Effect of Conductive Screens on the Stabilization of Plasma Channels with Currents of Hundreds kAmps

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Abstract. This research is a part of a work on improvement of switching capabilities of thyratrons used for transferring currents up to hundreds kA with switching energy more than 50 kJ. The available solutions require construction of complex magnetic fields and consume considerable amounts of energy. With respect to thyratrons, which operation is characterized by the presence of normally several high current plasma channels, this issue has not been yet studied thoroughly. Based on experimental data, we analyzed the results of the influence of an external conductive shield on stabilization of plasma channels in high-power pseudospark switches with reentrant and conventional design. Both non-ferrous and ferrous shields have been tested. The preliminary calculation of the magnetic field distribution is presented.

INTRODUCTION

TDI-thyratrons (pseudospark switches) are widely used in pulsed power installations [1]. They are normally operated in grounded grid circuits and in fact are arc switches, lifetime of which is defined primarily by rate of electrode erosion [2]. However in our experience, TDI-thyratrons, operating on the left branch of Paschen curve, have their own peculiarities in how the arc moves over the electrodes when switching charge over 0.1 C per shot and peak currents over 10 kA. For relatively short pulse the inevitable damage arc is virtually attached to the region of injection holes (Fig.1). High commutation losses lead to anode damage after come 100-400 thousands shots. Application of hollow anode construction makes the lifetime expectancy at least 10 times higher.

FIGURE 1. Arc drilling in anode of TDI1-50k/25 switch, operated in the following mode: Ua = 20 kV, frequency = 200Hz, peak current 7 kA, τ = 1.5 μs, Q=10 mC per shot, leading edge 100 ns.

FIGURE 2. Image of electrodes in thyratron TDI1-150k/25 after arcing.

The picture of erosion changes noticeably if charge transfer is increased. At the same time, the way how the switch is connected in the circuit has a serious influence on the switch lifetime. The erosion depicted on the images is caused by arc movement due to asymmetrical current flow around the switch. The tests have been carried out in the underdamped mode at 20 kV, 30-40 kA, Q=4 C per shot, 1-2 Hz, pulse width 30 μs. Thyratrons stop working due to loss of vacuum tightness or abrupt loss of hold-off voltage capability (Fig. 2).

Figures 3 show erosion of electrode surface in case of improved symmetry of current flow around flange circumference. The arc channel traces are limited duly arranged in cross-like shapes within diameter on which injection holes are located. A mark of arc pinching effect is seen in the center of electrodes. However after a long time of switch operation (in the underdamped mode at 16 kV, Q=4 C per shot, 150 kA, 0.2 Hz) the arc in increasing frequency reaches sidewalls of the tube and clutching of injection holes (Fig. 3) gets more and more definite, leading finally to misfires.

FIGURE 3. Traces of erosion of the cathode surface when of symmetrization current leads on the flange circumference

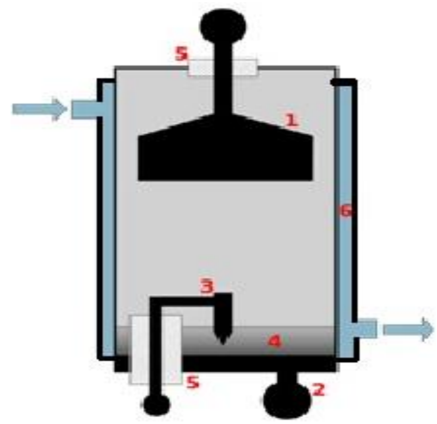

FIGURE 4. Ignitron layout: (1) Anode, (2) Cathode, (3) Ignitor, (4) Mercury, (5) Insulators, (6) Double metal wall with a cooling agent.

It is interesting that the mercury ignitrons for similar applications as TDI-switches but with rather different construction, with vapor pressure changing more rapidly and distributed more non-uniformly than in thyratrons, the effect does not manifest itself at pulse durations up to 1 ms. For longer pulse width the mercury arc has a tendency to migrate from a cathode fluid mercury pool to the tube sidewalls ending with burning through of the envelope [4]. The basic design feature of ignitrons is a discharge cell double wall, used primarily for water cooling (Fig. 4).

The stabilization of discharge is achieved by special measures to provide symmetry of current flow around the switch electrodes, for which external conductors, normally high-voltage coaxial cables, are placed evenly around the mounting flange, forming pattern of 2, 4 and more contacts (Fig.5. [3]).

By this, erosion of electrodes surface can be reduced dramatically with average material loss not more than fractions of one percent, allowing to anticipate thyratron lifetimes sufficient for the most of applications. Unfortunately the expected lifetime is not usually achieved in real life owing to inaccurate approach to thyratrons arrangements. When charge transfer exceeds 1 C per shot at high currents (> 50 kA) and energies (>10 kJ) especially in underdamped modes just a symmetrical arrangement is not sufficient for discharge stabilization and the arc is ejected to electrodes periphery, which leads to disastrous consequences for the tubes.

The problem of plasma buildup stabilization is of great importance in low- and high-temperature plasma applications, in particular in plasma fusion experiments. This is why a number of special current configurations and magnetic systems are being devised to cope with this problem. However existing solutions require formation of complex and high energy magnetic fields. In respect to thyratrons, operation of which is determined by simultaneous appearance of high-current plasma channels, this issue has not been investigated in details. The major complications in thyratrons operating with high charge transfer occur due to shift of arc channels onto device periphery, that is to ceramic walls, subsequent overheating and evaporation of ceramic, melting and ablation of lateral surface of electrodes, leading to abrupt degradation of hold-off voltage capability. We assume that the process is dominantly determined by Ampere-Lorentz forces, occurring at interaction of magnetic fields of conduction currents over

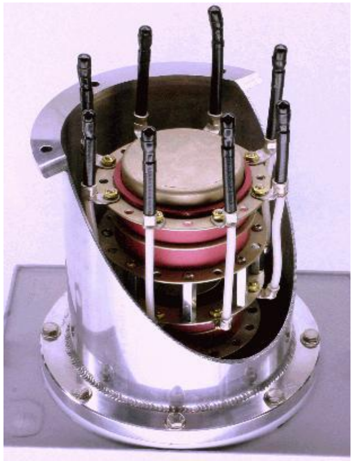

FIGURE 5. Thyratrons with symmetrical arrangements of coaxial cables. First image: main and crowbar thyratron with aluminum screen (cable and a part of the screen are eliminated) [3].

FIGURE 6. Assembly of two water-cooled thyratrons TDI1-200k/25HW with hollow anodes, operating in parallel in high-power pulsed plasmatron pulser [5]. The thyratrons switch 1.2 mF (up to 20 kJ per shot) at average current 10 A. The switches are placed into steel tubes – shields with thickness of 10 mm, consisting of 3 parts.

thyratron electrodes with arc channels similar to plasma focus devices [6] and plasma guns (plasma driven electromagnetic launcher [7]).

Numerous data on long-term energy switching of TDI-thyratrons in various applications have been received recently. In all cases an indispensable condition must be an installation of thyratrons using shielding case of conductive material (Fig. 6), which can serve (in case of copper and aluminum) as a coaxial current loop, reducing assembly inductance.

The theories describing plasma spatial instability phenomenon in publications available [3, 8] are not sufficient for process understanding, which gave a push to investigations aimed to improve reliability of thyratrons, operating at high levels of switching energy.

ASSESSMENT OF CURRENT DISTRIBUTION AND MAGNETIC FIELDS INFLUENCE ON THYRATRON PERFORMANCE

There are at least two versions of conductive shields influence on plasma channels spatial stability, one of which is an interaction of plasma channel with induction current, flowing along the generatrix of the shield, another is related to non-linear properties of ferromagnetic cylinder. It is obvious both require further analysis and selection of optimal parameters.

Interaction of Plasma Channels with Induced Currents Flowing over the Shield Generatrix

In real tubes conduction currents Ian, arising in electrodes when thyratrons is fired, can be different in terms of amplitude and direction (Fig.7). Besides, current distribution is defined not only by resistance of arc and contact area, at which cables are connected to electrodes of a switch, but also by a time and space spread of conductive channels in period of commutation. A solution of this problem in a full statement is rather complicated. For simplicity the principle of superposition has been used with assumption that current flow from thyratron in completely symmetrical and current density around the flanges is uniform. At the same time currents, flowing uniformly and symmetrically compensate each other and will not influence arc movement, hence can be eliminated. We expect that only the arc currents are unstable and the major problem due to non-uniformity to create extra forces, holding arc channels in the limits of flat part of the electrodes.

For investigation of influence of thyratron current heterogeneity on plasma arc channels they are represented as a set of stripes with currents $Ia = \Sigma Ian$, located along the circumference of the tube. In Fig.7 directions of Lorentz forces F_{L1} and F_{L2} action on arcing currents $Ia1$ and $Ia2$ in the thyratron on diametrically opposite sides are shown schematically.

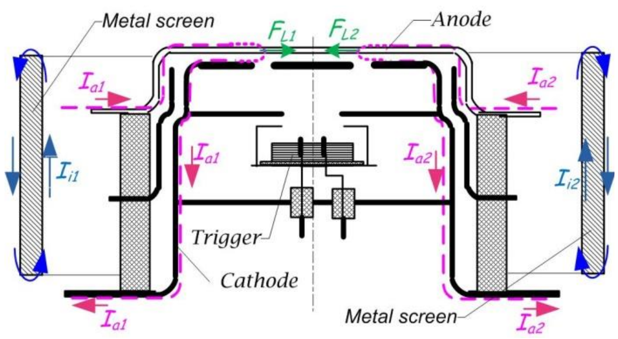

FIGURE 7. Shielding of TDI-thyratron with re-entrant design.

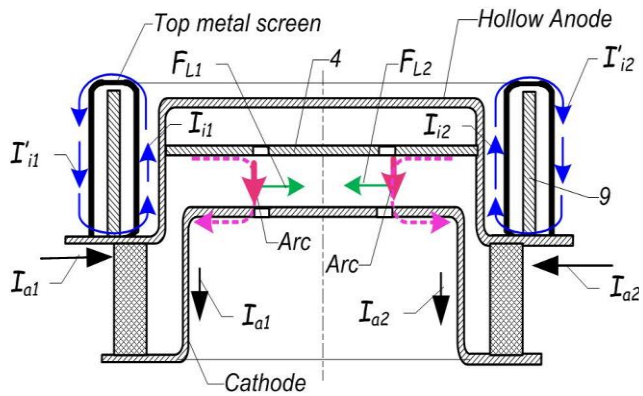

FIGURE 8. Hollow volume screen in anodic part of thyratron and current distribution scheme..

Passage of anode current I_a through the thyratron induces in metal shields induced currents $I_i=I_{i1}+I_{i2}+....= \Sigma I_{in}$. If arc channel, for example I_{a1}, moves in the arcing area between anode and cathode (e.g. under Lorentz force from left to the right), approaching metal screen, it will create repulsive forces between currents I_{an} and I_{in}, leading to automatic stabilization of arc channels close to the axis of the thyratron.

Thickness of the screens is also of great importance. This is explained by a fact that the arc movement is affected by a force, depending on vector sum of currents on external and internal screen surfaces parallel to the device axis $I_{i1}+I'_{i1}$. If screen thickness is approximately equal to skin-layer, this sum approaches zero, as for a thin screen the vector sum of anti-parallel currents I_{i1} and I'_{i1} reduces magnetic field down to shades, not allowing to stop arc movement. The indirect evidence of this theory serves the fact, that thin copper screens and electrodes (thickness ~2.5 mm) in thyratron (Fig. 2, 3) do not affect arc discharge stability.

The screen comprises a hollow volume on the top of anode flange (Fig.8, 9). The increase in volume of screen allows to separate from each other induced currents, circulating around the screen by a sufficient space, when external current I'_{i1} does not reduce magnetic field of current I_{i1} flowing across inner surface of copper screen. The ferromagnetic screen (9) is added to enhance effect and to shield the switch from external fields (for example, from another thyratron nearby). The currents flowing along the inner and outer side of the screen must be divided the space of at least 3 x the thickness of the skin layer. The inductance of the assembly with the screen increases insignificantly.

The way how the metal pipe-shaped screens can be used for plasma (10) transport in accelerator (Figure 10) is similar to that for thyratrons. The construction looks very fitting for deterioration of the plasma channel instabilities (11), which are known to be one of the most complicated problems for high-temperature plasma applications, including tokamaks, plasma colliders and so on. The internal pipe (8i) is made of refractory molybdenum. The outer wall (8o) may be hermetically sealed. Since it stays in a relatively low temperature zone, it can be made of cheap material, such as aluminum, having slit like in internal pipe or consisting of 2 half-pipes. The half-pipes with flange along the generatrix of the cylinder are easily disassembled and can be sealed-off with gaskets of rubber or Viton.

FIGURE 9. Thyratron TDI1-150k/50H with a screen in the test facility (from the left). Screen photos (inside view).

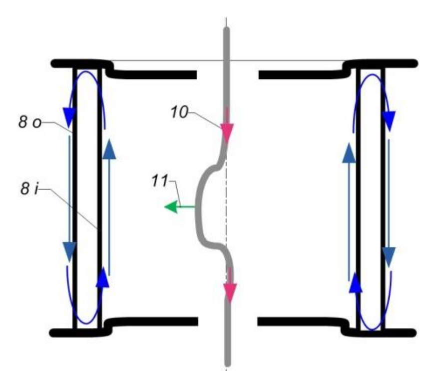

FIGURE 10. The design of the transport part of the plasma accelerator with a volume screen

Influence of non-linear properties of ferromagnetic screen

A measurement of magnetic fields in ferromagnetic medium with spatial system of magnetic fields is a complex task [9]. This is why for initial assessment a model task on thyratron operation with and without ferromagnetic conducting material in 3-dimensional definition was calculated (Fig.11). As 3-D simulation, made with Software Module COMSOL-Multiphysics, has demonstrated, this effect has an apparent character while using sheet ferrous material or ferrite for a shield. In Fig.12 magnetic field distribution inside ferromagnetic screen are shown with a current channel located in the center of system (curve 1) and when it is displaced from the center by 20% of the internal radius of the system (curve 2). Field induction in the shield material area (position 3) approaches magnetic saturation. Action of a solid ferromagnetic shield is less obvious due to skin effect influence.

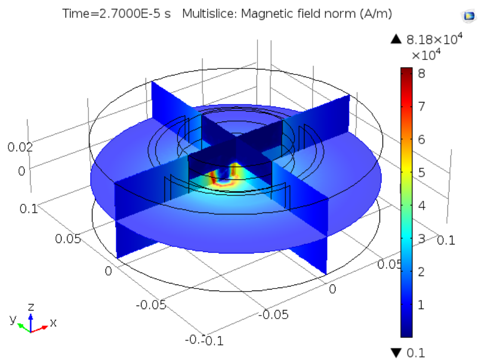

FIGURE 11. Simulation area configuration

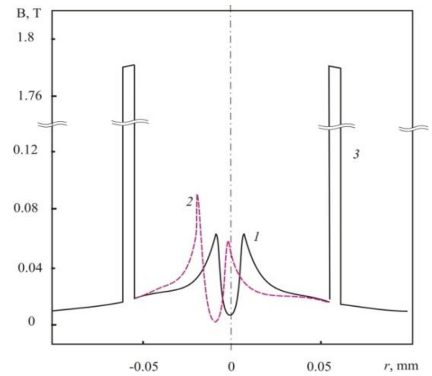

FIGURE 12. Radial distribution of field induction while using ferromagnetic screen

For direct registration of current distribution in the area of electrical discharge a series of experiments on a model installation at pressure 10 Torr was carried out with one of electrodes deliberately sectioned (Fig. 13-16). It enabled researchers to measure current in each of four sections by means of shunts and to investigate plasma channel bias dynamics. The experiments have demonstrated a stabilizing effect of ferromagnetic shield, manifested by absence of arc movement to electrode periphery and discharge cell walls (Fig. 15-16).

At the moment electrical tests of hollow volume shield for TDI1-200k/25H thyratrons with re-entrant electrode geometry, in which the main discharge is located in the upper part of the anode cell, are being carried out. The thyratron has been working for more than 600 000 shots without signs of degradation and without ceramic walls luminescence which normally accompanies arc surges.

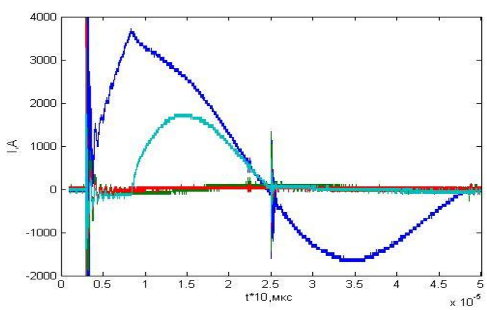

FIGURE 13. Current distribution over shield sections without shield.

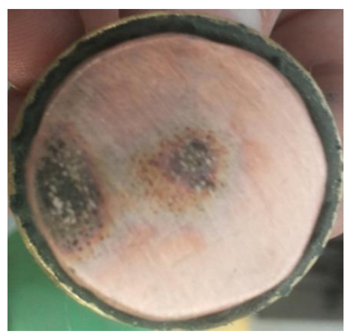

FIGURE 14. Arc traces without shield after multiple shots with current amplitude up to 5 kA.

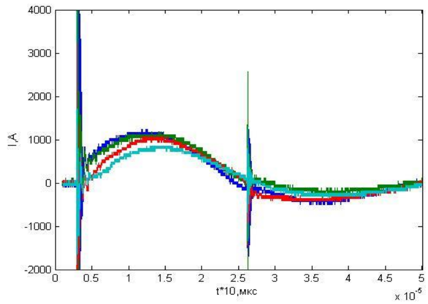

FIGURE 15. Current distribution over shield sections with a ferromagnetic shield.

FIGURE 16. Arc traces with a ferromagnetic shield after multiple shots with current amplitude up to 5 kA.

CONCLUSIONS

In experiment and in the real tubes positive effect of conductive shields on plasma channels special stability is observed. Authors have made attempts to explain these phenomena by two basic theories – interaction of plasma channels with induced currents, flowing by the shield generatrix and influence of ferromagnetic shield non-linear properties. Other versions are being considered. Obviously they shall be duly verified and optimized.

The analysis of magnetic fields in main discharge area of thyratron and results of preliminary tests have demonstrated advisability to use thick or hollow volume conducting shields to maintain stable operation of TDI-thyratrons and arc gaps when commuting charges up to 200 Coulombs.

It is necessary to clarify influence of material magnetic properties and shield thickness on a discharge spatial stability, as well as amplitude and timing stability of discharge currents. Meanwhile further improvement of lifetime expectancy is connected both with arc channels stabilization and with a requirements of hampering pinch-effect in the center of electrodes.

Such processes take place not only in thyratrons, but also in high-current devices with plasma transportation over long distances (e.g. in nuclear fusion reactors), this is why application of external shields of the constructions described can contribute to plasma stabilization.

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