THEORETICAL AND EXPERIMENTAL INVESTIGATION OF HIGH-CURRENT SOLID - STATE OPENING SWITCH BASED ON SOLID SOLUTION $(V_{1-X}Cr_X)_2O_3$[*]

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Abstract

A state of activities on development of a new high-current opening switch with solid solution $(V_{1-x}Cr_x)_2O_3$ is reviewed. A non-linear diffusion of a magnetic field into a substance, that undergoes a metal-insulator phase transition, as well as a development of thermomagnetic instability at the interphase boundary are studied analytically and numerically. A design of a high-current opening switch based on this solid solution is presented. Fabrication and fastening of breaking element, made of $(V_{1-x}Cr_x)_2O_3$, are discussed. The first experimental results on a full-scale model of high-current solid-state opening switch are presented.

I. Introduction

Sharp resistance changes in solids (e.g. a sharp positive temperature coefficient of resistance), which stem from metal – insulator transitions, can be used in high-current opening switches [1, 2]. Two factors mainly cause the transitions and current breaking process: the Joule heating-up and a magnetic field (thermal and magnetic switch). To be of practical interest the transition should take place at room or above-room temperatures. The resistance variation should be as sharp as possible and at least by a factor of 10^2 [1]. High-current switches require active substances with a high conductance. Solid solutions $(V_{1-x}Cr_x)_2O_3$ satisfy all these conditions. The temperature of the metal – insulator transition depends on chromium concentration and ranges between 200 K and 450 K.

It was demonstrated [1] that diffusion of the magnetic field into $(V_{1-X}Cr_X)_2O_3$ is characterized by low velocities of the mass transfer and small values of the magnetic Reynolds number. This implies that the motion of the medium can be ignored. We are interested only in the fast motion of the phase transition wave, i.e. in the case when a sharp interface between the metal and insulator phases exists.

An operation of a slow thermal solid-state switch was discussed in Ref. [3]. The current-breaking process in fast solid-state switch is quite different. Let us consider a capacitor bank C discharge on a strip-line (see Fig.1). The screen S made of an active substance is placed inside the strip-line. The pulsed current of a sufficiently short duration flows on the internal planes of the strips and internal boundary of the screen, i.e. the current distribution in the screen is strongly inhomogeneous. It concentrates within a skin-layer. Therefore, firstly a surface layer undergoes the sharp drop of the conductivity and a current wave starts propagating into the screen. This process can be considered as non-linear magnetic field diffusion into the substance. When the metal-insulator interphase boundary approaches the rear surface of the screen the current is switched over to the load (R_L and L_L).

II. Non-linear diffusion into $(V_{1-x}Cr_x)_2O_3$

The non-linear diffusion of a strong magnetic field in an unbounded medium was investigated analytically in Ref. [1]. The solid solution $(V_{1-x}Cr_x)_2O_3$ was considered as a model substance. The 1D model comprised (i) the Euler and continuity equations

$$\frac{\partial u}{\partial t} + u\nabla u = -\frac{1}{\rho}\nabla P, \quad \frac{\partial \rho}{\partial t} + \mathrm{div}(\rho u) = 0 \qquad \text{Eq.1}$$

where ρ is the density, u is the mass velocity, $P = P_h + P_m$, P_h and P_m are the hydrodynamic and magnetic pressure, (ii) the magnetic field diffusion equation

$$\frac{\partial \mathbf{B}}{\partial t} = \mathrm{curl}(\mathbf{u}\times\mathbf{B}) - \mathrm{curl}(\nu_m\,\mathrm{curl}\mathbf{B}) \qquad \text{Eq.2}$$

where $\nu_m = c^2/4\pi\sigma$ is the magnetic viscosity, σ is the

Figure 1. Scheme of switching circuit.

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conductivity of the media, and (iii) the heat balance equation

$$\rho\frac{\partial Q}{\partial t}=\frac{c^2(\nabla\mathbf{B})^2}{16\pi^2\sigma} \qquad \text{Eq.3}$$

where Q is the specific heat. In addition, the first order phase transition was assumed in the equation of state. Three phases were considered: a metal, an insulator, and a mixed (heterogeneous) phase. Firstly, it was shown that the magnetic Reynolds number is very small in the case of $(V_{1-x}Cr_x)_2O_3$. Thus, the first term on the right-hand side of Eq. (3) can be neglected. Two types of stationary analytical solutions (the magnetic field in the insulator is constant in time and the interphase boundary propagates with a constant velocity) were obtained. The heterogeneous phase exists at a slow propagation. A discontinuous metal-insulator boundary is formed at a fast propagation. In the last case, discontinuities in the thermodynamic quantities are appeared at the interphase boundary similarly to a shock wave. The fast regime is preferred for an opening switch since the mixed phase leads to tailing of the switching process. The adiabatic velocity of sound in the heterogeneous phase is the critical velocity separating these solutions. It was estimated as 100 m/s for $(V_{1-x}Cr_x)_2O_3$ that is much smaller than the velocity of sound in homogeneous phases. Therefore there is a wide range of velocities where the fast solutions exist. It also should be noted that there is a critical value of the magnetic field below which the slow solutions exist only.

A numerical 1D procedure was also developed [4] to investigate the diffusion of the magnetic field (current) pulse with an arbitrary shape into a screen of a finite thickness. Here, the main problem is a very large variation of the magnetic viscosity (greater than two orders of magnitude). That is why we transform Eq. (3) to the integral form [4]

$$f(Q)=\int_0^Q v_m(q)\,\mathrm{d}q=\frac{c^2}{4\pi}\int_0^t E^2\,\mathrm{d}\tau \qquad \text{Eq.4}$$

where $E=\frac{c^2}{4\pi\sigma}\nabla B$ is the electric field intensity. Since the dependence $v_m(q)$ is assumed to be known the function $f(Q)$ is also known. Calculating the inverse function $g\{f[Q(x,t)]\}=v_m(x,t)$ we find

$$v_m(x,t)=g\left[\frac{c^2}{4\pi}\int_0^t E^2\,\mathrm{d}\tau\right] \qquad \text{Eq.5}$$

The electric field intensity is continuous and the integral form is more stable against sharp variations of the absorbed energy. Because of these reasons the form (5) is turned out to be more convenient for numerical calculations. Boundary conditions on the fore and rare boundaries are due to external circuits (the current source and the load). The results obtained in Ref. [4] are presented in Fig. 2. One can see a steep edge of the current pulse in the load (line 4). The negative picks in line 2 and 3 (internal cross-sections) originate from the load inductance.

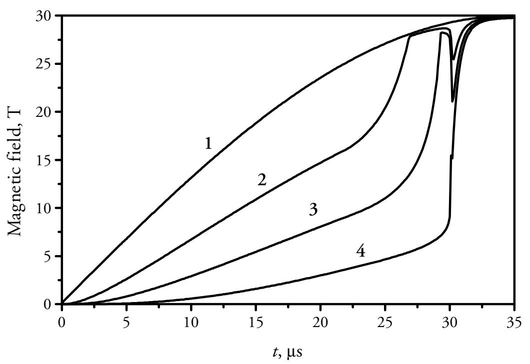

Figure 2. Diffusion of magnetic field through a screen of 1.5 cm in thickness, the inductance and resistance of the load is 1.2×10^{-8} nH and 5×10^{-4} Ohm, 1 and 4 are the fore and rear edges of the screen, 2 and 3 are 1/3 and 2/3 of full thickness [4].

From the standpoint of the practical applications, it is important to study the stability of the metal-insulator interphase boundary. No usual hydrodynamic instabilities can appreciably develop since a difference of the phase densities as well the mass velocities are very small. At the same, thermomagnetic instability (i.e. combined perturbation of the interphase boundary and a current distribution) can develop strongly. Analytical and numerical investigations [5] show that this type of instabilities can significantly affect an operation of the opening switch.

A ceramic technology for fabrication of elements made of $(V_{1-x}Cr_x)_2O_3$ was developed [6]. Ceramic samples of good quality up to cm^3 are available now.

III. Experimental investigation of opening switch operation

We have designed, assembled, and tested a full-scale model of the solid-state opening switch. A capacitor bank is of 20 mF in the capacity with the charging voltage up to 5 kV. The pulse rise time of the current is about 40 μs. The switching circuit is shown in Fig. 1. The current flow is controlled by two closing switches and directed by the convergent strip-line to an breaking element consisted of $(V_{1-x}Cr_x)_2O_3$ plates ($9\times9\times2$ mm^2) (see Fig. 3). The strip-line is made up of two copper plates of 10 mm in thickness that are reinforced by steel plates of 15 mm in thickness. There are two ways to arrange the breaking element (see Fig. 4). Both arrangements allow suppressing the thermomagnetic instabilities. In arrangement Fig. 4a the plates are separated by dielectric gaps and the instability develops within the only plate. At the same

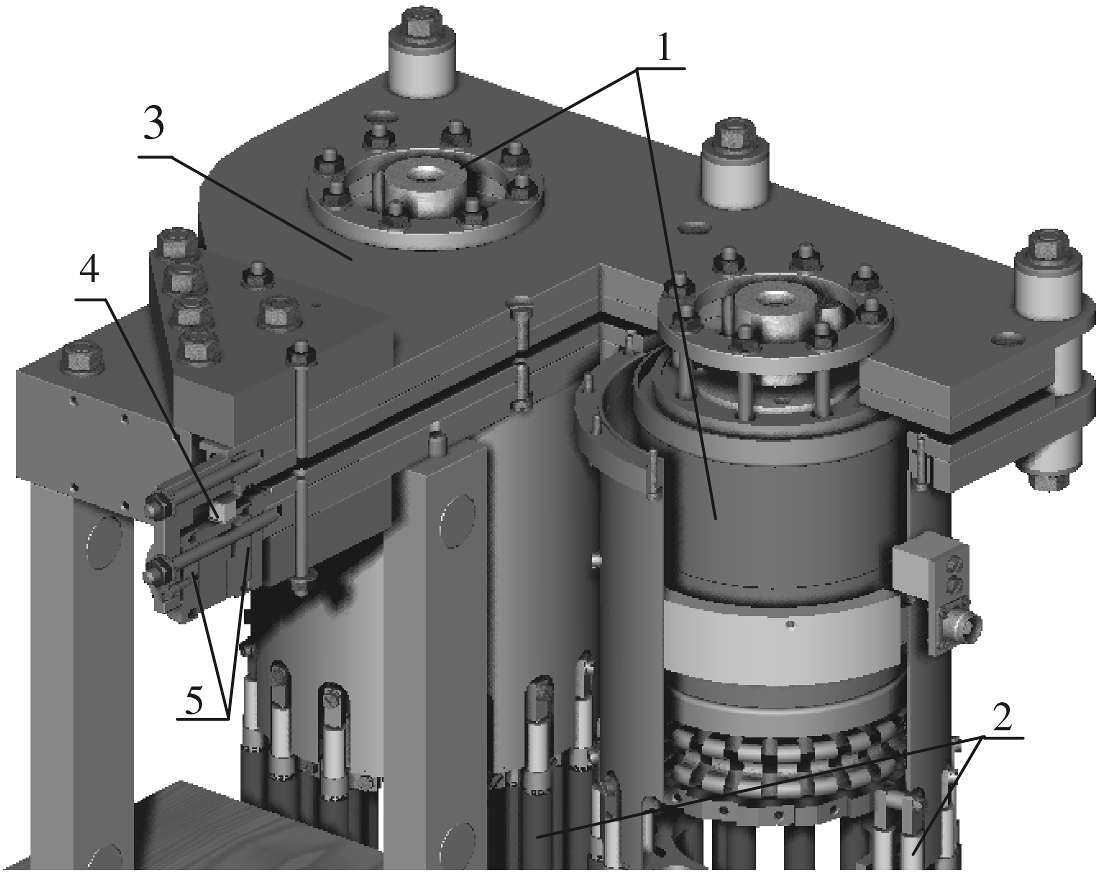

Figure 3. View of a full-scale opening switch model. 1 are the closing switches, 2 are the cables, 3 is the strip-line, 4 is the breaking element, 5 are the Rogowski belts.

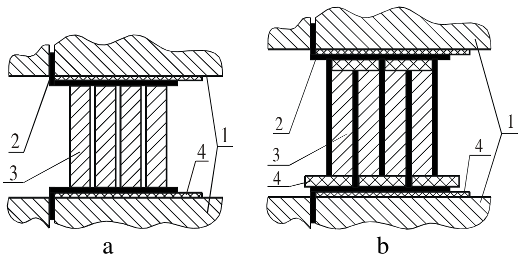

Figure 4. Arrangements of $(V_{1-x}Cr_x)_2O_3$ plates in switching circuit. 1 is the strip-line, 2 is copper foil, 3 are $(V_{1-x}Cr_x)_2O_3$ plates, 4 are insulating plates.

time, if the conductivity of the substance is low, one have to choose a thick screen. To lower the intrinsic inductance of the switch, we choose arrangement Fig.4b. For the ceramic conductivity $\sigma=2.5\ 10^2\ (\text{Ohm cm})^{-1}$ [6] we need 3 or 4 ceramic plates. Contact pads were fabricated by means silver paste. The plates were attached to thick copper foils by means of indium solder. The foils were connected to the strip-line. The loop behind the screen forms a load with low inductance. Two Rogovski belts were used to measure the currents of the source and the load. Another two Rogowski belts controlled the currents in the closing switches separately.

We initiated experimental investigations of the solid-state opening switch just before the conference. At the first stage we performed investigation of non-linear diffusion of the magnetic field through the breaking element Fig.4b. The current pulse of the source and the load are shown in Fig.5. The current through the breaking element was rather small and there was no steep fall in it, i.e. a sharp interphase boundary did not appear. We believe that this happened because of high resistance of copper foil – ceramics contact (about 5 mOhm). We are going to fix this problem in the next experiments. At the same time, the metal-insulator transition was clearly observed. Thus we have shown that the metal – insulator transition in $(V_{1-x}Cr_x)_2O_3$ is sufficiently fast to be used in microsecond opening switches.

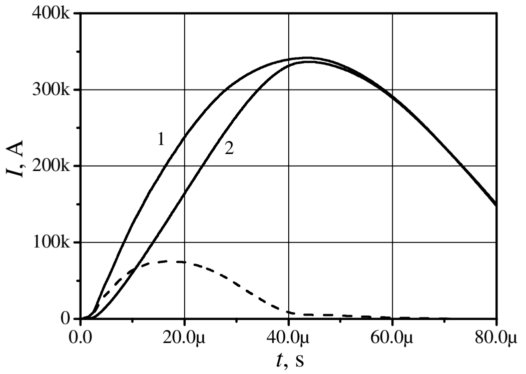

Figure 5. Diffusion of the magnetic field through the structure in Fig.4b. 1 is the current of the source, 2 is the current in the load. The dash line is the current through the breaking element.

IV. Conclusion

The feasibility of the solid-state opening switch of a new type based on $(V_{1-x}Cr_x)_2O_3$ solid solution is shown. The design of the switch and the ceramic technology of the solid solutions are developed. The thermomagnetic instabilities can strongly affect the switch operation but special design of the breaking element makes it possible to overcome this problem. It is shown that the metal-insulator transition in $(V_{1-x}Cr_x)_2O_3$ solid solution occurs during a short current pulse (40 µs) under the Joule heating-up.

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V. References

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