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HV DC INJECTORS FOR LARGE HEAVY-ION ACCELERATORS

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Summary

To meet the particular requirements of heavy-ion injection into large accelerators, a new model dc power supply was developed and built. A pair of 320 kV dc injector power supplies was installed in 1973 at the "Gesellschaft fuer Schwerionenforschung" (GSI) near Darmstadt, Germany. These power supplies deliver an electronically regulated pre-accelerating voltage for both dc and pulsed modes of operation. An improved bouncer system is utilized to keep the output voltage constant at pulsed operation. Furthermore, a new analog-digital voltage-regulating device is incorporated into the control facility. The 320 kV injector system has been in operation for more than a year, and performance has been completely satisfactory.

Introduction

Whereas the basic design considerations of injector power supplies have been previously described in these transactions[1], it is the purpose of this paper to discuss some details of voltage control and regulation with regard to the specifications for the new 320 kV power supplies. The main characteristics are given in Table I.

TABLE I

Maximum Operating Voltage	320 kV
Maximum Current, Continuous or Pulsed	40 mA
Pulse Lengths	1 ... 20 ms
Repetition Rate	50 Hz
Stability at Pulsed Load	±15 V
Response Time of the Regulating System	50 μs
Ripple Voltage at Maximum Output Ratings	15 Vpp
Long-Term Drift	5 V/h

The extremely high stability required by the specifications, as well as the demand to adapt control of the accelerating voltage to a centralized remote-control facility, led to the development of a new analog-digital regulating system. Although the original specifications merely called for a reference source that could be programmed from a computer, it was decided to apply the digital techniques, not only to the reference voltage source, but also to the closed-loop regulating system, thus taking advantage of the digital information provided by the 6-digit digital voltmeter (DVM) that indicates the accelerating voltage. The combination of analog and digital regulation resulted in a hybrid regulating system that also meets the requirement for fast correction of errors introduced by the pulsed load.

As reported by many authors, it is essential to keep the internal impedance of the complete power supply system as high as possible in order to avoid damage to the electrodes of high-gradient accelerating tubes in case of vacuum breakdowns.[2] For that reason, most pre-injector power supplies are powered from medium-frequency sources operating at frequencies in the kHz range. This permits minimizing the charging capacities of the voltage-multiplying circuit without losing the low ripple-voltage characteristics. However, to keep the accelerating voltage constant, not only at static operation, but also during the beam pulse period, additional filtering impedance must be placed in parallel to the accelerating tube. This impedance generally consists of a capacitance with a resistor inserted in series and determines the voltage drop as a function of the current and time:

$$V = I\left(R + \frac{t}{C}\right) \qquad (1)$$

This formula indicates that the voltage wave shape is composed of an initial drop followed by a linearly falling potential. As the impedance of the series RC network across the accelerating tube should never be as low as is required to achieve the specified voltage stability, the purpose of the bouncer is to supply a voltage that compensates for the voltage drop given in Equation (1).

Analog-Digital Regulation

The difference between conventional analog and digital regulation is best understood by comparing Figures 1 and 2.

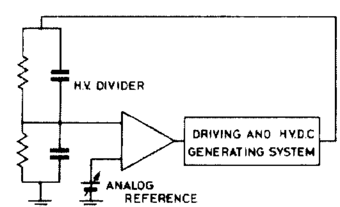

Fig. 1. Analog Regulating System

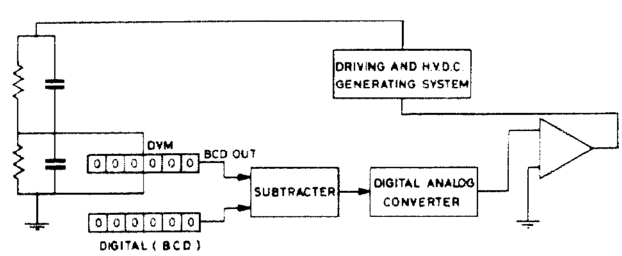

Fig. 2. Digital Regulating System

Figure 1 shows the basic analog circuit where the output voltage is determined by a highly stabilized analog reference source. A detailed discussion of analog voltage regulation was given in a paper presented at the 1967 Particle Accelerator Conference.[3] In the circuit in Figure 2, the analog reference voltage is replaced by a set of decade switches that supply a digital output in the BCD 1-2-4-8 code. The accelerating voltage is measured at the low-voltage tap of the HV divider by a digital voltmeter (DVM) with BCD output. Both the BCD output of the DVM and the BCD signals generated by the decade switches are applied to the inputs of a BCD subtracter that calculates the difference between the digital input signals. Consequently, the output of the subtracter represents the error signal of the closed-loop regulating system. A digital-to-analog converter is utilized to accommodate the error signal to the error-sensing amplifier. From that point, the system operates like a common analog feedback loop.

The sample rate of the DVM is of primary importance for dynamic behavior of the pure digital system. To achieve a stability of the output voltage that corresponds to the last digit of the DVM, the response time of the high-voltage generating system must be limited so that, during one sample period, the DVM will not read voltage changes higher than given by the last digit. As an example, let us consider the characteristics of a type of 6-digit DVM (HP 3460 B) manufactured by Hewlett-Packard. The last digit corresponds to 1 V at the top of the HV divider. The maximum reading rate is as high as 15 samples per second. These figures result in a very slow voltage rise of 15 V/s.

To overcome these effects and to take advantage of both the accuracy of digital regulation and the fast response time of analog regulation, a hybrid system (Figure 3) was developed.

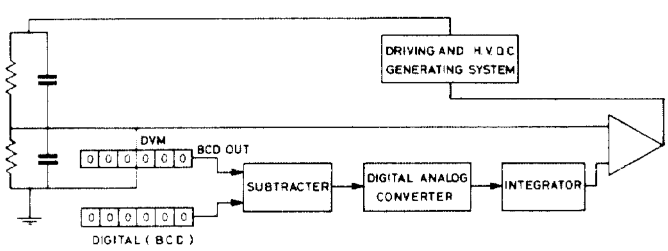

Fig. 3. Digital-Analog Regulating System

In steady-state operation, the output of the integrator can be considered as an analog reference voltage. This voltage remains constant as long as the BCD output of the DVM and the digital reference are of the same magnitude. The digital-to-analog converter is a special logic circuit that can supply three different dc voltage levels, each with a positive or negative sign. Depending on whether the difference between the output voltage and the reference input is higher than 1 V, 10 V, or 100 V, the output of the digital-to-analog converter supplies a 0.1 V, 1 V, or 10 V dc signal to the input of the integrator. With this method, it is possible to control the speed of the integrator that determines the rise time of the accelerating voltage. This kind of voltage regulation results in a DVM display that remains constant within one digit over any period of time. However, the actual long- and short-term fluctuations of the output voltage are determined by the accuracy of both the HV divider and the DVM.

Improved Bouncer System

In the simplified circuit shown in Figure 4, the bouncer is represented by two high-voltage electron tubes connected in a "series push-pull" arrangement.[4] In the closed-loop regulating system, particular attention must be given to the band widths of all links of the feedback network. The performance of the compensated HV divider was previously discussed in detail by G. Reinhold and R. Minkner.[5] The necessary band widths of the dc amplifier stages are easily achieved by the application of modern operational amplifiers with high sensitivities and unity-gain frequencies as high as 10 MHz. A typical amplifier that meets these requirements is the Philbrick-Nexus Type 1030.

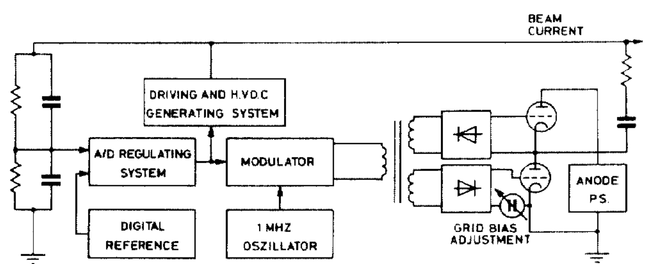

Fig. 4. Basic Circuit of the New Closed-Loop Regulating System

The performance of the fast regulating system is determined primarily by the time constants of the final stage. The frequency response of the bouncer is defined as:

$$g = \frac{K}{(1+j\omega\mu R_{gk}C_{pg})\ (1+j\omega R_p C_s)} \qquad (2)$$

K : low-frequency open-loop gain

μ : amplification factor of the high-voltage triodes

C_{pg} : plate-grid capacitance

R_{gk} : resistance between grid and cathode

R_p : plate resistance

C_s : stray capacitance between bouncer output and ground

Examination of Equation (2) shows that the band width of the bouncer results mainly from the first term of the denominator. As μ, C_{pg}, and R_p are characteristics of the electron tubes, the dynamic behavior can only be influenced by proper choice of the resistance R_{gk}. It must be noted, however, that this resistance loads the grid driving source. Whereas the first electronic bouncer systems operated with ac-coupled grid drive and high grid-cathode resistance, the new improved model includes a powerful 1 MHz carrier-frequency system that allows use of a low resistance between grid and cathode of both the upper and the lower triode. The output of the modulator is coupled to the grid potentials by an insulating transformer. Special high-frequency rectifier diodes are used to rectify the 1 MHz voltages. Further significant improvement of the bouncer system is achieved by an additional regulating loop that feeds the output of the bouncer back to the dc amplifier. This auxiliary feedback loop is, furthermore, used to stabilize the operating point of the bouncer.

Considering the improved performance of the fast regulating system, the criteria with regard to the accelerating tube mentioned in the introduction must be re-examined. As a matter of fact, it has been found in many accelerator laboratories that a bouncer system with a high-gain band-width product equals a low impedance across the tube. By applying feedback-control theory, it can be shown that the impedance (Z) between the bouncer and the output of the main power supply must be replaced with an equivalent impedance (Z_{eq}), in accordance with:

$$Z_{eq} = \frac{Z}{g} \tag{3}$$

where g denotes the complex open-loop gain.

In order to overcome this effect, Th. J. M. Sluyters, et al[2] have partly replaced closed-loop regulation with a pre-programmed open-loop system that responds only to the ion-source trigger signal and not to the microdischarges appearing randomly inside the tube.

Test Results

An external load circuit, consisting of a high-voltage triode and a series resistor, was installed to demonstrate the performance of the new bouncer system at pulsed current. To achieve the fast current rise necessary to simulate the pulsed-beam operation, a mercury-wetted chopper relay operating at 50 Hz was utilized to drive the grid of the high-voltage triode. Figure 5 shows the oscilloscope trace of the accelerating voltage for a positive load change.

The waveform of the bouncer voltage (Figure 6) is in accordance with the formula given in Equation (1) and is determined by the elements of the series RC network:

$$R = 100\ k\Omega$$

$$C = 10\ nF$$

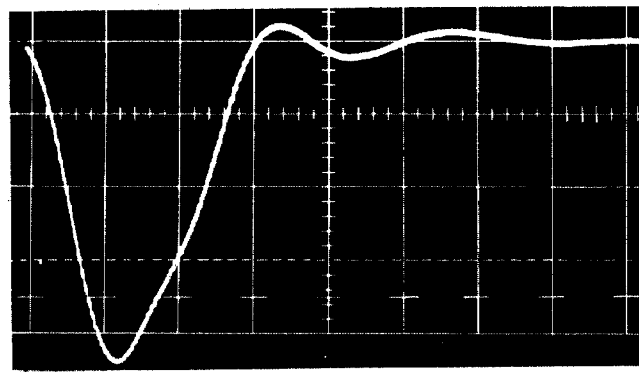

Fig. 5. Transient Response of Output Voltage Against a Positive Current Step 0 ... 40 mA. Vertical: 20 V/div. Horizontal: 20 μs/div.

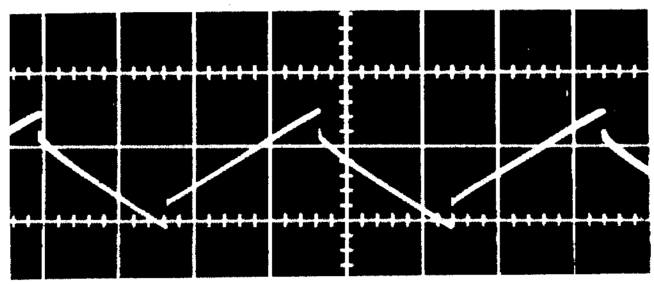

Fig. 6. Bouncer Voltage at 40 mA Pulse Current, 50 Hz Repetition Rate, and 50% Duty Cycle. Vertical: 10 kv/div. Horizontal: 5 ms/div.

The oscillographic record in Figure 7 shows the ripple voltage at a continuous load current of 40 mA:

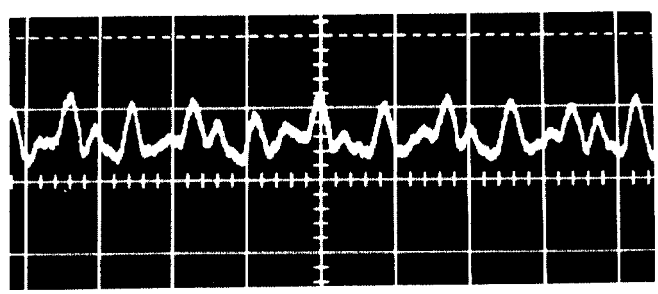

Fig. 7. Ripple Voltage. Vertical: 5 V/div. Horizontal: 100 μs/div.

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