2020 International Ural Conference on Electrical Power Engineering (UralCon)

Overcurrent Protection Scheme Utilising Reed Switches Instead of Current Transformers

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***Abstract*—This paper states the need to create overcurrent protection without the use of current transformers due to their inherent disadvantages. Reed switches are proposed as current sensors, since they can simultaneously act as a current sensor, a current relay, and an analog-to-digital converter. The known overcurrent protections utilising reed switches are analyzed. The three closest alternatives of the proposed protection scheme are considered in more detail. A certain disadvantage of these protection schemes is failure to trip in case of a short circuit if reed switch contacts are stuck. Another disadvantage is the possibility of a false tripping if an interference occurs in the reed switch control winding due to a magnetic field. To eliminate the first disadvantage, a corresponding time relay is proposed to be started after each tripping of the reed switch with a delay shorter than the protection time for the interval between the first and the considered tripping of the reed switch. To eliminate the second disadvantage, the control winding and contacts of the specified reed switch are proposed to be connected in series to the control winding and contacts of the blocking reed switch. The latter has normally closed contacts, which open only in case of interference in the control winding circuit. The operation of the protection circuits and the measurement device has been analyzed in various modes of operation. A method for the protection scheme measurement device adjustment is proposed, which takes into account the inequality of the calculated and actual inductions of the magnetic field acting on the reed switch.**

Keywords*—*overcurrent protection, measurement device, reed switch, contact sticking, adjustment

I. Introduction

Due to its simplicity, overcurrent protection is one of the most common protection schemes applied against short circuits of electrical installations with a voltage of 3-110 kV. This scheme, like the vast majority of other protection schemes, for example [1 - 3], utilises current transformers to obtain information about the current in the phases of the protected electrical installation. The current transformers have a number of well-known disadvantages [4, 5, 6, 7], including large amount of metal needed for construction and large dimensions. For example, a 6 kV current transformer contains 10 kg of steel and 2 kg of high quality copper, and with network voltage increase, the amount of these metals increases as well. Because of all these shortcomings, CIGRE conferences have repeatedly pointed out the need in protection schemes that do not utilise current transformers [8, 9, 10, 11]. Furthermore, Rogovsky coil or reed switches have been proposed to be used as current sensors. We chose reed switches, because they can simultaneously act as a current sensor, a current relay, and analog-to-digital converter, and also have some other advantages [12]. Reed switches have been already used to develop design principles of measurement devices [13], parallel-line protections [14] and transformer installation protections [15], differential-phase [16, 17] and remote [18] protections; reverse and zero sequence currents detection principles [19], as well as designs for attaching reed switches near busbars [20]. Certain overcurrent protection designs have been proposed [21–29]. At the same time, the protections in [21–24] are intended for low-voltage electrical installations and cannot be used without significant modifications. Protection schemes [25, 26] have reed switches located in close proximity to busbars, which requires the same expensive insulation as in current transformers, while the protection response parameters adjustment range is limited. The closest alternatives of the proposed protection scheme are devices presented in [27, 28]. The scheme [27] contains a reed switch with a pulse expander, a time relay, and an actuator connected in series to its contacts. Another scheme [28] with a timer measures the time reed switch contacts stay closed. This time allows to determine the current amplitude in busbars of the protected electrical installation. If the current exceeds the predefined value, a signal is issued to turn of the electrical installation. The third scheme [28] utilises two reed switches, while the current amplitude is determined by the time between the moments of recovery of these reed switches. The disadvantage of the protection schemes [28] is failure to trip at a short circuit if the reed switch contacts are stuck. A common disadvantage for all three alternatives is possible false tripping in case of an interference in the reed switch control winding circuit occuring when it is magnetized to increase the sensitivity. As for the adjustment of the measuring organs of these protections, to our knowledge, there is only one methodology [27]. However, while using it, induction actuation error can reach 40%. Therefore, in this work, the attempt to eliminate indicated disadvantages of current protection was made, as well as to create a methodology for adjustment their measuring organ, which allows to determine the operating value with high accuracy.

II. Overcurrent Protection Scheme

The protection scheme incorporates reed switches 1 for each phase installed in close proximity to the corresponding phase busbar of the installation, D-triggers 2, 3, ..., (n+1) with

This work was supported by the World Bank (grant No. 00722) and the MES of the Republic of Kazakhstan (grant No. AP05131351).

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sync inputs (n+2) (n+3), ..., (2n+1) information inputs (3n+3), (4n+11), ..., (5n+9) and direct outputs (2n+3), (2n+4), ..., (3n+2), elements OR-NOT (2n+2), NOT (3n+4), AND (3n+5), NOT (3n+7), OR (4n+7), AND (4n+8), NOT (4n+10), clock pulse generator (3n+6), time relays (3n+7), (3n+8), ..., (4n+6), (4n+9), actuator (5n+10).

The proposed protection scheme works as follows. In load mode, reed switch 1 has open contacts, since it's magnetomotive tripping force and configuration are selected to prevent tripping when the maximum load current of the electrical installation flows through the busbar. Therefore, the protection does not trip, and no signal is issued at the actuator's (5n+9) output. As a result, the dynamic sync inputs (n+2), (n+3),..., (2n+1) of D-triggers 2, 3,..., (n+1) do not receive signals from the reed switch 1 and element AND (3n+5), and no signals are issued at their direct outputs. Furthermore, the signal is present at OR-NOT element output and D-trigger 2 information input connected to it.

In the case of a single-phase short circuit, for example in phase A, the reed switch 1 (Fig. 1), installed near the busbar of this phase, begins to trip and issue signals (Fig. 2) to the dynamic sync inputs (n+2), (n+3),..., (2n+1) of D-triggers 2, 3,..., (n+1) and the time relay (4n+9). At the first closure of the reed switch 1 contacts, signals (Fig. 2) present at the information inputs (3n+3), (4n+11), ..., (5n+9) of D-triggers 2, 3, ..., (n+1) up to this point, appear on their direct outputs (2n+3), (2n+4), ..., (3n+2) and are maintained until the next actuation of the reed switch 1. Therefore, the direct output (2n+3) of D-trigger 2 has a signal, and the direct outputs (2n+4),..., (3n+2) of D-triggers 3, …, (n+1) have no signal, while the OR-NOT element stops issuing signals to the information input (3n+3) of D-trigger 2. From the direct output (2n+3) of D-trigger 2, the signal enters the time relay (3n+7), triggering it, and enters the information input (4n+11) of D-trigger 3 as well. When the reed switch 1 is triggered for the second time, the direct outputs (2n+3), (2n+4),..., (3n+2) of D-triggers 2, 3,..., (n+1) issue signals that were present at their information inputs (3n+3), (4n+11),..., (5n+9) after the first trigger of the reed switch 1. Therefore, D-trigger 2 does not issue a signal, and the time relay (3n+7) returns to its original state, and D-trigger 3 issues a signal to the input of the time relay (3n+8), triggering it, and issues a signal to the input of D-trigger 4 as well. At the same time, there is no signal at the information input (4n+11) of D-trigger 3. At the (n-1)-th tripping, the signal appears only at the direct output (3n+1) of D-trigger n and is sent the information input of D-trigger (n+1), as well as the input of the time relay (4n+6), triggering it, while the time relay (4n+5) (not shown in Fig. 1) returns to its original state. At nth tripping, the signal appears only at the direct output (3n+2) of D-trigger (n+1), while the time relay (4n+6) returns to its original state. Each time relay has a time delay:

$$t_i = t_{del} - (n-1) \cdot 0.01; \tag{1}$$

where t_{del} is protection time delay; 0.01 is the time between the reed switch trips (contacts are closed at a frequency of 100 Hz); (n-1) is the number of time relays in the protection scheme; n is the number of reed switch trips during t_{del}.

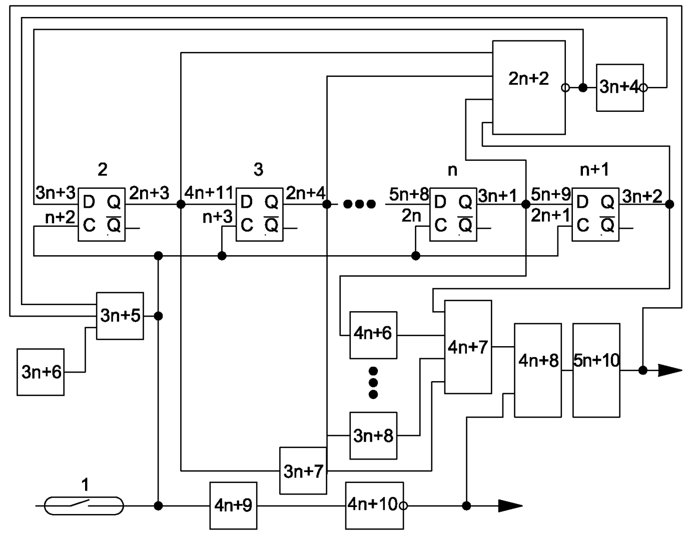

Fig. 1. Block Diagram of the Overcurrent Protection Utilising Reed Switches.

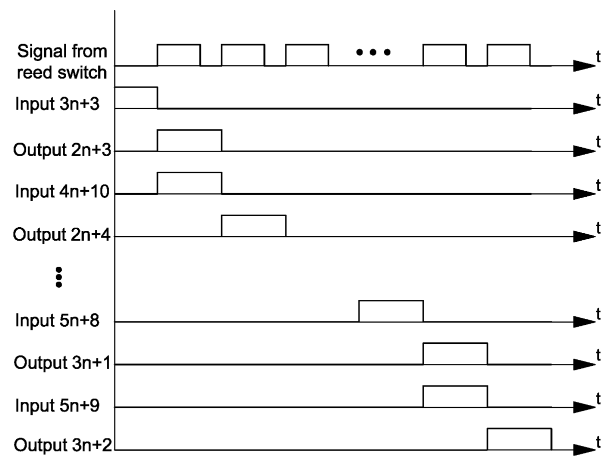

Fig. 2. Time Diagram of Triggers Operation When the Reed Switch is Triggered in Short-circuit Mode.

From the direct output (3n+2) of D-trigger (n+1), the signal enters the input of OR element (4n+7) and OR-NOT element (2n+2). From the output of OR element (4n+7), the signal is transmitted to AND element (4n+8), the other input of which receives a signal from NOT element (4n+10), since the time relay (4n+9) is not triggered. Therefore, AND element (4n+8) issues a signal, and the actuator (5n+10) sends a signal to turn off the electrical installation, as well as send a signal to the input of AND element (3n+5). The other inputs of AND element (3n+5) receive signals from the clock generator (3n+6) and NOT element (3n+4), since the input of OR-NOT element(2n+2) receives no signal. After the electrical installation is turned off, the reed switch 1 stops tripping. Furthermore, the signal at the direct output (3n+2) of D-trigger (n+1) is maintained. Therefore, AND element (3n+5) continues to send signals to the dynamic sync inputs (n+2), (n+3),..., (2n+1) of D-triggers 2, 3,..., (n+1) until the output of OR-NOT element (2n+2) has a signal. The protection scheme returns to its original state. At two-phase or three-phase short circuit, all three reed switches installed near the busbars of phases A, B, C are triggered, and outputs of AND elements (4n+8) have signals. The actuator (5n+10) is triggered, sending a signal to turn off the installation and return the protection scheme to its original state. After activation of the automatic circuit recloser or automatic transfer circuit breaker, the circuit breaker of the electrical installation is switched on. Furthermore, the reed switch 1 contacts are open and the protection does not trip.

When the contacts of the reed switch 1 are stuck at a single-phase short circuit, for example, at second tripping, the reed switch generates a continuous signal. Therefore, after the second tripping, the signal is maintained (Fig. 3) on the dynamic sync inputs (n+2), (n+3),..., (2n+1) of D-triggers 2, 3,..., (n+1). As a result, the time relay (4n+9) is triggered and a signal is generated only at the direct output (n+3) of D-trigger 3, which activates the time relay (3n+8). After the time delay t2= tdel-0.01 expires, the time relay (3n+8) is triggered sending a signal to the input of OR element (4n+7), from the output of which it is sent to the input of AND element (4n+8). NOT element (4n+10) sends a signal to another input of AND element (4n+8), while the time relay (4n+9) is not triggered as it's time delay has not expired yet. Therefore, AND element (4n+8) sends a signal to the actuator's input (5n+10), which in its turn sends a signal to switch off the circuit breaker of the electrical installation. After the circuit breaker is switched off, the time relay (4n+9) is triggered as its time delay expires, sending a signal to the input of NOT element (4n+10) and indicating the reed switch 1 contacts sticking. Therefore, the output of AND element (4n+8) generates no signal, and the protection is blocked. After activation of the automatic circuit recloser or automatic transfer circuit breaker, the circuit breaker of the electrical installation is switched on. Furthermore, despite the fact that the reed switch 1 contacts are closed since they are stuck, the protection is not triggered due to a signal from the time relay (4n+9) received at the input of NOT element (4n+10).

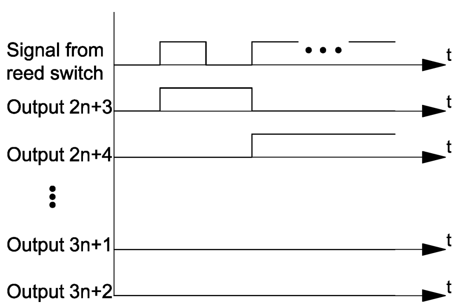

Fig. 3. Time Diagram of Trigger Operation in Case of Reed Switch Contacts Sticking.

III. Protection Scheme Measurement Device Adjustment Method

As with any protection scheme, the measurement device (in our case, the reed switch) shall be adjusted for the proposed scheme. For this purpose, an adjustment method [29] was developed and patented, which has the following sequence of operations. The design point A is selected at a safe distance from busbars 1 of the electrical installation. The distance from busbars to point A is calculated. The induction B_A of the magnetic field at point A at the protection tripping current I_{tc} is calculated using the Biot-Savard-Laplace law by the formula [30]:

$$B_A = \frac{k_{sh}\mu_0 I_{tc}}{2\pi}\cdot\left(\left|\frac{e^{ja1}}{h_1}+\frac{e^{ja2}}{h_2}+\frac{e^{ja3}}{h_3}\right|\right) \quad (2)$$

where e^{ja1}, e^{ja2}, e^{ja3} are complex numbers describing the phase shift angles between currents in busbars; h_1, h_2, h_3 are distances from busbars 1 to the design point A; μ_0 is the magnetic constant; k_{sh} – shape coefficient that consider geometric parameters of busbar.

The first inductor coil 2 is installed in the point A with a given number of coils W_1, length l_1 and cross-sectional area S_1. A power source 3 is connected to busbars 1, and the current I_1 much smaller than current I_{ct} is fed to busbars 1. The voltage E_1 at the ends of the first inductor 2 is measured using a voltmeter 4, and the power source 3 is turned off. The voltage E_2 is calculated at the ends of the first coil 2 at a current I_1 by the formula [31]:

$$E_2 = fW_1S_1B_Ae^{-j90} \quad (3)$$

where f is the AC frequency, 50 Hz.

Then the true induction B_{Atrue} at point A at a current I_{ct} is calculated using the formula:

$$B_{Atrue} = \frac{E_1}{E_2}\cdot B_A, \quad (4)$$

Further, a reed switch is selected and placed inside the second inductor coil (not shown in Fig. 4) with a given number of coils W_2 and length l_2, located in an arbitrary place. A power source is connected to the terminals of the second coil (not shown in Fig. 4). The current is fed to this inductor coil I_2, and the current values is recorded, at which the reed switch has tripped. Its tripping induction is calculated using the formula [32]:

$$B_{avr} = \frac{\mu_0 I_2 W_2}{l_1} \quad (5)$$

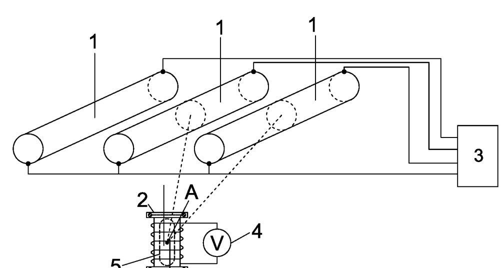

Fig. 4. Implementation of an Adjustment Method for a Current Protection Scheme Based on Reed Switches.

Then B_{avr} is compared with B_{Atrue}. If $B_{avr}=B_{Atrue}$, the reed switch 5 is installed inside the inductor coil 2. If $B_{avr} \neq B_{Atrue}$, then the next reed switch is taken and steps are repeated to determine B_{avr} and compare it with B_{Atrue}. These steps are repeated until the tripping induction of the reed switch is equal to the true induction of the magnetic field at point A. Next, the current I_I is fed to busbars, and the EMF E_3 is measured at the terminals of the inductor coil 2. The equality of EMF E_1 and E_3 is checked. If it is fulfilled, the current protection based on the reed switch is considered as adjusted. If this equality is not fulfilled, then the locations of the reed switch and the second inductor are changed to make EMF E_1 and E_3 equal. In cases when the reed switch with the necessary B_{avr} cannot be selected, and $B_{avr}>B_{Atrue}$, then the induction value B_{ind} is calculated, which is needed for reed switch 5 tripping:

$$B_{ind} = B_{avr} - B_{Atrue} . \qquad (6)$$

A power source is connected to the terminals of the inductor coil 2, and a current I_3 is supplied that can be determined from (5) by substituting B_{avr}, W_2 and l_2 with B_{ind}, W_1 and l_1, respectively.

IV. Protection Scheme Measurement Device Design

When the reed switch is magnetized, it may false trip due to interference induced in the wires that connect its control winding to the power source. To prevent false triggering of the measurement device, it can be designed in accordance with Fig. 5 [33]. The reed switch 1 is installed at a point on the cross-section of busbar 3 with its longitudinal axis perpendicular to the line 8 passing through the longitudinal axis of the busbar 3 and this point, while the reed switch 2 is installed along the line 10. At the same time, n coils of the control coil 6 are wound on the reed switch 1, and (n – m) turns of the control coil 6 are wound on the reed switch 2. The control coil 6 terminals are connected to the power source 7 using wires 8 and 9. Actually, two different coils can be used, connected in series.

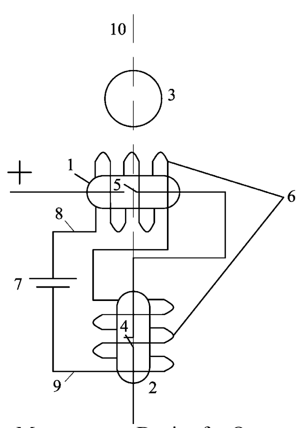

Fig. 5. High-reliability Measurement Device for Overcurrent Protection.

Let us consider the operation of the measurement device and an example of calculating the number of coils wound on reed switches 1 and 2. Suppose the reed switches 1, 2 are installed at point A at a distance of h=0.12 m from busbar 3, which operates with the maximum load at a current of I=40 a, and 400 A, if the electrical installation is short-circuited. Then, according to the Biot-Savard-Laplace law (excluding the effects of neighboring phases), the calculated induction B_A of the magnetic field created by a 400 A current at the reed switch 1 installation point is equal to

$$B_A = \frac{\mu_0 \cdot I}{2 \cdot \pi \cdot h} = \frac{4 \cdot \pi \cdot 10^{-7} \cdot 400}{2 \cdot \pi \cdot 0{,}12} = 6{,}7 \cdot 10^{-4} \ Тл . \qquad (7)$$

Let us assume that B_{Atrue}=0.7 V_A, and reed switches 1, 2 have tripping inductions $B_{tr1}=9.4\cdot10^{-4}$ T and $B_{tr2}=10.4\cdot10^{-4}$ T, and the control coil 6 has the number of coils n=5000. In order for the reed switch 1 to trip under the effect of the B_{Atrue} induction, its control winding shall create an induction acting along its longitudinal axis, $B_{ind}=4.04\cdot10^{-4}$ T. At the same time, to prevent the reed switch 2 from tripping in load mode and at short circuits, its control winding shall create an induction, $B_{pr}=0.8\cdot B_{avr2}=8.32\cdot10^{-4}$ T (taking into account the errors of calculations, installation, etc.). To calculate the number of coils of the control windings of reed switches 1 and 2, B_{ind} and B_{pr} shall be expressed in terms of the number of winding coils and the length l_{k1} and l_{k2} of their winding. Solving the jointly obtained expressions, taking $l_{k1}=l_{k2}$, we get m=1633 and (n-m)=3366. Let us suppose that $l_{k1}=l_{k2}$=0.02 m. Then, to enable the reed switch 1 to trip in case of a short circuit, the current I_{sc}=3.94 mA shall be applied to the control winding.

In the nominal mode of operation of the electrical installation and in the absence of interference in the connecting wires, the busbar 3 conduct a current of 40 A, which generates a magnetic field of $0.53\cdot10^{-4}$ T, and the biasing current of 3.94 mA in the control coil 6, which generates a magnetic field with induction of $4.04\cdot10^{-4}$ T and $8.32\cdot10^{-4}$ T, respectively. As a result, the total induction $B_\Sigma=4.57\cdot10^{-4}$ T acting on the reed switch 1, while the reed switch 2 is only affected by the control coil 6, since its axis is perpendicular to the induction vector of the magnetic field created by the current in the busbar 3. Reed switches 1, 2 do not trip, since the inductions acting along their longitudinal axes are less than B_{tr1} and B_{tr2}. Therefore, the measurement device does not send any signals to the circuit (Fig. 1).

When interference occurs in the connecting wires 8, 9 (or in the control coil 6 itself), the current in them increases. Let us assume that the EMF of E=5 V is induced in the wires, and the control coil 6 resistance is 600 Ohms. Then a total current of 12.2 mA flows through the control windings of the reed switches 1, 2 (from the induced EMF E and the power source 7). As a result, inductions $B_1=12.5\cdot10^{-4}$ T and $B_2=25.8\cdot10^{-4}$ T, respectively, act on reed switches 1 and 2. Since $B_1>B_{avr1}$ and $B_2>B_{avr2}$, reed switch 1 closes contacts 5, and reed switch 2 opens contacts 4. No signal is generated at the relay output of the reed switches, since the contact opening always occurs earlier. The measurement device does not false trip.

When short circuits occur in the electrical installation fed via busbar 3, the current in it increases to 400 A. In this case, the current in the control coil 6 does not increase, since there is no interference. As a result, only the reed switch 1 is triggered, and a signal appears at the output of the measurement device.

V. CONCLUSIONS

The proposed protection scheme based on reed switches does not use current transformers to get information, and also switches off a damaged electrical installation even if the reed switch contacts are stuck during a short circuit. The use of the presented version of the protection measurement device allows to simultaneously increase the sensitivity of the reed switch and prevent false tripping of the protection scheme against interference in the circuit of its control coil. The adjustment method for the measurement device is simple and allows to select reed switch tripping with high accuracy.

ACKNOWLEDGMENT

The paper was prepared with the support of the World Bank (grant No. 00722 "Commercialization of the Manufacture of Structures for Fastening the Reed Switches of Current Protection of Open and Closed Current Conductors") and the Ministry of Education and Science of the Republic of Kazakhstan (grant No.AP05131351 "Creation of a Globally Competitive Resource-Saving Relay Protection of Power Supply Systems").

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