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THREE-PHASE POWER SUPPLY FOR RESISTANCE WELDING MACHINE WITH CORRECTED POWER FACTOR

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ТРИФАЗНЕ ДЖЕРЕЛО ЖИВЛЕННЯ МАШИНИ КОНТАКТНОГО ЗВАРЮВАННЯ З КОРЕКЦІЄЮ КОЕФІЦІЄНТА ПОТУЖНОСТІ

Purpose. Development of a three-phase power supply for a single-phase resistance welding machine (RWM). The presented power supply utilizes active power factor correction and draws balanced grid currents. Usage of such power supplies allows ensuring electromagnetic compatibility of the RWM with the power grid.

Methodology. A mathematical model of the three-phase power supply for single phase RWM based on the frequency converter with direct coupling is developed. The model accounts for welding circuit parameters. Converter input and output currents, converter output voltage are shown. The following power quality parameters of the developed RWM power supply are calculated: power factor, harmonic distortion of input currents, negative sequence current ratio.

Findings. To ensure minimum power losses in the power grid, RWM power supply should present a symmetrical active load to the supply network. In case of symmetrical mains voltages, the consumed instantaneous active power is constant. On this basis, the RWM power supply converter operates in a rectifier mode providing constant power to the load. To avoid RWM transformer biasing and to prevent saturation of its magnetic core, the polarity of the converter output voltage is periodically changed. Thus, the primary voltage of the transformer has a form close to rectangular. Formation of the inverter output voltage with a predetermined amplitude and frequency is done by six bidirectional switches with pulse width modulation control. The developed control method allows controlling converter input currents to be proportional to the corresponding phase voltages.

Originality. The theoretical basis for the creation of new RWM power supplies with high energy efficiency and electromagnetic compatibility with the power grid is proposed.

Practical value. The use of the direct matrix type converter with developed control algorithm for RWM supply makes it possible to ensure the power supply electromagnetic compatibility with the power grid and to improve its energy efficiency by forming symmetrical input currents and eliminating reactive component of the input currents.

Keywords: *resistance welding machine (RWM), power supply, matrix converter (MC), power factor*

Introduction. Resistance welding machines (RWM) are widely used at enterprises of machine-building industry. Depending on the thickness of the welded products, power supplies (PSs) of these machines are divided into AC power sources, the rectified current sources and the capacitor (electrostatic energy storage) PS. Regardless of the type of RWM PS, they have a common feature, namely, they are non-linear consumers of electricity, which is caused by the use of thyristor circuits to control the welding process. The level of power consumption of RWM’s PS is large enough, and their power factor (PF) ranges from 0.4 to 0.7 [1–4]. In addition to low energy efficiency, such PSs have a negative influence on the electric power quality at the point of common coupling (PCC), especially when multiple single-phase PSs, unevenly distributed between phases of the three-phase network, are working simultaneously. This eventually leads to a reduction of the welding process quality.

Unsolved problems. The problem of increasing of resistance welding machine power supplies PF and of ensuring their electromagnetic compatibility with the mains is not new. The works of such scientists as V. K. Lebedev, A. A. Pismennyi [1], A. V. Lebedev, P. M. Rudenko and V. S. Gavrish [2] (Ukraine), A. S. Klimov, V. S. Klimov, A. A. Gerasimov, A. N. Antsiborov (Russia), J. Saleem, B. Oelmann, K. Bertillson (Sweden), L. J. Brown, M. Salem, W. Li, E. Feng, D. Cerjanec, Gerald A. Grzadzinski (USA) are devoted to resolving this problem.

Developments in the direction of improving the control methods of existing thyristor RWM power supplies and of using RWM inverter-based power supplies are under way [1]. In both cases, the problem of ensuring electromagnetic compatibility may not always be completely solved, and, in the global trend towards energy efficiency improvement, it does not lose its relevance. Furthermore, in the process of the development of new power supplies for RWM, one should take into account the new power quality standards (DSTU IEC

61000-3-2:2004, 61000-3-4:2004), which possess the limits for the input harmonic current emissions. This also confirms the relevance of the problem.

Analysis of the recent research. As noted above, the work of scientists is aimed mainly at the improvement of thyristor-based power supplies. Today, the task of balancing grid currents is dealt with in a variety of ways. In the works of V. K. Lebedev, the schematic solutions to provide symmetrical (or quasi-symmetrical) current consumption, are considered. The main disadvantages of these schemes are high THD of the consumed currents (80–90 %) and the need for a low-frequency transformer.

In [5], the operation of power supply, which is based on the frequency inverter with an intermediate DC link, was investigated. An uncontrolled six-pulse rectifier is installed at the input of this converter. The inverter utilizes one of the widely used topologies: full-bridge, half-bridge, push-pull. The use of an uncontrolled rectifier without additional filtering leads to a high THD of consumption currents (about 50–60 %), although allows achieving symmetrical currents consumption from the power grid phases.

Unsolved aspects of the general problem. Although it is possible to achieve a symmetrical current consumption with the known schemes and control methods, the problem of electromagnetic compatibility of RWM power supply with the power grid remains relevant.

Objectives of the article. One solution to this problem is the additional installation of an active power filters and/or balancers (APFB) [6]. The choice in favor of APFB is obvious in view of the non-stationary loads due to the welding process. However, in terms of economic efficiency, this approach is not always expedient to the industry, although it has a number of technical advantages. Thus, the use of APFB allows ensuring balancing of input currents, VAR and harmonic current compensation, and – in the case of using series APF – to provide voltage stabilization (within fixed power). Another advantage of the use of APFB is the opportunity to use existing power supplies. The main disadvantage of active APFB is their high cost, commensurate with the value of the RWM power supply.

In this regard, the purpose of the work can be formulated as to develop a three-phase power supply for the single-phase RWM, which utilizes active power factor correction and draws balanced grid currents. Using such power supplies allows ensuring electromagnetic compatibility of the RWM with the power grid.

Presentation of the main research. The three-phase power supply for the single-phase RWM is a series-connected converter (Fig. 1) and a welding transformer to the output of which the welding circuit with the impedance Z is connected.

The converter is connected to the electrical grid through the passive LC-type filter. This filter prevents PWM frequency currents from flowing into the grid. The main task of the converter is forming a predetermined welding current. The input signals to the converter control are the primary current and voltage measured by corresponding sensors (current sensor CS (6), voltage sensor VS (7), Fig. 1).

In this paper, the use of the direct matrix converter (MC) is considered. A feature of the MC is that the output voltage is fed directly to the load from the power grid without an intermediate DC link. Three-to-one phase matrix converter consists of six bidirectional switches, each of which connects one phase of power grid directly to the load (Fig. 2).

Bidirectional switches can be formed as two series-connected transistors with antiparallel diode. The transistor gates are connected to the control unit (CU) (*4*, Fig. 1).

The converter control utilizes pulse width modulation (PWM) with a high switching frequency. MC is connected to the power grid through the passive three-phase input filter (*1*, Fig. 2) which filters out high frequency components of the input current, occurring due to the commutation of the bidirectional switches. By adjusting the duty cycle of the control pulses generated within the control unit (CU, Fig. 2), one can control the MC to provide output voltage with controlled amplitude and frequency.

It is known that the minimum power losses in the power grid may be obtained by providing the proportionality between the consumed currents and the corresponding phase voltages. That is, the MC should present a symmetrical active load to the grid. When forming a continuous MC output current, duty cycle of switches control pulses of matrix converter should be proportional to the corresponding absolute values of the instantaneous phase voltages. In this case, if the voltages are symmetrical, local average (averaged over the PWM cy-

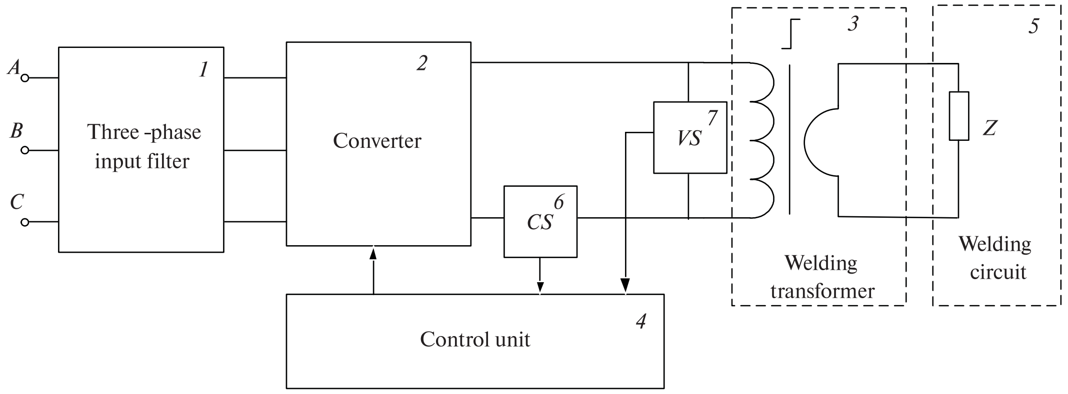

Fig. 1. Block diagram of connecting the RWM to the power grid

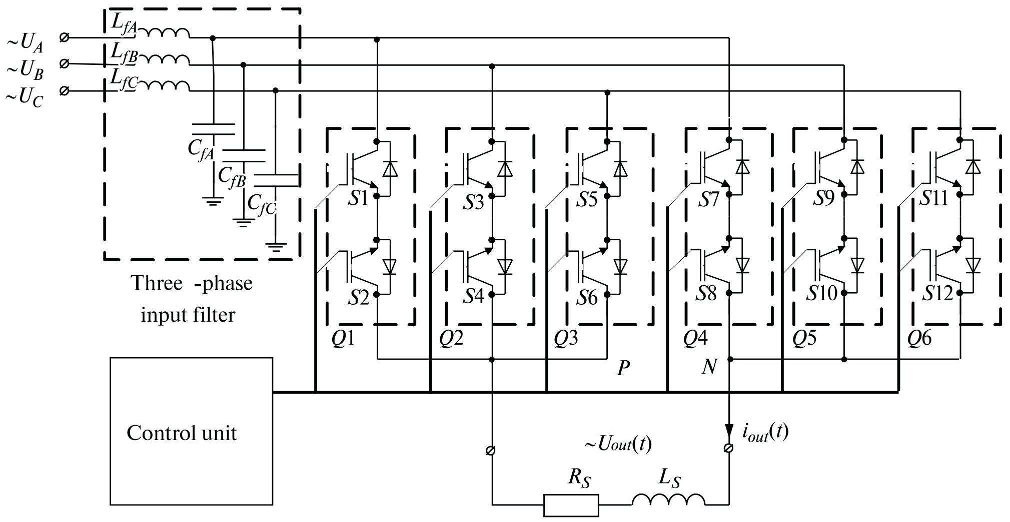

Fig. 2. Simplified circuit diagram of a matrix converter

cle) output voltage of the MC will be constant, so the consumed active power is also nearly constant.

DC current flowing through the primary winding of the welding transformer will lead to magnetic saturation and to significant increase in power losses.

The saturation can be avoided if the MC output voltage polarity is periodically changed to ensure the equality

$$\int_0^{T_{out}} U_{out}(t)dt = 0, \qquad (1)$$

where $U_{out}(t)$ is MC output voltage, V; T_{out} is MC output voltage period, s.

Period has to be chosen as large as possible to fully utilize transformer core while avoiding its saturation. Maximizing T_{out} has the benefits of reducing influence of secondary (welding) loop inductance and transformer leakage inductance on the welding current. The transformer output characteristic becomes “stiffer” allowing higher welding current and/or ensuring good welding quality during supply voltage sags.

That is, if the input voltages are symmetrical and sinusoidal, the converter generates an output voltage of rectangular shape and low frequency.

Formation of the output voltage of a predetermined (low) frequency is performed in the control unit. The input signals to the control unit are input voltages, predetermined output voltage and current, and modulation signal with PWM carrier frequency.

For the sake of simulation clarity the initial phase shift of the grid phase *A* voltage assumed to be zero, phase voltages are assumed to be symmetric with positive sequence and sinusoidal. Conventionally, mains voltage period is divided into six sectors. The first and fourth sectors correspond to the highest absolute value of the instantaneous voltage of phase *B* (the first – with a negative voltage of phase *B*, the fourth – with a positive), the second and the fifth ones – phase *A* (the second – with a positive voltage of phase *A*, the fifth – with a negative), the third and sixth ones – phase *C* (the third – with a negative voltage of phase *C*, the sixth – with a positive).

Choosing the desired pair of switches for positive polarity of the output voltage occurs in the control unit according to Table 1. Listed in Table 1, the duty cycle of the control pulses to *Q*1–*Q*6 are calculated by the following expressions

$$D_1 = \frac{u_A(t)\cdot U_{out}}{1.5U_m^2}; \quad D_2 = \frac{-u_B(t)\cdot U_{out}}{1.5U_m^2};$$
$$D_3 = \frac{-u_C(t)\cdot U_{out}}{1.5U_m^2}; \qquad (2)$$
$$D_4 = -D_1; \quad D_5 = -D_2; \quad D_6 = -D_3,$$

where $u_A(t)$, $u_B(t)$, $u_C(t)$ are instantaneous phase mains voltages, V; U_{out} is the converter output voltage (constant), V; U_m is the magnitude of the phase mains voltage, V.

To generate the negative polarity of output voltage control signals of switches Q*1*–Q*3* and Q*4*–Q*6* are reversed (Table 2).

The input signals for the controller are three mains voltages and three phase currents fed to the controller ADC via signal conditioning circuits. Current sensors are ACS758ECB-200B-PFF-T. Voltage measurement is performed using resistive voltage dividers. Setting the amplitude and frequency of converter output voltage is fed via the input devices (e.g. keyboard) to the controller. The desired sector is determined by the control system in real time by comparing the voltage grids against each other. The duty cycles of the control pulses to *Q*1–*Q*6 are calculated by the expressions (1) and fed with a PWM generator to the transistor gates according to Tables 1 and 2.

The IGBT modules DIM200MBS12-A000 are used as bi-directional switches. This module is designed for voltages up to 1200 V and currents up to 200 A. IGBT control circuit is made using a FOD3184 specialized optocoupler drivers. The control system is based on a STM32F100C6T6B ARM microcontroller.

Figs. 3 and 4 show diagrams of input and output voltages and currents of RWM power supply.

Table 1

Choosing a pair of switches to obtain positive output voltage

Sector, el.deg.	0...60	60...120	180...240	240...300	300...360
*Q*1	D1	1	0	1-D2-D3	0
*Q*2	1-D1-D3	0	1	D2	0
*Q*3	D3	0	0	D3	1
*Q*4	0	1-D5-D6	D4	1	D4
*Q*5	1	D5	1-D4-D6	0	D5
*Q*6	0	D6	D6	0	1-D4-D5

Table 2

Choosing a pair of switches to obtain negative output voltage

Sector, el.deg.	0...60	60...120	120...180	180...240	240...300	300...360
*Q*1	0	1-D5-D6	0	D4	1	D4
*Q*2	1	D5	0	1-D4-D6	0	D5
*Q*3	0	D6	1	D6	0	1-D4-D5
*Q*4	D1	1	D1	0	1-D2-D3	0
*Q*5	1-D1-D3	0	D2	1	D2	0
*Q*6	D3	0	1-D1-D2	0	D3	1

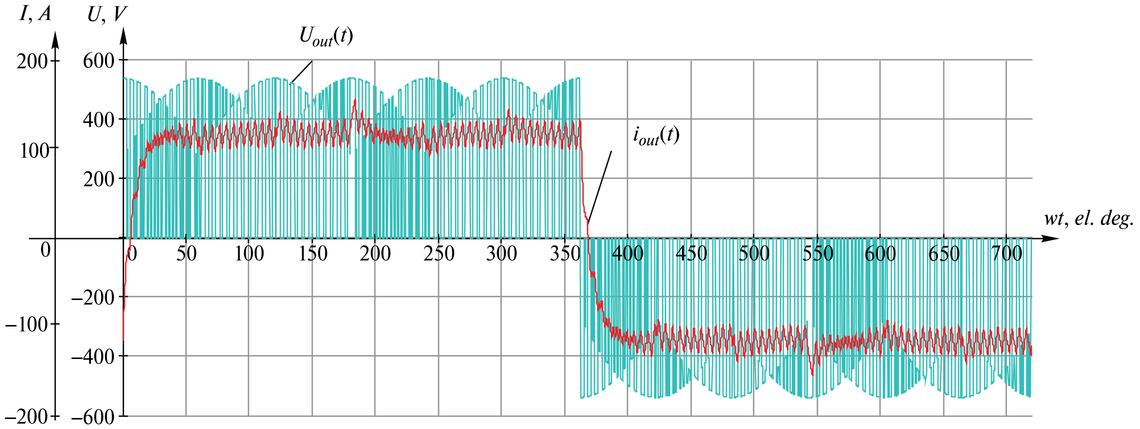

Fig. 3. The MC output voltage and output current diagrams

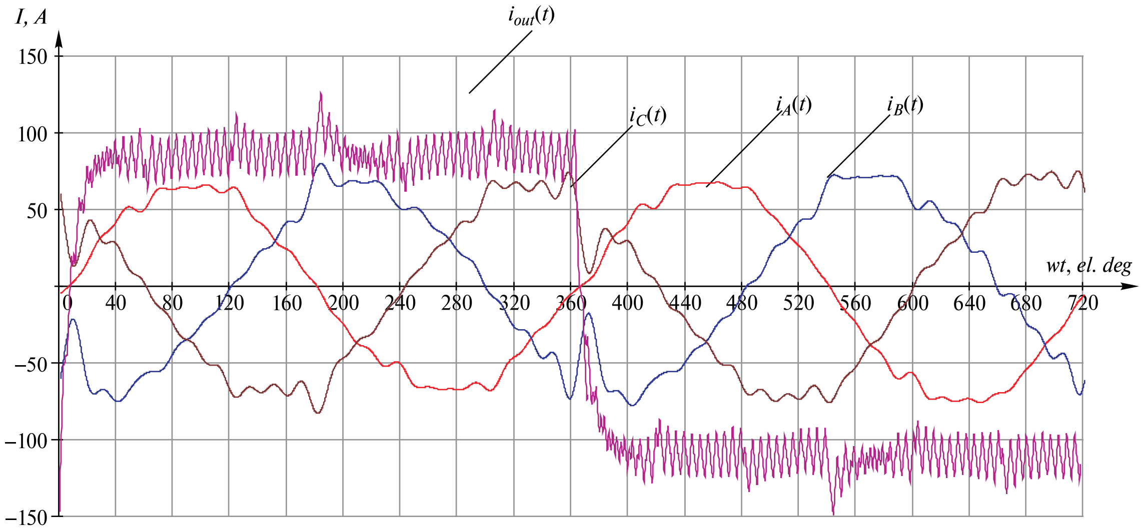

Fig. 4. The MC output current and input currents diagrams

Power supply parameters are as follows: switching frequency 3.2 kHz, output voltage – with rectangular shape, 25 Hz frequency and 300 V amplitude, transformer leakage inductance is 0.6 mH, total active resistance is 2.5 ohms (referred to primary); input filter inductance is 0.1 mH, the input filter capacitance is 24 uF. THD of the input currents is about 15 %, power factor is about 96 %, and currents unbalance coefficient is about 1.7 %. These characteristics are much better than those of the thyristor-based RWM power supplies [1].

Conclusions and recommendations for further research. A new schematic solution of the power supply for resistance welding machines, based on the principle of direct three-to-one phase conversion, is proposed. The control method, which allows providing high energy efficiency, was designed. The power supply has almost unity power factor. It allows ensuring minimum consumption of reactive power from the electrical grid and provides symmetrical current consumption on all three phases of the mains. Low input currents THD allows providing compliance of the input harmonic current emissions to the DSTU IEC 61000-3-2:2004, 61000-3-4:2004 standards.

The perspectives include further development of the converter control methods which will allow using power supply for the RWM as VAR compensator and active harmonic filter with limited capacity.

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Мета. Розробка джерела живлення однофазної машини контактного зварювання, що дозволяє при включенні його до трифазної мережі отримати високий коефіцієнт потужності й симетричне завантаження фаз мережі при забезпеченні електромагнітної сумісності машини контактного зварювання з електричною мережею.

Методика. Розроблена математична модель трифазного джерела живлення для однофазної машини контактного зварювання на основі перетворювача частоти з безпосереднім зв’язком, що включає моделювання безпосереднього перетворювача частоти. Отримані залежності вихідних напруги й струму перетворювача з урахуванням параметрів зварювального кола, а також вхідних струмів. Розраховані показники розробленого джерела живлення машини контактного зварювання: коефіцієнт потужності, коефіцієнт несинусоїдальності вхідних струмів, коефіцієнт несиметрії по зворотній послідовності.

Результати. Для забезпечення мінімуму втрат потужності в мережі джерело живлення по відношенню до останньої повинно представляти симетричне активне навантаження. При цьому, у разі симетричних напруг мережі, споживана активна потужність є постійною. Виходячи з цього, перетворювач живлення трансформатора машини контактного зварювання працює в режимі випрямляча з підтриманням заданої потужності. Щоб уникнути підмагнічування трансформатора машини контактного зварювання й недопущення насичення, полярність вихідної напруги перетворювача періодично змінюється. Таким чином, первинна напруга трансформатора має вигляд, близький до прямокутного. Формування вихідної напруги перетворювача із заданою амплітудою й частотою здійснюється шістьма двонаправленими ключами методом широтно-імпульсної модуляції відповідно до розробленого способу, що дозволяє забезпечити пропорційність мережевих струмів перетворювача відповідним фазним напругам.

Наукова новизна. Розроблені теоретичні основи створення нових джерел живлення машин контактного зварювання, що мають високі енергетичні показники й забезпечують електромагнітну сумісність із мережею живлення.

Практична значимість. Використання для живлення машин контактного зварювання безпосереднього перетворювача частоти матричного типу, управління яким здійснюється за розробленим алгоритмом, дає можливість забезпечити електромагнітну сумісність джерела з мережею живлення й підвищити його енергоефективність за рахунок симетричного завантаження фаз мережі та усунення реактивної компоненти споживаного струму.

Ключові слова: *машина контактного зварювання, джерело живлення, перетворювач матричного типу*

Цель. Разработка источника питания однофазной машины контактной сварки, позволяющего при включении его в трехфазную сеть получить высокий коэффициент мощности и симметричную загрузку фаз сети при обеспечении электромагнитной совместимости МКС с электрической сетью.

Методика. Разработана математическая модель трехфазного источника питания для однофазной машины контактной сварки на основе преобразователя 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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