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Measuring Bodies for Distance Protection that Does Not Use Current Transformers

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Abstract. It is noted that the replacement of current transformers with some other, less metal-intensive and bulky, current sensors is an urgent task in the electric power industry. The advantages and disadvantages of some of these sensors are briefly considered. The advantages of reed switches over other current sensors are given and their operating principle is described. It is stated that on the basis of obtaining information about the current in the phase of an electrical installation from reed switches, a number of short-circuit protections have already been developed. The full resistance measuring body is considered in detail and its operation in the short-circuit and load mode is described. A directional resistance relay is proposed with a simple circuit for test diagnostics of a fault, consisting of a button, a control winding worn on the starting reed switch, two intermediate relays and a current control block in the specified winding. The method of selecting the parameters of actuation of the measuring body is presented and its operation in various modes is described.

INTRODUCTION

Distance protections has been widely used for protection of transmission lines. At the same time, like the vast majority of relay protection devices, for example [1-6], they receive information about the current in the phase of the electrical installation from current transformers. These current converters, as is known [7-10], have a number of disadvantages: metal consumption, large dimensions and weight, errors in transient modes, high voltage at the terminals of the secondary winding when the connecting wires break, etc. Because of these shortcomings, proposals were repeatedly made [11-13] to replace current transformers with some other sensors, and the task itself was called one of the unsolved problems in the world energy industry. As such sensors, it was proposed to use an inductance coil [14], magnetic current transformers [15], a Rogovsky coil [7, 12, 16], and a Hall sensor [9, 17, 18, 19], reed switches [20-23], magnetotransistors [24], etc. Each of them has both advantages and disadvantages. For example, an inductance coil has a high sensitivity, the voltage at its terminals does not exceed the safe one. However, due to the small size of the output signal, amplifiers are necessary for its transmission, and the transmission itself is carried out not via control circuits, but via measuring ones. Hall sensors can produce a signal in both analog and discrete form, but they need stable power supply, are sensitive to temperature changes, and have a large range of parameters within a single batch. Therefore, it will be possible to judge which of them (or others) will be more suitable for the needs of relay protection only after completion of developments and operational experience.

We selected reed switches as current sensors, since when using them, the signal is transmitted via control circuits, they also simultaneously perform the functions of an analog-to-digital converter and relay, and also have other advantages [25] over the other magnetically sensitive elements listed above. The reed switch is a case (length 0.5-5 cm, diameter 0.5-5.4 mm) made of glass, inside which there are two or more contact plates. They touch, commuting the electric circuit, if the magnetic field induction reaches the induction of the reed switch actuation. Based on the use of information about the current in the phase of an electrical installation from a reed switch, the

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principles of construction and schemes of some relay protection devices have already been developed [26-40]. In this paper, we consider measuring bodies on reed switches for distance protection.

IMPEDANCE MEASURING BODY

The device [41] contains (Fig. 1) a reed switch 1 with windings 2 and 3 and contact 4, rectifiers 5 and 6, an amplifier 7, a voltage selection block 8, a capacitor 9, and a logic block 10.

The device works as follows [41]. When the current flows through the phase 11 of the protected line, a magnetic induction is created, which induces an electromotive force in the winding 2 of the reed switch 1. Under the action of an electromotive force, a current begins to flow in the winding 2, which passes through the amplifier 7, the capacitor 9, the rectifier 5 and is fed to the winding 3. On the other hand, the winding 3 receives current from the voltage selection block through the rectifier 6. In non-short-circuit (SC) modes, these two currents are equal, and an unbalanced current flows in the winding 3, which does not lead to the actuation of the reed switch 1. In the SC mode, the current received from the voltage selection block decreases, since the voltage that creates this current decreases, and the current of the winding 2 increases. This increases the current in the winding 3. If the electromotive force created by it is sufficient to actuate the reed switch 1, then its contact 4 is closed and a signal is sent to the logic block 10 to disconnect the line.

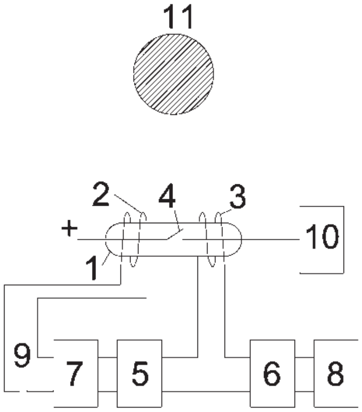

FIGURE 1. Impedance relay

Two voltages are applied to the circuit for comparing the protection of lines from SCs with the voltage selection device (the comparison is carried out in the winding 3):

$$\text{a) } U_1 = K_1 U_r ; \qquad \text{b) } U_2 = K_4 I_r , \tag{1}$$

Where K_1 and K_4 are coefficients selected for reasons of non-actuation of protection in self-start mode; U_r is output voltage of the block 8, *V*; I_r is winding current 2, *A*.

The condition for starting the protection actuation is as follows: $K_4 I_r = K_1 U_r$.

Dividing both parts of the equation by $K_1 I_r$, we find the resistance Z_r of the line, at which the protection will begin to act:

$$Z_r = Z_{act} = \frac{|U_r|}{|I_r|} = \frac{K_4}{K_1} = |Z| = const , \tag{2}$$

Where Z_{act} is relay actuation resistance, *ohm*.

This expression shows that the proposed device works as a distance protection at a resistance of $Z_r = Z_{act}$. The value of Z_{act} is determined by the ratio K_4 / K_1, which can be considered as the absolute value of the zone resistance. Therefore, the protection works for any Z_r whose modulus is equal to $|Z|$, regardless of the angle and sign, and has a response characteristic in the form of a circle with the center at the origin and a radius equal to $|Z| = K_4/K_1$.

DIRECTIONAL RESISTANCE MEASURING BODY

In cases where a directional measuring body is required, and even with increased reliability, the relay shown below can be used. At the same time, to ensure high reliability of its operation, a simple test diagnostics is implemented.

The device (Fig. 2) contains a reed switch 1 with windings 23 and 32 and contact 16, a reed switch 2 with windings 24 and 33 and contact 17, a reed switch 3 with windings 26 and 34 and contact 18, a reed switch 4 with windings 27 and 35 and contact 19, a reed switch 5 with winding 25 and contact 29, a reed switch 6 with winding 45 and contact 21, rectifiers 7 and 8, MEMORY elements 9 and 10, a phase comparison scheme 15 with information 11-14 and starting 22 inputs, a power source 20, measuring voltage transformer 28, forming circuits 30 and 31, logic block 36, intermediate relay 38 with normally closed contacts 37 and 42, intermediate relay 39 with normally open contact 44, button 40, resistor 41, current regulator 43 with a isolating transformer at the input.

The device works as follows. The phases of two specially formed quantities are compared [42]:

$$\dot{A} = \dot{k}_1 \dot{U} + k_2 \dot{I}; \tag{3}$$

$$\dot{C} = \dot{k}_3 \dot{U}, \tag{4}$$

Where $\dot{k}_1$, k_2, $\dot{k}_3$ are constant conversion coefficients that form a given characteristic of the relay (k_2 is a real number); $\dot{U}$ is voltage at the relay installation location, *V*; $\dot{I}$ is current in the controlled phase of the electrical installation, *A*.

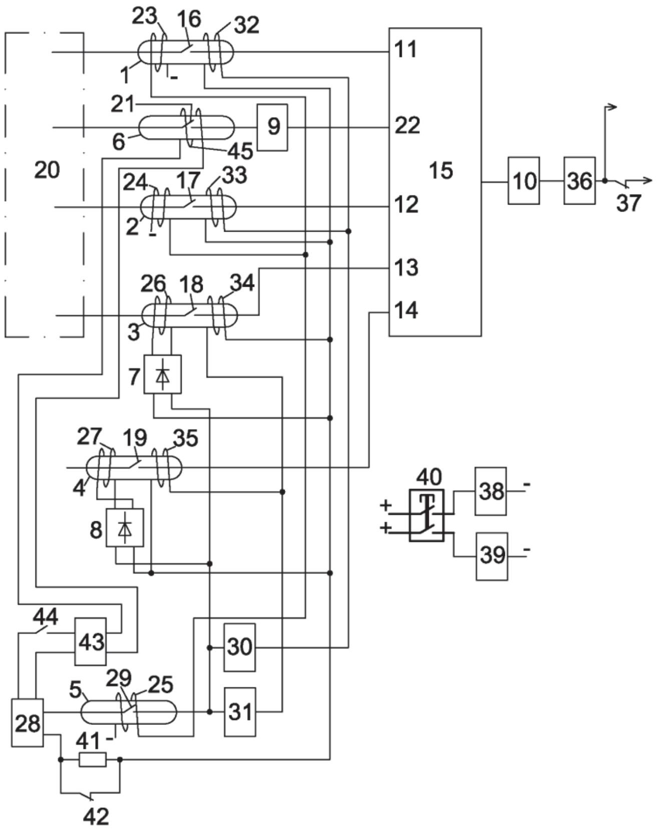

FIGURE 2. Diagram of the distance protection measuring body with test diagnostics

The value of $\dot{A}$ is formed using reed switches 1 and 2. Output signals (no voltage during the open state of contacts 16 and 17) of reed switches 1 and 2, carrying information about the phase of positive and negative half-waves ($+\dot{A}$ and $-\dot{A}$) are fed to inputs 11 and 12 of the phase comparison circuit 15. Similarly, signals are generated (no voltage during the open state of contacts 18 and 19) $+\dot{C}$ on the reed switch 3 and $-\dot{C}$ on the reed switch 4 and are fed to inputs 13 and 14, respectively. The comparison is made in each half-wave of change $\dot{A}$. Half-wave fixation (polarization) is carried out by applying direct current to the windings 23, 24, 26 and 27. Direct current is supplied using reed switches 5 and 6 (relay start) only when the current in the protected electrical installation increases to the value $1.3I_{op.max}$, $I_{op.max}$ – maximum operating current. This is done in order not to keep the reed switches 1-4 all the time in the actuated state. In the forming circuits 30 and 31, the voltage supplied from the voltage transformer 28 is rotated by a given angle and multiplied by a certain coefficient.

Reed switches 1 and 2 are installed in the magnetic field of the current of one of the phases of the electrical installation. In the windings 32 (34) and 33 (35) from the transformer 28 through the forming circuit 30 (31), the voltage $\dot{k}_1\dot{U}$ ($\dot{k}_3\dot{U}$) is supplied, the magnetic flux B_1^U (B_2^U) from the current in these windings, adding up with the magnetic flux B^I from the current of the phase of the electrical installation, forms $\dot{A}$ ($\dot{C}$).

Comparison of the generated values $\dot{A}$ and $\dot{C}$ is carried out in the phase comparison scheme 15 given in [42]. When a SC occurs in the protected area, a signal appears at the output of the scheme 15, which is stored by the MEMORY element 10 and transmitted to the logical block 36 of the protection, which sends a signal to turn off the switch of the electrical installation.

The total magnetic field induction B_Σ (MF) acting on reed switches 1 and 2 is expressed by the formula:

$$A = B_{\Sigma} = B^{I} + B_{1}^{U} = k'_{SC} B_{op.max}^{I} + k''_{SC} B_{op.min}^{U}\,, \tag{5}$$

$$k'_{SC} = \frac{I_{SC}}{I_{op.max}}\,; \tag{6}$$

$$k''_{SC} = \frac{U_{SC}}{U_{op.min}} = \frac{I_{SC} Z_{SC}}{U_{op.min}}\,; \tag{7}$$

$$I_{SC} = \frac{E_{EQ}}{Z_{EQ} + Z_{SC}}\,, \tag{8}$$

Where $B_{op.max}^{I}$ and $B_{op.min}^{U}$,*T*, are MFs inductions along the reed switch plates from the amplitude values of the current $I_{op.max}$ of the electrical installation phase and the current in the windings 32 and 33 at the minimum operating voltage $U_{op.min}$ at the relay installation site, respectively; I_{SC}, U_{SC} and Z_{SC} are current, voltage and SC resistance at the protection installation site to which the relay must respond; E_{EQ} is equivalent EMF of generators generating current I_{SC}, *V*; Z_{EQ} is resistance between EMF E_{EQ} and the protection installation site, *ohm*.

Contacts 16 and 17 of reed switches 1 and 2 are opened (closed after being actuated by direct current in windings 23 and 24) only in one half-wave B_{Σ} when the condition is met:

$$B_{\Sigma} > B_{mag1} - B_{ret}\,, \tag{9}$$

Where B_{mag1} is MF induction of magnetization from direct current in windings 23 and 24, *T*; B_{ret} is MF induction, in which contacts 16, 17 and 21 of reed switches 1, 2 and 6 return to their original position, *T*.

Then the magnitude of the MF induction of the magnetization

$$B_{mag1} \le \frac{B_{\Sigma min} + B_{ret}}{k_{det}^{I}}\,, \tag{10}$$

Where $B_{\Sigma min}$ is the minimum possible modulo value B_{Σ} , *T*; k_{det}^{I} is the detuning coefficient, $k_{det}^{I} = 1{,}2 - 1{,}3$.

To find $B_{\Sigma min}$, we transform (5) taking into account (8) and the conversion coefficients

$$B_{\Sigma min} = \frac{I_{SC}}{I_{op.max}} k_2 \sqrt{2} I_{op.max} + \frac{I_{SC} Z_{SC}}{U_{op.min}} k_1 \sqrt{2} U_{op.min} = \sqrt{2} k_2 I_{SC} + \sqrt{2} k_1 I_{SC} Z_{SC} = \sqrt{2} E_{EQ} \frac{k_2 + k_1 Z_{EQ}}{Z_{EQ} + Z_{SC}}\,. \tag{11}$$

When differentiating (11) by Z_{SC} , we get

$$\frac{dB_{\Sigma}}{dZ_{SC}} = \sqrt{2} E_{EQ} \frac{k_1 Z_{EQ} - k_2}{\left(Z_{EQ} + Z_{SC}\right)^2}\,, \tag{12}$$

Where from

$$\frac{dB_{\Sigma}}{dZ_{SC}} = 0 \text{ at } Z_{SC} = \infty\,. \tag{13}$$

So B_Σ is equal to $B_{\Sigma min}$ at one end of the interval

$$Z_{SC} = 0 + Z_{SET} , \tag{14}$$

Where Z_{SET} is resistance of the resistance relay setpoint, *ohm*.

The increase or decrease of B_Σ depends on the sign of the expression ($k_1 Z_{EQ} - k_2$).We will choose the coefficients k_1 and k_2 so that the inequality holds

$$k_1 Z_{EQ} - k_2 > 0 . \tag{15}$$

Then

$$B_\Sigma = B_{\Sigma min} = \sqrt{2} E_{EQ} \frac{k_2 + k_1 Z_{EQ}}{Z_{EQ} + Z_{SET}} = \sqrt{2} I_{SC,SET} \left(k_2 + k_1 Z_{SET} \right), \tag{16}$$

Where $I_{SC,SET}$ is current in case of damage at the end of the protected zone (that is, at a resistance of Z_{SET}), *A*.

To ensure the polarization of reed switches 1 and 2, the condition must be met

$$B_{mag1} > B_{act} . \tag{17}$$

Or

$$B_{mag1} = k_{det}^{II} B_{act} , \tag{18}$$

Where B_{act} is MF induction, *T*, at which contacts 16, 17 and 18 of reed switches 1, 2 and 6 are closed; $B_{mag1.min}$ – the minimum value of B_{mag1} , *T*; k_{det}^{II} – the detuning coefficient, $k_{det}^{II} = 1{,}2 - 1{,}3$.

The magnetic flux B_{mag1} and the current I_{mag1} in the windings are related by the ratio

$$I_{mag1} = \frac{l}{w} B_{mag1} , \tag{19}$$

Where w is number of turns of windings 23 and 24; l is length of windings 23 and 24, *m*.

So that reed switches 1 and 2 are eliminated in the corresponding half-wave of change $\dot{A}$, constant current I_{mag1} supplied to the windings 23 and 24 should be calculated on (9), (15), (17) and (18), and the direction of the flow from these windings must be opposite.

To ensure the non-actuation of reed switches 1, 2 and 6 in load mode and a reliable return after switching off the SC, starting and self-starting of the load electric motors, inequalities must be fulfilled:

$$B_{act} > B_{op.max}^{I} + B_{int} ; \tag{20}$$

$$B_{ret} > B'_{int} , \tag{21}$$

Where B_{int} is total MF induction of interference (from currents in the earth and neighboring lines, the Earth's MF, etc.), *T*; B'_{int} is constant component B'_{int} (determined experimentally), *T*.

By entering the detuning coefficients k_{det}^{III}, which takes into account interference and is equal to 1.3, and k_{det}^{IV}, equal to 1.1-1.2, we get

$$B_{act} = k_{det}^{III} B_{op.max}^{I} \; ; \tag{22}$$

$$B_{ret} = k_{det}^{IV} B_{int}' \; . \tag{23}$$

In order for the reed switches 3 and 4 to fix the negative and positive polarity of $\dot{C}$ supplied from the transformer 28 through the forming circuit 31, it is necessary that [43]

$$I_{mag2} = \left(15 \div 30\right) I_{act2} \; ; \tag{24}$$

$$I_3 = \left(1{,}3 \div 2\right) I_{mag2} = \frac{\dot{k}_1 \dot{U}}{Z_3} , \tag{25}$$

Where I_{mag2} is direct current, *A*, supplied to windings 26 and 27 via rectifiers 7 and 8; I_{act2} is actuating current of reed switches 3 and 4, *A*; I_3 is current supplied to windings 34 and 35, *A*; Z_3 is resistance of windings 34 and 35, *ohm*.

In the load mode of the protected electrical installation, direct current in windings 23 and 24 of reed switches 1 and 2 and constant voltage on windings 26 and 27 of reed switches 3 and 4, as well as alternating voltage on windings 32 and 33 of reed switches 1 and 2 and windings 34 and 35 of reed switches 3 and 4, is not supplied, since the reed switch 6 does not come into action, and there are no signals at the inputs of the phase comparison scheme 15.

At SC in the protection zone under the action of magnetic flux generated by the current phase of the installation, the reed switch 6 is actuated, the element MEMORY 9 stores the signal for 11 ms, so that during the time when the contact 21 of the reed switch 6 falls off between the half-waves of the alternating current of the installation, direct current continues to be supplied to the relay circuit. A signal appears at the starting input 22 of the scheme 15, and the windings 23-25 of reed switches 1, 2 and 5 are flowed by a direct current. The reed switch 5 is actuated and supplies an alternating voltage through the forming circuits 30 and 31 to the windings 26 and 27 of the reed switches 3 and 4. At the same time, values appear at the inputs 11 and 13, 12 and 14 of the phase comparison scheme 15, the ratio of which leads to the appearance of signals at its output and the output of the MEMORY element 10.

When external SC, start-up and self-start of electric motors, when the current in the electrical installation is greater than the setpoint of the actuation reed switch 6, contact 17 closes and the relay starts. But in this case the signal at the output relay is not appearing as – or the amount of magnetic flux in the reed 1 and 2 is insufficient for falling off their pins 16 and 17, i.e. at the outputs 11 and 12 scheme 15 missing phase information generated values $\dot{A}$, or if the contacts 16 and 17 will disappear, then the phase relationship of the generated values $\dot{A}$ and $\dot{C}$, which occurs every half-wave of change A11, the actuate time of the device will not exceed 0.021 s with even if set the output electromechanical relay, for example, polarized type [43].

Diagnostics of the device malfunction is performed as follows. When the button 40 is pressed, the relay 38 is actuated and opens contacts 37 and 42. Opens, contact 42 introduces resistance 41 into the scheme, lowering the voltage from the transformer 28, and contact 37 breaks the circuit of disconnecting the switch of the electrical installation. Then the relay 39 is actuated and closes contact 44, supplying voltage to the winding 45 of the reed switch 6 through the regulator block 43 with a isolating transformer at the input. As a result, the winding 45 of the reed switch 6 flows around the current, and it is actuated, starting the protection scheme. Further, the scheme works as with a SC. If all its elements are in good order, the logic block 36 sends a signal to the alarm circuit, indicating that the protection scheme is in good order. No signal is sent to turn off the switch of the electrical installation, since contact 37 is open. Note that the complexity and cost of the proposed relay, as shown by calculations, is approximately the same compared to existing similar ones.

As in any other protections based on reed switches, in the proposed one they must be located at certain points near the current-carrying phases of the electrical installation. For this purpose, in some cases, the designs presented in [44] can be used.

CONCLUSIONS

The considered directional and non-directional resistance relays can be used in the construction of distance protection that does not require metal-intensive current transformers. At the same time, their implementation is not more difficult than that of similar existing ones. In addition, the directional relay has increased reliability due to the presence of a simple test fault diagnosis.

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