Reed Switch and Magneto Resistor-Based Differential Protection Featuring Test Diagnostics for Converters

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***Abstract*—This paper states that constructing relay protections without current transformers is a relevant undertaking. To address this, the paper proposes using reed switches. Notably, the principles and some protection devices based on reed switches have already been developed, including differential protection of reed switch and magneto resistor-based converters; these solutions use the majority principle and functional diagnostics blocks. It should be emphasized that such protections lack test diagnostics, which means it cannot timely detect damaged majority elements or output relays, resulting in false positives or failure to trigger protections. This paper proposes a circuit for test diagnostics that, unlike other known designs, has three to six interconnected control windings on magneto resistors as well as button switches. The authors hereof discuss how protections act in a variety of converter operations as well as how to detect faults in three redundant protection kits, the majority element, or the output relay. To mount magneto resistors near the busbars of closed DC conductors, this paper proposes a simple and convenient mount that contains an L-shaped plate and angled fixtures. The paper further defines the applications of such protection.**

Keywords—converter; differential protection; reed switch; magneto resistor; reliability; majorization; diagnostics

I. Introduction

Constructing transformer-less protections, which CIGRE has many times referred to as an unresolved issue of the global electricity industry [1, 2], can be solved by magnetically controlled switches or reed switches. Since the 1980s, Toraigyrov Pavlodar State University has developed the principles [3-9] and some [10-13] devices for current, remote, and differential protection based on reed switches (complex RS-based protection are patent-pending, see [14-16]). However, there are still many challenges to address. For instance, the developed reed switch and magneto resistor-based differential protection for converters [17] lacks test diagnostics, which is currently deemed strongly recommendable [18-20] to the point of being mandatory; besides, there are no mounts for magneto resistors, without which such protections will not work; applications are not defined either. This paper is an attempt to address all of this.

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

II. Proposed Protection

A. Protection Circuitry

Like the one in [17], this protection uses a 2 / 3 majority principle, features functional diagnostics, and can keep running whenever one of the three protection kits are damaged (the trinity provides redundancy). The protection system features test diagnostics and [21] the instrumentation block (1), see Fig. 1, which has a Wheatstone bridge, one leg of which is a magneto resistor (2) fixed in the magnetic field of the DC conductor (3) of the converter, which features the rectifier (4) and the load (5) connected to it; other legs of the bridge of the resistors (6) to (8). One of the diagonals of the bridge serves as the outputs (9) and (10) of the block (1); the other one is connected to the output of the DC source (11). Blocks (12) and (13) have the same design. The instrumentation block (14) is contained in the magnetic field of the AC conductor (15), which carries phase A of the transformer (16) of the converter; this block is implemented as the winding-free reed switches (17) to (19) and the reed switches (20) to (22) that carry the control windings (23) to (25), the ends of which are connected to the outputs (9) and (10) of the blocks (1), (12), and (13). Block (14) also contains the functional diagnostics blocks (26) and (27) that utilize the time-pulse

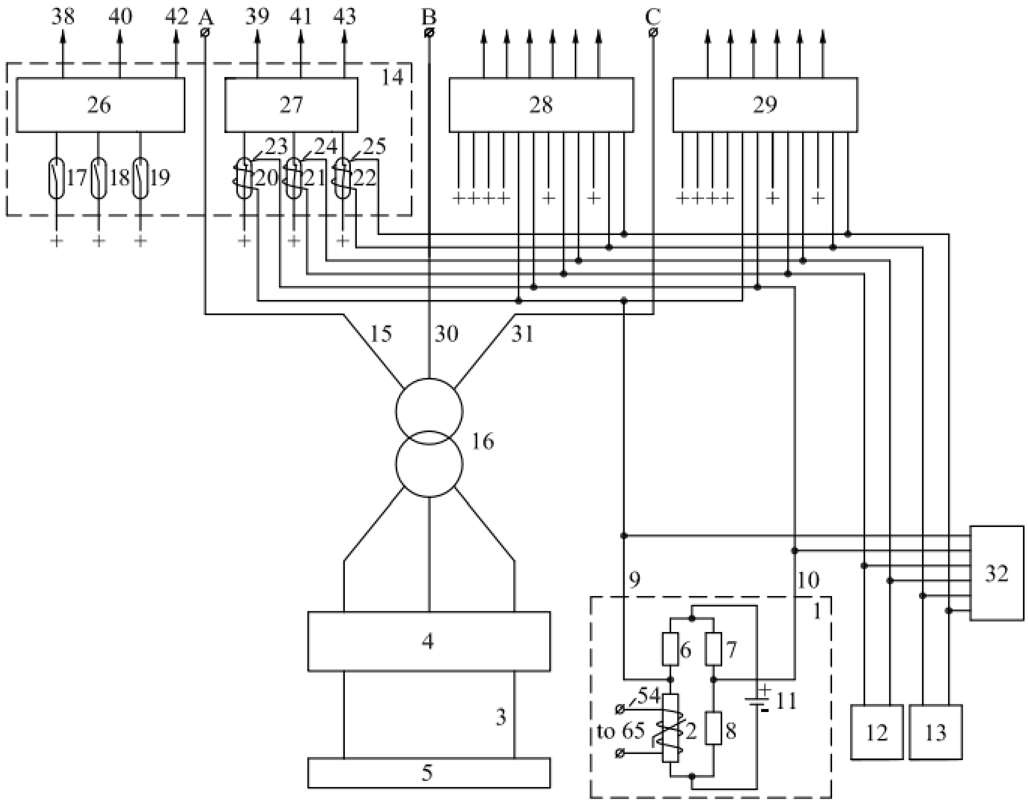

Fig. 1. Functional protection circuit, pt. 1

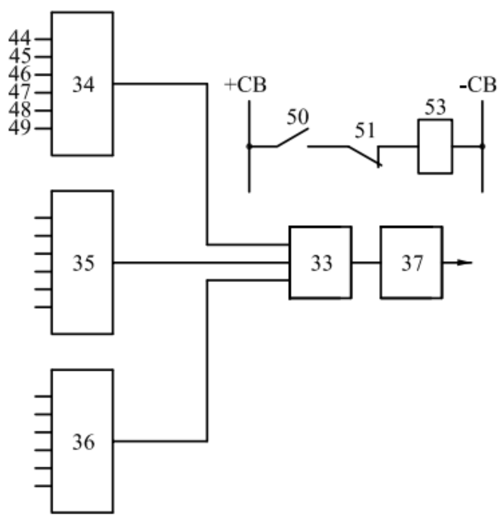

Fig. 2. Functional protection circuit, pt. 2

principle. The normally open contacts of the reed switches (17) to (19) are connected to an operational DC source (not shown in Figures 1 to 4) and to the inputs of the block (26). The normally closed contacts of the reed switches (20) to (22) are connected to the same current source and to the inputs of the block (27). Instrumentation blocks (28) and (29) are contained in the magnetic field of the conductors (30) and (31), respectively; they have the same design as the block (14). Integrity check block's (32) inputs are connected to the outputs of the blocks (1), (12), and (13). The inputs of the 2/3 majority element (33) in Figure 2 are connected to the outputs of the logic blocks (34) to (36), whilst its output is connected to the output relay (37). The outputs (38) and (39) (40 and 41; 42 and 43) of the block (14) are connected to the inputs (44) and (45) of the block (34) (35; 36). The outputs (38) and (39) (40 and 41; 42 and 43) of the block (28) are connected to the inputs (46) and (47) of the block (34) (35; 36). The outputs (38) and (39) (40 and 41; 42 and 43) of the block (29) are connected to the inputs (48) and (49) of the block (34) (35; 36).

B. *How the Circuitry Operates*

When the converter is loaded, the induction B_y, generated by the direct current I_y in the control winding of each of the reed switches (20) to (22), and the induction B_m of the magnetic field created by the current running in the conductor (15) affect the reed switches so that they remain triggered, their contacts are open, the block (27) receives no input, and the relay (37) is off.

A short circuit in the rectifier (4) will increase the current in at least one of the conductors (15), (30), or (31), and reduce

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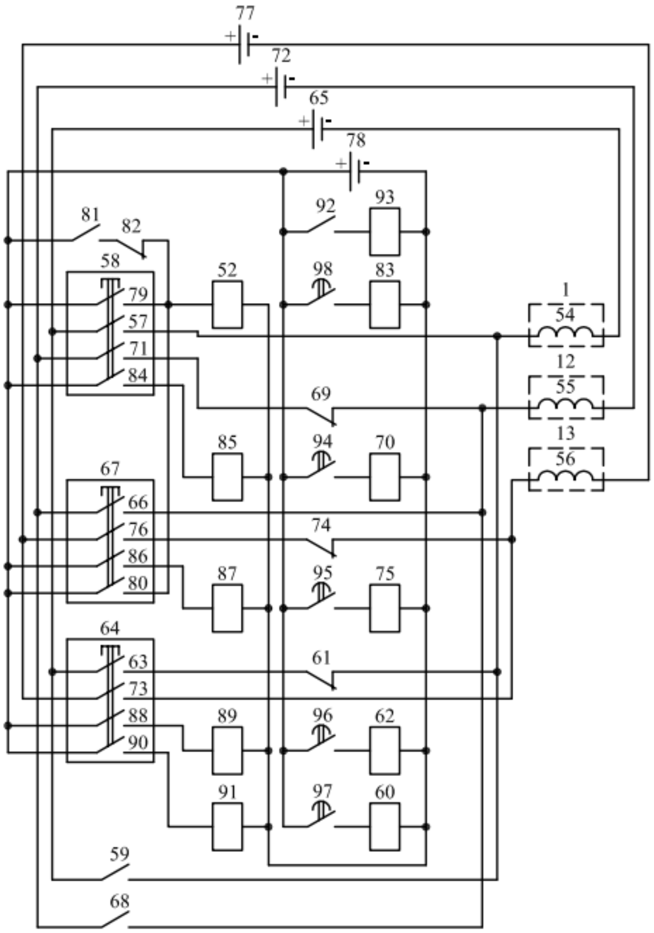

Fig. 3. Functional protection circuit, pt. 3

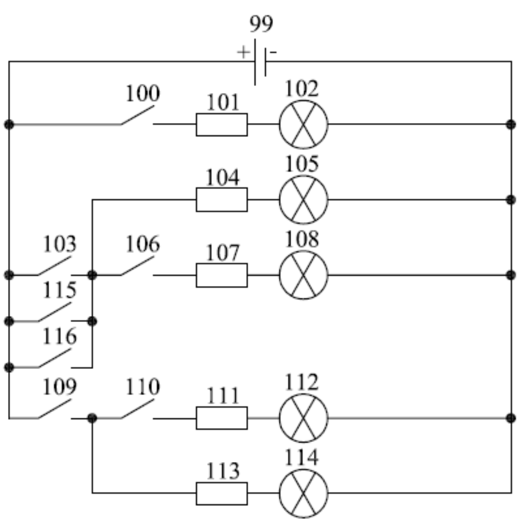

Fig. 4. Functional protection circuit, pt. 4

the current in the conductor (3), whereby the AC magnetic field that is acting e.g. on the reed switches (20) to (22) with their windings (23) to (25) will exceed the magnetic fields created by the current in these windings in one of the AC half-waves. As a result, the contacts of the reed switches (20) to (22) will close and send input to the block (27). The outputs (39), (41), and (43) of the block (14) will transmit signals to the inputs (45) of the blocks (34) to (36), which will differentiate the short-circuit current from the magnetizing current. Their outputs will produce signals that will pass through the majority element (33) to the input of the relay (37). This will trigger the relay (37), whose closing contact (50) will close the circuit of the coil (53), disabling the unit.

When energized or restoring the voltage after disconnecting the external short circuit, there will be a surge of magnetizing current. As in case of a short circuit, this will trigger the reed switches (20) to (22). Blocks (34) to (36) will differentiate SC current from magnetizing current and produce no output, thus they will not trigger the unit.

Blocks (26) and (27) monitor the timeframe during which the reed switches (17) to (22) are open or closed in order to prevent possible misfiring of the protection system. Block (32) diagnoses the blocks (1), (12), and (13) by comparing their output voltages pairwise.

C. Test Diagnostics

Faults in all the redundant protection kits, the majority element (33), and the output relay (37) are detected as follows. Press the buttons of the switches (58), (67), and (64), Figure 3, one by one. When holding the button of the switch (58), its contacts (57), (71), (79), and (84) close. This will energize the windings of the relay (52) and the slow-release relay (85), which has a delay

$$t_{PB1} = t_{c.з.} + t_{зап1} = 65{,}5 \cdot 10^{-3}\ \text{c}, \quad (1)$$

where $t_{c.з.} = t_1 + t_2 + t_3 = 15{,}5 \cdot 10^{-3}$ c is the protection trigger offset; $t_1 = 0{,}5 \cdot 10^{-3}$ c is the time needed for the normally closed contacts of the reed switches (20) and (21), blocks (14), (28), and (29) to return to the initial position; $t_2 = 11 \cdot 10^{-3}$ c is the delay of the slow-release relay in blocks (34) and (35), which is needed to differentiate SC current from magnetizing current; $t_3 = 4 \cdot 10^{-3}$ c is the time needed to trigger the output relay (37); $t_{зап1} = 50 \cdot 10^{-3}$ c is the time buffer adjusted for the errors these slow-release relay and the relay (37) may have.

The opening contact (51) of the relay (52) disconnects the circuit of the coil (53), whilst the closing contact (92) of the same relay triggers the slow-release relay (93) with a delay

$$t_{PB5} = t_{PB1} + t_{PB2} + t_{PB3} + t_{PB4} + t_{зап2} = 6{,}5\,\text{c}, \quad (2)$$

where t_{PB2} and t_{PB3} are the delays of the slow-release relays (87) and (89), whereby $t_{PB1} = t_{PB2} = t_{PB3} = 65{,}5 \cdot 10^{-3}$ c; $t_{PB4} = 2 \cdot t_{PB1} + t_{зап3} =$ $= 231 \cdot 10^{-3}$ c is the delay of the slow-release relay (91); $t_{зап2} = 6$c is the time buffer that allows the operator to press and hold for 1.5-2 seconds the buttons of the switches (58), (67), and (64) one by one; $t_{зап3} = 100 \cdot 10^{-3}$ c is the time buffer adjusted for the errors of the slow-release relay in blocks (34) to (36), the relays (37) and (89).

As the contact (81) of the relay (52) closes, the relay self-locks for the time t_{PB5},, after which the closing contact (98) will close with a delay sufficient to close the relay (93), triggering the relay (83), the opening contact (82) of which will disconnect the circuit between the contact (81), relay (52), and its winding, see Figure 3; the relay (52) will return to its initial position, closing the contact (51), see Figure 2.

Pushing the button (58) will energize the windings (54) and (55). This will alter the resistance of the magneto resistors (2), see Figure 1, reducing the voltages between the outputs (9) and (10) of the blocks (1) and (12), and therefore the current I_y in the windings (23) and (24). The contacts of the reed switches (20) and (21), blocks (14), (28), and (29), will close; if the blocks (34) and (35) are intact, their outputs will deliver signals. In this case, provided that the majority element (33) and the output relay (37) are intact, the latter will trigger and close its closing contact (100), see Figure 4, to fire up the light (102), showing that the majority element (33) and the output relay (37) are indeed intact.

Once the relay (85) is untriggered after the time t_{PB1}, its contact (94) will trigger the relay (70) to open the contact (69), thus deenergizing the winding (55). This will disable the signal at the block's (35) output; however, the output signal of the block (34) will remain. If the element (33) issues a signal in that case (and it should, provided that it has received two or three signals), the relay (37) will remain triggered. As the closing contacts (103) of the relay (70) and (106) of the relay (37) are closed, the light (108) will switch on, indicating that the majority element (33) is faulty. Releasing the button of the switch (58) will switch off all the lights and deenergize the winding (54). However, the relay (52), still self-locked, will keep the contact (51) open.

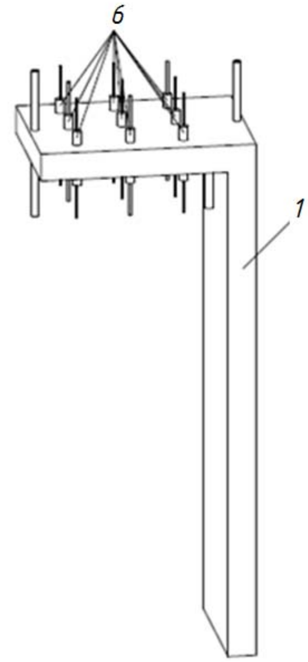

Fig. 5. General view of the plate

Pressing and holding the button of the switch (67) will first energize the windings (55) and (56), then, after the time t_{PB2}, only the winding (55). The circuitry operates as described above. Pressing and holding the button of the switch (64) will first energize the windings (54) and (56), then, after the time t_{PB3}, only the winding (56); after the time t_{PB4}, it will energy the windings (54) to (56) so as to test how the unit works when all the three redundant protection kits are triggered simultaneously.

Lights (105) and (114) signal that the buttons of the switches (58), (64), and (67) have been held long enough to trigger the intermediate relays (60), (62), (70), and (75). Pushing the buttons of all the three switches one by one will deenergize the winding of the relay (52) after the time t_{PB5} as a result of triggering the relay (83); this will cause the contact (51) to disconnect the open the circuit of the coil (53) to switch the unit off. The entire circuit returns to the initial position.

D. Mounts for Magneto Resistors Near the Busbars of Closed DC Conductors

The design contains (see Figures 5 and 6) the L-shaped plate (1), the cable trays (2), the lids (3) and (4), the mounting unit implemented as the angled fixtures (5). The shorter part of the L-shaped (1) has equidistant through holes that contain

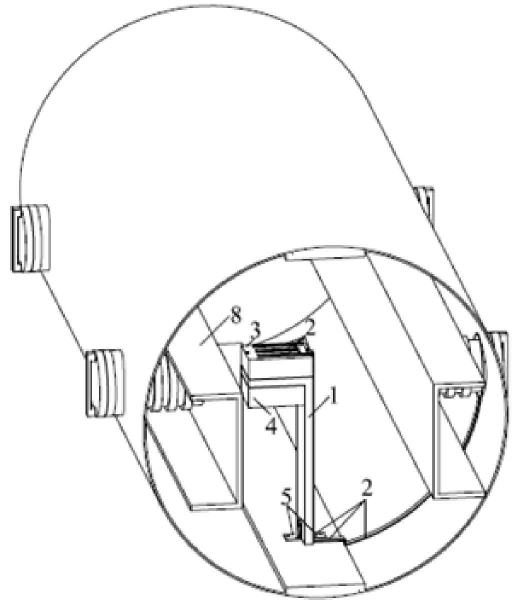

Fig. 6. The mount inside a closed DC conductor

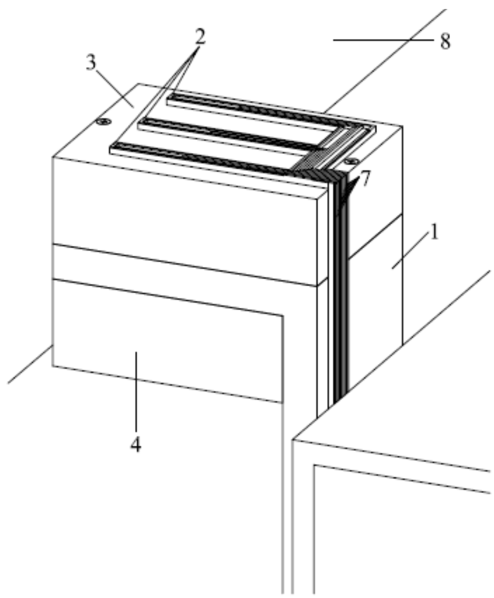

Fig. 7. The mount inside a closed DC conductor (developed isometric view)

the magneto resistors (6). Both edges of the shorter part of the plate (1) has cylindrical ledges with threaded holes that the lids (3) and (4) are affixed into; the lids are hollow rectangular parallelepipeds that, like the cable trays (2) on the outer sides of the lids, have through holes coaxial with the longitudinal axes of the magneto resistors (6); insulated cables run (7) through these holes, see Figure 7. One end of each cable is connected to a contact of the magneto resistors (6), whilst the other one is connected to a terminal pad (not shown in Figures 5 to 7). At the end of the longer part of the L-shaped plate (1), both sides carry screw-mounted angled fixtures (5) that enable the plate (1) to be contained in the magnetic field of the conductive bus (8) that belongs to the closed DC conductor. The design can carry up to nine magneto resistors at once. For the protection system under consideration, such design coupled with the majority principle behind its operation enables the protection to be triggered by three magneto resistors that are closer or farther of the conductive bus (8).

E. Applications

Applications usually depend on the sensitivity of the protection system. Compared to conventional differential protections that have the sensitivity coefficient $k_ч = I_{КЗ,мин} / I_{с.з.}$, , the coefficient for this system is

$$k_ч = \frac{B_{КЗ,мин}}{B_{с.з.}} = \frac{B_{КЗ,мин}}{1{,}1 \cdot \left(B_у^{КЗ} - B_{возв}\right)}. \qquad (3)$$

This is logical because $B_{КЗ,мин}$ is induced by $I_{КЗ,мин}$, which is the minimum short-circuit current at the output of the rectifier (4). Inducing $B_{с.з.} = 1{,}1 \cdot \left(B_у^{КЗ} - B_{возв}\right)$ is essentially the protection trigger. Here, $B_у^{КЗ}$ is the induction of the magnetic field generated in case of a short circuit by the direct current $I_у^{КЗ}$ in the control winding of the reed switch; $B_{возв}$ is the induction required for the normally closed contacts of the reed switches (20) to (22) to return to their initial position; 1.1 is the adjustment factor.

Calculating the induction values $B_{КЗ,мин}$ and $B_у^{КЗ}$ is detailed in [7, 11, 22]. For instance, consider a converter that feeds a DC motor with the load current $I_{нагр.} = 5 кА$ [23]. The motor is fed through a dual-winding transformer that has a capacity $6{,}3 МВ \cdot А$ and a rated primary-winding voltage of 10 kV. When using MKC-14104 reed switches ($B_{возв} = 0{,}4 \cdot 10^{-3}$ Тл) and FP 17L 200E magneto resistors placed at safe distances $h_1 = 0{,}12$ м and $h_2 = 0{,}05$ м off the AC and DC busbars, $B_{КЗ,мин} = 11{,}1 \cdot 10^{-3}$ Тл, , and $B_у^{КЗ} = 5{,}2 \cdot 10^{-3}$ Тл. Then, according to (3) $k_ч = 2{,}1$. Similar calculations using the data from [23] show that the proposed protection system will be sufficiently sensitive ($k_ч \geq 2$) for use in converters with a transformer capacity $6{,}3 \div 160 МВ \cdot А$ (primary-winding voltage 10÷110 kV) that feed electrolysis units, DC motors, and vacuum arc furnaces.

III. Conclusions

The idea to use control windings put on magneto resistors to transmit test signals was the concept that developed into a differential protection system for converters that, unlike the known alternative, features a relatively simple test diagnostics tool. This tool can detect a fault in any of the three redundant protection blocks in 5 to 7 seconds in addition to detecting faulty majority elements and output relays. The design allows mounting magneto resistors near closed DC conductors. The protection was found to be sensitive enough for use in converters with a transformer capacity $6{,}3 \div 160 \mathrm{MB} \cdot \mathrm{A}$.

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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