FUTURE HIGH VOLTAGE DC POWER SUPPLIES OF THE SHIELDED DESIGN

G. Reinhold and K. Truempy
Accelerator Department, Emile Haefely & Co., Ltd.
Basel/Switzerland

Summary

A large number of research laboratories are now using stabilized 600 kV dc power supplies of the entirely shielded design, with electronic ac supply and feed-back control systems.[1] Recently, a new 600 kV power supply with a rated current of 20 mA has been marketed. At the present time, 1 MV dc power supplies which will operate in aluminum vessels under pressurized sulphur hexafluoride gas insulation are being constructed. The standard models have an overall stability including ripple voltage and noise of 1 part in 1000, both for continuous and pulsed operation.

Electrical and mechanical layout of the high voltage generator

The high voltage rectifier in the 600 kV units consists of a 4-stage Cockcroft-Walton circuit, which uses oil-insulated ac and dc capacitors and selenium rectifiers. To protect the rectifier circuit from direct short-circuits to ground, a high-ohmic damping resistor, which together with the capacitive part of the ohmic-capacitive voltage divider, forms a filter, is connected to the high voltage terminal. The Cockcroft-Walton circuit is energized from a high voltage transformer at a frequency of between 7.5 kc/s to 10 kc/s. The components of the cascade rectifier are enclosed in a steel tank filled with high quality mineral oil. To improve the heat dissipation, a large number of cooling pipes are welded to the tank. No artificial or forced water or air cooling is required.

The high voltage is brought out by means of a special lead-through, consisting of an araldite socket and a cone-shaped plug, which fits the socket, attached to one end of the shielded high voltage cable. The space between the plug and the socket is filled with a special thick cable oil. Less than one hour is needed for connecting the high voltage cable to the rectifier tank.

The free end of the high voltage cable can be equipped with a standard 600 kV dc bushing of the air-insulated type or with another insulating plug terminal, for further feeding the output voltage into a pressure or oil vessel.

Power supplies, with an open air terminal, are used as high voltage dc test facilities i.e. for testing cables or insulators, while the ones with the plug termination, serve as supplies for installations such as electron accelerators for industrial irradiation or for electron microscopy.

Figure 1 shows a photograph of a 600 kV dc power supply during factory tests. The test installation includes a 600 kV dc bushing, a load resistor and a precision voltage divider used for measuring the stability of the output voltage.

AC supply and feed-back control systems

Figure 2 illustrates the simplified circuit diagram of the cascade rectifier, the ac supply system and the feed-back control.

The high voltage transformer is energized from a class B push-pull power amplifier which uses two water-cooled triodes type Eimac 3CW20000A1. The necessary 7 kV plate voltage is supplied by a 3-phase, full-wave, rectifier unit connected between the center tap of the primary of the high voltage transformer and ground. The high voltage transformer has been designed so that its inductance, together with the capacitance of the winding, forms a resonant circuit at the intended operating frequency.

An operating frequency in the range of 7.5 kc/s to 10 kc/s was chosen in order to reduce the size of the components in the rectifier stack as well as the stored energy of the capacitors, while maintaining a low voltage drop and ripple voltage. The frequency is limited also by the selenium rectifiers which have a large inverse current at frequencies in excess of 20 kc/s. Moreover, the design of the high voltage power transformer presents greater problems at higher frequencies.

To avoid excessive plate dissipation in the power amplifier, it is necessary to tune the operating frequency exactly to the ringing frequency of the high voltage transformer and the associated rectifier circuit. This is achieved by tuning the RC oscillator in such a way that no reactive currents are drawn by the high voltage transformer from the power amplifier. Experience has proven, that the operating frequency of the oscillator and the resonant frequency of the entire circuit will remain constant over very long periods of time, so that no resetting is required. The frequency adjustment is a simple procedure which can be made with an oscilloscope.

The power dissipation of the anodes is given by the following relationship:

$$P_p = \frac{E_{bb} \ I_{pm}}{\pi \cos \varphi} - \frac{E_{pm} \ I_{pm}}{4} \qquad (1)$$

where

P_p = plate dissipation

E_{bb} = dc plate voltage

I_{pm} = peak plate current

E_{pm} = peak plate voltage

φ = phase shift due to incorrect tuning

Because of the high power gain of these tubes, a simple preamplifier, with relatively low power output can be used for driving.

The operational data of the power amplifier are as follows:

dc plate voltage	7000 V
dc grid voltage	-1300 V
zero-signal dc plate current	1.5 A
max-signal dc plate current	7.0 A
peak ac grid driving voltage	1300 V
driving power	0 W
output power	29000 W

The power amplifier is protected by an over-current relay. Other protective circuits will prevent damages which may be due to lack of cooling water or to failures in the negative grid supply.

To achieve a high stability of the dc output voltage two feed-back loops are used. The operation of these feed-back loops can be better understood from the block diagram of figure 3 and from the simplified circuit diagram of figure 2.

The control signal of the first feed-back loop is obtained from an additional measuring winding on the primary of the high voltage transformer. This system includes a rectifier and filter unit, the modulator and the power amplifier. Primarily, it is designed in order to minimize the influence of the relatively high impedance of the high voltage transformer and the fluctuations of the mains supply voltage.

High voltage stability with respect to variations of the load is achieved by the second feed-back loop. The dc output voltage is measured by means of an ohmic-capacitive voltage divider. The output voltage of the secondary unit of the voltage divider is compared with an adjustable reference voltage. Any deviations between the reference voltage and the secondary voltage, i.e. error signals are amplified in separate ac and dc amplifiers and applied to the modulator through a mixer amplifier. The modulator serves to regulate the amplitude of the mean frequency, so that fluctuations of the dc output voltage will be outbalanced by the amplitude variations of the ac input voltage. Obviously, this system also compensates for variations of the mains supply voltage.

The reference voltage source uses special glow discharge tubes enclosed in a thermostate. Two helipots are provided for the coarse and fine adjustment of the reference voltage.

The relationship between the high voltage dc output and the reference voltage input is given by the formula:

$$V_{dc} = V_R \times \frac{G_1 \ G_2 \ G_3}{1 + H_1 \ G_2 + H_2 \ G_1 \ G_2 \ G_3} \qquad (2)$$

where G and H are the circuit parameters, as shown in figure 3. This formula implies that, for high gain regulation, the denominator must be much bigger than unity. Thus, formula (2) becomes

$$V_{dc} = \frac{V_R}{H_2} \quad \text{where} \quad H_2 = \frac{R_i}{R_m} \qquad (3)$$

and R_i = internal impedance of the voltage reference source.

R_m = resistance of the high voltage divider.

A detailed analysis of the stability criteria of the feed-back control is made in R. Minkner's thesis.[2]

The stability of the dc output voltage was measured by means of a precision high voltage divider, connected to the load resistor of the dc power supply. The output signal of the voltage divider was compared with the dc voltage of a Weston element by using a bridge circuit with precision wire-wound resistors and a sensitive recorder.

The short-time stability of the standard model is 5 parts in 10 000, whereas the long-term drift is 1 part in 1000 per hour. These figures hold true for fluctuations of plus and minus 5 percent in the mains supply voltage and a load variation of zero and full load.

For special applications the long-term stability can be improved by using for the voltage divider wire-wound precision resistors.

The ac supply and feed-back control systems are built into 19" standard racks. The 5-mA unit is provided with two racks, the so-called "power rack" and the "stabilization rack" which also includes the control unit, while in the larger, 20-mA models, the rectifier for the supply of the anode voltage of the power amplifier forms a separate unit.

Until the end of 1966, more than twenty such 600 kV dc power supplies were built and installed at nuclear research institutions and high voltage laboratories both in Europe and in the United States.

This type of power supplies are used for:

- positive ion accelerators,
- ion source development,
- electron accelerators for industrial irradiation,
- electron accelerators for the supply of high voltage electron microscopes,
- electrostatic particle separators of orbital accelerators,
- development of dc high voltage cables,
- testing of cables and isolators,
- pre-accelerators of linear and orbital accelerators.

Future 1 MV dc power supplies

At present, a 1 MV dc power supply with the same ac supply and feed-back control systems as the 600 kV model is being constructed.

In the new model, the Cockcroft-Walton generator and the voltage divider are enclosed in an aluminum tank under pressurized sulphur hexafluoride rather than mineral oil. The pressure tank can be installed either horizontally or vertically. The shielded high voltage cable enters the pressure vessel through a flange located at the lower end. Thus, easy access to the generator is provided by simple removal of the upper part of the tank without dismantling the high voltage cable termination. Otherwise, the design of the pressurized cascade generator is similar to that of the symmetrical 4 MV cascade generator.[3]

A significant feature, common to all shielded dc power supplies, is the fact that they are short-circuited proof. This important characteristic is obtained by using selenium rectifiers as well as a special high voltage transformer which has in case of external breakdowns, a linear distribution of surge voltages across the secondary.

References

1. G. Reinhold, R. Minkner and K. Truempy: Stabilized high voltage dc power supplies of the shielded design. IEEE Transactions on Nuclear Science, June 1965, Vol. NS-12, No. 3.

2. R. Minkner: Untersuchungen an Hochspannungsgleichrichtern zur Erzeugung konstanter Gleichspannungen. Dissertation Technische Universität Berlin, 1965.

3. G. Reinhold, K. Truempy and J. Bill: The symmetrical cascade rectifier, an accelerator power supply in the megavolt and milliampere range. IEEE Transactions on Nuclear Science, June 1965, Vol. NS-12, No. 3.

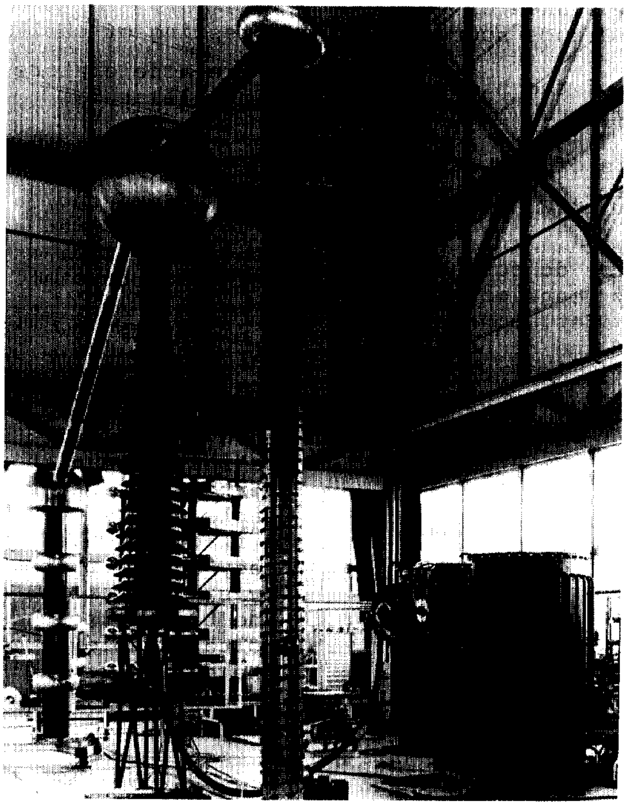

Fig. 1. Test installation for 600 kV dc power supplies with load resistor, high voltage bushing and precision voltage divider.

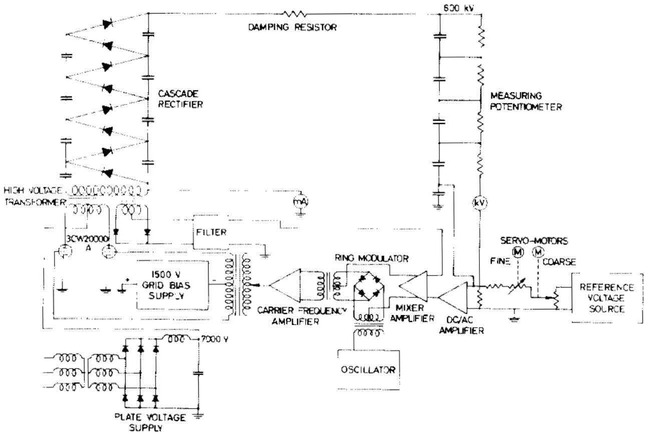

Fig. 2. Simplified circuit diagram of the 600 kV dc power supply.

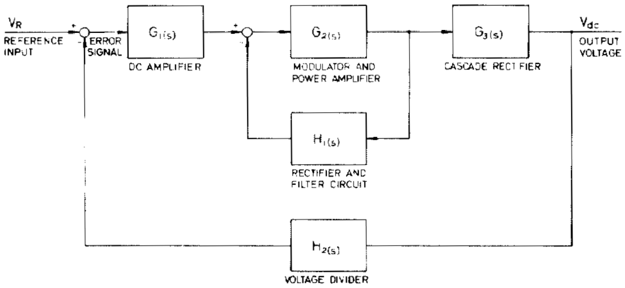

Fig. 3. Block diagram of the feed-back control of the 600 kV dc power supply.