Multipurpose Power System Protection Set that Provides Constant Remote Serviceability Control

Dauren Dzhambulovich Issabekov
Department of Electrical Power Engineering
NPJSC "Toraigyhrov University"
Pavlodar, Republic of Kazakhstan
dauren_pvl2012@mail.ru

Abstract—**In this paper, the author suggests a principle of layout and functioning of a resource-saving power system protection set that provides remote and constant serviceability control of each element of a switchgear. It is designed to provide universal protection of each switchgear bay (operating at 6-10 kV) from internal short circuits, arc faults, and external short circuits caused by faults of power equipment connected to the set. All the proposed suggestions combined can be treated as a new approach towards protective relays usage in power system protection. This multi-purpose set can provide many types of protection. For example, quick action against short circuits causing electric arcs; overload protection based on photodiodes, thermistors and reed switches, which are reactive to light intensity and temperature change observed in the cells of the set; overcurrent protection that is based on reed switches (sensitive to the magnetic field of the conductor phases) and protects against external phase-to-phase short circuits. The use of the presented protection methods can improve protection's reliability for both the cell and the electrical equipment connected to it. The discussed protective relay set can fit switchgears of all editions, both indoor and outdoor installations.**

Keywords—reed switch, thermistor, photodiode, LED, relay, microcontroller

I. INTRODUCTION

Development of more energy- and resource-saving protective relays, which protect electrical equipment from arc faults and phase-to-phase short-circuits, started in the second half of the 20th century. One of the potential options is replacing a metal-consuming current transformer (CT) with a ferromagnetic core that has its own drawbacks with other cheaper devices. Despite the introduction of now widely used microprocessor-based relays (digital relays), searching for CT alternatives is still a relevant topic for research [1-5]. A promising alternative to CTs is a protective device based on reed switches. Reed switch is an electrical switch that consists of a pair of ferromagnetic metal contacts encased in a hermetically sealed glass envelope. It is advantageous not only to CT, but also to other magnetic field-sensitive devices. Other alternatives can be photodiodes and thermistors suitable for arc fault protection [6-18]. Since the start of the 21st century, there have been a series of reed switch-based protection devices already produced suitable for placing inside the switchgear bay, convenient for both control and maintenance [19]. This work is focused on the metal-enclosed indoor switchgears due to their wide use in the electric power industry and discusses novel approaches towards power system protection. For example, quick protection against arc faults inside a switchgear bay (demonstrated on K-63 series), overcurrent protection and phase-to-phase short circuit protection [20]. These cells are widely used in the substations of industrial enterprises, where the current-carrying busbars are made of aluminum, and the housing is a rigid metal casing, with placement of all the necessary equipment in it. Cell enclosures are made of 2.5 mm thick sheet steel. On the front side of the cells there are doors of instrument compartment and withdrawable cart compartment. Cell K-63 has a removable wall of busbar compartment and a door of cable compartment. Service life of the cells is at least 25÷30 years. Designation K-63-10-20-U3: figures 63 is a series of execution; 10 is rated voltage, kV; 20 is rated current, kA; У3 is climatic modification and placement category.

II. OPERATING PRINCIPLE OF REED SWITCH OVERCURRENT PROTECTION

The reed switch is used as an element base in various relays, buttons, switches and other electrical devices [14].

Under the influence of a magnetic field created by a current-carrying busbar or a permanent magnet on the reed switch, the ends of its contacts are magnetized oppositely and bend to attract each other, closing the electrical circuit. Figure 1 shows common types of reed switches used [15]. In the presented overcurrent protection of electrical installations reed switches type KM-2 and MKC-27103 are used.

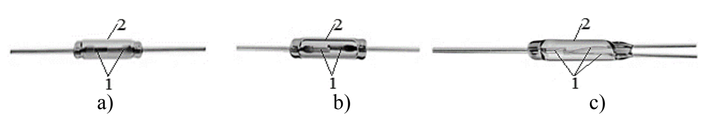

Fig. 1. Types of reed switches. a, b - closing, type MKA-20101 and KM2; c - switching, type MKC 27103: 1 - reed switch contacts; 2 - glass flask

Current protection with reed-based functional scheme consists of the following elements (fig. 2): 1 - reed switch, 2 - pulse expander, 3 - time relay, 4 - intermediate relay [6]. At the same time the time relay in some protections can be not used.

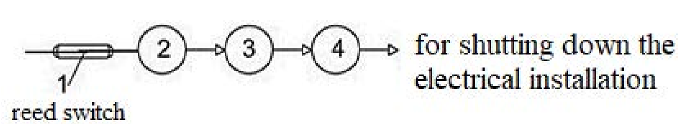

Fig. 2. Functional scheme of current protection on a reed

The principle of operation of the presented functional scheme is similar to that of traditional protection circuits with current transformers and current relays with ferromagnetic cores. The structural scheme works as follows. When a short circuit occurs on the outputs of the protected electrical installation, then there is a short-circuit current, which is many times the rated current of the electrical installation. Just under these conditions changes and the value of the magnetic field - it also increases. As the reed switch is located in the zone of action of the magnetic field, respectively, its contacts close or open, depending on the initial conditions. Contacts of reed switch type KM-2 in this case close, transmitting a signal to the pulse expander, the signal from it goes to the time relay, which after counting down a certain time interval sends a signal from its contacts to the intermediate relay, from which after triggering the signal goes to the coil trip circuit breaker. As a result, the protected electrical installation is disconnected.

If the reed switch is located at a safe distance h, for example, from the current-carrying busbar of phase A in the plane of its cross section [14], and without considering the influence of the remaining phases, according to the Bio-Savara-Laplace law, the reed switch actuates at an induction equal to [6]:

$$B_{PA} = I_{PA} \cos\varphi \mu_0 / 2\pi h = I_C \, \omega_C \mu_0 / L_C = F_C \mu_0 / L_C = H_{PA} \mu_0 \quad (1)$$

where I_{PA}, H_{PA} and B_{PA} are the minimum values of the current in the current-carrying bus, the strength and induction of the magnetic field, at which the reed switch is activated; ω_C- the number of turns of the inductance coil; L_C - the length of the inductance coil; μ_0 - magnetic permeability of air equal to $\mu_0 = 4\pi \cdot 10\text{-}7$ H/m.

However, in this way, the operating current I_{PA} is determined in electrical installations for direct and single-phase alternating current. In three-phase electrical installations, the operation current I_{PA} data already depends on the type of short circuit itself. And in this regard, a magnetic field with induction acts on the reed switch or inductance coil, which are located at distances L_A, L_B and L_C from current-carrying tires [16; 2]:

$$B = \mu_0 / 2\pi (I_A \cos_{\alpha A} / L_A + I_B \cos_{\alpha B} / L_B + I_C \cos_{\alpha C} / L_C), \quad (2)$$

where α_A, α_B, α_C — is the angle between the vector B_A, B_B, B_C of the induction of the magnetic fields created by the currents I_A, I_B, I_C of the three phases A, B, C and the axis of the reed switch itself.

Since the operating principle of reed current protection remains the same as that of conventional protection, it should not trip during self-start of electric motors:

$$I_{PA} \geq I_{OP.MAX} \cdot k_{OFF} \cdot k_{SELF}, \quad (3)$$

where $I_{OP.MAX}$– is the maximum operating current in the current-carrying bus under consideration; k_{OFF} and k_{SELF} are the detuning factor and the self-starting factor of the electric motor.

However, it is impossible to use formula (3) because the reed switch reacts to the magnetic flux and not to the current flowing in the current-carrying busbar. The reed switch is triggered at an induction equal to B:

$$B = B_P = F_P \mu_0 / L_C. \quad (4)$$

The sensitivity factor of protections, made on reed switches, as for traditional protections on current transformers with ferromagnetic cores is determined by formula 5:

$$k_{SENS} = I_{SC.MIN} / I_{PA}, \quad (5)$$

where $I_{SC.MIN}$ – is the minimum short circuit current, I_{PA} – is the protection operation current.

At the same time, this sensitivity coefficient for current protection made on reed switches in case of damage at the end of the protected section should have a coefficient equal to $k_{SENS} \geq 2$, and at the end of the reserve section $k_{SENS} \geq 1.6$, since the magnitude of the reed switch actuation current I_{PA} can be 30% more than the rated current, due to the installation error of the reed switch itself.

And for the reed switch and the inductance coil, the sensitivity coefficient is determined by the formula:

$$k_{SENS} = B_{SC.MIN} / B_{PA}, \quad (6)$$

where $B_{SC.MIN}$ – is the induction of the magnetic field created by the minimum short-circuit current flowing in the current-carrying busbars of the protected bay and at the reed switch installation point.

If the reed protection has the required sensitivity to short-circuits, then select a reed switch from the reference books with an induction of operation equal to:

$$B_{P.S} = F_P \mu_0 / L_C \approx B_{PA.S} \quad (7)$$

III. Overload and Arc Protection Device

In case of a short circuit over phase-to-phase arc as in busbar section 1, in circuit breaker section 2, and in cable section 3 of the switchgear, or in case of overload, the illumination changes inside this bay section. Also the temperature of the current conducting bus 4 increases. Here, the photodiodes (FD1-FD3) 5, which are placed on the cooling aluminum radiator, react to the occuring flash. At the same time, one of the thermistors (TR1-TR3) 6 reacts to the temperature change of the current conducting bus (fig 3a,3b).

First output of photodiodes 5 and thermistors 6 is connected to the positive pole of the DC generator (DC) 7, while the second one is connected to the first output of the control winding 8 of the first reed switches 9 (figs 3,4). The second output of the control winding 8 goes to the negative pole IP 7. The signal of photodiode 5 or thermistor 6 goes to the first output of the control winding 8 of reed switches 9, which are stationed inside the winding 8, and fixed together on the plate. The voltage over the winding 8 should be enough for the reed switches 9 to trigger. The closing contact 10 of the reed switches 9 is connected to the positive pole of DC 7. After a time delay of 0.02sec (this delay is necessary for filtering out possible short-term noise) it triggers and sends a signal on the first contact of the winding of one of the three two-contact time-delay relays 11, either the first relay (KT1), the second (KT2), or the third one (KT3) (fig 3). In its turn, one of the three relays 11 triggers after 0.08sec delay and closes its first contact (considering additional delay for the contact closure) (KT 1.1, KT2.1, or KT3.1) 12. Then, the signal reaches the first output of the winding of one of the three intermediate relays 13. It can be either KL1, KL2 or KL3.

This intermediate relay causes the closure of the contacts 14 (KL1.1, KL2.1, or KL3.1) and sends a signal to the first output of the trip coil of the circuit breaker (YAT) 16 via the index relay 15, either KH1, KH2 or KH3 index relay. The second contact of the trip coil is connected to the negative pole of IP 7. As a result, the circuit breaker switches off (fig 4). When one of the three index relays 15 triggers, "Arc fault protection" or "Overload" flash starts to blink.

IV. OVERCURRENT PROTECTION DEVICE

In case of phase-to-phase short circuit (in electrical equipment connected to a particular switchgear bay), the magnetic field parameters inside the switchgear bay change. At the same time, the induction force of the current conducting bus 4 increases enough to trigger the second reed switches 17 (fig 3, 4), which include switching 18, opening 19 and closing 20 contacts. The contacts 20 close. The switching contacts 18 are connected to the positive pole DC 7. Then, after 0.02 sec delay () the signal coming out of the closing contacts 20 goes to the first output of the windings of either fourth (KT4), fifth (KT5) or sixth (KT6) time-delay relay 21 (fig.3). The given relays 21 after a 0.15 sec delay send a signal through the first timed-closed contact (KT4.1- KT6.1) 22, which goes to the first output of the windings of either fourth (KL4), fifth (KL5) or sixth (KL6) intermediate relay 23.

Through closing contact (KL4.1- KL6.1) 24 these intermediate relays are connected to the first output of the windings of either fourth (KT4), fifth (KT5), or sixth (KT6) index relay 25. The index relays 25 through the second output of the windings are connected to the first output of the trip coil of the circuit breaker (YAT) 16. In case one of the three index relays 25 triggers, "Overcurrent" flash starts to blink.

The regulation of the overcurrent protection triggering is done by bringing the second reed switches 17 placed on bar 26 closer to the current conducting bus 4. The distance between the bar 26 and the bus 4 should be kept equal to 120 mm, according to the safety regulation (Electrical equipment arrangement regulations) [21]. For one type of power system protection one out of three reed switches 17 is used. Moving the bar 26 horizontally is done by loosening or tightening the first screws 27, which are attached to the axles 28 along the slots 29 and plates 30. Vertical movement is done by loosening or tightening the clamps 32 and axles 28. Meanwhile, the desired displacement of the second reed switches 17 is monitored on two scales, 33 and 34 (fig 3a, 3b).

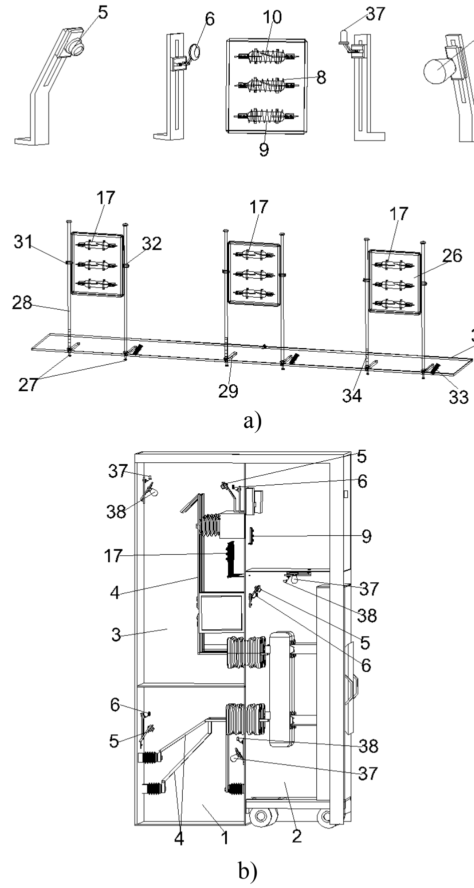

Fig. 3. Overcurrent, overload and arc protection devices and their components: a) location of multipurpose power system protection with constant remote serviceability control inside a switchgear bay b)

Before placing the overcurrent protection device inside a switchgear bay, two values should be evaluated: the required distance between the bus 4 and the reed switches 17 and the angle these reed switches and the magnetic lines of force, which are induced by the current conducted by the bus 4. The type of the reed switches 17 is choses according to the reference data with the configured magnetomotive force (fig.3b).

V. DIAGNOSTICS OF FAILURES IN RELAY PROTECTION

During operation, various faults can occur in relay protection devices. They are the cause of malfunctions of protection devices - when the devices are not able to perform their functions properly under failure conditions and normal modes of operation of the protected electrical installation. During operation, the reliability of the operation of protection devices is ensured through periodic diagnostics [22]. The final result of fault diagnosis - the result of the technical condition of the protected current protection device, indicating the location, type and cause of the fault.

Fault diagnostics is a set of means with the diagnosing device itself, which have the following types: a) according to the scope of the device: general - to diagnose the device as a whole and local - to diagnose only part of the device; b) according to the interaction between the protection device and diagnostics means; test diagnostics - the protection device is fed test signals, functional diagnostics, carried out during the protection device, which is exposed only to operating signals; c) according to the applied means Fault diagnostics of the protection device is carried out according to the algorithm, which has the composition and order of inspections of the diagnostic device and the method of analysis of their results.

During the operation of the current protection device it is necessary to check its serviceability. The available methods and means of maintenance prove to be ineffective in conditions of a significant increase in the number of installed sets of relay protection [22]. An effective measure to improve the maintenance of relay protection systems and increase their reliability is automation of monitoring their technical condition. This control of technical condition can be carried out in the form of test diagnostics.

Test diagnostics of protection failures. It consists in supplying to the input of the existing protections in the planned time of the diagnosed input signals, which imitate the failure. The state of the protection is evaluated by the results of analysis of its reaction to these signals. Diagnostics is carried out as with disconnected protection devices and protected electrical installation, and in the process of their operation. In this case the return of the tested protection, triggered by the test signal, must necessarily occur before its output organ to shutdown begins to act.

VI. Diagnostics of the Components of the Multipurpose Power System Protection Set

In order to achieve reliable operation of the arc and overload protection device, its serviceability should be constantly monitored and controlled. The control is done by using a microcontroller (MCU) 35, whose positive and negative contacts are connected to the DC generator DC 7. The MCU has a preset time delay equal to 0.06 sec, after which it sends a diagnostic signal to (of positive potential) through the closed contact 36 (KL1.2, KL2.2, KL3.2) of first, second and third intermediate relay 13 to the first output of the LEDs 37 (SV1-SV3) and the filament light bulbs 38 (FL1-FL3). The negative potential of the MCU 35 is constantly sent to the second output of the LEDs 37 and the filament light bulbs 38 (fig.4).

When the LEDs 37 and the filament light bulbs 38, which are fixed inside the switchgear bay, trigger, a flash of light occurs and actuates the photodiodes 5. A temperature increase concurrently triggers the thermistors 6. After that, the diagnostic signal goes to the control winding 8 of the first reed switches 9. The control winding 8 causes magnetic field induction that actuates the closing contact 10 of the first reed switches 9 (fig.3,4). Next, the two-contact time-delay relays 11 become activated and close the second timed-closed contacts 39 (KT1.2, KT2.2, KT3.2) after a 0.02 sec delay.

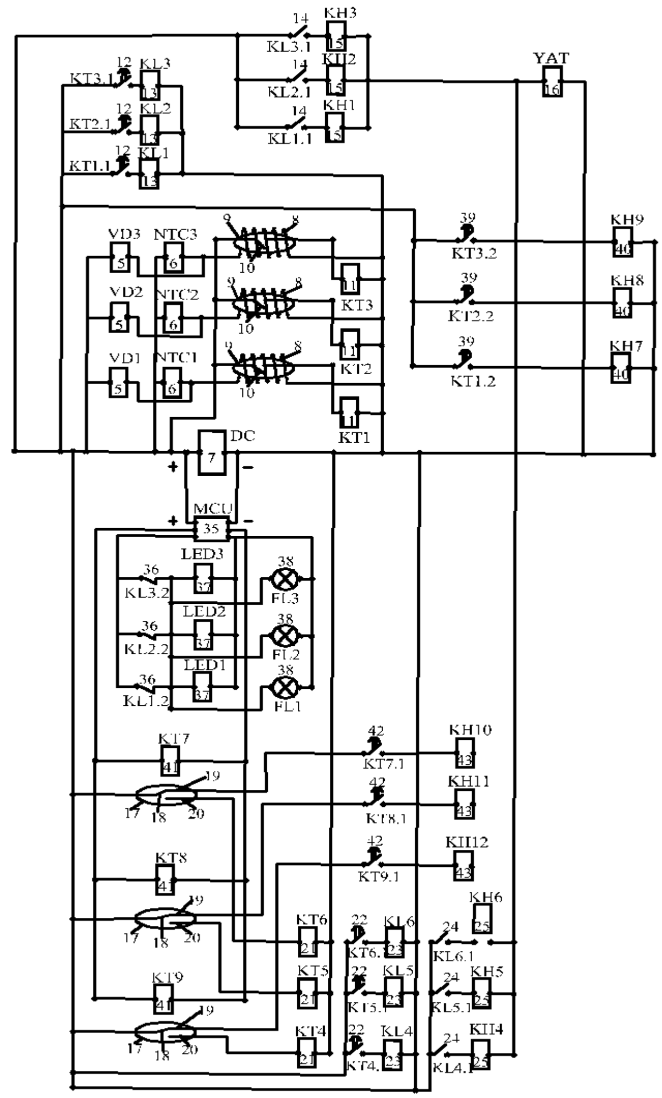

Fig. 4. Structural schematics of the multipurpose power system protection set with a constant remote serviceability control

From the contacts 39 the diagnostic signal goes to the first output of the windings of seventh (KH7), eighth (KH8) and ninth (KH9) index relays 40, which indicate the activation of the serviceability control circuit. The first timed-closed contacts 12 of the time-delay relays 11 with a 0.08 sec delay send a signal to the intermediate relays 13. However, the intermediate relays 13 do not make it due to the longer delay (0.08 sec), which is longer than the second contacts' delay (0.02 sec) (fig.4).

For the purpose of the serviceability control of the overcurrent protection device the diagnostic signal (positive and negative potentials) are initiated by the MCU 35 with a 0.01 sec time delay, which sends it to the winding of seventh (KT7), eighth (KT8) and ninth (KT9) time-delay relays 41. The positive potential of the DC generator 7 goes through the switching contact 18 and opening contact 19 of the second reed switches 17 to the timed-closed contacts 42 (KT7.1, KT8.1, KT9.1) of the time-delay relays 41. The relays 41 close the contacts 42 after a certain delay and send the diagnostic signal to the first output of the windings of tenth (KH10), eleventh (KH11), and twelfth (KH12) index relays 43. The relays 43 inform about actuation of the serviceability control circuit of the overcurrent protection device (fig.4).

After a time interval equal to 600 sec that is preset on the MCU, the serviceability control of all components of the power system protection device starts again and the diagnostic signals resume the procedure described above.

Since the MCU, the time-delay relays (first-ninth), the intermediate relays (first-sixth) and the index relays (first-twelfth) are installed in the protection cabinet, a constant remote control of serviceability is necessary for ensuring the reliable operation of the power system protection set (fig.3b).

In case of malfunctioning or damage of one of the components, the first and second reed switches do not receive a diagnostic signal. Hence, the seventh and twelfth index relays do not actuate, which can be conveniently detected by the maintenance personnel.

VII. CONCLUSION

The presented universal set of relay protection performs simultaneously the functions of three protections - from arc short circuits, from overcurrent and from inter-phase short circuits, while carrying out constant control of the state of health of all its elements. Absence of use of metal-intensive, expensive and bulky current transformers with ferromagnetic cores meets the urgent issue of relay protection - resource saving, which has significant priorities in the power industry. All structural elements of this set are made without using any metal constructions, namely from light and durable plastic of "PLA" type, printed out on 3D printer. The result is that all of the above together allows to use this universal kit to implement all the presented protections.

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