Source of the accelerating voltage in the high-voltage tandem accelerator for neutron capture therapy

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As it was specified in [1], the source of an accelerating voltage of an accelerator - tandem should have an output voltage equal to half a value of proton energy and depending on the generator operation run the voltage value should be equal to either 0.94 MV or 1.25 MV.

The rectifier load current is equal to the double value of the proton beam current whose value is determined assuming the reasonable time proceeding from requirements of reasonable time of exposure (about ten minutes) for obtaining the required therapeutic doze (about 20 Gy). In the neutron therapy facility the value 5 – 25 mA is considered us maximum, i.e. the maximal current consumed from a source is equal 50 мA.

To such requirements satisfies the high-voltage sectioned rectifier for ELV-4 industrial accelerator with maximal voltage 1.5 MV [2]. Besides this source of a high voltage provides necessary parameters as the power and voltage, its attractive feature is its high reliability confirmed by the long-term operation of many tens of ELV-type accelerators using similar HV sources at the industrial plants and research centers.

For the first stage – a stage of design and physical start of a tandem-accelerator reasonably to be guided by the minimal current of a proton beam.

Design of the high-voltage rectifier.

The source of high voltage used in ELV type electron accelerators and in some other types of ion accelerators is a cascade generator with an inductive link and a parallel feeding of cascades, which one is planned to be used in the project of BNCT.

Inside the pressure vessel filled with insulating gas (SF_6) there are: a primary winding, a column of rectifying sections, magnetic guides of the return flow (ground and cylindrical). The primary winding has 32 terns water-cooled copper pipe. It generates a longitudinal alternate magnetic field with the feeding mains frequency of 400 – 1000 Hz. The primary winding turns are isolated from the high voltage gap by electrostatic screen made of a thin sheet of stainless steel.

In comparison with “conventional” transformers this design is distinguished by the absence of the central magnetic guide. Outside the primary winding is “wrapped” by the magnetic guide. Two additional magnetic guides are placed on the bottom of a vessel and over a high-voltage electrode. These magnetic guides eliminate heating a tank by eddy currents.

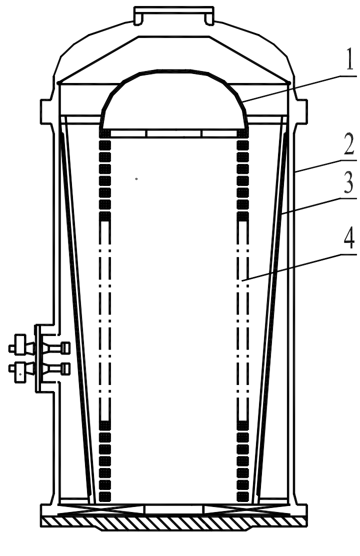

Fig. 1. High-voltage rectifier:
1. *High-voltage electrode;*
2. *Pressure vessel;*
3. *Primary winding;*
4. *Rectifying sections.*

The column of the high-voltage rectifier consists 37 rectifying sections connected in series. Each section is a coil of a secondary winding and a double voltage circuit based rectifier. The coil contains 3000 turns separated by polymer-mica isolation. The maximal voltage of the coil is 20 kV. Thus, the section output voltage can reach the value of 40 kV. The quantity consistently connected sections defines the maximum output voltage of the high-voltage rectifier. Operating voltage of the coil in the project does not exceed 17 kV, i.e. the voltage of section is 34 kV. For rectifying the alternate voltage CDL-0.4-800 diodes with a forward current up to 0.4 amperes and the maximal inverse voltage of 80 kV are used. The inverse voltage of diodes does not exceed 34 kV during the rectifier operation. K15-10-type capacitors are used for filtering and simultaneously for protection elements of the high-voltage rectifier (coils, diodes) from the overloads arising at breakdowns of vacuum or gas isolation.

The accelerator primary winding is power supplied with an alternate voltage of 400 – 1000 Hz from the converter of frequency. Now on the accelerator the electric motor converter of frequency with frequency of 400 Hz is installed but we plan to change its on IGBT frequency converter with frequency of 1000 Hz. Electromechanical converters involve with the cheapness, simplicity and reliability. They possess acceptable efficiency (65 - 80 % depending on power). A feeding from static converters of frequency based on IGBT transistors is possible too. Efficiency of static converters makes 85-92 %. The opportunity to increase frequency up to 1000 Hz reduces pulsations of the accelerating voltage more than twice.

In figure 2 the circuit diagram of HV rectifier is shown.

Requirements to stability of HV

For operation with the near-threshold mode, where the proton energy ranges within 1.883 – 1.890 MeV the required stability is 10^{-3}. For another operation mode with the energy of 2.5 MeV from the viewpoint of generation of proton high stability of HV is not necessary.

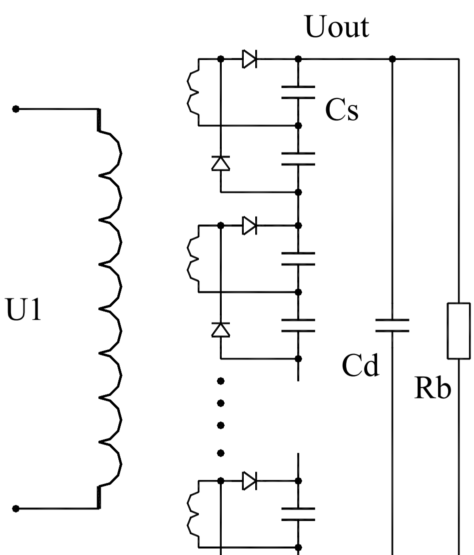

Fig. 2. Cs – capacitors of sections (20 nF), Cd - stray capacitance (200 pF), Rb – resistance of load.

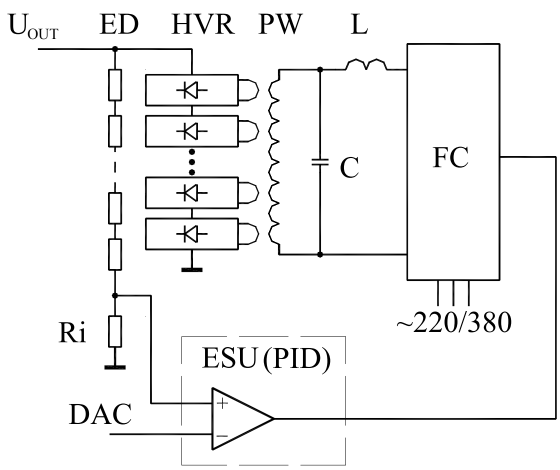

Fig. 3. Function diagram of the system for stabilizing the output voltage of the cascade generator.

Operation principle of energy stabilizing system of ELV-type accelerator.

By an operation principle this stabilization system belongs to continuous a static systems of regulation with feedback. Similar systems allow simple enough ways to provide high accuracy, a wide range of regulation, high parameters of quality of transients.

In figure 3 the function diagram of system is shown.

The regulation contour includes the following feedback sections:

1. The object of regulation including of cascade generator HVR and primary winding PW;
2. The measuring device ED;
3. The stabilizer unit (ESU) with PID-regulator;
4. The frequency converter FC;
5. The impedance matching circuit C, L.

Let's consider briefly all units which ones are included in a loop of a feedback.

The measuring device (ED)

In system of stabilization achievable accuracy is determined by accuracy of measurement of a high voltage.

As the measuring device ELV type accelerators use the resistive divider of a voltage. The resistive divider is located inside high-voltage column. The using of a resistive divider of a voltage is most simple method for measurement of a high voltage. Unfortunately, the domestic industry does not offer a wide choice of precise high-voltage resistors. Micro-wire precise resistors such as C5-23 or C5-24 types possess the big size and require special protective action for protection against high-voltage breakdowns as a result they badly match with the high-voltage rectifier design. The most suitable (in its design) of C3-14 type has an accuracy of resistance $\pm 10\,\%$ and temperature factor of resistance from -2×10^{-3} up to $+1 \times 10^{-3}$ 1/°C. That is obviously does not satisfy required accuracy of stability. However, long-term supervision of variations with time of accelerators parameters equipped with energy dividers based on such resistors and calibration of these dividers with the help of precision dividers show that accuracy characteristics of these dividers can clearly be placed within 5 % scale. Such accuracy is sufficient for the majority of technological applications of ELV type accelerators but may be not enough for BNCT project. We shall note, that here we mean an absolute accuracy. The relative accuracy is a few times higher and with no account for temperature dependence lays within the range of 0.5 – 1 %.

The passband of the resistive divider placed inside of a high-voltage column is limited by parasitic capacitor currents from screens of coils of high-voltage sections and makes shares of hertz.

For increase of stability accuracy it is possible to use resistors of firm CADDOCK ELECTRONICS (USA) such as MG735 with resistance of 100 Mohm, accuracy of ± 0.1 % and temperature factor of 80 ppm/C° Resistors of TG950 type have same accuracy but temperature factor of 25 ppm/C°. The divider based on these resistors will provide accuracy of measurement of a high voltage at a level 10^{-3}. We plan to make a divider from these resistors.

Stabilization unit (ESU)

The stabilization unit compares an input reference analog signal from DAC and an output signal of a high voltage divider, provides amplification of an error signal, forms the gain-frequency characteristic of a contour of the stabilizer of energy. The error signal amplifier is based on the circuit of the PID-regulator. Proportional, integrating, differentiating amplifying circuits are used the separate precision operational amplifiers. By adjustment of time constants of integrating and differentiating circuits and amplification factor of a proportional circuit of the stabilizer, it is possible to provide easily enough stability of a regulator, at the same time keeping high parameters of quality of regulation. The unit is made using modern element base. Used precision operational amplifiers are possible to provide accuracy not worse, than 10^{-4}.

The frequency converter

The frequency converter can be either electro-machine type converter or static converter based on IGBT bridge circuit. In any case the voltage of an industrial 3-phase AC will be converted to a 1-phase AC voltage of the increased frequency.

The electro-machine converter of frequency combines the asynchronous electric motor and the inductor type of AC generator.

The transistor converter includes the rectifier of mains voltage and the transistor inverter constructed under the classical circuit of the bridge inverter of a voltage.

The impedance matching circuit LC will match output impedance of the frequency converter with input impedance of the primary winding of HV rectifier. We shall note, that in case of using of the electro-machine type of converter instead of inductance it is possible to use capacity.

Ripples of an output HV voltage.

Analytically rippling of output voltage of the high-voltage rectifier can be calculated by a method shown in [1]. However it is easier to calculate amplitude of a pulsation by computer modelling. On fig. 4 is shown the circuit, which was used for modelling. The substantiation of applicability of the model shown on fig. 4 is beyond the given work.

On fig. 5 results of modelling are shown.

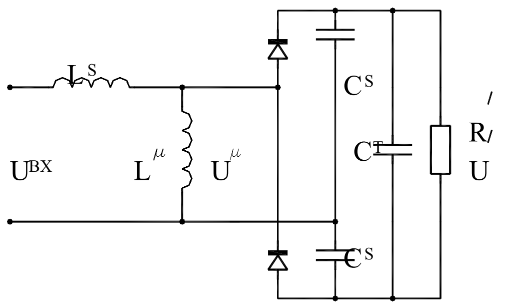

Fig. 4. L_S –leakage inductance of the high-voltage transformer; L_μ – magnetizing inductance of the high-voltage transformer; C_S – capacity of all sections, re-counted to the magnetizing inductance of the HV transformer; C_T – capacity of HV terminal, re-counted to the magnetizing inductance of the HV transformer; $R^{/}$ - resistance of load, re-counted to the magnetizing inductance of the HV transformer.

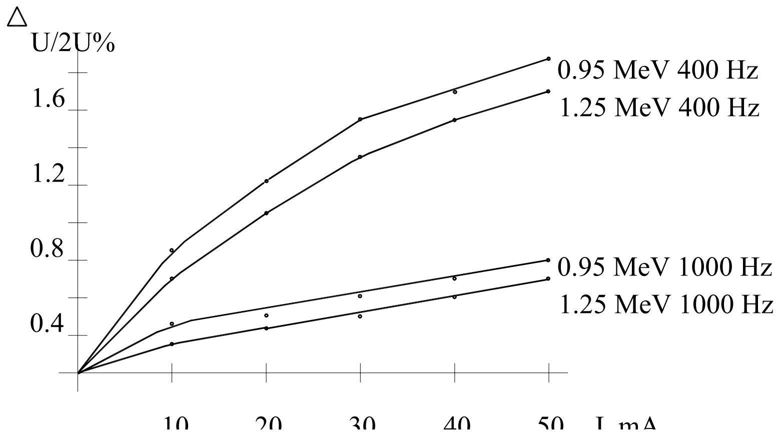

Fig. 5. Ripples of accelerating voltage.

From the graphics follows, that for power supply frequency of 1000 Hz and for load current less than 10 mA at a stage of physical start of tandem accelerator it is possible to operate without system of active damping of ripples.

For active damping of ripples there is capacitor ("liner") between ground and HV terminal. If the "liner" connected to the controlled AC generator with frequency of ripples and antiphase of ripples it means ripples will be damping. There is capacitor probe for ripple value measurement which one is located above the "liner". The arrangement of the "liner" and the capacitor probe is shown on fig. 6.

Fig. 5. A constructive arrangement of the "liner" for active damping of ripples.

The capacitance value between "liner" and HV terminals makes 100 pF approximately. Taking into account, that the total capacitance of a HV rectifier column and the tandem accelerator makes 340 pF for load current of 10 mA the AC voltage of "liner" should has value about 10 kV with frequency of 2000 Hz for full ripple suppression.

In summary we shall note, that final requirements to stability of an accelerating voltage and to allowable ripple value can be formulated only after real operation with proton and neutron beams.

References

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