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Reed-Switch Short-Circuit Protection with Zero-Sequence Current Filter, Self-Diagnostics and Duplication

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***Abstract*—A need in replacing metal-consuming current transformers with magnetically sensitive elements is noted. It is suggested to design relay protections which receive information about current in the electrical installation busbar from reed switches. It is pointed out that a number of reed switch protections have already been designed, but the issues of ensuring their reliability have not been considered. For current protections of network components with grounded neutrals and coplanar phases, a new measurement unit is suggested on the basis of reed switches. Its reliability is ensured by simple design, functional diagnostics, and duplication of its components. It simultaneously functions as a current relay which responds to the total phase currents and a zero-sequence current filter. The technique for selecting filter parameters is presented; it consists of twenty-three formulas. The operation of the measurement unit and the protection on its basis in different modes is described. The features of self-diagnostics are noted. Examples of constructions for mounting protection reed switches in the magnetic field of the phase currents of an electrical installation are given.**

Keywords—relay protection, measurement unit, reed switch, zero sequence, diagnostics, duplication, current.

I. INTRODUCTION

A need in using some other current sensors instead of traditional metal-intensive current transformers, which provide most relay protections with information about current in busbars of an electrical installation, including newly designed protections, has been discussed many times since the 60s [1–5]. In recent decades, this issue has been named one of the unsolved problems of the world energy [6]. In attempts to solve this problem, it was suggested to use different magnetically sensitive elements, such as: reed switch [7–14], Rogowski coil [15, 16], Hall sensor [17, 18], etc. However, the work is still far from being completed, so it is still impossible to decide which direction is better. We have chosen reed switches because they are widely used in engineering [19]. In relay protection, they have some advantages [9] over other magnetically sensitive elements; they have already become the basis for a new relay protection system. For example, there have been developed principles of design [20–22] and several protection devices [23–30] and structures for mounting reed switches [31–33]. However, the issues of ensuring the reliability of operation of most of these devices and filters were not considered. In this work, a new protection with a measurement unit is suggested, where the problem of reliability is solved due to the simple design, duplication, and functional diagnostics. Protection is intended for electrical installations with coplanar phases and networks with grounded neutrals.

II. MEASUREMENT UNIT

The measurement unit is suggested for relay protection devices in networks with grounded neutrals, which use reed switches as measuring current transducers. The measurement unit (Fig. 1) includes 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, logic unit 15, actuator 16, comparison circuit 17, and signaling unit 18.

Reed switches 1 and 4 are responding elements of a zero-sequence current filter, and reed switches 2 and 3, of overcurrent protection against phase-to-phase short circuits. Amplifier 9 (10) is connected by the inputs to winding 6 (7) of reed switch 2 (3), and by the outputs, to the inputs of phase-shifting circuit 11 (12), which is 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.

Reed switches 1 (3) and 2 (4) are fixed in the magnetic field of conductors 19, 20, and 21 of horizontally located phases A, B, and C, respectively. Their positions are determined by the distance *h* between horizontal line 22 (23), which passes through the centers of gravity of reed switches 1 (3) and 2 (4), and conductors 19–21 in the vertical plane; by the distances x_1 (x_3) and x_2 (x_4) from the center of gravity of reed switches 1 (3) and 2 (4) to vertical line 24 (25), which passes through the center of the conductor of phase A; by the angles γ1 (γ3) and γ2 (γ4) between line 22 (23) and the longitudinal axis of reed switches 1 (3) and 2 (4) in the vertical plane; and by the distance *l* between the vertical planes where the reed switches are located. The distance *l* is chosen so as to exclude the mutual effect of reed switches with windings [20]; l = 10–15 cm is enough. To design a zero-sequence current filter, the distances x_1 (x_3) and x_2 (x_4) and the angles γ_1 (γ_3) and γ_2 (γ_4) are

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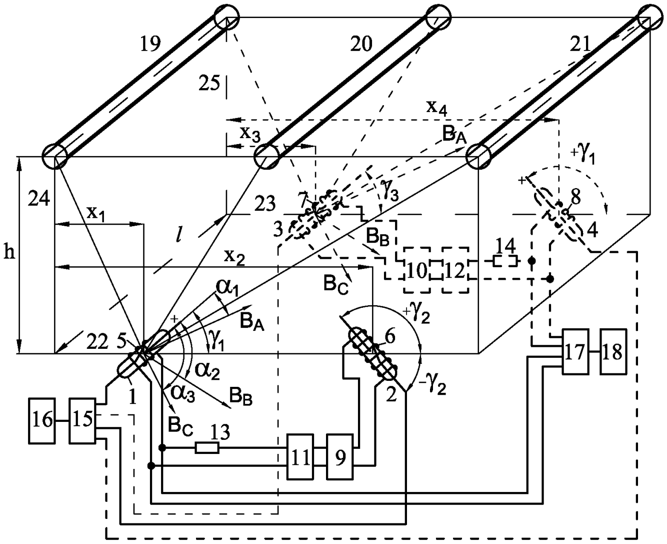

Fig. 1. Reed-switch measurement unit for horizontally arranged phase conductors

selected so that the magnetic field created by the currents of phases A and B acts on reed switch 1 (3), and by the currents of phases B and C, on reed switch 2 (4).

For this, let us consider the well-known equation for the induction of a magnetic field which acts along the reed switch longitudinal axis [30]:

$$\begin{aligned}\dot{B}_{lon} &= B_A\cos\alpha_1 + B_B\cos\alpha_2 + B_C\cos\alpha_3 = \\ &= \mu_0\left(g_A\dot{I}_A + g_B\dot{I}_B + g_C\dot{I}_C\right)/2\pi,\end{aligned} \tag{1}$$

where B_A, B_B, and B_C are the inductions of magnetic fields at the point of center of gravity of reed switch 1 produced by the currents of phases A, B, and C, respectively; α_1, α_2, and α_3 are the angles between the longitudinal axis of reed switch 1 and B_A, B_B, and B_C, respectively; μ_0 is the air permeability; g_A, g_B, and g_C are the coefficients found from the elementary geometry and the Biot–Savart–Laplace as

$$g_A = \frac{h\cos\gamma + x\sin\gamma}{h^2 + x^2}; \tag{2}$$

$$g_B = \frac{h\cos\gamma + (x-d)\sin\gamma}{h^2 + (x-d)^2}; \tag{3}$$

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

For reed switch 1 to function as a responding element of the zero-sequence current filter, a magnetic field with the induction

$$\dot{B}_{lon} = \frac{\mu_0 g_A^{R1}}{2\pi}\left(\dot{I}_A + \dot{I}_B + \dot{I}_C\right) = \frac{3\mu_0 g_A^{R1}}{2\pi}\dot{I}_0 \tag{5}$$

should act along its longitudinal axis.

Since

$$\dot{B}_{lon} = \dot{B}_{lon}^{R1} + \dot{B}_{lon}^{win}, \tag{6}$$

the following conditions should be true for Eq. (5) to fulfill:

$$\dot{B}_{lon}^{R1} = \frac{\mu_0 g_A^{R1}}{2\pi}\left(\dot{I}_A + 0.5\dot{I}_B\right), \tag{7}$$

$$\dot{B}_{lon}^{win} = \frac{\mu_0 g_A^{R1}}{2\pi}\left(\dot{I}_C + 0.5\dot{I}_B\right). \tag{8}$$

Here, $\dot{B}_{\text{lon}}^{\text{R1}}$ is the induction of a magnetic field which acts along the longitudinal axis of reed switch 1 and is produced by the currents $\dot{I}_{\text{A}}$ and $0.5\dot{I}_{\text{B}}$ of conductors 19 and 20; $\dot{B}_{\text{lon}}^{\text{win}}$ is the induction of a magnetic field produced by the current $\dot{I}_{\text{out}}$ in winding 5, which is generated at the exit of amplifier 9 in the presence of phase-shifting circuit 11 and control resistor 13 (they are required for controlling $\dot{I}_{\text{out}}$). Equation (7) is derived from Eq. (1) under simultaneous fulfillment of the conditions

$$\text{a) } 0.5g_A^{R1} = g_B^{R1} \text{ and b) } g_C^{\Gamma 1} = 0. \tag{9}$$

The induction $\dot{B}_{\text{lon}}^{\text{win}}$ of the magnetic field produced in winding 5 of reed switch 1 should be equal in amplitude and phase to the induction $\dot{B}_{\text{lon}}^{\text{R2}}$ of a magnetic field which acts along the longitudinal axis of reed switch 2 and its winding 6 and is produced by the currents $0.5\dot{I}_{\text{B}}$ and $\dot{I}_{\text{C}}$ of phases B and C. It is defined by the equation

$$\dot{B}_{lon}^{R2} = \frac{\mu_0 g_A^{R2}}{2\pi}\left(\dot{I}_C + 0.5\dot{I}_B\right). \tag{10}$$

Equation (10) is derived from Eq. (1) under simultaneous fulfillment of the conditions

$$\text{a) } 0.5g_C^{R2} = g_B^{R2} \text{ and b) } g_A^{R2} = 0. \tag{11}$$

To find the coordinates of reed switch 1 let us consider Eq. (9) as simultaneous equations with unknown x_1 and γ_1. Setting $g_C^{R1} = 0$ (4), we have

$$\gamma_1 = \arctan\left(\frac{h}{2d - x_1}\right). \tag{12}$$

Since $0.5g_A^{R1} = g_B^{R1}$,

$$\gamma_1 = \arctan\left(\frac{0,5h^3 + 0,5hx_1^2 - 0.5hd^2 + dhx_1}{-0.5x_1h^2 + 0.5x_1d^2 - 0.5x_1^3 + dh^2}\right). \tag{13}$$

Hence, equating the parentheses, we find

$$\text{a) } x_1 = d/2 \text{ and b) } \gamma_1 = \arctan\left(2h/(3d)\right). \tag{14}$$

Similarly, for reed switch 2, from Eq. (9) with $g_A^{R2} = 0$ (2), we find

$$\gamma_2 = \arctan\left(\frac{h}{x_2}\right), \tag{15}$$

and since $0.5g_C^{R2} = g_B^{R2}$,

$$\gamma_2 = \arctan\left(\frac{0,5h^3 + 0,5hx_2^2 - 3.5hd^2 - 3dhx_2}{3d^3 - 5.5x_2d^2 - 0.5x_2h^2 + 3x_2^2 - 0.5x_2^3}\right). \tag{16}$$

Therefore,

$$\text{a) } x_2 = 3d/2 \text{ and b) } \gamma_2 = -\arctan\left(2h/(3d)\right). \tag{17}$$

Magnetic flux $\dot{\Phi}_6$ through the area $S = \pi D_{\text{out}6}^2/4$ ($D_{\text{out}6}$ is the outer diameter of winding 6) of a cross-section of winding 6 of reed switch 2 induces EMF of mutual induction in the winding; its instantaneous value is defined by the equation [30]:

$$\begin{gathered} e_6 = -W_6\frac{d\psi}{dt} = --W_6\frac{d\left(\dot{\Phi}_6 \sin\omega t\right)}{dt} = \\ = -\omega W_6\dot{\Phi}_6\cos\omega t = -2\pi f W_6 S B_{lon}^{R2}\sin\left(\omega t + 90°\right), \end{gathered} \tag{18}$$

where f is the commercial current frequency; W_6 is the number of turns in winding 6 of reed switch 2. Its effective value can be calculated as

$$\dot{E}_6 = -\left(2\pi f W_6 S\dot{B}_{lon}^{R2}\right)e^{j90} = \left(2\pi f W_6 S\dot{B}_{lon}^{R2}\right)e^{j90} = K_1\dot{B}_{lon}^{R2}. \tag{19}$$

The EMF $\dot{E}_6$ is shifted by the angle π/2 with respect to $\dot{\Phi}_6$. This shift is compensated by phase-shifting circuit 11 later on. The EMF $\dot{E}_6$ is amplified by amplifier 9 and produces the current $\dot{I}_{out}$ in winding 5 of reed switch 1,

$$\dot{I}_{out} = \dot{E}_6 K_y / Z_{out}, \tag{20}$$

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.

The current $\dot{I}_{out}$, the phase of which can be controlled by the parameters of phase-shifting circuit 11; and the amplitude, by variation in the resistance of resistor 13 (smoothly) and by the gain factor K_y of amplifier 9 (coarsely), should produce a magnetic field at the center at the axis of winding 5 with the induction $\dot{B}_{lon}^{win}$ (8) [30], i.e.,

$$\dot{I}'_{\text{out}} = \frac{\dot{B}_{\text{lon}}^{\text{win}}\sqrt{\left(0.5l_5\right)^2 + \left(0.5D_{\text{av}5}\right)^2}}{\mu_0 W_5} = K_2\dot{B}_{\text{lon}}^{\text{win}}, \tag{21}$$

where 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, or round-section windings of standard relays can be used. In the latter case, the inner diameters of windings 5 and 6 should be a little larger that the diameters of the reed switch buses to mount the reed switches inside the windings, and the lengths l_5 and l_6 of the windings should be approximately equal to the lengths of buses of reed switches 1 and 2.

Equations (19)–(21) in the absence of control resistor 13 provide for the following equation for the gain factor:

$$K_y^{lon} = \frac{2K_2\left(Z_{win5} + Z_{cab}\right)}{W_6 f\pi^2 D_{out6}^2}. \tag{22}$$

The value of K_y^{lon} calculated by Eq. (22) is rounded up to a standard voltage gain value. Equation (22) implies that K_y of amplifier 9 depends only on the parameters of windings 5 and 6.

After selection of an amplifier by K_y, it is necessary to calculate the active resistance r_{out} of the output circuit of amplifier 9 accounting the resistance r_{13} of control resistor 13 with the use of I'_{out} (21) by the equation

$$r_{out} = E_6 K_y / I'_{out}. \tag{23}$$

Then, neglecting the resistance Z_{cab} of cables, the active resistance of control resistor can be calculated as

$$r_{13} = r_{out} - r_{win5}. \tag{24}$$

Phase-shifting circuit 11 should compensate the phase difference between I_{out} and I'_{out} calculated by Eq. (20) in the absence of phase-shifting circuit and Eq. (21), i.e.,

$$e^{j\alpha_{PAS}} = I_{out} / I'_{out}. \tag{25}$$

If $\dot{B}_{lon}^{win}$ is expressed in terms of $\dot{B}_{out}^{R2}$ with the use of Eqs. (19)–(21), then

$$\dot{B}_{lon}^{win} = \frac{K_1 K_y}{K_3 Z_{out}} \dot{B}_{lon}^{R2} = K_{lon} \dot{B}_{lon}^{R2} . \qquad (26)$$

If the calculation is correct, then K_{lon}=1 in Eq. (26). Again, the induction of a magnetic field which acts along the longitudinal axis of reed switch 1

$$\dot{B}_{lon} = \dot{B}_{lon}^{R1} + \dot{B}_{lon}^{win} = \dot{B}_{lon}^{R1} + \dot{B}_{lon}^{R2} = \frac{3\mu_0 g_A^{R1}}{2\pi} \dot{I}_0 , \qquad (27)$$

and the reed switch functions as a responding element of the zero-sequence current filter.

The action of magnetic fields produced by zero-sequence currents on reed switch 4 is ensured in a similar way. In this case, $x_3 = x_1$, $x_4 = x_2$, $\gamma_3 = \gamma_1$, and $\gamma_4 = \gamma_2$; the gain factor of amplifier 10 is equal to K_y (22). The angle of phase-shifting circuit 12 is calculated by Eq. (25) accounting that EMF in winding 7 is induced by the currents $\dot{I}_A$ and $0.5\dot{I}_B$ in the conductors of phases A and B.

The zero-sequence current filter operates as follows. There are no zero-sequence currents when an electrical installation operates in the standard mode, and a magnetic field with the induction B_{ib} (the strength H_{ib}) of imbalance acts on reed switch 1 (4). The imbalance is due to the inaccuracy of mounting reed switches 1 (3) and 2 (4) at the coordinates calculated and admissible asymmetry of the system of currents A, B, and C, which flow through the conductors. For reed switch 1 (4) not to actuate in the standard mode, its actuation strength $H_{act}^{R1} = B_{act}^{R1} / \mu_0$ should be higher than the imbalance strength, i.e.,

$$H_{act}^{R1} = k_{off} H_{ib} , \qquad (28)$$

where k_{off} is the offset coefficient, k_{off} =1,2.

In the event of a short circuit to ground, zero-sequence currents flow through the conductors of the electrical installation. The actuation strength of reed switches 1 and 4 is lower that the strength of the affecting magnetic field produced by the zero-sequence current and the reed switches operate: they close contacts and signal to actuator 16 via logic unit 15.

The protection operates as follows. Under the load and self-starting of electric motors, reed switches 2 and 3 do not close the contacts, since their actuation strength H_{act} is offset from the maximal strength produced by the load and self-starting currents flowing in phases A, B, and C of the electrical installation. Under phase-to-phase short circuits, the strength of the magnetic fields which acts on reed switches 2 or 3 increases and becomes higher than H_{act}. Therefore, they actuate and signal to logic unit 15 of the protection (Fig. 1). As a result, the electrical installation breaker opens.

Let us note that the sensitivity of the measurement unit may be insufficient in some cases, because reed switches 2 and 3 are mounted at an angle to the busbars of an electrical installation, since the measurement unit functions as a zero-sequence current filter. In this case, two additional reed switches should be mounted at different angles α at the points which allow one to decrease the protection operation current.

The functional diagnostics of the measurement unit suggested is performed as follows. In all operation modes of the filter, EMFs, which are applied to windings 5 and 8 with the absolute values E_5 and E_8 ($E_5 \neq E_8$), are supplied to the inputs of comparison circuit 17. For comparison circuit 17 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:

$$E_{op} = \left| k_{off} \left(E_5 - E_8 \right) \right| . \qquad (29)$$

The difference $\left(E_5 - E_8 \right)$ exceeds E_{op} in the case of a damage in cables of elements connected to windings 5 and 8, comparison circuit 17 is triggered and signals to signaling unit 18.

III. EXAMPLES OF STRUCTURES FOR MOUNTING REED SWITCHES NEAR BUSBARS OF A 110-KV ELECTRICAL INSTALLATION

Such a structure (Copyright certificate SU no.1573456) is exemplified in Fig. 2, where reed switch 1 is mounted using clamps 2 on insulating bar 3. This bar is connected by means of axel 4 to plate 5 with scale 6. Plate 5 is attached with screws 7 to the front side of movable rod 8 with scale 9. This scale shows the distance *h*. Rod 8 moves in the slots of rotary unit 10 with sight 11 and is adjusted by locking screw 12. Cables 13 are connected to terminals 2, which serve to connect the contacts of reed switch 1 with the logic unit of the protection. The tilt of reed switch 1 is varied by turning bar 3. The required angle is measured on scale 6. This structure is mounted under the busbars on the base the supporting insulators holding them are attached to.

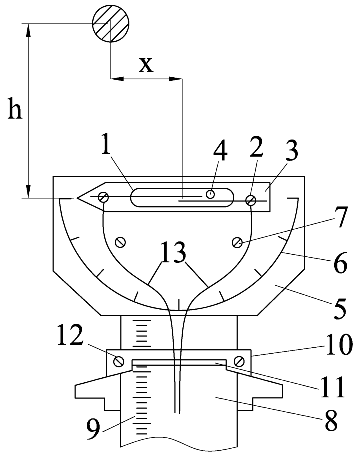

Fig. 2. Structure for mounting reed switches under busbars of an electrical installation

IV. CONCLUSIONS

The measurement unit suggested can serve a basis for a protection against simultaneously short circuits to the ground and phase-to-phase, without the use of metal-intensive current transformers. Simple design, functional diagnostics, and duplication ensure higher reliability than of well-known reed switch protections. The technique presented makes it possible to determine the coordinates of mounting the reed switches near the busbars of an electrical installation for them to function as a zero-sequence current filter and to calculate filter parameters. The research is to be continued for different arrangement of phases.

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