Alternative Resource-Saving Current Protections for Electric Motors

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***Abstract*—In the article the author presents the principle of operation of alternative resource-saving maximum current and longitudinal differential protections, the purpose of which is to protect high-voltage electric motors from external and internal short circuits. The presented protections are performed without the use of widely used in the electric power industry measuring current transformers (CT) with metal cores, which have significant weight and dimensional parameters and high cost. The proposed protections are made using magnetically controlled elements such as reed switches and inductance coils. Protections with their application can be used as an alternative to traditional motor protections and at the same time are not inferior to them in terms of speed. The developed protections represent an innovative approach in realization of relay protection of various electrical installations. Resource-saving of these protections is in the use of inductive coils and reed switches, which are, both in terms of cost and weight and dimensional parameters, an order of magnitude cheaper and smaller in size and weight than the above-mentioned current transformers. Protections are recommended for use in high-voltage electric motors, presented in the form of maximum current protection (MCP) and differential protection against multiphase short circuits and internal faults. The proposed protections are performed in the form of devices, with their installation inside the cell of complete switchgear (complete switchgear), voltage 6-10 kV and electric motor. The use of the presented protections increases the reliability relay protection, as protected electric motors, and the cell of the complete switchgear.**

***Keywords*—maximum current protection, longitudinal differential protection, electric motor, inductive coil, reed switch**

I. INTRODUCTION

The issue of resource saving in the power industry has been raised many times at international conferences on large power systems (CIGRE), remaining relevant for relay protection of electric motors against short circuits, without the use of expensive and having significant weight and dimensional parameters of metal-intensive current transformers (CTs) with metal cores [1]. The problem becomes even more large-scale in connection with the wide introduction together with traditional current protections, expensive microprocessor protections, reliability of tripping and non-tripping of which in some cases is sometimes insufficient [2-3]. To improve the reliability of relay protection it is advisable to use alternative protections, and to maximize the effect it is necessary to use an alternative of both the protection device and the current transformer. Works on creation of resource-saving protections without current transformers with metal cores, which have their own disadvantages, have been carried out since the 60s of the last century. Below is presented on what element base such protections are performed. Protections made on magnetic current transformers (MCT) [4]. These magnetic current transformers are used to supply relay protection circuits of both high and extra-high voltages. A magnetic current transformer is essentially an induction-type magnetic probe, which in turn is subdivided into freestanding and built-in magnetic current transformers. Protections using Hall sensors, in which the Hall effect occurs when a magnetic field is applied to the current that flows through a semiconductor [5]. The main property of this sensor is its ability to develop an electromotive force when it is placed in a magnetic field, if a current flows through it. Protections made on the basis of magnetoresistor, which has its basic characteristic, where there is a dependence of resistance on induction R=f(B) [6]. Protections made with the help of magnetodiodes and magnetotransistors, in which the magnetodiode effect is the best known effect arising when a semiconductor with non-equilibrium conductivity is placed in a magnetic field, manifested by the injection of carriers from the p-n junction when a direct current flows through them [7]. Protections made with the use of current sensors on the basis of Rogowski coil, which is a wire wound on a core of non-magnetic material, placed around the conductor in which it is necessary to measure the current flowing through it [8]. Protections based on a reed switch as part of an electrical circuit, in which the reed switch is a contact that changes its state by mechanical closing or opening, when it is exposed to a control magnetic field [9,10]. Under the influence on the reed switch of an external magnetic field created by a conductive rail, permanent magnet or control coil, the ends of the contacts are magnetized differently, their ends bending attract, closing the electric circuit.

Reed switches and inductance coils have been selected for the construction of relay protection of electric motors without

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the aforementioned current transformers. Their choice is conditioned by the fact that in comparison with other magnetosensitive elements they have important advantages for relay protection, consisting in the fact that signal transmission is carried out not through measuring circuits, but through control circuits, they can simultaneously perform the functions of the analog-discrete and measuring converter, measuring protection body, have low cost, low weight and dimensional parameters in comparison with current transformers with metal cores. Over the last decades, a number of reed and inductive coil based current protections have been developed. Below are presented which protections have been developed so far. Protection based on reed switches and inductive coils [11]. Protection based on reed switches. Relay protection based on reed switches without the use of current transformers [12]. Developed installation for the study of electromagnetic field inside the complete switchgear for the purpose of further construction of protection on inductive coils or reed switches. Designs for the installation of reed switches near busbars of electrical installations with remote selection of current protection operation settings [13]. Gas protection of power transformers based on reed switches as an alternative to the existing conventional gas protection. A multifunctional protection set that provides constant and remote control of protection performance [14]. This paper presents and discusses the principle of operation of the maximum current and differential protection of high-voltage electric motors, made in the form of devices.

II. Relevance and Scientific Significance

As it is known, the maximum current protection trips when the current of the protected high-voltage electric motor exceeds the set operating current. Longitudinal differential protection reacts to internal faults inside the electric motor.

One alternative way to detect this type of fault is to use inductance coils and reed switches instead of traditional current transformers with metal cores. In this connection it is necessary to consider the realization of maximum current and longitudinal differential protection of high-voltage electric motors in the form of devices.

III. Method

The purpose of the research: creation of alternative current protections for electric motor protection, such as maximum current and longitudinal differential current protection, made of reed switches and inductance coils, without the use of current transformers and current relays with metal cores for these protections. The main factor is the refusal to use metal-intensive, bulky and expensive current transformers and current relays.

Main tasks: to achieve the set goal it is necessary to develop a maximum current protection, as well as longitudinal differential protection for the protection of high-voltage electric motors.

IV. Resource-Saving Maximum Current Protection of Electric Motors

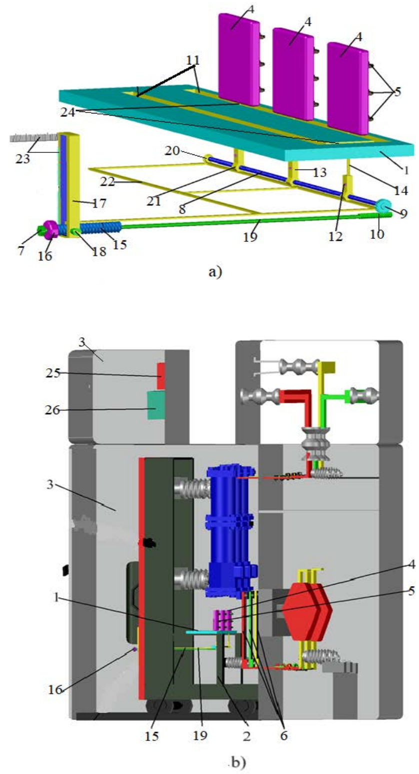


Fig. 1. Resource-saving maximum current protection of a high-voltage electric motor: (a) its device; (b) placement of the maximum current protection device inside the cell of a complete switchgear cubicle.

Maximum current protection of high-voltage electric motors, presented as a device, is installed in a cell, for example, series KRU-2 in the following sequence [15]. In this device, the platform 1 is mounted on the frame 2 of the withdrawal cart of the circuit breaker (Fig. 1a). Before installing the device in the cell 3 determine the optimal place of installation of the plate 4 with reed switches 5 fixed on it, that is, the place where the intensity of the magnetic field has the maximum value, taking into account the required distance from the current-carrying bus bars 6 to reed switches 5, as well as the angle at which they should be located, in relation to the power lines of the magnetic field created by the current bus bar 6 [16]. Moving to this optimum place of the plate 4 with reed switches 5 is carried out by rotation of the first wing 7, by means of a threaded rod 8 connected with a worm wheel 9, which has a clutch with a worm shaft 10 and is moved along the first longitudinal 11 slot of the platform 1, located at a distance of 120 mm. (minimum permissible safety distance according to the Electrical Installations Regulations for electrical installations with voltage of 10 kV). One full turn of the thumbwheel 7 is equal to moving the plate 4 from a distance of 0.5 cm. Since three plates 4 with their reed switches 5 are used, each located opposite its current-carrying busbar 6, when setting the maximum current protection only one of them is moved, for example one plate 4 with reed switches 5, the other two remaining plates 4 are not moved. This operation is carried out by tightening the first screw 12 securing inside the clamping bracket 13 the first axis 14 fixed to the plate 4, and vice versa for the other two plates 4 by unscrewing their first screw 12. At the same time, the clamping brackets 13 of the plates 4 are encamped with removal of their first axes 14. After that, one of the plates 4 moves, but the other two plates 4 do not. After reaching the optimum position of the plate 4 in the cell 3, the first screw 12 is tightened (Fig. 1a). The same operations are performed for the other two plates 4 when they are installed relative to their current carrying bars 6.

If it is necessary to install the plate 4 reed switches 5 on the second longitudinal slot 11 of the platform 1 (at a distance of 180 mm. from the conductor bars 6), it is moved from the first longitudinal slot 11 with the help of the shaft 15 - by rotation of the second thumbscrew 16 and with fixation at these positions of the shaft 15 to the first bar 17 by the second screw 18 (Fig. 1a,b). These actions are carried out as follows. Since the first 7 and the second 16 thumbs are located on the same geometric axis, when the second thumbs 16 are rotated and the distance between them equal to 0.5 cm. is overcome, the first wing 7, having connection with the second axis 19, connected to the worm shaft 10, which is connected to the worm wheel 9, having connection with the threaded rod 8, fixed on two rigid rings 20, the clamping bracket 13 with plates 4 with reed switches 5 fixed thereon by means of the first axis 14, as well as the screw nut 21 are moved to the stand 22. The distance by which the plate 4 is moved horizontally and vertically is determined by the scales 23. One full revolution of the second wing 16 is equal to moving the plate 4 from a distance of 1 cm along the transverse slit 24.

Maximum current protection of electric motors works as follows. In case of inter-phase short circuits on the motor terminals connected to the cell 3, the current exceeding the protection tripping current increases (Fig. 1b). In this case, the induction of the magnetic field acting on the reed switches 5 also increases and becomes sufficient for their operation and as a result closes its contacts one of the three reed switches 5, giving a signal to the input of the time-setting organ 25, the output of which is connected to the actuator 26, which its output is connected to the circuit breaker trip circuit (Fig. 1a, b). When operating in normal mode, the rated motor current does not exceed the protection tripping current and, accordingly, reed switches 5 are not tripped.

The presence of the first 7 and second 16 thumbs allows, at horizontal and vertical positions of the platform 1, relative to the plane of current-carrying tires 6 to realize the remote and adjustable movement of both plates 4 with reed switches 5, and the platform 1 together with these plates 4. As a result, it makes it possible to install reed switches 5 in the places of maximum magnetic field induced in the cell 3 of the complete switchgear, in order to further realize the selection of maximum current protection tripping settings.

V. Resource-saving longitudinal differential protection of high-voltage electric motors

Longitudinal differential protection of electric motors, presented as a device, consists of elements fixed in the cell of the complete switchgear in the following sequence. On the current-carrying conductors 1 of the power cable, placed inside the cable compartment 2, for example, the cell of a complete switchgear, series type K-63, in compliance with the minimum permissible distance according to the Rules of the device electrical installations, equal to 120 mm. (for electrical installations with voltage U=10 kV) from them and exactly at the middle of the length of the segment of these conductors (from the current-carrying busbars 3 to their exit from the first end coupling 4) fix the supporting stand 5 together with the first group of inductance coils (IC1–IC3) 6 [16, 17] fixed on it, located perpendicular to the plane of the cross-section of the current-carrying conductors 1 (Fig. 2a). To install the second group of inductance coils (IC4–IC6) 6 inside the electric motor 7 on the leads of its stator windings 8, a supporting stand 5 is also used (Fig. 2b). The support stand 5 itself is fixed on the middle of the stator winding leads 8 (Fig. 2b). Before installing and fixing the inductance coils (IC4–IC6) 6 on the current-carrying conductors 1 and on the terminals of stator windings 8, they are installed in the points of maximum values of the magnetic field induce induced by each conductor 1 and stator winding (closer to its terminals) 8, as well as taking into account the convenience of placement of these inductance coils (Fig.2a, b). Then turn on the circuit breaker 9 and on the first contact cores 10 of reed switches 11 the potential "plus" is applied (Fig. 2c).

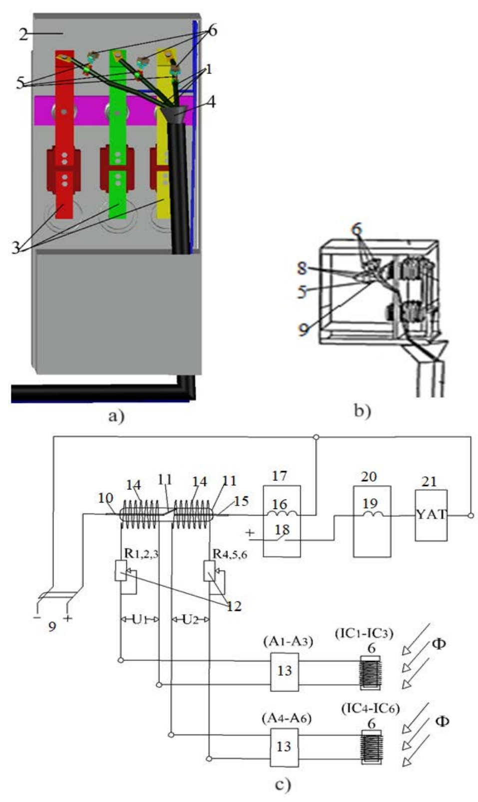


Fig. 2. Device of resource-saving longitudinal differential protection of a high-voltage electric motor: (a) placement of inductive coils in the busbar compartment of a complete switchgear cell and (b) of the terminals of the stator windings of the electric motor; (c) structural diagram of the longitudinal differential protection of the electric motor.

The operating principle of the device is based on comparison of magnetic field induction values. The protected zone is the area between the two groups of inductance coils

(IC1–IC3 and IC4–IC6) 6 having the same parameters - set by means of adjustable resistors (R1, 2,3 and R4, 5,6) 12. The effect of magnetic fluxes F created by the currents in current carrying cores 1 and stator windings 8 on inductance coils 6 is shown by arrows (Fig. 2c). The voltage amplifier (A)13 amplifies the voltage taken from the terminals of the inductance coils 6 to the required value.

Longitudinal differential protection of electric motors works as follows. In normal operation mode of the electric motor, the parameters in the longitudinal differential protection are adjusted by means of resistors 12 so that the voltages U1 and U2 coincide in magnitude. This allows the device circuitry not to react to external short circuits – outside the current carrying cores 1 and stator windings 8 of the electric motor 7 (Fig.2c). In case of a short circuit in the protected electric motor 7, the current in its stator windings 8 increases and the inductance coils 6 react to the change in magnetic field induction. As a result, an increased value of electromotive force is induced in them (Fig.2c). In this case, the voltages U1 and U2 are directed in different directions and are not equal to each other - they will be different, and in connection with this will be different and currents in the control windings 14 of the reed switch 11, creating a magnetic flux affecting the reed switch 11 (Fig. 2c). Due to the fact that this value of voltage taken from the terminals of the inductance coil 6 is small (about 5-7 V), then it is increased with the amplifier (U) 13 to a voltage value equal to U = 220 V. and fed to the first terminal of the control winding 14 reed switch 11 (Fig. 1c). As a result of reaching this difference between the voltages U_1 and U_2 - a value sufficient to trigger the reed switch 11, it under the influence of the magnetic field created by the control winding 14 triggers and closes its first 10 and second 15 contact cores, sending a signal "plus" from the circuit breaker 9 to the first terminal of the winding 16 of the intermediate relay 17 (Fig. 2c).

The relay 17, having tripped, gives a signal to the first lead of the winding 19 of the indicating relay 20 to the first lead of the trip coil (YAT) 21 of the circuit breaker through the first lead of the winding 18 connected to its closing contact. The second leads of the winding of the intermediate relay 17 and the trip coil (YAT) 21 are connected to the minus pole of the circuit breaker 9. As a result, the electric motor 7 is disconnected from the general power supply (Fig. 3).

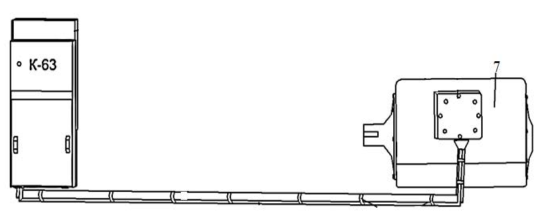
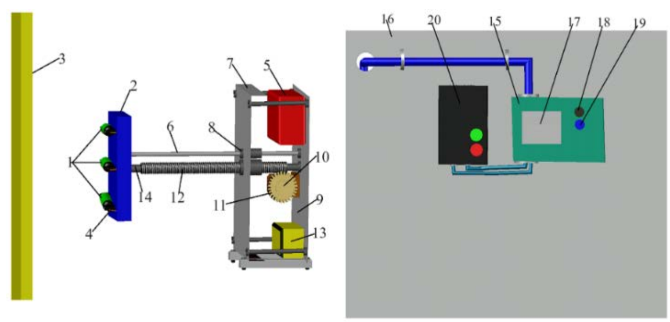


Fig. 3. Connection of the protected electric motor to the complete switchgear cell.

VI. Electrical motor current protection with remote setpoint selection

Current protection with remote setpoint selection, presented in the form of a device in its composition consists of reed switches 1 (Fig. 4a), which are mounted on the plate 2 and are located at different angles to the plane of the cross section of the current-carrying bus 3 cells KRU series K-63 [17]. The leads of contacts 4 of reed switches 1 are connected to the time-zapper 5. The plate 2 is fixed to the first end of the support post 6 and is located opposite the current-carrying busbar 3, at a safe distance from it. The other end of the support stand 6 is fixed inside the container 7 with the help of the sleeve 8, fixed to the wall of the container 7. Inside the container 7 on the platform 9 the motor-reducer 10 is fixed, on which the worm wheel 11 is mounted, as well as the worm shaft 12, the time setter 5, as which uses a time relay and the actuator 13 as which uses an intermediate relay, are installed and fastened. On the rear wall of the container 7, the platform 9, the time-holder 5 and the actuator 13 are mounted. The plate 2 is connected to the first end of the worm shaft 12 by means of the hollow cylinder 14, the second end of the worm shaft 12 is attached to the back wall of the container 7. The motor-reducer 10 is attached to the platform 9. The penstock 7 is fixed in the switchgear panel. The number of these peninsulas 7 is three, each located opposite its current-carrying busbar 3 (Fig.4a).

The gearmotor 10 is powered by the control unit 15 installed in the protective cabinet 16. On the front panel of the control unit 15 there is a display 17 for controlling the operation, as well as the "forward-backward" control buttons 18; 19 for the gearmotor 10. The control unit 15 is powered by the circuit breaker 20 (Fig.4b).



a) b)

Fig. 4. Current protection device: a) placed in the switchgear panel; b) gearmotor control unit.

Regulation of triggering parameters of current protections from short-circuit currents is carried out by approaching the current-carrying busbar 3 plate 2 reed switches 1. At the same time for one protection use one of the three reed switches 1. Moving the plate 2 by means of geared motor 10, pressing buttons 18; 19. The required distance from the plate 2 to the current-carrying bus 3 in a cubicle switchgear, defined by turning the geared motor 10, implemented by a microcontroller (not shown in the diagram) mounted in the control unit 15.

Before installing the device in the switchgear cubicle calculates the necessary distance from the current-carrying bus 3 to the reed switches 1 and the angle at which the reed switch 1 must be in relation to the lines of force of the magnetic field created by the current in the current-carrying bus 3 and according to the table, take the reed switch 1, with a given magnetomotive force of operation.

The current protection works as follows. In the busbar compartment of the cell at a safe distance equal to 0.12 m. (the minimum allowable distance according to Electrical Installation Regulations from live parts of electrical installations with voltage U=10 kV) from the live busbars 3, install three penalized enclosures 7. In the 16 bay protection cabinet place and connect the control unit 15 and circuit breaker 20. Then turn on the circuit breaker 20 supplying power to all elements of the current protection device (Fig.4b).

As an example, consider the setting of protection for phase A, made with one of the three reed switches 1 (the first), located on the plate 2 relative to the plane of the cross-section of the current-carrying busbar 3 at an angle 0^0. The remaining two reed switches 1, also located on the plate 2, are designed to provide a more accurate choice of settings, and will be used, in case the reed switch 1 (the first) cannot be selected with the necessary magnetomotive force. At the very beginning, the display 17 of the control unit 15 shows the distance to the current-carrying busbars 3 at which the plate 2 with the reed switches 1 is currently located, e.g. 0.15 m. Then by pressing the "Forward" button 18 the geared motor 10 is started which moves the plate 2 together with the reed switches 1 closer to the current-carrying busbars 3. After the display 17 shows the value 0.12 m, release button 18 and thus the reed switch 1 is smoothly set at the necessary distance from the current-carrying busbar 3 of phase A. Similarly, the current protection (the other two hangers 7) is set for the other two phases B and C.

When a short circuit in the protected electric motor, the current flowing on the current-carrying bus 3 of the switchgear panel, exceeds the current operation of protection, at which one of the reed switches 1 triggers (closes contacts), sending a signal to the time setter 6, which after a specified time delay sends a signal to the executive 13, which in turn sends a signal in the circuit breaker off the electric motor.

In nominal load modes, the electric motor current does not exceed its maximum value, and in this regard, the reed switches 1 are not triggered. The motor reducer 10 makes it possible to remotely adjust the distance from the reed switches 1 to the current-carrying busbar 3 of the switchgear panel, thus ensuring the selection of the required setting of the electric motor current protection operation, and the absence of the use of expensive and bulky current transformers ferromagnetic cores (compared with reed switches) provides significant savings in material resources, which together makes it possible to use this current protection in any series of switchgear cells to implement current protections of electric motors of any type and voltage class.

VII. Current Protection with Continuous Fault Monitoring

The principle of operation of this protection, presented in the form of a device based on the impact of magnetic fluxes Φ (shown by arrows), created by currents of current-carrying busbar of switchgear, to which is connected to the protected electric motor on the inductor coil 1 (Fig.5). This device can be installed inside the cells of a complete switchgear and closed switchgear, either for all three phases in one set, or for each phase separately in the place where there is a maximum value of magnetic fluxes. Application of the microcontroller 2 is conditioned by monitoring the serviceability of the elements of current protection, which carries out the alternate supply of potentials from a direct current source 3 and alternating voltage 4 (fig. 4a). In this case, its contacts 5 and 6, connected to the AC voltage source 4, as well as 7 and 8 are connected to a DC source 3 trigger simultaneously and in pairs, i.e., for example, when the contact closes at 6 opens contact 8 and by the same analogy with the closure of the contact 5 opens contact 7. When a short circuit of the terminals of the prtected electric motor, current in the busbars of the cell of the switchgear increases and the inductor coil 1, installed at a safe distance from the busbar "Rules for Electrical Installation" reacts to changes in the magnetic field, and it induced an increase in the electromotive force (Fig.5b). Due to the fact that the value of the voltage taken from the terminals of the inductor coil 1 has a value of about 5 V, it rises with a voltage amplifier (A) 9 to a value equal to U = 220 V (In this case the gain amplifications to $K_\alpha = \frac{U_2}{U_1} = \frac{220}{5} = 44$) and fed to the leads of the control winding 10 reed switch 11. As a result, the reed switch 11 under the influence of the magnetic field created by the control winding 10 closes its contact 12 and sends a positive potential "+" coming from a constant current source 3 to the first lead of the winding 13 of the intermediate relay 14. This relay 14, when triggered, applies potential "+" through its contact to close 15 and passes through the contact to open 7 microcontroller 2 to the first terminal of the pointer relay 16, and for it to the first terminal of the trip coil winding (CW) 17 of the electric motor switch. As a result, the protected electric motor is turned off. Triggering of the electric motor current protection is detected by the indicating relay (IR) 16.

In normal operation of the electric motor, the parameters in the voltage amplifier 9 are adjusted so that it triggers only when the voltage on its terminals exceeds 5 V, and when the voltage is less than this value, this protection from turning off the electric motor does not work. In order to ensure the reliable operation of this current protection, there is a continuous control of the serviceability of its elements. This control is performed using the microcontroller 2, which performs with a set time delay, equal to 0,02 s. (At an interval of 180 seconds) from an AC voltage source 4 of one of the phase potential "~" through its contact to close 6 to the first terminal of the voltage amplifier 9, on the second terminal of the amplifier 9 through the contact to open 8 microcontroller 2 continuously comes from a source of alternating voltage 4 of the other phase potential "~"(Fig. 5a).

After that, the voltage output from the amplifier 9 also increases to a value of U = 220 V (as in the case of a short circuit), the gain is also equal to $K_\alpha = 44$ and fed to the leads of the control winding 10 reed switch 11. The reed switch 11 under the influence of the magnetic field created by the winding 10 closes its contact 12 and sends the positive potential coming from the direct current source 3. This potential passes through the winding 13 of the intermediate relay 14, which closes its contacts 15 and 18 by triggering.

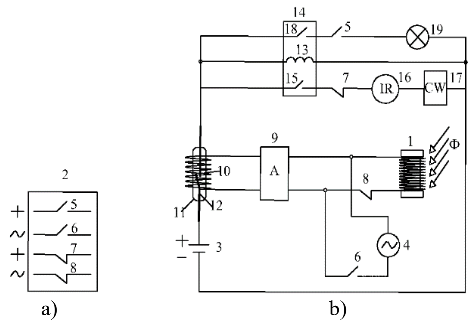


Fig. 5. Motor current protection with functional fault monitoring: a) microcontroller; b) structural protection schema

Then the positive potential flow from the contact 15 of the relay 14, as well as through the contact to close 5 microcontroller 2 to the signal lamp 19, which lights up to indicate the serviceability of the device (Fig.5b). After a time interval equal to 180 s. this check of the device operability is repeated again according to the algorithm described above. If any part of the device is damaged, there is no positive potential to the signal lamp 19 and it does not light up, which can be easily detected by the service personnel.

VIII. Recommendations and conclusions

Presented and considered protections have features, consisting in the fact that the current protection of electric motors has a function of monitoring the serviceability of their elements, which is carried out automatically without human intervention, allow you to choose their settings by remote movement of reed switches, relative to the plane of current-carrying busbars of the switchboard. This does not disrupt the operation of the motor connected to the switchboard, as it is not required to disconnect it due to the need to roll out the circuit breaker (vacuum, low-oil and others). Operations on setting of current protections are performed remotely. All structural elements of the presented protections are made of heat-resistant, durable and lightweight plastic of "PLA" type, printed on a 3D printer. The absence of current relays and current transformers (remote and built-in) with ferromagnetic cores, containing expensive copper, steel and high-voltage insulation, as well as having significant weight and dimensional parameters in these protections meets the current problem of energy - resource-saving materials, which allows to significantly save copper and steel, representing a completely new approach to the implementation of current protections of electric motors and, as a consequence, the use of the presented devices for re-protection of electric motors.

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