Comprehensive Protection of Furnace Transformers on Magnetically Sensitive Elements

Mark Kletsel
dept. Electrical Power Engineering
Toraighyrov University
Pavlodar, Kazakhstan
mkletsel@mail.ru

Alexandr Barukin
dept. Electrical Power Engineering
Toraighyrov University
Pavlodar, Kazakhstan
alexbarukin@mail.ru

***Abstract*—A comprehensive protection of furnace transformers on magnetically sensitive elements is proposed, consisting of differential protection and protection against damages to individual phase conductors from low voltage side. In differential protection, a reed switch is installed on the lower side near the conductors of each phase. Its control winding is connected to the current transformer from the higher voltage side. The magnetic fluxes created by the currents in the mentioned conductor and in the winding are compared. If their difference exceeds the value required for the reed switch to operate, it gives a command to turn off the transformer switch. In the first protection against damages to the conductors, the EMF induced in them by the currents of the conductors at *n* (*m*, *p*) points near phase A (B, C) is measured using inductance coils, the average EMF values from the *n* (*m*, *p*) coils are determined, and if one of the values reaches the specified value, the mentioned command is given. In the second protection, three equal groups of phase conductors are each covered by a Rogowski coil; the EMF induced in them by the currents in the conductors are compared with each other, and if the difference of any pair of EMF exceeds a certain value, a signal is given to turn off the switch. Schemes of all developed protections and detuning from the influence of voltage regulation under load of the protected transformer are given. The behavior of the protections in various modes is analyzed.**

***Keywords*—furnace transformer, differential protection, reed switch, inductance coil, Rogowski coil, conductor, damage**

I. Introduction

Transformers supplying arc steelmaking and ore-thermal furnaces operate in a mode close to short-circuit (SC), and have a wide range of regulation of the transformation coefficient, which causes the flow of sufficiently large currents (from 25 kA) from their low voltage [1–6]. For this reason, current transformers are usually not installed here. Thus, the only protection against damages from the low voltage side of the furnace transformer is overcurrent protection, which is set on the side of its higher voltage and is detuned of the maximum operating current of the furnace. Often, this current differs slightly from the current at phase-to-phase SCs behind the transformer, so the protection may be insensitive to these damages [7, 8]. Also, the protection cannot detect breakages of individual conductors of the same phase from the low voltage side of the transformer and SCs between them. Differential protection can be more sensitive to phase-to-phase SCs behind the transformer. However, for the possibility of its implementation, it is necessary to use such current sensors that could become an alternative to current transformers from the low voltage side of the transformer, taking into account the above-mentioned features of its operation. Works [9–20], as well as our developments [21–31] on the construction of protections on reed switches for 6-35 kV networks are devoted to such current sensors (work has begun [32, 33] on the construction of protections for higher voltage networks as well). This paper proposes a comprehensive protection of furnace transformers on magnetically sensitive elements, consisting of differential protection and protection against damages to individual phase conductors from the side of their low voltage.

II. Differential Protection of Furnace Transformers

A. Protection Scheme

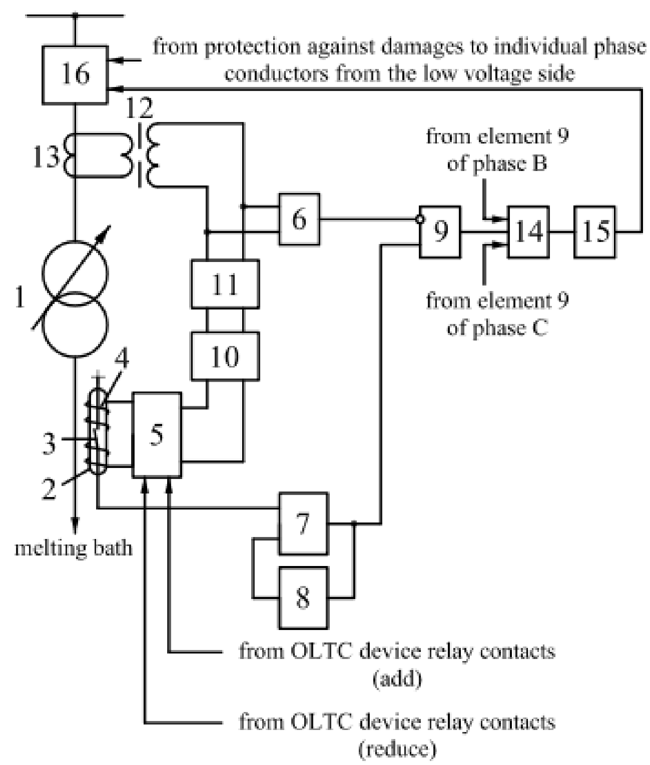

Fig. 1. Functional Scheme of Differential Protection

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

978-1-7281-4587-7/21/$31.00 ©2021 IEEE

The differential protection scheme (Patent of the Republic of Kazakhstan No.19001) contains for each phase of the furnace transformer 1 (Fig.1) reed switch 2 with normally open contacts 3 and put on it a control winding 4, block 5 of the detuning from the influence of an on-load tap-changer (OLTC), block 6 for monitoring the presence of aperiodic component in the inrush of the magnetizing current, elements 7 MEMORY, 8 TIME and 9 AND with two inputs, one of which is inverse, phase-turning scheme 10, voltage limiter 11, transreactor 12, current transformer 13 and also common to all phases element 14 OR and executive body 15, acting on switch 16.

The scheme of the block 5 of the detuning from the influence of an OLTC contains (Fig. 2): resistors 17–20; relays 21–24; elements 25-28 NOT; triggers 29-36 with an element AND at the input; elements 37–40 AND with three inputs, among which one is inverse; elements 41-44 AND with three inputs, among which two are inverse. The number of elements in block 5 depends on the number of control stages. Fig. 2 for example shows a scheme for a transformer having ±2 tap-changer taps.

B. Operation of the Scheme

Reed switch 2 with winding 4 is fixed in the magnetic field of the phase conductor from the low voltage side of the transformer 1. The induction $B_{cond.}$ of the magnetic flux (MF) created by the current in the conductor acts directly on the contacts 3 of the reed switch. Its control winding 4 through the block 5, phase-turning scheme 10 and voltage limiter 11 is connected to the secondary winding of transreactor 12, the primary winding of which is connected to the secondary winding of the current transformer 13, installed on the high voltage side of the transformer 1. Thus, the current $I_{wind.}$ (proportional to the phase current from the higher voltage side) passes through the block 5 into the winding of the reed switch 2, creating a MF, the induction $B_{wind.}$ of which also acts on its contacts.

The parameters of the winding 4 of the reed switch 2, its position in space, the parameters of the block 5 and the transreactor 12, as well as the transformation ratio of the current transformer 13 are selected so that in the load mode of the protected transformer 1 and with external SCs, conditions $B_{op} \geq B_{unb.1} = k_{det}\left(B_{wind.}^{load} - B_{c}^{load}\right)$ and $B_{op} \geq B_{unb.2} = k_{det}\left(B_{wind.}^{ext.SC} - B_{c}^{ext.SC}\right)$ are satisfied, where $k_{det} = 1.5$ is the detuning coefficient; B_{op} is the induction of the MF, under the action of which the reed switch is operated. Therefore, the reed switch 2 does not operate and the protection does not work.

When the transformer 1 is switched on under voltage or when the voltage is restored after disconnecting the external short circuit, the inrush of the magnetizing current (IMC) is thrown. If this is an aperiodic IMC, then the reed switch 2 is operated, since there is no current in the phase conductor from the low voltage side of transformer 1 $\left(B_{c}^{IMC} = 0\right)$ and only induction $B_{wind.}^{IMC} > B_{op}$ acts on the reed switch through the winding. The signal from the contacts 3 of the reed switch 2 through the element 7 MEMORY is fed to the direct input of the element 9 AND (the element 8 TIME is also started). The inverse input of element 9 AND is connected to the block 6 for monitoring the presence of aperiodic component in the IMF, at the output of which there is a signal. Therefore, there is no signal at the output of element 9 AND, and the protection does not work. After time $t = 0.1$ s, the signal from the output of element 8 TIME goes to the reset input of element 7 MEMORY. With periodic IMC, the reed switch 2 does not operate, since in addition to the above-mentioned detuning from the inductions $B_{unb.1}$ and $B_{unb.2}$, the induction of its operation B_{op}, by analogy with traditional protections, is selected so that the condition $B_{op} \geq 1.3 B_{wind.,rat.}$ is satisfied, where $B_{wind.,rat.}$ is the induction of the MF created by the current $I_{wind.,rat.}$ in the reed switch winding is proportional to the nominal phase current from the higher voltage side of the transformer 1. Therefore, the direct input of element 9 AND the signal is not received and the protection does not work.

In the internal SC mode in the transformer 1, the reed switch 2 is operated by the induction $B_{wind.}^{int.SC}$ of the MF created by the current $I_{wind.}^{int.SC}$ in its winding 4, and through the element 7 MEMORY it sends a signal to the direct input of the element 9 AND (the element 8 TIME is also started). Block 6 recognizes the SC current and there is no signal at its output. Thus, at the output of element 9 AND, a signal appears, which through element 14 OR triggers the executive body 15. The protection is operated, and the switch 16 turns off the transformer 1. After time $t = 0.1$ s, the signal from the output of element 8 TIME goes to the reset input of element 7 MEMORY.

When regulating the voltage under load in the block 5 of the detuning from the influence of an OLTC from the relay contacts (not shown in Fig. 2) of the OLTC device, an additional resistance is shunted (when decreasing) or introduced (when increasing the voltage). Its nominal value must be such that the equality $B_{c} = B_{wind.}$ is observed. In this case, the protection does not react to changes in the tap position of the OLTC device.

Block 5 works as follows. Suppose transformer 1 operates with an OLTC located on tap -2. When the voltage drops in the network, it is necessary to raise it by switching the OLTC device one step higher, and therefore reduce the current $I_{wind.}$ in the winding 4 of the reed switch 2.

When switching the OLTC device to -1 tap, the automation device operates, the final relay of which is the "add" relay. The inputs of element 25 NOT and trigger 29 are connected to one of the contact groups of this relay. When the contacts of the relay "add" are closed, trigger 29 and relay 21 are triggered, and from the secondary winding of the transreactor 12 the current is supplied to the winding 4 of the reed switch 2 through the resistor 17. After releasing the contacts of the "add" relay, a trigger 30 is operated through element 25 NOT, preparing the scheme to wait for the next signal from the same relay or from the "reduce" relay.

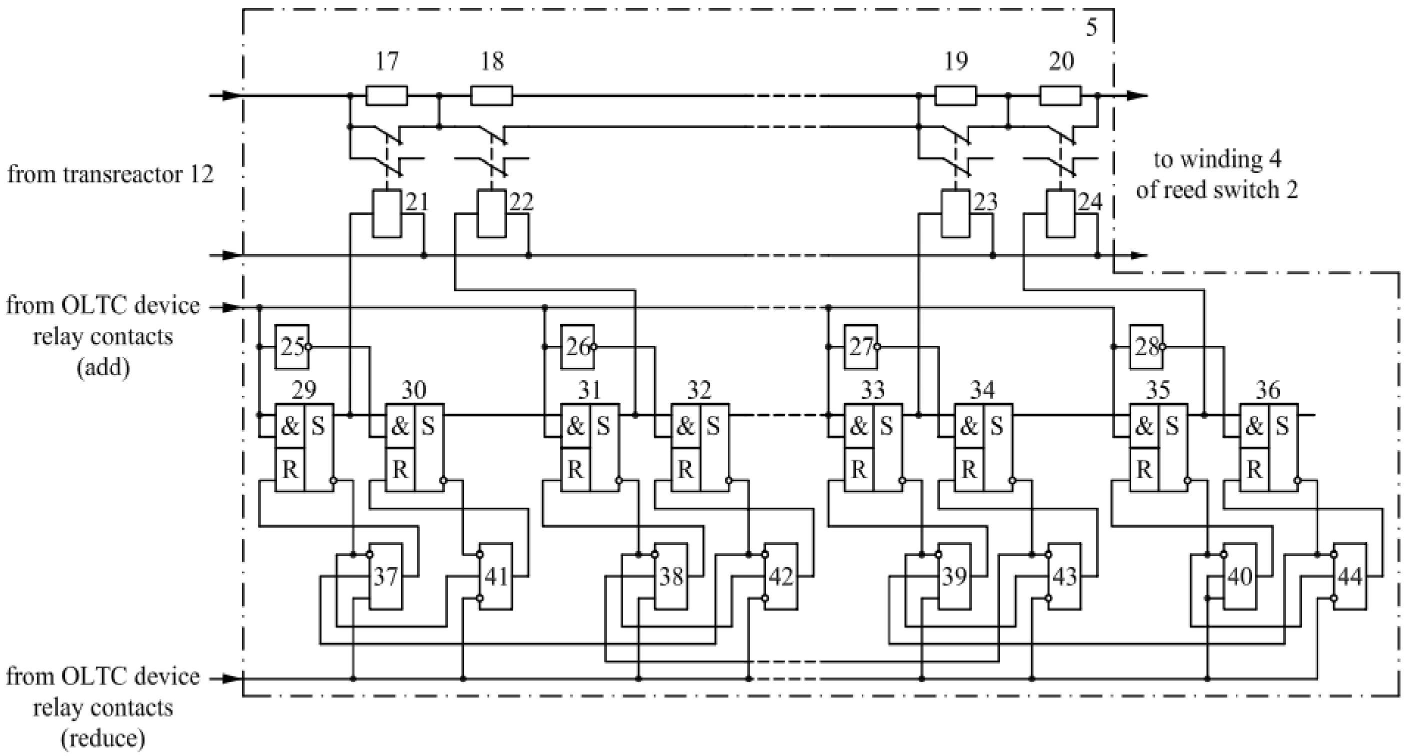

Fig. 2. Scheme of the Block of the Detuning from the Influence of an OLTC

When the voltage in the network increases, it is necessary to reduce it by switching the OLTC device one step lower, and therefore increase the current $I_{wind.}$ in the winding 4 of the reed switch 2. When the contacts of the relay "reduce" are closed, a signal appears at the output of the element 37 AND, which will reset the trigger 29. The relay 21 will return to its original position, thereby shunting the resistor 17 with its contacts, and the current from the secondary winding of the transreactor 12 to the winding 4 of the reed switch 2 will be fed through its contacts. After the trigger 29 is reset, the signal from its inverse output goes to the input of element 41 AND. The latter will work and the signal from its output will reset the trigger 30, preparing the scheme to wait for the next signal from the relay "add" or"reduce".

If there is an OLTC device on the transformer 1 with a large number of control stages, additional cascades of elements are connected to the circuit in the gap of connections shown in Fig. 2 dotted, and the total number of cascades should be equal to the number of taps of the OLTC.

III. Protection of Furnace Transformers Against Damages to Individual Phase Conductors from Their Low Voltage Side

A. The First Protection Variant

The protection scheme (Patent of the Republic of Kazakhstan No. 31950) is shown in Fig. 3, *a*. Here: 1, 2, 3 – groups of conductors of phases A, B, C from the low voltage side of the furnace transformer; 4, 5, 6, n (n+1, n+2, n+3, n+m; n+m+1, n+m+2, n+m+3, n+m+p) – EMF sensors (as which, for example, inductance coils can be used) located near a closed non–magnetic core covering group 1 (2; 3) of conductors of phase A (B; C) 7, 8, 9 – adders; 10, 11, 12 – dividers; 13 – setpoint setting block; 14, 15, 16 – comparison schemes; 17-element OR; 18 - output intermediate relay, the contacts of which are included in the circuit of disconnecting the switch of the furnace transformer (Fig. 1).

In normal modes, when there is no damages to the conductors in any phase, the average EMF values from *n*, *m* and *p* sensors ($E_n^A = \frac{\sum_{i=1}^{n} E_i}{n}$, $E_m^B = \frac{\sum_{j=1}^{m} E_j}{m}$, $E_p^C = \frac{\sum_{q=1}^{p} E_q}{p}$) located near phases A, B and C are less than the specified reference value $E_{ref.}$, as a result of which there are no signals at the outputs of the comparison schemes 14-16 and the protection does not work.

When a SC between the two conductors is in phase or when the fastening of a conductor is loose (when changing the resistance in the contact area) changes one of the average values of EMF (E_n^A, E_m^B or E_p^C depending on the phase in which the damage occurred), which is becoming more than $E_{ref.}$, with the result that the output of one of the comparison schemes 14–16 appears a signal, which is fed to the output intermediate relay 18, which gives a command to turn off the switch of the furnace transformer.

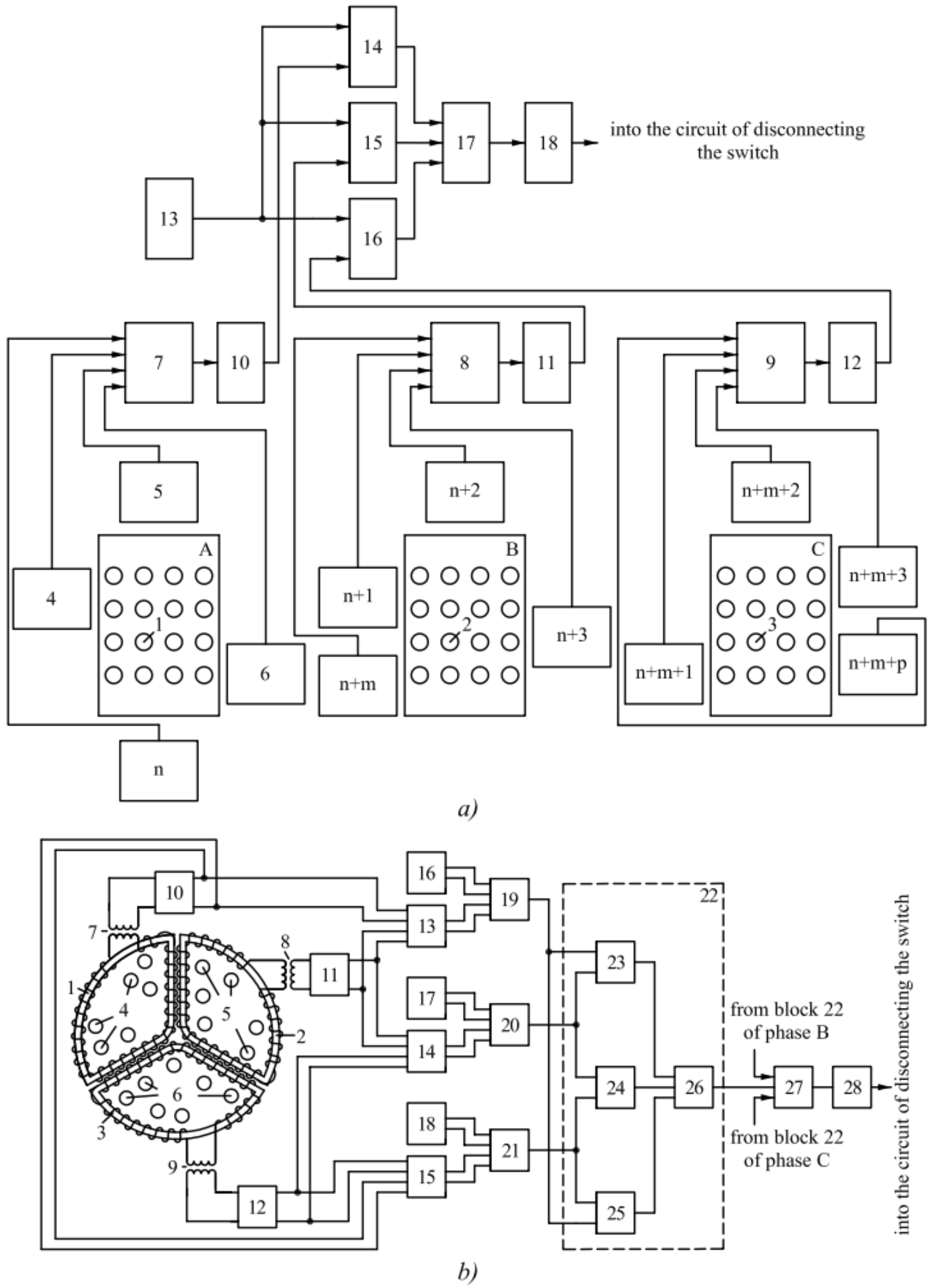

Fig. 3. Functional Schemes of the First (*a*) and Second (*b*) Variants of Constructing Protection of Furnace Transformers Against Damages to Individual Phase Conductors from their Low Voltage Side

B. *The Second Protection Variant*

The protection scheme (Patent of the Russian Federation No. 2618216) contains for each phase of the furnace transformer from the low voltage side the Rogovsky coils 1-3 (Fig. 3, *b*), covering the first 4, second 5 and third 6 groups of phase conductors, isolation transformers 7–9, rectifiers 10–12, subtractors 13–15, reference setters 16–18, comparison schemes 19–21, logic block 22, made in the form of elements 23–25 AND and 26 OR, as well as common for all phases element 27 OR and output intermediate relay 28, whose contacts they are included in the circuit of disconnecting the transformer switch (Fig. 1).

When there is a SC between two conductors in the phase, for example, in the first group of conductors 4, the current in the conductors of the damaged phase changes, as a result of which different EMF values are applied to the inputs of the subtractors 13 and 15. From the subtractors 13 and 15, the voltages are fed to the comparison schemes 19 and 21, where they are compared with the reference setters 16 and 18. The value of the reference voltage $U_{ref.} = k_{det} U_{unb.}$ is selected taking into account the detuning from the unbalance voltage $U_{unb.}$ in the normal mode, which may occur due to the inequality of turns in the Rogovsky coils, and most importantly – due to the asymmetric arrangement of the conductors in each group. Then, from the outputs of the comparison schemes 19 and 21, signals are sent to element 25 AND. The use of signals from two comparison schemes for each of the elements 23–25 AND allows to implement the majority principle of "2 out of 3", which ensures an increase in the reliability of operation and non-operation of protection. Further, the signal through the elements 26 and 27 OR goes to the output intermediate relay 28, which gives the command to turn off the switch of the furnace transformer.

IV. Conclusions

The use of magnetically sensitive elements (reed switches, inductance coils and Rogovsky coils) allows to implement a comprehensive protection of furnace transformers, consisting of differential protection and protection against damages to individual phase conductors from their low voltage side. At the same time, the proposed differential protection due to the presence of a block of the detuning from the influence of the operation of the transformer's OLTC device will have a higher sensitivity than known analogs. The proposed two variants of constructing protection against damages to individual phase conductors make it possible to detect not only breakages and short circuits between them, but also to weaken their fastening. The introduction of the considered comprehensive protection of furnace transformers will allow achieving a significant economic effect due to the reduction of their downtime and repair costs due to the timely detection of emerging damages.

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").

References

[1] R. Dugan, "Simulation of arc furnace power systems," IEEE Transactions on Industry Applications, no. 6, pp. 813–818, 1980.

[2] Ya. Metelitsa, S. Pavlikov, and G. Chechushkov, "Relay protection of the supply transformer and the low voltage network of the electric furnace installation," Industrial power engineering, no. 7, pp. 32–33, 1984.

[3] K. Jagiela, J. Rak, M. Gala, and M. Kepinski, "Variation of load-carrying capacity indices of an AC Arc furnace network transformer," Proc. of 2014 16th Int. Conf. on Harmonics and Quality of Power, 2014.

[4] H. Samet, E. Farjah, and Z. Sharifi, "A dynamic, nonlinear and time-varying model for electric arc furnace," Int. Transactions on Electrical Energy Systems, vol. 25, no. 10, pp. 2165–2180, 2015.

[5] I. Yakimov and A. Radionov, "Investigation of direct-arc ultra-high power electric furnaces with controlled current by contactless regulator in intermediate circuit of furnace transformer," Proc. of 2017 IEEE Conf. of Russian Young Researchers in Electrical and Electronic Engineering, 2017.

[6] V. Zinovkin, O. Blyzniakov, and J. Vasilieva, "Non-stationary Electromagnetic Processes in power-Intensive Electrical Facilities with Highly Varying Loads," Proc. of 2019 IEEE Int. Conf. on Modern Electrical and Energy Systems, 2019.

[7] V. A. Andreev, Relay protection and automation of power supply systems. Moscow: Higher School, 2006.

[8] C. Boonseng, R. Boonseng, and K. Kularbphettong, "Investigation of Failure and Fault Diagnosis of 120MVA Transformers for Electrical Arc Furnace Systems and Data Mining Surveillance Techniques," Proc. of 2020 8th Int. Conf. on Condition Monitoring and Diagnosis, 2020.

[9] L. A. Kozhovich and M. T. Bishop, "Modern relay protection with current sensors on the basis of Rogovsky Coil," Modern Development of Relay Protection and Power System Automation Systems. Materials of International Scientific and Technical Conf., pp. 39–48, 2009.

[10] K. Arushanov, S. Karabanov, I. Zeltser, R. Maizels, and E. Moos, "New technology of modification of reed switch contact surfaces with the usage of ion-plasma nitriding," Proc. of 26th Int. Conf. on Electrical Contacts, 2012.

[11] V. D. Lebedev, G. A. Filatova, and A. E. Nesterikhin, "Measuring current converters for digital relay protection and automatic devices," Modern Development of Relay Protection and Power System Automation Systems. Materials of 4th Int. Scientific and Technical Conf., pp. 1–7, 2013.

[12] A. Sarwade, P. Katti, and J. Ghodekar, "Use of Rogowski Coil for accurate measurement of secondary current contaminated with CT saturation in distance protection scheme," Proc. of 2016 IEEE 6th Int. Conf. on Power Systems, 2016.

[13] P. Fubin, G. Lei, Y. Yubo, B. Qiangsheng, and J. Jianfei, "Effects of geometrical parameters on the performance of Rogowski coil for current measuring," Proc. of 2016 IEEE PES Asia-Pacific Power and Energy Engineering Conf., 2016.

[14] A. Abdulwahid and S. Wang, "A busbar differential protection based on fuzzy reasoning system and Rogowski-coil current sensor for microgrid," Proc. of 2016 IEEE PES Asia-Pacific Power and Energy Engineering Conf., 2016.

[15] K. Hinohara, "Reed switches," Electrical Contacts, pp. 673-702, 2017.

[16] K. Draxler and R. Styblikova, "Magnetic shielding of Rogowski coils," IEEE Transactions on Instrumentation and Measurement, vol. 67, no. 5, pp. 1207–1213, 2018.

[17] T. Ghanbari, H. Samet, M. Jarrahi, and D. Daryabar, "Implementation of Rogowski Coil Based Differential Protection on Electric Arc Furnace Transformers of Mobarakeh Steel Company: Design Step," Proc. of 2018 IEEE Int. Conf. on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe, 2018.

[18] P. Oramus, K. Kóska, J. Kozak, and T. Chmielewski, "Research on Surge Voltage Withstand of Medium Voltage Vacuum Reed Relay," Proc. of 2018 14th Selected Issues of Electrical Engineering and Electronics, 2018.

[19] R. Oganyan, M. Lankin, and N. Gorbatenko, "Research of the Effect of Displacement Primary Winding of a Measuring Current Transformer Based on the Rogowski Coil on the EMF of Secondary Winding," Proc. of 2020 Int. Conf. on Industrial Engineering, Applications and Manufacturing, 2020.

[20] B. Miedzinski, "Approach to Control of a Polarized Reed Switch Using an Equivalent Solenoid Method," Proc. of 2020 21st Int. Symposium on Electrical Apparatus & Technologies, 2020.

[21] M. Kletsel, N. Kabdualiyev, B. Mashrapov, and A. Neftissov, "Protection of busbar based on reed switches," Przegląd Elektrotechniczny, vol. 90, no. 1, pp. 88–89, 2014.

[22] M. Kletsel, V. Borodenko, A. Barukin, A. Kaltayev, and R. Mashrapova, "Constructive features of resource-saving reed relay protection and measurement devices," Rev Roumaine des Sciences Techniques-Series Electrotechnique et Energetique, vol. 64, no. 4, pp. 309–315, 2019.

[23] A. Barukin, A. Kaltayev, and Y. Lenkov, "Majority voting schemes of differential protections without current transformers with functional diagnostics for converting units and electric motors," Proc. of 2020 Int. Conf. on Industrial Engineering, Applications and Manufacturing, 2020.

[24] M. Kletsel, R. Mashrapova, and B. Mashrapov, "Methods for the construction of protection with magnetosensitive elements for the parallel circuits with single end supply," Proc. of 2020 Int. Conf. on Industrial Engineering, Applications and Manufacturing, 2020.

[25] A. Kaltayev, B. Mashrapov, and O. Talipov, "Designs for Mounting Reed Switches in Closed Complete Current Conductors and on Cable Lines," Proc. of 2020 Int. Conf. on Industrial Engineering, Applications and Manufacturing, 2020.

[26] M. Kletsel, A. Barukin, and A. Gabdulov, "Construction of Resource-Saving Differential Protections for Converter Units with Transformers with 2N Secondary Windings and 2N Rectifiers," Proc. of 2020 Int. Ural Conf. on Electrical Power Engineering, 2020.

[27] B. Mashrapov, O. Talipov, and R. Mashrapova, "Overcurrent Protection Scheme Utilising Reed Switches Instead of Current Transformers," Proc. of 2020 Int. Ural Conf. on Electrical Power Engineering, 2020.

[28] M. Kletsel, A. Barukin, and B. Mashrapov, "Designs for Mounting Reed Switches in Vicinity of AC and DC Buses," Proc. of 2020 Int. Ural Conf. on Electrical Power Engineering, 2020.

[29] M. Kletsel, A. Barukin, and D. Amirbek, "Reed Switch and Magneto Resistor-Based Differential Protection Featuring Test Diagnostics for Converters," Proc. Of 2020 Int. Multi-Conf. on Industrial Engineering and Modern Technologies, 2020.

[30] B. Mashrapov, "Improving the Reliability of Diagnosing Reed Switch-Based Overcurrent Protection Circuits," Proc. Of 2020 Int. Multi-Conf. on Industrial Engineering and Modern Technologies, 2020.

[31] A. Barukin, A. Berguzinov, and O. Talipov, "Mounting Measuring Devices of Reed Switch Protection Near Conductors of Electrical Installations," Proc. Of 2020 Int. Multi-Conf. on Industrial Engineering and Modern Technologies, 2020.

[32] M. Kletsel and B. Mashrapov, "Traversal protection of two parallel lines without voltage path," Przeglad Elektrotechniczny, vol. 92(2), pp. 168–170, 2016.

[33] M. Kletsel and B. Mashrapov, "Differential protection of three and four parallel lines of idling current control," Przeglad Elektrotechniczny, vol. 93, no. 10, pp. 109–112, 2017.