Filter Reed-Switch Current Protections

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***Abstract*—Filters for symmetrical current components can be designed with the use of not only ferromagnetic current transformers, but also with inductors and reed switches. Reed switches are preferable, but this design should include duplication and self-diagnostics to ensure reliability. A measurement unit on the basis of reed switches fixed near the coplanar phases of an electrical installation to be protected is suggested. It simultaneously functions as a current relay and a negative-sequence current filter. The reliability of its operation is ensured by the design simplicity, self-diagnosis of malfunctions, and duplication of elements. A technique for calculating the parameters of the current filter elements is developed. It consists of 29 formulas, most of which are used for the calculation of the coordinates of the reed switches and of the inductions of magnetic fields affecting them. The features of operation of protection with this measurement unit and self-diagnostics procedures are described.**

***Keywords*—relay protection, current, measurement unit, reed switch, negative sequence, self-diagnostics**

I. Introduction

Filters for symmetrical current components are widely used in the relay protections of electric power systems. They traditionally receive information from current transformers, like most relay protection devices (e.g., [1]). Current transformers contain hundreds and sometimes thousands of times more high-quality copper and steel than the filters (for example, filter protections of synchronous generators) and are the same times heavier. It was shown in [2] that filters could be constructed without current transformers, on the basis of conventional inductors, but that idea was not developed and brought to implementation, apparently because of a need in the solution of the following problems: it was necessary to amplify the voltage from the inductor while amplifiers were imperfect, to develop other protections without current transformers since the only filters did not ensure protection against all types of short circuits (SC), which meant the construction of a new relay protection system.

Most works on the construction of such systems are currently oriented toward magnetically controlled contacts—reed switches, which have important advantages for relay protection over other magnetically sensitive elements. Some principles of design and protection devices have already been suggested, including structures for mounting reed switches [3–10] and filters for symmetrical current components. However, the issues of ensuring the reliability of phase-to-phase short-circuit protections were not considered. In this work, an attempt to fill this gap is made.

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II. Protection Design

The measurement unit (Fig. 1) consists of reed switches 1–4 with normally open contacts and windings 5–8, amplifiers 9 and 10, phase-shifting circuits 11 and 12, control resistors 13 and 14, OR (15) and AND (16) elements with one inverted input, logic unit 17, the comparison circuit 18, and signaling unit 19.

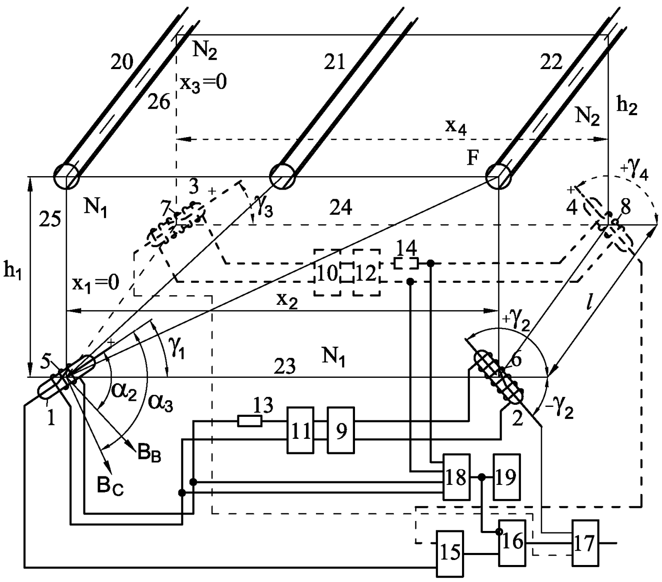

Fig. 1. Measurement Unit Located Near Phase Conductors

Reed switches 1 and 4 function as responders of a negative-sequence current filter (react only to two-phase SC), reed switch 2 responds to three-phase SC, and reed switch 3, to overloads. Inputs of amplifier 9 (10) are connected to winding 6 (7) of reed switch 2 (3), and its outputs, to the inputs of phase-shifting circuit 11 (12). The outputs of the latter are connected to winding 5 (8) of reed switch 1 (4) through control resistor 13 (14). Reed switches 1 and 4, 2 and 3, windings 5 and 8, 6 and 7 have equal parameters to ensure functional diagnostics of the measurement unit.

The reed switches are mounted in the magnetic field of conductors 20, 21, and 22 of phases A, B, and C, respectively (Fig. 1). The reed switch coordinates are determined by the distance h_1 (h_2) from horizontal line 23 (24), which passes through the centers of gravity of reed switches 1 (3) and 2 (4), in the plane N_1 (N_2) to the plane F, where conductors 20–22 are located (planes N_1 (N_2) and F are perpendiculars), which should not be shorter than the minimal admissible distance h_{min}

for safety reasons; by the distances x_1 (x_3) and x_2 (x_4) from the centers of gravity of reed switches 1 (3) and 2 (4) to line 25 (26), which passes through the center of the conductor of phase A normal to line 23 (24); by the angles γ_1 (γ_3) and γ_2 (γ_4) between line 23 (24) and the longitudinal axis of reed switches 1 (3) and 2 (4) in the plane N_1 (N_2); and by the distance l between the planes N_1 and N_2, where the reed switches are located. The distance l is chosen so (l=10–12 cm) as to exclude the mutual effect of the reed switches with windings.

III. Negative-Sequence Current Filter Design

The distances x_1 (x_3) and x_2 (x_4) and the angles γ_1 (γ_3) and γ_2 (γ_4) are chosen so that reed switches 1 (3) and 2 (4) be under the magnetic fields produced by the currents in conductors 20–22, which do not include zero-sequence components. For this, let us consider the well-known equation for the magnetic induction of a field that acts along the longitudinal axis of a reed switch:

$$\dot{B}_{lon} = B_A \cos\alpha_A + B_B \cos\alpha_B + B_C \cos\alpha_C = \\ = \mu_0 \left(\frac{\cos\alpha_A}{h_A} \dot{I}_A + \frac{\cos\alpha_B}{h_B} \dot{I}_B + \frac{\cos\alpha_C}{h_C} \dot{I}_C \right) / 2\pi, \quad (1)$$

where B_A, B_B, and B_C are the magnetic field inductions at the center of gravity of the reed switch produced by the currents of phases A, B, and C, respectively (the Biot–Savart–Laplace law is used here when changing from the induction to the current); α_A, α_B, and α_C are the angles between the longitudinal axis of the reed switch and B_A, B_B, and B_C, respectively; μ_0 is the air permeability; h_A, h_B, and h_C are the distances from the center of a cross section of the conductors of phases A, B, and C to the center of gravity of the reed switch. Hereinafter, α_A, α_B, α_C and h_A, h_B, h_C have the superscripts $R1$ for reed switch 1 and $R2$ for reed switch 2. The ratio of cosines to the distances can be found on the basis of elementary geometry:

$$\frac{\cos\alpha_A}{h_A} = \frac{h\cos\gamma + x\sin\gamma}{h^2 + x^2}, \quad (2)$$

$$\frac{\cos\alpha_B}{h_B} = \frac{h\cos\gamma + (x-d)\sin\gamma}{h^2 + (x-d)^2}, \quad (3)$$

$$\frac{\cos\alpha_C}{h_C} = \frac{h\cos\gamma + (x-2d)\sin\gamma}{h^2 + (x-2d)^2}. \quad (4)$$

As is known from [11], zero-sequence components are formed by three in-phase vectors $\dot{I}_{A0} = \dot{I}_{B0} = \dot{I}_{C0} = I_0$. Hence, if, e.g., one accepts

$$\text{a)}\ \frac{\cos\alpha_B^{R1}}{h_B^{R1}} = -0.4\frac{\cos\alpha_A^{R1}}{h_A^{R1}} \ \text{and b)}\ \frac{\cos\alpha_C^{R1}}{h_C^{R1}} = -0.6\frac{\cos\alpha_A^{R1}}{h_A^{R1}} \quad (5)$$

in Eq. (1) for reed switch 1, then this reed switch is not exposed to the zero-sequence magnetic field produced by the currents of the controllable phases. These conditions for reed switch 2 are

$$\text{a)}\ \frac{\cos\alpha_B^{R2}}{h_B^{R2}} = -0.4\frac{\cos\alpha_C^{R2}}{h_C^{R2}} \ \text{and b)}\ \frac{\cos\alpha_A^{R2}}{h_A^{R2}} = -0.6\frac{\cos\alpha_C^{R2}}{h_C^{R2}}. \quad (6)$$

The induction

$$\dot{B}_{lon} = \frac{\mu_0 \cos\alpha_A^{R1}}{2\pi h_A^{R1}} \begin{pmatrix} \left(\dot{I}_A - 0.4\dot{I}_B - 0.6\dot{I}_C\right) + \\ + \left(-0.6\dot{I}_A - 0.4\dot{I}_B - \dot{I}_C\right)e^{j47^\circ} \end{pmatrix} \quad (7)$$

should acts along its longitudinal axis. Equation (7) fulfils if the induction proportional to the first component in the parenthesis is produced by the currents in conductors 20–22, and the induction proportional to the second component, by the current in winding 5, that is

$$\dot{B}_{lon} = \dot{B}_{lon}^{R1} + \dot{B}_{lon}^{win}, \quad (8)$$

$$\dot{B}_{lon}^{R1} = \mu_0 g_A^{R1} \left(\dot{I}_A - 0.4\dot{I}_B - 0.6\dot{I}_C\right) / 2\pi, \quad (9)$$

$$\dot{B}_{lon}^{win} = \mu_0 g_A^{R1} \left(-0.6\dot{I}_A - 0.4\dot{I}_B - \dot{I}_C\right)e^{j47^\circ} / 2\pi, \quad (10)$$

where $\dot{B}_{lon}^{R1}$ is the induction of a magnetic field which acts along the longitudinal axis of reed switch 1 and is produced by the currents in conductors 20–22; $\dot{B}_{lon}^{win}$ is the induction of a magnetic field produced by the current $\dot{I}_{out}$ in winding 5, which is generated at the output of amplifier 9 in the presence of phase-shifting circuit 11 and control resistor 13 required for controlling $\dot{I}_{out}$.

Equation (9) is derived from Eq. (1) under fulfillment of Eq. (5). The induction of $\dot{B}_{lon}^{win}$ of the magnetic field produced by the current $\dot{I}_{\text{out}}$ should be equal in amplitude to $\frac{h_C^{R2}\cos\alpha_A^{R1}\dot{B}_{lon}^{R2}}{h_A^{R1}\cos\alpha_C^{R2}}$, where $\dot{B}_{lon}^{R2}$ is the induction of a magnetic field which acts along the longitudinal axis of reed switch 2 and its winding 6 and is produced by the currents of phases A, B, and C. The induction $\dot{B}_{lon}^{R2}$ is defined by Eq. (1) under fulfillment of Eq. (6):

$$\dot{B}_{lon}^{R2} = \mu_0 g_C^{R2} \left(-0.6\dot{I}_A - 0.4\dot{I}_B - \dot{I}_C\right) / 2\pi. \quad (11)$$

The phase shift by 47° (Eq. (10)) is ensured by phase-shifting circuit 11.

To find the coordinates of reed switch 1, we consider Eq. (5) is like simultaneous equations with unknown x_1 and γ_1. From Eq. (5a), we derive

$$\gamma_1 = \arctan\left(\frac{1,4h_1^3 + 1,4h_1x_1^2 + 0,4h_1d^2 - 0,8dh_1x_1}{-1,4x_1h_1^2 - 0.4x_1d^2 + 1,8x_1^2d - 1,4h_1x_1^3 + dh_1^2}\right), \quad (12)$$

and from (5b),

$$\gamma_1 = \arctan\left(\frac{1,6h_1^3 + 1,6h_1x_1^2 + 2,4h_1d^2 - 2,4dh_1x_1}{-1,6x_1h_1^2 - 2.4x_1d^2 + 4,4x_1^2d - 1,6x_1^3 + 2dh_1^2}\right). \quad (13)$$

Then, equating Eq. (12) to Eq. (13), we derive the fourth-power equation

$$1.5x_1^4 + x_1^3d + 3x_1^2h_1^2 - 2x_1^2d^2 + x_1dh_1^2 + 1.5h_1^4 - 2h_1^2d^2 = 0, \quad (14)$$

which is the most simply solved if $x_1=0$, that is, if the center of gravity of reed switch 1 is under the conductor of phase A. Then $h_{\min}=0.9d$ [12], and the equation takes the form

$$1.5h_1^2 - 2d^2 = 0, \quad (15)$$

from which

$$h_1 = \sqrt{2d^2}/1.5 = 0.96d > h_{\min} = 0.9d, \quad (16)$$

$$\gamma_1 = \arctan\left(\frac{1.4h_1^2 + 0.4d^2}{dh_1}\right). \quad (17)$$

Solving Eq. (6) for reed switch 2, we derive the equations for γ_2, which are similar to Eqs. (12) and (13). We again get a corresponding fourth-order equation, set $x_2=2d$ in it, which means the position of reed switch 2 under the conductor of phase C, and derive

$$h_2 = 0.96d, \quad (18)$$

$$\gamma_2 = \arctan\left(\frac{1.6h_2^2 + 4d^2}{1.2dh_2}\right). \quad (19)$$

A magnetic flux produced by the currents in conductors 20–22 induces the emf $\dot{E}_6$ of mutual induction, which is 90° shifted with respect to the flux:

$$\dot{E}_6 = \left(fW_6\pi^2D_{out6}^2\dot{B}_{lon}^{R2}\right)e^{j90}/2 = K_1\dot{B}_{lon}^{R2}, \quad (20)$$

where f is the current commercial frequency; W_6 is the number of turns in winding 6 of reed switch 2; D_{out6} is the outer diameter of winding 6.

The emf $\dot{E}_6$ is amplified by amplifier 9, shifted by phase-shifting circuit 11, and produces the current $\dot{I}_{out}$ in winding 5 of reed switch 1,

$$\dot{I}_{out} = \dot{E}_6K_ye^{j47}/Z_{out} = K_yK_2\dot{E}_6, \quad (21)$$

where Z_{out} is the resistance of the output circuit of amplifier 9, which consists of resistances Z_{win5} of winding 5 of reed switch 1 and r_{13} of control resistor 13.

On the other hand, the current $\dot{I}_{out}$ should produce a magnetic field along with the contacts of reed switch 1 with the induction $\dot{B}_{lon}^{win}$. Then,

$$\dot{I}'_{out} = K_3\dot{B}_{lon}^{win}, \quad (22)$$

where

$$K_3 = \frac{\sqrt{\left(0.5l_5\right)^2 + \left(0.5D_{av5}\right)^2}}{\mu_0W_5},$$

l_5 is the length of the support of winding 5 of reed switch 1; D_{av5} is the average diameter of winding 5; W_5 is the number of turns of winding 5 of reed switch 1. Windings 5 and 6 can be winded immediately on reed switches 1 and 2. When using standard round-section windings, their inner diameters should be a little larger that the diameters of the reed switch buses, and the lengths should be approximately equal to the lengths of the buses.

Equating Eq. (21) to Eq. (22) with accounting (20) and $\dot{B}_{lon}^{win} = \frac{h_C^{R2}\cos\alpha_A^{R1}\dot{B}_{lon}^{R2}}{h_A^{R1}\cos\alpha_C^{R2}}$, we calculate the preliminary gain factor K_y^{pr} in the absence of a control resistor ($r_{13}=0$):

$$K_y^{pr} = \frac{2h_C^{R2}K_3z_{win}\cos\alpha_A^{R1}}{K_2\pi^2fW_6D_{out6}^2h_A^{R1}\cos\alpha_C^{R2}} \quad (23)$$

and round it up to a standard value. Equation (23) implies that the K_y of amplifier 9 depends only on the parameters of windings 5 and 6 and the coordinates of the reed switch mounting.

The amplifier is chosen by K_y. Then it is necessary to find r_{13}. For this, we calculate the active resistance r_{out} of the output circuit of amplifier 9 accounting r_{13} by the equation

$$r_{out} = E_6 K_y / I'_{out} \,. \quad (24)$$

Then,

$$r_{13} = r_{out} - r_{win5} \,. \quad (25)$$

Phase-shifting circuit 11 should compensate the phase shift of $\dot{B}_{lon}^{win}$ and $\dot{B}_{lon}^{R2}$, i.e.,

$$e^{j\alpha_{PSC}} = \dot{B}_{lon}^{win} / \dot{B}_{lon}^{R2} \quad (26)$$

We can write

$$\dot{B}_{lon}^{win} = K_{lon} \dot{B}_{lon}^{R2} , \quad (27)$$

where $K_{lon} = K_1 K_2 K_y / K_3 g_C^{R5}$.

In this case, the induction of the magnetic field which acts along the longitudinal axis of reed switch 1

$$\dot{B}_{np} = \dot{B}_{lon}^{R1} + \dot{B}_{lon}^{win} = \dot{B}_{lon}^{R1} + \dot{B}_{lon}^{R2} = 1.1\mu_0 \dot{I}_2 \cos\alpha_A^{R1} / \pi h_A^{R1} \,, \quad (28)$$

and the reed switch functions as a responding component of the negative-sequence current filter.

The action of magnetic fields produced by negative-sequence currents on reed switch 4 is ensured by a similar procedure, but there is no factor $e^{j47°}$ in Eq. (7) and the first term in the parenthesis is multiplied by $e^{-j47°}$. Reed switches 3 and 4 are fixed in the plane β_2 at points with the coordinates h_2=h_1, x_3=0, x_4=2d, γ_3=γ_1, and γ_4=γ_2; the gain factor of amplifier 10 is K_y (23), the angle of phase-shifting circuit 12 is calculated by Eq. (26).

The filter works as follows. If an electrical installation normally operates, then there are no negative-sequence currents, and a magnetic field with the imbalance induction B_{ib} acts on reed switch 1. The imbalance is due to the inaccuracy of mounting reed switches 1 and 2 at points with the coordinates calculated and admissible asymmetry of the three-phase current system. For reed switch 1 not to actuate in the normal mode, its actuation induction B_{act}^{R1} must be higher than B_{ib}, i.e.,

$$B_{act}^{R1} = k_{off} B_{ib} \quad (29)$$

where k_{off} is the offset coefficient, k_{off} =1.2.

In the event of an SC to ground, zero-sequence currents flow through the conductors of the electrical installation. The calculated coordinates of the reed switch mounting ensure the zero-sequence magnetic field created by the currents of the phases controlled do not act on the reed switches and their windings. This can be easily verified by substituting the set of zero-sequence currents formed by three in-phase vectors $\dot{I}_{A0} = \dot{I}_{B0} = \dot{I}_{C0} = \dot{I}_0$ into Eq. (7). In this case, B_{ib}=0 in Eq. (7), and reed switch 1, which functions as a responding component of the filter, does not operate.

In the event of two-phase SC, negative sequence currents flow through the conductors of the electrical installation; B_{act}^{R1} turns out to be lower than the induction of the acting magnetic field produced by the negative-sequence currents. This can be verified by substituting the set of negative-sequence currents $\dot{I}_{A2} = \dot{I}_2 e^{j0°}$, $\dot{I}_{B2} = \dot{I}_2 e^{j120°}$, and $\dot{I}_{C2} = \dot{I}_2 e^{j-120°}$ in Eq. (7). In this case, $B_{lon} = \dfrac{1.1\mu_0 g_A^{R1}}{\pi} \dot{I}_2 e^{-j36.6°}$ in Eq. (7). Reed switch 1 operates: it closes the contacts and sends a signal through OR (15) and AND (16) elements to logic unit 17, which sends a trip signal to the object protected in a delay specified.

Positive-sequence currents also flow through the conductors under the same SC. But a magnetic field created by the positive-sequence currents does not act on reed switch 1. This can also be verified by substituting the set of positive-sequence currents $\dot{I}_{A1} = \dot{I}_1 e^{j0°}$, $\dot{I}_{B1} = \dot{I}_1 e^{-j120°}$, and $\dot{I}_{C1} = \dot{I}_1 e^{j120°}$ in Eq. (7). In this case, B_{lon}=0 in Eq. (7). Therefore, reed switch 1, which functions as a responding element of the filter, does not operate.

Thus, a signal at the filter exit appears only in case of electrical installation damages accompanied by negative-sequence currents.

In networks with isolated neutrals, the current protection operates as follows. Reed switch 2 does not close the contacts under the load and self-starting of electric motors, since the actuating induction B_{act} is offset from the maximal induction created by the load and self-starting currents flowing through conductors 20–22. Reed switch 3 operates in the case of self-starting, but its operation time is longer than the start-up and self-start times, like in traditional protections. Under three-phase SC, the inductions of magnetic fields which act on reed switches 2 and 3 increase and become higher than B_{act}. Therefore, reed switches 2 and 3 operate and signal to logic unit 17 of the protection (Fig. 1). As a result, the electrical installation breaker opens with the same delay as in the case of two-phase SC. In case of overloads, only reed switch 3 operates.

Self-diagnosis of the measurement unit suggested is performed as follows. In all operation modes, emf induced at windings 5 and 8, with the absolute values E_5 and E_8, is applied to the inputs of comparison circuit 18; $E_5 \neq E_8$ because of the inaccuracy of mounting reed switches 1–4 and asymmetry of the currents. For comparison circuit 18 not to signal in the absence of damages in the circuits of windings 5 and 8, its operation parameter E_{op} should be offset from the maximal emf difference:

$$E_{op} = \left| k_{off} \left(E_5 - E_8 \right) \right| \quad (30)$$

The difference $(E_5 - E_8)$ becomes higher than E_{op} in the event of any damage in the circuits of windings 5 and 8, the comparison circuit 18 is triggered and signals to signaling unit 19 and to the inverse input of AND element 16, thus disabling the filter.

IV. Conclusions

The protection suggested allows detecting negative-sequence currents and the total currents of phase-to-phase SC without the use of metal-intensive current transformers. It is more reliable than similar reed-switch protections due to the simple self-diagnosis of faults and duplication of components of its circuit. The technique presented makes it possible to determine the coordinates of mounting the reed switches near the busbars of an electrical installation and to calculate the parameters of the components of the negative-sequence current filter.

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References

[1] M. Y. Kletsel' and K. I. Nikitin, "Analysis of the sensitivity of back-up protections for distribution networks in power systems," Electricity, no. 2, pp. 19–23, 1992.

[2] E. A. Meerovich, L. A. Nazarov, G. Kh. Karabaev, and B. P. Kokurin, "Measurement of currents in high-voltage lines by their magnetic fields," Electricity, vol. 7, pp. 32–40, 1980.

[3] P. He, L. Wang, D. Liu, Y. Du, and H. Lu, "Transformer composite monitoring module with quick protection function," China Patent 202372563-U, 2012.

[4] A. Zhantlesova, B. Issabekova, and D. Nosovskii, "The control system of a steady short-circuit current measurement using the expert estimation method," Proc. of 2015 Int. Siberian Conf. on Control and Communications, 2015.

[5] A. Barukin, A. Berguzinov, and O. Talipov, "Mounting Measuring Devices of Reed Switch Protection Near Conductors of Electrical Installations," Proc. of 2020 Int. Multi-Conf. on Industrial Engineering and Modern Technologies, 2020.

[6] Z. Issabekov, M. Kletsel, A. Barukin, and B. Mashrapov, "Measuring bodies for distance protection that does not use current transformers," AIP Conf. Proc., 2021.

[7] M. Kletsel, A. Barukin, and V. Mel'nikov, "Reed Switches Differential Protection of Conversion Facilities with the Second-harmonic Lockout," Proc. of 2021 IEEE Conf. of Russian Young Researchers in Electrical and Electronic Engineering, 2021.

[8] Z. Issabekov, B. Mashrapov, D. Issaberov, and G. Mashrapova, "Structures for mounting reed switches near the busbars of electrical installations with remote control of their position," AIP Conf. Proc., 2021.

[9] B. Mashrapov and R. Mashrapova, "Interference Free Measuring Devices for Current Protection on Reed Switches without Current Transformers," Proc. of 2021 Int. Conf. on Industrial Engineering, Applications and Manufacturing, 2021.

[10] A. Zhantlesova, B. Issabekova, and M. T. Tokombayev, "Methods for attaching magneto sensitive elements to build protections," AIP Conf. Proc., 2021.

[11] L. A. Bessonov, Theoretical foundations for electrical engineering. Moscow: Vyschaya shkola, 1996.

[12] Requirements for Electrical Installations. St. Petersburg: Dean, 2002.