SOLID-STATE MODULATORS FOR PARTICLE ACCELERATORS

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Abstract

A series of the wide parameter range solid-state high-voltage modulators has been developed and built as a power supplies for the magnetrons and the klystrons in the particle accelerators. The series includes 60 kV/100 A/6 μsec modulator with pulse transformer for 3 MW magnetron, 60 kV/300 A/6 μsec direct switch modulator for 6 MW multi-beam klystron, 110 kV/80A/6 μsec direct switch modulator for 3 MW klystron, 130 kV/100 A/6 μsec modulator with pulse transformer for 5 MW klystron, 250 kV/250 A/6 μsec modulator with pulse transformer for 20 MW klystron. The last modulator is under construction. All other modulators have been supplied to customers in Russia as well as in Europe.

INTRODUCTION

The solid-state modulators are used to feed klystrons and magnetrons in the particle accelerators more and more often. These modulators include the semiconductor HV switch (IGBT or MOSFET) instead of the tube one in traditional modulators. The main advantages of the solid-state modulator are low voltage on each switch connected in series, long lifetime, and easy control.

Several schemes of the solid-state modulator are used at the modulator building.

The first modulator type is a series switch. It includes serial IGBT switches discharging the full-voltage capacitor to the load (klystron) [1, 2].

The second modulator type is a high-voltage pulse generator with parallel charging of the capacitors and discharging them to the load in serial circuit. V. K. Arkadiev and N. V. Baklin have built this generator with mechanical switch in 1904. E. O. Marx suggested the use of the discharger as a switch in this generator in 1924. IGBT is used as a switch in this generator now [3]. The voltage in the load is a sum of the capacitor voltages.

These modulator types can be used with the pulse transformer.

The next modulator type includes a number of modules, each of which includes the capacitor, the switch and the pulse transformer [2]. The secondary windings of these pulse transformers are connected in series, so the load voltage is a sum of module voltages.

Another approach is used in the modulator including one complex pulse transformer with several primary windings and one secondary one [4]. The modules are connected to the primary windings. The magnetic flows of the primary windings are added in the pulse transformer core. So the secondary voltage is a sum of primary voltages times transformer ratio.

MODULATOR WITH ADDING MAGNETIC FLOW

The modulator with adding magnetic flow in the pulse transformer has been built for HV feeding of 2.5-3 MW S-band magnetron in the electron linac [5].

Eleven 1 kV modules are connected to eleven primary windings of the pulse transformer. All equipment is located in the oil-tank as this is shown in Figure 1.

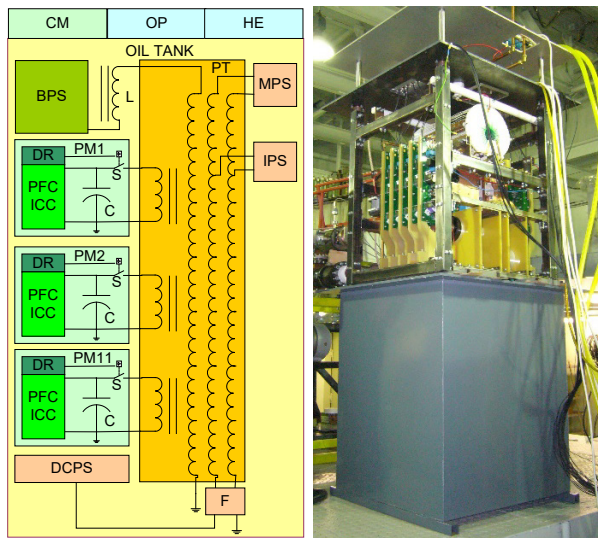

Figure 1: Modulator with adding magnetic flow.

Main modulator parameters are

- voltage 55 kV;
- current 100 A;
- pulse length 0-6 μsec;
- average power 4.5 kW;
- bifilar secondary winding for power supply of magnetron filament;
- terminals at secondary winding for reduced injector voltage.

DIRECT SWITCH 60 KV MODULATOR

The direct switch solid-state Arkadiev type modulator has been developed for 6 MW multi-beam klystron. Two modulators have been built for the 40 MeV electron linac [6]. Each modulator includes 6 modules with 10 levels of the Arkadiev generator. The modulator is shown in Figure 2, in the cabinet, where the klystron is located too.

Main parameters of the modulator are:

- voltage 60 kV;
- current 300 A;
- pulse length 0-6 μsec.

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ISBN 978-3-95450-181-6

Figure 2: Direct switch solid-state 60 kV modulator.

The voltage and current pulse shapes are shown in Figure 3. The modulator allows switching off the load voltage within the pulse with limitation of the current in case of break-down. The oscillograms corresponding to this fast interlock are shown in Figure 4.

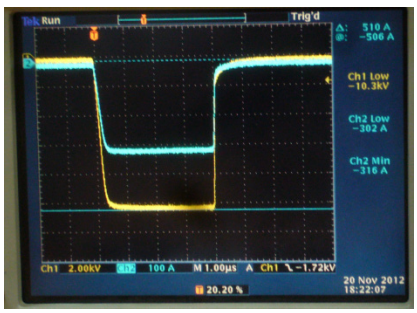

Figure 3: Voltage and current pulse shape.

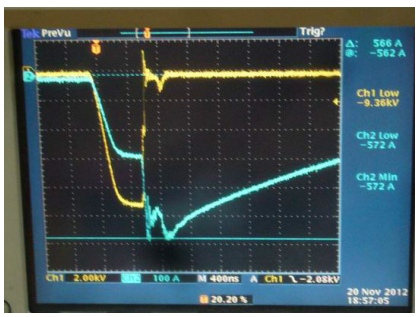

Figure 4: Voltage and current pulse shape in case of the fast interlock event (break-down).

DIRECT SWITCH 110 KV MODULATOR

Another direct switch solid-state Arkadiev type modulator has been developed and built for 3 MW klystron [7]. It is shown in Figure 5.

Eleven modules with ten levels in each are located in the oil-tank. The klystron is located on the top of the oil-tank.

Main parameters of the modulator are:

- voltage 110 kV;
- current 80 A;
- pulse length 0-6 μsec.

Figure 5: Direct switch solid-state 110 kV modulator:
- out of oil-tank with test resistive load on the left and
- in the oil-tank with the klystron on the right.

The pulse shape in the modulator is shown in Figure 6.

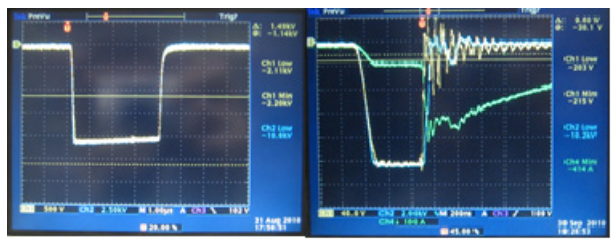

Figure 6: The pulse shape in 110 kV modulator (normal and in case of interlock event).

130 KV MODULATOR WITH PULSE TRANSFORMER

130 kV modulator has been developed and built for the 3-5 MW klystron. The modulator includes six 10 kV modules in the cabinet, producing dual output voltage ±24 kV, which is transmitted to the transformer primary (48 kV). Figure 7 shows (from left to right) the pulse transformer in the oil-tank (with klystron and local shielding on the top), the modulator cabinet and the control cabinet.

Figure 7: 130 kV modulator with pulse transformer.

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Measured parameters of the modulator&transformer are:

- voltage 130 kV;
- current 100 A;
- pulse length 0-6 usec;
- pulse-to-pulse output voltage instability (peak-to-peak) 0.19%;
- RMS voltage fluctuation 0.03%;
- flat-top voltage non-uniformity <1%.

The pulse shape in the modulator is shown in Figure 8.

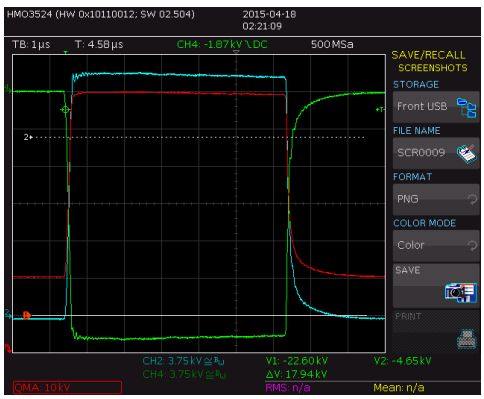

Figure 8: The pulse shape in 110 kV modulator (BLUE is positive voltage, GREEN is negative voltage, RED is differential voltage).

The modulator operates as a part of the complex equipment in Europe.

250 KV MODULATOR WITH PULSE TRANSFORMER

The next modulator has been developed to feed 24 MW S-band klystron. It consists of two dual 22 kV modules in the cabinet and the pulse transformer in the oil-tank with the klystron on the top. 3D design of the modulator and the pulse transformer in the oil tank with the klystron is shown in Figure 9.

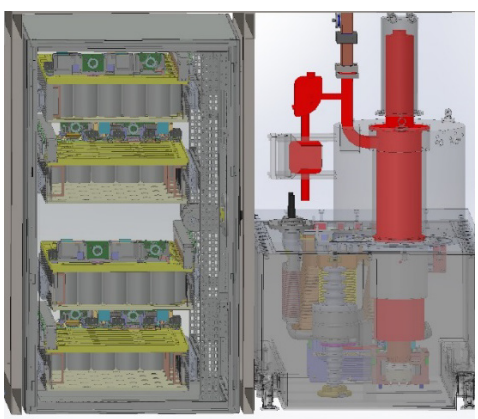

Figure 9: 250 kV modulator with pulse transformer and klystron.

Main parameters of the modulator are:

- voltage 250 kV.
- current 250 A.
- pulse length 0-6 µsec.

The modulator is under construction now.

CONCLUSION

A number of solid-state modulators have been developed and built for klystrons and magnetrons.

The modulators cover a wide range of the parameters: voltage up to 250 kV, current up to 300 A, pulse length up to 6 µsec.

The solid-state modulators have been built with different schematics: direct switch, with adding the magnetic flow, with or without pulse transformer. Therefore, any customer requirements can be fulfilled on base of developed and built modulator series.

The solid-state modulators have following advantages over the tube-based modulators:

- module type of the building;
- easy parameter scaling on base of module type;
- low voltage of the single switch;
- long lifetime of the semiconductor switch;
- easy control of the voltage, pulse length, rise time;
- availability of the fast break-down interlock, switching off the voltage on the klystron within the pulse with limitation of the klystron current.

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