ABSTRACT

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IMPROVEMENT OF RESOURCE-SAVING PROTECTION SYSTEMS FOR CONVERTER UNITS AGAINST SHORT CIRCUITS

This dissertation is devoted to improving resource-saving protection systems for converter units against short circuits. It was developed in accordance with the priority scientific development area "Energy, Advanced Materials, and Transport" and the research areas of Research Committee B5 "Relay Protection and Automation" of the International Organization CIGRE, which unites scientists and specialists in the field of electric power systems throughout Europe and the CIS countries.

Relevance of the Problem. Converter unit (CU) protection has traditionally been achieved using current protection, and for high-power or highly critical units, differential protection systems were also used. Both types receive information from current transformers (CTs), which contain approximately 50 times more steel and copper than the protection devices themselves, for example, at 110 kV, and hundreds of times more high-voltage insulation. The problem of moving away from CTs arose back in the 1970s and was identified at the 2006 CIGRE session as a fundamentally unsolved problem in the electric power industry. Toraigyrov University proposed solving this problem using reed switches, and current and differential protection systems have already been developed for various electrical installations, including converter installations.

M. Ya. Kletsel and A. S. Barukin made significant contributions to the development of reed switch-based protection systems for PUs. However, many issues remain unresolved. Thus, the differential protection of high-power reed-switch-based relays is insensitive to short-circuits in the rectifier due to the lack of detuning for the transformer's magnetizing current surges. Even if present, it may not distinguish between surges and short circuits with a significant aperiodic component. Both the sensitivity and reliability of diode protection in rectifiers prove insufficient at low power levels. Many rectifier protection designs lack functional diagnostics, and all lack testing. Improving the reliability of relay protection (RP) by majorizing reed-switch protection without CTs, proposed by A.S. Barukin in his dissertation, increases the reliability of short-circuit interruption, but only if the RP circuit breaker is in good working order. To achieve maximum effect, it is necessary to seek ways to increase the reliability of short-circuit interruption in the RP (currently, this is achieved by replacing the circuit breakers with more reliable ones being developed). Furthermore, the operability of reed switch protection, including those with majorization, has only been confirmed by mental modeling. However, this is clearly insufficient for commercializing protection without CTs. It follows from the above that improving the protection of CPs without CTs, implemented using reed switches, to eliminate these shortcomings is a pressing issue.

The object of this study is relay protection of control units.

The subject of this study is relay protection of control units without current transformers.

The connection of the dissertation topic with general scientific (state) programs. The work was carried out in accordance with the priority area of scientific development "Energy, Advanced Materials, and Transport" and the scientific directions of Research Committee B5 "Relay Protection and Automation" of the International Organization CIGRE, which unites scientists and specialists in the field of electric power systems throughout Europe and the CIS countries.

The objective of this study is to create protection models for control units without current transformers, devoid of the above-mentioned shortcomings.

To achieve this objective, the following tasks were set and solved:

1. To build test and functional diagnostic devices for control unit protection using reed switches;

2. To increase the sensitivity and reliability of control unit protection using reed switches by complicating the protection circuits.

3. To increase the sensitivity of control unit protection using reed switches and current transformers, to develop a blocking system for the inrush current of control unit power transformers. 4. Develop devices that detect diode damage in rectifiers of power converters that are more sensitive and reliable than existing ones.

5. Improve differential protection for power converters with a majority scheme: develop a blocking system for the power converter and test diagnostics on reed switches, refine the selection of settings, and confirm operability using simulation modeling.

6. Improve the reliability of disconnecting the converter unit from the electrical system during a short circuit.

Research Methods. In solving the assigned problems, fundamental principles of the theoretical foundations of electrical engineering, relay protection and automation, reliability theory and similarity theory, fundamentals of the design theory of mechanisms and machines, and a full-scale experiment were used.

The validity and reliability of the scientific principles, conclusions, and recommendations are confirmed by: correct application of the fundamentals of reliability theory, transient processes and relay protection; competently executed simulation modeling; and testing in the form of an article published in the journal Electrical Engineering, report at an international conference. 4 patents in the Republic of Kazakhstan, 1 patent in the Russian Federation and 1 Eurasian patent (Appendix A).

Scientific novelty of the work:

1. Using reed switches with windings, it is proposed to increase the sensitivity of the protection of control units without CTs by: a) developing two diode protection devices: one based on reed switches, the other on inductors; b)

constructing differential protection for the control unit rectifier; c) introducing into the differential protection a device for blocking the magnetizing inrush current of the control unit power transformer, developed with the decisive participation of the author of the dissertation.

2. By selecting the settings of differential protection for control units without CTs, the tripping and non-tripping conditions of the protection are more accurately determined.

3. Using a mathematical model developed jointly with A.S. Barukin, the protection of control units using reed switches and a magnetoresistor is studied.

New scientific results of the work:

1. Two protection circuits for control unit rectifier diodes have been developed;

2. a) a new circuit based on reed switches for blocking devices from the BTN of the control unit power transformer for control unit protection; b) differential protection circuits for rectifiers without CTs.

3. The selection of differential protection settings for rectifiers without CTs has been refined;

4. The simulation modeling confirmed the operability of the rectifier protection with majorization and its response speed comparable to that of leading global companies.

Practical value of the work.

1. The two diode protection devices developed allow not only to detect their damage but also to determine which diode is damaged and whether the device itself is damaged.

2. The developed differential protection for the rectifier using reed switches has higher response speed and sensitivity during short circuits in the rectifier than the general differential protection, and increases the reliability of clearing such short circuits.

3. More accurate selection of settings reduces the likelihood of non-operation or false tripping of the differential protection for the rectifier.

4. The results of the simulation modeling confirm the operability of the differential protection of the converter unit, implemented according to the majority principle.

5. The use of reed switches with windings to perform both differential and overcurrent protection functions for the rectifier simplifies implementation.

The following are submitted for protection:

1. A method for protecting a power transformer from short circuits with blocking during a power transformer overvoltage (PT) using reed switches.

2. A separate differential protection device for the rectifier using redundancy and majorization, two devices for protecting the rectifier using reed switches and inductors.

3. Reed switch protection devices with functional and test diagnostics.

4. A differential protection model for the rectifier based on reed switches and a magnetoresistive resistor with test diagnostics and a unique blocking device against inrush current of the power transformer.

5. Simulation modeling confirming the operability of differential protection of the converter unit on reed switches, implemented according to the majority principle.

Work approval. The main provisions of the dissertation were presented at the 2024 International Ural Conference on Electrical Power Engineering (UralCon) and at an extended meeting of the Electrical Power Engineering Department of the NAO Toraigyrov University.

Publications. The research results have been published in 8 scientific papers, including 7 publications in journals recommended by the Committee, including 4 patents of the Republic of Kazakhstan, 1 patent of the Russian Federation, 1 Eurasian patent, 1 article in a Scopus-ranked journal with a 62 percentile; and 1 publication in the Proceedings of an international conference. In co-authored publications, the author's personal contribution is at least 60%.

Dissertation Structure and Scope. The dissertation consists of an introduction, three sections, and a conclusion. The work is presented on 87 pages of computer text and includes 6 tables and 30 figures. The list of references includes 71 titles.

The introduction substantiates the relevance of the dissertation topic, defines the goals and objectives of the study, highlights the scientific novelty and practical significance of the obtained results, and indicates ways to implement the objectives formulated in the dissertation.

The first chapter examines traditional protection systems for converter units and their implementation principles. The paper presents protection systems for converter units implemented using both electromechanical and modern microprocessor relays. A review of known resource-saving short-circuit protection systems for converter units is provided.

The traditional rectifier diode protection devices discussed above have several disadvantages, including: slow response time, the need for adjustments to allowable overloads, failure of the fuse link after operation, low sensitivity in the presence of overcurrent protection, and, in the presence of differential protection, bulky and metal-intensive CTs. Furthermore, the use of a disconnector to create an artificial short circuit reduces the reliability of the rectifier protection system. Therefore, improving the sensitivity and reliability of protection systems that detect diode damage in the rectifier remains important.

The study identified some resource-saving protection devices that do not protect the PU transformer and lack test and functional diagnostics, which is a significant drawback. Therefore, improving the sensitivity and reliability (by introducing test and functional diagnostics) of both the transformer and PU rectifier protection remains a pressing issue.

The magnetizing current surge upon energizing a power transformer reaches 5-8 In, requiring a detuning of the protection against short-circuit faults (SVRs). These faults occur when the converter unit transformer is energized and when voltage is restored after external short circuits, significantly reducing sensitivity. In existing SVR protection systems using reed switches, SVR blocking is either not implemented or is accomplished using a second-harmonic filter connected to the output of the reed switch winding, which serves as a source of EMF induced by the magnetic flux of in-phase currents. However, this method is not sufficiently reliable, due to the fact that the second harmonic can appear in the short-circuit current if it contains an aperiodic component. Therefore, the development of a blocking system for SVR faults in power transformers is urgent.

The second chapter improves the sensitivity and reliability of the differential protection device for a converter unit (CU). The device uses three reed switches with windings installed at a safe distance from the current-carrying buses of three phases on the high-voltage side of the CU transformer, and a fourth switch near the DC busbar. Sensitivity was increased by introducing second-harmonic filters for each phase, eliminating the need to tune out magnetizing current surges. Reliability was also improved through the development of functional and test diagnostics and the additional installation of two reed switches near the fourth switch and the connection of the windings of the first (second and third) and fourth (fifth and sixth) reed switches.

Based on the previous development (described above), a comprehensive CU protection model with higher short-circuit sensitivity in the CU rectifier was created by introducing three reed switches with windings on the low-voltage side of the CU transformer and three on the DC side, the windings of which are connected in the same way as in the protection described above. In the resulting differential protection system for the rectifier, the reed switches on the low-voltage side of the transformer are more sensitive than those on the high-voltage side (they are closer to the busbars). Additionally, additional blocking of the power transformer's magnetizing inrush current has been introduced. Unlike second-harmonic blocking, this prevents the rectifier from blocking when the short-circuit current is large, thus increasing the reliability of the rectifier.

Additional resource savings are achieved by using reed switches with windings that simultaneously perform differential and overcurrent protection functions for both the rectifier and the rectifier. The presented selection of its parameters presents no difficulty for a qualified relay engineer.

Two versions of diode protection devices for the converter unit have been developed (their innovation is protected by patents). The protection devices feature high sensitivity due to the use of inductors and high reliability due to the availability of functional fault diagnostics.

The third chapter improves the differential protection of converter units with a capacity of 6.3-160 MVA, implemented on reed switches and a magnetoresistor according to the majority principle. As before, this new protection can save copper, steel, and insulation materials to an unprecedented extent for relay protection, as it does not use current transformers. Its sensitivity has been increased by more precisely defining the tripping and non-tripping conditions of the protection, as well as by taking into account the possibility of reducing the load to 0.1I . Test diagnostics for reed switches and a unique blocking system against inrush current of the power transformer magnetizing using reed switches have been introduced. The introduction of additional switches in $1/\lambda_s$ (λ_s - the frequency of switch failures in disconnection) will increase the reliability of disconnecting the converter unit from the power system in the event of a failure of its main switch, and in the event of its emergency repair will ensure uninterruptible power supply, as well as in the case of its failure to turn on during automatic reclosing. Simulation modeling of the improved protection system demonstrated that it detects faults in no more than 25 ms, meeting the performance requirements of leading global companies while remaining operational even during faults in any of its component units. The protection system was standardized (in terms of using it for converter units of different power) using MathCad to define its parameters.

The results of the study are as follows:

The deficiencies identified in this study in resource-saving protection systems for converter units (CU) with a capacity of 6-160 MVA, based on reed switches, identified in publications and patents, were eliminated:

1. The insufficient sensitivity of some protection systems is addressed by developing blocking during magnetization inrush current on the reed switches, constructing a separate differential protection system for the CU rectifier, and using inductors. 2. Questionable reliability – through simple duplication and majorization, development and improvement of functional and test diagnostics, introduction of additional circuit breakers, with justification for this method allowing for a twofold increase in the reliability of disconnecting the control unit from the power grid during a short circuit and in the event of emergency repairs, ensuring uninterrupted power supply to the control unit.

3. Insufficient confirmation of the operability of the control unit protections using reed switches – through simulation modeling.

4. Approximate selection of installations – through an in-depth analysis of the tripping and non-tripping conditions of the protections, as well as taking into account a load reduction to 0.1 Inom.

5. Lack of proposals for unification of protections – through the use of MathCad.