IOP Conf. Series: Journal of Physics: Conf. Series **830** (2017) 012021 doi:10.1088/1742-6596/830/1/012021

Linear transformer and primary low-inductance switch and capacitor modules for fast charging of PFL

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Abstract. A step-up linear pulse transformer and a modular primary powering system were developed for fast (≈350 ns) charging of a pulse forming line (PFL) of a high-current electron accelerator. The linear transformer is assembled of a set of 20 inductors with circular ferromagnetic cores and one–turn primary windings. The secondary turn is formed by housing tube walls and a voltage adder with a film-glycerol insulation installed inside of the inductors. The primary powering system assembles 10 modules, each of them is a low-inductance site of two capacitors of 0,35 μF and one gas switch mounted at the same enclosure. The total stored energy is 5.5 kJ at the charging voltage of 40 kV. According to test results, the equivalent parameters at the output of the transformer are the next: a capacity – 17.5 nF, an inductance – 2 μH, a resistance – 3.2 Ohms.

1. Introduction

Linear transformers take a special place among the variety of existing high voltage pulse transformers. They assemble a series set of one-turn transformers with primary windings fed separately and the common one-turn secondary winding. The coaxial version with the volume primary winding and the secondary winding formed by a common housing and a central stalk-voltage adder have the lowest possible induction and a minimal resistance of windings. It reduces both the energy transfer time and losses [1-3].

The following are the design and the basic characteristics of linear pulse transformer with an output voltage of 800 kV and the modular capacitive energy storage in the form of low-inductance capacitor-switch modules, designed for fast (≈350 ns) charging of a pulse forming line of a nanosecond high-current accelerator.

2. Linear pulse transformer

2.1. Linear pulse transformer design

The design concept of the linear pulse transformer is shown in Figure 1.

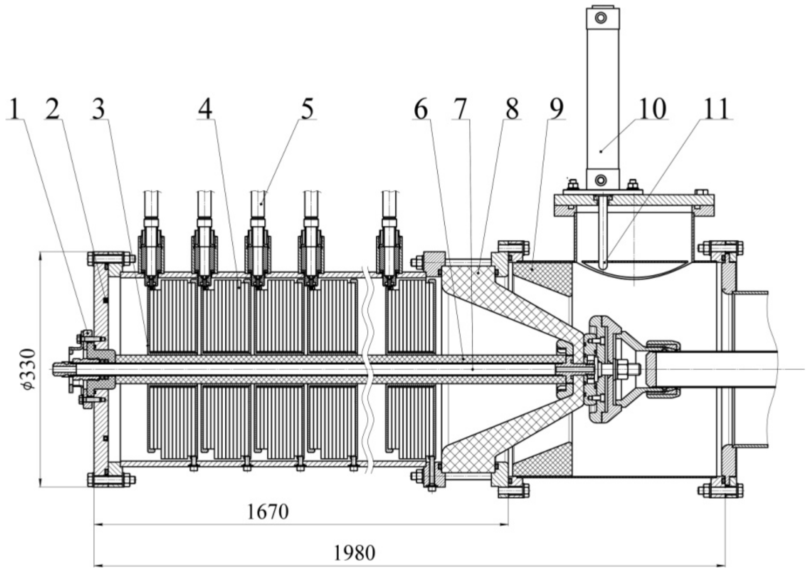

Figure 1. The design of the linear pulse transformer. 1 – small annular gap air switch, 2 - Rogowski coil, 3 – primary winding, 4 – ferromagnetic core, 5 – cable feedthrough, 6 – multi-layer film-glycerol insulation of stock-adder, 7 - stock-adder, 8 – conical insulator, 9 - dielectric insert, 10 - pneumatic actuator, 11 - grounding rod.

The linear pulse transformer assembles 20 series inductors (ferromagnetic sections) placed inside a metal housing with an inner diameter of 275 mm. Each of the inductors assembles an annular ferromagnetic core inside of the primary winding of the rectangular cross-section. The one-turn winding is formed by the housing part, a cylinder segment inside of the annular core and two discs, one of which connects one end of the cylinder segment to the housing, and the second one with a smaller outer diameter is connected to the four high-voltage cable feedthrough. The feedthrough design provides a tight connection with the KVIM cables that are used for the transmission the energy of storage capacitors to the primary windings. The inner diameter of the primary winding is 40 mm, its length - 70 mm.

The outer housing and a central stalk-voltage adder of 18 mm diameter with a multilayer film-glycerol insulation inside all of the 20 ferromagnetic sections form a secondary winding. At the low-voltage side of the transformer, the stock insulated from the housing by an annular air switch is mounted for feeding the magnetization current. A small (1-1.5 mm) air insulated gap of the annular switch is quickly closed at the beginning of the high-voltage pulse generation, grounding this end of the stock during the working cycle. The second high-voltage end of the stock is connected to the load through the output conical insulator. The internal volume of the transformer including the ferromagnetic system and the central stock is filled with glycerol. The conical insulator separates it from an intermediate section between the transformer and the pulse forming line with water insulation.

The central stock is the most stressed element of the pulse transformer. The electric field in the last section of the transformer exceeds 1.1 MV/cm at the maximum output voltage of 800 kV for the selected diameter of the stock 18 mm and the internal diameter of the primary winding of 40 mm. A multi-layer insulation made of a polyethylene film and impregnated with glycerol provides the required dielectric strength [4]. Based on the available data, the resource of the insulation is estimated for 1000 pulses, which is comparable with the lifetime of cables and capacitors.

2.2. Ferromagnetic system

A ferromagnetic core of the inductors is made of 2NSR alloy with the full-scale induction of 3 T in the magnetic field of 800 A/m [5].

Each of the cores is assembled of 12 rings wound by a tape of 5 mm width and of 30 microns thickness. The inner diameter of rings is 50 mm, an outer diameter of the core is 250 mm in the middle section (7 rings) while those located near the ends of the primary winding have a diameter 240 mm (2 rings) and 220 mm (3 rings). With a given fill factor of 0.7, an efficient cross section of the core is S=42 cm^2. The polymer films are used for the insulation of ferromagnetic rings from each other and from the primary winding. The total weight of the ferromagnetic system of the transformer is about 300 kg.

The measured volt-second integral of all twenty inductors is 0.24 volt-second. Energy losses for the full scale of magnetization are about 30 J, which correlates well with the estimates based on the known values of specific losses for the core material ≈0.1 J/kg.

Prior to the generation of a high-voltage pulse, the transformer cores are magnetized by a pulsed current in the secondary winding. The magnetization current generator is connected to the central stock at the low voltage side of the transformer where the stock is insulated from the housing by the annular air switch. During the magnetization, a pneumatically operated grounding rod in the transition section with water insulation grounds the high-voltage end of the central stock. The unipolar magnetization current is generated by discharging a 100 μF capacitor charged to a voltage of 1 kV, through a thyristor switch and a connected in series inductor of 35 μH. This inductor reduces the current rate providing a reliable switching off of the thyristor at zero current and protects the generator circuit from surge prior to the closing of the ring switch.

2.3. High-voltage feedthrough to the intermediate section with water insulation

A conical insulator made of polyethylene is used as a barrier between the transformer filled by glycerol and an intermediate section with water insulation. Its length is determined by the voltage distribution along the film-glycerol insulation at the output part of the stock outside of the last inductor. In addition, a shaped ring insert made of polyethylene is placed immediately after the insulator in the section with water insulation. It acts as a diverging lens for an electric field in water and equalizes the voltage distribution along the insulator surface.

The geometry of the transition region together with the calculated pattern of the equipotential lines is shown in Figure 2.

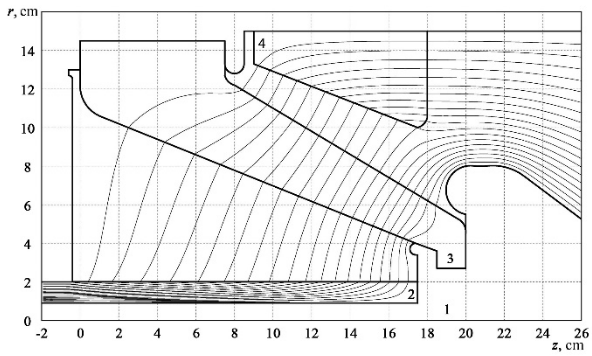

Figure 2. Geometry of transition section with plot of equipotential lines. 1 – high-voltage electrode, 2 – film-glycerol insulation of the stock, 3 – insulator, 4 – plastic insert. Step of the lines is 0.05U.

3. Primary energy storage and switching system

The primary driving system assembles 10 energy storage and switching modules, each of which is a set of two capacitors and one gas switch. The modules are mounted on both sides of the cylindrical housing of the transformer all along its length. The outputs of four capacitors of two modules, which are located at the opposite sides of the transformer, are connected to the primary windings of the four

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inductors (sections). High-voltage cables KVIM with the length of 0.5 m are used for energy transmission from the modules to the transformer inductors.

A photo of the linear transformer assembled together with the primary energy storage and switching modules is shown in Figure 3.

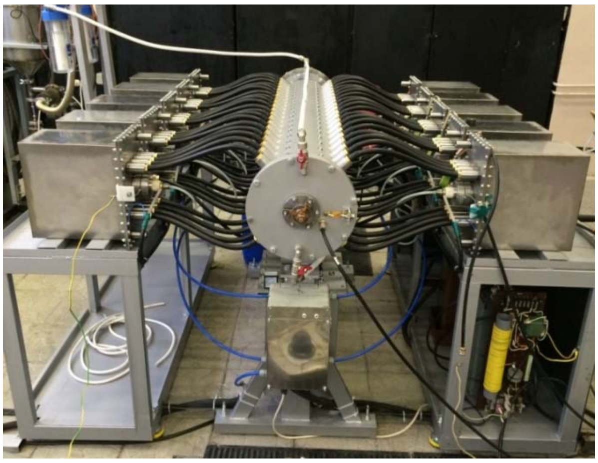

Figure 3. 800 kV linear transformer together with energy storage and switching modules. View from the low-voltage side of the transformer.

3.1. The design of the capacitive storage and switching module

The capacitive energy storage and the switching module is a compact capacitors-switch set, each of which assembles two capacitors of 0.35 μF, one common triggered gas switch and 8 output cables – 2 groups of 4 from each of the capacitors. The design of the module is shown in Figure 4.

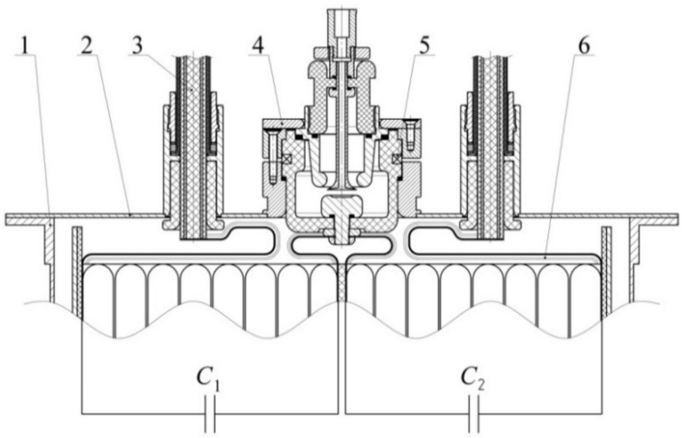

Figure 4. Cross-section of the energy storage and switching module. 1 - housing, 2 – cap, 3 - cable output, 4 - gas switch, 5 - Rogowski coil, 6 oil-barrier insulation.

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

The output from the midpoint of the two capacitors is connected to the high voltage electrode of the triggered gas switch installed on the cover in front of the midpoint. Outer packages of the capacitors are connected to the central conductors of the output cables. Wide buses isolated by the paper-oil insulation are used for connections inside the module. Very close locations of all elements of the module together with a low-inductance design of the connecting buses and the use of 4 output cables KVIM in each arm provide a low total inductance of the discharge circuit (≤40 nH).

A three-electrode gas switch with a "field distortion" is used for fast switching of the capacitors. The sketch of the switch is shown in Figure 4.

The switch consists of an insulating housing made of polyamide plastic “caprolon”, which is installed in a metal base welded to the module cover, two main electrodes and a disk trigger electrode. Dry air with the pressure up to 4 bars is used as an insulating gas. One of the main electrodes, installed in the bottom of the insulator, is connected to the midpoint of the capacitors and a high-voltage charging cable (not shown in Figure 4). The second electrode is grounded. The position of the disk edge of the trigger electrode corresponds to 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 via a resistive divider in the trigger pulse generator unit.

Closing of the switches of all 10 modules is initiated by supplying pulses of an opposite polarity with an amplitude of the voltage up to 40 kV from one common generator to the trigger electrodes using 3 m long coaxial cables. The rise time of the trigger pulse is ≈15ns. Measurements have shown that the average time delay for the switch closing, relative the beginning of the trigger pulse, is about 25 ns, and the its deviation does not exceed ± 5 ns for system of all 10 switches.

4. Test results

The assembled system was tested in several operation modes which differed by the load at the output of the transformer.

4.1. Short-circuit mode

The tests in a short circuit mode were performed at a reduced to 20 kV capacitor charging voltage, corresponding to the total stored energy of 1400 J.

Figure 5 shows the current waveform measured by Rogowski coils in the secondary circuit of the transformer and the switch current of one module.

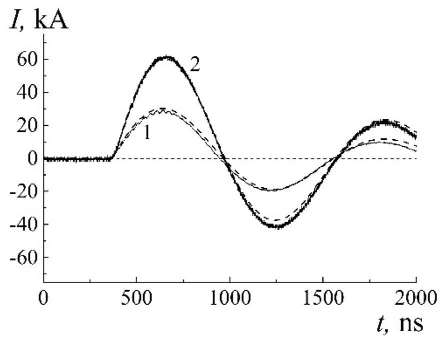

Figure 5. Waveforms of currents at the output of the transformer (1) and through the switch of one of the modules (2) for short circuit mode. The dashed lines show the calculated currents.

The amplitude of the short-circuit current at the transformer output for the charging voltage of 20 kV is ≈30 kA, while measured in the circuit of the switch discharge current of two capacitors, was two times higher and reached ≈60 kA.

As a result of measurement, the parameters of the simplified equivalent circuit in the form of the RLC-circuit have been determined as the transformer output: a capacity - 17.5 nF, an inductance - 2.03

μH, and the total series resistance 3.2 Ohms. The results of the test calculation using the developed equivalent circuit are shown in Figure 5 as a dotted line.

4.2. Resistive load mode

Two loads with a resistance of 20 and 40 Ohms were used to test the dielectric strength of the insulation for long aperiodic discharge mode. High-voltage liquid resistors were formed by filling the volume of the transition section, which was closed by a flange with a solution KCl.

Figure 6 shows the waveforms of the load current and the module switch current obtained for the load resistance of 20 Ohms and the primary charging voltage of 30 kV. The dashed lines show the currents calculated using the equivalent circuit.

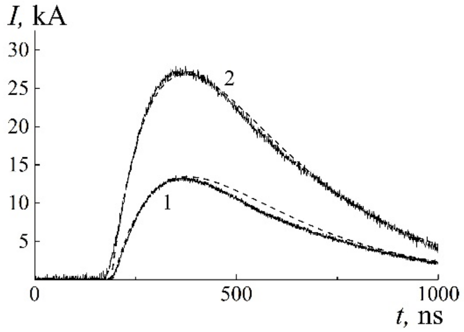

Figure 6. Waveforms of the load current at the output of transformer (1) and module switch current (2) for resistive load of 20 Ohm and charging voltage of 30 kV. The dashed lines show the calculated currents.

The results of measurements in this mode indicate the absence of breakdowns and parasitic leakages due to an insulation failure under increasing exposure to an electrically stressed state.

5. Conclusion

Now, the designed linear pulse transformer together with 10 module primary driving system is successfully used for the fast (≈350 ns) charging of a forming line of a nanosecond high current accelerator. The experience shows a high repeatability of the output pulses due to a stable synchronous operation of all 10 modules of the primary energy storage and a switching system. The modular design of the system, the limited voltage on its elements, low levels of an electromagnetic interference due to a closed design of the transformer and the modules with connecting coaxial cables, as well as the absence of a transformer oil and a related peripheral equipment ease up an installation operation.

The work was supported by the Russian Science Foundation (project 16-15-10355).

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