SIMULATION OF COMPLEX ELECTRIC CIRCUITS WITH SUPERCONDUCTING ELEMENTS.

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Effective computer simulation of transient and stationary processes in different power circuits with superconducting elements (SE) becomes possible due to creation of a set of user's models and available commercial analog simulation systems such as SPICE, NAP or the like with a standard set of electrotechnical elements in the library. The suggested method of simulation as compared to analytical ones is less inertial. Camparison of calculated and experimental data shows their good correspondence even in complex cases when n - s boundary in SE moves with positive or negative acceleration.

INTRODUCTION

The use of commercial analog simulation systems such as SPICE, NAP or the like with a standard set of electrotechnical elements in the library along with a set of user's models of superconducting elements (SE) allows computing the processes in complex electrical circuits including along with SE facilities on semiconducting devices.

THE MODEL

Dependence of switch gate resistance versus current and temperature is given by its piecewise linear voltage-current characteristic [4]:

$$R_K = \begin{cases} 0, & n < 0 \\ n R_c, & 0 \le n \le 1 \\ R_m, & 1 < n \end{cases} \qquad (1)$$

where R_c - gate resistance at critical temperature (and zero field, current); R_m - gate resistance in normal state;

$n = 1 - \frac{1 - \bar{T}}{\bar{I}}$, - part of normal state electrones current in complete gate current; $\bar{T} = T_c / T_K$, $\bar{I} = I_c / I_K$ - reduced gate temperature and current respectively.
where T_c - critical temperature of switch at $I_K = 0$; I_c - critical current at $T_c = T_{He}$; R_m - resistance of PC in normal state.

Power cryotron (PC) included into the superconducting converter circuit is cooled by a liquid helium and heated first by the heater and, second, by the heat released in PC in its normal state when it draws current I_K.

Dependence of switch gate temperature T_K vs time t and power dessipation p_v is given by thermal conductivity equation:

$$C \frac{\partial T_k}{\partial t} = p_v - \frac{\partial q_y}{\partial y} - \frac{\partial q_x}{\partial x} , \qquad (2)$$

where C- specific volume heat capacity; $q_{y,x}$- heat fluxes in y, x directions; ∂y (∂x) - thermal size in y (x) - direction.

Combining equations (1-2) with Kirkhoff equations for circuit (which are in this case presented by simulation program) one can calculate switch gate resistance, voltage drops, circuit currents, etc versus time.

Using this approach, we simulate the processes in energy storage and extraction circuit with nonlinear load.

SIMULATION OF ENERGY EXTRACTION CIRCUIT FROM SC STORAGE SYSTEM INTO THE EXTERNAL LOAD

SC magnetic system (SCMS) as a special power source for powerful electrophysical devices whose load is electrovacuum and gas-discharg chambers, injectors of thermonuclear and laser units is connected to the external load by means of superconducting switch (SCS).

General circuit of SCMS current input-output (Fig.1) includes SCMS simulated by inductance Lms, SCS, current input device (ID) and external load Zn connected to SCMS by means of current leads. Cryotron converter is used as ID.

SCS in Fig.2 includes PC and control system with one capacitor Cy and switch Ky. Inductance of cryotron L_K, inductance and resistance of wires in control system Ly, Ry are shown in the diagram. Device for capacitor recharge is not shown here.

SCS in its input mode is superconducting and connects SCMS parallel to the cryotron converter. To take out energy to the external load Zn, SCS is triggered to the normal state and current from SCS starts to be drawn by Zn.

Zn is simulated nonlinearly changing as dependent on the voltage Un on it and current of In conductivity through it. Zn is nonconducting when power supply voltage drops on it. But if it exceeds a certain threshold value U_{th1}, its conductivity recover. Current In appears. With an increase of In Un drops down to U_{th2} and then Zn changes by the formula Zn = k / In, where k- constant coefficient for the given type of the load. Zn present by VAC is analogous to the gas discharge.

As a result of calculations and joint solution of the Kirkhoff equations for electric SCMS-PC-Zn circuit and equation of the heat conductivity the values of currents and voltages in the circuit, Rк, Zn are obtained.

Effective values are laid into the calculations: critical temperature of PC at I_K= 0 Tc=20K; critical current at $T_c=T_{He}$ Ic=4кA; resistance of PC in normal state R_m=60 Ω; Lк=1E-6 H, Lms=2E-3 H; Cy=1E-6 F; Ly=3E-6 H; Ry=0.1 Ω; load inductance Ln=4E-6 H; load resistance (except for Zn) Rn=1E-2 Ω; Zn=0.5 Ω at In=50кA, Zn=1.43 Ω at In=10кA, Zn=2 Ω at In=1кA; U_{th1} =50кV; initial current on SCMS Ims(0)=Iк(0)=3.9кA; initial voltage on Cy Uc(0)=10кV.

Calculation results are given in diagrams of Fig. 3.- 6.

Before operation start Cy is charged to a certain voltage, current Ims is fully drawn through SCS In=0.

After shorting of Ky Cy starts discharging through PC, control currents and Ims directing the same way. Iк increases. Temperature Tк = T_{He} = 4.2K. Rк=0. Inductance $L_{aм}$ prevents control current surge into the SCMS circuit and load.

When Iк achieves the value of a critical current Ic for Tк=T_{He} PC is transformed into a mixed state. Rк becomes greater than 0 and goes on increasing. Tк increases as well since Ims is drawn through Rк as before. Voltage drop on PC Uк grows, therefore Un also increases. When Un achieves the value Uпор the load starts conducting.

Tк and Rк monotonuously increase until Tк achieve the value Tc. Rк becomes equal R_m. PC is transformed into its normal state. After this majority of Iк is drawn by Zn (in proportion R_m / Zn).

SCS circuit has operated, interruption has taken place. Next stage of operation- charge of Cy and cooling of PC begins.

In certain cases more complicated models are used (as compared to zero-dimensional). Unidimensional PC model allows simulating a change of the PC normal zone lenght and motion of n-s boundary when volume, cooling area and PC resistance change correspondingly.

CONCLUSIONS

Developed software allows full and finishing simulation in complex electric circuits with superconducting elements to check their serviceability and ability to meet the requirements of technical tasks. A program of this level permits calculating processes in complex electrical circuits which include along with SC elements facilities on semiconducting devices and electrovacuum and gas-discharg chambers. Described software proves its efficiency in complex circuits with low and high temperature SE due to decreasing of physical simulation volumes and terms.

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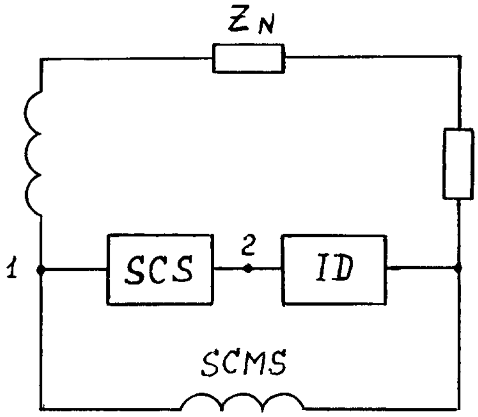

Fig.1.General circuit of SCMS current input-output.

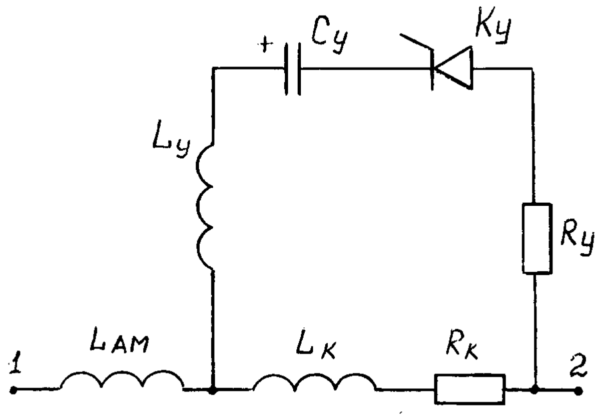

Fig.2. Superconducting switch.

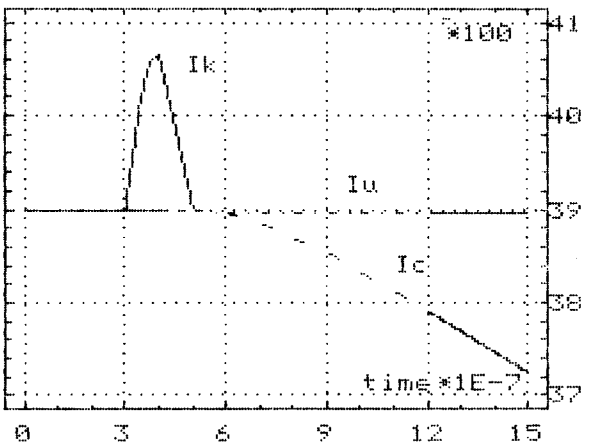

Fig.3.SCS current IK, current SCMS Ims, current in L_{aM}- I_{aM}

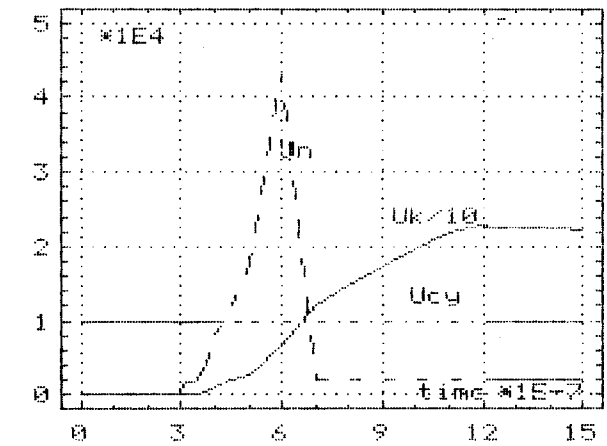

Fig.5.Load voltage Un, cryotron voltage divided into 10 UK/10, voltage on the cont. capacity Ucy

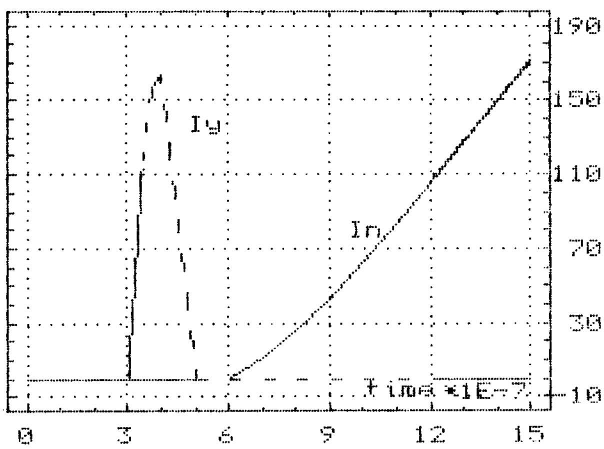

Fig.5. Load current In, control current Iy.

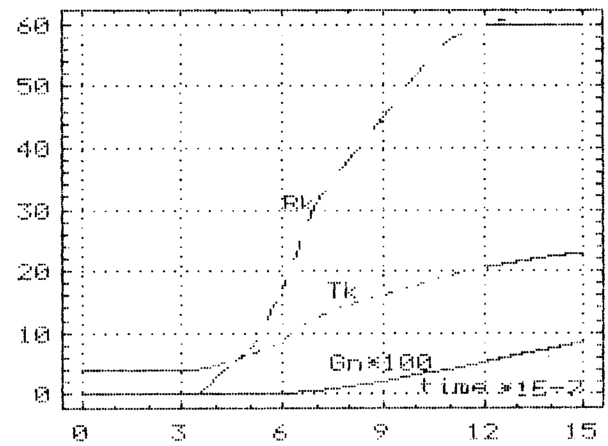

Fig.6.Resistance RK and temperat. TK of power cryotron, load conductivity multiplied into 100 Gn*100.