2020 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM)

Majority Voting Schemes of Differential Protections without Current Transformers with Functional Diagnostics for Converting Units and Electric Motors

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***Abstract*—It is stated that the issue of building up protection relays without CTs is relevant. The solution to this issue using reed switches is proposed. It is noted that the differential protection of converting units and the phase-comparison protection of reed switch-based motors without CTs have low dependability and security in the event of any faulty element. Herewith, the lack of functional diagnostics does not allow determining the faulty element. The authors propose two new protection schemes based on the majority voting principle - the faulty electrical unit trip signal is generated if at least two of the three mutually redundant sets send alarms, which leads to an improvement in both the dependability and security. The operation of the functional diagnostic units, based on the time-pulse principle, is considered. It is shown that the functional check of conductors will allow avoiding the protection malfunction in case of their failure.**

Keywords—converting unit, electric motor, differential protection, reed switch, reliability, majority voting, diagnostics

I. INTRODUCTION

For years, current transformers (CTs) having such shortcomings as large errors and secondary winding breaking voltages, dimensions, weight, and the use of expensive materials have been used as the main primary converters for protection relays (PRs) and measuring [1, 2]. Due to these shortcomings, the International Councils on Large Electric Systems (CIGRE) repeatedly raised the issue, e.g. in [3, 4], on the need to use or develop sensors alternative to CTs. One way to solve this issue may be the reed switches applied in technology [5], which are viable for use [6] and have benefits essential in PR. Thus, reed switches are capable of simultaneously functioning as a current transformer, a measuring protection element, and an analog-to-digital converter; they do not need amplifiers to transmit signals, while the transmission is carried out via control circuits and not measuring ones; there is no need in devices that mitigate the effect of temperature [7–9]. At this stage, in the S. Toraighyrov Pavlodar State University, the protection principles and a number of reed switch-based devices have been developed [10–20], including attempts to build up differential protection for converting units (CUs) [21] and phase-comparison protection for electric motors (EMs) [22] widely used in the power industry. Low reliability is a shortcoming of the protection schemes [21] and [22], since they fail or malfunction if any of their elements are faulty. Herewith, the lack of functional diagnostics does not allow determining the faulty element in case of protection failure. Herein, the CU differential protection and EM phase-comparison protection schemes are proposed, which are free of these shortcomings.

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

II. MAJORITY VOTING SCHEME OF DIFFERENTIAL PROTECTION WITH FUNCTIONAL DIAGNOSTICS FOR CONVERTING UNITS

A. Protection Scheme

The proposed protection model [23] includes (Fig. 1 and Fig. 2) an actuator 1, the output of which is connected to the CU transformer 2 trip circuit (also consisting of a rectifier 3 connected to load 4), reed switches 5-13 with control windings, reed switches 14–22 without windings, a measuring unit 23 with a constant voltage source 24 in the form of a Wheatstone bridge, one of the arms of which is a magnetoresistor 25 fixed in a magnetic field (MF) of direct current conductor 26 of rectifier 3 and the other arms are resistors 27–29. One Wheatstone bridge diagonal is used as the unit 23 output and another is connected to the constant voltage source 24 output. Differential protection also includes measuring units 30 and 31 built similarly to unit 23, alarm units 32–34, controlling reed switches with control windings 35–37, and adjustable resistors 38–40, through which the control winding ends of reed switches 5–13 are connected to the first outputs of units 23, 30, 31 (inputs of these windings are connected to the second outputs of measuring units 23, 30, 31), magnetizing inrush (MI) offset units 41–49, and functional diagnostic units 50-55 based on a time-pulse principle, comparing elements 56-58, AND gates 59–67, and OR gates 68-71. Reed switches with control windings 5-7, 8-10, and 11–13 are placed in the magnetic field of AC conductors 72, 73, and 74 of the CU phases A, B, and C, respectively, like those without windings 14–16, 17–19, and 20–22.

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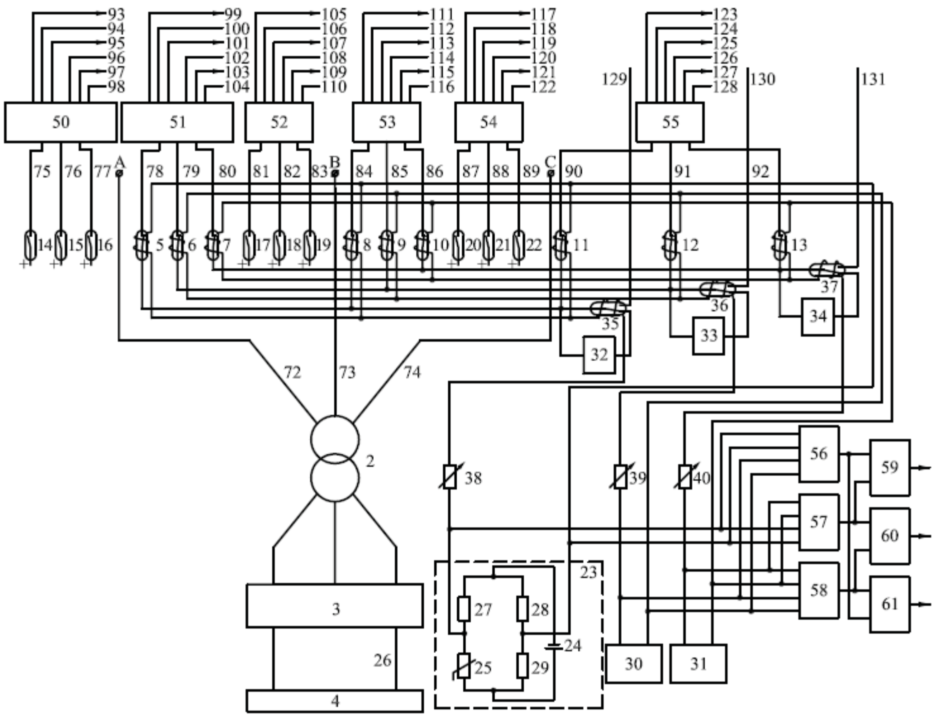

Fig. 1. Functional Protection Scheme (Part 1)

B. The Scheme Operation

In the CU load mode, the density B_c created by DC I_c in the control winding of each reed switch (e.g. 5-7) and the magnetic density created by current in conductor 72 bring the reed switches into the tripped position, their contacts are open, inputs 78-80 of functional diagnostic unit 51 do not receive signals, and actuator 1 does not operate.

At a short circuit (SC) in rectifier 3, the current in at least one of conductors 72–74 increases and in conductor 26 decreases and in one of the AC half-waves, MF generated by the conductor AC and effecting on e.g. reed switches with control windings 5–7 turns out to be more than that generated by currents in the control windings. As a result, the contacts of reed switches 5–7 take out, close and send signals to the inputs 78–80 of functional diagnostic unit 51, output signals 100, 102, and 104 of which are respectively transmitted to the second inputs of the MI offset units 41, 44, and 47, whose first inputs receive signals from tripped reed switches 14–16 from outputs 94, 96, and 98 of functional diagnostic unit 50. In the event of MI, the open contact time for reed switches 14-16 is much longer than that at internal SCs. Units 41, 44, and 47 make a distinction between the SC and magnetizing currents and generate output signals received at the inputs of OR gates 68-70, the output signals of which through AND gates 62-67 are transmitted to the inputs of OR gate 71. The output signal of the latter is sent to the input of actuator 1, which generates a signal to turn off the unit (not shown in Fig. 1 and 2).

When turning on under voltage or recovering voltage after the external SC clearing, the magnetizing inrush occurs. Reed switches 5-7 will trip the same way as in the event of SC. MI offset units 41, 44, and 47 make a distinction between the SC and magnetizing currents and do not generate signals and the protection does not trip.

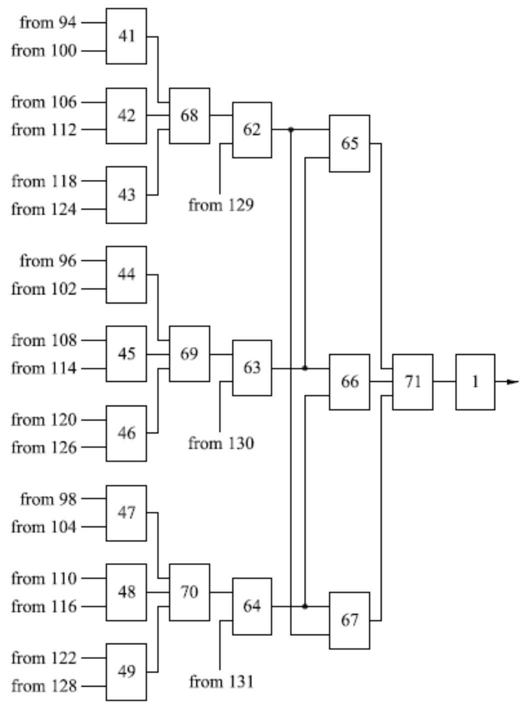

Fig. 2. Functional Protection Scheme (Part 2)

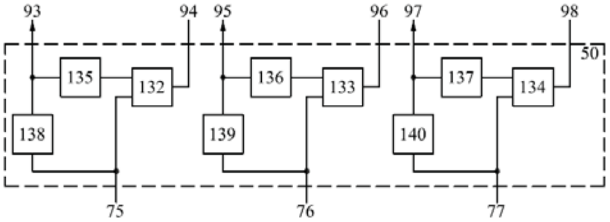

Fig. 3. Functional Diagnostic Unit Scheme

C. *Functional Diagnostic Units Operation*

Each of the functional diagnostic units, e.g. unit 50 contains (Fig. 3) three AND 132-134, three NOT 135-137, and three TIME 138-140 gates, which control the closed contact time of reed switches 14-16 (their sticking is diagnosed), while the TIME gate response time depends on the reed switch type and its trip setting. Functional diagnostic units 51-55 are built similarly to unit 50.

Let us consider the operation of functional diagnostic units exemplified by unit 50. If the closed contact time of reed switch 14 (15, 16) exceeds the setting of TIME gate 138 (139, 140), then the last one generates a signal indicative of the reed switch moving contact sticking, which is sent via the alarm circuit through NOT gate 135 (136, 137) to the second input of AND gate 132 (133, 134), the output signal of which is thus cleared. Clearing output signals of the respective AND gates prevents the possible protection malfunctions when the reed switch movable contacts are stuck.

Using the comparing elements 56-58, diagnostics of the measuring units 23, 30, and 31 are performed, the output voltages of which are compared in pairs. If any of the resistors of the Wheatstone bridge being a part of each measuring unit, e.g. unit 23 fails, then comparing elements 56 and 57 generate output signals that are transmitted to the inputs of AND gate 59. The output of the latter is sent to the alarm circuit.

III. Majority Voting Scheme of Phase-Comparison Protection with Functional Diagnostics for Motors

A. *Protection Scheme*

The proposed protection model [24] consists of failure detection units 1-3 (Fig. 4) receiving information of protected EM 4 and its power cable from units 5-16 fixed upstream EM 4 near the A, B, and C phase conductors. Units 1-3 duplicate each other like units 5-7; 8-10; 11-13; and 14-16. Units 5-13 include two reed switches (Fig. 5) with common parameters and units 14-16 include one reed switch. The first reed switches of units 5-13 trip in a positive AC half-wave, while the second ones in a negative AC half-wave, i.e. reed switches in units are polarized.

Each of units 5-13 contains reed switches 28 and 29 with control windings 30 and 31 with winding 30 connected to the cathode of diode 32 and winding 31 connected to the anode of diode 33. The units also include a phase-shifting circuit 34, an amplifier 35, and an inductance coil 36 (Fig. 5). The use of two polarized reed switches allows the protection to detect a failure in both AC half-waves. This substantially complicates the protection, especially when using redundancy and troubleshooting. For EMs operating in explosive and fire hazardous environments, this is apparently advisable, and in other cases, detecting a failure in one half-wave for 0.02 s without complicating the protection is enough.

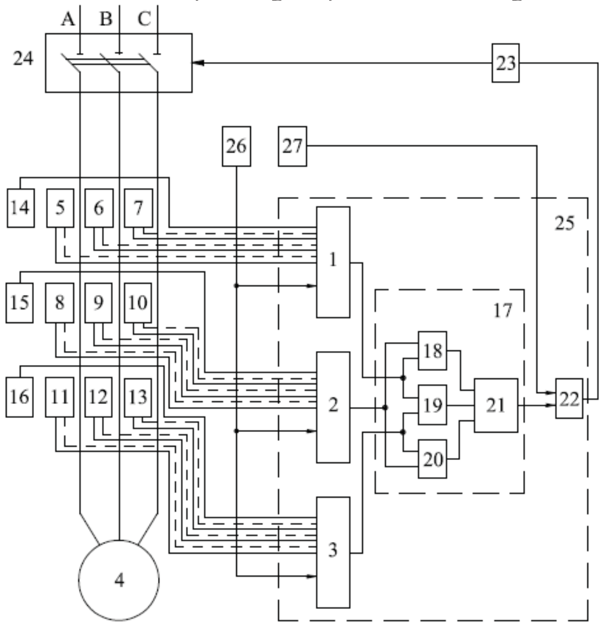

Fig. 4. Functional Protection Scheme

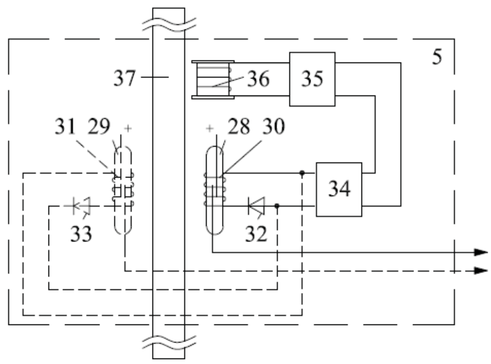

Fig. 5. Unit with Polarized Reed Switches Tripping in a Positive and Negative AC Half-Wave

The reed switch trip signals of units 5-13 are transmitted to units 1-3 by wire (like in conventional protection schemes) and from these units to majority element 17 consisting of AND gates 18-20 and OR gate 21. Through a non-inverting input of AND gate 22, element 17 sends a signal to actuator 23, which commands to turn off switch 24.

To put the device into action, 15 analog signals to be sent to protection unit 25, which should be able to receive them. For these purposes, Arduino Mega microcontrollers (Mega 2560, Mega ADK) can be used; however, units 1-3 and majority element 17 may be part of microcontroller 25.

To timely detect sticking the reed switch contacts and the breakage of their connecting wires, functional diagnostic units 38-40, each of which contains NOT gate 41, TIME gates 42 and 43, and OR gate 44 have been included in units 1-3.

B. *Operating Principle*

It is known that in the normal EM operating mode, the angle between the stator phase currents is 120^0; at the inter-winding fault in one stator phase – $60^0 \div 110^0$ (between fault-free phases); when one phase breaks, the fault-free phase currents are shifted by 180^0; in the event of interphase faults in the EM and its power cable, the faulted phase currents are shifted relative to the fault-free phase by $120^0 \div 180^0$ [25]. Reed switches located in the MF of each phase will trip in each of the AC half-waves. A change in the interphase shift angle and consequently the time between the reed switches' trips indicates a fault in the EM.

In the event of an inter-winding fault in EM 4, e.g. in phase A, the phase shift between the fault-free phase currents is within $60^0 \div 110^0$. The time between trips of the reed switches in units 6 and 7 is within $3.3 \le t_{tr} \le 6.1$ ms. The reed switches in units 6 and 7 trip and voltages U_6 and U_7 emerge at their outputs, which are alternately given to the inputs of timer 48 (Fig. 6). A signal from the first tripped reed switch $U_6 \ge U_{thr}$ ($U_7 \ge U_{thr}$, where U_{thr} is the threshold voltage) starts timer 48, which counts the time until a signal from the second reed switch $U_6 \ge U_{thr}$ ($U_7 \ge U_{thr}$) arrives, whereupon timer 48 stops. The time between trips of the reed switches t_{tr} fixed by the timer is stored and compared with the setting to detect inter-winding faults in comparing element 51. If $3.3 \le t_{tr} \le 6.1$ ms, a signal is sent to the input of MEMORY gate 55. In MEMORY gate 55, this signal is stored for a time equal to the AC oscillation period and then fed to majority element 17, where it is compared with signals from other units.

The signals from units 1-3 are fed in pairs to AND gates 18-20. If at least two of the three units generate signals, then OR gate 21 sends a signal to the input of actuator 23, which trips and generates a signal to turn off switch 24.

If one of EM 4 phases, e.g. phase C breaks, the fault-free phase currents are in antiphase, and the angle between them is equal to 180^0. The time between trips of the reed switches in units 5 and 6 is within $7.8 \le t_{tr} \le 10$ ms. The device works the same way as in the event of an inter-winding fault. In the event of two-phase SC in EM 4, the faulted phase currents are shifted relative to the fault-free phase by $140^0 \div 180^0$. Protection works the same way as in the event of phase failure. In the event of three-phase SC, when EM 4 is turned on, the upstream reed switch of unit 14 (15, 16) located in the MF of one of the EM 4 phases and offset from the inrush starting and self-starting currents $I_{tr} \ge 5 \div 7 I_{ratedEM}$ trips.

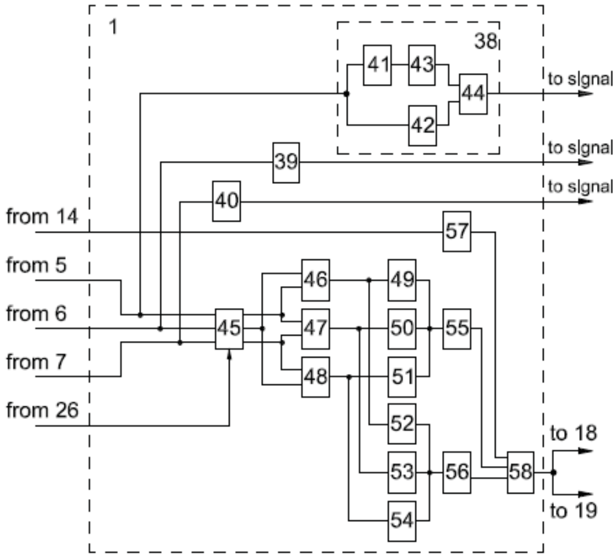

Fig. 6. Failure Detecting Unit Scheme

To prevent the protection malfunction in the event of external SC that may lead to a shift in the angle between phase currents other than that in the normal mode, a power-directional relay 27 is used. It sends a blocking signal to the inverse input of AND gate 22 and the protection does not trip.

C. *Reed Switch Troubleshooting Algorithm*

If any of units 5-13, e.g. unit 5 fails, voltage is applied to TIME gate 42, which controls the time of failure t_{fail1} (reed switch contacts closed). If $t_{fail1} \ge t_{set1}$ (t_{set1} is the time setpoint), a failure alarm is generated. The t_{set1} time is adopted equal to 0.02 s, as the reed switch trips and takes out during a single AC half-wave (0.01 s). Therefore, adopting $t_{set1} = 0.02$ s allows detecting failures that cause continuous alarms. If the wires are broken or unit 5 is destroyed due to lack of voltage, TIME gate 43 is triggered, which controls the time of failure t_{fail2} (reed switch contacts open) in the absence of a signal and if $t_{fail2} \ge t_{set2}$ ($t_{set2} = 0.02$ s), a failure alarm is generated. The failure alarms of units 5-13 and connecting wires from TIME gates 42 and 43 are sent to the alarm circuits. In this case, the protection will not malfunction as it is built based on the 2 of 3 voting logic and the failure of its individual elements does not generate a signal to turn off switch 24.

IV. CONCLUSIONS

The differential protection schemes without CTs for CUs and EMs built based on the majority principle proposed herein may function when one of three sets duplicating each other fails. The use of functional diagnostic units built based on the time-pulse principle will allow detecting the reed switch contacts sticking and monitoring the health of the connecting wires will allow avoiding the protection malfunctions in case of their failure. Simplification of the protection maintenance due to the possibility of replacing a faulty unit with a healthy one will reduce expenses for repair of the electrical installations protected.

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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