

DIRECT METHODS OF MEASURING AND STABILIZATION OF DC ACCELERATING VOLTAGE IN ELV ACCELERATORS DESIGNED ON THE BASIS OF CASCADE GENERATORS

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Abstract

The methods of measuring of DC accelerating voltage within the range of voltages of up to 3 million volts are described. The problems arising at using the voltage resistor dividers are revised. The method of measurement by means of rotor voltmeter being used in ELV type accelerator is discussed. Estimated precisions of accessible measurements are shown. The construction of stabilization and regulation systems in a wide range of accelerated particles energy is studied.

INTRODUCTION

DC voltage sources are widely used in modern science and technology. They are used in electrostatic generators, industrial accelerators and other facilities. In the range of voltages of several hundred kilovolts up to million volts cascade generators are commonly used. Recently, output power of such sources covers the range from several kilowatts up to hundred kilowatts. Thus, for example, industrial electron accelerators of direct action with extracted beam power up to 0.5 MW are produced and designed. In the range of voltages from 0.5 MV and more high-voltage rectifier gas insulation is commonly used. The design of such rectifier is cylinder sectioned high-voltage column placed into high pressure vessel filled with isolating gas (SF₆). Usually, the column is completed by spherical high-voltage electrode forming uniform electric field between high-voltage rectifier output and grounded tank body. In industrial electron accelerators the accelerator tube is commonly built inside the column of high-voltage rectifier. Such assembly is used for ELV series accelerators produced by Budker Institute of Nuclear Physics (Novosibirsk city) and for "Electron" accelerators manufactured by NIIFA (St. Petersburg city), and others. Any high-voltage source should sustain output voltage accuracy, defined by specific use of a source. In this way, if for the source used in industrial accelerator for radiation treatment of cable insulation the accuracy of several percents is allowed, the high-voltage sources of facilities meant for electron cooling of proton and ion beams requires stabilization accuracy $10^{-3} \dots 10^{-4}$. The same accuracy of accelerated particles energy stabilization is approximately required for design of the complex for cancer treatment by boron-neutron capture therapy. In any case, we should solve the problem of measuring and stabilization of high voltage.

Let us stop at singularity of measuring system and stabilization of accelerating voltage taking as an example industrial ELV series accelerator. Operation principle of

high-voltage rectifier is cascade generator with inductive coupling and parallel feeding of cascades [1].

METHODS OF MEASURING

Accelerator performance criteria, its maximum power and reliability depend directly on quality of energy and beam current stabilization systems. For most radiation-technological processes recently used, the required and sufficient accuracy of those parameters is 3...5%.

In energy stabilization system the accessible accuracy is determined by precision of measurements of high voltage. The simplest method of energy measurement is the use of resistive ratio device.

Unfortunately, domestic industry does not propose a wide choice of precise high-voltage resistors (fly-wire precision resistors such as C5-23 and C5-24 are too big and require special safeguarding methods preventing high-voltage breakdowns, and, as a result, fit into cascade generator design poorly). It is experimentally found, that in powerful (hundred kilowatt) accelerators the divider resistance depends on radiation level, the source of which is accelerator. The most suitable resistor of C3-14 type has resistance tolerance $\pm 10\%$, temperature coefficient of resistance from $-2 \cdot 10^{-3}$ up to $+1 \cdot 10^{-3}$ $1/^\circ\text{C}$ [2], it obviously does not satisfy the required accuracy. However, long-term observations of drift parameters of ELV accelerators equipped by energy dividers of such type of resistors and calibration of these dividers by means of precision dividers show that accuracy characteristics of those dividers are knowingly in the range of 5% scale. Such a precision is enough for most technological applications of ELV accelerators. Let us note, that here the matter is absolute precision. Relative precision is several times higher and, without taking into account temperature dependence, is in the range 0,5–1 %.

The shortcomings mentioned above are specially solved by means of the change of voltage divider by rotary voltmeter.

The operation principle of rotary voltmeter is based on the effect of charges induction (division) at metal surfaces placed into electric field [3].

It is evident, that in insulating gas gap between high-voltage electrode and grounded accelerator tank the electric field is formed. E field intensity in each gap point is proportional to applied voltage value.

The rotary voltmeter was designed as a fixed disc and rotating grounded metal propeller.

Fixed disc and rotating grounded metal propeller are installed in alignment perpendicularly to force line of electric field E. Rotating disc either opens or shields the

plates from electric field action. During certain time when the plate is completely opened, a certain charge Q_V is induced on it. As the plate is closed by rotating propeller, the value of this charge will be linearly decreased up to zero. If the plates are to be connected with "earth" through metering circuits, alternating current the value of which would be determined by charge changes into time unit will arise in those circuits.

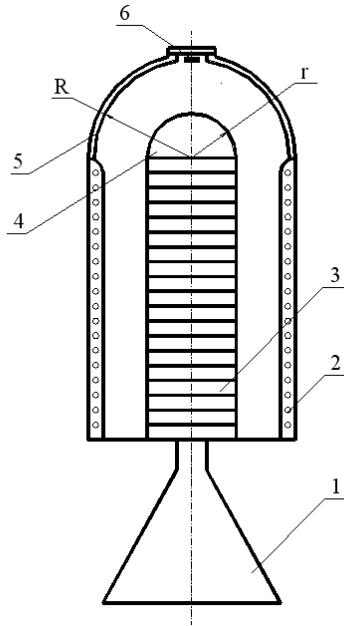


Figure 1: Design of high-voltage rectifier of ELV accelerator. 1 – Extraction device. 2 – Primary winding. 3 – Column of high-voltage rectifier. 4 – High-voltage electrode. 5 – Steel accelerator vessel. 6 – Possible place of rotary voltmeter location.

. Let us estimate output current of described voltmeter.

In present construction the external diameter of fixed disc is 100 mm, the internal diameter is 45 mm. For ELV-8 accelerator the radius of high-voltage electrode r is 0.38 meter, the radius of internal surface of the tank R is 0.75 meter.

It can be considered, that fixed disc of rotary voltmeter is assembled at internal surface of sphere, the radius of which is equal to R . This sphere surrounds spherical high-voltage electrode by radius r .

To estimate maximum value of the charge at the plate we use the formula for spherical capacitor capacity.

$$C = \frac{4\pi\epsilon\epsilon_0 rR}{R-r} \quad (1)$$

The value of capacitor charge will be

$$Q = CU,$$

where: U – measured high voltage, and C – capacity measured by formula 1.

Surface charge density δ will be equal to

$$\delta = \frac{CU}{S_R},$$

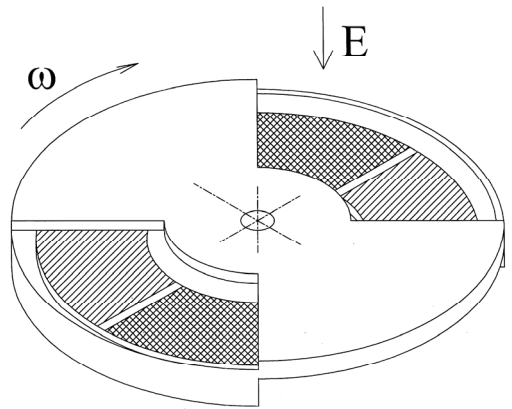


Figure 2: The rotary voltmeter.

where: S_R – sphere surface area of radius R .

Hereof – maximum charge induced at the voltmeter plate will be equal to

$$Q_V = \delta S_V,$$

where: S_V - voltmeter plate area.

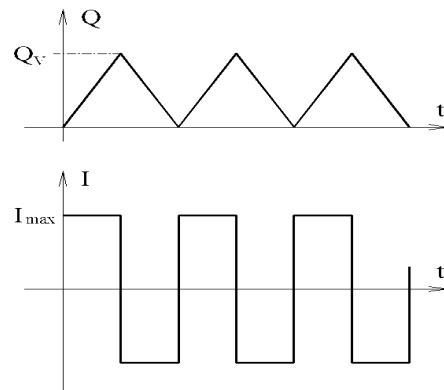


Figure 3.

Plate output current is determined by the change of the charge into time unit. Current waveform is a periodic rectangular signal (see Figure 3) and its peak value will be equal to

$$I_{\max} = \frac{2Q_V}{T}$$

Here, period T is determined by angle speed of propeller rotation.

Let us note that the value of output voltmeter voltage is determined by parameters of metering circuit. At pure active behavior of metering circuit $U_{\max} = I_{\max} R$ and voltage waveform is agreed with current waveform. In this case the instability of motor rotation speed enters in voltmeter precision in direct proportion. If the behavior of metering circuit is pure capacitive, than the waveform of measured voltage will be triangular, and its amplitude won't be dependent on rotation speed and will be determined by metering capacity and charge Q_V only.

However, practically it is difficult to realize pure capacitive behavior of metering circuit. Moreover, possible corona discharges from voltmeter plates will charge input capacitance, it is not permissible.

At resistance-capacitance metering circuit the dependence of average rectified voltage on rotation period is:

$$\bar{U} = I_{\max} R \left(1 + \frac{2Rc}{T} \ln \left(\frac{e^{-T/Rc} + 1}{2} \right) \right),$$

where R and C – resistance and metering circuit capacity. Taking into account the dependence of rotary voltmeter current on the period and integral summation of the signal of both plates:

$$\bar{U} = \frac{2QR}{T} \left(1 + \frac{2Rc}{T} \ln \left(\frac{e^{-T/Rc} + 1}{2} \right) \right).$$

Thus, to get the 1% accuracy of high voltage measuring by means of rotary voltmeter it is enough to achieve instability of motor rotation speed of $\pm 20\%$.

METHODS OF STABILIZATION

In Figures 4 and 5 the functional circuits of energy stabilization systems at accelerator power supply from transistor frequency converter are shown. Figure 4 presents the measuring of high voltage by means of resistive divider, Figure 5 illustrates the measuring of high voltage by rotary voltmeter.

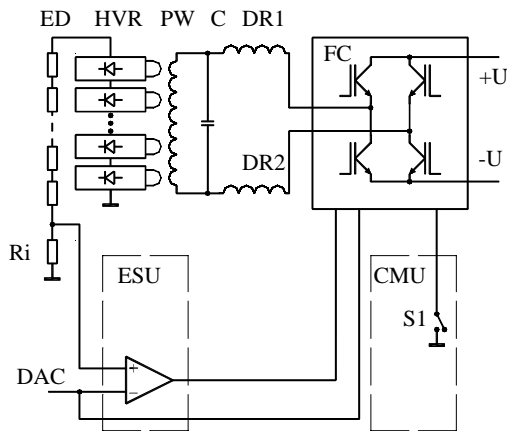


Figure 4.

Feedback circuit in high voltage stabilization mode consists of measuring element (divider or rotary voltmeter), energy stabilization unit (ESU), transistor frequency converter control circuit, inductance-capacitance circuit DR1, DR2, C, high-voltage rectifier. Stabilization unit compares input reference analog signal DAC with output signal of high-voltage meter, provides error signal amplification, forms amplitude-frequency

characteristic of energy stabilizer contour. Error-signal amplifier is designed in accordance with PID control circuit. Proportional link, integrator and differentiating element are made on separate precision operational amplifiers. Changing the time constants of integrator and differentiating element and amplification factor of proportional link at stabilizer adjustment it is possible to provide controller stability enough easy and, at the same time, to save high exponents of regulation quality. The unit is designed on the basis of modern elements. The used precision operational amplifiers can provide the accuracy no worse than 10^{-4} .

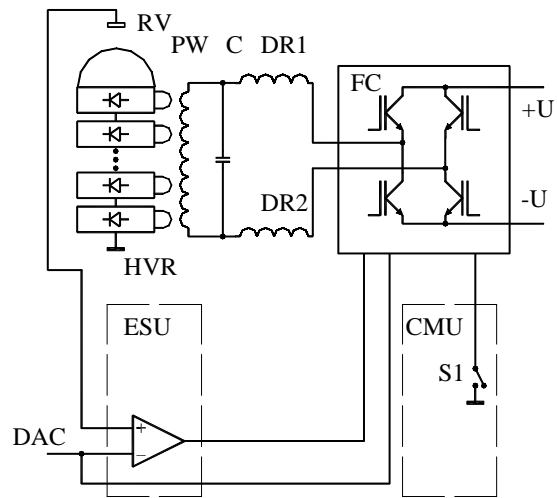


Figure 5.

Knowing from our experience we may state that for high-voltage rectifiers designed on the basis of cascade generators and placed in a high pressure tank, for accuracies of about several percents, measuring dividers designed on metal-film resistors of common application can be successfully used. For accuracies of the range of $10^{-3} \dots 10^{-4}$ precision metal-film resistors can be used. If rectifier operates for accelerator creating high radiation level inside the tank, for accuracies of about several percents the mentioned rotary voltmeter may be successfully used. For more high accuracies it is necessary to use rotary voltmeter of compensation type or indirect measuring methods, the description of which goes beyond the scope of present report.

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