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DEVELOPMENT OF PRINCIPLES AND METHODS FOR CALCULATION OF DIRECT CURRENT HYBRID CONTACTORS

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Показано, що принцип керування гібридним контактором струмом головного кола створює ряд позитивних якостей, що підвищують конкурентоспроможність. Проведені дослідження нестаціонарних процесів, що забезпечують живлення і керування контактора струмом кола. Розроблені методики і дані рекомендації для розрахунку електронної частини гібридного контактора постійного струму на напругу до 1000 В і струми 100–630 А

Ключові слова: гібридний контактор, головні контакти, напівпровідниковий ключ, трансформатор струму, керування струмом

Показано, что принцип управления гибридным контактором током главной цепи создаёт ряд положительных качеств, повышающих его конкурентоспособность. Проведены исследования нестационарных процессов, обеспечивающих питание и управление контактора током цепи. Разработаны методики и даны рекомендации для расчёта электронной части гибридного контактора постоянного тока на напряжения до 1000 В и токи 100–630 А

Ключевые слова: гибридный контактор, главные контакты, полупроводниковый ключ, трансформатор тока, управление током

1. Introduction

Hybrid contactors, first developed in the 1970s (at the Institute of VDIIelectroacoustics, Kharkov), were designed for currents of 100–630 A and voltage up to 660 V for circuits of alternating current, and for currents of 600–630 A and voltage up to 440 V – for DC circuits.

The developed contactors surpassed classical electromagnetic contactors by 20–25 times by switching durability but underperformed significantly in terms of cost and weight-dimensional parameters. Therefore, such contactors were technically and economically feasible to apply only for difficult operating modes. Such modes have the following categories of use of contactors: AC-3 and AC-4 – for circuits of alternating current, DC-4 and DC-5 – for circuits of direct current. It is also advisable to use such contactors under conditions of increased requirements for explosion and fire safety [1]. However, we should note that hybrid DC contactors did not gain much demand in the market of electrical products due to their relatively high cost, large size and weight, due to the existence of a complex system of forced commutation. As a result, production of such contactors stopped as opposed to successfully tested hybrid AC contactors.

And only elaboration and dynamic development of fully controlled integrated power semiconductor devices (SDs) created real prerequisites for further successful development of hybrid commutation devices, in particular hybrid DC contactors. Devices such as dual-operation thyristors of modular constructions (GTO and GCT), powerful transistors and field transistors of IGBT, IEGT, MCT, other types can switch megawatt power flows without the above-mentioned forced commutation systems. There are facts that facilitate this: a cost of such SDs reduces continuously given the growing availability of electronic components in the world market [1, 2].

We should also note that there is a tendency for large-scale development of both micronetworks of direct current for low disturbance (up to 1 kV) and high-voltage distribution networks of direct current for medium voltage (up to 10 kV) in the leading countries in recent years. That is mainly because of the intensive development of both information telecommunication systems and alternative sources of electricity, respectively [3]. However, despite advantages of DC networks – power losses, lack of reactive power – they also have disadvantages associated with a lack of reliable security and control commutation devices. Because of complexity of practical implementation of conditions for arc control in circuits of a direct current [1, 3]. The above-mentioned became undoubtedly an additional weighty argument for expansion of the demand for semiconductor hybrid commutation devices for direct current, including hybrid contactors.

Therefore, the study should focus on the creation of more advanced hybrid commutation devices of direct current.

2. Literature review and problem statement

Paper [4] proposes a hybrid electromagnetic contactor of direct current. Main contacts are connected to a power IGBT transistor in parallel. It uses a control scheme with an implemented auxiliary contact as a synchronizing element to provide arcless commutation of main contacts, both when switching on and off. This contactor is equipped with a special node of overvoltage protection due to the accumulated energy in network inductance. A node contains a condenser connected through a diode to the input of a contactor, and a parallel IGBT transistor connected to it, which turns on only when a level of voltage at the input of a level of network voltage is connected. Thus, over-voltages are limited to the permissible level. Disadvantages of a contactor are: there is no galvanic interconnection of a network and a load, an electronic part of a circuit is under voltage in switched on and off contactor states, we cannot use it in reversing switching circuits.

Work [5] presents a high-voltage hybrid DC contactor. A contactless switch, which is connected through the power-supply contact in parallel to the main contacts, provides its arcless commutation both when switching on and off. In this case, a kinematic connection between the mentioned contacts is such that an auxiliary contact is activated before the main contacts when switched on and unplugged later than the main contacts when switched off. A driver and a controller manage fully controlled semiconductor switch of a non-contact circuit breaker. The design of a power semiconductor switch provides uncontrolled switching of the main contacts in the course of a current flow in one, and in other directions. Unlike the previously discussed contactor, it provides a galvanic solution to a network and a load in the off state of a device. Disadvantages of a contactor: presence of a rather complex control circuit, we do not see how scattering of energy accumulated in load inductances and in a network during switching load occurs, we cannot use it in reverse switching circuits.

Source [6] proposes a hybrid electromagnetic contactor of direct current, which contains main contacts, parallel to which a controlled semiconductor switch (IGBT-transistor) is connected by a rectifier. It also contains a controller that enables switching on and off both a coil of an electromagnetic actuator and a controlled semiconductor switch, depending on a level of a signal withdrawn from a contact gap. When switched off, a semiconductor switch is activated only when the main contacts begin to diverge and an electric arc arises between them. In this case, a controller provides a kind of pulse mode of a switch, in which a switching process goes almost without overvoltage due to the energy of a short-range arc at the contact interval. That is, energy accumulated in a pre-enabled inductance of a network dissipates in an arc during a switching off process. Disadvantages: an increased wear of contacts when switching off a circuit, a complicated and expensive control system, we cannot use it in reversing circuits, it requires an additional power supply.

Work [7] investigates ways of perspective development of high-power commutation hybrid devices of a new generation intended for operational commutation of electric power in autonomous systems of power supply. It considers technical principles of DC hybrid devices.

Paper [8] considers problems of optimal synthesis of low-voltage hybrid devices and physical phenomena, which implement commutation laws in DC circuits.

Disadvantages of hybrid contactors given in [7, 8] are complex kinematic connections in the construction of the devices, a value of the maximum reliable current commutated by such devices does not exceed 100 A.

Work [9] investigates a hybrid DC contactor for a voltage of 2 kV based on a vacuum switch. The research carried out confirms its reliable work. Its disadvantages: we cannot use it in reversing switching circuits, it requires additional power source of high power, a high cost.

Thus, paper [10] presents principles of construction of hybrid switches capable of interrupting emergency currents in several milliseconds. We can use it in both micronetworks and low voltage DC systems, as well as in high-voltage DC systems (HVDC). Results of modeling confirm the principles of construction of switches.

Work [11] shows that a reliable, high-speed, low-loss circuit switch is necessary for the development of a large high-voltage HVDC DC network. This is, in the opinion of ABB company (Switzerland), a hybrid switch, the main element of which is a two-directional LCS commutation key. There is a system model of HVDC hybrid switch for the study of criteria for its design developed. Researchers built and tested a full-scale prototype of the device at the center of ABB HVDC, Ludwick, Sweden.

In all of the above hybrid switches [10, 11] there are standard power drivers with special additional voltage sources for control of a semiconductor switch, which, along with obvious advantages, create certain problems for application of such technical solutions for creation of simpler devices such as hybrid contactors, where a price and dimensions of a device are of first and foremost importance.

Since the mentioned sources did not apply the principle of control of a hybrid contactor with current of the main circle, it is quite natural that there are no studies on processes due to this in literary sources.

A literary analysis shows that development of hybrid DC commutation devices is quite active. At the same time, due to the rapid progress of power electronics, the research process in this industry is becoming more dynamic. But objectives of the researches are always almost unchanged and aimed at increasing competitiveness of devices in the market of electrical products. This is realized through creation of devices with increased reliability and improved technical and economic performance compared with existing products.

The conducted analysis of samples of hybrid DC contactors also showed that, along with their inherent positive properties, they have disadvantages that reduce competitiveness, and hence a demand for them. Therefore, studies aimed at creation of new principles for construction of hybrid contactors, which not only eliminate disadvantages of the samples considered, but also create new qualities that increase competitiveness, are promising.

3. The aim and objectives of the study

The objective of present study is to create principles and methods for calculation of operation modes and parameters of DC hybrid contactors.

We solved the following tasks to achieve the objective:

– investigation by analysis that the principle of control of a hybrid contactor with a current of the main circuit makes it possible to create qualities that increase its competitiveness in comparison with existing contactors;

– performance of theoretical and experimental studies of non-stationary electromagnetic processes, which provide power and control of contactor with current of its main circuit;

– development of methods for calculation of electronic circuit elements that provide control over main circuits current and provide recommendations for choosing parameters of a semiconductor switch that shunts main contacts.

4. Technical solutions for creation of hybrid DC contactors and their analysis

Researchers at the O. M. Beketov KhNUUE (Ukraine, Kharkiv) developed technical solutions presented in the form of two options of electrical circuits of two-pole hybrid DC contactors with control by the main circuit current. Introduction of a small-sized current transformer with two primary windings provides achievement of the principle. The first of windings is connected to the first pole in series with the main contact (MC), and the second one – in series with a fully controllable SS, which shunts this contact and in front of the first one. A current transformer has one secondary winding, which provides power to a control circuit of a fully controlled SS at the moment of switching off a device only. The main technical solutions used in such contactors are protected by patents [12, 13].

Fig. 1, *a* shows electric circuits of the first option of a double pole hybrid DC contactor with a use of IMBT transistor, and Fig. 1, *b* – with a use of a dual-operation thyristor [12].

A classical contactor represents a basic contact device.

There are contactor elements on the circuits: main contacts MC1 and MC2, a current relay MR1, IGBT transistor VT1, or a dual-operation thyristor VS1, primary windings of transformer current CT1w$_{1-1}$ and w$_{1-2}$ form its main power circuit. In addition, MC1 and MC2 are adjusted so that the second main contact is unlocked later than the first one (delay time is 7–9 ms). We use magnetically operated contacts (reed switch) as MR1.1 contacts of MR1 current relay. R1 varistor serves to disperse energy accumulated in network inductance, and VS3 optron thyristor – to disperse energy accumulated in load inductance at the time of interruption of a current. In this case, a use of an optron thyristor instead of a diode gives possibility to use the proposed contactor in reverse switching circuits. R2 resistor, C1 condenser and VD2 diode (only for IGBT transistor) reduce a level of commutation overvoltage on fully operated SS at switching off.

The rest of elements form a control circuit for commutation VT1 or VS1.

In switched off and on contactor states, all elements of its electronic part are deenergized.

Paper [12] gives detailed description of the device.

The second option of a hybrid contactor [13] differs from the first one because it excludes an insufficiently reliable contact control circuit based on a current relay from a switching circle of a fully operated SS. Instead, there is a contactless circuit for its switching introduced. It is made based on an optron thyristor inserted into a circuit of control of a coil of a contactor electromagnetic actuator (Fig. 2). Work [13] considers this scheme in detail [13].

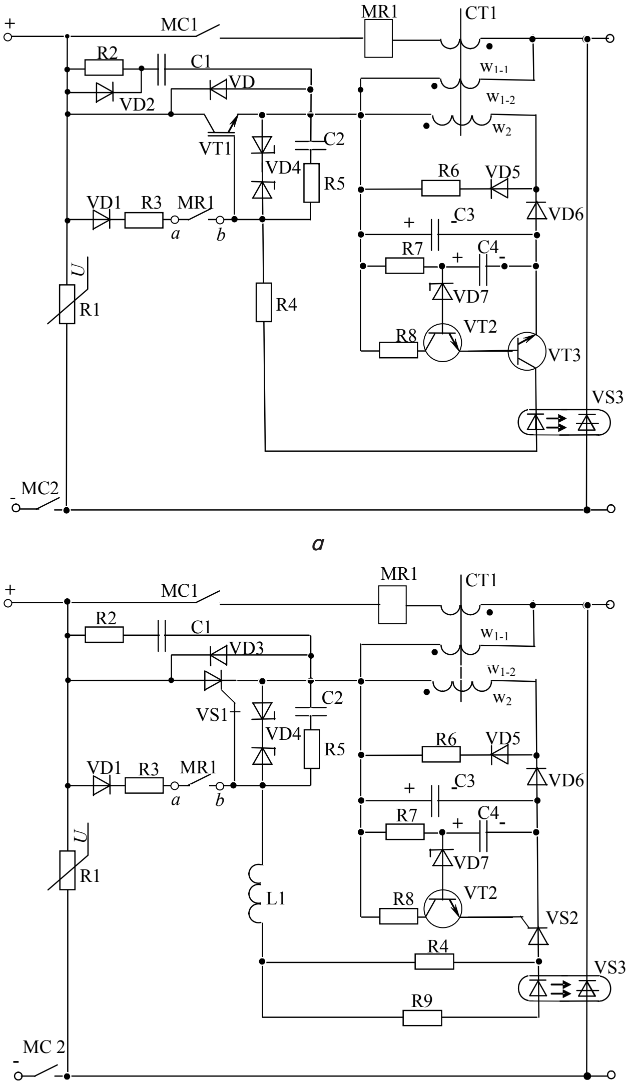


Fig. 1. Electrical circuit of the first option of hybrid DC contactor with main circuit current control: *a* – based on IGBT transistor, *b* – based on a dual-operation thyristor

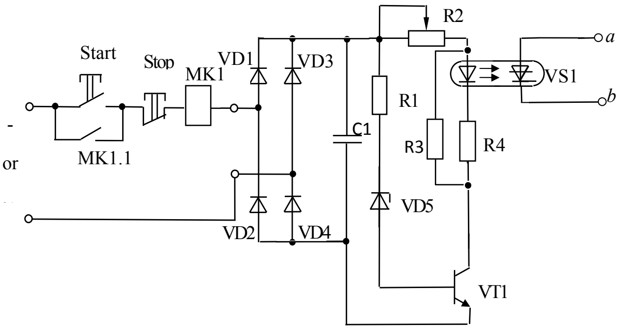


Fig. 2. Contactless circuit of a fully controlled SS for the second option of a hybrid contactor

Remaining elements of the electrical circuit of the second option will be the same as in the first version (Fig. 1, *a, b*), except that an output circle of VS1 optron thyristor will be switched on between the dots *a* and *b* instead of contacts of a current relay, and a current relay will be removed from a circuit of MS1 main contact. In this case, the principle of operation of remaining elements of the circuit remains unchanged.

We should note, however, that it is possible to use the second option only in the case of the use of an electromagnetic contactor as a base device, whereas the first option does not have such limitation, that is, it is universal.

As follows from the foregoing, technical solutions proposed by authors of the commutation of a fully managed semiconductor switch with a current of the main circle gives possibility to create hybrid DC contactors, which, in comparison with the existing, have the following additional positive properties:

1) there is no need for an additional source for supply of the control circuit of an electronic part of a contactor, because power is provided by the main current by introducing a low-power current transformer into the circuit;

2) economical mode of operation of components of an electronic part. Since they are under load at the moment of commutation of a fully controlled SS only for a few milliseconds, and during switched on and off state of a contactor they are almost in storage mode, which increases reliability of a contactor significantly. Work [14] shows that the intensity of a failure of electronic components that are loaded several times higher than unloaded elements;

3) parameters and an operating mode of a control circuit of an electronic part do not depend on an input voltage of a network and is determined only by the current, which can be switched off;

4) ability to perform a control circuit in the form of a unified block, which can be applied almost unchanged for different performances of contactors for different voltages;

5) there is no need for application of fully controlled SS of a high-value and dimensional driver with a special power source for commutation.

This enhances competitiveness of the proposed contactors through improved performance and simplified production significantly.

To substantiate the results obtained in this section as well as to provide practical implementation, it is necessary to conduct theoretical and experimental studies of processes occurring in a circuit of a contactor during switching of a load. In addition, based on the general regularities obtained at the same time, to develop necessary methods of calculation.

5. Theoretical studies of non-stationary processes in circuits of hybrid contactors

Below are theoretical studies of processes occurring in a circuit of a contactor during commutation of a load. One of the main processes is a charging process of a commutating condenser. Fig. 3 shows the calculation of schemes for the study of the process.

There are two stages of the process of charging of a commutation condenser C: the first one – when current flows from MC circuit, the second one – with its full flow to SS.

For the first stage, provided the process equation is as follows:

$$U_a - w_1 S\frac{dB}{dt} + i_1R_1 + L_1\frac{di_1}{dt} = \\ = w_2 S\frac{dB}{dt} + \Delta U_{SS} + i_2R_2 + L_2\frac{di_2}{dt}; \quad (1)$$

$$w_3 S\frac{dB}{dt} = u_C + i_3R_3 + \Delta U_{VD} + L_3\frac{di_3}{dt}, \quad (2)$$

$$i_1 + i_2 = I, i_2w_2 = i_1w_1 + i_3w_3 + H_C l; \quad (3)$$

where U_a is the voltage on a "short" arc on MC; B is the magnetic induction; S is the area of a cross section of a magnetic circuit; R_i, L_i (i=1, 2, 3) are the active resistance and inductance of dissipation of branches, respectively; w_i is the number of turns of a winding; ΔU_{SS}, ΔU_{VD} is the voltage drop on corresponding semiconductor devices; C, u_C are the capacity of a commutation condenser and a voltage on it, respectively; H_C is the coercive force; l is the mean length of a magnetic circuit.

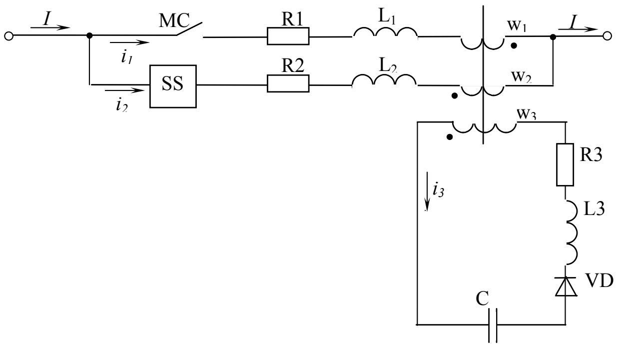


Fig. 3. Calculation scheme for studying a process of charging of a commutation condenser

For the second stage:

$$w_3 S\frac{dB}{dt} = u_C + i_3R_3 + \Delta U_{VD} + L_3\frac{di_3}{dt}, u_C = \\ = U_C(0) + \frac{1}{C}\int i_3 \mathrm{d}t; \quad (4)$$

$$i_2w_2 = i_3w_3 + H_C l, i_2 = I, \quad (5)$$

where $U_C(0)$ is the voltage on a condenser at the end of the first stage.

We can neglect a value of H_C almost without an increase in error due to the fact that we used a material with a rectangular and narrow hysteresis loop for currents of higher 63 A as a material for a magnetic conductor of a current transformer [1]. In addition, experimental studies of current flowing from MC circuit to a shunting circuit, carried out for already developed hybrid contactors, showed that in the course of the existence of a "short" arc, current flows into a shunting circuit with virtually constant velocity K, which lies in the range of 9–11 A/ms [1].

The indicated suggestion makes possible to propose a simplified version that eliminates complexity of the first option, due to the fact that equations of this option are above 2 orders and then we can solve them numerically only, as well as with uncertainties in determination of R_i, L_i.

In this case, equations, which describe a charging process of a commutation condenser become simpler and will have the following form:

First stage:

$$w_3 S\frac{dB}{dt} = u_C, u_C = U_C(0) + \frac{1}{C}\int_0^t i_3 \mathrm{d}t; \quad (6)$$

$$i_1 = I\frac{w_2}{w_1+w_2} - Kt,$$

$$i_2 = I\frac{w_1}{w_1+w_2} + Kt,$$

$$i_3 = Kt\frac{w_1+w_2}{w_3}. \tag{7}$$

Second stage:

$$w_3 S\frac{dB}{dt} = u_C, u_C = U_C(0) + \frac{1}{C}\int_0^t i_3 \mathrm{d}t; \tag{8}$$

$$i_3 = I\frac{w_2}{w_3}, \tag{9}$$

where

$$U_C(0) = U_C(t_1),$$

$$t_1 = \frac{I}{K}\frac{w_2}{w_1+w_2}$$

is the time of the end of the first stage.

As a result of the solution of the equations at the first stage, we obtain an expression for determination of a magnitude of induction of a magnetic conductor at this stage

$$\Delta B = \frac{Kt_1^3(w_1+w_2)}{6SCw_3^2}, \tag{10}$$

and expression for determination of a voltage on a condenser

$$U_C(t_1) = \frac{Kt_1^2}{2C}\frac{w_1+w_2}{w_3}, \tag{11}$$

which are necessary for solution of equations at the 2nd stage.

As a result of the solution of the equations at the second stage, we obtain expressions for determination of a saturation time of a magnetic conductor at this stage

$$t_2 = \frac{Cw_3\left[-U_C(t_1) + \sqrt{U_C(t_1)^2 + 2Iw_2 {S}/{C}\left(2B_S - \Delta B\right)}\right]}{Iw_2}, \tag{12}$$

where B_S is the saturation induction,

as well as an expression for determination of a voltage on a commutation condenser at the end of a charge

$$U_C(t_3) = U_C(t_1) + U_C(t_2) = \frac{Kt_1^2}{2C}\frac{w_1+w_2}{w_3} + \frac{Iw_2 t_2}{w_3}. \tag{13}$$

In this case, a full charge time of a condenser will equal to

$$t_3 = t_1 + t_2. \tag{14}$$

From expression (13) we obtain one more dependence for t_2

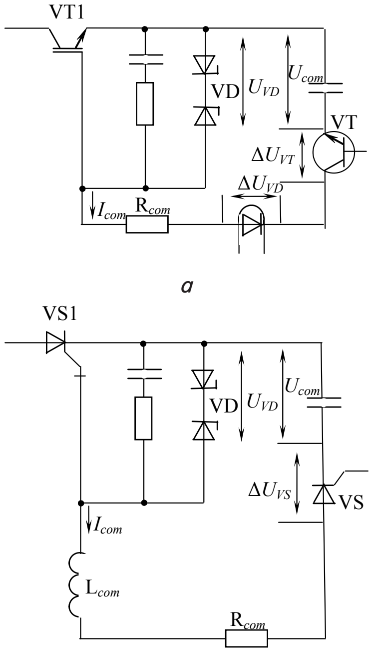
$$t_2 = \frac{U_C(t_2) w_3 C}{Iw_2}. \tag{15}$$

We equate expressions (12) and (15), perform the corresponding transformations and obtain expressions for determination of a cross-sectional area of a magnetic conductor

$$S = \frac{\left[U_C{}^2(t_3) - U_C{}^2(t_1)\right]C}{2Iw_2(2B_S - \Delta B)}. \tag{16}$$

We study a locking process of a fully controlled SS additionally to determine unknown parameters C and $U_C(t_3)$.

Fig. 4, *a* shows the calculation scheme for these studies for VT1 transistor, and Fig. 4, *b* – for VS1 thyristor.



a

b

Fig. 4. Calculation schemes for study of a locking process: *a* – VT1 transistor, *b* – VS1 thyristor

Obviously, a value of capacity of a commutation condenser C_{com} and an initial voltage on it $U_{com} = U_C(t_3)$ must always be such as to ensure an arcless commutation of the main circuit over the entire range of operation contact currents $(0{,}2-0{,}25)I_{nom}$ [1].

The following expressions determine i_{com} currents, which are commutated in the above schemes, as shown in paper [15]:

– for the scheme in Fig. 4, *a*

$$i_{com} = \frac{\left[U_{com} - U_{VD} - \Delta U_{VD} - \Delta U_{VT}\right]}{R_{com}} e^{-\frac{t}{\tau}}, \tag{17}$$

– for the scheme in Fig. 4, *b*

$$i_{com} = \frac{U_{com} - \Delta U_{VS}}{L_{com}(p_2 - p_1)}\left(e^{p_1 t} - e^{p_2 t}\right), \tag{18}$$

where

$$p_{1,2} = -\frac{R_{com}}{2L_{com}} \pm \sqrt{\left(\frac{R_{com}}{2L_{com}}\right)^2 - \frac{1}{L_{com}C_{com}}}. \tag{19}$$

In this case, the maximum value of this current will be at the time determined by the expression

$$\frac{di_{com}(t)}{dt}=\frac{U_{com}-\Delta U_{VS}}{L_{com}(p_2-p_1)}\left(p_1e^{P_1t}-p_2e^{P_2t}\right)=0, \qquad (20)$$

hence

$$t_m=\frac{\ln\frac{p_2}{p_1}}{p_2-p_1}. \qquad (21)$$

Thus, at the moment of time t_m

$$I_{com\max}=\frac{U_{com}}{L_{com}(p_2-p_1)}\left(e^{P_1t}-e^{P_2t}\right), \qquad (22)$$

$$U_{com}(t_m)=\frac{U_{com}}{p_2-p_1}\left(p_1e^{P_1t}-p_2e^{P_2t}\right). \qquad (23)$$

We should note that throughout the whole range of I_{com} commutated currents the maximum value of $I_{com\max}$ locking current should be higher than the current of activation of VS3 optron thyristor for the scheme Fig. 1, *a*, but also higher than the current of locking of VS1 thyristor for the scheme Fig. 1, *b*.

We apply known methods for calculation of transition processes in a delay cycle [15] and obtain the following expression for determination of a delay time for activation of VT3 commutation transistor (Fig. 1, *a*) or VS2 commutation thyristor (Fig. 1, *b*):

$$t_4=\tau\ln\frac{U_C(t_3)-U_C(t_0)}{U_C(t_3)-U_{VD7}}+t_0, \qquad (24)$$

where $\tau=R_7C_4$ is a constant of time;

$$t_0=\frac{U_C(t_3)\cdot C_3w_3}{Iw_2}=t_3$$

is the time of charging of commutation condenser;

$$U_C(t_0)=\frac{Iw_2}{w_3\cdot C_3}\left(\tau e^{-t_0/\tau}+t_0-\tau\right)$$

is voltage on C_4 condenser C4 at t_0; U_{VD7} is the stabilization voltage of VD7 stabilitron.

6. Results of calculation of parameters of elements of a control circuit by a semiconductor switcher

Tables 1, 2 show calculated values of main parameters of the current transformer and a switching circuit at commutation of the maximum contactor current for the circuits shown in Fig. 1, *a, b* respectively. We carried out calculations with a use of formulas (10)–(18), (22).

The output data for calculation were the following parameters: a range of commutated currents –

$$I_C=(0{,}2-2{,}5)I_{nom},$$

a rate of current flowing from the main circuit MC1 – $K=10$ A/μs, induction saturation of a material of a magnetic conductor – $B_S=1{,}5$ T, a current of locking of dual operation thyristor $0{,}25I_C$ and its rate of growth – (20–100) A/μs [2]. A limit value of a voltage at SS input SS – ±15 V. Full charge time of commutation condenser – $t_3<1$ ms.

At commutation of the minimum current $(0{,}2I_{nom})$ the voltage on a commutation condenser at the start of a locking of a fully controlled SS will be 22.6 V (for the scheme in Fig. 1, *a*) and 19.8 V (for the scheme in Fig. 1, *b*), which is sufficient (with a a large reserve) for their reliable locking. Because of the fact that a value of a voltage on a commutation condenser capacitor decreases in proportion $\sqrt{I_C}$ to a commutated current decreasing (formulas (11)–(13)).

Analysis of the results of the calculation shows that there is reliable locking of fully controlled SS provided throughout the whole range of commutated currents of a contactor without a use of special value drivers. At the same time, the energy consumed from a network for one switch off of the maximum possible current for IGBT transistor option does not exceed 0.1 J. Mass, dimensions and cost of elements used for this purpose are quite acceptable and determined only by values of current that is activated, but do not depend on the voltage of a network. As a result of the analysis, we found that a locking circuit of IGBT-transistor in terms of dimensions, weight, dissipation power and cost is better than locking circuits of a dual-operation thyristor with the same parameters.

Table 1

Results of calculations for the scheme Fig. 1, *a* at I_C=2.5I_{nom}

I_{nom}, A	Parameters of a current transformer				Parameters of a switch off circuit				
	w_1	w_2	w_3	S, sm^2	C_{com}, μF	$U_c(t_3)$, V	R_{com}, Ω	$I_{com\max}$, A	t_3, μs
100	1	2	500	0.22	10	80,0	250	0.26	817
160	1	2	600	0.20	15		180	0.36	927
250	1	2	700	0.18	20		150	0.43	938
400	1	1	450	0.27	25		120	0.54	950
630	1	1	550	0.20	30		100	0.65	917

Table 2

Results of calculations for the scheme of Fig. 1, *b* at I_C=2.5I_{nom}

I_{nom}, A	Parameters of a current transformer				Parameters of a switch off circuit					
	w_1	w_2	w_3	S, sm^2	C_{com}, μF	$U_c(t_3)$, V	R_{com}, Ω	L_{com}, μH	$I_{com\max}$, A	t_3, μs
100	1	2	200	0.49	30	70.0	0.8	1.0	78	856
160	1	2	200	0.50	50		0.5	1.0	120	900
250	1	2	200	0.53	80		0.3	1.0	187	935
400	1	1	100	1.05	128		0.18	1.0	290	946
630	1	1	100	1.05	200		0.114	0.5	468	969

However, IGBT transistors are almost three times inferior to dual-operation thyristors in the area of controlled currents for overload capability [2]. The latter leads to the fact that with the same nominal contact currents, a current of a long mode of IGBT-transistor as many times will exceed the same current in the version with a dual-operation thyristor approximately.

As a result, at nominal currents above 160 A, the use of IGBT transistor as an SS contactor becomes economically unjustified, and the use of SS as a dual operation, on the contrary, is economically feasible. Since dimensions and cost of switching off circuit of a dual-operating thyristor is incomparably smaller than the rest of elements, this shortcoming is not decisive when choosing a dual-operation thyristor as SS.

Papers [1, 16] provide the methodology for calculation of reloading capability of a fully controlled SS as well as a varistor overvoltage limiter [1, 16]. We can see that power semiconductor devices that act as SS in hybrid contactors operate without coolers. In this case, a value of the maximum impulse current of IGBT transistor I_{CM} and the maximum commutated current of a dual-operation thyristor I_{TGOM} shall not be less than the value of the maximum current of the switched off contactor. We achieve the permissible level of overvoltage less than $2{,}5U_{\mathrm{nom}}$ successively – in parallel with activation of low-power varistors with acceptable weight and cost [16].

7. Experimental studies of a process of charging of commutation condenser

We determined experimentally the most important parameters for the analysis of the control scheme: a value of a voltage on a commutation condenser and a time of its charge from a current transformer in a process of switch off. We carried out the study on a special installation. Fig. 5 shows its electric circuit.

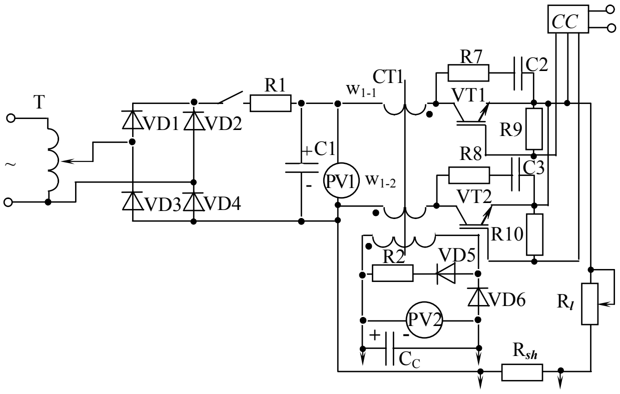


Fig. 5. Experimental circuit of the installation for the study

According to the circuit, in order to exclude an influence of inductance of a network on a commutation switching process as a voltage source, we use a previously charged C capacitor battery of high capacity $C1 = 0{,}1$ F, and, as a load, we use an active resistance to a rheostat. CT1 current transformer: twisted magnetic conductor, electrotechnical cold-rolled steel with an active section of 0.5 cm^2, an average length of a magnetic conductor is 9.42 cm, a number of turns of primary and secondary windings $w_{1-1} = 2$, $w_{1-2} = 4$, $w_2 = 200$, resistance of the windings is 0.56 Ω. Parameters of a commutation condenser: capacity $C = 30$ μF, voltage 100 V. Thus, the parameters of the current transformer and the commutation condenser correspond to the calculated parameters of a hybrid contactor on $I_{\mathrm{nom}} = 100$ A with a dual-operation thyristor as a fully controllable SS.

Circuit commutation goes with a use of transistors VT1 and VT2 executed on IGBT transistors of ABB company of 5SMY 12H/280 type. The control circuit (CS) provides a short-term, consistent switching off the transistors under a mode close to the real operation mode of CT in hybrid contactors with $I_{\mathrm{nom}} = 100$ A.

We made measurements using a digital oscilloscope and a digital voltmeter. Table 3 gives results of the comparison of experimental and calculated values and voltage on the commutation condenser and its charging time. In this case, we carried out calculations using the formulas (10)–(14).

Table 3

Results of measurements and calculations of the voltage on a commutation condenser $U_C(t_3)$ and its charging time t_3

Commutated current I_C, A	Value of voltage in commutation condenser, V		Error δ_1, %	Time value on a commutation condenser, ms		Error δ_2, %
	calc.	meas.		calc.	meas.	
250	70.0	68.5	2.1	0.865	0.84	1.9
200	62.5	61.0	2.4	0.957	0.92	3.8
150	54.4	52.5	3.4	1.100	1.05	4.5
100	44.5	42.5	4.5	1.345	1.28	4.8
50	31.6	29.5	6.0	1.890	1.78	5.8

Analysis of the results presented in Table 3 showed a high convergence of results. The maximum error does not exceed 6 %, which is quite suitable for engineering calculation methods. Since the experiment used a current transformer and a commutation condenser, parameters of which corresponded to the calculated values, the evaluation is integral, that is, it extends to the entire methodology.

8. Discussion of results of the conducted study of hybrid DC contactors

Application of hybrid contactors in the above schemes for control of an electronic part with a main circuit current created a number of positive qualities that increase their competitiveness. Due to the introduction of a small-sized current transformer with two primary windings into a contactor. The first windings is connected to the first pole in series with the main contact, and the second one – in series with a fully controlled (SS), which shunts the contact. Such activation leads to the fact that a magnetic conductor stays in a saturated state under action of a current load and there is no EMF on the secondary winding and circuits of an electronic part of a contactor are thus deenergized. And only when a contactor is switched off when current is transmitted to a circuit, which shunting the main contacts, a magnetic conductor of a transformer begins to reverse in the opposite direction, and the secondary winding yields EMF that provides a constant current for the charging of a commutation condenser for a forced switch-off of a fully controllable SS. The process is short-lived (several milliseconds) and stops when a magnetic conductor is reversed in the opposite direction, after which the current stops in the secondary circuit of a transformer.

As a result, we obtain the economical mode of operation of electronic circuit elements (they are almost in storage mode and intensity of their failure will be several times lower than in the case of their operation under load). Therefore, reliability of a contactor, and hence its service life, increases significantly. There is no need for additional power supplies and large drivers, which are commonly used in existing models. This simplifies an electronic part of a contactor significantly.

Thus, we improved the operational quality of the proposed contactors and made the organization of their production easier, that is, their competitiveness increases.

The disadvantage of the proposed contactors is a use of a non-standard low-power current transformer, which complicates introduction into production. But this disadvantage is offset by several positive properties shown above.

The conducted studies of non-stationary processes, which take place in contactor circuits during commutation made it possible to develop methods for calculation of the main elements of an electronic part of a contactor suitable for engineering calculations.

The studies showed that the voltage on a commutation condenser, which ensures a forced switching-off of a control switch at given values of its capacity and a cross section of a transformer, is proportional to a square root of commutated current and does not depend on the number of turns of a secondary winding. This significantly reduced a cost of calculation of parameters of elements of an electronic part, as calculation would be sufficient only for the case of commutation of the maximum current. At the same time, for smaller currents, we always provided a secure lock of a controlled switch.

The results of calculation and experimental studies show the real possibility of creating hybrid DC contactors calculated on currents of 100–630 A and voltage up to 1,000 V.

The obtained study results can be useful in the development of hybrid contactors for heavy operating modes for frequent starts of engines, for example in electric transport, crane equipment, rolling mills of metallurgical plants, etc., as well as under conditions of increased explosion and fire safety requirements, while their positive qualities, mentioned above, increase their competitiveness greatly.

9. Conclusions

1. We substantiated that the proposed hybrid contractors have the following advantages in comparison with the existing ones:

– they increased reliability due to introduction of a low-power current transformer to the main circuit, which provides power to an electronic part of a contactor in a short period of time only (several milliseconds) when it is switched off. As a result, elements including a semiconductor switch are unloaded for a period of time when a contactor was turned on and off, that is, almost in a storage mode, when a bounce rate is lower than in a load mode. It also naturally eliminates need for an additional power source;

– parameters and operation conditions of a control circuit of an electronic part of a contactor do not depend on a voltage of a network and are determined only by current that switches off, which makes possible to perform it in the form of a unified block, which operate unchanged at different voltages;

– as a result of the application of the proposed technical solutions in the construction of circuits to enable and disable fully controlled switches, as well as a choice of rational mode of operation of the circuits, there is no need to use high-value standard drivers with special power units for control of switches.

2. The study showed that the charging of a commutating capacitor occurs due to a direct current under an action of EMF, which occurs on the secondary winding of a transformer during its re-magnetization by the current of a shunting circuit. At the same time, at given values of a cross section of a magnetic conductor and capacity of a condenser, a voltage level, to which it is charged, does not depend on the number of turns of the secondary winding, but is proportional to a square root of a value of commutated current. The time of its charging under the same conditions is proportional to the number of turns of the secondary winding.

This makes it possible to approach reasonably the definition of parameters of elements that provide reliable locking of semiconductor switches and to obtain positive effects from introduction into production.

3. The developed methods of calculation of main elements of a control scheme of the proposed hybrid contactors give possibility to carry out the indicated calculations with sufficient accuracy for engineering calculations, which is confirmed by the results of experimental research. In this case, a volume of calculations reduces, because they are executed only at the maximum commutated current for this execution of a contactor. Because voltage of a commutation condenser charge, as indicated earlier, is proportional to a square root of commutated current, it will always be ensured that a lower voltage of a contactor working range is safely switched off.

4. The results of the calculations show that the proposed contactors at preserved cost and mass-dimensional indicators achieved for the best samples provide reliable commutation of load across the whole range of commutated currents. In this case contactors with a use of IGBT-transistor as switches should be used for switching currents up to 500–600 A, specifically for contactors for nominal currents I_{nom} up to 160 A. This is explained by the fact that IGBT transistors designed for larger currents are not mass-produced and have a high cost, in addition they have a low reloading capacity by current. Unlike these devices, dual-operation thyristors have a higher reloading capacity and are designed for commutation of larger currents, so contactors on $I_{nom} > 160$ A should be used on their basis.

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