Alexandria Engineering Journal (2022) 61, 6061–6069

HOSTED BY ELSEVIER

Alexandria University

Alexandria Engineering Journal

www.elsevier.com/locate/aej
www.sciencedirect.com

Resource-saving current protections for electrical installations with isolated phase busducts

Vladimir Goryunov [a], Mark Kletsel [b], Bauyrzhan Mashrapov [b,*], Zhasulan Mussayev [b], Olzhas Talipov [b]

[a] *Omsk State Technical University, Mira av., 11, Omsk 644050, Russia*
[b] *Toraighyrov University, Lomova str., 64, Pavlodar 140008, Kazakhstan*

Received 6 August 2021; revised 31 October 2021; accepted 14 November 2021
Available online 24 November 2021

KEYWORDS

Reed switch protection;
Busduct enclosure;
Current;
Noise;
Experiment;
Magnetic field induction

Abstract Protections are suggested on the basis of a current relay with two capacitors and a reed switch, which is mounted at a safe distance from a busbar inside the busduct enclosure. The relay does not need in current transformers thus saving copper, steel, and insulating materials. It differs from reed switch based analogs in the noise immunity due to signaling after two actuations of the reed switch; non-operation in the case of sealing (due to the control of duration of breaker contact); the presence of a reed switch fastening structure, and built-in test diagnostics by mean of current supply into the reed switch winding. A technique for selecting protection parameters and assessing their sensitivity is presented. The inductions of magnetic fields which affect the reed switch are calculated with the use of the simplest formulas for the shielding coefficient and of the Bio–Savart–Laplace law, where experimentally derived correcting coefficients are introduced. Examples of the calculation of the induction of protection operation and of reed switch selection are presented along with an oscillogram which confirms the cutoff operability and speed.

1. Introduction

Instantaneous cutoff and overcurrent protection are the most common short circuit (SC) protections of 3–110 kV electrical installations (EI). Like other protections, including up-to-date [1,2], they receive information from current transformers (CT) [3,4]. Disadvantages of CTs (they are metal-consuming, heavy, large, etc.) put forward the problem of construction of relay protections without CTs. This problem is topical during the past 20 years [5–7].

Protections without CTs are known. They are based on measuring magnetic fluxes with: inductance coils [8–10], Hall sensors [11–13], magnetically operated contacts (reed switches) [14–21], magnetic transistors [22], magnetoresistors [23,24], and Rogowski coils [7,25–27]. Each of these sensors has advantages (in addition to small size and weight and low cost) and disadvantages. For example, inductance coils are highly sensitive, and the voltage at its terminals does not exceed the safe

* Corresponding author.
E-mail addresses: vladimirgoryunov2016@yandex.ru (V. Goryunov), mkletsel@mail.ru (M. Kletsel), bokamashrapov@mail.ru (B. Mashrapov), zhaslan.mail.ru@mail.ru (Z. Mussayev), talipov1980@mail.ru (O. Talipov).

Peer review under responsibility of Faculty of Engineering, Alexandria University.

https://doi.org/10.1016/j.aej.2021.11.031
1110-0168

Nomenclature

Designations

B_{act}	actuation induction [T]
B_r	reed switch relay time [T]
B_{pa}	protection actuation induction [T]
B_i	induction of field produced by current in busbar i [T]
$B_{sc.min}$	induction of field produced by minimal SC current [T]
k_{off}	offset coefficient
k_{self}	self-starting coefficient
k_1	coefficient considering the effect of busbar enclosure, shape, and length and alternating current
k_2	coefficient similar to k_1 but ignoring the enclosure
k_3	coefficient of field decay outside the enclosure due to the busbar current inside the busbar
k_{sh1}	shielding coefficient
k_{sens}	protection sensitivity factor
k_r	reset factor
k_{rel}	coefficient of overcurrent protection matching reliability
k_a	adjusting factor
k_e	eddy-current factor
r	inner diameter of the busduct enclosure [mm]
d	thickness of enclosure wall [mm]
I_{act}	busbar current producing B_{pa} [A]
$I_{op.max}$	maximal operation current in the phase of the electrical installation [A]
I_4	current in busbar 4 [A]
I_{load}	load current in the busbar of the neighboring electrical installation [A]
I_{sc}	short circuit current in the busbar of the neighboring electrical installation [A]
I_{pa}	protection actuation current [A]
I_r	rated current of the electrical installation [A]
$I_{sc.min}$	minimal SC current [A]
F_{act}	magnetomotive force of reed switch actuation [A]
l_c	winding length [m]
h_1	space between busbar 1 and the center of gravity of the reed switch [m]
h_4	space between busbar 4 and the center of gravity of the reed switch [m]
μ_0	magnetic constant [H/m]
t_{close1}	time of closed states of the reed switch contacts [ms]
I_1	current in busbar 1 [A]
$I_{r.t}$	rated current of transformer [A]
t_{open}	time of open states of the reed switch contacts [ms]

Abbreviations

SC	short circuit
CT	current transformer
MF	magnetic field
EI	electrical installations

Greek letter

γ	angle between the longitudinal axis of the reed switch and the induction vector

value. However, their output signals are weak and, therefore, amplifiers are required for its transmission; parameters of inductance coils depend on the ambient temperature, and the signal is transmitted not via control circuits, but via measuring ones. Hall sensors can produce both analog and digital signals, but they need in a stable power supply, are sensitive to temperature variations, and have a residual voltage. Magnetic transistor output signals are proportional to the instantaneous value of controllable current; converters based on magnetoresistors can provide information about the current in the form of an analog signal or a digital code. However, their output power is low, noise is present in the output signal, their parameters depend on the temperature, and many magnetic transistors are required to construct a converter. Advantages and disadvantages of magnetoresistors are similar. Rogowski coils have linear operation parameters, the voltage of its output signal is safe for maintenance personnel, and saturation is absent. But the output signal power is low, and high-voltage insulation is required to mount a coil, which significantly increases the size and weight of the device. We have selected reed switches because of their advantages important for cutoff and overcurrent protection: they digitize analog signals and simultaneously fix the protection operation current.

2. Research goals

The main goal of the work is to create sensitive, rapid, and reliable cutoff and reed switch overcurrent protection (without CT) for electrical installations with isolated phase busducts of 6–35 in voltage. Such electrical installations have been chosen because the most cumbersome and metal-consuming CTs (e.g., of GAR 10 type, up to 500 kg in weight [28]) are used in them.

To achieve this goal, it is necessary to design a noise-immune reed switch relay with built-in test diagnostics, a structure for fixing it inside the busduct enclosure, and a technique for selecting protection parameters and to experimentally confirm their operability.

3. Significance of research

The protection for electrical installations with isolated phase busducts of 6–35 in voltage has been designed for the first time; it does not use CT, which allows saving copper, steel, and insulating materials.

3.1. Research contribution

This work contributes into the development of a new direction in the relay protections, that is, avoidance of using current transformers, by means of design of a highly reliable relay, a structure for fixing it, and a technique for calculation of cutoff and overcurrent protection parameters for EI with isolated busducts.

3.2. Impact of research

The protection created influences the development of the relay protection engineering, because it proves a possibility of saving copper, steel, and insulating materials due to refuse to use current transformers, which contain these components in amounts which are tens, hundreds, and thousands times higher than in protection systems.

4. Boundary conditions and assumptions

We consider only the cutoff and overcurrent protection which are based on reed switches only for electrical installations with isolated phase busducts with tubular busbars of 6–35 in voltage. It is impossible to use the simplest formula of the Biot–Savart–Laplace law without experimentally obtained coefficients for calculation of the induction of magnetic fields created by alternating currents. The cutoff response time should be less than 0.03–0.04 s to meet the speed requirement (restricts the detuning from long-term interference). The offset coefficient k_{off}, the self-starting coefficient of electric motors k_{self}, and the sensitivity factor k_{sens} of the cutoff and overcurrent protection suggested should be like in traditional protections, since they are time-tested.

The following *assumptions* are made: the effects of the magnetic fields of the earth and of EI spaced more than 10 m apart are neglected, as well as short-circuit current calculation errors used in all device measurements; they are taken into account by the offset coefficient.

5. Reed switch and its parameters

Reed switch is a reliable sealed glass tube 0.4–4 cm long and 1–5 mm diameter with an inert gas, inside which ferromagnetic plates (contacts) are fixed. Its main parameters, which should be taken into account when designing protection systems, are given in Table 1. Here, the ranges of the parameters are specified for MKS27103 (Russia) and ORD624 (USA) reed switches as examples.

Table 1 Parameters of MKS27103 and ORD624 reed switches.

Parameter	MKS27103	ORD624
Operation EMF, A	40–90	7–30
Reset factor	0.35–0.9	0.07–0.28
Actuation time, ms	1.5	0.4
Release time, ms	2.5	0.05
AC/DC switching voltage, V	200/220	200/150
Switching current, A	1	0.5
Cutoff current, A	1	1
Switching power, W/VA	30/1.5	–/10

Reed switch actuates each alternating current (AC) half-wave (closes previously broken contacts for 0.3–2 ms) when the magnetic field induction B, which acts along the reed switch contacts, attains the actuation induction $B_{\text{act}} = \mu_0 F_{\text{act}}/l_{\text{c}}$, where F_{act} is the magnetomotive force of reed switch actuation measured at the manufacturing plant in a coil with the winding of l_c in length with a reed switch inside.

In our work, reed switches are mounted near busbars at a safe distance h and respond to the magnetic field (MF) produced by the current I in these busbars. The busbar current I_{act} under which the reed switch actuates can be determined from the simplest equation of the Biot–Savart–Laplace law $B_{act} = \mu_0 I_{act} \cos\gamma/(2\pi h)$, where μ_0 is the magnetic constant; γ is the angle between the longitudinal axis of the reed switch and the MF induction vector. This law is valid for direct current (DC) flowing through a thin and long conductor. In our case, the current is alternating, and the conductor is not thin. In addition, there are screens (busduct enclosures). Therefore, we experimentally determine the coefficients which allow these features to be taken into account with the use the above form of the law, but without cosγ, since it is convenient to use a reed switch with $\gamma = 0$ in practice. To mount a reed switch, a special structure is required.

6. Structure for reed switch mounting inside busduct enclosure

The reed switch position is chosen proceeding from safety, sensitivity, and ease of mounting. The structure should be simple, cheap, and made of dielectric materials. The structure suggested in [29] satisfies these requirements (Fig. 1). Reed switches 2 are fixed at bar 1 (of 0.22 × 0.07 × 0.01 m in size) so as $\gamma = 0$. Bar 1 is fastened with clamp 3 at busbar 4. Cable 5 connects the reed switch contacts with the logical part of the protection, which is outside the busduct, and is taken out through a hole in busduct enclosure 6. This structure (of 1.2 kg in weight) is 35–400 times lighter and 800–3000 times smaller than a CT. For example, TSHV15B current transformer (Russia) is 45 kg in weight and 0.76 × 0.796 × 0.24 m in size.

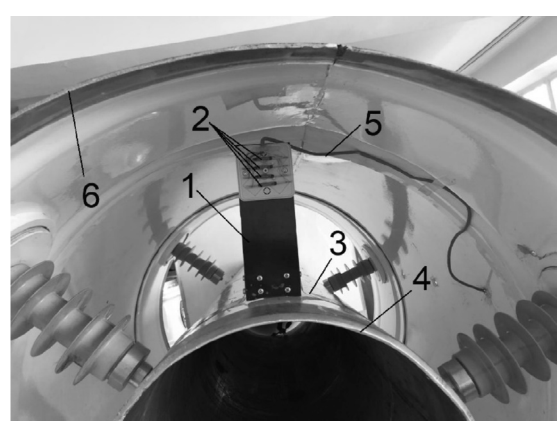

Fig. 1 Structure for mounting reed switches inside a busduct: bar (1); reed switches (2); clamp (3); busbar (4); cable (5); busduct enclosure (6).

7. Transformerless reed relay for current protections [30]

In the case of a short circuit in an electrical installation, the currents flowing through its busduct 1 (Fig. 2) create MF with the induction higher than B_{act}, and reed switch 2 close plates 3 and 4 and breaks plates 4 and 5. Capacitors 6 and 7 start charging from direct current source 8; the charging time of capacitor 7 is longer than of capacitor 6. The capacitance of capacitor 6 and the resistance of resistor 12 are selected so as relay 9 closes contact 11 after the second actuation of reed switch 1, which prevents false operation of cutoff in the case of short-term noise. After charging capacitor 6, output relay 9 actuates and its contact 11 sends a tripping signal to the electrical installation breaker (cutoff) or to the input of the time relay (overcurrent protection). When the electrical installation is switched off, plates 4 and 5 close, if plates 3 and 4 are not sealing, and capacitor 7 is discharged to winding 14 of relay 13 and resistor 19. However, contact 15 does not break because the capacitor 7 voltage is insufficient for relay 13 operation. If plates 3 and 4 are sealing, then plates 4 and 5 remain broken. Capacitor 7 is recharged, and relay 13 operates breaking contact 15 and closing contact 16. Lamp 17 signals sealing, relay 9 does not trigger the time relay, and the device does not false operate under the action of, e.g., a recloser, when the short circuit is self-clearing.

For fault diagnostics, reed switch 2 is equipped with a control winding (Republic of Kazakhstan patent no. 33108), which is supplied from an external AC source by means of closing a button (omitted in Fig. 2), and the trip circuit simultaneously breaks. If contact 11 is not closed in 2–3 s, then a fault signal is sent.

The relay actuation time does not exceed 0.025 s. This is confirmed by the oscillogram (Fig. 3), which shows that intermediate relay 9 actuates (the voltage U_2 abruptly changes) in t_{act} = 0.024 s after the first closure of contacts 3 and 4 under the third voltage pulse U_1 across resistor 12. The pulse duration determines the time during which capacitors 6 and 7 are charged and corresponds to the duration t_{close} of breaker contacts 3 and 4. In our case, t_{close} = 7.5 ms, which almost coincides with the value found below in Sect. 5. Thus, in terms of speed, the current cutoff based on the relay suggested meets the requirements (for example, the Siemens MICOM P115 relay response time can attain 40 ms [31]). In a prototype, we used a MKS-27103 reed switch, miniature intermediate RT570220 relays, capacitors with a capacity of 3.3 and 5.7 μF, changeable resistors with rated resistances of 5, 20, and 47 kOhm.

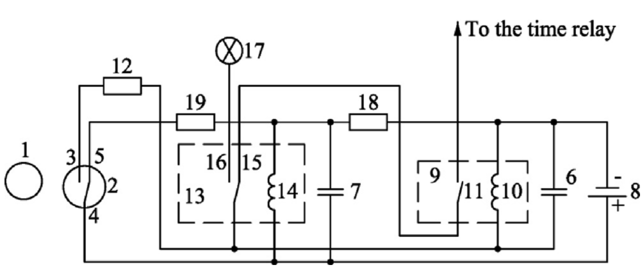

Fig. 2 Principal scheme of the reed switch current protection for one phase: busduct (1); reed switch (2) with plates (3, 4, and 5); capacitors (6 and 7); DC source (8); relay (9) with winding (10) and contacts (11); resistors (12, 18, and 19); relay (13) with winding (14) and contacts (15 and 16); lamp (17).

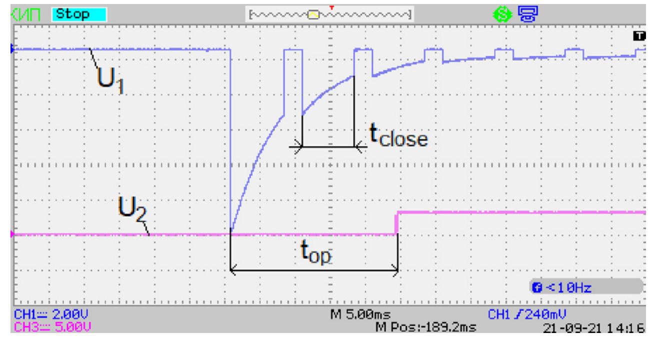

Fig. 3 Oscillograms of voltages U_1 and U_2 across resistor 12 and output of relay 9 (t_{act} = 0.024 s, t_{close} = 7.4 ms).

The relay is designed to protect EI with voltage of 6–35 kV at a frequency of 50–60 Hz. The consumed power $P \leq 1$ W; the rated power supply voltage range is 12–220 V (depends on the output intermediate relay and reed switch types). The relay reset factor $k_r \approx 1$, since the reed switch takes out every AC half-wave and does not actuate if the amplitude of induction of the affecting MF has not attained V_{act}. The switching capacity depends on the intermediate relay type used, for example, it is 1500 VA for a SCHRACK Technik PT570220 relay (Austria) [32].

8. Selection of actuating parameters for the overcurrent protection

The actuating parameter (actuating current) of a traditional overcurrent protection [3]

$$I_{act} = k_{off} \cdot k_{self} \cdot I_{op.max}, \tag{1}$$

where $I_{op.max}$ is the maximal operation current in the phase of the electrical installation protected; k_{self} is the self-starting coefficient; k_{off} is the offset coefficient.

The protection suggested operates according the same principle; therefore, it is also offset from the self-starting currents of electric motors. However, the reed switch is actuated by a MF at the point where it is mounted (e.g., point N in Fig. 4), and it is affected not only by the MF produced by the self-starting current in busbar 1, but also by the MFs produced by currents in busbars 2 and 3 of neighboring phases (*A* and *B*) of the electrical installation protected and in busbar 4 or enclosure 5 of a neighboring electrical installation, as well as the MFs from electrical installations spaced more than 10 m apart and from the earth, which can be ignored because of their smallness as compared to values produced under the load and SC. Therefore, we suggest to define the protection actuation parameter (induction B_{pa}) as

$$B_{pa} \geqslant 1.05 k_{off}(B_1 + B_2 + B_3 + B_4), \tag{2}$$

where the factor 1.05 considers the error in reed switch mounting; B_1, B_2, and B_3 are the inductions of MFs produced by the current in busbars 1, 2, and 3 (Fig. 4) of the electrical installation protected; B_4 is the induction of MF produced by currents in busbar 4 (or enclosure 5) of the busduct of a neighboring electrical installation under double short to earth.

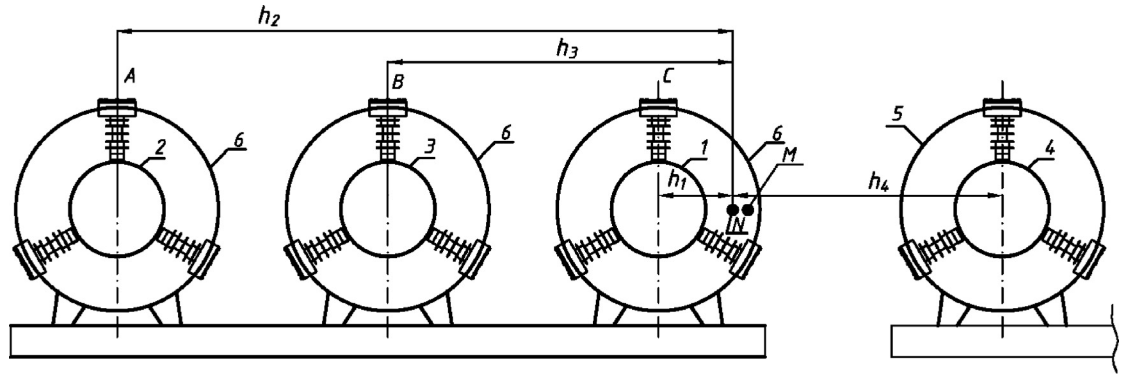

Fig. 4 Point N of reed switch (inductance coil) mounting and the distance from it to the axes of the busducts of the protected (h_1, h_2, and h_3) and neighboring (h_4) electrical installations: busbars of the busducts of EI protected (1, 2, 3, and 6); busbar and closure of the busduct of neighboring EI. Adapted from [33].

The inductions B_1–B_4 are calculated by the Biot–Savart–Laplace law with the following coefficients: $k_1 = 1.4$ for B_1, which is found from measurements inside enclosures of three busducts and takes into account the effect of the enclosure, shape, and length of busbar 1 and ac, but not DC, in it; k_2 [19] for B_2–B_4, which are similar to k_1, but do not consider the enclosure; shielding coefficients k_{sh1}, which are determined from the ratio of the inductions of MFs produced by the same current in a busbar outside the enclosure and at a point inside it (with and without the enclosure), and $k_3 = 0.9$ for B_2–B_4, which takes into account that the enclosure decreases the external MF produced by the current in the busbar inside it.

The induction of the MF produced by the current in enclosure 5 is calculated in the same way as B_4, but with the corresponding k_2 and without k_3. Thus, under currents I_1 and I_4 in busbars 1 and 4:

$$\text{a)}B_1 = \frac{\mu_0 \cdot I_1}{2\pi \cdot h_1 \cdot k_1}; \quad \text{b)}B_4 = \frac{\mu_0 \cdot I_4 \cdot k_2 \cdot k_3 \cdot k_{sh1}}{2\pi \cdot h_4}, \tag{3}$$

where h_1 and h_2 are the distances from the busbar axes to the point N, where the reed switch is mounted.

Fig. 5 shows a laboratory setup for determining shielding coefficient k_{sh1}. It consists of laboratory transformer 1 with the primary winding energized via circuit breaker 2 and with the secondary winding connected to the primary winding of load transformer 3, output of which are connected by cables 4 to busbar 5. Enclosure 5 of busduct with insulators 7, for which k_{sh1} is determined, is mounted parallel to busbar 5. Inductance coil 8 is fixed as a point inside enclosure 6 and connected to multimeter 9 by cables 10. A current is supplied to busbar 5, its value is controlled by clamp-on ammeter 11, and the EMF induced in coil 8 is measured. Then, the EMF is measured at outputs of coil 8, fixed at a point specified, but without enclosure 6. The coefficient k_{sh1} is equal to the ratio of these EMFs. As shown by experiments on the Russian TENE and TZKR busducts with diameters of 0.88 and 0.7 m and aluminum pipes with diameters of 0.08 and 0.34 m, the coefficient k_{sh1} (with generally accepted ratios between the length and diameter of a folded shield $k \geq 4$) can be calculated by formula [34] with the adjusting factor $k_a = 1.3$ and eddy-current factor $k_e = 0.12\ \text{mm}^{-1}$:

$$k_{sh1} = 2 \cdot k_a / \left(2 + k_e^2 \cdot r \cdot d\right), \tag{4}$$

where r is the inner diameter of the busduct enclosure and d is the thickness of its wall.

According to the calculations, the sum of inductions of MFs produced by the currents in busbars 2 and 3 (Fig. 4) does not exceed 3% of the induction of MF produced by the current in busbar 1 and affecting the reed switch. Therefore, we accept $B_2 + B_3 = 0.05B_1$. In view of this and taking into account Eqs. (1), (3) and (4), $k_1 = 1.4$, and $k_3 = 0.9$, we can write Eq. (2) as

$$B_{pa.1} \geqslant \frac{1.05 \cdot 1.05 \cdot \mu_0 \cdot k_{off} \cdot k_{self} \cdot I_{op.max}}{2\pi \cdot h_1 \cdot k_1} = \\ = \frac{1.6 \cdot 10^{-7} \cdot I_{pa}}{h_1} \tag{5}$$

in the absence of neighboring electrical installation ($B_4 = 0$);

$$B_{pa.2} \geq \frac{1.05 \cdot k_{off} \cdot \mu_0}{2\pi} \cdot \left(\frac{1.05 \cdot I_{op.max}}{1.4 \cdot h_1} + \frac{I_{sc} \cdot k_2 \cdot k_3 \cdot k_{sh1}}{h_4}\right) = \\ = 1.6 \cdot 10^{-7} \cdot k_{off} \cdot \left(\frac{I_{op.max}}{h_1} + \frac{1.2 \cdot I_{sc} \cdot k_2 \cdot k_{sh1}}{h_4}\right) \tag{6}$$

$$B_{pa.3} \geqslant 1.6 \cdot 10^{-7} \cdot k_{off} \left(\frac{k_{self} \cdot I_{op.max}}{h_1} + \frac{1.2 \cdot I_{load} \cdot k_2 \cdot k_{sh1}}{h_4}\right) \tag{7}$$

in the presence of a neighboring electrical installation; in this case, the maximum of two B_{pa} is selected. Here, I_{sc} and I_{load} are the SC and load currents in the busbar of the neighboring electrical installation.

Reed switch protections are coordinated in exactly the same way as traditional overcurrent protections, but by the inductions of MFs produced by the corresponding currents. Its selectivity is ensured by a time delay. The current cutoff actuation parameters are selected according to Eqs. (5), (6), or (7), but $I_{op.max}$ in Eqs. (5) and (7) is replaced by the maximal SC current at the busbars of the neighboring substation and $k_{self} = 1$, and for overload protection, according to Eq. (5), where I_r is changed to $1.4I_r$ (I_r is the rated current of the EI).

9. Reed switch selection and protection sensitivity

The protection sensitivity factor is commonly calculated by the equation k_{sens} I_{sc}.min/Ipa [3]. However, by the same reasons as those mentioned after Eq. (1), we use the equation

$$k_{sens} = B_{sc.\min}/B_{pa} \tag{8}$$

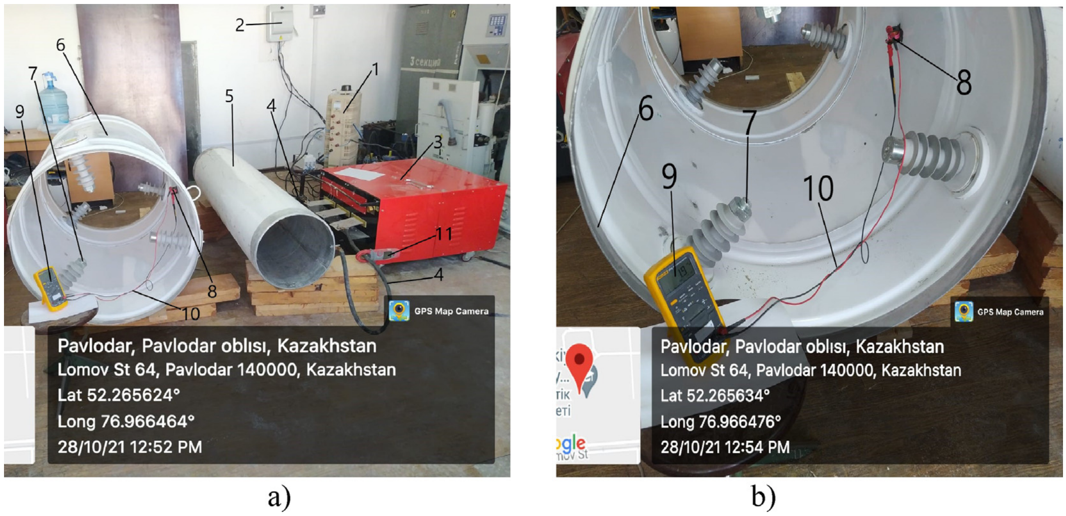

Fig. 5 Laboratory setup for determining the shielding coefficient: laboratory autotransformer (1); circuit breaker (2); load transformer (3); cable (4); busbar (5); busduct enclosure (6); insulators (7); inductance coil (8); multimeter (9); cables (10); clamp-on ammeter (11).

in our protection, where $B_{sc.min}$ is the induction of MF produced by the minimal short-circuit current ($I_{sc.min}$) in the busbar at the point of reed switch mounting (calculated accounting k_1).

If B_{pa} is selected according to Eq. (5), then the protections suggested have the same sensitivity as traditional and microprocessor-based ones. The fact is that the errors of the induction calculation by the Bio–Savard–Laplace law with the correction coefficient do not exceed 5%. When the reed switch is mounted at a given point, the error is 4%, as our experiments have shown. In total, this is no higher than the permissible error of current transformers (10%), which are absent in the protection. If B_{pa} is selected according to Eqs. (6) or (7), then the protection sensitivity may be lower, because B_{pa} increases under the effect of currents in the neighboring EI.

It is impossible to exactly select a reed switch with B_{act1} =-B_{pa}; therefore, we check the protection sensitivity at $B_{act1} > B_{pa}$ by Eq. (8). Minimum permissible k_{sens} = 2. If $k_{sens} \geq 2$ at the beginning of the segment protected [3], then the cutoff with $B_{pa} = B_{act1}$ is mounted. If $k_{sens} < 2$, then the reed switch is fixed closer to the busbar. Since h_1 decreases and h_4 increases (Fig. 4), B_{pa} is recalculated by Eqs. (4)–(6). Now $B_{pa} = B_{pa4}$. Again, we compare B_{pa4} with B_{act1}. If $B_{act1} \geqslant B_{pa4}$, then we calculate k_{sens}. The calculation ceases at $k_{sens} \geq 2$. If $k_{sens} < 2$, then the reed switch is shifted toward the busbar and the procedure is repeated.

If $B_{act1} < B_{pa}$, then the reed switch is moved (h_1 and h_4 change) away from the busbar to the point M (Fig. 4), and B_{pa} is recalculated. If the resulted $B_{pa5} \leq B_{act1}$, then we check the sensitivity. If $k_{sens} \geq 2$, then the reed switch is fixed at the point M. If $B_{pa5} > B_{act1}$, then the reed switch is moved closer to the busduct enclosure, and the procedure is repeated. If the reed switch cannot be fixed at a distance larger then safe, reed switch are changed until a suitable reed switch is not found.

Let us note that the parameters of cutoff circuit components depend on k_{sens} and the reset factor k_r; $k_r = B_r/B_{act1}$, where B_r is the induction under which the normally open reed switch contacts return to the initial state after operation. Considering k_{sens} = 2, from (8) we have, $B_{act} = B_{sc.min}/2$. Considering the current sinusoidal (Fig. 6), we can write:

$$\text{a)}\, B_{act} = B_{sc.min} \cdot \sin\varphi_1; \quad \text{b)}\, B_r = B_{sc.min} \cdot \sin\varphi_2 \tag{9}$$

From Eq. (9),

$$\varphi_1 = (-1)^{n_1} \arcsin(1/2) + \pi n_1;$$
$$\varphi_2 = (-1)^{n_2} \arcsin(k_r/2) + \pi n_2, \tag{10}$$

In Eq. (10) n_1 is multiple of 2; $n_2 = n_1 + 1$, since actuation and return of the reed switch occur, correspondingly, before and after the current passes through the amplitude value.

Then, time of closed (t_{close1}) and open (t_{open}) states of the reed switch contacts are

$$t_{close1} = \frac{(\varphi_2 - \varphi_1) \cdot 0.01}{180}; \; t_{open} = 0.01 - t_{close1} \tag{11}$$

From Eq. (11), t_{close1} = 7.4 ms at k_r = 0.6 and 7.8 ms at k_r = 0.3.

Thus, k_r and k_{sens} determine the time during which capacitor 6 is charged and discharged every AC half-wave. Knowing t_{open} and t_{close}, it is easy to calculate the capacitance of capac-

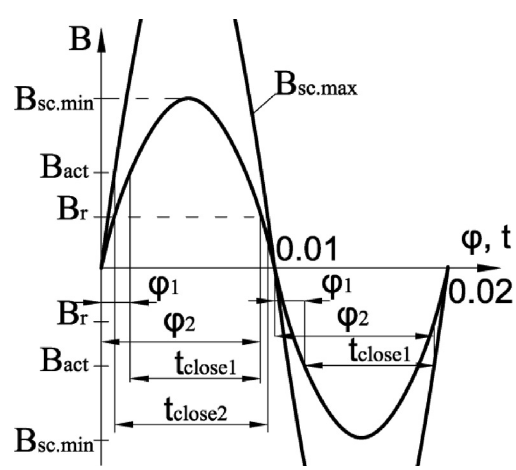

Fig. 6 Time t_{close1} и t_{close2} under the action of inductions $B_{sc.min}$ and $B_{sc.max}$ from SC current.

itor 6 and the resistance of resistor 12. They should be such (Fig. 7) as capacitor 6 is charged after the second actuation of reed switch 2. The capacitance of capacitor 7 and the resistance of resistor 18 are determined in the same way, and the charge time of the latter should be longer than the sum of the protection operation time and the break time. Otherwise, relay 13 open contact 15 in the electrical installation breaker trip circuit before the latter is triggered.

10. Example of calculation of reed switch overcurrent protection actuation parameters

Let the protection should be mounted from the side of power supply of an auxiliary 10.5/6.3 kV transformer of 16 MVA in power and the rated current $I_{r.t} = 0.88$ kA, which is connected to the generator via (Fig. 4) busducts 1–3 with the enclosure diameter 0.54 m and the busbar diameter 0.14 m (busduct 4 is absent, $B_4 = 0$). Let overcurrent protections with the actuation currents $I_{pa1} = I_{pa2} = 2.8$ кA be mounted at both 6-kV leads. For safety reasons, we select point N, where a reed switch is to be fixed, at $h_1 = 0.19$ m.

Let us find the protection actuation current with the overcurrent protection matching reliability coefficient $k_{rel} = 1.3$ with protections at the 6-kV side [35]:

$$I_{pa} = k_{rel}\left(I_{pa.1} + I_{op.max2}\right) = 1.3(2.8 + 0.4) = = 4.2 \text{ kA} \quad (12)$$

In Eq. (12) the maximal operation load current of the section of 6-kV busbars $I_{op.max2} = 0.5I_{r.t}$.

Since $B_4 = 0$, we calculate the induction B_{pa1} by Eq. (5):

$$B_{pa1} = \frac{1.6 \cdot 10^{-7} \cdot I_{pa}}{h_1} = \frac{1.6 \cdot 10^{-7} \cdot 4.2}{0.19} = 3.5 \text{ mT} \quad (13)$$

Let us assume that there is a reed switch with the actuation induction $B_{act.1} = 3.3$ mT, which is the closest to B_{pa1} from Eq. (13). Since $B_{pa1} > B_{act1}$, a false protection actuation is

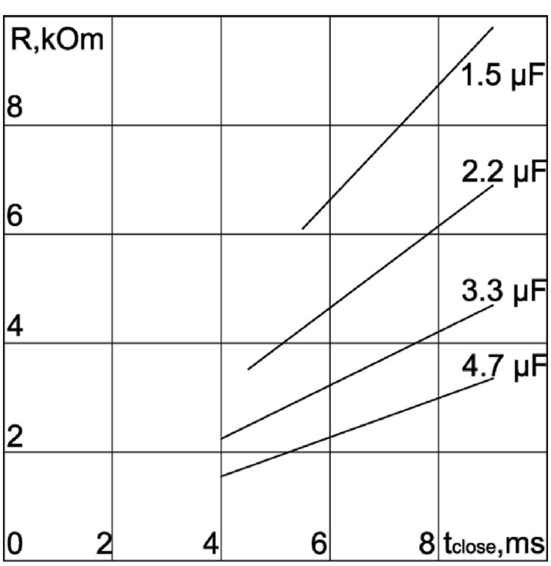

Fig. 7 Dependence of the resistance of the resistor 12 on the time t_{close} of the closed state of the reed switch contacts with capacities 1.5; 2.2; 3.3; 4.7 μF of capacitor 6.

possible. Therefore, it is necessary to increase the distance between the reed switch and the busbar to h_1', at which $B_{pa2} = B_{act1}$, and to check the sensitivity. From Eq. (5),

$$h_1' = \frac{1.6 \cdot 10^{-7} \cdot I_{pa}}{B_{act1}} = \frac{1.6 \cdot 10^{-7} \cdot 4.2 \cdot 10^3}{3.3 \cdot 10^{-3}} = 0.2 \text{ m} \quad (14)$$

We calculate the minimal SC current at 6-kV busbars and reduce to the 10-kV side $I_{sc.min} = 6.15$ kA. Then, from Eq. (3a) at from Eq. h_1' (14), we find the induction of MF produced by $I_{sc.min}$, which acts the reed switch, and k_{sens} (8):

$$B_{sc.min} = \frac{\mu_0 \cdot I_{sc.min}}{2\pi \cdot h_2 \cdot k_{np1}} = \frac{4\pi \cdot 10^{-7} \cdot 6.15}{2\pi \cdot 0.2 \cdot 1.4} = 4.4 \text{ mT};$$
$$k_{sens} = \frac{4.4}{3.3} = 1.3 \quad (15)$$

Since $k_{sens} = 1.3 > 1.2$ in Eq. (15), then the reed switch is fixed at the point M (Fig. 4) with $h_1' = 0.2$ m.

11. Results and discussion

11.1. Major findings

The technique developed for protection of 6–35 kV electrical installations with isolated phase busducts makes it possible to construct reed-switch current protections without current transformers capable of detecting a short-circuit for 0.025 s, which meets the speed requirements (and is not worse than, for example, Siemens systems). Their sensitivity is the same as of protections with CT in most cases. They are more reliable than reed-switch analogs, because they are based on a short-term noise immune relay, which does not false operate in the case where the reed switch contacts cannot break after closing, have built-in test diagnostics, and are equipped with structures for mounting reed switches.

11.2. Research outcome

The relay is made of two capacitors, miniature intermediate relays, and a reed switch. Its power consumption is lower by 6.5 VA than that of an electromagnetic current relay; by 8.5 VA than that of a static relay, and by 7.5 W than that of microprocessor-based relays (for example, Siemens [31]) (accounting losses in the current transformer [36]). Switching capacity and return ratio are the same as for microprocessor-based relays. The cost of protection for one phase will be cheaper than the cost of a current transformer; for isolated phase busducts, it ranges from 300 to 3500 US dollars (for example, for the busduct used in our experiments, the price of a Russian TShL-20 current transformer is 1800 US dollars [37])

Techniques for selecting the cutoff and overcurrent protection parameters (taking into account the errors in EI mounting and the noise effect) and estimating their sensitivity, as well as a system which allows mounting a reed switch near the busbar have been developed. The correction coefficients have been found, which make it possible to calculate the parameters with the use of the simplest equations for shielding coefficient and of the Biot–Savart–Laplace law. The assumptions accepted in the work do not influence the research results, since they are taken into account via the offset coefficient, like in traditional relay protections.

11.3. Usefulness of research

The protections designed provide an important possibility of saving copper, steel, and insulating materials due to avoidance of using current transformers. The assemblage becomes easier, since there is no need to mount a current transformer of 300–500 kg in mass inside a busduct.

11.4. Research gaps

No in-service tests of the prototype were carried out. The temperature range, where the current relay used in the protection system correctly operates, was not determined. The comparison with traditional protection systems in terms of reliability was not performed because of lack of statistical data.

12. Limitations of the proposSed protection system

Reed switches have a limited sensitivity, which is sufficient only for the use in electrical installations of up to 100 kV in voltage. For example, HSI Sensing and Standex (USA) reed switches operate at a SC current of 250 A in 10-kV EI busbars being spaced 12 cm away from them. Under 110 kV, the safe distance is 1 m and a reed switch operates at 2 kA; it operates at 3.6 kA under 220 kV and at 8 kA under 500 kV. They are insensitive at 220–500 kV.

The response time of the proposed protection system is limited to 0.02 s, since the failure of the protection against short-term interference requires at least two reed switch actuations.

13. Future scope of research

The research can be continued in the following directions: design of cutoff and overcurrent protection for other busducts and connections, including complete switchgear of up to 110 kV in voltage, where main tasks are determination of adjusting factors similar to those found in this work; creation of systems for controlling set points and mounting reed switches; enhancement of reliability of the relay protection system in general due to the use of the protections developed instead of traditional ones, but connected according to the majorization principle, or like duplicating traditional and microprocessor-based protections with CTs according to the same principles. This can help to prevent accidents in the case of cyberattacks. It is of interest to work on expansion of applicability of the created cutoff and overcurrent protection in power lines with similar busducts under voltages above 110 kV. Our experiments have shown that the sensitivity of a reed switch can be increased by 5–7 times if it is magnetized by direct current applied to the reed switch control winding.

14. Major beneficiary of research

The results can be used by specialists from scientific and design organizations engaged in the development of relay protection for electric power systems, primarily electrical installations with isolated phase busducts, such as generators, high-voltage lines, and electrolysis plants.

15. Conclusions

Reed switch current protections developed for electrical installations with isolated phase busducts will be hundreds of times smaller in volume and weight than protection with traditional current transformers, and will save tens of kilograms of copper, steel, and high-voltage insulating materials per one connection, since they do not need in current transformers. These protections meet the requirements for speed and, in most cases, sensitivity. They are more reliable than reed switch based analogs.

The magnetic inductions which affect a reed switch inside a busduct can be determined with the use of the Bio–Savart–L aplace law in simple forms and the shielding coefficients with experimentally found correction factors.

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.

Acknowledgements

This work was supported by Ministry of Education and Science of the Republic of Kazakhstan (grant no. AP05131351).

References

[1] A. Elmitwally, E. Gouda, S. Eladawy, Optimal allocation of fault current limiters for sustaining overcurrent relays coordination in a power system with distributed generation, Alex. Eng. J. 54 (4) (2015) 1077–1089, https://doi.org/10.1016/j.aej.2015.06.009.

[2] S.K. ElSayed, E.E. Elattar, Hybrid Harris hawks optimization with sequential quadratic programming for optimal coordination of directional overcurrent relays incorporating distributed generation, Alex. Eng. J. 60 (2) (2021) 2421–2433, https://doi.org/10.1016/j.aej.2020.12.028.

[3] V. Andreev, Relay Protection and automatics of power supply systems, fourth ed., Vyssshaya shkola, Moscow, 2008 [in Russian].

[4] J. Das, Power Systems Protective Relaying, CRC Press, Boca Raton, 2018.

[5] A. D'yakov, Electric-power industry in the world in early 21st century (according to the materials of the 39th CIGRE session, Paris), Energetika Zarubezhom 4–5 (2004) 44–45.

[6] L. Kojović, M. Bishop, Modern protection relay with current sensors based on the Rogowski coil. Modern trends in the development of relay protection and automation of power systems, in: Proc. CIGRE, Moscow, Sept. 7–10, 2009.

[7] L. Kojović, Non-conventional instrument transformers for improved substation design, CIGRE Session 46, 2016.

[8] I.M. Sirota, Schemes for inductive measurement of current in high-voltage three-phase circuits, Electrichestvo 4 (1967) 22–24.

[9] I.M. Sirota, I.M. Shurin, Phase sequence network in circuits with remote sensors, Electrichestvo 11 (1971) 26–31.

[10] A.N. Novozhilov, V.N. Goryunov, T.A. Novozhilov, Protection of a single-phase transformer from interwinding failure in

windings of integral magnetic transformers, Rus. Electr. Eng. 89 (2018) 118–121.

[11] E.A. Meerovich, L.A. Nazarov, G.Kh. Karabaev, Measurement of currents in high-voltage lines by their magnetic fields, Electrichestvo 7 (1980) 32–40.

[12] Changhe Sun, Yumei Wen, Ping Li, Weisheng Ye, Jin Yang, Jing Qiu, Jing Wen, Self-Contained Wireless Hall Current Sensor Applied for Two-Wire Zip-Cords, IEEE Trans. Magn. 52 (7) (2016) 1–4, https://doi.org/10.1109/TMAG.2016.2524671.

[13] Kun-Long Chen, Nanming Chen, A New Method for Power Current Measurement Using a Coreless Hall Effect Current Transformer, IEEE Trans. Instrum. Meas. 60 (1) (2011) 158–169, https://doi.org/10.1109/TIM.2010.2049234.

[14] V. Gurevich, Electric Relays: Principles and Applications, CRC Press, Boca Raton, 2005.

[15] J. Teng, Sh. Luan, W. Huang, D. Lee, Yu. Huang, A cost-effective fault management system for distribution systems with distributed generators, Int. J. Electr. Power Energy Syst. 65 (2014) 357–366, https://doi.org/10.1016/j.ijepes.2014.10.029.

[16] M. Kletsel, A. Barukin, O. Talipov, About the Biot-Savart-Laplace law and its use for calculations in high-voltage AC installations, Prz. Elektrotech. 93 (2017) 129–132.

[17] Mark Kletsel, Asemgul Zhantlesova, Pavel Mayshev, Bauyrzhan Mashrapov, Dauren Issabekov, New filters for symetrical current components, Int. J. Electr. Power Energy Syst. 101 (2018) 85–91.

[18] P. Zahlmann, J. Birkl, T. Bohm, K. Buehler, J. Maget, A. Ehrhardt, E. Shulzhenko, Germany Patent no. 102018111308-B3, 2019.

[19] M. Kletsel, V. Borodenko, A. Barukin, A. Kaltayev, R. Mashrapova, Constructive features of resource-saving reed relay protection and measurement devices, Rev. Roum. Sci. Tech-El. 4 (2019) 309–315.

[20] A. Barukin, A. Kaltayev, Y. Lenkov, Majority Voting Schemes of Differential Protections without Current Transformers with Functional Diagnostics for Converting Units and Electric Motors, in: Proceedings of 2020 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM), Sochi, 2020. https://doi.org/10.1109/ICIEAM48468.2020.9112078.

[21] M. Kletsel, A. Barukin, D. Amirbek, Reed Switch and Magneto Resistor-Based Differential Protection Featuring Test Diagnostics for Converters, Proc. of 2020 International Multi-Conference on Industrial Engineering and Modern Technologies (FarEastCon), 2020.

[22] G. A. Engazaryan, Magnetic diodes and magnetic transistors and their application, Ed. By G. A. Engazaryan and V.I. Stafeev (Radio i svyaz', Moscow, 1987) [in Russian].

[23] W. Kim, S. Luo, G. Lu, K.D.T. Ngo, Integrated current sensor using giant magneto resistive (GMR) field detector for planar power module, in: Twenty-Eighth Annual IEEE Applied Power Electronics Conference and Exposition (APEC), 2013, pp. 2498–2505, https://doi.org/10.1109/APEC.2013.6520647.

[24] S.J. Nibir, M. Biglarbegian, B. Parkhideh, Performance study of magnetic field concentration techniques on magnetoresistor/rogowski contactless current sensor, IEEE Sens. (2016) 1–3, https://doi.org/10.1109/ICSENS.2016.7808725.

[25] R. Weiss, A. Itzke, J. Reitenspieß, I. Hoffmann, R. Weigel, A Novel Closed Loop Current Sensor Based on a Circular Array of Magnetic Field Sensors, IEEE Sens. J. 19 (2019) 2517–2524.

[26] Peng-Yu Gu, Qing Chen, Hong-Bin Li, Chen Hu, Hui Gong, Yang Jiao, PCB Rogowski Coils for 300 kA Current Measurement on a Multi-Split Conductor, IEEE Sens. J. 19 (16) (2019) 6786–6794, https://doi.org/10.1109/JSEN.736110.1109/JSEN.2019.2914730.

[27] Mohamed E. Ibrahim, Amr M. Abd-Elhady, Design and Modeling of a Two-Winding Rogowski Coil Sensor for Measuring Three-Phase Currents of a Motor Fed Through a Three-Core Cable, IEEE Sens. J. 21 (6) (2021) 8289–8296, https://doi.org/10.1109/JSEN.736110.1109/JSEN.2020.3045373.

[28] https://all-pribors.ru/opisanie/52591-13-gar10-gar20-55939#ot (accessed Jule 2021).

[29] M. Kletsel, A. Berguzinov, RU Patent No. 2570328, Byull. Izobret. No. 34 (2015).

[30] M. Kletsel, B. Mashrapov, A. Barukin, RU Patent No. 2629958, Byull. Izobret. No. 25 (2017).

[31] MiCOM P115, Manual (global file) P115/EN M/C43.

[32] https://image.schrackcdn.com/datenblaetter/h_pt270024-_de.pdf.

[33] K. Doroshev, Busducts and busbars for power plants and substations, Energoatomizdat, Moscow, 1996 (in Russian).

[34] I. Gordnev, Electromagnetic shielding in a wide frequency range, Svyaz, Moscow, 1972.

[35] M. Shabad, Calculations of relay protection and automation of distribution networks, IEIPK, St.-Petersburg, 2003.

[36] https://portal.tpu.ru/SHARED/b/BATSEVAN/Uchebnaiarabota/AnnotationESIS/%D0%A0%D0%90%D0%A1%D0%A7%D0%95%D0%A2_%D0%A2%D0%95%D0%A5%D0%9D%D0%9E%D0%9B%D0%9E%D0%93%D0%98%D0%A7%D0%95%D0%A1%D0%9A%D0%98%D0%A5_%D0%9F%D0%9E%D0%A2%D0%95%D0%A0%D0%AC.pdf.

[37] https://energotet.ru/catalog/current_transformers/bus_bar_current_transformers_tshl_20_i/.