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MEGAWATT HV DC POWER SUPPLIES

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Summary

For the injection of heavy, multiply charged ions into accelerators or for injection of cluster ions into fusion reactors, physicists require high-voltage dc power supplies with voltages in the range of 0.5 to 3 MV and currents of the order of several hundred milliamperes, and even amperes. Several power supplies in this range have been built recently, some for particle injectors and some for testing UHV dc transmission line components. In 1974, high-voltage dc power supplies with the following output ratings were completed: 2.5 MV/200 mA, 2.2 MV/200 mA, 1.2 MV/100 mA, and 1.0 MV/120 mA. All power supplies are built according to the symmetrical Cockcroft-Walton generator principle and are either air-insulated open structures or built into a pressure vessel and insulated with high-pressure sulphur hexafluoride. Based upon theoretical considerations and experience gained with units previously built, it appears feasible to design even more powerful generators.

Theoretical Considerations

The principle of the so-called Cockcroft-Walton voltage multiplier has been known for many years and has been the subject of many papers.[1,2,3] The exact calculations are very complicated and can be performed only in conjunction with electronic computers. For our discussion of the main features of this design, it suffices to consider only the most basic and approximate equations. Even though, for completeness, formulas are given for the regular and the symmetric generators, only the symmetric one is important for high-current applications.

The output voltage at no-load is given by

$$U_g = 2\sqrt{2}\, N\, U_O \qquad (1)$$

where N = number of stages
U_O = effective value of input transformer

This output voltage is reduced by capacitive currents and the load current. In most high-current applications, however, only the current-dependent voltage drop is important. The voltage drop and the ripple voltage caused by the load current are given in Table I.

TABLE I

	Normal Generator	Symmetric Generator
ΔU_g	$\frac{I}{fC}\frac{N}{3}\left(2N^2+1\right)$	$\frac{I}{fC}\frac{N}{3}\left(\frac{N^2}{2}+1\right)$
δU_g	$\frac{I}{fC}\frac{N}{2}\left(N+1\right)$	$\frac{I}{fC}\frac{1}{2}\ N$

where ΔU_g = voltage drop of generator
δU_g = peak-to-peak ripple voltage of generator
I = load current
N = number of stages
C = capacitance per stage
f = operating frequency

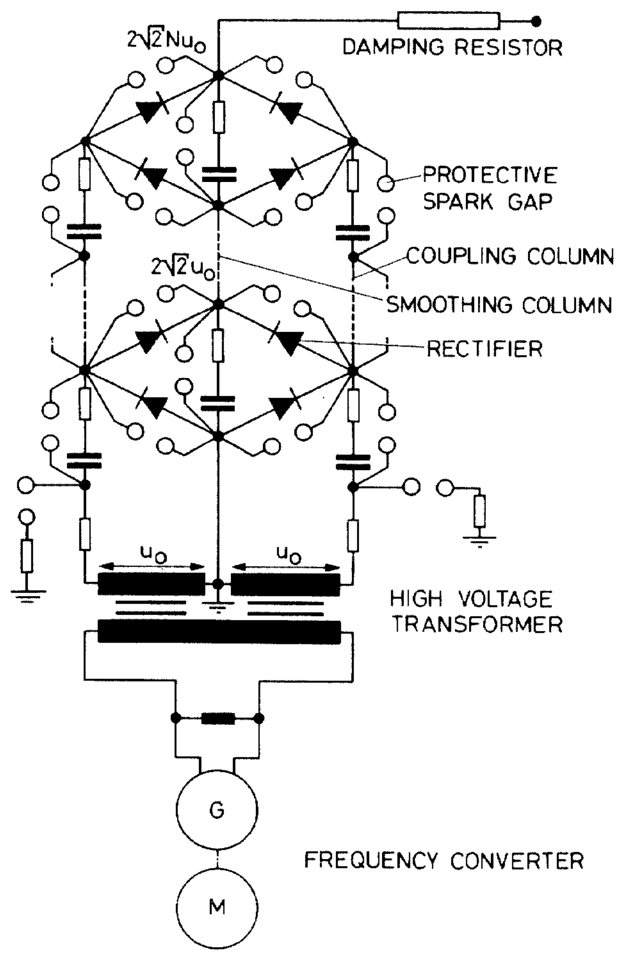

Figure 1. Schematic Diagram of Symmetrical Cockcroft-Walton Generator

The voltage drop and ripple voltage resulting from capacitive currents is discussed by G. Reinhold in a paper[4] to be published in Switzerland.

The ripple voltage will not be discussed further here, because, in any design, the ripple voltage is of the same order of magnitude and smaller than the voltage drop, as can be seen in Figure 2.

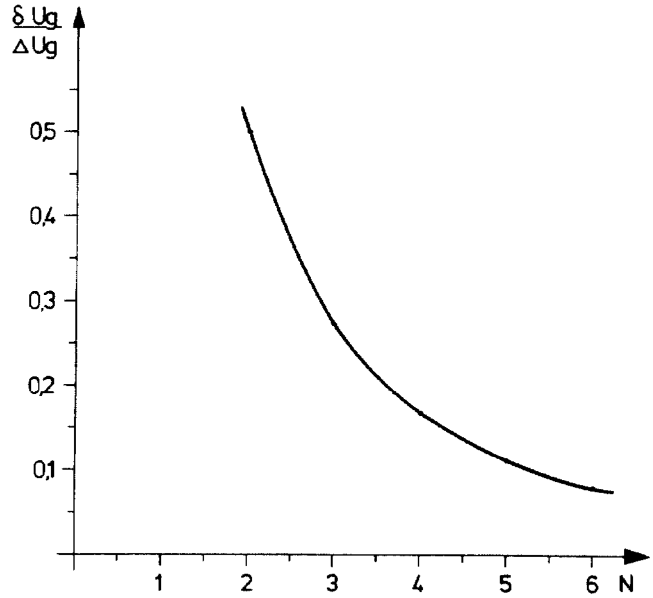

Figure 2. Ratio of Ripple Voltage to Voltage Drop as a Function of the Number of Stages N

From the formula for the voltage drop, one can see that there are three parameters which can be varied to achieve a certain voltage drop ΔU_g with a certain load current I; namely, the capacitance per stage C, the operating frequency f, and the number of stages N.

Design Considerations

Practical limits in varying the parameters are to be observed.

Operating Frequency

For a small voltage drop, a high frequency is desired. However, high-power, high-voltage transformers are limited in frequency; and, in practice, 2 kHz seems to be a reasonable choice. At this frequency, the transformer core can still be built with a normal thickness of iron sheet metal and the losses will still be low.

Capacitance

The capacitance per stage is limited by the stored energy in the generator. Experience has shown that a stored energy of 30 kJ should not be exceeded, as considerable damage can result (either in the accelerating tube or in the generator itself) by accidental sparks.

Number of Stages

The voltage drop is very dependent on the number of stages N, since it rises with the third power of N. If the total capacitance, and therefore the stored energy, is kept constant, only the square of N is involved.

$$C_{tot} = 3\,\frac{C}{N} \qquad (2)$$

where C_{tot} = total capacitance.

The voltage drop is then given by

$$\Delta U_g = \frac{I}{f}\,\frac{N}{3C}\left[\frac{N^2}{2} + 1\right] = \frac{I}{fC_{tot}}\left[\frac{N^2}{2} + 1\right] \qquad (3)$$

Decreasing the number of stages means increasing the voltage over the individual capacitors and rectifiers. This leads to nonlinear voltage distribution across those components, which in turn leads to voltage breakdowns. Experience with existing designs shows that 400 kV per stage is about the limit before encountering the above difficulties. It seems feasible today, however, to further increase the voltage per stage by redesigning the components; for instance, by subdivision and careful resistive and capacitive grading.

Protection

In high-voltage Cockcroft-Walton generators for higher currents, the impedances become lower; and special care must be taken to protect the various components.

Accelerating Tube

To protect the accelerating tube from damage when voltage breakdown occurs, a damping resistor is introduced between the generator and accelerator. The higher the value of the resistor, the better; but 1 to 10 Ω/J has been found to be adequate. This resistor also protects the generator and avoids nonlinear voltage distribution in case of breakdown. For the protection of the generator, the resistor should limit the current to 50 to 100 times the nominal current.

Rectifiers

High-current Cockcroft-Walton generators have become possible through the use of silicon diodes. Since these diodes cannot withstand high voltages, strings of many diodes must be connected in series. Careful capacitive and resistive grading is a necessity to assure good voltage distribution. In the event of breakdown, the maximum current must be limited in such a way that, for a certain type of diode, the value of $\int I^2 dt$ stays below a maximum value which is achieved by series resistors.

Capacitors

DC capacitors are quite sensitive to ac voltages, and it has become common practice to use series resistors. The value of these resistors is chosen in such a way that a discharge of the capacitor is in every case at least critically damped, and no oscillations can occur. In the Cockcroft-Walton multiplier, however, the lowest capacitor of the coupling columns carries N times the ac current so that the dissipation in the series resistor can heat up the capacitor, which in turn decreases its voltage-holding capability.

Transformer

Because sparkovers can cause traveling waves of a magnitude as high as the generator voltage, they must be prevented from reaching the transformer. A special fast-triggered spark gap was developed for this purpose.

Since a fast short circuit can be as deadly to the transformer as too high a voltage, series resistors must be installed in the connecting lines.

General Remarks

As we can see from the foregoing, most of the protection is achieved by ohmic resistors. But with high-power generators, the values chosen cannot be very high; and power dissipation must be kept in mind at all times. Careful distribution of these resistors over the whole generator and proper choice of their ohmic value provides enough protection to enable all components to withstand any accidental sparking. Additional protection against overvoltage is achieved by introducing spark gaps over practically every component.

Applications

Figure 3 shows a 2.5 MV/200 mA air-insulated power supply. It is possible to reverse polarity by remote control by reversing all the silicon rectifiers. Also, a remotely controlled discharge device is incorporated, permitting the generator to be discharged in a few seconds. This particular power supply is used in tests of UHV dc transmission lines. It is 16.4 m high.

Figures 4 and 5 show a 1 MV/120 mA generator built into a pressure vessel and insulated by sulphur hexafluoride at a pressure of 4 bar. This power supply will be used by the Gesellschaft für Kernforschung, Karlsruhe, as a voltage source for a cluster injector, accelerating ionized hydrogen clusters and injecting them into a fusion reactor after neutralization. Figure 5 shows this power supply with a 1 MV bushing which was required to conduct preliminary ion-source tests. The cluster injector will be completely encapsulated and insulated, also with sulfur hexafluoride. The 1 MV bushing is built with an outside insulator tube graded over the whole surface with a resistor chain, an inner conductor, and an intershield to reduce the maximum electric field strength. The inside is pressurized with 4 bar of SF_6. For the dimensions and voltages of the inside conductors, an optimum design was chosen to give the lowest field strength for a fixed outside diameter. In our case, this was determined by manufacturing conditions. In an optimum design of a three-cylinder configuration, the voltage of the intershield and the radii of the inner conductors are defined as:

$$U_2 = \frac{e-1}{e} U_1 \tag{4}$$

$$r_2 = r_3 \, e^{-\left(\frac{e-1}{e}\right)} \tag{5}$$

$$r_1 = \frac{r_2}{e} \tag{6}$$

where U_1 = voltage of inner conductor
U_2 = voltage of intershield
r_1 = radius of inner conductor
r_2 = radius of intershield
r_3 = radius of outer conductor

Figure 5 also shows a water resistor for load tests. This resistor withstands 1 MV and 120 mA for about 10 seconds without overheating. Several water resistors in parallel can be used for higher currents.

Based on experience with these power supplies, it appears feasible to build generators in the megawatt power range where limitations are set primarily by geometric dimensions of either the building or the pressure vessel.

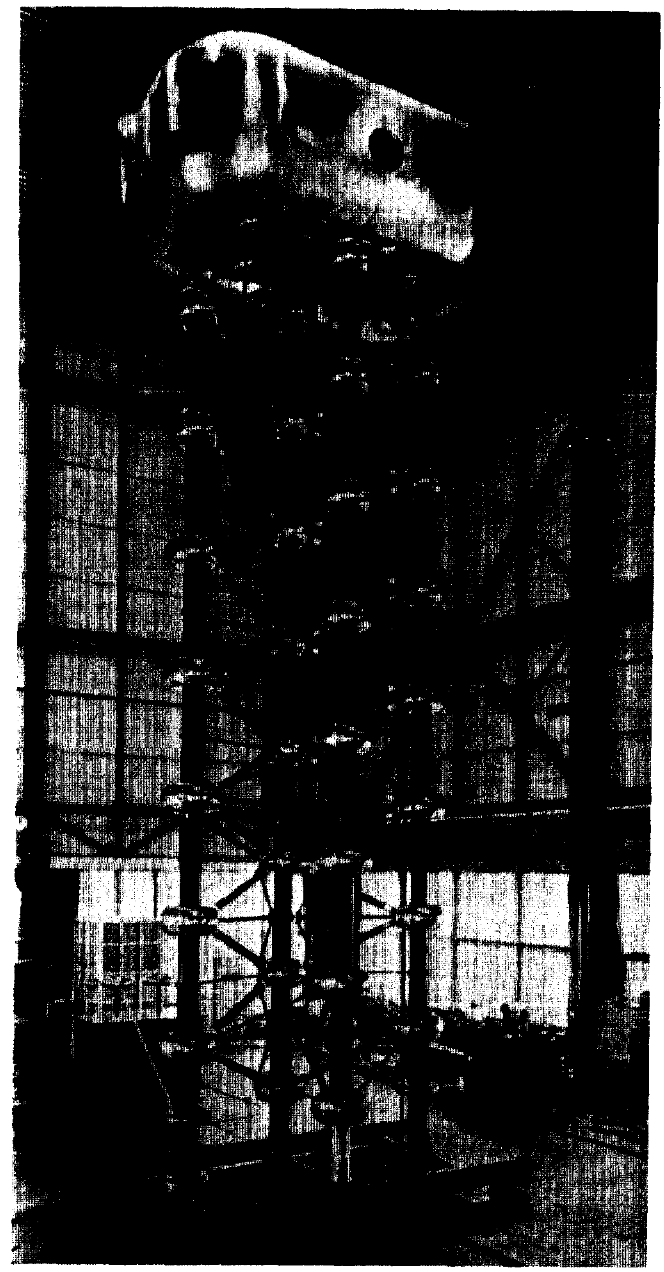

Figure 3. 2.5 MV/200 mA dc Power Supply

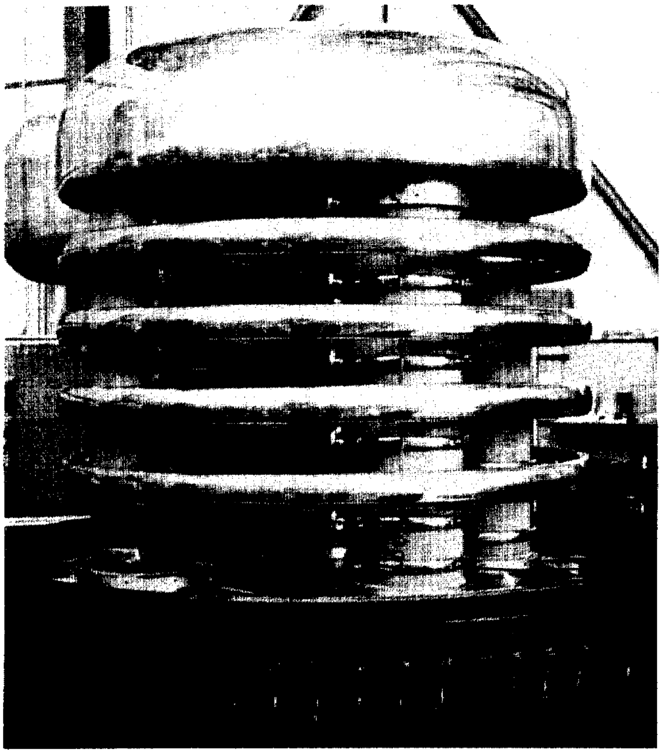

Figure 4. 1 MV/120 mA dc Power Supply with Cover of Pressure Vessel Removed

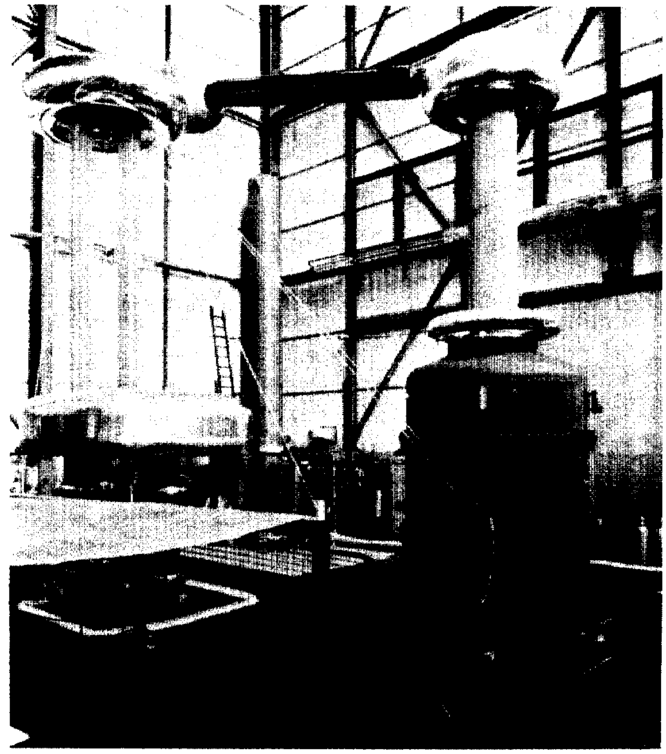

Figure 5. 1 MV/120 mA dc Power Supply under Test

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