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CONSTRUCTIVE FEATURES OF RESOURCE-SAVING REED RELAY PROTECTION AND MEASUREMENT DEVICES

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It is shown that relay protection and measurement devices for electrical installations with voltages of 6–20 kV can be constructed on the basis of reed relays. To calculate the currents in the busbars at which the reed relays are located, equations are suggested based on the Biot–Savart–Laplace law and the experimentally derived improving coefficients. The method for determining and accounting for interferences acting on reed relays is presented. The sensitivity of reed relays and errors in determining currents according to the equation suggested are estimated.

1. INTRODUCTION

Relay protection (RP) and measurement devices in the majority of cases (including the newest [1]) receive information about current using closed-steel-core current transformers (CTs). CTs are reliable, but metal-consuming (for example, CTs for protection of generators [2–7] contain up to 90 kg of copper and steel), can have unacceptable errors in transient regimes and dangerous voltages at the ends of an open secondary circuit. Because of these shortcomings, a question about a need in using or developing such sensors that could become an alternative to CTs is repeatedly raised at the International Council on Large Electric Systems (CIGRE) (*e.g.,* [8, 9]). As shown in [10–16], one of the ways of solving this problem for ac installations is the use of reed switches, which are widely used in engineering [10], have prospects of use [11] and, in comparison with other magnetosensitive elements, have important advantages for RP [12–16]: they can simultaneously perform the functions of an analog-discrete converter and measuring element of the protection; do not require amplifiers for signal transmission; the transmission is carried out via control circuits, but not via measuring ones, and do not need in devices that reduce the temperature effect. The principles of construction of some reed protections [13, 14] and some devices, for example [17–19], which do not require CTs to receive information, have been already developed. Thus, the connection of contacts of a reed switch to a pulse counter allows designing a simple circuit of maximal current protection [17]. To control alternating and direct current six reed switches (three of which with control windings) and a magnetoresistor are used in the differential protection model of a converter installation [18]. Reed switches are located in the magnetic field (MF) of ac current conductors of each phase on the side of the highest voltage of the converter transformer. The magnetoresistor is fixed in the MF of the dc conductor busbar. The model of differential-phase protection of a power transformer [19] is constructed on the basis of reed switches, located in the MF of phases on the side of its high and low voltages, and the contacts of the reed switches are connected to the phase-sequence specification unit.

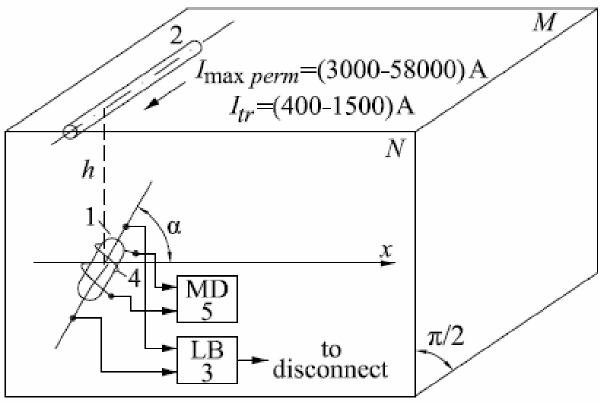

Fig. 1 – Scheme of location and connection of current sensor.

2. THE PRINCIPLE OF CONSTRUCTION OF REED RP AND MEASUREMENT DEVICES WITHOUT THE USE OF CURRENT TRANSFORMERS

In the protections [17–19], reed switches are mounted at specified points at a safe distance h (mm) [20, 21] from the busbar of the electrical installation (EI) and trigger (close or switch contacts, which are fixed in a glass bulb 0.7 to 5 cm long for 0.1–3 ms) under the action of the MF created by the current in the busbar. To calculate the minimal current I_{tr} (A) in the busbar (which can be considered as an infinitely long and thin conductor in a homogeneous MF), at which a reed switch is triggered, the following formula is used in [13–16] (in accordance with the Ampere law):

$$I_{tr} = 2B_{tr}\pi h/(\mu_0 \cos\alpha), \tag{1}$$

where $B_{tr} = \mu_0 F_{tr} / l_{wind} = \mu_0 w I_{wind} / l_{wind}$ is the MF induction (T) directed along the reed switch contacts; α is the angle between its longitudinal axes and a horizontal plane (Fig. 1); $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is the magnetic permeability of air; F_{tr} is the magnetomotive force (A) minimum at which this reed switch, placed in a factory inductance coil, is triggered; I_{wind} is the current in its winding at the instant of triggering; w and l_{wind} are the number of turns and winding length (m).

Under certain conditions, the calculation of I_{tr} can be carried out on the basis of the methods proposed in [22–24].

If all the reed switches in the devices [17, 19] and the closing reed switch in [18] are equipped with windings,

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then the problem of measuring the EI load currents is easily solved, since the complex of ferromagnetic contact plates of a reed switch and the winding around them is an analog of an open-core magnetic current sensor [25]. It should be noted that the effect of the current flowing through the winding and connecting wires on the trigger of the reed switch is negligible, since the internal resistance of the measuring instrument attains 10 MOhm. In Fig. 1, the reactive element of the protection, reed switch 1, is located in N plane, perpendicular to busbar 2 plane M, at a safe distance h from busbar. The contact of the reed switch is connected to logic block 3 of protection, and winding 4 is connected to measuring device 5. The rms value of electromotive force (EMF) E_{calc} at the winding terminals at $\alpha = 0^0$ (to provide the maximal sensitivity of the reed switch) is determined by the known equation [26]:

$$E_{calc} = 2\pi B_{load} fws = 2\pi\mu_0 I_{load} fws/(2\pi h) = \\ = \mu_0 I_{load} fws/h, \quad (2)$$

where B_{load} is the induction of the MF created by the load current I_{load} flowing in the busbar; f is the industrial frequency ($f = 50$ Hz); s is the winding cross section area (mm^2). B_{load} is found from Eq. (1), where the subscript "tr" is replaced by "load".

In Fig. 1, the range of calculated currents I_{tr} in busbar 2 is shown, at which a wound reed switch, located in the busbar MF, is actuated. The range of $I_{\max perm}$ includes busbar currents which can be changed with the use of the reed switch winding.

It is reasonable to implement the considered idea of simultaneous use of a reed switch with a winding for construction of RP and measurement devices on the basis of reed relays (RR), since the end product is used. However, it is necessary to solve a number of tasks.

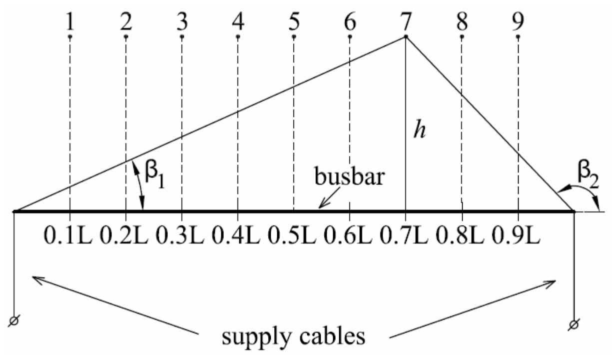
Implementation tasks

1. To refine the formulas for calculating the triggering and load currents, since they essentially repeat the Biot–Savart–Laplace law under the above assumptions. In this regard, it is necessary to: a) find and introduce into these formulas the coefficient k_{corr} that assesses the effect of the shape and sizes of the busbars of the switchgears (SGs) and current conductors (CCs), and the coefficient k_{infl} that takes into account the mutual influence of several RRs when they are mounted side by side; b) estimate a possibility of mounting RRs without refinement of their parameters in laboratory conditions.

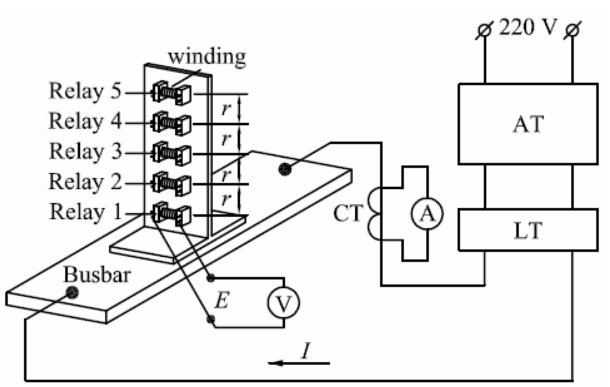
2. To develop techniques for determining and eliminating the influence of interferences on the calculation results in laboratory researches and during operation.

3. To estimate the sensitivity of the RRs and the coefficients k_{conv} of busbar current I_{load} conversion into the EMF E_{meas}, measured at the terminals of their windings ($k_{conv} = I_{load}/E_{meas}$), in order to determine the field of use and calibrate the measuring instruments.

The present work is devoted to the solution of these tasks.



a)



b)

Fig. 2 – Scheme of the experimental installation (*a*, *b*).

3. DETERMINATION OF THE COEFFICIENTS k_{corr} AND k_{infl}

The length L of busbars in the SGs, at a distance h from which RRs can be mounted, varies from 0.3 to 1.2 m at a thickness of (5–10) mm and a width of (50–80) mm; in the CCs, the busbar length is from 2 to 6 m at diameters D from 0.12 to 0.65 m. Such busbars cannot be considered as infinitely long conductors; therefore, calculation of the current I_{tr} by Eq. (1) gives large errors. In such cases, it is recommended [27] to use the Biot–Savart–Laplace law for calculations of I_{tr} for thin finite-length round wire (Fig. 2, *a*):

$$I_{tr} = \frac{4B_{tr}\pi h}{\mu_0(\cos\beta_1 - \cos\beta_2)} = k_1 B_{tr}; \\ I_{load} = \frac{2hE_{calc}}{\mu_0 fws(\cos\beta_1 - \cos\beta_2)} = k_2 E_{calc}, \quad (3)$$

where k_1 (m^2/H) and k_2 (A/V) are the conversion coefficients found theoretically.

However, busbars of SGs are not round, and the busbars of the CCs are not thin. Therefore, in order to refine the calculations, it is necessary to find the coefficients k_{corr} and k_{infl} and introduce them into Eqs. (3). To find them experiments were carried out with SG busbars with cross section of 50x5, 60x6, and 80x8 mm^2 and a length L from 0.3 to 1.2 m, as well as for tubular CC busbars with $L = 2$ m and $D = 0.12$, 0.14, 0.18, 0.28, and 0.424 m.

The current I_{load} in each busbar (Fig. 2, *b*) was controlled by a TDGC2-20K autotransformer (AT) and a

Table 1

The coefficients a_1, b_1 and a_2, b_2 for the calculation of $k_{corr\ 1}$ and $k_{corr\ 2}$ by Eq. (7)

h [mm]	RR location in terms of the busbar length L	Busbar type							
		FB (50x5) mm²		FB (60x6) mm²		FB (80x8) mm²		TB	
		a_1	b_1 [m^{-1}]	a_1	b_1 [m^{-1}]	a_1	b_1 [m^{-1}]	a_2	b_2 [m^{-1}]
120	(0.1–0.2)L and (0.8–0.9)L	1.1	0.21	1.04	0.15	1.07	0.17	1.17	0.08
	0.3L and 0.7L	1.08	0.19	1.03	0.13	1.06	0.16	1.16	0.05
	(0.4–0.6)L	1.08	0.18	1.03	0.13	1.06	0.15	1.15	0.04
160	(0.1–0.2)L and (0.8–0.9)L	1.12	0.23	1.06	0.17	1.15	0.21	1.16	0.06
	0.3L and 0.7L	1.11	0.21	1.05	0.15	1.13	0.19	1.15	0.04
	(0.4–0.6)L	1.1	0.2	1.05	0.14	1.12	0.18	1.14	0.03
200	(0.1–0.2)L and (0.8–0.9)L	1.14	0.24	1.08	0.18	1.16	0.24	1.16	0.03
	0.3L and 0.7L	1.12	0.22	1.07	0.16	1.14	0.21	1.14	0.02
	(0.4–0.6)L	1.11	0.21	1.07	0.15	1.14	0.2	1.14	0.02

load transformer (LT), the rms value I_{load} was measured with a TTE-125-4000/5A current transformer and a Fluke 87V multimeter. An induction coil with the number of turns $w = 2250$ and the area $s = 554\ \text{mm}^2$ was used as a MF sensor; the coil was located at points 1–9 (Fig. 2, *a*) at distances $h = (120 - 200)$ mm from the busbar. The rms EMF value E_{meas} at the induction coil terminals, induced by the MF of the busbar current, was measured by the Fluke 87V multimeter. All instruments were metrologically calibrated.

The procedure for determining the coefficient k_{corr} is the following. ac currents $I_{load\ i}$ (I = 1, 2, …, 16), from 40 to 640 A, are fed into the busbar, and the corresponding rms values EMF $E_{meas\ i}$ are measured at the induction coil terminals. They are represented as

$$E_{meas\ i} = E_{calc\ i} + E_{int\ 1} + E_{sh\ i}, \tag{4}$$

where $E_{calc\ i}$ is the EMF calculated by (3) at given values of k_2 and $I_{load\ i}$; $E_{int\ 1}$ the EMF induced by interference from nearby EIs, cables, and the Earth (though it is well known that the Earth's MF induction $B_E \approx 5 \cdot 10^{-5}$ T is an order of magnitude lower than the inductions required for RR actuation in protections); $E_{sh\ i}$ is the EMF induced by the effect of the busbar shape and size at the current $I_{load\ i}$ in it.

Then the busbars are replaced with thin conductors (cables with $D = 4.5$ mm) of the same lengths. Then the rms EMF values $E_{meas\ j}$ (j=1, 2, …, 16) measured at the induction coil terminals at the current $I_{load\ j}$ from 40 to 640 A in the cable contains only two components:

$$E_{meas\ j} = E_{calc\ j} + E_{int\ 1}. \tag{5}$$

If Eq. (5) is subtracted from Eq. (4), in view of the fact that $E_{meas\ i}$ and $E_{meas\ j}$ were measured at the same current in the busbars and cables ($I_{load\ i} = I_{load\ j}$), then the effect of all interferences, including the Earth effect, on the calculation results are excluded. We get $E_{sh\ i} = E_{meas\ i} - E_{meas\ j}$. The coefficient k_{corr} that takes into account the effect of the SG (CC) busbar shape and size on the I_{tr} and I_{load} currents is calculated as

$$k_{corr\ i} = (E_{calc\ i} + E_{sh\ i}) / E_{calc\ i} = \\ = 1 + E_{sh\ i} / E_{calc\ i}. \tag{6}$$

According to Eq. (6), the coefficient k_{corr} is independent of the busbar current, since $E_{sh\ i}$ and $E_{calc\ i}$ are proportional to it. This is confirmed by experiments, according to which the equations for $k_{corr\ 1}$ for flat busbars and $k_{corr\ 2}$ for tubular busbars have been derived by a linear approximation (verified by the Fisher criterion):

$$k_{corr\ 1} = a_1 - b_1 L;\ k_{corr\ 2} = a_2 + b_2 D. \tag{7}$$

Table 1 shows the coefficients a_1, b_1 (m^{-1}) and a_2, b_2 (m^{-1}) for each busbar type, different values of h and location of RR relative to the busbar beginning (for example, at point 7, Fig. 2, *a*). Thus, the coefficients $k_{corr\ 1}$ and $k_{corr\ 2}$ depend on the busbar shape, its length L or diameter D, the distance h, and the RR location. As an example, let us find the coefficient $k_{corr\ 1}$ for the busbar of SG with a cross section of (50x5) mm², the length $L = 1$ m, $h = 120$ mm (point 7, Fig. 2, *a*). According to Table 1, $a_1 = 1.08$, $b_1 = 0.19$ m^{-1}; from Eq. (7), $k_{corr\ 1} = 0.89$. Thus, introduction of the coefficient k_{corr} into Eqs. (3) makes it possible to significantly improve the calculation accuracy.

In protections, for example [28–30], it is required to mount several reed switches at distances 1–2 cm from each other. In this case, due to ferromagnetic contacts, the uniformity of MF acting on each reed switch is violated.

Table 2

Coefficients c and d in Eq. (8)

Number of relays	Relay No.	Relay type							
		RGK-49		RGK-50		RGK-52		RGK-54	
		c	$d \cdot 10^{-4}$ [mm^{-1}]	c	$d \cdot 10^{-4}$ [mm^{-1}]	c	$d \cdot 10^{-4}$ [mm^{-1}]	c	$d \cdot 10^{-4}$ [mm^{-1}]
2	No. 1	0.93	26	0.99	4	0.92	14	0.98	4
	No. 2	0.89	38	0.93	22	0.94	7	0.92	14
3	No. 1	0.97	10	0.97	10	0.85	24	0.97	6
	No. 2	0.88	46	0.93	26	0.84	30	0.86	24
	No. 3	0.9	30	0.89	40	0.86	26	0.89	18
4	No. 1	0.99	4	0.96	16	0.92	14	0.95	8
	No. 2	0.86	50	0.9	34	0.83	34	0.85	30
	No. 3	0.86	50	0.89	40	0.84	30	0.88	16
	No. 4	0.92	24	0.87	46	0.85	30	0.87	26
5	No. 1	0.96	14	0.97	10	0.95	10	0.96	4
	No. 2	0.84	56	0.91	32	0.81	36	0.88	24
	No. 3	0.84	46	0.89	40	0.77	50	0.85	24
	No. 4	0.83	54	0.83	60	0.77	50	0.89	20
	No. 5	0.91	24	0.87	46	0.82	40	0.78	60

This introduces errors in calculations, which have not been determined yet. Nonuniformity also occurs when RRs are used instead of reed switches. To find the coefficient k_{infl} of the mutual influence of the RRs on the calculations (which is defined by the ratio $k_{infl} = k_2 / k_{conv\,infl}$, where k_2 and $k_{conv\,infl}$ (A/V) are the conversion coefficients of the RR considered without and with accounting the influence of other relays, respectively), several experiments were carried out with typical relays RGK-49, RGK-50, RGK-52, and RGK-54 manufactured by one of the Russian plants. Five samples of each of these RR types were selected from different lots. The relays were mounted (Fig. 2, *b*) at the distance $h = (20 - 300)$ mm from a busbar using an U-shaped plate. The plate was attached perpendicular to the busbar. Four cases were considered for each RR type under study: (1) two RRs; (2) three RRs; (3) four RRs, and (4) five RRs (a relay with a smaller serial number was always at the shortest distance *h* from the busbar, Fig. 2, *b*). In each case, an equal distance r between the centers of gravity of the RRs was set, which was then varied to determine the dependence of k_{infl} on r. Based on the experimental results, the following equation was derived by linear approximation (verified by the Fisher criterion):

$$k_{infl} = c + dr, \tag{8}$$

where c and d (mm^{-1}) are the coefficients (given in Table 2) that depend on the relay type and number.

The calculations by Eq. (8) allowed us to ascertain that the mutual effect of adjacent sensors is excluded ($k_{infl} = 1$) for the RRs under consideration at $r_1 = 28 - 88$ mm depending on the relay type and quantity. In practice, a situation may arise where it is impossible to provide distances that allow the mutual effect of RRs to be excluded ($r_2 < r_1$). In this case, k_{infl} is determined by Eq. (8), where $r = r_2$ and the coefficients c and d are substituted. As an example, let us calculate k_{infl} for three RGK-50 relays mounted at $r = 10$ mm. From Table 2, we find the values $c_1 = 0.97$ and $d_1 = 10 \cdot 10^{-4}$ mm^{-1}, $c_2 = 0.93$ and $d_2 = 26 \cdot 10^{-4}$ mm^{-1}, $c_3 = 0.89$ and $d_3 = 40 \cdot 10^{-4}$ mm^{-1} for the first, second, and third relays, respectively; following Eq. (8), $k_{infl\,1} = 0.98$, $k_{infl\,2} = 0.96$, and $k_{infl\,3} = 0.93$.

Proceeding from all the above said, it follows that to increase the calculation accuracy for the busbar currents in RR-based RP and measuring devices, it is necessary to introduce the coefficient k_{infl} into Eqs. (3), which, with accounting for the coefficient k_{corr}, take the form

$$I_{tr} = k_1 B_{tr} / (k_{corr} k_{infl}); \quad I_{load} = k_2 E_{meas} / (k_{corr} k_{infl}). \tag{9}$$

The use of k_{infl} in both Eqs. (9) is reasonable, since they are the same dependences of the busbar current on the induction acting on the reed switch and its winding ($B_{tr} = E_{tr} / 2\pi f w s$).

4. I_{tr} AND I_{load} ERRORS

When calculating the currents by Eqs. (9), the errors occur due to the instrumental error ε_{instr}; the error ε_{int} induced by the action of various interferences on the RR under consideration (for example, the MF of nearby EIs and the Earth); the error ε_{set} due to the inaccuracy of RR mounting at the calculated point near the EI busbar, and the error ε_{wind} associated with the deviation of the number of turns in RR windings from those specified by the manufacturer.

The coefficient k_3 that takes into account the maximum possible effect of the errors ε_{instr}, ε_{set}, and ε_{wind} in calculation of I_{tr} by (9) is suggested to be defined as

$$k_3 = \frac{I'_{tr}}{I_{tr}} = \frac{4\pi h(1+\varepsilon_{set}) w (1+\varepsilon_{wind})}{\mu_0(\cos\beta_1 - \cos\beta_2)(1-\varepsilon_{set})} \times \frac{I_{wind}(1+\varepsilon_{instr})}{l_{wind}(1-\varepsilon_{instr}) k_{corr} k_{infl}} \times \frac{\mu_0(\cos\beta_1 - \cos\beta_2)}{(1-\varepsilon_{instr}-\varepsilon_{set}-\varepsilon_{wind})^2} \times \frac{l_{wind} k_{corr} k_{infl}}{4\pi h w I_{wind}}, \tag{10}$$

where I'_{tr} is the EI busbar current calculated by Eqs. (3) and (9) with accounting for the maximum errors; the expression $(1-\varepsilon_{instr}-\varepsilon_{set}-\varepsilon_{wind})^2$ in the denominator is the result of multiplying the coefficients k_{corr} and k_{infl} at their maximum errors.

The error $\varepsilon_{instr} \le 0.7$ % when using up-to-date digital devices. The error $\varepsilon_{set} \le 2.5$ % in the case of RRs mounting with the use of the constructions developed by us. This error was determined with the help of simple and cheap devices available in the laboratory. Let us assume that this value will not be exceeded in the case of using special devices. When RRs act as current transformers for measuring instruments with the required accuracy according to [20, 21] their winding resistance should not deviate from the rated one by more than 0.5 %. This requirement can be provided within the agreement with the manufacturer. In this regard, let us accept $\varepsilon_{wind} \le 0.5$ %. Substituting the values of ε_{instr}, ε_{set}, and ε_{wind} in Eq. (10), we obtain $k_3 = 1.16$. Similarly, to find I_{load}, the coefficient $k_4 = 1.19$ was calculated.

As for the error ε_{int}, it can be estimated and excluded from the calculations in the following way. A relay is placed at the calculated point near the busbar under consideration and the current $I_{load\ k}$ is applied to it. The rms EMF value $E_{meas\ k}$ at the RR winding terminals is measured at maximal currents in neighboring EIs and is represented as

$$E_{meas\ k} = E_{calc\ k} + E_{int\ 2}, \quad (11)$$

where $E_{calc\ k}$ is the EMF calculated at known $I_{load\ k}$, k_2, k_{corr} and k_{infl} by Eqs. (9), where the subscript "meas" is replaced by "calc"; $E_{int\ 2}$ is the EMF produced by interference from nearby EIs and the Earth.

The value of $E_{int\ 2}$ is found from Eq. (11) and is introduced into Eqs. (9). These equations take the final form with accounting for the k_3 and k_4 coefficients:

$$\begin{aligned} I_{tr} &= 1.19(k_1 B_{tr} + k_2 E_{int\ 2})/(k_{corr} k_{infl}); \\ I_{load} &= 1.19 k_2 (E_{meas} - E_{int\ 2})/(k_{corr} k_{infl}). \end{aligned} \quad (12)$$

In the equation for I_{tr}, k_3 is taken equal to 1.19 instead of 1.16, because it is difficult to chose a RR for which the condition $B'_{tr} = B_{tr}$ it true in practice (B'_{tr} and B_{tr} are the real and calculated MF inductions at which the RR is triggered). In the future, the errors are assumed to be estimated (including those caused by interference and inequality of B'_{tr} and B_{tr}) for specific electrical installations and protections.

The constructions for fixing reed relays ensure their arrangement near busbars. Several models of metal-free constructions have been designed for SGs and CCs [28, 31]. One of them is shown in Fig. 3 for example [28]. It contains bar 1 with reed relays 2 fixed at its first face parallel to each other at equal distances and connected to logic unit 3 with the help of connecting wires 4. Bar 1 is attached to partition 5 under busbar 6 of CC 7 so that a safe distance h is maintained.

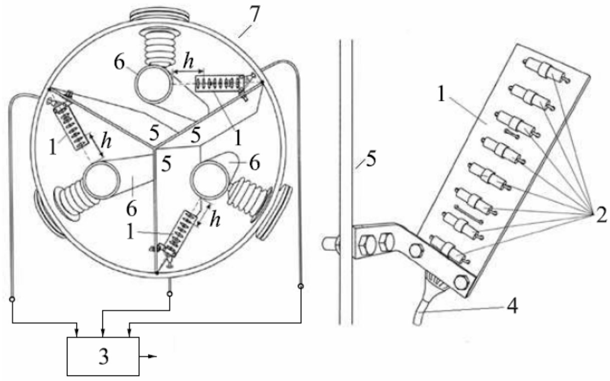


Fig. 3 – Constructions for fixing the reed relays inside a CC.

5. POSSIBLE FIELD OF USE OF REED-RELAY RP AND MEASUREMENT DEVICES

Possible field of use of reed-relay RP and measurement devices is mainly limited by the sensitivity of reed switches and the magnitude of EMF at the coil terminals. The sensitivity is determined by the minimum short-circuit (SC) current $I_{SC\ min}$, which can be detected by the protection, and is estimated by the coefficient of sensitivity

$$k_s = I_{SC\ min} / I_{tr}, \quad (13)$$

the value of which should be no less than 1.2 at the end of the reserved area.

Using Eq. (12) (neglecting $E_{int\ 2}$), the dependences $I_{tr} = f(h)$ were plotted in Fig. 4 for RRs under study based on experiments. Here 1–4 are the dependences for RGK-49, RGK-50, RGK-52, and RGK-54 relays, respectively, when installed near the SG-6 busbar (10 kV, cross section (50x5) mm², and the length $L = 1$ m); 5–8 are the dependences for the CC busbar (diameter $D = 0.424$ m and length $L = 2$ m) used in the circuit of generators with a

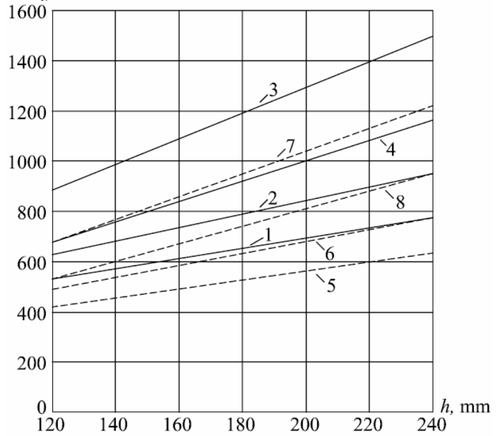


Fig. 4 – Dependences $I_{tr} = f(h)$ for reed relays mounted near the SG and CC busbars.

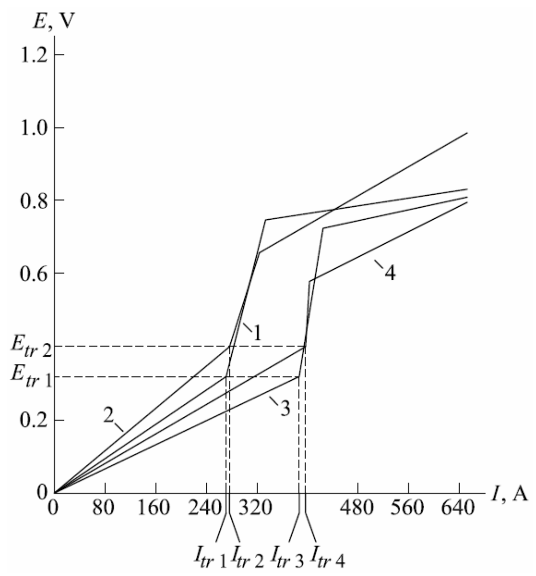


Fig. 5 – Conversion characteristics of reed relays.

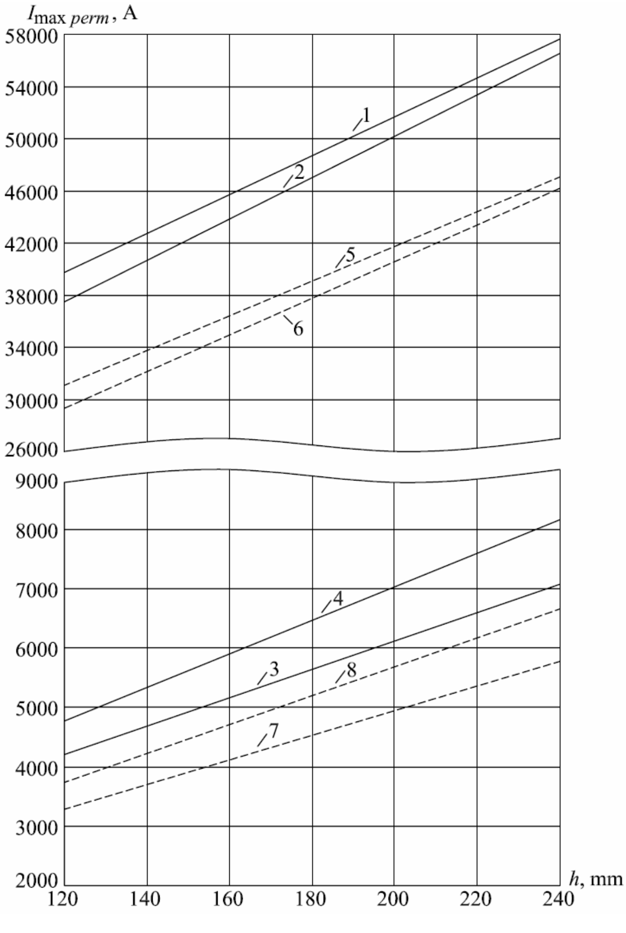


Fig. 6 – Dependences $I_{\max\,perm} = f(h)$ for RRs mounted near SG and CC busbars.

voltage of 20 kV. Substituting $k_s = 1.2$ and values of I_{tr} (Fig. 4) in Eq. (13) for each RR type mounted at safety distances $h_1 = 120-180$ mm from the SG and CC busbars, the values of $I_{SC\,\min}$ were found within the limits 0.63–1.16 kA. According to [13], the SC currents exceed 1.16 kA at the end of the protected area for most EIs with voltages of 6–20 kV of industrial enterprises. Hence, RRs have sufficient sensitivity for constructing the protection of EIs of these voltages.

It should be noted that when RRs are used as ac converters for RP devices, it is important to know the degree of reliability of the manufacturer data on their triggering parameters. Using a RETOM-21 test device for a series of five RRs of each of the above types, the spread of F_{tr} values was studied. Deviations from the mean F_{tr} for RGK-49 relays did not exceed 6.4%; for RGK-50, 4%; for RGK-52, 2.3%; for RGK-54, 15.3%. Hence, only RGK-52 relays can be used without examining their parameters. Therefore, it is necessary to refine RR parameters in laboratory conditions before using.

When measuring rms values of ac I_{load} in busbars with the help of RRs, the special role is played by the coefficients of conversion k_{conv} (A/V), which allow us to estimate the current magnitude by the value of E_{calc} of the EMF induced at the winding terminals of the RRs ($I_{load} = k_{conv}E_{calc}$). Equation (12) (neglecting $E_{int\,2}$) shows that the coefficient of conversion $k_{conv} = 1.19k_2/(k_{corr}k_{infl})$. Below, k_{conv} is considered to be equal to this ratio. Since the values of k_2, k_{corr}, and k_{infl} are constant for each particular busbar at a given distance h between it and RR under consideration, then k_{conv} should be also constant in the normal EI operating conditions.

The results of the investigations carried out with RRs on a flat busbar (50x5) mm^2 ($L = 1$ m) for insulation gaps $h_1 = 40$ mm and $h_2 = 60$ mm confirm this. For example, for RGK-49 and RGK-50 relays with $h_1 = 40$ mm, $k_{conv} = 827$ A/V and 677 A/V, respectively. In the case of SC, the dependence of current on EMF remains linear, but shifts, as shown, for example, in Fig. 5 for RGK-49 (dependences 1 and 2 for busbar–relay distances $h_1 = 40$ mm and $h_2 = 60$ mm, respectively) and RGK-50 (dependences 3 and 4). This is also true for the RGK-52 and RGK-54 relays. During the study, the influence of the spread of RR parameters on the coefficient of conversion k_{conv} was additionally estimated. For a series of five RGK-49 relays, the deviation of k_{conv} from the mean did not exceed 8.2 % at equal currents I_{load} in the busbar; for RGK-50, 8.4 %; for RGK-52, 6.3 %, and for RGK-54, 5.9 %. These spreads are due to the fact that the resistances of the RR windings vary within 10 % of the rated values specified in the catalog data.

The values of the maximal currents that can be measured with RRs without causing unacceptable overvoltages in their windings were determined for the above-mentioned SG and CC busbars using the known coefficients k_{conv} (taking into account the maximum permissible EMF at the winding terminals of the RRs $E_{per} = 24$ V for RGK-49 and RGK-50 and 15 V for RGK-52 and RGK-54). The results (Fig. 6) show that RGK-49 and RGK-50 relays (dependences 1 and 2 for SG busbars and dependences 5 and 6 for CC busbars) can be used as ac converters for measuring devices in all EIs with voltages of 6–20 kV, the maximum possible SC currents of which do not exceed 57 kA. The use of RGK-52 and RGK-54 relays (dependences 3, 4 and 7, 8 in Fig. 6) for the same purposes is possible in the cases where SC currents do not exceed 8 kA.

6. CONCLUSIONS

1. Reed relays (RRs) can simultaneously perform the functions of an ac converter for measuring instruments and new short-circuit protection in electrical installations (EIs) with voltages of 6–20 kV, which saves copper and steel (no current transformers are used). When constructing read-relay RP and measurement devices, RR parameters should be refined in laboratory conditions.

2. When performing RR protection and measurements devices, the currents in the EI busbars can be calculated by Eqs. (12) derived on the basis of the Biot–Savart–Laplace law and improving coefficients k_{corr} (7) and k_{infl} (8).

3. The experimental techniques suggested allow easily finding and accounting the total interferences produced by nearby EIs, cables, and the Earth both in laboratory and in operating conditions.

4. In order to exclude the mutual influence of the RRs mounted side by side (the coefficient of influence $k_{infl} = 1$), it is necessary to ensure experimentally determined distances between them, for example, 28–88 mm for the relays considered. If this is impossible, k_{infl} should be calculated by Eq. (9).

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