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Interference Free Measuring Devices for Current Protection on Reed Switches without Current Transformers

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***Abstract*—It is noted that in relay protection, it is possible to ensure resource saving by building it on the basis of much less metal-intensive current sensors compared to traditional current transformers. It is indicated that a reed switch can be used for this purpose. On its basis, a simple scheme of the measuring device for current protection is proposed, which does not work falsely with short-term interference acting on the sensing reed switch. The method of calculating the parameters of the circuit elements of the measuring device is presented. Two variants of its improvement are proposed by the additional introduction of one or two reed switches to detect interference in the control circuits of the sensing reed switch, when magnetization is used to increase its sensitivity. The operation of measuring devices in various modes is described in detail.**

Keywords—current protection, reed switch, magnetization, interference, nonoperation

I. INTRODUCTION

In recent decades, much attention has been paid to resource conservation. In various energy sectors, this is achieved by the development of renewable energy sources, the use of energy-saving technologies, etc. In relay protection, it is possible to ensure resource saving by replacing current transformers used to obtain information about currents in the phases of electrical installations with various protections, for example [1, 2, 3], with sensors that require hundreds or even thousands of times less copper and steel to manufacture. Work in this direction has been carried out for decades and it was proposed to use reed switches [4–10], Rogovsky coils [11], Hall sensors [12], magnetoresistors [13], etc. to build relay protection devices. We preferred the reed switch, which, unlike others, can also simultaneously perform the functions of a current relay and an analog-to-digital Converter [14]. Using reed switches as a source of information about the current in the bus of an electrical installation, the principles of construction and schemes of various protections with designs for fixing reed switches have already been developed [15–23]. There are also proposals for the construction of current protections [24–27], and work is underway on the construction of such protections [28, 29] with more complex algorithms of action. At the same time, the issues of ensuring noise immunity of protections on reed switches were left aside and not considered. In this paper, an attempt is made to partially fill this gap.

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II. MEASURING DEVICE RESISTANT TO SHORT-TERM INTERFERENCE

The measuring device (Fig.1) contains (RU Patent No. 2629958) a sensing reed switch 1 with contacts 2, 3 and 4, a reed switch 5 with contacts 6, 7 and 8 and with a control winding 10, a signal lamp 9, resistors 11, 12 and 13, an intermediate relay 14 with a contact 15 and a control winding 16, capacitors 17 and 18. The reed switch 1 is set close to a bus of the electrical installation at a safe distance from it, and the switch 5 along with the rest of devices in the relay compartment of the complete switchgear (CS) cell.

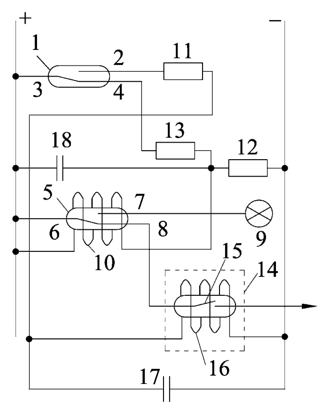

Fig. 1. Circuit of the measuring body that does not work in case of external interference

The device works as follows. In the load mode, a magnetic field created by the current in the bus of the electrical installation acts on the reed switch 1. However, it does not work, since the value of the induction of this field does not exceed the induction required for the operation of the reed switch 1. Therefore, its contacts remain stationary, and the measuring device does not work.

In case of short circuits in the electrical installation, the currents flowing through its bus create a magnetic flux with an induction sufficient to trigger the reed switch 1, and it is triggered, contacts 2 and 3 are closed, and 3 and 4 are opened. The first 17 and second 18 capacitors start charging. After charging the capacitor 17, the voltage on the winding of the intermediate relay 14 (reed relay) is sufficient for its operation,

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and it closes its contacts 15, through which a signal is sent to the circuit of disconnecting the switch of the electrical installation.

After disconnecting the electrical installation, if the contacts of the reed switch 1 are not " stuck”, they return to their original state. Contacts 3 and 4 are closed, shunting the capacitor 18, which begins to discharge to the control winding 10 of the reed switch 5 and the resistor 13. In this case, the reed switch 5 does not open contacts 6 and 8, since the voltage on the plates of the capacitor 18 is not enough for its operation. If the contacts 2 and 3 of the reed switch 1 is "stuck", then the capacitor 18 to be charged to a voltage actuation of the reed switch 5, which operating, opens contacts 6 and 8 in the power supply circuit relay 14 and closes the contacts 6 and 7, signaling of the presence of "sticky" contacts of the reed switch 1. Measuring device rendered inoperative to prevent false triggering of the device overcurrent protection when the automatic reclosing and automatic load transfer.

To ensure the nonoperation of the proposed relay in case of short-term interference acting on the reed switch 1, the contacts 15 of the relay 14 are closed only at the third operation of the reed switch 1. This is provided by specially selected resistances of resistors 11, 12, 13 and capacitances of capacitors 17 and 18. Their values should be such that the voltage on the windings 10, 16 after a given time is exactly the voltage of the operation of the U_{op} and the return of the U_{res} of the reed switch 5 and the relay 14.

To calculate the voltage at each moment of time after the closure or opening of the reed switch contacts, which occurs twice per period, we use the well-known operator method [31]. Substitution circuits and equations are compiled according to the first and second Kirchhoff laws for the modes when the contacts 2, 3 of the reed switch 1 are closed and open. As an example, consider a system of equations when contacts 2 and 3 of the reed switch 1 are closed.

$$\begin{cases} i_1(p) = i_2(p) + i_3(p), \\ i_1(p)\cdot R_{11} + \dfrac{i_3(p)}{pC_{17}} = \dfrac{U_r}{p} - \dfrac{U_{C17}(0)}{p}, \\ i_2(p)\cdot\left(pL_{16}+R_{16}\right) - \dfrac{i_3(p)}{pC_{17}} = L_{16}\cdot i_2(0) + \dfrac{U_{C17}(0)}{p}, \\ i_4(p) = i_5(p) + i_6(p), \\ i_4(p)\cdot R_{12} + \dfrac{i_5(p)}{pC_{18}} = \dfrac{U_r}{p} - \dfrac{U_{C18}(0)}{p}, \\ i_4(p)\cdot R_{12} + i_6(p)\cdot\left(pL_{10}+R_{10}\right) = L_{10}\cdot i_6(0) + \dfrac{U_r}{p}. \end{cases} \quad (1)$$

where $U_{C17}(0)$ and $U_{C18}(0)$ are the voltages at capacitors 17 and 18; $i_2(0)$ and $i_6(0)$ are the currents in control windings 10 and 16 before the closure of contacts 2 and 3; U_r – is the rated voltage of the direct current source; $i_1(p)$, $i_2(p)$, $i_3(p)$, $i_4(p)$, $i_5(p)$, and $i_6(p)$ are the currents in the branches of the equivalent circuit after the closure of contacts 2 and 3; R_{11} and R_{12} are the resistances of resistors 12 and 13; R_{10} and R_{16} are the active resistances and L_{10} and L_{16} are the inductances of control windings 10 and 16; C_{17} and C_{18} are the capacities of capacitors 17 and 18.

We solve the system (1) for the first closure of contacts 2, 3 of the reed switch 1 in the general case. It can be seen from (1) that the first three equations of the system are not related to the second three. Therefore, it can be divided into two systems of equations. Consider the first one. We determine the initial conditions, i.e. voltage $U_{C17}(0)$ and current $i_2(0)$. Since before the closure of contacts 2, 3, the mode is steady, then $U_{C17}(0)=0$ and $i_2(0)=0$. Substituting these values in (1) and expressing $i_1(p)$ and $i_2(p)$ through $i_3(p)$, we get:

$$\begin{cases} i_1(p) = i_2(p) + i_3(p), \\ i_1(p) = \dfrac{U_н}{pR_{11}} - \dfrac{i_3(p)}{pC_{17}R_{11}}, \\ i_2(p) = i_3(p) / pC_{17}\cdot\left(pL_{16}+R_{16}\right). \end{cases} \quad (2)$$

Substituting $i_1(p)$ and $i_2(p)$ in the first equation, we find $i_3(p)$:

$$i_3(p) = \frac{U_н \cdot pC_{17}\cdot\left(pL_{16}+R_{16}\right)}{p\cdot\left(p^2C_{17}R_{11}R_{16} + p\cdot\left(C_{17}R_{11}R_{16}+L_{16}\right) + R_{11} + R_{16}\right)}. \quad (3)$$

Then the images of the voltage on the capacitor 17 and the current in the winding 16 have the form

$$U_C(p) = \frac{i_3(p)}{pC_{17}} = \frac{U_н\cdot\left(pL_{16}+R_{16}\right)}{p\cdot\begin{pmatrix} p^2C_{17}R_{11}R_{16} + \\ +p\cdot\left(C_{17}R_{11}R_{16}+L_{16}\right) + \\ +R_{11}+R_{16}\end{pmatrix}} = \frac{F_1(p)}{F_2(p)}; \quad (4)$$

$$i_2(p) = \frac{U_н}{p\cdot\begin{pmatrix} p^2C_{17}R_{11}R_{16} + \\ +p\cdot\left(C_{17}R_{11}R_{16}+L_{16}\right) + \\ +R_{11}+R_{16}\end{pmatrix}} = \frac{F_{11}(p)}{F_2(p)}. \quad (5)$$

To find the voltage on the capacitor 17 and the current in the winding 10:

1. Calculate the roots of the denominator at which it is zero:

$$p_1 = 0; \quad (6)$$

$$p_2 = -\left(C_{17}R_{11}R_{16}+L_{16}\right) + \sqrt{\begin{aligned}&\left(C_{17}R_{11}R_{16}+L_{16}\right)^2 - \\ &-4\cdot C_{17}R_{11}R_{16}\cdot\left(R_{11}+R_{16}\right)\end{aligned}}; \quad (7)$$

$$p_3 = -\left(C_{17}R_{11}R_{16} + L_{16}\right) - \sqrt{\left(C_{17}R_{11}R_{16} + L_{16}\right)^2 - 4\cdot C_{17}R_{11}R_{16}\cdot\left(R_{11}+R_{16}\right)}. \quad (8)$$

2. Find the first derivative of the expression in the denominator

$$F_2'(p) = 3p^2C_{17}R_{11}R_{16} + 2p\cdot\left(C_{17}R_{11}R_{16} + L_{16}\right) + R_{11} + R_{16}. \quad (9)$$

3. Calculate the values of the functions $F_1(p)$, $F_{11}(p)$ and $F_2'(p)$ for $p=p_1$, $p=p_2$ and $p=p_3$.

4. Write down the voltage on the capacitor 17 and the current in the winding 16 as:

$$U_{C17} = \frac{F_1(p_1)}{F_2'(p_1)}\cdot e^{p_1 t_{close}} + \frac{F_1(p_2)}{F_2'(p_2)}\cdot e^{p_2 t_{close}} + \frac{F_1(p_3)}{F_2'(p_3)}\cdot e^{p_3 t_{close}}; \quad (10)$$

$$i_2 = \frac{F_{11}(p_1)}{F_2'(p_1)}\cdot e^{p_1 t_{close}} + \frac{F_{11}(p_2)}{F_2'(p_2)}\cdot e^{p_2 t_{close}} + \frac{F_{11}(p_3)}{F_2'(p_3)}\cdot e^{p_3 t_{close}}, \quad (11)$$

where t_{close} is closed state time of contacts 2 and 3

Consider the second system of equations. We determine the initial conditions, assuming that there was a steady state.

$$U_{C18}(0) = \frac{U_r\cdot R_{13}\cdot R_{10}}{R_{12}\cdot R_{10} + R_{13}\cdot R_{10} + R_{13}\cdot R_{12}}; \quad (12)$$

$$i_6(0) = \frac{U_r\cdot R_{13}}{R_{12}\cdot R_{10} + R_{13}\cdot R_{10} + R_{13}\cdot R_{12}}. \quad (13)$$

We substitute them into the second three equations of the system (1).

$$\begin{cases} i_4(p) = i_5(p) + i_6(p), \\ i_4(p)\cdot R_{12} + i_6(p)\cdot\left(pL_{10} + R_{10}\right) = L_{10}\cdot i_6(0) + U_r/p, \\ i_4(p)\cdot R_{12} + i_5(p)/pC_{18} = U_r/p - U_{C18}(0)/p. \end{cases} \quad (14)$$

Find the current $i_6(p)$ by Kramer's method.

$$\Delta = \begin{vmatrix} 1 & -1 & -1 \\ R_{12} & 0 & pL_{10}+R_{10} \\ R_{12} & 1/pC_{18} & 0 \end{vmatrix} = \frac{p^2C_{18}R_{12}L_{10} + p\left(C_{18}R_{12}R_{10} + L_{10}\right) + R_{10} + R_{12}}{pC_{18}}. \quad (15)$$

$$\Delta_{i_6(p)} = \begin{vmatrix} 1 & -1 & 0 \\ R_{12} & 0 & L_{10}i_6(0) + \dfrac{U_r}{p} \\ R_{12} & \dfrac{1}{pC_{18}} & \dfrac{U_r}{p} - \dfrac{U_{C18}(0)}{p} \end{vmatrix} = \frac{U_r + pC_{18}R_{12}U_{C18}(0) + pL_{10}i_6(0) + p^2C_{18}R_{12}L_{10}i_6(0)}{p^2C_{18}} \quad (16)$$

$$i_6(p) = \frac{\Delta_{i_6(p)}}{\Delta} = \frac{\left(U_r + p\left(C_{18}R_{12}U_{C18}(0) + L_{10}i_6(0)\right) + p^2C_{18}R_{12}L_{10}i_6(0)\right)}{p\left(p^2C_{18}R_{12}L_{10} + p\left(C_{18}R_{12}R_{10} + L_{10}\right) + R_{10} + R_{12}\right)}. \quad (17)$$

Then the voltage on the capacitor is 18

$$U_{C18} = i_6(p)\left(pL_{10} + R_{10}\right) = \frac{\left(U_r + p\left(C_{18}R_{12}U_{C18}(0) + L_{10}i_6(0)\right) + p^2C_{18}R_{12}L_{10}i_6(0)\right)\left(pL_{10} + R_{10}\right)}{p\left(p^2C_{18}R_{12}L_{10} + p\left(C_{18}R_{12}R_{10} + L_{10}\right) + R_{10} + R_{12}\right)}. \quad (18)$$

Next, the voltage U_{C18} and current i_6 are calculated as was done for U_{C17} and i_2. Substituting in these expressions the duration t_{close} of the closed state of the contacts 2, 3 of the reed switch 1, we find the voltages on the capacitors 17, 18 and the currents in the windings 10, 16 through t_{close}. The time t_{close} is determined experimentally in the laboratory. The calculated values of the voltages on the capacitors 17, 18 and currents in the windings 10, 16 are the initial conditions for calculating the circuit after opening the contacts 2, 3 of the reed switch 1. Similarly, a system of equations is compiled and solved when opening the contacts 3 and 4 of the reed switch 1.

Given the resistances of the resistors and capacitances of the capacitors, we find the voltages on the capacitors 17 and 18 after a given time. If it is equal to the operating voltages of the reed switch 5 and the relay 14, then the calculation is stopped. Otherwise, other resistances and capacitances are selected and the calculation is repeated. With this as a starting point can be taken such of the resistors 11 and 12, at which in the steady state voltage on the windings 10 and 16 equal to the voltage of triggering of the reed switch 5 and the relay 14. For the resistor 13 - at which the voltage across the coil 10 is equal to the return voltage of the reed switch 5. Capacitors 17 and 18 can be approximately determined by the known formula [31], considering that the charge time of first is 0.02 s (the time between the first and third actuations of the reed switch 1) and of the second should be slightly longer response time of protection and circuit breaker of electrical installation.

III. Circuit of Switching of the Sensing Reed Switch to Detect Interference in Its Magnetization Circuit

In those cases, when to ensure the required sensitivity of the measuring device of the protection the reed switch 1 is magnetizing, then for nonoperation from interference in the magnetizing circuits can be used to connect a reed 1 according to the scheme (RU Patent No. 2707277), shown in Fig. 2 (in the circuit in Fig. 1 introduces an additional reed switch). In series with the closing contacts 3 of reed switch 1 (Fig. 2) normally closed contacts 4 of reed switch 2 are connected (Fig. 1 these contacts will be between the contact 2 of the switch 1 and the resistor 11). On the reed switch 1 is wound m turns of the coil 5, with which the magnetization is carried out, and magnetic reed switch 2 – (n-m) of turns of the coil 5 control (n is the total number of turns of the coil 5). The terminals of the control coil 5 are connected to the power supply 6.

This relay on reed switches works as follows. The reed switch 1 is fixed at a point on the plane of the cross section of the bus 7 so that its longitudinal axis 8 was perpendicular to line passing through the longitudinal axis 7 of the tire and that point, and the reed switch 2 is fixed along the line 8. In the nominal mode of operation of the installation and in the absence of interference in the connecting wires the reed switches 1, 2 do not work because the magnetic fields created by the currents in the electrical bus 7 and the coil 5, is not sufficient for their operation

If a short circuit in the protected electrical installation, the current in the bus 7 increases and becomes sufficient to trigger the reed switch 1, which closes the contacts 3. The reed switch 2 does not work, as it is located perpendicular to the induction vector of the magnetic field created by current in the busbar 7, and the current in the coil 5 is insufficient. Contacts 4 of the reed switch 2 remain closed. The relay is triggered.

When interference occurs in the connecting wires, the current in the coil 5 increases and becomes sufficient to trigger the reed switches 1, 2. However, the relay does not work, since when the contacts 3 are closed, the contacts 4 open, breaking the circuit.

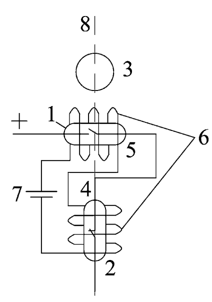

Fig. 2. Connection circuit of reed switches for detecting interference in the control windings

IV. Circuit of Switching on the Sensing Reed Switch to Detect Interference and Damage in Its Magnetization Circuit

To simultaneously ensure the nonoperation of the measuring device of protection in the event of interference in the control winding circuits of reed switch 1 (Fig. 2) and identify damage in these circuits, you can use the connection scheme of reed switches (KZ Patent No. 34768), shown in Fig. 3 (in the circuit in Fig. 2, another reed switch with a control winding is additionally introduced). In this case, all three reed switches have their own control windings and there is no need to break the circuit between pin 2 and resistor 11 (Fig. 1), as in the previous version.

Reed switches 1, 7, 10 are installed near the busbar of the electrical installation, and reed switches 7 and 10 in such a way that they are not affected by the induction of magnetic fields created by currents in it. In the nominal mode of operation of the electrical installation and in the absence of interference in the connecting wires in the conductor 3 and windings 2, 8, 9 draws a currents, which create magnetic fields acting on the reed switches 1, 7, 10. Thus on the reed switch 1 is valid for the summarized magnetic field from the currents in the conductor 3 and the control winding 2, and the reed switches 7, 10 only the magnetic field from the currents in control windings 8, 9, respectively. Reed switches 1, 7 do not work, since the values of the inductions of the created magnetic fields are insufficient, and the reed switch 10 is in the triggered state. Therefore, the contacts of reed switch 7 are closed, and reed switches 1 and 10 are open. The measuring device does not work.

When an interference occurs, the current in the circuit of the control windings 2, 8 increases, and the reed switches 1 and 7 are triggered. In this case, the contacts of the reed switch 7 open faster than the contacts of the reed switch 1 close. Therefore, after opening the contacts of the reed switch 7, the current in the control winding 2 disappears, and the reed switch 1 does not have time to close the contacts. The measuring organ does not operate unnecessarily.

When a short circuit occurs in an electrical installation powered by a conductor 3, the current in it increases. As a result, the reed switch 1, under the action of the total induction of the magnetic field created by the currents in the conductor 3 and the control winding 2, closes the contacts and sends a signal to the input of the logical part 4. Logic part 4 is triggered and sends a signal to the circuit of disconnecting the switch of the electrical installation. The measuring device is triggered. On the reed switch 7 is only affected by the induction of the magnetic field from the current in the control winding 8 is the same as in the nominal operating mode of the electrical installation. The reed switch 7 does not work.

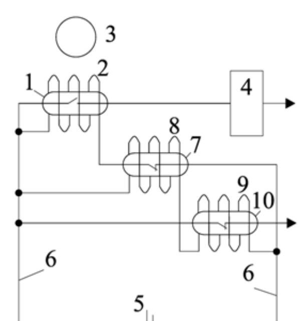

Fig. 3. Connection circuit of reed switches for detecting interference and damage in the circuits of their control windings

When the connecting wires 6 are broken, the current from the DC operating current source 5 to the control windings 2, 8, 9 does not flow. Therefore, the reed switch 10 returns to its original state and closes the contacts, signaling the breakage of the connecting wires 6.

If a short circuit occurs between the wires 6, which lead direct current from the source 5 to the control windings 2, 8, 9 of the reed switches 1, 7, 10, then the control winding 9 of a switch 10 is deenergizated. The reed switch 10 will close the contacts and signal a fault.

V. Conclusions

The proposed measuring device for current protection allows you to save resources by using reed switches instead of metal-intensive and expensive current transformers. It does not trigger falsely in case of external short-term interference and is taken out of operation after switching off the circuit breaker of the electrical installation, if the contacts of the sensing reed switch are stuck. The addition on circuit of the measuring device another reed switch with a control winding allows you to block the work of sensing reed switch, when interference in the its control circuits, and two is to identify and damage these circuits.

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