APPLICATION OF TPI1-10k/50 THYRATRONS FOR BUILDING A MODULATOR, INTENDED FOR SUPPLY OF INDUCTIVE-RESISTIVE LOAD IN DOUBLE-PULSE MODE

A.V.Akimov[1], **P.V.Logachev**
Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia

V.D. Bochkov[2], **D.V. Bochkov**, **V.M. Dyagilev**, **V.G. Ushich,**
Pulsed Technologies Ltd., 5, Yablochkova str., 390023, Ryazan, Russia

Abstract

The circuit of modulator, serving to supply inductive-resistive load in double-pulse mode with currents up to 10 kA and pulse duration of 300 ns, is described. As switching components thyratrons (pseudospark switches) designated as TPI1-10k/50 with anode voltage up to 50 kV have been used. TPI-thyratrons are capable of operating in circuits with grounded cathode, which allows obtaining higher performance reliability and longer service lifetime in contrast to other known designs of pseudospark switches, operating with grounded grid. The thyratrons can be considered as alternative to present switches, including hot cathode hydrogen thyratrons and up-to-date power solid state devices, especially for switching of high-currents with sub-nanosecond jitter, turn-on time of 3÷5 ns and average current up to 0.3 A.

The results of tests, confirming possibility of reverse dielectric strength recovery within some microseconds after switching of 10 kA forward anode current, are presented. Basic electrical parameters, effecting thyratron operation in the indicated mode, are analyzed. To clarify prospects of further development of TPI-thyratrons, pentode version of the thyratron, serving to reduce recovery time, is designed.

I. INTRODUCTION

In various accelerators applications it can be required to obtain a series of consecutive high-voltage high-current pulses in a load. In the Budker Institute of Nuclear Physics SB RAS (BINP) a prototype modulator capable of formation of a double-pulse burst with voltage up to 20kV, currents up to 10 kA, pulse width of 300 ns in an inductive-resistive load is developed. The interval between pulses can be varied in a wide range starting from 2 µs.

In Figure 1 a schematic circuit of modulator, providing double-pulse load supply is presented. The modulator consists of 2 two parallel-connected pulse forming networks (PFN1 and PFN2), each discharged via corresponding switch (T1, T2) onto a matched load, which represents a parallel connection of resistor R_{load} and inductor L_{load}.

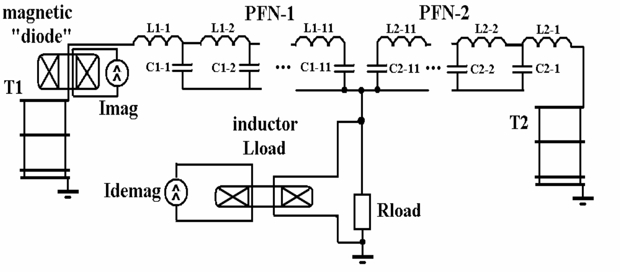

Figure 1. Modulator schematic circuit.

For the first pulse shaping a closing of first switch T1 is sufficient. When shaping second pulse at the expense of the second switch T2 closure, to T1 will be applied reverse voltage equal to load voltage. For this it will be necessary that during the pause between the pulses the first switch dielectric strength is recovered and when closing the second one the former does not conduct current in inverse direction. In order to decouple one PFN from another magnetic "diode" can be used; however more effective will be to use switches with diode characteristics. Such switches are expected to have inverse dielectric strength recovery time not more than several microseconds, ideally hundreds nanoseconds at anode voltage up to 40-50 kV, peak current up to 10 kA with pulse width up to 300 ns, jitter below 2 ns and turn-on time below 10 ns.

In various pulsed power installations hot cathode thyratrons and solid state switches (e.g. IGBT, MOSFET as well as SOS-diodes as pick-off valve) are widely used [1, 2].

Time of inverse dielectric strength recovery of thyratrons (*tr*) mainly depends on amplitude and duration of switching current, anode voltage, voltage rate of rise, working gas (hydrogen) pressure, grid circuit impedance.

---

[1] E-mail: avakim@mail.ru
[2] E-mail: pulsetech@mail.ru

1-4244-0914-4/07/$25.00 ©2007 IEEE.

Presence of anode positive voltage, keeping currents at the level of few mA, increases *tr*. In normal circumstances plasma density in the anode-grid space drops at characteristic time of 2-8 µs. Cathode-grid area recovers as much as 2-4 times slower. The recovery time of pentode thyratron with hot cathode CX1535 (e2v Technologies) right after 1 kA current switching at voltage 1 kV, grid 2 bias voltage minus 300 V, grid 2 impedance of 100-300 Ω is 3÷3,5 µs. Current and voltage increase leads to sharp rise of *tr*.

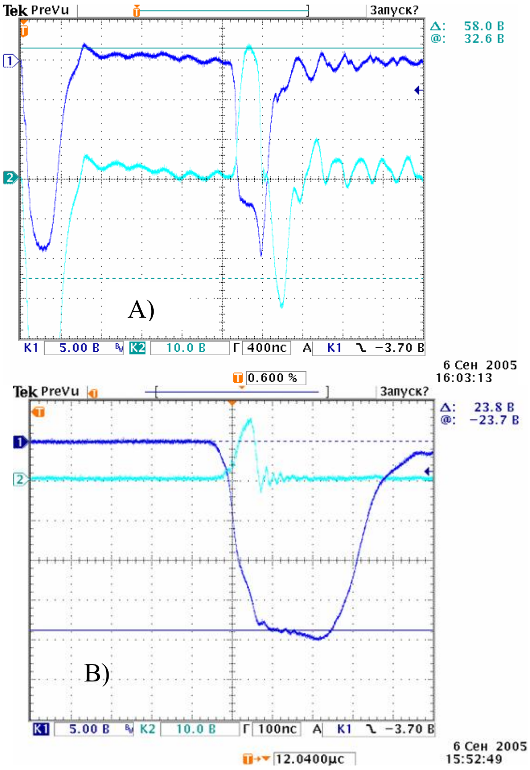

Figure 2. Pulse shapes of voltage on a load (beam 1) and current via SOS-diodes assemblies (beam 2).
A)*ΔTd* = 2 µs, B) *ΔTd* = 12 µs. Scales: beam 1 – 2250V/div, beam 2 – 300A/div.

Using different types of high-current IGBTs (100÷200A /1200V) at reliably short leading edge (100 ns) and wavetail (150 ns) it is possible to achieve peak current via single switches up to 1 kA. On the contrary there is a problem of serial connection of IGBT assembly at 10-20 kV. The objective appears to be expensive, labour-intensive and not well-studied at the moment. Nevertheless, presently at the BINP a development of solid-state switches capable of switching peak currents up to 3 kA at forward voltage on the open switch up to 5-10 kV is being conducted.

The main purpose of SOS-diodes [2] is super-fast inverse current breakdown. In order to estimate inverse recovery time of SOS-diodes in pick-off valves circuit a diode assembly for 2 kA forward current and 40 kV inverse voltage was tested. At the start the diode conducts forward pulse current (2 kA, 300 ns), after which to the diode with definite delay *ΔTd* inverse voltage of 11 kV is applied with simultaneous diode current measurement (Fig.2).

It was discovered that inverse current via the diode (positive polarity) appeared even after 12 µs from the moment of 2 kA forward current conduction (negative polarity). Thus the following conclusion can be made that the tested SOS-diodes at 1÷2 kA failed to recover completely in inverse direction with the required period (2÷10 µs).

II. TPI-THYRATRONS DESIGN AND TRIGGER FEATURES

The performance analysis and tests of the known presently switches have shown that the thyratrons with unheated cathode TPI1-10k/50 [3] (pseudospark switches) are very promising for this application.

The design and arrangement of high-voltage electrodes in respect to insulator of TPI1-10k/50 are typical for double-gap classical thyratrons – there is anode, gradient grid, cathode, trigger grid and preionization electrode.

The main feature, intrinsic to TPI-thyratrons, is an effective discharge in patented hollow cold cathode, used as a source of emission.

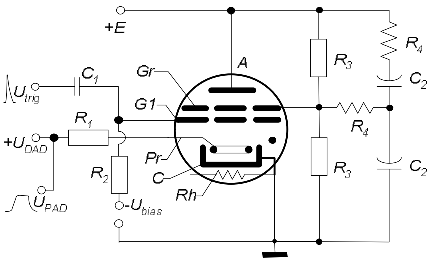

Figure 3. Schematic drawing of thyratron TPI1-10k/50 supply and triggering. *A* – anode; *Gr* – gradient electrode; *G1* – grid; *C* – cathode; *Pr* – preionization electrode; *Rh* – hydrogen reservoir heater; *R3, R4, C2* – RC divider.

For reliable operation of TPI1-10k/50 thyratrons we chose a double-pulse triggering circuit (Fig.3). Direct auxiliary discharge voltage U_{DAD} = 0.8÷1.5 kV and preionization pulse auxiliary discharge voltage U_{PAD} = 1÷3 kV are applied to the preionization electrode. Forward negative bias voltage *Ubias* = –(50÷150) V and triggering pulse are applied to grid G1.

The absence of hot (normally up to 850÷1150 ºC) cathode provides in the cathode area, responsible for discharge formation, as much as 2-3 times higher gas density which leads to shorter turn-on time. The absence of constant electrons emission speeds up a process of deionization after current pulse advancing. Simultaneously it simplifies the thyratron design, relieve it of additional power supply and source of heat. There is no need for forced cooling as well.

It is worth mentioning that absence of hot cathode results in some more additional improvements. Firstly, there is no output of cathode active materials (Ba-Sr-Ca) into an anode-grid space enabling more reliable high dielectric strength. Secondly, using a patented built-in device “SNRV” it is possible to build a thyratron capable of operating without heating at all, i.e. the switch operating both without cathode heating and, which is even more valuable, without hydrogen reservoir heating. Simultaneously in this design we improve operating parameters of the switches, including a range of operating temperatures, simplify circuits in case of high-potential cathode (or both cathode and anode), provide for “instant” operation readiness. Such a decision in principle allows to have novel switches, combining best features of thyratrons, vacuum and spark gaps, solid-state switches.

III. SWITCHING FEATURES OF TPI1-10K/50 THYRATRON

The results of investigation of switching features of TPI1-10k/50 thyratron, such as discharge development time, switching time, turn-on stability, and voltage drop are described in details in [4]. Presently a modified model of the thyratron is being commercialized. The tests have shown that the switch features a qualitative distinction from a previous model, in particular, the switch features preionization discharge firing potential ($U_{pr.\ disch}$) of 110-150 V (instead of 300-400 V), hydrogen reservoir voltage range is increased (ΔU_R = 0.7÷1,0 V), which improves its energy, longevity and time characteristics. Anode current jitter and discharge delay time (t_d) are kept within 2÷4 ns and 50÷60 ns respectively in a range U_R close to the upper limit (5.5-6.0 V). Voltage drop through the thyratron at pulse current of 5 kA width of 300 ns on the top of the pulse is ~ 500 V, at 10 kA ~ 1000 V, which is less than for conventional thyratrons in the modes with submicrosecond pulse width.

The behavior of the thyratron in cases when 20 kV, 300 ns inverse polarity pulse is applied to an anode 2÷10 µs after start of 10 kA, 300 ns forward current pulse is investigated. In order to tests the inverse dielectric strength of the thyratron we used the circuit, represented in Fig. 1 **without** magnetic “diode”.

In Fig.4 a time diagram of load voltage and current is presented. In the interval t_0-t_1 operating voltage U_{load} is applied to the load. During a pause between pulses (t_1-t_2) in the thyratron T1 forward inductor demagnetization current occurs, recharging PFN-1 up to definite voltage $U_{PFN\text{-}rev}$. At the moment when the inductor is saturated by inverse voltage (t_2), PFN-1 recharging voltage ($U_{PFN\text{-}rev}$) is applied to thyratron anode with negative potential leading to thyratron breakdown. It was discovered that for module $|U_{PFN\text{-}rev}| \leq 4$ kV the thyratron withstands inverse voltage without prefire.

When triggering T2 and discharging network PFN-2 the second voltage pulse U_{load} occurs on a load with the given delay (moment t_3), which leads to occurrence on T1 additional inverse voltage drop. Thus the overall negative voltage applied to thyratron T1 is:

$$U_{t\text{-}rev}=U_{PFN\text{-}rev}+U_{load}.$$

Inverse voltage $U_{t\text{-}rev}$, appearing on anode at the moment t_3, can lead to thyratron breakdown.

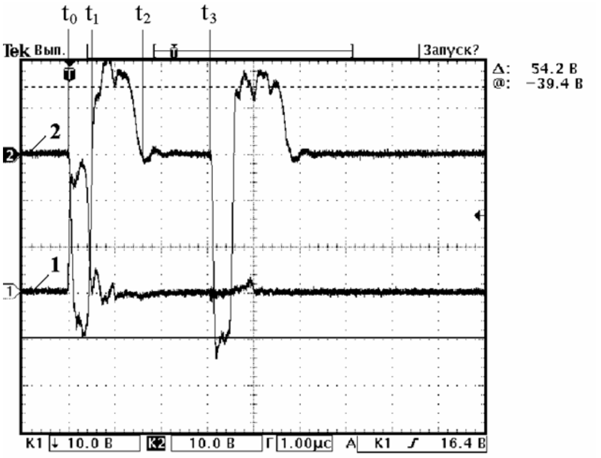

Figure 4. Experimental pulse shapes on a load.
Curve 1 – T1 thyratron current, curve 2 – inductor voltage. Time scale: 1 µs/div; voltage scale: 2250 V/div; current scale: 1200 A/div.

In Table 1 a dependence of inverse breakdown voltage module $|U_{t\text{-}rev\text{-}br}|$ on width of interval between pulses $Dt_{2p} = t_3 - t_0$ at different values of forward anode current (Ia) is presented. Anode current varied depending on PFN charging voltage and load resistance. It is necessary to consider that $Dt_{2\text{uмн}}$ includes time interval within which the thyratron conducts current in forward direction (t_0-t_2) and during which one could not talk about inverse dielectric strength recovery in the thyratron.

Table 1. A dependence of inverse breakdown voltage module on width of interval between pulses.

Dt_{2p}, µs	$\lvert U_{t\text{-}rev\text{-}br}\rvert$ /I$_a$, kV/kA
2.6	12.3 / 3.8
3	17.9 / 5.8
3.5	18.5 / 6.2
4	15.3 / 7.5
5	19 / 7.5
6	>24 / 10
7	>24 / 10
8	>24 / 10

As a conclusion, commonly the faster a thyratron recovers in inverse direction the less the anode current is switched in forward direction.

Also it is noticed, that basically the rate of inverse dielectric strength of thyratron is <u>not affected</u> significantly by the following factors:

1. The negative bias cycling to the thyratron grid in time interval t_1-t_3. The voltage was supplied by voltage source 300 V via small limiting resistance (5 Ω).
2. The transition from direct auxiliary discharge U_{DAD} to the pulse auxiliary discharge. Supply voltage U_{DAD} was switched off at the moment of thyratron closing (t_0).
3. The closure of preionization electrode via small resistance (5 Ω) to the cathode at the moment of thyratron activation (t_0) for speeding up a process of charged particles resorption.
4. The setting-up a leveling RC-divider onto a system of electrodes “Anode-Gradient-Cathode” (Fig.3).

Meanwhile it was noticed that after conducting forward anode current at the moment of application of negative anode voltage of several kilovolts to the thyratron, gradient electrode voltage ($U_{Gr} – U_{G1}$) is hundreds of volts. It demonstrates that the lower part of anode chamber, limited by gradient electrode, at the expense of charged particles source (hollow cathode) proximity is in conducting state and will not withhold total reverse voltage. It leads to the fact that within the first several microseconds virtually all negative anode voltage is applied to the upper part of anode chamber ($U_{Gr} – Ua$). In this connection a pentode thyratron with additional grid, screening anode chamber volume from cathode cavity, is developed and being tested. The application of the design is expected to increase dielectric strength of chamber $U_{Gr} – U_{G1}$.

III. CONCLUSION

The thyratrons with cold cathode TPI1-10k/50 switching peak current up to 10 kA feature a number of advantages if compared to hot hydrogen thyratrons:

- –absence of power heating circuits;
- –shorter discharge development time and recovery time;
- –lower weight and smaller dimensions;
- –cost-effectiveness.

The absence of hot cathode enables more homogenious distribution of gas density and hence shorter turn-on time. Simultaneously, it simplifies thyratron design, releive it of additional power supply and source of heat. There is no need for forced cooling as well.

Taking into consideration specific requirements to the switches in terms of inverse voltage we have definite presuppositions to decrease inverse dielectric strength recovery time at the expense of thyratron pentode design application.

As a whole we can conclude that TPI-thyratrons, and in particular TPI1-10k/50, are the most prospective alternative to the presently known high-current switches, being pre-eminent in a number of performances.

VII. REFERENCES

[1] H.C. Kirbie, et al. "Development of Solid-State Induction Modulators for High PRF Accelerators," LLNL, Livermore, CA, UCRL-JC-119582, *10th IEEE Pulsed Power Conference,* Albuquerque, NM, 1995.

[2] G.I. Mesyats, S.N. Rukin, S.K.Lyubutin et al. Semiconductor opening switch research at IEP/ *X Int. IEEE Pulsed Power Conderence*, Albuquerque, NM, USA,1995, p.298.

[3] V.D. Bochkov, Yu.D. Korolev, et.al. , "Sealed-off pseudospark switches for pulsed power applications (Current status and prospects)", *IEEE Trans. on Plasma Sci.*, vol.29, No.5, p. 802, 2001.

[4] A.V. Akimov, P.A Bak, I. V. Kazarezov et.al. Investigation of cold cathode TPI1-10k/50 thyratron parameters at voltage up to 50 kV, current up to 10 kA, pulse duration of hundred nanoseconds. *Problems of Atomic Science and Technology. Series: Nuclear Physics Investigations.* 2006, No.3(47), p.92-94.