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The Electrotechnical Complex of the KTM Tokamak Pulsed Power Supply System

D. B. Zarva[a,*], A. A. Deriglazov[b], E. G. Batyrbekov[a,c], I. L. Tazhibayeva[a,c], V. M. Pavlov[b], A. M. Li[b], A. A. Mezentsev[b], S. V. Merkulov[b], and Yu. N. Golobokov[b]

[a] *Republican State Enterprise National Nuclear Center of the Republic of Kazakhstan, Kurchatov, 071100 Kazakhstan*
[b] *Tomsk National Research Polytechnic University, Tomsk, 634050 Russia*
[c] *National Research Nuclear University MEPhI, Moscow, 115409 Russia*
**e-mail: @@@*

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Abstract—The pulsed power supply equipment belongs to the basic technological systems intended for implementing the required scenarios of changing currents in magnetic coils. The accuracy of implementing these scenarios directly determines the possibility of attaining the plasma breakdown and the required ultimate plasma parameters. Given the uniqueness of each facility under construction in the world and the installed capacity of the electrotechnical equipment applied in the power supply configuration, one can state with confidence that the construction of similar power supply complexes and their control systems, the optimization of their electrotechnical parameters, and the subsequent accident-free operation are vital tasks in mastering controlled thermonuclear fusion technologies. This paper describes the pulsed power supply system of the KTM tokamak (Kazakhstan) designed for material testing, the digital control system for its power conversion equipment, electrotechnical solutions adopted in the design of the KTM tokamak pulsed power supply system, and findings of tests of some items of equipment and their components. The tests have demonstrated sufficient efficiency of the adopted electrotechnical solutions and the possibility of applying them to implement the pulsed power supply systems for small and medium sized tokamaks.

Keywords: KTM tokamak, pulsed power supply, semiconductor converters, control and diagnostics system of conversion equipment, high-current DC circuit breakers, distribution of currents in parallel-connected semiconductor devices

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INTRODUCTION

The KTM tokamak constructed presently in Kurchatov, Republic of Kazakhstan, is the world's only "megaampere" facility with the plasma current $I = 0.75$ MA designed for testing materials and technologies under standard and emergency (plasma disruption) operating conditions of fusion reactors at the aspect ratio $A = 2$, which allows for studies of the plasma confinement physics to be conducted in the boundary region between the spherical ($A < 2$) and classical ($A > 2$) tokamaks [1–3].

A plasma discharge can be obtained in a tokamak-type electrophysical facility directly depending on the possibility of implementing complex scenarios of changing currents in electromagnetic coils. For the above scenarios of changing currents in the KTM electromagnetic coils to be implemented, a corresponding pulsed electric supply system for them is being developed.

FORMULATION OF THE PROBLEM

The development of the pulsed power supply systems for the tokamak-type electrophysical facilities is a complicated scientific and engineering task, since in every particular case the developers have to solve numerous problems caused by considerable drastic changes in the nature and amounts of consumed power, restrictions imposed by the supply grid, restrictions related to the load parameters (in this case, the electromagnetic coils of the tokamak), the necessity of minimizing the output current and voltage ripples, the necessity of reducing the impact of the power sources on the power network, the necessity of high-accuracy control and stabilization of the load currents at high rates of change, etc.

Further, currently there are no standard commercial prototypes of electrotechnical components and conversion equipment required for assembling pulsed power supplies for the tokamaks, which necessitates devising nonstandard prototypes and solutions that will meet the requirements of a particular task. Given

Table 1. Basic parameters of the KTM electromagnetic coils and the direct-current-carrying busbar system

Parameter/coil	Number of turns	I_{max}, A	U_{max}, V	R of coil, mΩ	L of coil, mH	Stored energy W, kJ	R of busbar, mΩ
PF1	40	18000	1000	8.90	2.60	421.2	1.81
PF2	8	18000	1000	3.80	0.37	59.94	1.81
PF3	40	10000	1000	25.80	11.00	550	1.45
PF4	48	30000	1000	6.70	3.10	1395	0.78
PF5	16	30000	1000	7.61	1.40	630	0.73
PF6	40	10000	1000	25.70	11.10	555	1.56
HFC+	36	3000	1000	106.60	8.80	39.6	3.51
HFC–	36	3000	1000	105.90	8.80	39.6	3.51
CS	423	30000	3300	30.50	11.40	5130	0.60
TF	80	60000	1000	6.70	8.00	14400	0.30

the installed capacity of the electrical equipment and the number of semiconductor components used to assemble the above equipment, the matters of minimization of the probability of accidents and their consequences, optimization of load and overload characteristics, and the need for on-line diagnostics of the conversion equipment are becoming topical.

The input data that impose imperative requirements on the pulsed power supply system of the tokamak electromagnetic coils are the scenarios of changes in currents in them during the basic "engineering" plasma scenario of the facility discharge and the basic parameters of the electromagnetic coils themselves. In Table 1, the basic parameters of the KTM electromagnetic coils measured immediately after assembling the facility and the calculated parameters of the direct-current-carrying busbar system are presented.

The cross section of the KTM facility and the spatial arrangement of the coil blocks are shown in Fig. 1. The notation adopted in the figure is as follows: PF1–PF6 are the poloidal field coils; CS is the central solenoid coil; HFC +/– are the upper and lower fast vertical plasma shift stabilization coils; passive coils are the passive stabilization coils; TF is the toroidal field coil.

PULSED POWER SUPPLY SYSTEM OF THE KTM TOKAMAK ELECTROMAGNETIC COILS

Given the fact that, in the course of the plasma discharge in the KTM facility, the calculated power consumed from the power network does not exceed 126 MVA and the short-circuit power of the network reduced to the voltage of 220 kV on the territory of the KTM electrical substation is $S = 1.332$ GVA, the KTM pulsed power supply system was connected jointly

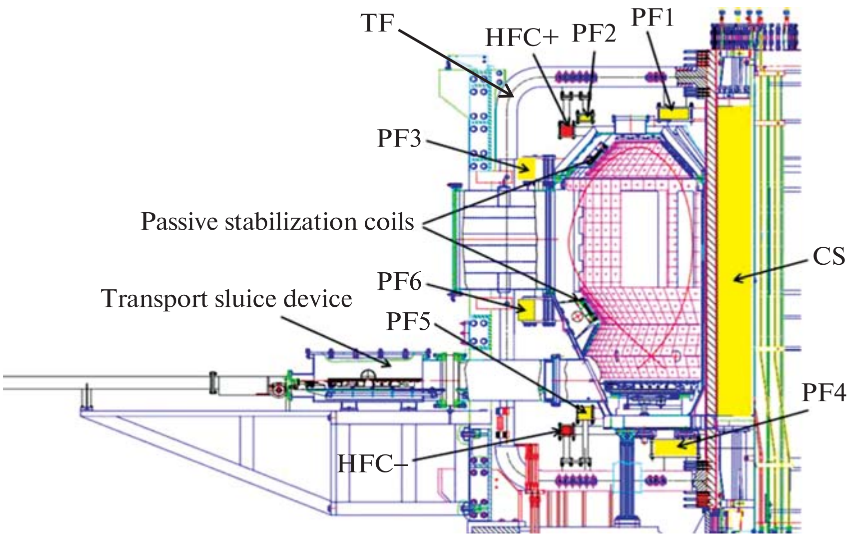

Fig. 1. Cross section of the KTM tokamak.

Table 2. Basic characteristics of the KTM pulsed power supplies

Power supply (PS)	Pulsation rate	PS parameters		Structure	Controllability characteristic	Type and number of semiconductor devices
		I_{max}, kA	U_{max}, kV			
PS of toroidal field coil TF	$q = 1\%$ ($k = 12$)	60	1	Modular, four thyristor converters TC	Fully controllable, only rectifier mode	SCR 1200/18 thyristor, 144 pcs.
PS of central solenoid coil CS)	$q = 1\%$ ($k = 12$)	±30	3	Modular, eight thyristor converters TC—direct-current breaker switch	Fully controllable, current reversal in shared control mode	SCR 1200/18 thyristor, 288 pcs. in thyristor converter SCR 1200/18 thyristor, 102 pcs., 1500/16 diode, 60 pcs. in breaker switch
PS of poloidal field coil PF1	$q = 1\%$ ($k = 12$)	±15	±0.6	Modular, four opposite-parallel connected thyristor converters TC with 2 TCs for each PS	Fully controllable, current reversal in separate control mode	SCR 1200/18 thyristor, 72 pcs.
PS of poloidal field coil PF2	″	″	″			SCR 1200/18 thyristor, 72 pcs.
PS of poloidal field coil PF3	″	″	″	″	″	SCR 1200/18 thyristor, 72 pcs.
PS of poloidal field coil PF6	″	″	″	″	″	SCR 1200/18 thyristor, 72 pcs.
PS of poloidal field coil PF4	″	±30	″	Modular, four opposite-parallel connected thyristor converters TC with 4 TCs for each power supply	″	SCR 1200/18 thyristor, 144 pcs.
PS of poloidal field coil PF5	″	″	″			SCR 1200/18 thyristor, 144 pcs.
	$q = 4{,}0\%$ ($k = 6$) in direct current link	±3	±1	Modular, two in-series connected thyristor converters TC with 2TCs for each power supply	Fully controllable, 1 kHz voltage inverter, PWM control	SCR 1200/18 thyristor, 36 pcs.
				Monoblock (voltage inverter)		IGBT transistor 2400/17, 12 pcs.

with the system of auxiliary plasma HF heating without using intermediate power storage systems directly to the supply network via the main TRDTsNM-100000/200000/220/10U1 220/10 kV step-down transformer of the KTM substation with a power of 100 MVA. The rated capacity of the transformer was selected on the basis of the pulsed operating mode of the KTM facility and the overload capacity of the above transformer.

The currents in the electromagnetic coils of the KTM facility are generated using nine pulsed power supplies that constitute a group of two 31.2 MVA step-down transformers for a voltage of 10/0.7 kV (T1 and T2 in Fig. 2), seven 6.3 MVA step-down transformers for a voltage of 10/0.4 kV (T3–T9 in Fig. 2), a semiconductor converter consisting of 30 thyristor converters with a power of 15 MW each (TC in Fig. 2), a semiconductor breaker switch for a current of up to 30 kA in the power supply of the central solenoid coil, a voltage inverter with a frequency of 1 kHz and a power of 3 MW in the power supply of the fast vertical plasma shift stabilization coils (SC in Fig. 2), ten current balancing reactors for currents of up to 30 kA (CBR in Fig. 2), and other electrotechnical equipment. In Table 2, the basic electrotechnical characteristics of the pulsed power supplies of the KTM facility are presented.

The basic component of the pulsed power supply system of the KTM tokamak is thyristor converter TC based on a six-pulse bridge rectification circuit (Larionov's circuit). The engineering solutions adopted when developing the thyristor converter ensure high accessibility of the power supplies. This is achieved using modular structures at the level of both power circuits and electronic devices to control the thyristor switches and measure the electric parameters of the converter (diagnostics).

A thyristor converter is an electrical cabinet with 12 power-switch cells (converter sections) with three in-series connected SCR 1200A/1800V thyristors in each, which in turn are connected forming two three-phase fully controllable bridge rectifiers. The bridge

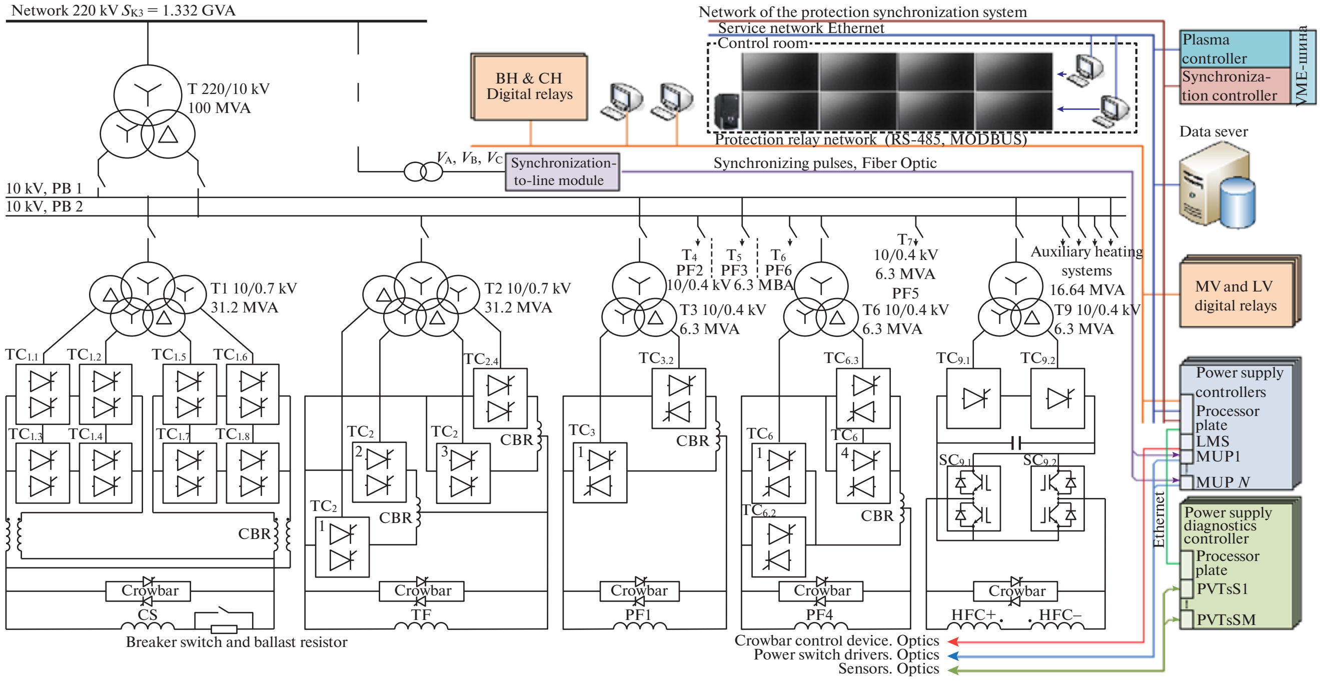

Fig. 2. Structural schematic of the pulsed power supply system of the KTM facility and its digital control system ("crowbar" means the bypass valve).

rectifiers are parallel connected in the working TC configurations of the power supplies of TF and CS coils and antiparallel connected in power supplies PF1–PF6 to ensure the current reversal mode under separate control. The TC cabinets are cooled by circulating deionized water.

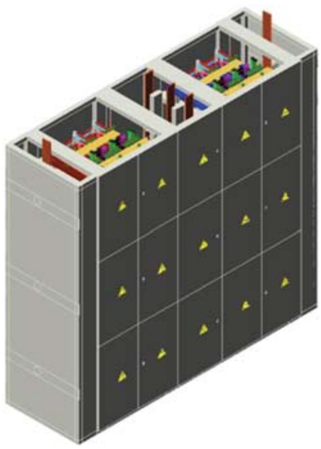

Fig. 3. 3D model of the TC cabinet of the KTM pulsed power supply system.

In Fig. 3, a 3D model of the TC cabinet is shown with 12 converter sections in it. With the help of 3D modeling, the optimal spatial arrangement of the converter components was found and the current-carrying power bus lines, measurement and control cables, and cooling system components were routed. The obtained data were used to calculate the mechanical strength of the converter components and to make the working drawings of the power structure of the cabinet. A photograph of the room for the pulsed power supplies of the KTM tokamak with the installed conversion equipment of the thyristor converters, current-balancing reactors, and busbars is shown in Fig. 4.

SOLUTION TO THE PROBLEM OF THE ARRANGEMENT AND UNIFORM DISTRIBUTION OF THE CURRENTS IN THE POWER CONVERTERS

The implementation of the parallel connection of semiconductor switches in superpower AC/DC converters is a nontrivial task. This factor determines the efficient use of the converter switches, the load characteristics of the converter, and its reliability as a whole. Various circuitry and geometric methods of connection are used to connect the converter compo-

Fig. 4. Photograph of the KTM pulsed power supply room with the installed thyristor converters.

nents that allow the minimization of the current imbalance in parallel branches [4–7].

When developing the thyristor converter system of the KTM pulsed power supply, a rather original solution to the problem of the current distribution in the parallel-connected thyristors was applied. A liquid-cooled silicon resistor with the resistance $R = 0.001\ \Omega$ was connected in series to each thyristor; in addition to solving the problem of distributing the currents, such a resistor allowed the real-time diagnostics of every particular thyristor of the converter system [8]. The configuration of the reversible TC cabinet and the schematic circuit of its converter section are shown in Fig. 5.

It can be seen from the schematic of the arrangement that the same TC can be assembled to operate as both a reversible and nonreversible converter depending on the intended use of the particular power supply. In the case of the nonreversible configuration, the peak output current of a single TC is doubled accordingly and equals 15 kA. The converter sections (TC panels) are divided in this case into conventionally positive (in red) and conventionally negative (in blue) sections. The difference is in the position of the thyristor cathodes with respect to the direct and alternating current buses. A single TC panel contains the following components: fast response fuses FU1–FU3, tablet-type silicon shunts $R1$–$R3$, SCR 1200A/1800V thyristors denoted in the figure by VS1–VS3, snubber circuits FV1–FV3, a measurement and control instrumentation module composed of DSK-6A-MPT SCR thyristor drivers, and a PIT-3 three-channel module to measure the current that flows through the thyristors of the TC converter section.

In Fig. 6a, a 3D model of a single TC converter section is shown, and in Fig. 6b, a photograph of the above converter section installed in the TC cabinet is presented.

The electrotechnical tests proved fairy high efficiency of the solution to the problem of distributing the currents in the parallel connected thyristors in the KTM converter system. One can see in Fig. 7 that the shape and the peak and mean current pulse values in the thyristors of one of the converter sections are practically identical. Overall, a mean current imbalance factor of 5.85% was achieved for all 30 TC cabinets with 20% considered to be an acceptable figure for the thyristor converters of the power supply systems [5, 6, 9].

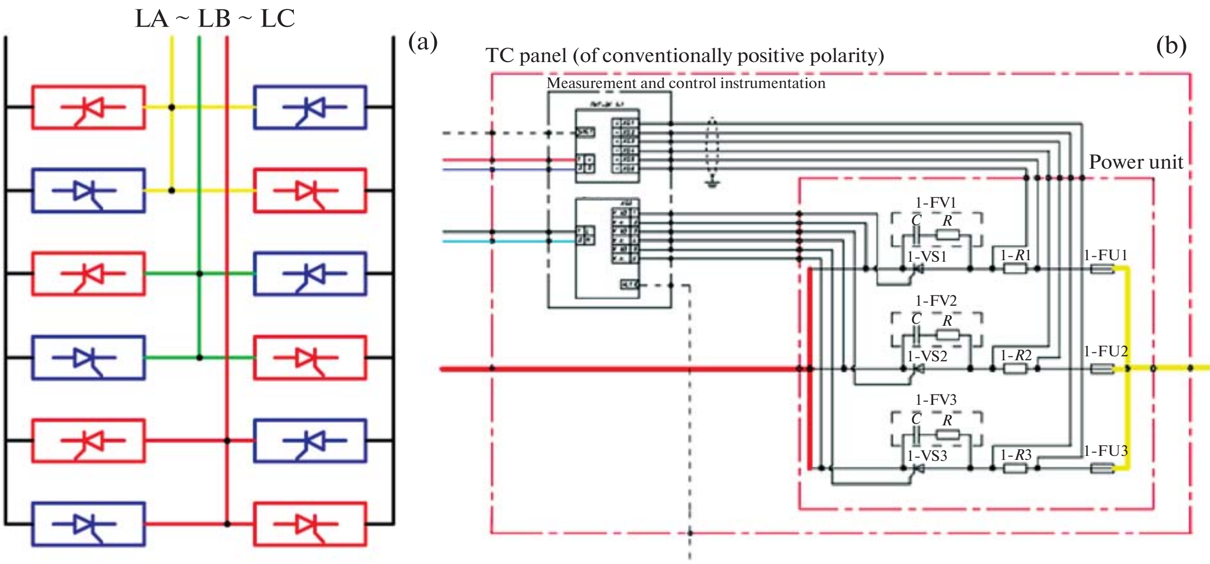

Fig. 5. (a) Layout of the TC cabinet and (b) schematic circuit of its single converter section: (—— , ——) power buses; (- - -) POF fiber-optic cables; (——) 24-V (+) direct current supply network wire; (——) 24-V (0) direct current supply network wire; (——) 24-V (L) direct current supply network wire; and (——) 24-V (N) direct current supply network wire.

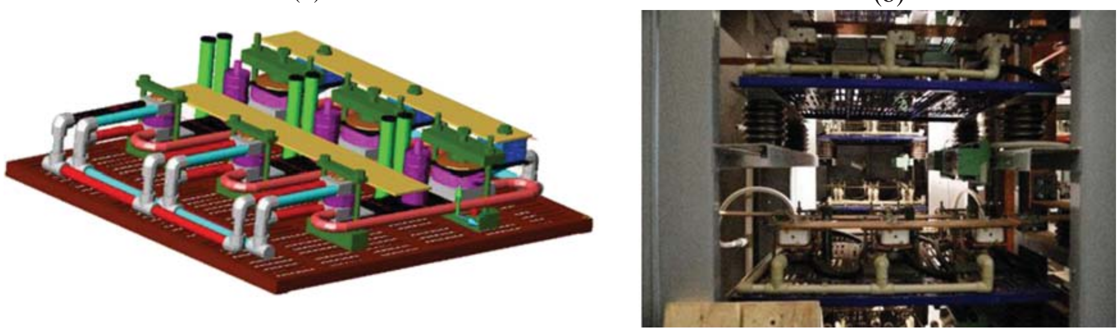

Fig. 6. Single converter section: (a) 3D model and (b) photograph.

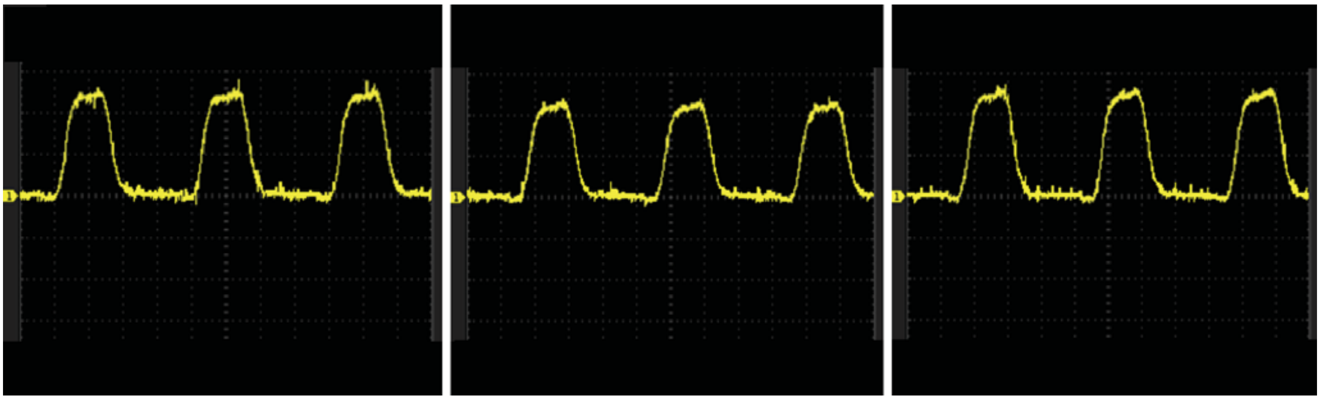

Fig. 7. Oscillograms of the currents through three parallel-connected thyristors of a converter section of the TC system of the KTM pulsed power supply.

30-kA DC CIRCUIT BREAKER OF THE POWER SUPPLY OF THE KTM CENTRAL SOLENOID COIL

The phase of a sharp reduction in the current value is characteristic of the scenario of change in the current in the central solenoid coil of the KTM tokamak; this phase, which follows the preliminary “pumping” phase, is necessary to achieve the peak voltage level—the maximum vortex electromagnetic field strength—in the bypass of the vacuum chamber to attain the working gas breakdown and a rapid increase in the plasma current value. It can be seen from Fig. 8 that the current in the KTM central solenoid coil must decrease from 30 kA to 0 within a time interval of ~0.23 s, which corresponds to a current reduction rate in the coil of ~130.4 kA/s.

The required current reduction rate in the central solenoid coil can be achieved by applying a voltage at a level that exceeds the required voltage for other discharge phases by many times.

To achieve the required current reduction rate in the KTM central solenoid coil, a solution was applied based on the introduction of an auxiliary resistive component (a ballast resistor) into the power supply circuit of the coil at the moment of the plasma discharge initiation. Since the time of the current reduction in the central solenoid coil t is described by the relation $t = -T\ln(1 - R/U)$, where I is the initial current in the coil, R is the ohmic resistance of the power supply circuit, U is the coil voltage, and T is the time constant of the circuit determined by the relation $T = L/R$, where L is the inductance and R is the ohmic resistance of the circuit, the time constant decreases

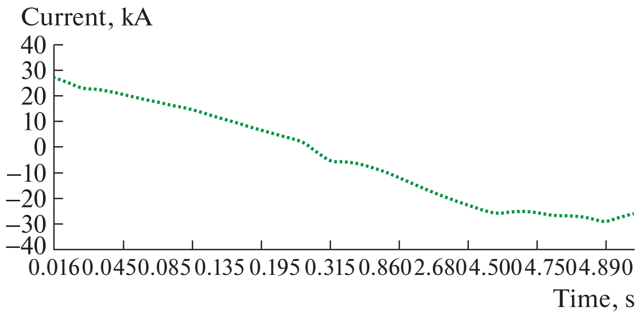

Fig. 8. Engineering scenario of change in the current in the central solenoid coil of the KTM tokamak during a plasma discharge.

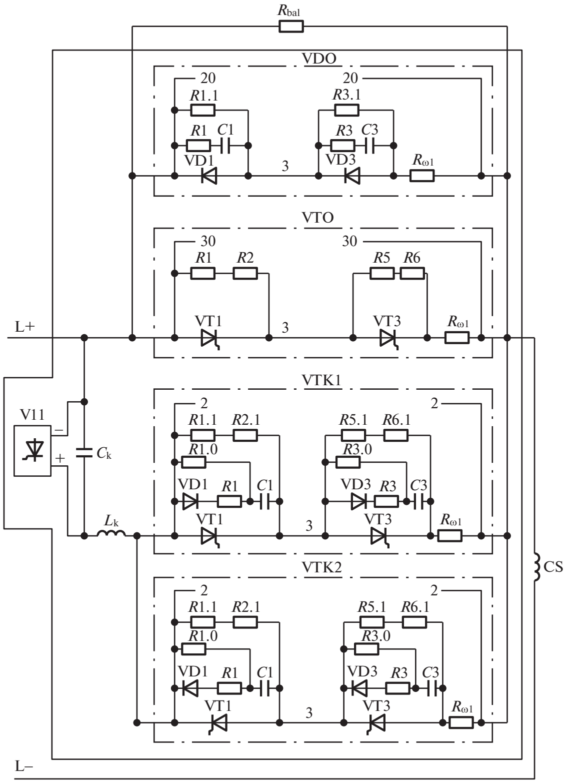

Fig. 9. Schematic circuit of the DC breaker switch.

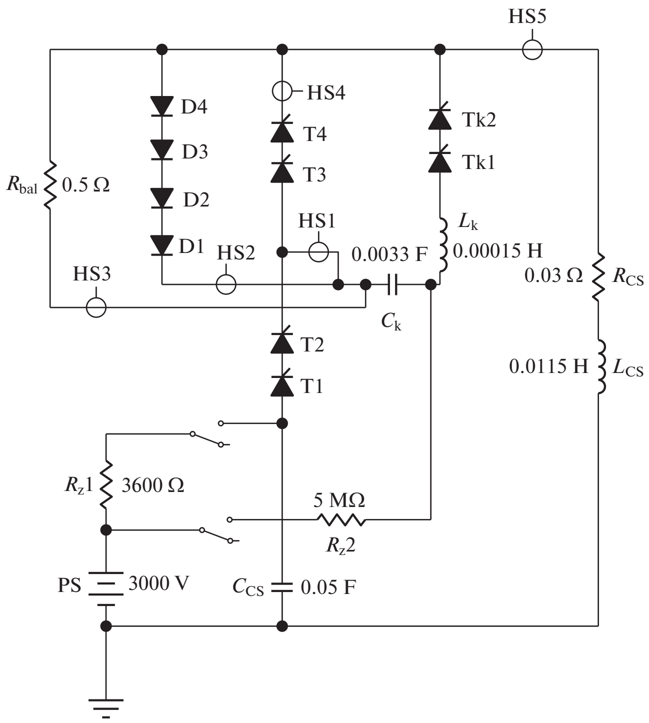

Fig. 10. Schematic circuit of the DC breaker switch mock-up.

upon the introduction of the auxiliary resistor into the power supply circuit, which results in a considerable reduction in the current fall time. At the central solenoid coil winding leads, a voltage of the required level is induced that exceeds the voltage level of the power supply.

The auxiliary resistance is introduced into the power supply circuit of the KTM coil using a semiconductor breaker switch for a total load current of 30 kA that differs from the well-known breaker switches [10–14] in its circuitry solution based on the use of gate-controlled SCR thyristors and power diodes without using electromechanical bypass circuits. In Fig. 9, the schematic circuit of the direct-current breaker switch of the power supply of the KTM central solenoid coil is shown.

At the beginning of the current scenario in the CS coil, the coil is "pumped" up to a working current of 30 kA via a group of 30 parallel connected thyristor sections VTO in each of which three in-series connected SCR 1200A/1800V thyristors are used to reach the required working voltage and current levels. At the time of the plasma discharge initiation, capacitor unit C_k precharged from standalone charger VT1 creates a current pulse via thyristor section VTK1 in countercurrent to section VTO. The total load current is composed of the current of the CS coil power supply and the current of circuit C_k–L_k. At this moment, the current through VTO is interrupted and, upon the completion of the discharge of capacitor unit C_k, the current of the CS coil power supply circuit is reswitched to ballast resistor *R*. Further, during the plasma discharge when the current in the central solenoid coil moves over zero, the reversible component of the power supply begins to feed the load via 20 parallel connected diode sections VDO consisting of three in-series connected 1500A/1600V diodes and capacitor unit C_k is recharged via thyristor section VTK2 to prepare the following KTM plasma discharge

To validate the developed circuitry solution, a full-scale breaker switch mock-up was produced using a bank of capacitors as the power supply of the central solenoid. The full-scale mock-up allowed one to refine the switching modes without damaging the standard thyristor converters of the KTM central solenoid power supply and make sure that the scheme was workable.

For the mock-up, a breaker-switch circuit was proposed in which, in contrast to the standard circuit, the type of the power supply and the number of parallel connected semiconductor power components were changed. In Fig. 10, the proposed circuit of the breaker-switch mock-up based on a capacitor power supply is shown. Here, thyristors T1 and T2 belong to the capacitor power supply and thyristors T3 and T4 correspond to thyristor assembly VTO. Diodes D1–D4 are connected in a way similar to diode assembly VDO and thyristors Tk1 and Tk2 are connected in a

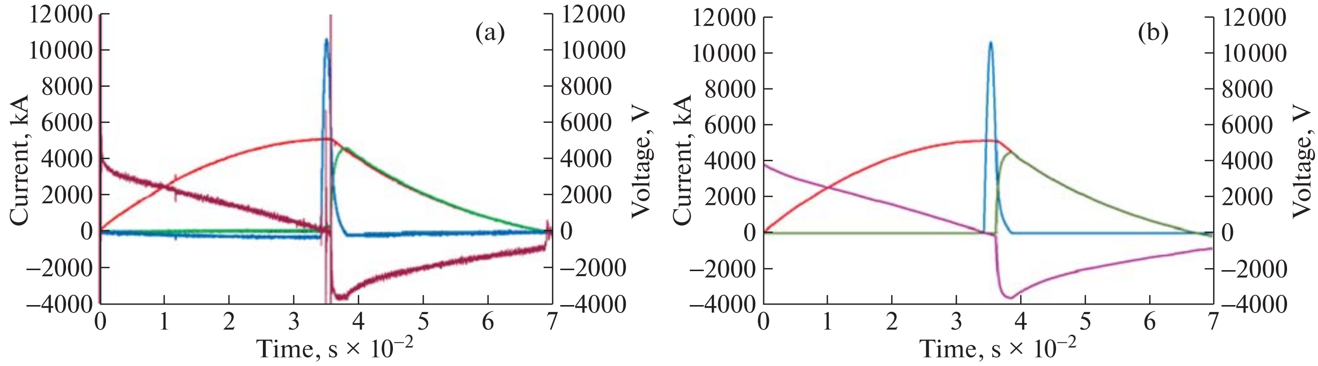

Fig. 11. Current and voltage in the circuit of the breaker switch mock-up: (a) measured and (b) calculated values; (—) L_{CS}; (—) L_{bal}; (—) L_k; and (—) $L_{CS}dL_{CS}/dt$.

way similar to thyristor assembly VTK1 in the standard circuit. The mock-up circuit was supplemented with Hall effect sensors HS1–HS5 to measure the currents in all current circuits under investigation.

To select the initial value of ballast resistance R_{bal}, the design restriction on the voltage on the central solenoid coil $U \leq 3300$ V and the necessity of achieving the highest voltage at the initial moment of the breakdown stage upon reswitching the load current to R_{bal} were considered. For this purpose, a system of equations of the following form that describes the dynamics of the current in the central solenoid coil and the induced vortex current on the tokamak vacuum chamber was solved numerically:

$$L_{CS}\frac{dI_{CS}}{dt} + R_{CS}I_{CS} + M_{CSVC}\frac{dI_{VC}}{dt} = U_{CB} - \frac{1}{C}\int_0^t I_{CS}dt;$$

$$L_{VC}\frac{dI_{VC}}{dt} + R_{VC}I_{VC} + M_{VCCS}\frac{dI_{CS}}{dt} = 0,$$

where L_{CS}, I_{CS}, and R_{CS} are the inductance, current, and ohmic resistance of the power supply circuit of the central solenoid coil; L_{VC}, I_{VC}, and R_{VC} are the inductance, current, and ohmic resistance of the tokamak vacuum chamber; U_{CB} is the voltage of the capacitor-based power supply; and M_{CSVC} and M_{VCCS} are the mutual inductances of the vacuum chamber and the KTM central solenoid coil.

The numerical solution of the above system of equations made it possible to calculate the current dynamics in the central solenoid coil prior to the reswitching of the current with the ohmic resistance of the circuit equal to R_{CS} (with the zero initial conditions) and upon the reswitching of the current with the ohmic resistance of the circuit equal to the sum of R_{bal} and R_{CS} (with the nonzero initial conditions). The results of comparing the calculated and experimental data are shown in Fig. 11. In this figure, the following notation is used: I_{CS} is the current in the CS coil; I_{bal} is the current in the ballast resistor; I_k is the current of the C_k–L_k assembly; and $L_{CS}dI_{CS}/dt$ is the inductive voltage on the CS coil. It can be seen from Fig. 11 that the calculated and experimental data practically coincide.

The basic components of the DC breaker switch mock-up of the KTM central solenoid power supply are shown in Fig. 12. The photographs depict (a) the bank of capacitors C_{CS} (on the left) and ballast resistor R_{bal} (in the center), (b) the power component assemblies in the wiring closet, (c) the high-power thyristor assembly of straight current branch T1–T4, (d) the assembly of high-power current breaker diodes D1–D4, and (e) the assembly of high-power current breaker thyristors Tk1 and Tk2.

In the course of the experiments with the breaker switch mock-up, the fuse ratings of the key components of the standard switch circuit were optimized and their influence on the reliability and the speeds of breaking the current and reswitching it to the ballast resistor were determined. The peak current of switching branch C_k–L_k required for the stable reswitching of the working current in the central solenoid coil to the ballast resistor was determined. In the experiments, the interrupted working current of the central solenoid coil was I_{CS} = 5000 A and the ballast resistance was $R_{bal} = 0.3\ \Omega$ at the parameters $C_k = 0.0033$ F and $L_k =$ 0.00015 H. Consequently, the stable interruption of the current and its reswitching to the ballast resistor were achieved within a time of about 3 ms. The results of the experiments with the DC breaker switch mock-up of the power supply of the KTM central solenoid are shown in Fig. 13.

Figure 13a shows a discharge during which the stable reswitching of the central solenoid coil current to the ballast resistance $R_{bal} = 0.3\ \Omega$ was achieved at the parameters $C_k = 0.0033$ F and $L_k = 0.00015$ H; Fig. 13b shows a magnified fragment of the moment of reswitching the current to the ballast resistor during the same discharge. It can be seen in Fig. 13a that, upon reswitching the total current of the central sole-

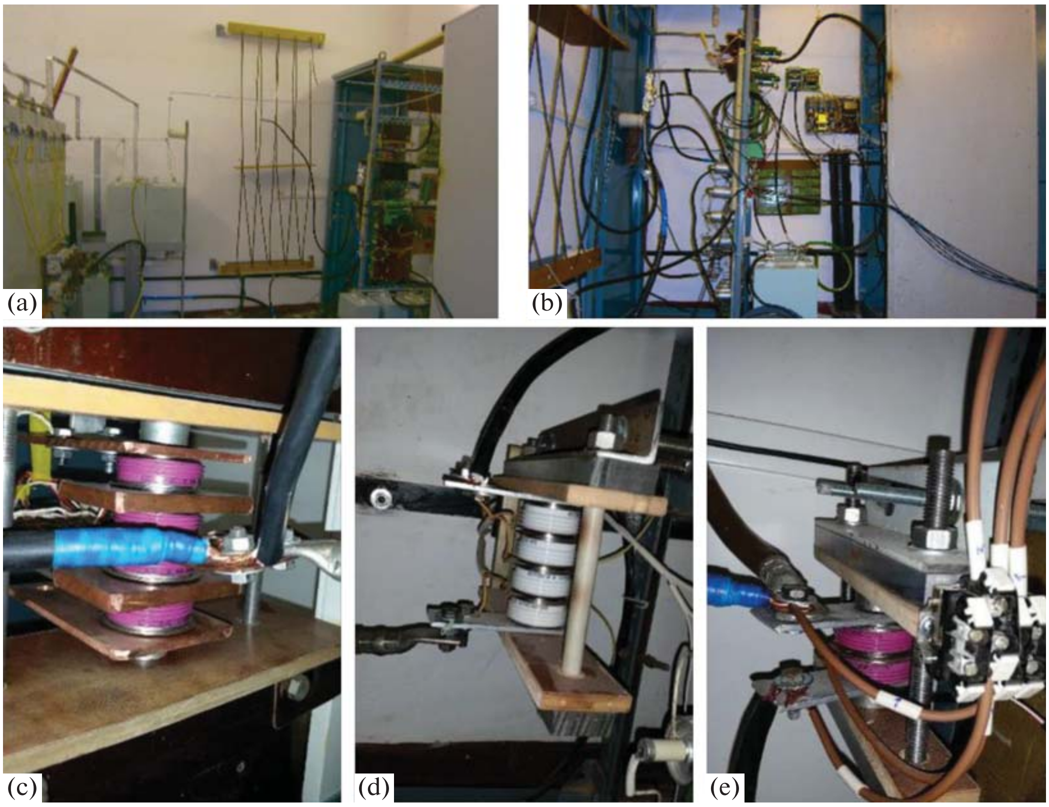

Fig. 12. Photographs of fragments of the full-scale breaker switch mock-up.

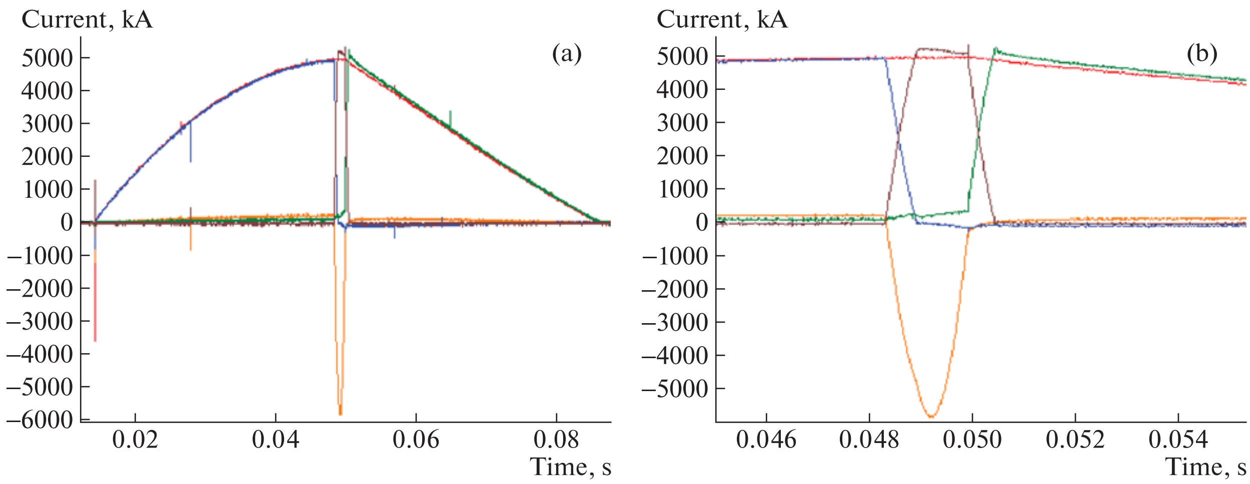

Fig. 13. Diagram of the currents in the power supply of the CS coil during a plasma discharge: (a) full image and (b) magnified fragment of the moment of reswitching the current to the ballast resistor; (—) HS5, current in the CS inductor; (—) HS4, summed T3 and T4 thyristor current; (—) HS1, discharge current C_k to T3 and T4 tyristors; (—) HS2, currents of D1 and D2 diodes; and (—) HS3, current in R_{bal}.

noid coil $I_{CS} = 5000$ A to the ballast resistor, the slope and shape of the curve of current change in the power supply circuit of the CS coil become much steeper (they do not replicate the shape of the quarter period of a sinusoid), which is evidence of a considerable increment in the current fall rate at the time of the breakdown.

CONCLUSIONS

At the present time, the overall cycle of testing the equipment of the pulsed power supply system of the KTM tokamak as well as of the digital control system has almost been completed. The preliminary tests have proven sufficient efficiency of the adopted electro-technical solutions for the basic equipment and components and the possibility of using them to implement the pulsed power supply systems of high- and medium-powered tokamaks. The installed capacity of the electrical equipment corresponds to the level required for the reliable power supply of the electromagnetic coils of the KTM tokamak, and the system of the digital control of the conversion equipment allows the real-time implementation of the necessary control and diagnostic algorithms. The reliability of the design solutions and the efficiency of the informational and algorithmic support of the pulsed power supply system ensured successful performance of the initial stages of the physical start-up of the KTM tokamak, which allows us to predict the efficiency and serviceability of the system at the subsequent start-up stages and during the operation of the KTM tokamak at design parameters.

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