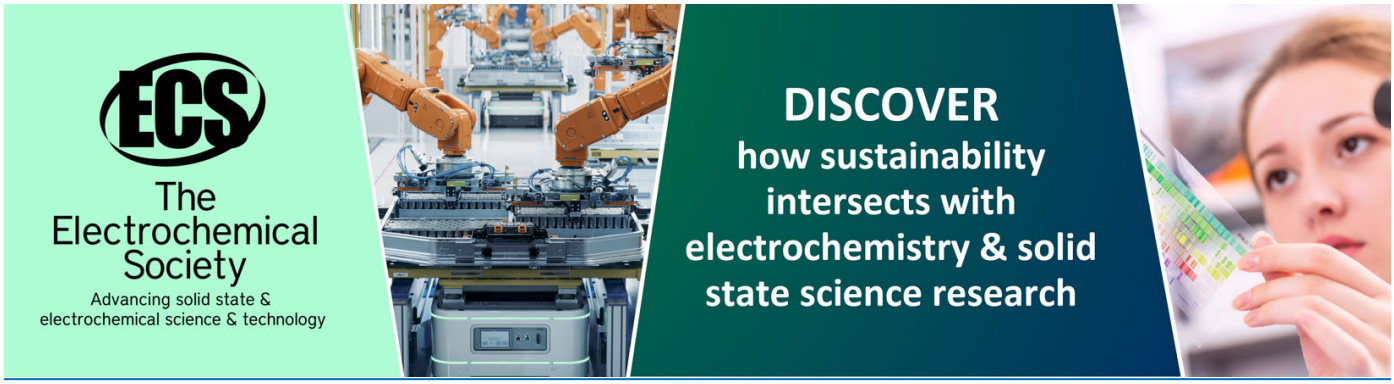
Modular compact solid-state modulators for particle accelerators



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Modular compact solid-state modulators for particle accelerators

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Abstract. The building of the radio frequency (RF) particle accelerator needs high-voltage pulsed modulator as a power supply for klystron or magnetron to feed the RF accelerating system. The development of a number of solid-state modulators for use in linear accelerators has allowed to develop a series of modular IGBT based compact solid-state modulators with different parameters. This series covers a wide range of needs in accelerator technology to feed a wide range of loads from the low power magnetrons to powerful klystrons. Each modulator of the series is built on base of a number of unified solid-state modules connected to the pulse transformer, and covers a wide range of modulators: voltage up to 250 kV, a peak current up to 250 A, average power up to 100 kW and the pulse duration up to 20 μsec. The parameters of the block with an overall dimensions 880×540×250 mm are: voltage 12 kV, peak current 1600 A, pulse duration 20 μsec, average power 10 kW with air-cooling and 40 kW with liquid-cooling. These parameters do not represent a physical limit, and modulators to parameters outside these ranges can be created on request.

1. Introduction

The solid-state modulators are increasingly being used instead of tube modulators to feed the klystrons and the magnetrons. The main advantages of the solid-state modulator are low voltage of each switch connected in series, long lifetime, and easy control.

2. Different solid-state modulator schematics

Extensive development of the solid-sate modulators leads to different schematics, main of which are [1]

- modulator with adding magnetic flow (AMF),
- direct switch modulator (DC),
- modulator with the pulse transformer (PT).

2.1. *Modulator with adding magnetic flow*

The first type of the modulator includes the complex pulse transformer with several primary windings and one secondary one. The high-voltage solid-state modules are connected to the primary windings as a loads. The current of each module creates the magnetic flow in the transformer core. The magnetic flows of all primary windings are added in the pulse transformer core. So the secondary voltage is a sum of primary voltages times transformer ratio. The modulator with adding magnetic flow in the pulse transformer has been built for HV feeding of S-band magnetron in 5 MeV electron linac [2, 3].

The modulator includes eleven 1 kV modules connected to eleven primary windings of the pulse transformer. The whole modulator is located in the oil-tank as this is shown in Figure 1.

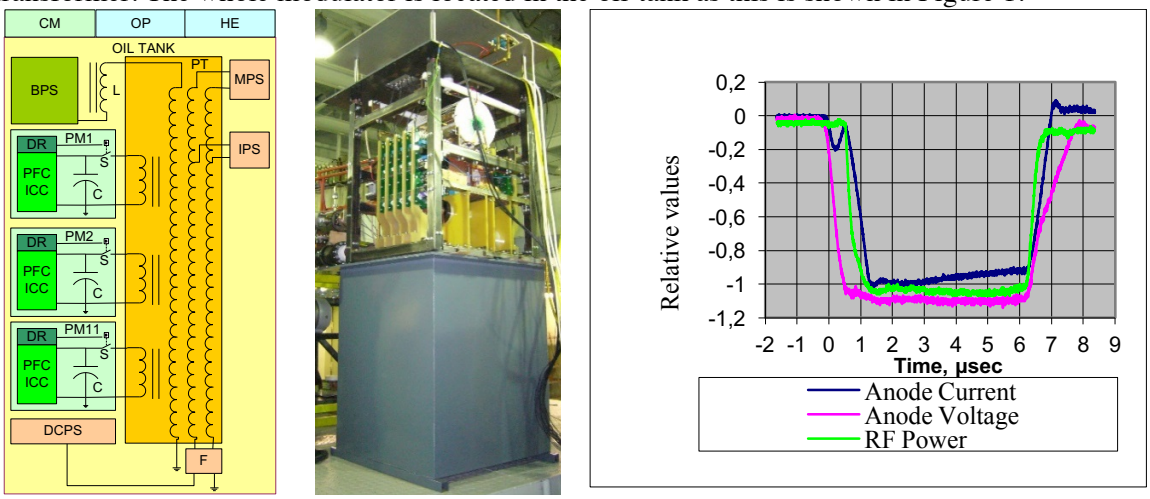

Figure 1. Schematics, view of the modulator with adding magnetic flow and the pulse shape.

2.2. Direct switch modulator

The second modulator type includes several high-voltage modules built on the Arkadiev schematics with solid-state switches. Such modulator has been developed for 6 MW multi-beam klystron. Two modulators for 6 MW multi-beam klystron have been built for the 40 MeV electron linac [4]. Each modulator includes six 10 kV modules. . The modulator allows switching off the load voltage within the pulse with limitation of the current in case of break-down. The modulator and the klystron are located in the cabinet.

The modulator is shown in Figure 2.

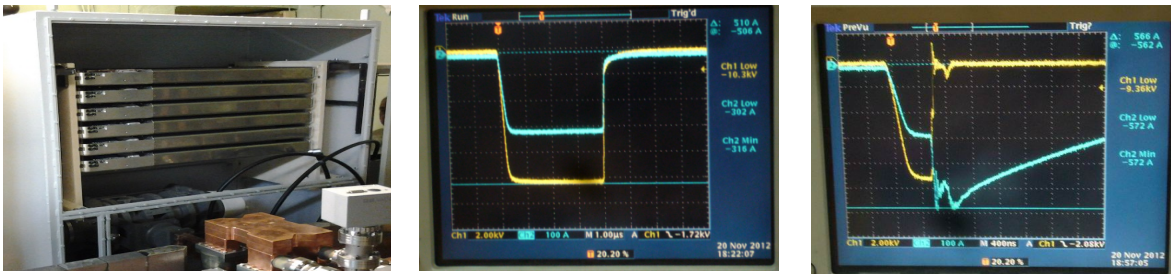

Figure 2. 60 kV direct switch modulator and the pulse shape in normal operation (top) and in case of break-down (bottom).

110 kV direct switch modulator with eleven 10 kV modules has been built for the S-band klystron [5]. The modulator is shown in Figure 3.

2.3. Modulator with pulse transformer

130 kV modulator with the pulse transformer has been built to feed the klystron [1]. The modulator includes six 10 kV modules in the cabinet and produces dual output voltage ±24 kV, which is transmitted to the transformer primary (48 kV). Figure 4 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.

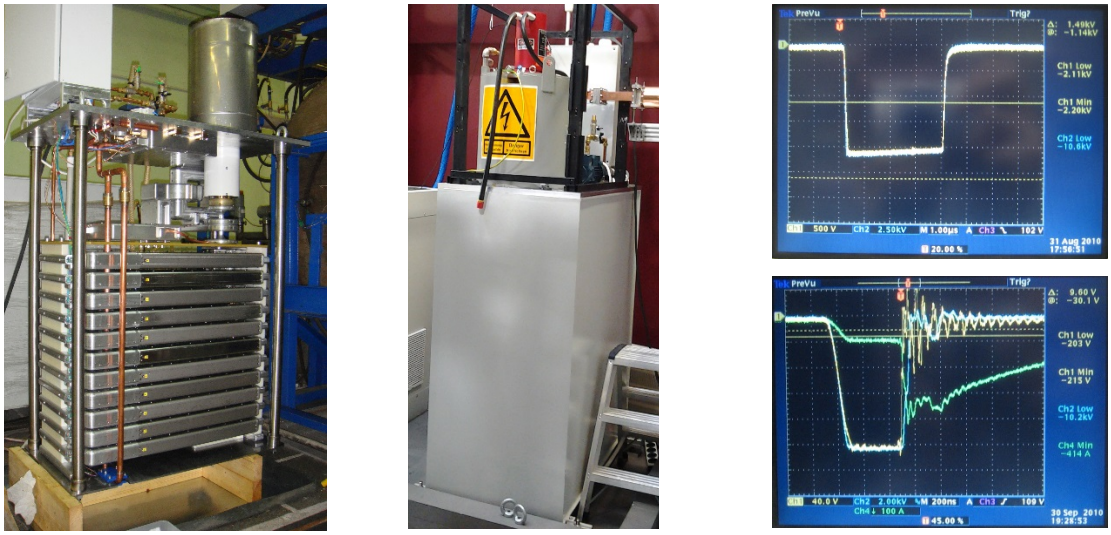

Figure 3. 110 kV direct switch modulator and the pulse shape in normal operation (top) and in case of break-down (bottom).

Figure 4. 130 kV modulator with pulse transformer and the pulse shape (BLUE is positive voltage, GREEN is negative voltage, RED is differential voltage).

250 kV modulator with the pulse transformer has been built to feed the klystron [1]. The modulator includes two dual 24 kV modules in the cabinet and the pulse transformer in the oil-tank with the klystron on the top. 3D design of the modulator, 3D design of 12 kV block and assembled 12 kV block are shown in Figure 5. The modulator is under construction.
The parameters of the described modulators are summarized in Table 1.

3. 24 kV unified module

The new high-voltage module has been designed during development of the 250 kV modulator with the pulse transformer [1]. The module includes two 12 kV blocks with eleven Arkadiev levels. The number of parallel IGBT in each level can be one or two. The number of parallel capacitors in each level can be from one to five. The number of IGBT and the capacitors in each level can be chosen depending on the required peak current, pulse length and flat-top slope. 3D design and assembled block are shown in Figure 5.

The assembled block has been tested at full designed voltage and current. The test results are shown in Figure 6.

The module includes two blocks, connected in series, and one common control unit. The module parameters are summarized in Table 2.

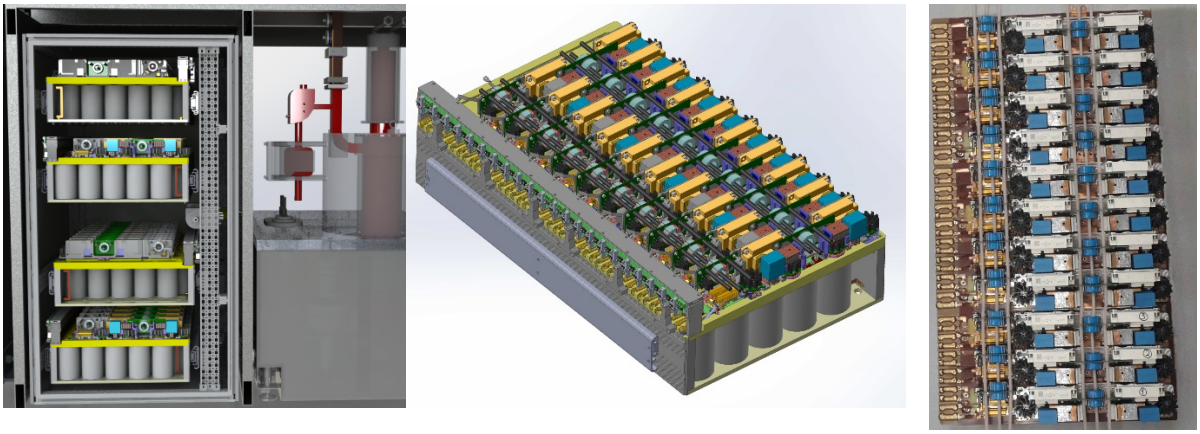

Figure 5. 250 kV modulator with pulse transformer.

Table 1. Parameters of the modulators.

Parameter	Unit	AMF modulator	DC modulator	DC modulator	PT modulator	PT modulator
Voltage	kV	55	60	110	130	250
Current	A	100	300	80	100	250
Pulse length	μsec	6	6	6	6	6
Repetition rate	Hz	300	160	10	10	10
Number of modules	-	11	6	11	6	2
Transformer coefficient	-	6	-	-	2.3	5.7
Average power	kW	4.5	18	6	6	6
Load	-	Magnetron	Klystron	Klystron	Klystron	Klystron
Peak RF power	MW	3	6	3	3-5	24

Parameter	Unit	Value
Level voltage	kV	1.1
Block voltage	kV	12
Block current	kA	1.5
Pulse length	μsec	6
Rise time	μsec	0.6
Flat-top slope	%	<0.5

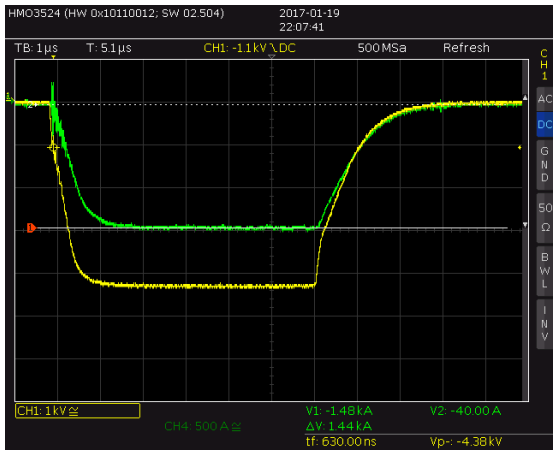

Figure 6. Test result of the 12 kV block.

4. Development of the modulator series

Developed 24 kV module allows us to develop the series of the solid-state modulators with the module as a common base. Parameters of the series modulators are shown in Table 3.

The block-diagrams of the modulators are shown in Figure 7.

The block-diagram of the Pulse transformer oil tank and the photo of the pulse transformer are shown in Figure 8.

Table 2. Parameters of 24 kV unified module.

Parameter	Unit	Value
Max operating voltage	kV	24
Max operating voltage in accordance with IGBT specs	kV	37
Max operating current in accordance with IGBT specs	A	2400
Max pulse length	μsec	20
Flat-top slope (22kV@1467A@6 μsec)	%	0,84
Max average power with air-cooling	kW	10
Max average power with liquid-cooling	kW	40
Number of levels	-	2×11=22
Number of IGBT in the level	-	2
Total number of IGBT	-	44
Capacitance of each capacitor	μF	420
Total number of capacitors in the level	-	5
Total number of capacitors	-	110

Table 3. Parameters of the module-type modulators.

Parameter	Unit	Value				
Modulator Ind.	-	M1	M2	M3	M4	M5
Voltage	kV	250	175	135	60	60
Current	A	250	125	84	250	100
Module impedance	Ohm	15,5	50	50	50	50
Number of modules	-	2	2	2	2	1
Trans impedance	Ohm	31	100	100	100	50
Tran coefficient	-	5,7	3,7	4,0	1,5	3,5
Trans input voltage	kV	44	47	34	39	17
Module voltage	kV	22	23	17	19	17
Module current	A	1420	468	337	387	346
Load	-	Klystron	Klystron	Klystron	Magnetron /Klystron	Magnetron
Peak RF power	MW	24	10	5,5	7.5/5,5	5,5

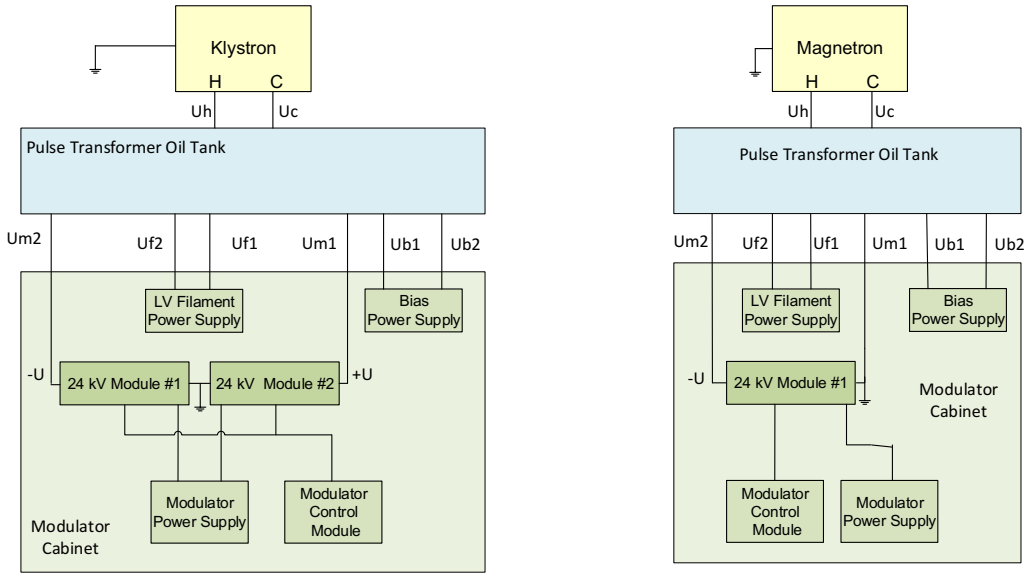

Figure 7. Block-diagrams of the modulators M1-M4 (left) and M5 (right).

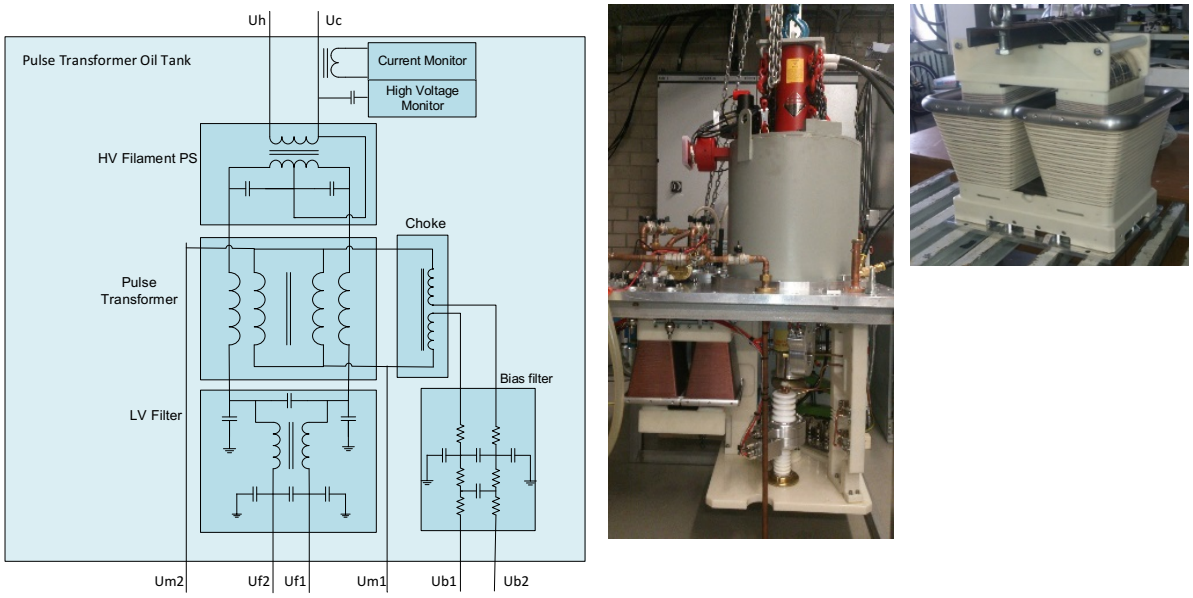

Figure 8. Block-diagram of pulse transformer.

5. Conclusion

The solid-state modulator series for klystrons and magnetrons has been developed on base of built 24 kV unified module.

The modulators cover a wide range of the parameters: voltage up to 250 kV, current up to 250 A, pulse length up to 20 μsec.

The work has been done on base the experience of the building of the solid-state modulators with different schematics: with adding the magnetic flow, with direct switch, with or without pulse transformer.

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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