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Low-inductance switch and capacitor energy storage modules made of packages of industrial condensers IK50-3

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Abstract. A low-inductance module of a high-current capacitive energy storage with an operating voltage of 40 kV is developed. The design of the module is based on the application of capacitive sections of the industrial condenser IK50-3. The module includes two capacitors of 0.35 µF each, one common low-jitter triggered gas switch and 2 groups of output cables of 4 from each capacitor. A bus bars topology developed for the switch and cables connections provides a small total inductance of the discharge circuit, for the module with the output cables KVIM of 0.5 m long, it is lower than 40 nH. The set of 10 modules is now used for driving the 20 stages linear transformer for a fast charging of the pulse forming line of the high-current nanosecond accelerator. A design of the module and the results of tests of a single module and a set of 10 are presented.

1. Introduction

The increased rate of energy transfer from the primary capacitive storage to the load requires a reduction of the total discharge circuit inductance, including the inductance of the capacitor, the switch, and the connecting bars. One of the implementable ways to reduce the inductance is to reduce a length of the connecting bus with an optimization of their topology by combining into a single structure of the storage capacitor and the switch, and reducing the inductance of the outputs, which are not under a constant high voltage. Such devices, called a capacitor-switch module, produce pulse currents with the amplitude of more than 100 kA at a pulse duration ≈200-300 ns [1, 2]. These parameters are achieved using specially developed high-voltage high-current foil capacitors, a design of which together with a gas switch and output electrodes forms a low-impedance coaxial system [3]. Due to their uniqueness and the lack of mass production, they are expensive and difficult to obtain.

Below, it is given a description and the basic characteristics of the capacitor-switch module based on the use of packages of the industrial condensers IK 50-3, which significantly simplifies and reduces the cost of its manufacture. The assembly is a single module of the 10-module primary power supply of the 20-stage linear pulse transformer for a voltage of 800 kV, used for the fast (300-400 ns) charging of a forming line of a high-current electron accelerator.

2. Module design

The compact capacitor-switch module combines in a single package two series-connected capacitors of 0.35 µF each, a gas switch, 8 output cables jointed in two group of 4 from each capacitor, and one charging cable. The module design is shown in Figure 1.

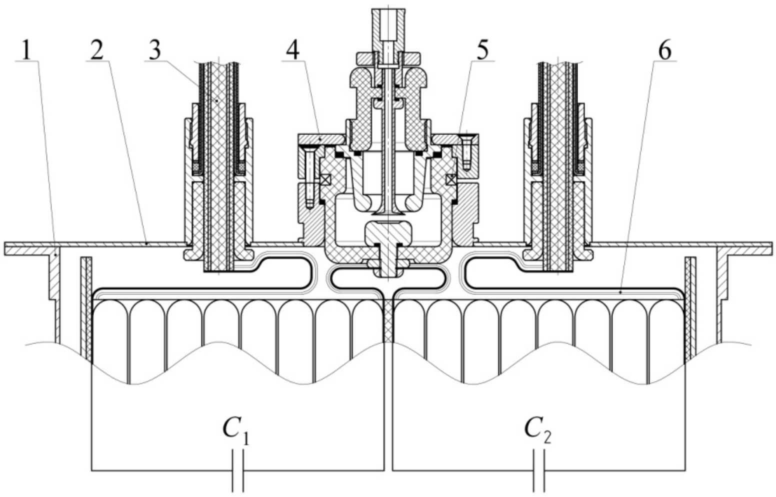

Figure 1. The cross-section of capacitor-switch module: 1 – housing, 2 – cover, 3 – output cables, 4 – gas switch, 5 – Rogowsky coil, 6 – oil-barrier insulation.

The design of the module is based on the using of capacitor packages of the industrial capacitor IK50-3. One of four sections of IK50-3 capacitor is used in one module. The section consists of two connected in series groups of 8 capacitor packs each, tightly fastened together into a single structure by metal shrouds between the end metal plates. Each of the packs group is a high-current capacitor of 0.35 µF for voltage of 50 kV. The section is placed into a metal housing of the module, with dimensions 314x314x160 mm3, and isolated from it by a paper-oil insulation, for the full voltage of 50 kV.

The midpoint of the two capacitors of the section is connected to the high voltage electrode of a triggered switch, and the outlets from the outer packages of capacitors are connected to the central conductors of the output cables.

2.1. Gas switch

The three-electrode gas switch of a "field distortion" type is used for switching the both capacitors. Dry air with a pressure up to 4 bars is used as an insulating gas.

The design of the switch is shown in Figure 1. It assembles an insulating housing made of polyamide plastic “caprolon”, installed in a metal base welded to the module cover, two main electrodes with a toroidal working surface, and a disk trigger electrode. The main electrode, mounted at the base of the insulating casing, is connected to the midpoint of the capacitors and to the central wire of a charging cable (not shown in Figure 1). The second main electrode is connected to the grounded base welded to the cover.

The trigger electrode is placed into the main gap through the cavity in the main grounded electrode. It is a hollow rod, gradually widening and turning into a sharp-edged disk with a diameter of 16 mm. The outer edge of the disc is placed at a distance of ≈0.7 mm from the top of the grounded electrode. Its position corresponds to the position of the equipotential surface with a potential of 1/3 of the voltage *U* applied to the switch. The same voltage of *U*/3 is applied to the trigger electrode from the outside located resistive voltage divider (installed in a trigger generator unit)

The plot of equipotential lines in the spark gap calculated for an initial state, for the trigger electrode voltage $U_{tr}=U/3$, is shown in Figure 2a.

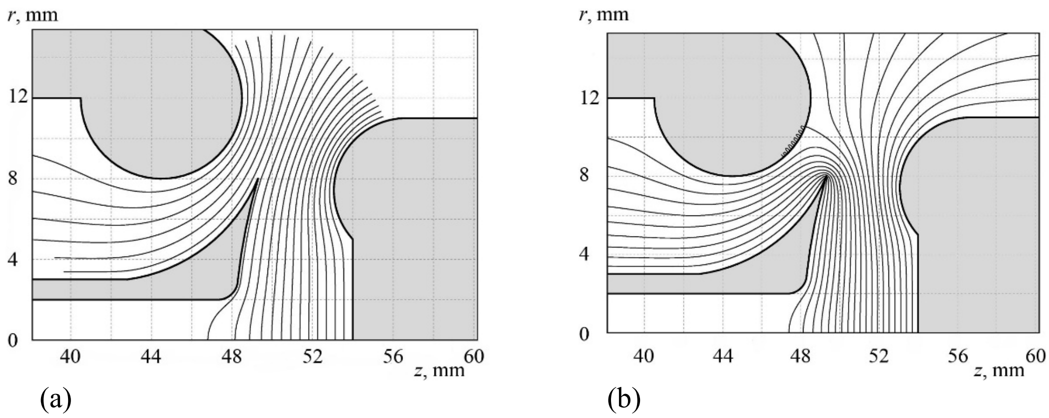

Figure 2. The calculated pattern of the equipotential lines in the gap of the switch:
a – $U_{tr} = U/3$, b – $U_{tr} = -U$.

The closing of the switch is initiated by supplying a trigger pulsed voltage of the opposite polarity to the trigger electrode. Figure 2b shows the calculated plot of the equipotential lines corresponding to the trigger voltage $U_{tr} = -U$, where U is the charging voltage of the capacitor. The high field enhancement near the edge of the trigger electrode provides conditions for the fast development of the discharges on both sides with a low time delay of a gas breakdown, which under these conditions is determined by the time of the development of spark channels.

2.2. The connecting buses

Connections inside of the module are made of wide buses isolated by a paper-oil insulation to reduce the inductance of the discharge circuit. A cross-section of the buses is shown in Figure 1. It was designed to satisfy the requirements of a minimal stray inductance at an acceptable electric field distribution, providing the required electric strength of the isolation. The gaps between the buses, connecting the outer capacitor packages with the output cables and connecting the midpoint of the capacitors with the switch high voltage electrode, were determined mainly by electric field distribution over the switch insulator.

A calculated plot of the equipotential lines in the area of the switch, before and after switching, is shown in Figure 3. The pattern of the lines in Figure 3a shows that for the selected configuration of the connecting buses and the gap between them, the voltage distribution on the switch insulator is close to uniform. For the buses topology shown in the picture, there are no zones of the local field enhancements.

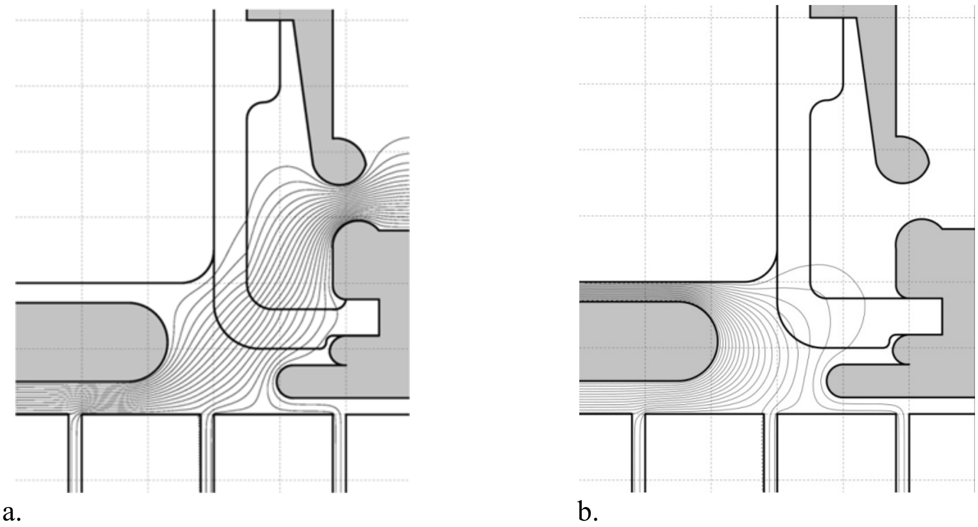

Figure 3. The calculated plot of the equipotential lines: a – before switching and b – after the switch closing. The trigger electrode is not shown.

After switch closing, as shown in Figure 3b, a high field is observed only in the areas between the output buses and the module cover. On the basis of the calculated field values, the parameters of the oil-barrier insulation have been determined.

The estimated inductance of the designed connecting buses is in the range from 20 to 25 nH.

3. Test results

The main characteristics of the manufactured modules were determined experimentally during the several stages of testing.

3.1. Module testing in the static mode

Tests included the slow charging (30 seconds) of the capacitor module to the operating voltage of 40 kV, the exposure for 60 sec, and the subsequent discharge on to the high-resistance load. The tests were aimed to identify possible defects in the insulation and contacts. Additionally, the values of the electric capacity and the dielectric loss (tgδ) were measured before and after the implementation of a charge-discharge cycle. The absence of breakdowns during the static measurements and differences in the measured values of the capacitance and the dielectric loss showed that there are no defects in the module.

3.2. Module testing in the pulsed mode

The tests were aimed at a determination of the parameters of an equivalent circuit of the module and obtaining the amplitude and the time characteristics of the discharge circuit as a whole. Rogowski coil mounted into the housing of the switch was used for measurements of the discharge current, the pulse voltage was measured by a HV probe (divider 1:1000) Tektronix 6015. The measurements were carried out within the range of charging voltages from 20 to 40 kV. The switch was triggered by a fast rising pulse with the voltage amplitude up to 60 kV from the external trigger generator.

As a result of measurements in various modes, the parameters of all elements of the discharge circuit were determined and the equivalent circuit of the module was constructed. The equivalent circuit of the module in the mode of the short circuit at the ends of the output cables is shown in Figure 4.

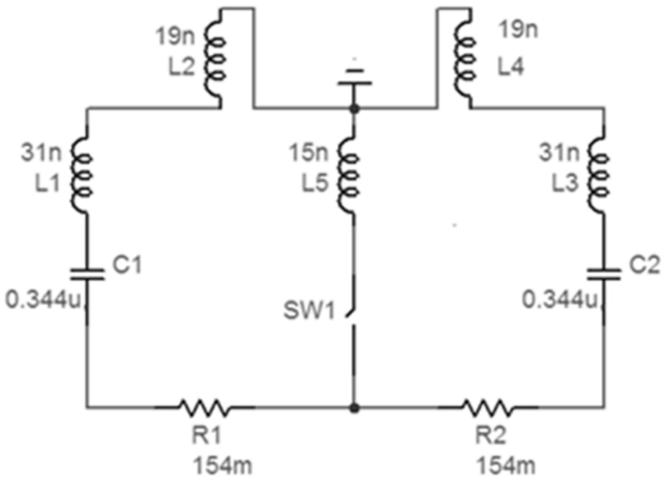

Figure 4. The equivalent circuit of the discharge circuit

L1 and L3 – the total inductances of the capacitor and the connecting bus inside the module, L2 and L4 – the total inductances of 4 KVIM cables connected in parallel, L5 is the inductance of the switch, R1 and R2 are the series resistances of the two branches of the circuit, SW1 – switch, C1 and C2 – measured capacitance of the module capacitors.

The pulses of the discharge current in the short circuit mode for the charging voltage of 20 kV are shown in Figure 5, the dotted line is the calculated current for the given equivalent circuit.

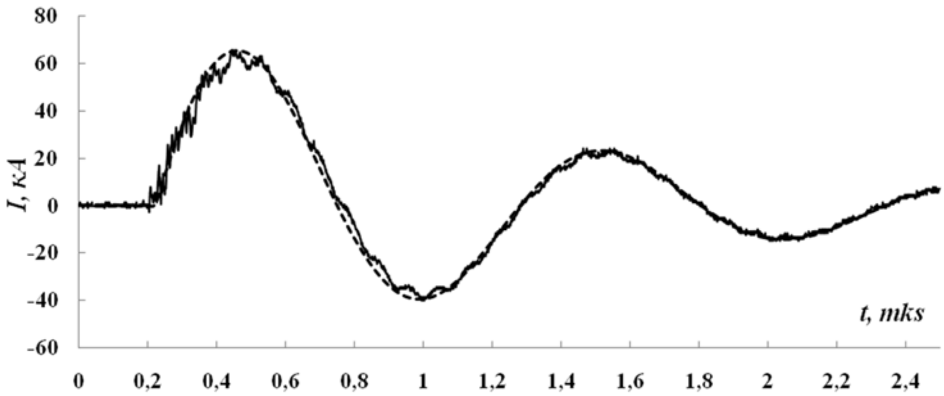

Figure 5. Discharge current pulses in the short circuit mode at the cable outlets. Charging voltage 20 kV.

The measured and the alculated currents practically coincide during the entire discharge cycle. The amplitude of the first peak of the current ≈ 60 kA, the duration of the first half-wave of the current is close to 450 ns. At the charging voltage of 40 kV, the measured amplitude of the total current flowing through the switch was as high as 120 kA.

3.3. Synchronous working of 10 modules in the power supply system of the linear pulse transformer

The power system of the linear pulse transformer includes 10 modules that are installed on both sides of the transformer casing, opposite to the corresponding inputs of the primary windings of the inductors.

The scheme of the connections of modules to the primary windings of the transformer is shown in Figure 6.

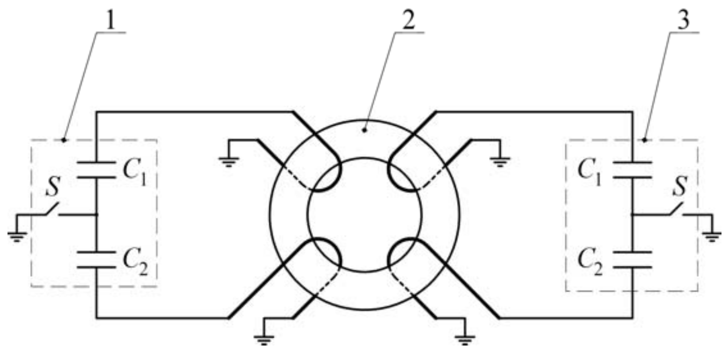

Figure 6. The scheme of the connections of modules to the primary windings of the transformer. 1, 3 – modules, 2 – inductor with ferromagnetic core and one-turn primary winding.

Each one-turn primary winding of the transformer has 4 entry points which are connected to one of the four output cables from both capacitors from the two modules located on both sides of the transformer. Simultaneously, the same voltage with the other cables is supplied to the primary windings of three neighboring inductors. Thus, 4 capacitors of two modules are discharged to the primary turns of the four inductors.

The strong coupling between modules for this transformer powering system, chosen for reduction of the lengths of the connecting cables, imposes strong requirements on the dispersion of the switching time of the modules. A single, common trigger pulse generator is used to provide a mall temporary variation of the closing time for all 10 switches of all 10 modules.

During the test of the 10 modules power supply system, the following data were obtained. For a trigger pulse with a rise time ≈15 ns, an average time delay of the switch closing, relative to the beginning of the pulse, is ≈25 ns. It provides a stable simultaneous operation of all 10 switches with the maximal deviation of the closing time within ±5 ns.

4. Conclusion

The parameters of the developed module meet the requirements of its application in the system of a primary powering of the pulsed linear transformer for fast charging of a pulse forming line of a high-current electron accelerator. The use of the packages of industrial condensers IK50-3 simplifies the module production and reduces its cost. The designed topology of the connecting buss bars, the use of 4 output cables in each arm, and the merge into a single structure with the switch provide the low total inductance of the module (≤40 nH).

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References

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