nd and 6th terms are equal to 1. Therefore, $O_1 = 1$. The protection behaves similarly in the case of failure of other reed switches to operate.

In the case of a SC between, for example, the phases $A$ and $B$ in $L_1$ in $l_{ca}$, the protection does not produce signal $O_1$ to open $Q_1$ until opening the breaker on the receiving side. This can be explained by the following. Let the short-circuit currents in $L1$ and $L2$ produce MFs with the inductions higher than $B_{po4}$. Then, there are signals $G_1$–$G_8$ and $G_9$–$G_{16}$ from reed switches 1–8 and 9–16, and the 7th term in (10) is zero. Terms 1–6 are also zero, since the difference between the currents in $L1$ and $L2$ is negligible under a short circuit in $l_{ca}$. Therefore, $\Delta t < \Delta t_{po}$, there are no signals $T_1$–$T_6$, and $O_1 = 0$. After tripping $L1$ from the receiving side, the currents in the phases of $L2$ are insufficient (the entire SC current flows through $L1$) for actuation of reed switches 2, 4, 6, 8, 10, 12, 14, and 16. Therefore, $G_2 = G_4 = G_6 = G_8 = G_{10} = G_{12} = G_{14} = G_{16} = 0$, and signals $F_2$ and $F_{10}$ are also absent (they are generated similarly to $F_1$ following (12)), since reed switches 2 and 10 are in good order. Reed switches 5, 13, and 21 signal, $G_5 = G_{13} = G_{21} = 1$, but there are no $Z_5$, $Z_{13}$, and $Z_{21}$, because 10 ms has not elapsed after their actuation. As a result, the 7th term in (10) is equal to 1, and $O_1 = 1$. If, for example, reed switch 2 has not actuated before tripping $L1$ from the receiving side due to a fault, then signal $G_2 = 0$ after tripping $L1$, and $F_2 = 1$. Therefore, the 7th term is equal to 1 and $O_1 = 1$. If reed switch 2 has actuated and its contacts remain closed, then $G_2 = 1$ and $Z_2 = 1$, since the contacts of reed switch 2 have not broken within 10 ms. But reed switch 6 does not actuate ($G_6 =$

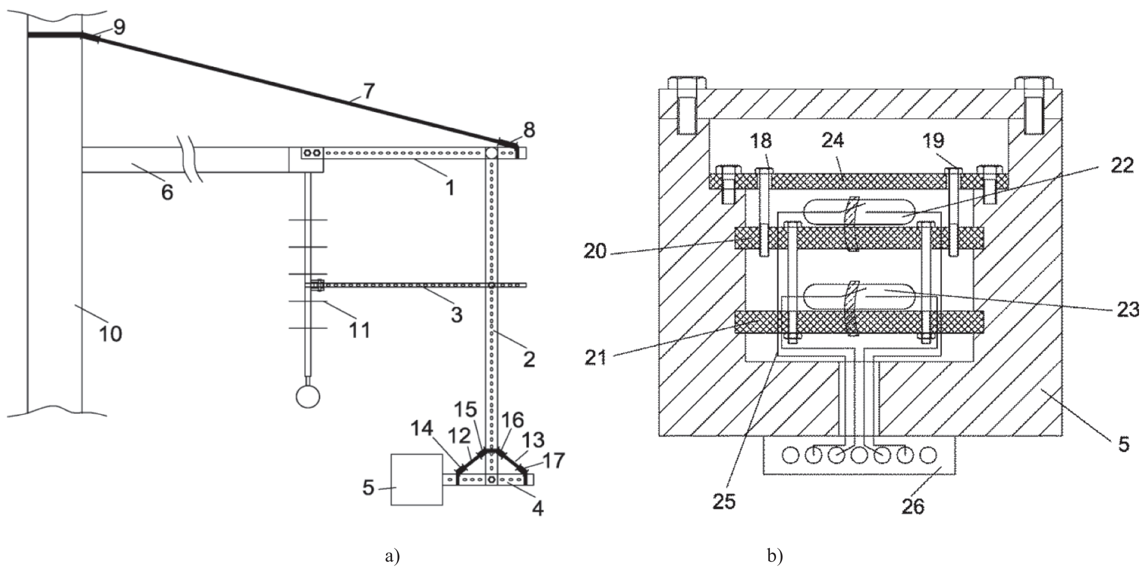



**Fig. 6.** (a) General view of the structure for fastening reed switches; (b) case 5 in section (single column fitting image.).

0). As a result, $O_1 = 1$.

Let us consider a ground fault at two points, where one point is in $l_{ca}$, for example, on phase $A$ of line $L1$, and another is on phase $B$ of the connection branching off from the busbars of the receiving substation. Let us show that the protection does not produce $Q_1$ and $Q_2$ trip signals. Before $L1$ is tripped from the receiving side, short-circuit currents flow through phases $A$ and $B$ of lines $L1$ and $L2$. In phases $B$ they are equal, but in phases $A$ they are different. Therefore, there are signals $G_1$–$G_8$ and $G_9$–$G_{16}$, if reed switches 1–8 and 9–16 are in good order, but the time between the instants of actuation of reed switches 1 and 2, 3 and 4, 9 and 10, and 11 and 12 is shorter than $\Delta t_{po}$, and there are no $T_1$, $T_2$, $T_3$, and $T_4$. Hence, $O_1 = O_2 = 0$, and $L1$ and $L2$ remain in operation. After tripping $L1$ from the receiving side, short-circuit currents flow through its phase $A$ and phase $B$ of line L2. Reed switches 1, 3, 5, 7, 10, 12, 14, and 16 actuate, and signals $G_1$, $G_3$, $G_5$, $G_7$, $G_{10}$, $G_{12}$, $G_{14}$, and $G_{16}$ are produced, as well as signals $R_1$, $R_3$, $R_{10}$, and $R_{12}$ (that reed switches 1, 3, 10, and 12 have actuated before reed switches 2, 4, 11, and 13). Therefore, all terms in (10) and (11) are equal to zero, and $O_1 = O_2 = 0$. If reed switch 1 did not close the contacts ($G_1 = 0$) or closed ($G_1 = 1$) and did not break within 10 ms ($Z_1 = 1$) because of a fault, then $O_2 = 0$, since there is $G_5$. Other modes are considered in a similar way.

## 9. Structure for fastening reed switches

She (Fig. 6) includes [29] bars 1–4 with scales and holes and case 5. One end of bar 1 is attached to traverse 6, and another end is attached to support 10 by cable 7 and tambuckles 8 and 9. The electrical safety distance is counted on the scale of bar 1, and it is fastened to one end of bar 2 at this point. Bar 3 is attached to set of insulators 11 at one end and to bar 2 at the other end so as bars 1 and 2 are mutually perpendicular. The distances from traverse 6 and the axis of bar 2 to the reed switch fixing point are measured on the scales of bars 2 and 4. Bars 2 and 4 are connected with a bolt. Bar 4 is fixed with cables 12 and 13 and tambuckles 14–17. Using bolts 18 and 19 as handles, rigidly fastened disks 20 and 21 are rotated in the grooves of case 5 to a required angle (counted on the scale on cover 24). Their position is fixed by screwing bolts 18 and 19 into the holes in disk 20. Reed switches 22 and 23 are connected to microprocessor 25 by cables through terminal block 26. When designing the protection with four reed switches per phase, another case 5 with two reed switches is attached to bar 4. Other reed switches are fastened at points specified using the same structure. The weight of each of them does not exceed 5 kg. Note that this structure can also be used for 6–10-kV lines.

**Table 1**
An example of a table.

| Voltage (kV) | Weight (kg) | | | |
|---|---|---|---|---|
| | Total | Copper | Steel | Insulation |
| 6 | 60/11 | 9/1 | 21/2 | 30/- |
| 10 | 90/11 | 12/1 | 33/2 | 45/- |
| 35 | 300/30 | 32/1.5 | 118/3.5 | 150/- |

## 10. Estimated resource saving due to the protection suggested

Table 1 presents the weight and size parameters of the protection suggested and an ABB protection with six current transformers.

This table shows that the traditional protection requires 9 and 10 times more copper and steel, respectively, than the protection suggested at a voltage of 6 kV, 12 and 16 times more, at a voltage of 10 kV, and 21 and 33 times more, at a voltage of 35 kV. It also requires 30–150 kg of high-voltage insulation, which is not required for the protection suggested. The analysis of similar data for protections of several other companies has showed the ratios close to those given in Table 1.

## 11. Example of calculation of the protection operation parameters for lines in Fig. 2a

Transformer T is of TDN-40000/110 type with a low voltage of 38.5 kV. The voltage control range is ± 16%; the short-circuit voltages $u_{SC.max} = 11.02\%$ and $u_{SC.min} = 10.35\%$. The lines are made from AC 120/19 cable with the resistances $r_{spec} = 0.25$ Ohm/km and $X_{spec} = 0.41$ Ohm/km; their length is 30 km (PM35-2FT supports). The distances between the phases are given in Fig. 3b. A power of 8 MW is transmitted through every line at $cos\varphi = 0.9$. The system resistance before the transformer $X_S = 0$. The rated load current amplitude $I_{load.r} = 0.207$ kA.

Let us find the ratio between $X_{S.max}$ and $X_L$. $X_S = 0$; therefore, $X_{S.max} = X_{T.max} = 4.85$ Ohm ($X_{T.max}$ – maximal resistance of the transformer). Since $X_{S.max} > 0.15X_L$, we continue the calculations. In the case of a SC at the boundary $l_{ca} = 0.25\ l$, we calculate the maximum currents $I_{SC.L1} = 2.06$ kA and $I_{SC.L2} = 1.24$ kA in $L_1$ (fault) and $L_2$, respectively, and the minimum current $I_{1ca} = 1.46$ kA in $L_1$. They are required to determine the number of reed switches to be mounted near a phase and to check the performance of the protection. Since $k_1 = I_{SC.L1}/I_{1ca} = 1.4 < 1.5$, then

**Table 2**
Maximal length $l$ (km) of lines the protection can be mounted at.

| Cross section, mm$^2$ | 70 | 95 | 120 | 150 | 185 | 240 |
|---|---|---|---|---|---|---|
| Rated power of the transformer (T), MVA | Length ($l$), km | | | | | |
| 16 | 45 | 20 | – | – | – | – |
| 25 | 45 | 35 | 20 | | – | – |
| 40 | 45 | 40 | 30 | 20 | – | – |
| 63 | 45 | 45 | 40 | 35 | 20 | – |
| 80 | 35 | 45 | 40 | 35 | 30 | 20 |

two reed switches per phase are to be mounted.

To calculate $B_{f1}$, we find the maximum current $I_{tr.L1} = 2.31$ kA in $L_1$ with a short circuit at the boundary $l_{ca}$ ($L_2$ is broken), and to determine $B_{ca.\min}$, the minimum current $I_{ca.\min} = 1.41$ kA in the event of a bus SC in the receiving substation. To calculate $B_{f2}$, we find the current $I_{SC.ca}$ of an earth fault at two points. It is maximal when the first closing point is located at the boundary $l_{ca}$, and the second, near the busbars of the receiving substation. Taking into account that the double fault current is comparable with the current $I_{SC}$ of a double phase SC, we take $I_{SC.ca} = I_{SC}$ to ensure the $B_{th1}$ margin, which is determined in the case of a short circuit at the boundary $l_{ca}$ in the maximum mode of the system operation. Then, $I_{SC.ca} = I_{SC} = 2.01$ kA.

Let us select the parameters of the protection operation with reed switches 1, 5, 2, and 6. The induction $B^n_{lon}$ acting, for example, on reed switch 1 is minimal if the point $M$ (Fig. 3b), where it is fixed, belongs to the plane under the phases, and $\gamma = 124^\circ$ (Fig. 3b). In this case, the cosines of the angles between the axis of reed switch 1 and inductions produced by currents in the phases $A$, $B$, and $C$ of both lines are $\cos\alpha_{A1,1} = 1$, $\cos\alpha_{B1,1} = 0.77$, $\cos\alpha_{C1,1} = 0.9$, $\cos\alpha_{A2,1} = 0.74$, $\cos\alpha_{B2,1} = 0{,}93$, and $\cos\alpha_{C2,1} = 1$ (in the subscripts, the numbers 1 and 2 after the letters $A$, $B$, and $C$ means the first and the second lines, and the number after a comma is the reed switch number). The distances between the point $M$ and the axes of phases of the lines are $h_{A1,1} = 0.4$ m, $h_{B1,1} = 4.63$ m, $h_{C1,1} = 7.68$ m, $h_{A2,1} = 5.33$ m, $h_{B2,1} = 8.11$ m, and $h_{C2,1} = 9.14$ m. Reed switch 5 is fixed next to reed switch 1 at a point on a straight line passing through point $M$ parallel to the phase $A_1$ at the same angle $\gamma = 124^\circ$. Therefore, the ratios of the cosines to the distances found for point $M$ are also valid for the reed switch 5 point. Reed switches 2 and 6 are mounted symmetrically to reed switches 1 and 5 relative to the support.

Let us calculate the absolute values of the inductions $B_{load.\max}$, $B_{ca.\min}$, $B_{f1}$, and $B_{f2}$ which act along the axes of reed switches 1 and 5:

$B_{load.\max} = 1.94 \times 10^{-4}$ T; $B_{ca.\min} = 6.62 \times 10^{-4}$ T; $B_{f1} = 1.83 \times 10^{-5}$ T; $B_{f2} = 1.71 \times 10^{-5}$ T.

Following (7) and (3), $B_{th2} = B_{ca.\min}/1.5 = 4.4 \times 10^{-4}$ T; $B_{th1} = B_{th2}/1.5 = 2.93 \times 10^{-4}$ T.

We take these induction values as operation settings, since conditions (4) and (5) is fulfilled, and the reed switches are selected based on them. Let reed switches 1, 2, 5, and 6 be of the HSA-12126 type, with the actuation inductions $3 \times 10^{-4}$ T, $2.9 \times 10^{-4}$ T, $4.3 \times 10^{-4}$ T, and $4.5 \times 10^{-4}$ T, respectively. In this case, $\Delta t_{th} = 460$ μs (Appendix B). Let us check whether the protection detects a short circuit, for example, in $L_1$, at the boundary of $l_{ca}$. We calculate the amplitudes of inductions $B_{SC.L1}$ and $B_{SC.L2}$ under currents $I_{SC.L1} = 2.06$ kA and $I_{SC.L2} = 1.24$ kA in $L_1$ and $L_2$ taking into account $\varepsilon_1 = 0.03$: $B_{SC.L1} = 9.4 \times 10^{-4}$ T and $B_{SC.L2} = 5.97 \times 10^{-4}$ T. We find the ratios $B_{SC.L1}/B_{th1} = 3.13$ and $B_{SC.L2}/B_{th1} = 2.06$. Using Fig. 4 we find the time $\Delta t = 650$ μs. The operation settings of the other reed switches and $\Delta t$ between the actuation of reed switches 9 and 10, 17 and 18 are also determined. Similar calculations showed that the protection can be mounted at lines no longer then the values given in Table 2.

## 12. Results and discussion

The protection without current and voltage transformers is suggested for double-circuit transmission lines for the first time. It allows saving copper, steel, and high-voltage insulation in amounts unprecedented for relay protections. Thus, the consumption of these materials for 6–35-kV lines can be reduced by 8–30, 20–115, and 30–150 kg, respectively. The protection is quite simple: two reed switches are fixed near each phase and connected to a microprocessor, if $k_1 \leq 1.5$ ($k_1$ is the ratio of maximum to minimum SC current at the boundary of the cascade action zone), and four reed switches, if $1.5 < k_1 \leq 2$. A technique for selection of the protection operation parameters and an algorithm of its operation are developed. A design is suggested for fastening reed switches at the PM35-2FT support. It can be used with other supports with minor modifications.

The protection suggested meets the sensitivity requirements [28] for transverse directional protections if: (a) the operation inductances of the selected reed switches differ from the calculated values by no more than ± 3%; (b) the rated action time of the reed switches, between the time of closing the contacts of which the time is measured, does not exceed 0.3 ms. The protection is not inferior to up-to-date protection devices in terms of speed, since it is also based on a microprocessor, and the reed switches actuate within 5 ms from the instant of occurrence of a short circuit.

For reliable operation of the protection in all modes, the algorithm of its operation takes into account a probability of failure of any of the reed switches. A possibility of its detection is also provided, but only in the event of a short circuit. To do this in the load mode, it is necessary to equip the protection with test diagnostics– reed switches are used with a control winding, where signals are sent from an external voltage source simulating different short circuit types. Further, the protection operates following the above algorithms. To improve its reliability, the majorization principle can be used. For this, two similar protections are additionally mounted, and a fault line breaking signal is produced if two of the three protections have operated. Current sensors (reed switches) are also duplicated, unlike protections with current transformers. This increases its reliability in comparison with well-known non-microprocessor protections. However, only operating experience will show which design is more reliable.

As for the field of use of the protection, it is smaller than that of devices with current transformers. It is limited by a need to take into account the noise effect and a possibility of implementing the principle in those lines where the resistance of one circuit does not exceed the maximal resistance of the system (including the resistance of the supply transformer) by>6.6 times, and the ratio of maximal to minimal short-circuit current at the boundary of the cascade action zone does not exceed 2.

We should note that the reed switch differential protection [21] can be already used instead of classical protections with current transformers (CTs) at 10(35)-kV power transformers of at least 6.3 (40) MVA in power. The field of use of the protection suggested is presented in Table 2 and in the previous paragraph. Reed switch current protections [6] can be used for 6–110-kV electrical installations like traditional ones, except the cases where short-circuit currents are comparable with load currents. The protection reed switches (no more than three) should be provided with windings and connected to appropriately calibrated standard measuring instruments after increased the EMF induced on its terminals by the phase current. This is necessary because traditional overcurrent protections are often connected to the same CTs as the measuring instruments. The design of reed switch protections for electrical installations with voltages above 110 kV is still limited by insufficient sensitivity of reed switches due to large (according to safety regulations) distances from busbars with current. The special role of reed switch protections is that they can help to increase the reliability (by dozens of times theoretically) of the existing relay protection systems with CTs via duplication by the majorization principle. Current transformers are also duplicated, but this is not done now, which is one of the reasons for the delay in using this principle.

## 13. Conclusions

Measuring the time between the actuation of two reed switches fixed near the same phases of double-circuit lines and sequencing their actuation we have designed a short-circuit protection without current and voltage transformers. It opens prospect for unprecedented resource saving in the relay protection of 6–35-kV double-circuit lines, i.e., up to 30, 110, and 150 kg of copper, steel, and high-voltage insulation, respectively. The protection operation algorithm described ensures fail-safety in the cases of failure of reed switches and signaling about them and can be implemented on the basis of logical components of any nature. The analysis of the microprocessor protection with a logical part which functions following this algorithm allows expecting its correct operation in all modes and sensitivity and speed no worse that those of traditional transverse directional protections. However, it should be used in the cases where the maximal resistance of the system (including the line supplying transformer) is at least 15% of the resistance of one line circuit at a rated reed switch action time of up to 0.3 ms.

**Funding sources**

This research is funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP13268753).

## CRediT authorship contribution statement

**M.Ya. Kletsel:** Conceptualization, Methodology, Writing – review & editing. **B.E. Mashrapov:** Data curation, Writing – original draft, Funding acquisition. **R.M. Mashrapova:** Investigation, Visualization.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The main data is given in the article, the rest data will be made available on request

## Appendix A. Experimental derivation of the dependence of the time *t* on the ratio *k*

To derive the dependence of $t$ on $k$, experiments were carried with the setup shown in Fig. A.1. Four HSI Sensing reed switch types and six Russian reed switches with $t_r = 0.3$–$2$ ms were studied. Applying a DC voltage to induction coil (IC) 1 (with a reed switch fixed inside) from the first outputs of source 2 through breakers 3, the voltage $U_1$, under which the reed switch was activated, was recorded at the outputs of IC 1 by voltmeter 4 ($U_1$ is proportional to $B_{act}$). The closure of its contacts was determined using oscillograph 5 by rectangular voltage pulses at resistor 6 connected through these contacts to the second outputs of source 2. Then, the alternating voltage $U_2$ (proportional to $B_{lon}$) from source 9 was applied to IC 1 through breakers 7 and resistor 8. In that case, the ratio $k$ of the amplitude of that voltage to $U_1$ varied from 1 to 17. Further, at those ratios, the time $t$ was measured from the $U_2$ zero-crossing time to the reed switch actuation time by oscillograms of voltages measured at resistors 6 and 8.

## Appendix B. Statement of the need for fulfilment conditions (3), (6), and (7)

To explain how Eq. (3) is derived, we determined $B_{th2}$. Let us begin from conditions (6) and (7). In the case of SC at the boundary of the zone $l_{ca} = 0.25\,l$, e.g., in $L_1$,

$$I_{1ca} + I_{2ca} = 0.87U/(X_{S.\max} + 0.47X_L) \tag{A.1}$$

$$I_{1ca}/I_{2ca} = (l + l_{ca})/(l - l_{ca}) = 1.66 \tag{A.2}$$

where $U$ is the rated voltage of the lines; $I_{1ca}$ and $I_{2ca}$ are the currents in $L_1$ and $L_2$ in the case of a double phase SC at the boundary of $l_{ca}$ in the minimal system operating mode.

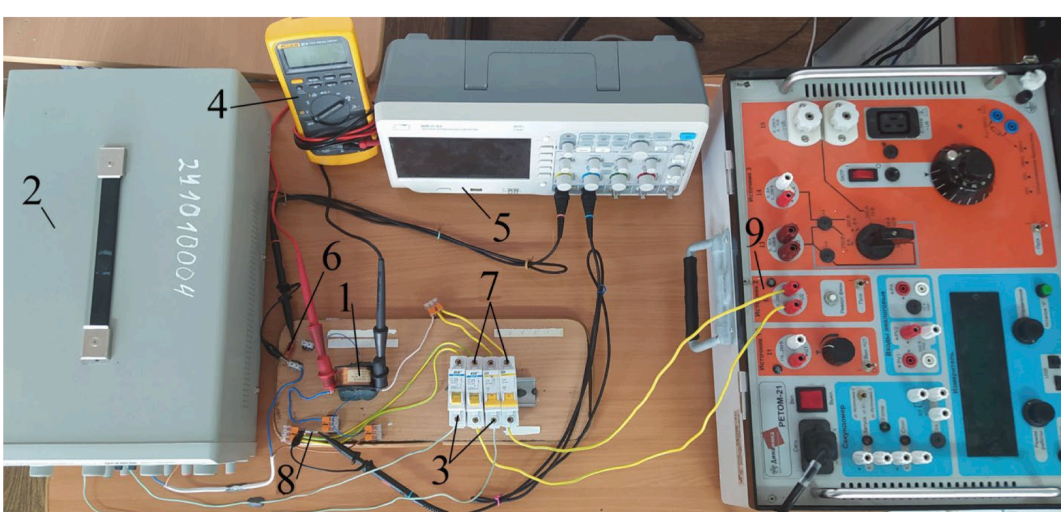



**Fig. A.1.** Laboratory setup (2-column fitting image.).

In the event of a bus SC in the receiving substation, when one of the lines is broken, the current

$$I_{ca.\min} = 0.87U/(X_{S.\max} + X_L) \tag{A.3}$$

From Eqs. (A1) - (A3),

$$I_{1ca}/I_{ca.\min} = 0.6(X_{S.\max} + X_L)/(X_{S.\max} + 0.47X_L); \tag{A.4}$$

The ratio is less than 1 when $X_{S.\max} > 0.4X_L$. Hence, the ratio of the inductions $B_{ca.r}$ and $B_{ca.\min}$ is the same. In the both cases, the sensitivity coefficient $k_s \geq 1.5$ is required. Therefore, condition (6) should be satisfied when $X_{S.\max} > 0.4X_L$, and condition (7), when $X_{S.\max} \leq 0.4X_L$.

Let us find the relationship between $B_{th1}$ and $B_{th2}$ to ensure $\Delta t > \Delta t_{th}$ in the case of a SC at the boundary $l_{ca} = 0.25\ l$. Let us analyze the values of $\Delta t$ in this mode at different $k_1$ and compare them with $\Delta t_{th}$ calculated at different $k_3 = B_{th2}/B_{th1}$ with allowance for the errors. Let $X_{S.\max}$ less than $0.4X_L$ and $k_3 = 1.5$. Then the maximum possible values $B_{th2} = 0.67B_{ca.\min}$ and $B_{th1} = 0.44B_{ca.\min}$. To determine the ratio of inductions acting on reed switches 1 and 2 in the case of a SC at the boundary of $l_{ca}$, we express them in terms of $B_{SC.\min}$ (i.e., the induction of a MF produced by the current $I_{SC.\min}$ in one line circuit in the case of a double phase bus SC in the receiving substation in the minimal system operating mode when both lines are live). The current $I_{SC.\min} = 0.87U/2(X_{S.\max} + 0.5X_L)$. Considering it and Eqs. (A1) – (A3), we derive

$$I_{2ca}/I_{SC.\min} = 0.75(X_{S.\max} + 0.5X_L)/(X_{S.\max} + 0.47X_L) \tag{A.5}$$

$$I_{2ca}/I_{SC.min} = 1.25(X_{S.max} + 0.5X_L)/(X_{S.max} + 0.47X_L) \tag{A.6}$$

$$I_{ca.\min}/I_{SC.\min} = (2X_{S.\max} + X_L)/(X_{S.\max} + X_L) \tag{A.7}$$

According to Eqs. (A5) – (A7), with, e.g., $X_{S.\max} = 0{,}15X_L$, the currents $I_{1ca} = 1.31I_{SC.\min}$, $I_{2ca} = 0.79I_{SC.\min}$, and $I_{ca.\min} = 1.13I_{SC.\min}$. Hence, the inductions of the MF produced by these currents $B_{ca.r} = 1.31B_{SC.\min}$, $B_{ca.n} = 0.79B_{SC.\min}$, and $B_{ca.\min} = 1.13B_{SC.\min}$; $B_{th1} = 0.5B_{SC.\min}$. Let $k_1 = 1.5$. Then, the inductions produced by the currents in the fault and fault-free lines in the maximal system operating mode $B_{ca1} = 1.97B_{SC.\min}$ and $B_{ca2} = 1.19B_{SC.\min}$. With allowance for $\varepsilon_1 = \varepsilon_3 = 0.03$, we can find the ratios

$$B_{ca.r}/B_{th1} = 1.32B_{SC.\min}(1 - \varepsilon_1)/((1 + \varepsilon_3)0.47B_{SC.\min}) = 2.47;$$

$$B_{ca.n}/B_{th1} = 0.8B_{SC.\min}(1 + \varepsilon_1)/((1 - \varepsilon_3)0.47B_{SC.\min}) = 1.68;$$

$$B_{ca1}/B_{th1} = 3.7$$

$$B_{ca2}/B_{th1} = 2.5$$

Using these ratios and Fig. 4, we find the time between actuation of reed switches 1 and 2 in the minimal and maximal system operation modes: $\Delta t_{SC.\min} = 0.74$ ms and $\Delta t_{SC.\max} = 0.48$ ms. Then, $\Delta t_{im1} = 0.35$ ms at $k_3 = 1.5$ and $\Delta t_{th} = 0.46$ ms. Since $\Delta t_{SC.\max} > \Delta t_{th}$, $l_{ca} \leq 0.25\ l$. The same calculations for other ratios $k_1$ and $k_3$ and $X_{S.\max}$ and $\varepsilon_3$ with the use of the dependences of $t$ on $k$ and for reed switches with $t_r > 0.3$ ms have shown the following.

(1) To ensure sensitivity, the reed switches used to measure $\Delta t$ should have $t_r \leq 0.3$ ms, and $\varepsilon_3 \leq 0.03$ is required. For reed switches with $t_r > 0.3$ ms, the time $t$ changes faster, and with $\varepsilon_3 > 0.03$, $\Delta t_{th}$ is longer, which does not allow selecting $k_1$, $k_3$, and $X_{S.\max}$ at $l_{ca} \leq 0.25\ l$.
(2) At $k_1 \leq 1.5$, for $l_{ca} \leq 0.25\ l$, it is necessary to fix two reed switches near each phase, $k_3 = 1.5$, and $X_{S.\max} \geq 0.15X_L$.
(3) At $k_1 > 1.5$, for $l_{ca} \leq 0.25\ l$, it is necessary to ensure actuation of these reed switches at the inductions higher than $B_{th1}$ and $B_{th2}$. It is difficult to change their actuation inductions versus $k_1$. Therefore, auxiliary reed switches are mounted near each phase. Thus, at $1.5 < k_1 \leq 2$, two more reed switches are mounted (3, 7 and 4, 8 in Fig. 3a); one actuates at $B_{th3} > B_{th1}$, and another, at $B_{th4} > B_{th2}$.
(4) If $k_1 > 2$, more reed switches should be mounted. This is unreasonable, since the protection becomes more complex and its reliability decreases.

## Appendix C. Explanation of conditions (4) and (5)

Let us consider why conditions in (4) are required. Let a phase-to-phase short circuit occurs in $L_1$ in the $l_{ca}$ zone. The protection does not operate before braking $L_1$ on the receiving side, since $\Delta t < \Delta t_{th}$. After the breaking, short-circuit current flows in $L_1$, and load current flows in $L_2$. Let $B_{th1}$ does not satisfy (4), and the current in $L_2$ is sufficient for actuation of reed switch 2, but not reed switch 6 (Fig. 3a). The protection does not detect a short circuit, since reed switch 2 closes the contacts earlier than reed switch 1 (the load current leads the short circuit current in phase). In this case, the actuation of reed switch 5 and non-operation of reed switch 6 indicate a large difference between the currents in L1 and L2. This difference can take place in the case of an external fault because of errors. To distinguish between these modes, reed switch 2 should be offset from the maximal effective induction after breaking $L_1$ from the receiving side in the event of a short circuit in $l_{ca}$, i.e. (4) should fulfill. Then, a $Q_1$ opening signal is produced if one of the reed switches with $B_{th2}$ near $L_1$ has actuated, and all the reed switches with $B_{th1}$ near $L_2$ failed to actuate. The same is in case of a short circuit in $L_1$ in the vicinity of the busbars of the supply substation, if the currents in $L_2$ produce a MF with the induction lower than $B_{th1}$.

In the case of a ground fault at two points, let one of them be at the phase A1 and another be at the phase B of the connection connected to the busbars of the receiving substation. The protection does not operate before the circuit breaker opening from the receiving side, since $\Delta t < \Delta t_{th}$ (currents in the phases $B_1$ and $B_2$ are equal; and the phase $A_1$ short circuit point is in $l_{ca}$). After the breaker opening, reed switches 9 and 17 (Fig. 3a) near the phases $B_1$ and $C_1$ and reed switches 2 and 18 near the phases $A_2$ and $C_2$ do not actuate, since they are offset from the effect of currents in the phases $A_1$ and $B_2$ according to (5). As a result, $\Delta t$ is not measured. The conditions for protection operation considered in the case of a phase-to-phase short circuit in $l_{ca}$ are not satisfied as well. Therefore, no $Q_1$ and $Q_2$ opening signals are produced.

## Appendix D. Explanation of the use of $Z_1$ and $Z_5$ signals

In the external fault mode, reed switches 1, 2, 5, and 6 are affected by equal inductions (equal currents in $L1$ and $L2$). Reed switches 1 and 2 close the contacts the first, because the induction of their actuation is lower than that of reed switches 5 and 6. At the time of actuation (point 1 in Fig. D.1),

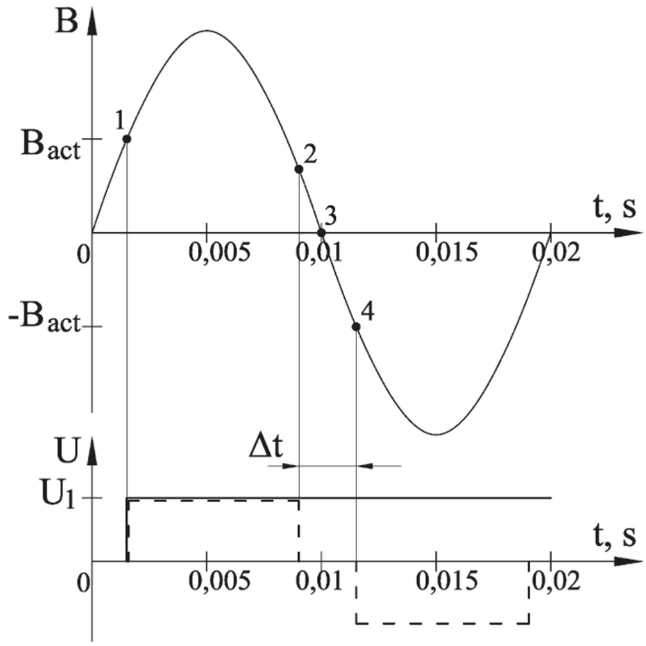
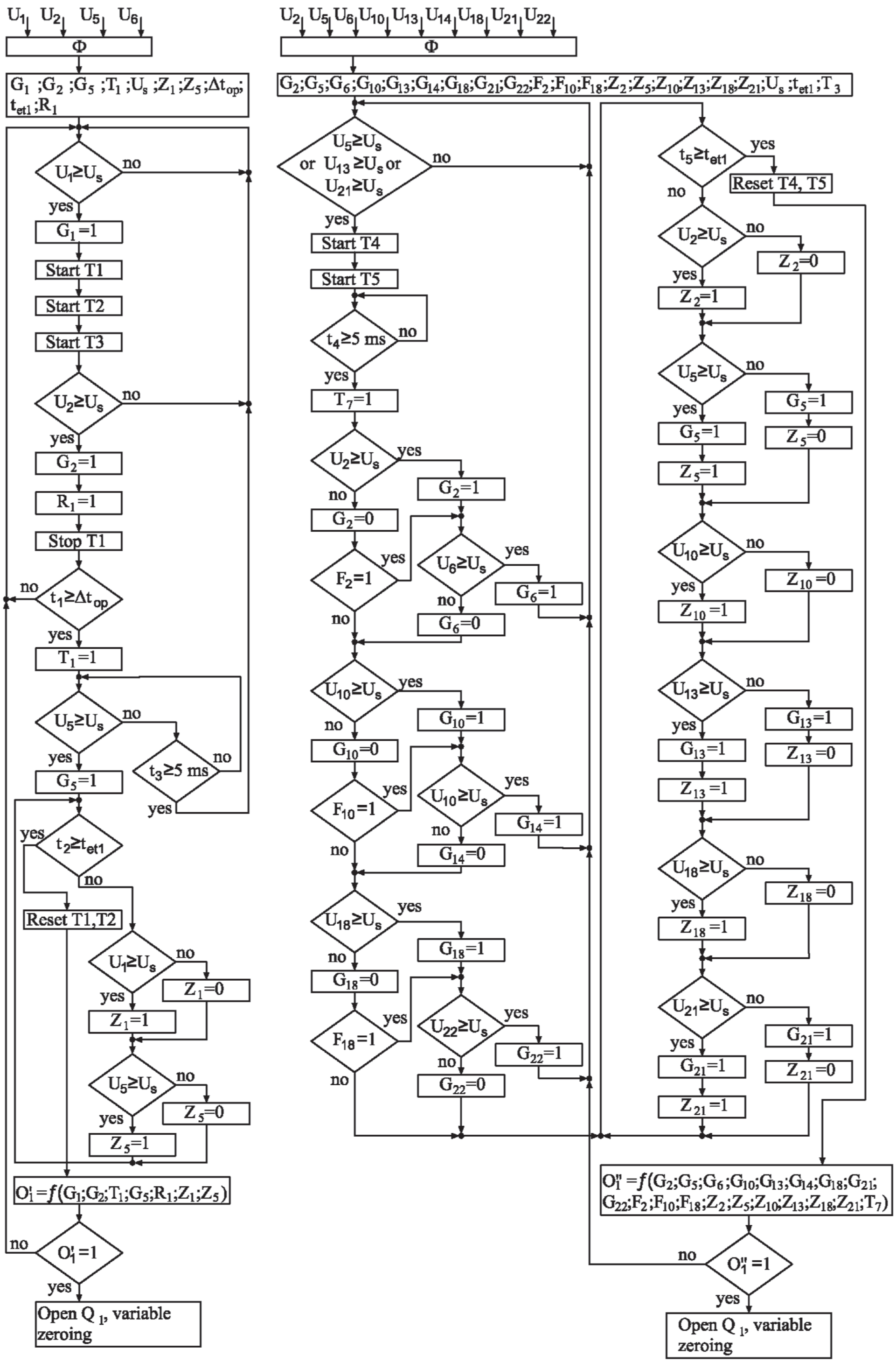



**Fig. D.1.** Time $\Delta t = 10$ ms within which the contacts of reed switch 1 are closed and the contacts of reed switch 2 break (the signal from reed switch 1 is shown by the solid curve, and from reed switch 2, by the dashed curve).

they send signals $G_1$ and $G_2$ (voltages $U_1$ are shown by the solid and dashed curves) to different inputs of microcontroller 25. Within 5 ms after reed switches 1 and 2 is operate, reed switches 5 and 6 close the contacts. If reed switches 1 and 2, 5 and 6 are in working order, then they stop signaling (signals $G_1$ and $G_2$ at point 2) before the induction sine curve crosses zero (point 3), and the signal duration does not exceed 10 ms. Therefore, there are no $Z_1$ and $Z_5$. If the contacts of reed switch 1 do not return to the original state, and of reed switch 2, return, then signal $G_1$ continues (the solid curve in Fig. D.1 does not break at point 2) and signal $G_2$ ceases. Therefore, at the time of breaking the contacts of reed switch 2 (point 2), signal $R_1$ is generated (that reed switch 1 has actuated the first), and the time $\Delta t$ is started counting until their re-closing (point 4). In this case, $\Delta t > \Delta t_{po}$, and signal $T_1$ is produced. Signals $R_1$ and $T_1$ are memorized for 5 ms. Reed switch 5 closes the contacts within the same time and produces signal $G_5$. However, the protection does not produce signal $O_1$, since 10 ms elapses before the actuation of reed switch 5, during which the contacts of reed switch 1 are closed, and signal $Z_1$ is produced.

## Appendix E. Block diagrams of algorithms

Fig. E.1 shows the block diagrams of algorithms for implementation of the 1st and 7th terms in (10) in the microcontroller. Fig. E.2 shows the block diagrams of algorithms for detecting malfunctions of reed switches 1 and 3. In the block diagrams: $U_i$ (i = 1, 2, 3, 5, 6, 7, 10, 11, 13, 14, 18, 19, 21, 22) is the voltage applied to the microcontroller input when the contacts of the corresponding reed switch are closed; $U_s$ is the voltage at which the microcontroller considers a signal to arrive at its input; $G_i$, $Z_i$, $R_i$, and $F_i$ are the signals specified in the section "Protection diagram and algorithm of operation"; $T_1$ and $T_7$ are the signals that the time between the actuations of reed switches 1 and 2 attains $\Delta t_{po}$ and that 5 ms has expired from the time of actuation of reed switches 5, 13, or 21; $t_1$, $t_2$, $t_3$, $t_4$, and $t_5$ are the times counted by timers $T_1$–$T_5$; $t_{et1}$ is the time required to detect that the contacts a reed switch have not broken in the same AC half-wave during which they have closed (10 ms); $O_1^{'}$ and $O_1^{''}$ are the variables with values equal to the results of calculation of the 1st and 7th terms in (10). Note that timer $T_1$ counts the time between the actuations of reed switches 1 and 2; timers $T_2$ and $T_5$, the duration of the closed state of the reed switches; timer $T_3$, the time for which signals $R_1$ and $T_1$ are memorized, and timer $T_4$, the time after the actuation of reed switches 5, 13, or 21.




a) b)

**Fig. E.1.** Block diagram of algorithm for implementation of the (a) 1st and (b) 7th terms in (10).

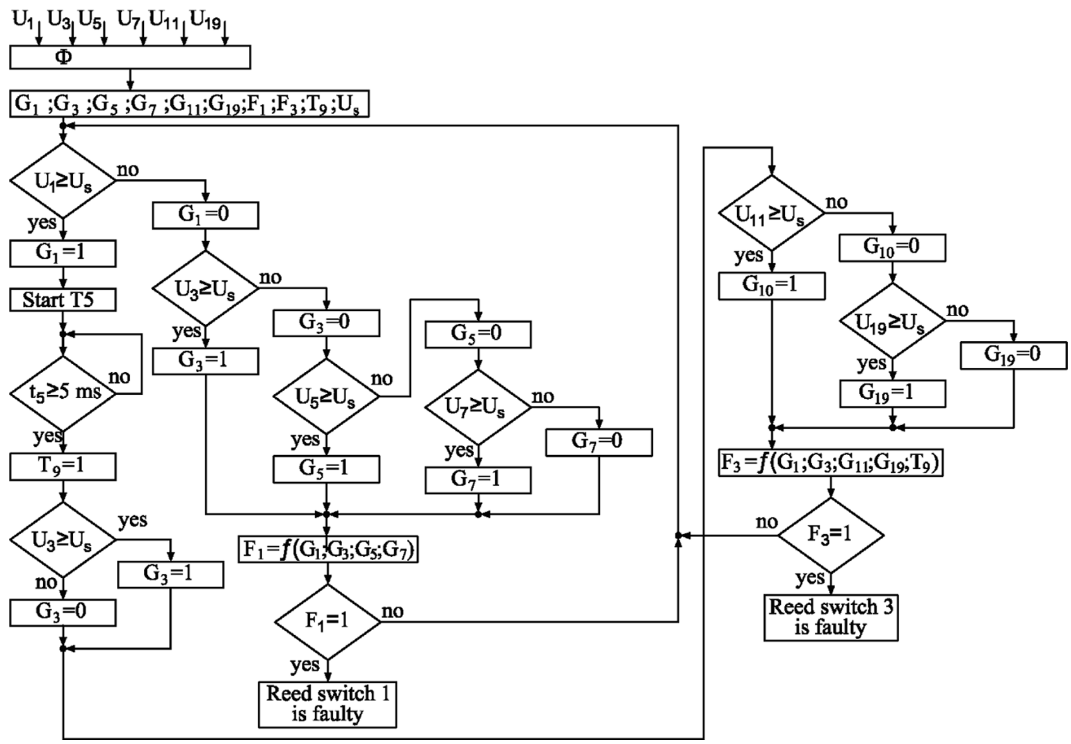



**Fig. E.2.** Block diagram of algorithm for detecting malfunction of reed switches 1 and 3.

## References


[1] Forcan M, Stojanović Z. An algorithm for sensitive directional transverse differential protection with no voltage inputs. Electr Power Syst Res 2016;137: 86–95. https://doi.org/10.1016/j.epsr.2016.03.052.

[2] Zhang G, Shu H, Lopes FV, Liao Y. Single-ended travelling wave-based protection scheme for double-circuit transmission lines. Int J Electr Power Energy Syst 2018; 97:93–105. https://doi.org/10.1016/j.ijepes.2017.10.025.

[3] Forcan M, Stojanović Z. Transverse differential protection scheme for double-circuit lines with single-pole tripping and reclosing. Int Trans Electr Energ Syst 2019;30:e12152.

[4] Dyakov AF. World electrical power engineering in the beginning of XXI century (based on the 39-th session of CIGRE, Paris). Energy International 2004;4–5:176.

[5] Kojović LA. Non-conventional instrument transformers for improved substation design. CIGRE SESSION 2016;2016:B3–101.

[6] Goryunov V, Kletsel M, Mashrapov B, Mussayev Z, Talipov O. Resource-saving current protections for electrical installations with isolated phase busducts. Alex Eng J 2022;61(8):6061–9. https://doi.org/10.1016/j.aej.2021.11.031.

[7] Sirota IM. Diagrams for measurements of induction current in three-phase high-voltage circuits. Electrichestvo 1967;4:22–4.

[8] Miedzinski B, Szymanski A, Dzierzanowski W, Wojszczyk B. Performance of Hall sensors when used in ground fault protections in MV networks. In: 39th International Universities Power Engineering Conference; 2004;1:753-757.

[9] Yablokov A., Dvoynenkov M., Sharygin D., Kabakov P. Research and development of algorithms for the functioning of the phase-to-phase overcurrent protection based on data from digital transformers with rogowski coils for overhead and cable power lines 35 kV. In: 2022 International conference on industrial engineering, applications and manufacturing (ICIEAM); 2022 doi:10.1109/ICIEAM54945.2022.97 87280.

[10] Kazanskii VE. Measuring Current Transformers in Relay Protection. Moscow: Energoatomizdat; 1988 [in Russian].

[11] Sirota IM. Symmetrical component filters in circuits with remote sensors. Electrichestvo 1971;11:26–31.

[12] Novozhilov AN, Goryunov VN, Novozhilov TA. Protection of a single-phase transformer from interwinding failure in windings of integral magnetic transformers. Russ Electr Eng 2018;89(2):118–21.

[13] Siddique AH, Barkat B, Poshtan M. Smart electrical protection method for industries operations. In: 2013 IEEE Electric Ship Technologies Symposium (ESTS); 2013. doi: 10.1109/ESTS.2013.6523766.

[14] Zahlmann P, Birkl J, Bohm T, Buehler K, Maget J, Ehrhardt A, Shulzhenko E. Apparatus for detecting electrical currents at or near electrical conductors. Patent DE 102018111308 B3, May 09, 2019.

[15] Gurevich V. Electric relays: principles and applications. Boca Raton: CRC Press; 2005.

[16] Jhunjhunwala S, Pandey K, Kumar R. A microcontroller based embedded system to provide complete self protection (CSP) to any distribution transformer. In: 2018 international conference on power energy, environment and intelligent control (PEEIC), Institute of Electrical and Electronics Engineers Inc.; 2018. https://doi.org/10.1109/PEEIC.2018.8665655.

[17] Majumder R, Dolui S, Agasti D, Biswas S. Micro-controller based over current relay using Hall Effect current sensor. In: 2018 Emerging Trends in Electronic Devices and Computational Techniques (EDCT); 2018. doi: 10.1109/EDCT.2018.8405086.

[18] Kletsel M, Zhantlesova A, Mayshev P, Mashrapov B, Issabekov D. New filters for symetrical current components. Int J Electr Power Energy Syst 2018;101:85–91. https://doi.org/10.1016/j.ijepes.2018.03.005.

[19] Zaytseva N., Fedosov D. Development of an algorithm for improving the reliability of digital differential protection in transient modes. In: 2020 International Ural Conference on Electrical Power Engineering (UralCon); 2020. doi:10.1109/UralCon49858.2020.9216232.

[20] Kojovic LA, Bishop MT, Sharma D. Innovative differential protection of power transformers using low-energy current sensors. IEEE Trans Ind Appl 2013;49: 1971–8. https://doi.org/10.1109/TIA.2013.2264792.

[21] Kletsel' MY, Maishev PN. Specific features of the development of differential-phase transformer protection systems on the basis of magnetic reed switches. Russ Electr Eng 2007;78(12):629–34.

[22] Teng J-H, Luan S-W, Huang W-H, Lee D-J, Huang Y-F. A cost-effective fault management system for distribution systems with distributed generators. Int J Electr Power Energy Syst 2014;65:357–66. https://doi.org/10.1016/j.ijepes.2014.10.0 29.

[23] Hemant K. Mody. Fault locator and selectivity sensor. US Patent 20030128035 A1, Jully 10, 2003.

[24] Li B, Wen M, Shi X, Wang Li, Chen Yu. An improved fast distance relay to mitigate the impacts of rogowski coil transducer transient. IEEE Trans Power Delivery 2022; 37(3):1549–58.

[25] Kletsel MYa, Musin VV, Alishev ZhR, Manukovskiy AV. The properties of hermetically sealed reed relays used in relay protection. Elektrichestvo 1993;9: 18–21.

[26] Kletsel MYa, Mashrapov BE, Mashrapova RM, Sulaymanova VA. Double-circuit lines protection method. KZ Patent 33003, August 6, 2018.

[27] Karabanov SM, Maisels RM, Shoffa VN. Magnetically controlled contacts (reed switches) and reed switch based products. Dolgoprudny: Intellect Publishing House; 2011. p. 408.

[28] Andreev V. Relay Protection and automatics of power supply systems. 4th ed. Moscow: Vyssshaya shkola; 2008.

[29] Mashrapov BE, Mashrapova RM, Sarybay AM, Nigmatullin RR. Measuring device for protection of double-circuit transmission lines against short circuits. KZ Patent 35546, April 9, 2022.