вателя частоты с непосредственной связью, включающая моделирование непосредственного преобразователя частоты. Получены зависимости выходных напряжения и тока преобразователя с учетом параметров сварочной цепи, а также входных токов. Рассчитаны показатели разработанного источника питания машины контактной сварки: коэффициент мощности, коэффициент несинусоидальности входных токов, коэффициент несимметрии по обратной последовательности.

Результаты. Для обеспечения минимума потерь мощности в сети источник питания по отношению к последней должен представлять симметричную активную нагрузку. При этом, в случае симметричных напряжений сети, потребляемая активная мощность является постоянной. Исходя из этого, преобразователь питания трансформатора машины контактной сварки работает в режиме выпрямителя с поддержанием заданной мощности. Во избежание подмагничивания трансформатора машины контактной сварки и недопущения насыщения полярность выходного напряжения преобразователя периодически меняется. Таким образом, первичное напряжение трансформатора имеет вид, близкий к прямоугольному. Формирование выходного напряжения преобразователя с заданной амплитудой и частотой осуществляется шестью двунаправленными ключами методом широтно-импульсной модуляции в соответствии с разработанным способом, позволяющим обеспечить пропорциональность сетевых токов преобразователя соответствующим фазным напряжениям.

Научная новизна. Разработаны теоретические основы создания новых источников питания машины контактной сварки, имеющих высокие энергетические показатели и обеспечивающие электромагнитную совместимость с питающей сетью.

Практическая значимость. Использование для питания машины контактной сварки непосредственного преобразователя частоты матричного типа, управление которым осуществляется по разработанному алгоритму, дает возможность обеспечить электромагнитную совместимость источника с питающей сетью и повысить его энергоэффективность за счет симметричной загрузки фаз сети и устранения реактивной компоненты потребляемого тока.

Ключевые слова: *машина контактной сварки, источник питания, преобразователь матричного типа, коэффициент мощности*

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RESEARCH ON EFFECT OF DIFFERENTIAL-PHASE PROTECTION OF BUSBARS SYSTEM WITH VOLTAGE OF 110–750 KV

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ДОСЛІДЖЕННЯ ДІЇ ДИФЕРЕНЦІЙНО-ФАЗНОГО ЗАХИСТУ СИСТЕМ ЗБІРНИХ ШИН НАПРУГОЮ 110–750 КВ

Purpose. The choice of the optimal method from the technical point of view of implementing the algorithm for comparing the phases of the feeder currents in differential-phase protection of busbar systems with voltage of 110–750 kV.

Methodology. During the studies methods of mathematical modeling and simulation of steady and transient external and internal short circuits were used to analyze the behavior of the reacting organ of differential-phase busbar protection. The empirical method was implemented for studying the functioning of the technology of the differential-phase busbar protection, as well as the comparative analysis method to select the most perfect method for operating protection algorithm.

Findings. There were received oscillograms of steady and transient conditions of the power system, the action or no-action of differential-phase busbar protection was fixed, particularly, the time of the action and the time of trip of circuit breaker in condition with short circuit within the protected area were fixed. Conclusions about the appropriateness of application of each of the developed methods of implementation the differential-phase busbar protection

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have been made. According to the obtained results of comparative characteristic the most optimal option was proposed for use.

Originality. For the first time, a model of differential-phase protection of busbars was developed and investigated, in which the principle of comparing the phase of the feeder currents was used as the main and only way to ensure the absolute selectivity of the action of this protection, which led to conclusions about the possibility of its application and the effectiveness of the action. The effectiveness of the implementation of the technical solution for the implementation of this tire protection system is confirmed by the results obtained from its simulation and practical tests using the test complex of the microprocessor protection laboratory of the Dniprovska Power System.

Practice value. From the technical point of view the optimal way to implement the functional algorithm of the reacting part of the differential-phase busbar protection is chosen which can be used to develop advanced algorithms for the operation of the device.

Keywords: *differential-phase busbar protection, relay protection, microprocessor device, phase comparison relay, busbars*

Introduction. Reliable and uninterrupted operation of the power system (PS) and its components are ensured by relay protection devices, which eliminates the damage to electrical equipment and transmission lines and, thereby, prevents the development of emergency conditions associated with a disturbance of the stable operation of the power system or a violation of the electricity supply of a significant number of consumers [1]. There are several principles for the implementation of relay protection devices for the elements of electrical grids, and their use depends on the type of protected electrical equipment or transmission lines, on the functions assigned to the device and the task it solves. So, in particular, to ensure the protection of busbar systems with a voltage of 110–750 kV, which form primary electrical connections in the switchgears of power facilities, a differential principle is mainly used due to such advantages as absolute selectivity of relay protection operation in case of external and internal faults, high speed of protection operation and reliable detuning from transient fault currents of unbalance [1, 2]. However, it is worth noting that this principle of implementing the protection of the BS also has inherent drawbacks, the main ones of which are difficulty of providing the required sensitivity, in accordance with [3], the sensitivity of protection in all design modes of the PS, as well as increased requirements for the accuracy of the current transformers (CTs), to the secondary circuits of which protection is connected [4, 5]. Accuracy of the CTs is determined by the operating conditions of the PS, as well as the resistance and the nature of the load connected to their secondary winding. The errors of CTs in different conditions of their operation change nonlinearly, in particular the current errors increase more significantly than angular errors, as indicated in [6, 7]. So, in transient processes with the most unfavorable conditions of their flowing, the angular errors of the CTs are no more than 46–50 degrees (about 50–55 %), whereas the current errors may be 89 % according to [2, 6].

Relevance. Based by the foregoing, it can be concluded that it is advisable to carry out the busbar protection which in accordance with its principle of operation does not react to CT current errors in emergency conditions of the power system and determines only phase (angular) relationships between the currents flowing through bays connected to the common busbar system [4].

A topical issue is the investigation of the possibility of using differential-phase busbar protection (DFBP), the development and selection of the most technically perfect method for its implementation [4].

Objectives of the article. The paper aims at studying the ways of implementing the reacting element of the DFBP, the features of its operating in transient and steady-state modes of the PS.

Presentation of the main research. The differential-phase principle of the busbar protection operation is based on the comparison of the phases of the primary currents of all bays connected to the common busbar system. Like the differential busbar protection (DBP), the range of the DFBP is limited to CT sets, to whose secondary circuits it is connected [4, 5]. In more detail, the operation principle of the DFBP device, as well as its structural scheme, are considered in [4].

The main reacting element of the DFBP is the phase comparison relay (PCR). The PCR performs a number of consecutive mathematical and logical operations to determine the relationships between the phases of the currents circulating along the bays connected to the common busbar system. The relay performs continuous comparison of the phases of the currents among themselves and their comparison with the parameters of the protection settings [4, 7]. To ensure the functioning of the PCR, there are several methods developed by the authors that can be used to implement its action algorithm, the most optimal of which will be selected based on the results of their comparative characteristics:

1. Use of sets of pulses of the transformed signal and pauses between them. It is based on the determination of the coincidence time of rectangular pulses formed from half-waves of positive and negative polarity of secondary connection currents, the time of their mismatch and the total duration of the signal existence in the interval between pauses during the current period of the industrial frequency.

2. Use of the reference signal. It is based on determining the phase of each of the converted connection currents with the phase of the reference signal, which can be the converted current of any load supply connected under load, or the signal generated by the protection device itself;

3. Use of derivative currents of connections and derivative of a differential current. It is based on the determination of the coincidence times of the pulses of positive and negative polarity of secondary currents formed from the derivatives and the derivative of the differential current.

4. Use of pauses between pulses in the aggregate signal. It is based on the determination of the duration of the pauses in the sets of the unipolar impulses of the currents of the connections and comparing them with each other.

In order to study the functioning of the PCR DFBP according to each of the above methods of its implementation, the authors developed their functional models shown in Figs. 1–4.

As the object of modeling and subsequent laboratory tests of the operation of the PCR DFBP, a single busbar system was adopted, to which three supply bays (feeders) with sources of alternating sinusoidal current with a frequency of 50 Hz are connected. In the circuit of each of these bays, circuit breakers are installed with their own switch-off time of 20 ms, which is typical for modern SF6 circuit breakers [1].

As shown in Figs. 1–4, the PCR is connected to secondary CT circuits (CT1, CT2, CT3), also installed on each of the above bays. The transformation of the secondary currents of these CTs is realized by the formers of rectangular pulses of positive and negative polarity voltage (S_1, S_2, S_3) when the sinusoid of these currents passes through zero [4].

Fig. 1 shows the structural diagram of the PCR whose algorithm is performed according to the method by which it is envisaged to use sets of pulses of the transformed signal and pauses between them.

The logical blocks $Y1$, $Y2$, $Y3$ (AND, OR, NOR) correspond to the logical conditions that the protection uses to determine the location of the fault. The PCR determines the coincidence times of the pulses of the separately positive and negative polarity, the duration of the pause between them, and the duration of the signal existence in the interval between pauses. The calculated values are processed by integrating them (blocks Int1, Int2, Int3) on the interval $[t_0; t_0 + T]$, where T is the period of the current of the industrial frequency, t_0 is the initial time of the measurement, and are compared with the set protection settings $T1$, $T2$, $T3$ in ms, which are determined based on the adopted blocking angle of the DFBP, $\varphi_{bl} = 90°$ [4]. To form the START command by protection, all the above logical conditions must be simultaneously executed on the block Y1 & Y2 & Y3 (AND). The protection action for tripping the circuit breakers (TRIP) will only occur after the time that is determined by the configurations parameter of the block D(t). Entering of this delay time of the DFBP is necessary to exclude the possible unwanted operation of protection in case of absence of damage to the busbar [4]. In the case of a short-term start of protection in the presence of all the start-up conditions and the disappearance of at least one of them during one period (T = = 20 ms), a reactive protection element is returned. When the DFBP triggers, the PCR generates the output TRIP command, which affects the switching off of the breakers of all supply bays. After the last circuit breaker is turned off, the protection is automatically reset.

In Fig. 2 there is a structural diagram of the PCR whose algorithm is performed according to the method by which the reference signal is provided.

Logic blocks $Y1$, $Y2$, $Y3$ (XOR) are used to determine the PCR of the difference between the phase of the reference periodic signal generated in this case by the S_{op} block and the phases of the converted secondary connection currents. The computed values, like the above-described way of implementing the PCR, are processed by integrating them using Int1, Int2, Int3 blocks on the interval $[t_0; t_0 + T]$ and are compared with the setting of

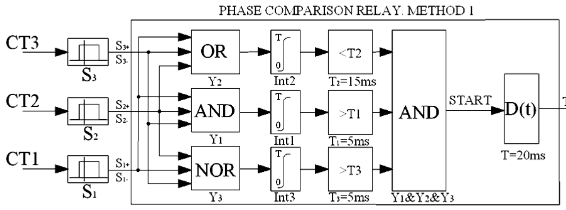

Fig. 1. Structural diagram of the PCR whose algorithm is executed according to the method using the sets of pulses of the transformed signal and pauses between them

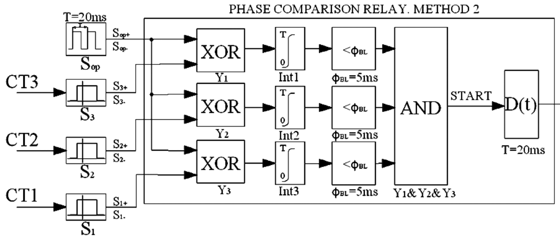

Fig. 2. Structural diagram of the PCR whose algorithm is executed according to the method using the reference signal

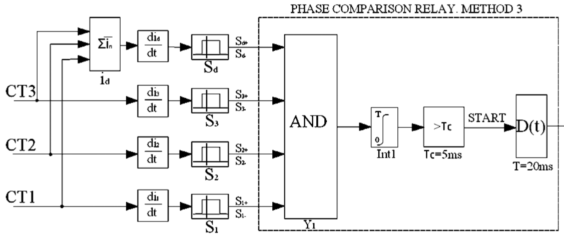

Fig. 3. Structural diagram of the PCR whose algorithm is executed according to the method with the use of derivative currents of the bays and derivative of the differential current

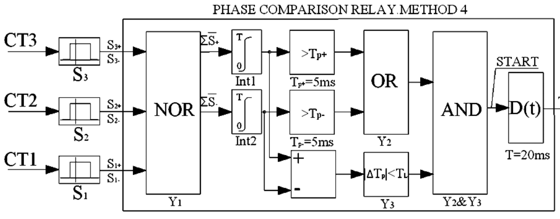

Fig. 4. Structural diagram of the PCR whose algorithm is executed according to the method using the pauses between pulses in the cumulative signal

the blocking angle of protection, φ_{bl}, given in ms. The start and operation of the DFBP occurs in the same way as it was described in the discussion of the operation of the PCR performed using sets of pulses of the converted signal and pauses between them.

Fig. 3 shows the structural diagram of the PCR whose algorithm is executed according to the method by which the use of derivative currents of bays and derivative of the differential current is provided.

In addition to the previously considered schemes, it includes the circuits for calculating the differential current (i_d) and its derivative $\left(\dfrac{di_d}{dt}\right)$ in its composition as well as the derivatives of the secondary bays currents $\left(\dfrac{di_1}{dt}, \dfrac{di_2}{dt}, \dfrac{di_3}{dt}\right)$. The formation of rectangular voltage pulses occurs at the sections of the positive and negative signs of the derivatives. With the help of the logic block Y1 (AND), it is possible to determine the coincidence time of positive and negative pulses and then compare it with the protection setting T_c by preliminary converting by the integrator Int1 on the interval $[t_0; t_0 + T]$. The T_c setting is determined based on the adopted blocking angle of the DFBP, $\varphi_{bl} = 90°$ [4, 7]. When the phases of derivatives of secondary currents coincide with the derivative of the differential current, protection is triggered and after the time determined by the configurations parameter of the block D(t), its operation occurs, provided that the starting conditions are maintained.

Fig. 4 shows the structural diagram of the PCR whose algorithm is executed according to the method by which it is provided for using pauses between pulses in the aggregate signal.

The logic block $Y1$ (NOR) is used to determine the duration of the pauses between the sets of pulses of positive T_{p+} and negative T_{p-} polarity. The PCR compares the obtained values with the protection setting $\mathrm{T_p}$ determined from the adopted blocking angle of the DFBP $\varphi_{bl} = 90°$ [4]. Condition $Y2$ (OR) is performed if the pause time between sets of positive or negative pulses exceeds the setpoint value T_p. An additional condition for starting and operation of the DFBP is finding the difference in the durations of the pauses between the unipolar pulses and comparing the obtained value with the setting T_L ($Y3$).

In the case of simultaneous execution of the starting conditions $Y2$ & $Y3$ (AND), there occur starting of the DFBP and its operation after the time elapses on the timer $D(t)$, provided that the conditions for starting the protection are true.

To carry out experimental studies and get practical results of the functioning of the reacting elements of the DFBP device, the algorithm of which was implemented using each of the methods developed by the authors, a hardware microcontroller platform of the ARDUINO UNO type was used, which has the minimum necessary equipment for carrying out this kind of laboratory research. For this purpose, 4 identical UNO electronic cards were used, processing incoming information in parallel and generating output commands, signaling the operation or non-operation of the DFBP device. Each of the microcontrollers (ATmega328 AVR) included in the used electronic cards was programmed in accordance with the diagrams shown in Figs. 1–4 of logical algorithms of the operation of the PCR DFBP, that is, 4 independent programs were developed, each of them processed and implemented by each individual microcontroller. The electrical parameters of the steady-state and transient modes under study, namely the secondary phase currents of the CTs, were modeled using the Matlab Simulink simulation software environment and transmitted through a serial communication interface to each of the microcontrollers operating in parallel. The results of the functioning of these devices, namely the behavior of the PCR in the simulated modes, were output back to the Simulink environment via the same serial communication port and displayed using the digital oscilloscope block in the set of the standard Simulink library, in the form of oscillograms for recording analog and discrete signals (Figs. 5–8). In addition, for informative purposes, the signals on the operation of the PCR were additionally output to the ARDUINO UNO LED indicator, which was made for the possibility of visualizing the fact of operation of these devices when they were fed with the emergency parameters related to the damage to the protected busbar system.

Fig. 5 shows the obtained oscillogram of the steady-state process of internal fault with the fixation of the fact and the time of operation of the DFBP with the command on switching off the breakers using four developed methods for implementing the RPCR action algorithm.

Fig. 6 shows the oscillogram of the normal operating mode of the PS with the appearance of perturbation which caused a short-time reversal of the current in one of the supplying bays, the fact that the DFBP was triggered, and therefore the disconnection of the bays circuit breakers, connected to the busbar system, was not recorded.

In the oscillograms, shown in Figs. 5–6, the first measuring analog channel is used to measure the sec-

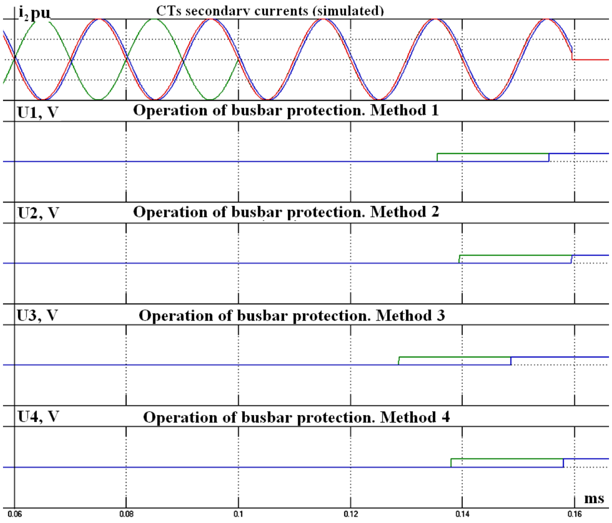

Fig. 5. Oscillogram of the steady-state internal fault with fixation of the fact of the operation of the PCR

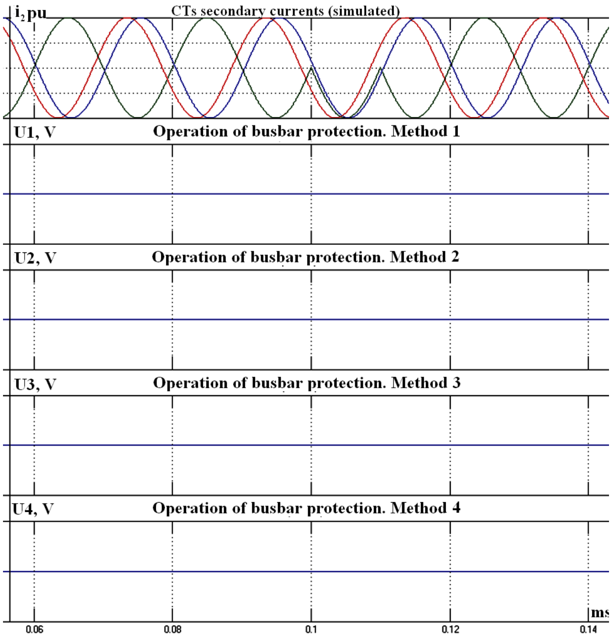

Fig. 6. Oscillogram of the normal operating mode of the PS with the appearance of a perturbation which caused a short-time reversal of the current in one of the supply bays

ondary CT currents of each bays (i_1, i_2, i_3), the remaining four discrete channels are used to record the fact of the operation of the PCR whose algorithm is executed according to each of the developed methods of its implementation, and the fact of disconnection breakers of each bays connected to the faulty busbar.

In steady state of internal fault, as shown in Fig. 5, after 100 ms from the beginning of the registration of the emergency process, there is a fault on the busbar, as indicated by a change in the phase of the current i_1 to the opposite one. The current i_1 is in a single phase with currents i_2, i_3, which is the basic condition for starting and tripping of the protection, the performance of which is confirmed by changing the levels of discrete signals in all the discrete channels of the fault recorder. After 20 ms after the operation of the DFBP, the cut-off breakers of the bays connected to the faulty busbar system are disconnected. At the same time, the speed of the PCR whose algorithm of operation was realized using the developed methods, was: $t_1 = 36$ ms, $t_2 = 39$ ms, $t_3 = 29$ ms, $t_4 = 38$ ms.

In the normal condition of the PS, as shown in Fig. 6, after 100 ms from the initial time of the process registration, disturbance occurs in the PS, in which the current i_1 changes its phase twice to the opposite one. As a result, the current i_1 is in antiphase to the currents i_2, i_3, which corresponds to the normal condition of the PS or external fault at the first bay. The fact of the operation of the PCR by the recorder was not fixed, which is confirmed by the unchanged zero level of the signals of its discrete channels.

Figs. 7–8 show the oscillograms of the transient processes of internal and external faults. The sinusoids of the currents at the initial time of the onset of the fault, namely 100 ms from the start of the process registration, are asymmetric with relation to the time axis, which is due to the presence in the primary current of the short-circuit aperiodic component which is partially transformed into the secondary winding of the CTs and gradually damps with a certain time constant T_a [2].

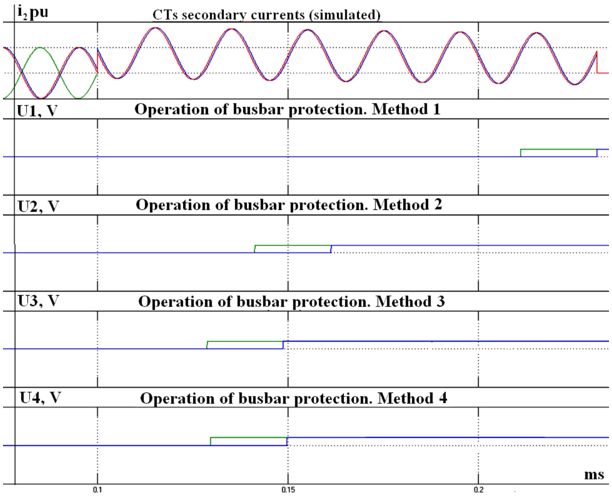

Fig. 7. Oscillogram of transient condition of the internal fault with the fixation of the fact of the operation of the PCR

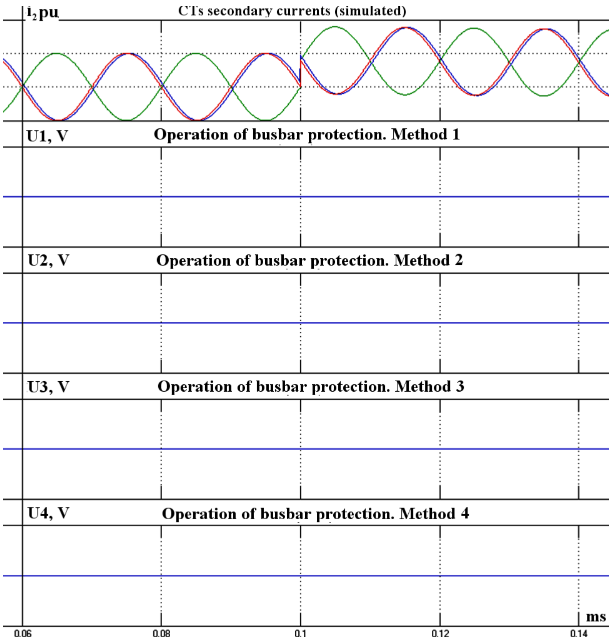

Fig. 8. Oscillogram of transient process of the external fault on the first bay

In the transition mode of the internal fault, as shown in Fig. 7, the operation time of the PCR whose algorithm is executed according to the method by which the sets of pulses of the transformed signal and pauses between them are envisaged, is substantially increased and amounts to about 112 ms, which indicates a low efficiency of using this method without using an additional mechanism for detuning the PCR from influence aperiodic component of the fault current.

In this case, the PCR operates only as an aperiodic component of the primary fault current decays and its sinusoidal shape is restored, which leads to decrease in the protection operation time. The speed of the PCR whose algorithm is executed according to the method which involves using the reference signal, as well as the use of the derivative currents of the bays and the derivative of the differential current, is the same in the transient mode as in the steady-state mode of internal fault, which is an indicator of the stability of its operation in transient modes, in particular, stability to the influence of transient currents. The speed of the PCR whose algorithm is executed according to the method that provides for the use of pauses between pulses in the cumulative signal, is slightly increased in the transient mode in comparison with the time of its operation in the steady-state of the internal fault, which is a positive moment in terms of the effectively of internal faults tripping, but at the same time protection is unstable to transient modes.

In the transient mode of the external fault, as shown in Fig. 8, the registrar does not record the fact of the operation of the PCR, which indicates compliance with the requirement of selectivity of the protection operation [3].

For the analysis and comparative characterization of the developed methods for realizing the algorithm of the PCR action, the following criteria were selected by the authors [3]:

- the speed of the DFBP in the steady-state and transient modes of internal faults;

Table

Comparative characteristics of the developed methods for implementing the PCR algorithm

№	Method Criteria	Method 1	Method 2	Method 3	Method 4
1	Speed operation: 1.1 Steady fault 1.2 Transient fault	36 ms 112 ms	39 ms 41 ms	29 ms 29 ms	38 ms 29 ms
2	Operation reliability of the PCR DFBP (operation at faults in the protected zone and non-operation under other conditions)	High reliability is achieved by verifying the performance of three starting conditions for voltage pulses of positive and negative polarity simultaneously	Operation reliability of the PCR is ensured by comparing the phases of the bays currents with the phase of the reference signal alternately	High reliability is achieved by obtaining a differential current additionally and determining its derivative phase	Operation reliability of the PCR is ensured by an additional comparison of the durations of pauses in sets of multipolar pulses
3	The selectivity operation of the PCR in the steady and transient modes of the PS	Not violated	Not violated	Not violated	Not violated
4	Stability operation of the PCR in the transient modes of external and internal faults	The stability operation of the PCR is broken, additional measures are required to detune the PCR from the effect of the aperiodic component of the primary faulty current	The stability operation of the PCR in the transient modes of faults is not violated	The stability operation of the PCR in the transient modes of faults is not violated	The stability operation of the PCR is broken, while the speed of protection is determined by the conditions of the transient modes of faults
5	Ease of implementation of the operation algorithm for comparing urrents phases of the PCR	The operation algorithm of the PCR is complicated by checking three conditions for starting and tripping of protection: time of coincidence of the pulses of positive and negative polarity secondary currents, time of their non-coincidence and the duration of the continuous existence of the signal in the interval between pauses	The relative ease of implementing the operation algorithm of the PCR is achieved by comparing the phases of the measured currents of each of the bays with the phase of the reference signal alternately, forming a trip command in case of phase coincidence of the bays currents with the phase of the reference signal and blocking the protection operation under other conditions	It has the most complex operating algorithm for implementing the functional capabilities of the PCR, which is due to the need to derive derivatives of secondary currents of bays and derivative of the differential current, which also leads to additional errors in the measuring path of protection	It has the simplest implementation of the operating algorithm of the PCR, which is achieved by testing only one starting condition, particularly, it is the duration of pauses in a set of unipolar impulses of the currents of bays. The second test condition is the comparison of the durations of the pauses between sets of positive and negative pulses, which is an additional measure to exclude excessive protection operation when there is an aperiodic component in the primary faulty current

- reliability of the DFBP functioning, i.e. operation at fault in the protected zone and non-operation under other conditions;
- the selectivity operation of DFBP in the steady and transient modes of the PS;
- stability of the operation of the DFBP in the transient modes of external and internal faults;
- ease of implementation of the functionality algorithm of the PCR.

The results of the comparative characteristic of the methods, developed by the authors for implementing the algorithm for the operation of the PCR, are given in Table.

Conclusions. In the paper one of the actual problems of the electric power industry is considered such as providing reliable and effective busbar relay protection switchgears with a voltage of 110–750 kV of power plants and substations.

The authors carried out a study of the functioning of the reacting element of the DFBP by simulation of the developed methods for implementing the operating algorithms of the PCR, and also conducting practical tests in the laboratory of microprocessor protection of the Dniprovska electric PS.

Based on the results of the conducted studies, the authors found that the most optimal technical solution is the implementation of the PCR DFBP according to the method based on the comparison of the phases of the derivatives of secondary bays currents with each other, and also with the derivative of the differential current. This method of implementing the operating algorithm of the PCR has the best technical indicators due to the following advantages over other proposed methods:

- high operation reliability of the DFBP;
- sufficiently high operation speed – over 30 ms in steady-state and transient modes of internal faults;
- the stability of the operation of the PCR in the transient modes of faults in the protected area and beyond.

Despite some difficulty in implementing the operating algorithm of the PCR according to this method in comparison with others, it is the most optimal solution for the prospective development of the extended operation algorithms of the DFBP.

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Мета. Дослідження диференційно-фазного принципу дії релейного захисту систем збірних шин напругою 110–750 кВ, що виконаний відповідно до розроблених способів його реалізації, вибір найбільш оптимального з технічної точки зору способу виконання захисту.

Методика. При проведенні досліджень використовувалися методи математичного та імітаційного моделювання усталених і перехідних процесів зовнішніх і внутрішніх коротких замикань для аналізу поведінки реагуючого органу диференційно-фазного захисту шин. Емпіричний метод дослідження функціонування пристрою диференційно-фазного захисту шин, а також метод порівняльного аналізу для вибору найбільш досконалого способу реалізації функціонального алгоритму захисту.

Результати. Отримані осцилограми усталених і перехідних режимів роботи енергосистеми, зафіксовано факт спрацювання або не спрацювання реагуючого органу диференційно-фазного захисту шин, час дії захисту й момент відключення вимикачів при пошкодженні в межах зони, що захищається. Зроблені висновки щодо можливості й доцільності застосування кожного із розроблених способів реалізації диференційно-фазного захисту шин, за результатами аналізу їх порівняльної характеристики запропоновано до реалізації найбільш оптимальний з технічної точки зору варіант.

Наукова новизна. Уперше розроблена й досліджена модель реалізації диференційно-фазного принципу дії захисту шин в якості основного та єдиного, що дало змогу зробити висновки щодо можливості його застосування та ефективності дії. Ефективність реалізації технічного рішення із впровадження диференційно-фазного принципу дії релейного захисту збірних шин підтверджується отриманими результатами від проведення моделювання й натурних випробувань з використанням випробувального комплексу лабораторії мікропроцесорних захистів Дніпровської електроенергетичної системи.

Практична значимість. Обрано найбільш оптимальний з технічної точки зору спосіб реалізації функціональних можливостей реагуючого органу диференційно-фазного захисту шин, що може бути використаний для розробки розширених функціональних алгоритмів пристрою захисту.

Ключові слова: *диференційно-фазний захист шин, релейний захист, мікропроцесорний пристрій, реле порівняння фаз струмів, збірні шини*

Цель. Выбор оптимального с технической точки зрения способа реализации алгоритма сравнения фаз токов присоединений в дифференциально-фазной защите систем сборных шин напряжением 110–750 кВ.

Методика. При проведении исследований использовались методы математического и имитационного моделирования установившихся и переходных процессов внешних и внутренних коротких замыканий для анализа поведения реагирующего органа дифференциально-фазной защиты шин. Эмпирический метод исследования функционирования устройства дифференциально-фазной защиты шин, а также метод сравнительного анализа применены для выбора оптимального способа реализации функционального алгоритма защиты.

Результаты. Получены осциллограммы установившихся и переходных режимов работы энергосистемы, произведена фиксация факта срабатывания (не срабатывания) реагирующего органа дифференциально-фазной защиты шин, времени действия защиты и момента отключения выключателей при повреждении в пределах защищаемой зоны. Сделаны выводы о возможности и целесообразности применения каждого из разработанных способов реализации дифференциально-фазной защиты шин, по результатам анализа их сравнительной характеристики предложен к использованию оптимальный с технической точки зрения вариант.

Научная новизна. Впервые разработана и исследована модель дифференциально-фазной защиты сборных шин, в которой принцип сравнения фаз токов присоединений использован в качестве основного и единственного способа обеспечения абсолютной селективности действия указанной защиты, что позволило сделать выводы о возможности ее применения и эффективности действия. Эффективность реализации технического решения по внедрению данной системы защиты шин подтверждается полученными результатами от проведения ее моделирования и натурных испытаний с использованием испытательного комплекса лаборатории микропроцессорных защит Днепровской электроэнергетической системы.

Практическая значимость. Выбран оптимальный с технической точки зрения способ реализации функционального алгоритма реагирующего органа дифференциально-фазной защиты шин, который может быть использован для разработки расширенных алгоритмов действия устройства.

Ключевые слова: *дифференциально-фазная защита шин, релейная защита, микропроцессорное устройство, реле сравнения фаз, сборные шины*

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