Analysis of research and area of application of self-resetting liquid metal fuse

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Abstract. The article shows that the level of research to date, both in Russia and abroad, does not yet allow the development of industrial samples of liquid metal self-resetting fuses. However, the high speed and current-limiting properties of the self-resetting liquid metal fuse are of interest in continuing research. The use of the self-resetting liquid metal fuse as a current limiter competitive with current-limiting reactors received a more complete scientific substantiation and development. It has been found that a common disadvantage of all structures of self-resetting liquid metal fuses is that during the switching process the channel of the dielectric bushing of the self-resetting liquid metal fuse is subjected to arc erosion with each triggering, which reduces its switching resource. There are proposals to increase the switching resource through the use of materials more resistant to the effects of an electric arc, constructive and circuit solutions. From the point of view of speed and current-limiting properties, it is preferable to use fusible alkali metal inserts in the self-resetting liquid metal fuse. It is noted that the amount of research that has been conducted makes it possible to create a current-limiting device based on a competitive self-resetting liquid metal fuse with current-limiting reactors. To do this, it is necessary to combine the efforts of all interested industrial and scientific organizations, to create and explore a mock-up sample.

1. Introduction

The first publications about prototypes of self-resetting liquid metal fuse appeared in the 60s of the last century. However, the level of research to date, both in the Russian Federation and abroad, does not yet allow the development of industrial models of self-resetting liquid metal fuse for use in power supply systems. Such studies are conducted by individual initiative groups in different countries of the world. These are Japan, USA, Germany, China, Russian Federation, etc. [1-14]. The self-resetting liquid metal fuse and devices based on them have higher current-limiting properties and speed than the electrical apparatus mastered by industry [1, 3]. This arouses interest and need for the development and continuation of research in the direction of creating prototypical and industrial designs of self-resetting liquid metal fuses and defining the scope of their application.

The self-resetting liquid metal fuse is an electrical apparatus that uses liquid metal as a fusible element (indium, gallium, mercury, alkali metals, etc.) located in the dielectric bushing channel. When excessive current flows through the liquid metal fuse, the metal evaporates, causing an explosive increase in pressure. At high pressure, metal vapors have significant resistance. As a result, the current is sharply limited. After that, an electric arc is formed in the channel, which is extinguished due to the natural passage of current through a zero value. After cooling and condensation of the liquid metal's vapors, the electrical circuit is restored. Experimental studies show that the recovery time varies
widely enough and can be commensurate with half the period of the network frequency [1]. In the mentioned work, in the second, third and subsequent half-periods, the process can be repeated until the moment of disconnecting the circuit with an additional switching device.

2. Materials and methods

The construction of a self-resetting liquid metal fuse with controlled recovery time is shown in Figure 1. It consists of a metal case 1 in which a dielectric bushing 2 made of heat-resistant ceramics is placed with a hole 3, a cylinder 4 leaving, the hole in the sleeve and in the cylinder is filled with liquid metal 5. The bellows 6, which serves as a damping device located in this cylinder, is connected to the second bellows 7, located cylinder 8, filled with compressed gas 9, through a check valve 10 and a bypass tube 11 with a valve 12. Both bellows are filled with liquid 13, for example, oil. The total body of 14 cylinders serves as one of the contact points. The second pin 15 is insulated from the case with an insulation layer 16 [1].

In normal mode, the current passes from one contact output to another through the liquid metal, filling the hole in the dielectric sleeve 2. The valve 12 is closed. When an emergency current occurs, the liquid metal in the hole of the dielectric bushings evaporates, forming a vapor stopper, thus providing an open circuit. Explosive evaporation of the liquid metal leads to an increase in pressure, as a result of which the bellows 6 is compressed, the excess liquid in it through the check valve 10 flows into the bellows 7, which increases its volume and increases the gas pressure in the cylinder 8. After extinguishing the arc, cooling and condensation of vapors of the liquid metal into the hole of the dielectric sleeve, the pressure drops. When the pressure drops below the pressure in the gas cylinder 8, the check valve 10 closes, preventing the liquid from flowing from the bellows 7 to the bellows 6. After the final condensation of the liquid metal vapor in the narrowed part of the channel, a vacuum space is formed, since the initial volume of the liquid metal cylinder was less. The chain rupture caused by the presence of a vacuum bubble persists until the intervention of the personnel on duty or the operation of automation.

To turn on the self-resetting liquid metal fuse, it is necessary to open the valve 12. At the same time, the fluid from the bellows 7 through the bypass tube 11 flows into the bellows 6 ensures the pressure leveling of the cylinders. As a result, the hole 3 of the dielectric bush is filled with liquid metal. The fuse is ready for re-action.

![Figure 1. Self-resetting liquid metal fuse design with controlled recovery time [1].](image-url)
Figure 2. Construction of self-resetting liquid metal fuse UlSTU [2]. 1 - dielectric sleeve of heat-resistant ceramics; 2 - a casing; 3 - liquid metal; 4 - the piston; 5 - lower contact output; 6 - cylinder filled with gas; 7 - top pin; 8 - heat-resistant electrode.

Figure 3. Device current limiter SamSTU [13]. Where: 1 - sealing washers; 2 - ceramic insulating plates; 3 - apertures; 4 - capillary section, forming insulating channels; 5 - copper conductive plates; 6 - through holes; 7 - holes in solid metal electrodes; 8,9 - damping bellows.

The advantages of the first construction are expressed in a relatively small amount of the liquid metal used, which is significant as it decreases the amount of toxic, fire-hazardous metals, such as mercury, alkalis. The second design allows the use of several partitions, which provide a narrowing of the fuse-link. As the number of constricted parts increases, the conditions for extinguishing the electric arc are improved. The disadvantage of the design is the restriction on the location in space. Work of the structure is possible in a horizontal position. The angle of rotation around a vertical plane is allowed up to 45-50°.

A common disadvantage of both designs is that during the switching process, the channel of the dielectric bushing self-resetting liquid metal fuse is subjected to arc erosion with each actuation [1]. Elimination of erosion is not possible due to the significant difference between the melting point of the known dielectric materials and the plasma temperature of the electric arc.

Experimental research of the self-resetting liquid metal fuse with a sleeve of heat-resistant vacuum-dense ceramics based on beryllium oxide with a melting point of 2670 °C showed that the diameter of the channel of the dielectric sleeve increased more than three times [1]. The tests were carried out in a circuit with a shock current of 50 kA and a voltage of 240 V. In each experiment, the prototype was exposed to a short-circuit current for one half period. The number of experiments was five. The self-resetting liquid metal fuse remained operable after each experiment, but its current-limiting properties deteriorated. Arc erosion imposes a limitation on the self-resetting liquid metal fuse switching resource. Under the operating conditions after the first fault, the parameters of the self-resetting liquid metal fuse can change in such a way that they will not meet the requirements of protection of network elements. In some cases, it will require replacement. Arc erosion impedes the creation of reusable the self-resetting liquid metal fuse. The switching resource can be increased through the use of materials more resistant to electric arc effects than beryllium oxide ceramics. These may be metal carbides and other materials with a melting point from 3000 to 4000 °C [15]. However, information about their use is not currently detected.

The commutation life of the self-resetting liquid metal fuse can be increased not only by using materials with a high resistance to the effects of an electric arc. It is enhanced by both constructive [1, 2] and schematic solutions. Figure 2 shows self-resetting liquid metal fuse with an increased switching resource. Increased switching resource is achieved by the fact that in addition the self-resetting liquid metal fuse contains inside the contact output 7 and the channel of the dielectric sleeve 1 refractory
electrode 8. It forms a section with a resistance value increased relative to the fusible insert from the liquid metal. When an emergency current flows through the self-resetting liquid metal fuse, the sections of current-carrying parts with increased resistance heat up faster. When the electrode reaches the boiling point of the liquid metal, part of the liquid metal in the zone of the immediate vicinity evaporates, providing an electrical break and subsequent extinguishing of the electric arc.

The response time of the structure is determined by the conductivity and cross section of the electrode, which do not change during switching processes. The change in the cross section of the liquid metal part of the fusible insert during arc erosion of the channel walls in this case does not affect the response time during a short circuit. Switching tests [1] of mock-up samples with a refractory tungsten electrode confirmed this. The switching resource of such a construction is determined by the length of the electrode, which decreases under the action of an electric arc in the period of each switching.

Circuit solution involves shunting the self-resetting liquid metal fuse by low-resistance resistor, which reduces the energy released in the channel the self-resetting liquid metal fuse during the arc stage of the process [1, 6, 7, 11, 12, 14]. Part of the energy is absorbed and dissipated by shunt resistance. The option of using the self-resetting liquid metal fuse in a complex with shunting resistance and an additional switching device has received a more complete scientific substantiation and development. The scientific groundwork in this respect is closest to the practical output.

3. Results and discussion
The self-resetting liquid metal fuse in the set with shunt resistance can find its application for limiting short-circuit currents in the electrical network [1, 3, 6, 10, 12]. At present, current-limiting reactors and matching transformers with high short circuit voltage are used to limit short-circuit currents in networks. They allow to avoid overstatement of the nominal parameters of network elements caused by thermal and dynamic effects of short circuit current; use in the network switching equipment with a maximum breaking capacity below the possible short-circuit current; instead of expensive switches with high breaking capacity, use switches with reduced breaking capacity, etc. Unfortunately, reactors and matching transformers create additional losses of electricity in the normal mode, due to the active resistance of their windings. The use of current-limiting devices based on the self-resetting liquid metal fuse allows to reduce these losses of electricity in the network.

When creating the self-resetting liquid metal fuse, the important point is the choice of liquid metal for their structures. There are a lot of metals with a melting point close to the ambient temperature. From the point of view of speed, it is desirable to give preference to metals with low resistivity. In [8, 12], the results of studies and a comparative analysis of several metals for a fusible insert are given [1]. The figure 4 shows the dependence of the integral of fuses with fusible inserts of various materials. The analysis of dependences shows that the speed of fusible inserts from alkali metals is much higher than fusible inserts from mercury and silver. As a result, it can be said that alkali metals may be the preferred material for the fusible insert.
Figure 4. Estimated dependences of the integral of disconnecting self-resetting liquid metal fuse with fusible inserts of various materials at a rated current of 63 A on the short circuit current.

Judging by literary sources, the volume of research carried out shows the possibility of creating a current limiting device based on the self-resetting liquid metal fuse competitive with current limiting reactors. For this, it is necessary to unite the efforts of all interested industrial and scientific organizations, to create and research a mock-up sample.

4. Conclusions
1. The self-resetting liquid metal fuse and devices based on them have higher current-limiting properties and speed than the electrical devices mastered by industry [1, 3]. This arouses interest and need for the development and continuation of research in the direction of creating prototypical and industrial designs of living wiring and defining the scope of their application.

2. Today, we can talk about self-resetting liquid metal fuse as a current limiter similar to a current-limiting reactor. The use of the self-resetting liquid metal fuse is possible only when connected in series with a conventional switching device. In this regard, in literary sources there is information about the structures and their research, allowing to draw conclusions about their viability and the possibility of obtaining a practical way out.

3. A common disadvantage of the self-resetting liquid metal fuse structure is that during the switching process the dielectric bushing channel of the self-resetting liquid metal fuse undergoes arc erosion with each triggering. Elimination of erosion is not possible due to the significant difference between the melting point of the known dielectric materials and the plasma temperature of the electric arc.

4. Arc erosion prevents the creation of reusable self-resetting liquid metal fuse. The switching resource can be increased through the use of materials more resistant to electric arc effects than beryllium oxide ceramics. These may be metal carbides and other materials with a melting point from 3000 to 4000 °C. However, information about their use is not currently detected.

5. There are design solutions that use a refractory electrode in the channel of the dielectric sleeve, which does not collapse when exposed to a short circuit current. Circuit solution involves shunting of self-resetting liquid metal fuse low-resistance resistor, which reduces the energy released in the channel self-resetting liquid metal fuse during the arc stage of the process.

6. The option of using self-resetting liquid metal fuse in a complex with shunting resistance and an additional switching device has received a more complete scientific substantiation and development. The scientific groundwork in this respect is closest to the practical output.
7. From the point of view of speed and current-limiting properties, it is preferable to use fusible inserts from alkali metal in the self-resetting liquid metal fuse.

8. The scope of the research shows the possibility of creating a current-limiting device based on the self-resetting liquid metal fuse, which is competitive with current-limiting reactors. For this, it is necessary to unite the efforts of all interested industrial and scientific organizations, to create and research a mock-up sample.

References
[1] Kuznetsov A V 2006 Liquid Metal Fuse and Investment Attractiveness of Their Development (Moscow: Energoatomizdat) 207
[2] Kuznetsov A V and Sycheva I V Dec. 20. 2004 Liquid metal self-healing current limiter RU. Patent 2242818
[3] Niayesh K, Tepper J and König F A 2006 Novel current limitation principle based on application of liquid metals IEEE Trans. Compon. Packag. Technol. 29(2) 303-9.
[4] Yijing L, Yi W, Chen H and Hailong H 2014 Investigation on the behavior of GaInSn liquid metal Current Limiter IEEE Trans. Compon. Packag. Technol. 2 209-15
[5] Zienicke E, Ben-Wen Li, Thess A, Krázschmar A and Terhoeven P 2008 Theoretical and Numerical Stability Analysis of the Liquid Metal Pinch Using the Shallow Water Approximation Journal of Thermal Science 17(3) 261-266
[6] Itoh T, Miyamoto T, Wada Y, Mori T, and Sasao H 1973 Design considerations on the P. P. F. For a control center IEEE Trans. Power App. Syst. PA-92(4) 1292–97
[7] Namitokov K K, Ilina N A and Shklovsky I G 1988 Devices to protect semiconductor devices (Moscow: Energoatomizdat) 279
[8] Wu H, Li X, Zhang M, Stade D and Schau H 2009 Analysis of a liquid metal current limiter IEEE Trans. Compon. Packag. Technol. 32(3) 572–577
[9] Voronin A A, Kireev K V, Kulakov P A and Prikhodchenko V I 2008 Experience in the Application of Liquid-Metal Working Medium in High-Current Commutators and Contact Joints Russian Electrical Engineering 79(8) 415–9
[10] He H et al. 2018 Study of Liquid Metal Fault Current Limiter for Medium-Voltage DC Power Systems IEEE Trans. Compon. Packag. Manufacturing Technol. 8(8) 1391-1400
[11] Prikhodchenko V I, Serpukhovitov M E, Skripachev M O and Sitnikov A V 2011 Liquid metal current limiter Proc. of Higher Educ. Institutions. Electromechanics 3 60-1
[12] Wilfried H, Werner H, Klaus-Dieter R, Alf W and Rainer S-F Mar. 1. 2007 Selbstrückstellendes Strombegrenzungselement D.E. Patent 102006029693
[13] Voronin A A, Gol’dshe’te n V G, Erofeev R I, Kazantsev A A, Kosorlykov I A and Serpyhovitin M E Mar. 20.2013 Current limiter RU. Patent 12489
[14] Kuzhekov S L, Vasiliev B T and Kurov N.N. 2012 Performance evaluation of a self-resetting liquid metal fuse Proc. of Higher Educ. Institutions. Electromechanics 2 134-136
[15] Krzhizhanovsky R E and Shtern Z Yu 1976 Thermophysical properties of non-metallic materials (carbides) Directory (Leningrad: Energy) 120