Repetitively Pulsed High-Voltage Generator Based on the Linear Transformer and SFL with Discrete LC-Elements for Accelerators of Powerful Ion Beams


Nuclear Physics Institute of National Research Tomsk Polytechnic University
2, building 4, Lenin ave., Tomsk, 634050, Russia
Phone/fax: +7 (3822) 417-962/423-934, E-mail: anatolyvp@tpu.ru
*University of California, Irvine, CA, USA
**Tri Star Alpha Energy, Inc., 19631 Pauling str., Foothill Ranch, CA 92610, USA

Abstract – The results of development and testing of the high-voltage pulse generator, designed for operation with the powerful ion diode as a load, (though other technological applications are possible) are presented. Technical parameters of the generator: voltage up to 280 kV, pulse duration is 600 ns, impedance is 12.4 Ohm, and operation frequency is 25 Hz in a burst of 5 pulses. The generator consists of the linear transformer (LTR) having 7 stages, each of which is a load of the single forming line (SFL) on discrete LC-elements. The SFL charging is realized by a resonance method by a two-stage scheme of the voltage rise consisting of the primary and intermediate energy storages. The SFL charging voltage is up to 80 kV, the stored energy is 770 J. The process of the generator operation is controlled in a wide range ~ 140–280 kV of the working voltages and is set by a general control unit.

1. Introduction

The development of pulsed technologies based on the low-energy (~100–300 keV) long-pulsed (~ 0.5–1 µs) powerful ion beams stimulates the development and creation of the energy-efficient frequency generators of accelerating voltage pulses of the specified range. Application of such beams in large-scale scientific experiments makes additional demands to the voltage pulse shape in combination with high energy intensity of the generator and the necessity of its parameters control in wide ranges.

One of the approaches to creation of such generators is based on application of LTR-technologies with a direct energy transfer from the capacitive storages to the load [1, 2]. The intermediate stage of the power compression in the form of SFL with discrete LC-elements was used in this development for the pulse shaping. The applied charging circuit provided high efficiency of the pulse transmission of energy to SFL ~ 94%. The generator, taking into account its energy intensity (~ 5.4 kJ) and average power (~ 135 kW), is distinguished by compact sizes: length – 335 cm, height – 235 cm, width – 69 cm. The transformer oil or gas (SF₆) is used in LTR or SFL as insulation, under the excessive pressure of ~ 1 atm. at voltages of ≤ 200 kV. The results of the generator testing on the active matched load using gas insulation are given below.

2. The generator structure

Operation principle. The external view and the electric circuit of the generator are shown in Figs. 1 and 2.

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*Fig. 1. External view of the generator*

*Fig. 2. Electric circuit of the generator*
Originally, the energy is accumulated in capacitors of the primary storage C1.1–C1.5, which are charged to the given voltage value (to 5 kV).

After the switch K1.1 actuates the energy transfers from the capacitor C1.1 through the autotransformer ATR1.1 with the transformation ratio 1:8 to capacity C2 of the intermediate storage, charging it to 40 kV for 970 µs.

The maximum currents in the primary and secondary windings of the autotransformer ATR1.1 are ~ 3.6 kA and ~ 0.44 kA, respectively. The protective circuit consisting of the diode D1 and resistor R1 (~ 0.8 Ohm) serves for the pulse energy dissipation, which did not proceed to the load due to actuation of the following switches to the voltage maximum or in case of a misfire and energy return to the primary storage.

When the voltage is close to maximum, the switch K2.1 of the intermediate storage actuates and seven single forming lines SFL3.1–SFL3.7 are charged to the voltage of 80 kV for ~ 22 µs through the autotransformer ATR2.1 with the transformation ratio 1:2 through the charging inductances L3.1–L3.7. The current in the primary circuit ATR2.1 at the voltage of 40 is 21.3 kA, and in the secondary one it is – 10.6 kA (charging current of all SFL). At this moment, the switches K3.1–K3.7 of SFL – gas three-electrode dischargers actuate from the general start unit (Fig. 2) on cable lines KL4.1–KL4.7, charged to the voltage equal to half of the SFL charging voltage. After the SFL switches’ actuation, the voltage of the opposite polarity with respect to the SFL charging voltage is applied to the primary turns of LTR stages. The secondary voltage inversion is achieved by a corresponding connection of the LTR windings. The voltage from the secondary turn of LTR is supplied to the independently executed load along the cable transmitting line (TL). The process is repeated with the frequency of 25 Hz with the actuation of the following capacitor C1.2 of the primary storage. The diodes D1.6–D1.10 provide decoupling of the discharge circuits.

The primary energy storage consists of the charging voltage source for 5 kV, five identical cells, each of which contains a storage capacitor (450 µF × 5 kV), voltage divider, switch-ignitron IRT-6 with the actuation unit, the diode, connected in series with ignitron, pulse autotransformer ATR1.1 (5–40 kV, Stangenese, USA) and protective circuit of D1 and R1. D1.6–D1.10 and D1 are assembled of two diodes D143-400-36 connected in series.

The intermediate energy storage involves the high-voltage pulse autotransformer ATR2.1 (40–80 kV, produced by Stangenese, USA) in a metal tank with the transformer oil, storage capacitor 6.72 µF × 100 kV, switch – thyatron TDI1-50k/45 with the actuation unit, input and output voltage dividers.

All the elements of the primary and intermediate energy storages are located in a separate unit with dimensions of 1.5 × 2 m², 1 m height.

**Single forming lines.** Seven identical SFL are performed on the lumped LC-elements by a standard staircase circuit. Each SFL consists of twelve identical LC cells and is connected to the primary LTR turns through the gas three-electrode discharger (Fig. 1). The capacities of the SFL cells consist of capacitors of 20 nF × 100 kV (General Atomics, USA) with the self-inductance of 20 nH. The SFL inductance is formed by a three-electrode stripline connecting the capacitors. The inductances of cells are identical – 75.6 nH, except for the output cell, where it is higher by a factor of 1.5. The SFL impedance equals 1.67 Ohm.

The gas three-electrode dischargers of SFL with the keep-alive corona discharge operate when filled with dry air to the pressure of 3 atm. The uniform voltage distribution on the discharger electrodes is set by the active divider R4.1, R4.2 (Fig. 3). The primary discharge gap is formed by the electrodes with the diameter of 32 mm, made of copper and tungsten alloy. The discharger gaps are identical and equal to 5.5 ± 0.1 mm. The insulators, dividing the discharger electrodes, are performed of plexiglass.

![Fig. 3. Actuation circuit of the SFL dischargers](image)

The whole construction is tied up by caprolon studs. The corona-forming tungsten electrode of ~ 1 mm diameter is located in the cavity of 10 mm diameter of the high-voltage discharger electrode. The corona current occurring at the SFL charging is set by resistor of 100 kOhm and was chosen on condition of preservation of a linear dependence of the discharger breakdown voltage against the air pressure in a working range. The general actuation unit (fig. 3) consisting of thyatron TPI1-10k/50 and seven pieces of the coaxial cable KV1-120 of identical length of 10 meters is used for connection of SFL dischargers. After thyatron switching, the start voltage pulse of negative polarity proceeds to the middle electrode of the discharger. Such implementation of the dischargers and actuation system enabled to obtain stable operation with low jitter in the breakdown voltage in a wide pressure range.

The generator construction is shown in Fig. 4. SFL are performed in the form of sections (Fig. 5) placed in separate cases on the carts and matched with the LTR stages. The top cover of each section contains coaxial electrical connections and gas-service pipes required for operation with SFL and LTR. The coaxial cables KV1-120 are used for connection to the intermediate storage. There are manometers, electromag-
ngetic valves and drain system on the dock sides of the cases for filling and replacement of the air in SFL dischargers after the burst of pulses.

Fig. 4. The generator structure: 1 – SFL; 2 – line of capacitors; 3 – SFL capacitor; 4 – high-voltage cable; 5 – ferromagnetic core of LTR; 6 – SFL discharger; 7 – cart

LTR consists of seven identical stages. The stage represents a coaxial construction with the primary turn covering the toroidal ferromagnetic core. The stage core is located in the nipple of stainless steel with the diameter of 200 mm and consists of nine separate rings made of metglass 30KSR with dimensions of 160 × 60 × 30 mm. The secondary LTR turn is a high-voltage cable KVI-350, which is simultaneously a transmitting line 2 meters long for the voltage supply from the generator to the load. The cable (TL) has a combined insulation of polytetrafluorethylene belts protected by a layer of solid polymer, and trailers for connection. The cable operating voltage is up to 350 kV, wave resistance is 20 Ohm, external diameter is 39.5 mm.

The transfer of LTR cores to the initial magnetic state is realized at the SFL charging (Fig. 2). Simultaneously, the demagnetizing unit providing dc current of 25 A and its division to seven primary LTR turns is used for the same purposes.

3. Experimental results

The SFL and generator testing was conducted generally on the matched loads at the charging voltage of the primary storage of 3.5 kV. In the generator testing there was used the active load with the water solution of salt KCl, with the volume sufficient for the energy dissipation of the burst of 5 pulses. The equivalent load in these measurements was located in the tank with the transformer oil. When testing the generator, the load was adjusted so that to obtain the matched operation mode, which corresponded to the impedance of 12.4 Ohm.

The voltage pulse shape at the primary capacitive storage discharge and on the primary winding of the autotransformer ATR1.1 is shown in Fig. 6. Fig. 7 shows the SFL charging voltage. Fig. 9 shows the pulse shape on the matched load of 1.67 Ohm of one SFL. The efficiency factor of the generator

\[ \eta = \eta_1 \eta_2 \approx 0.91 \]

is determined at these parameters primarily by the transmission efficiency by current from the primary LTR turn to the load: \( \eta_1 = I_G/(I_G + I_M) \), where \( I_G \) is the generator current, \( I_M \) is the LTR magnetization current. The transmission coefficient by voltage \( \eta_2 \) takes into account voltage losses in the discharge circuit connected with the losses in SFL switches. The energy transfer efficiency from the primary storage to the load was 85.5%.

Fig. 6. Typical oscillograms of voltage during the storage operation. The upper beam shows the voltage pulse shape on the primary winding of ATR1.1 during the intermediate storage charging of 1.4 kV/div. The lower beam shows the discharge voltage of the primary storage, 1.9 kV/div. The time scale – 250 µs/div
Fig. 7. The voltage pulse shape during the SFL charging. The time scale is 10 µs/div

Fig. 8. Shapes of the output voltage and current pulses during the generator operation on the matched load (the charging voltage of the primary storage is – 3.5 kV). The upper beam is the current in the end of the transmitting line (9 kA), the top second is the load voltage (160 kV/div), the third one is the current in the beginning of the transmitting line (8 kA/div). The time scale is 250 ns/div

Fig. 9. The voltage pulse shape with SFL on the matched load of 1.67 Ohm, 100 ns/div, 4 kV/div

4. Conclusion

A new repetitively-pulsed generator based on LTR and SFL with discrete LC elements for the formation of ~ 600 ns duration pulse was suggested. The generator with the impedance of 12.4 Ohm is meant for operation in a wide range of voltages (140–220 kV) with an independently implemented load. Testing of the generator with the gas insulation (insulating gas) at the electric field intensities of ~1 kV/cm along the generator was performed. The efficiency of the stored energy transfer to the matched load was 85.5%.

References
