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Ultra-high voltage DC power supplies for large currents

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Summary: This paper presents the well-known equations for capacitive and load-dependent voltage drops as well as for load-dependent ripple, and discusses the possibilities for advanced development of the cascade generator towards higher voltages and currents. Also, an equation for capacitive ripple is given for the first time. These fundamental design considerations are discussed with the example of a 2.5 MV, 200 mA test facility.

Introduction

With the widespread development of high-voltage dc transmission, test equipment for very high voltages and high currents has gained particular significance in the past few years. Previously, standard facilities were high-voltage dc test plants with voltages up to 2 MV and currents up to 30 mA. However, component development for ultra-high voltage dc transmission lines required voltages between 2 MV and 3 MV, as well as currents which are generally ten times higher than before. The advanced development of high-voltage dc power supplies for higher voltages and currents was not only prompted by UHV dc transmission projects but also by the growing interest of plasma physicists in high-current injectors for experiments on controlled nuclear fusion.

It is remarkable that modern high voltage dc power supplies – like impulse voltage generators – are based on a circuit which has been known for decades. The Marx multiplier circuit used in impulse voltage generators corresponds to the cascade circuit used in dc generators invented by Greinacher who, in the years 1920 and 1921, was the first to describe the cascade rectifier circuit which received his name [1]. However, the cascade circuit did not become known until experiments were carried out by Cockcroft and Walton who, independently of Greinacher, reinvented the cascade generator in 1932 and used it to power a proton accelerator [2].

Fundamental Theory

Ideal Cascade Rectifier

In the simple cascade circuit shown in Figure 1, a high dc voltage is generated by rectification and multiplication from a relatively low ac voltage. The functional principle and the theory of the cascade rectifier have been described very often and were also topics of scientific papers in the recent past [3; 4]. The exact equations for determination of the critical characteristics of the cascade rectifier are complex and can only be accurately evaluated numerically with the aid of a computer. For the purposes of this paper, it is usually sufficient to use the conventional approximations. These approximate equations show minor differences, depending on the author and the method of derivation, which are generally negligible.

The theoretical no-load voltage of a simple (or symmetrical) cascade rectifier can be calculated according to the equation

$$V_0 = 2\sqrt{2}\,N\,v_0 \qquad (1)$$

wherein: N = Number of stages

v_0 = secondary rms voltage of the supply transformer.

Relation (1) misleads to the false conclusion that an arbitrarily high dc voltage could be obtained simply by correspondingly increasing the number of stages. In reality, voltage losses occur during the multiplication process which set definite physical limits to multiplication.

Capacitive Voltage Drop and Capacitive Ripple

Concurrently with Woodyard, Everhart and Lorrain first considered the cascade rectifier as a recurrent network in order to calculate the capacitive voltage drop [5]. This was done in view of the stray capacitance between the cathode and the anode of the thermionic rectifiers used previously. However, this consideration is up to date again; because, with modern high-voltage rectifiers equipped with silicon diodes, shunt capacitors must be employed to obtain uniform distribution of the inverse voltage over the diodes connected in series. Furthermore, a non-negligible stray capacitance is present between the coupling column and the smoothing column of the cascade generator which also causes a capacitive voltage drop and a capacitive ripple. To compute the capacitive voltage drop and the capacitive ripple, it is permissible to ignore the dc voltage over the coupling and smoothing capacitors. For these deliberations, the N-stage cascade rectifier shown in Figure 1 is represented by a recurrent network with n = 2N filter sections (Figure 2). Each rectifier is assigned one filter section of the recurrent network. C_S is the sum of the stray capacitance of a high-voltage rectifier and the stray capacitance per half stage. Since the capacitive voltage drop already occurs when the cascade rectifier is not loaded, the recurrent network is examined under a no-load condition. This means that the current drawn from the last stage is zero.

In our example, C is the capacitance of a coupling or smoothing capacitor. The bottom coupling capacitor has double capacitance.

The propagation constant g of the recurrent network (Figure 2) can be calculated with the relation

$$\cosh g = 1 + \frac{1}{2}\cdot\frac{C_s}{C} \qquad (2)$$

By expanding cosh g in a series, we find

$$1 + \frac{g^2}{2!} + \frac{g^4}{4!} + \frac{g^6}{6!} + \ldots = 1 + \frac{1}{2}\cdot\frac{C_s}{C} \qquad (3)$$

Since the ratio C_S/C, i.e., the ratio of the stray capacitance of a filter section to the capacitance of a coupling or smoothing capacitor, is very small in practical cases, we can neglect the higher terms of the expansion. In this manner, we obtain

$$g \approx \sqrt{\frac{C_s}{C}} \qquad (4)$$

Impedance Z is significant for the following calculations. According to the recurrent network theory, we find

$$Z \approx \frac{1}{j\omega\sqrt{CC_s}} \qquad (5)$$

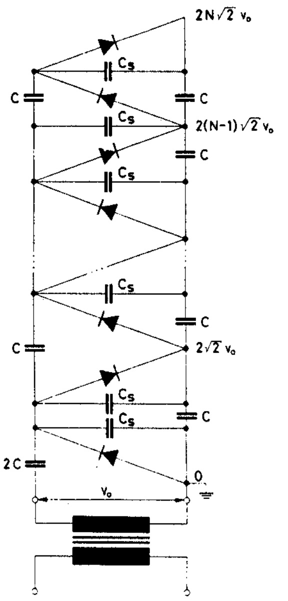

Figure 1. Diagram illustrating the Principle of a Simple N-Stage Cascade Generator with Stray Capacitances C_s

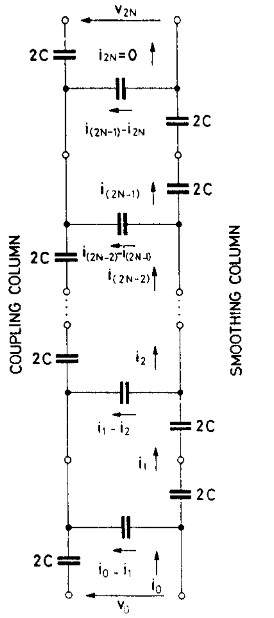

Figure 2. Diagram of the Cascade Generator shown in Figure 1 Designed as a Recurrent Network with 2 N Filter Sections

The actual dc voltage V'_o which occurs at the cascade rectifier in the no-load condition is equal to the sum of the maximum dc voltages over the 2N rectifiers. The peak value of each rectifier dc voltage is obtained from the peak value of the reactive current which flows parallel to this rectifier and from the impedance of the stray capacitance. In this manner, we find for the actual open-circuit dc voltage

$$V'_o = \frac{\sqrt{2}}{j\omega C_s}\left[(i_0 - i_1) + (i_1 - i_2) + \dots + (i_{2N-1} - i_{2N})\right] \qquad (6)$$

Since $i_{2N} = 0$ in the open-circuit condition, relation (6) can be written in a simplified form as

$$V'_o = \frac{\sqrt{2}}{j\omega C_s}\, i_0 \qquad (7)$$

With

$$i_0 = \frac{v_0}{Z} \tanh 2Ng \qquad (8)$$

it is possible to calculate the ratio of the actual to the ideal open-circuit dc voltage

$$\frac{V'_o}{V'_o} = \frac{1}{2N\sqrt{\frac{C_s}{C}}} \tanh 2N\sqrt{\frac{C_s}{C}} \qquad (9)$$

Equation (9) shows that a voltage drop occurs over the cascade generator even under no-load, so that it is necessary to provide a higher transformer voltage v_o to obtain a given dc voltage than would have been anticipated according to relation (1). The numerical evaluation of (9) is depicted in Figure 3. It is useful to apply the recurrent network theory in computing capacitive ripple as well.

Figure 2 shows that the capacitive ripple $\delta V'_o$ is given as the sum of the voltage drops which occur due to the reactive currents over the smoothing capacitors. The diagram of the recurrent network indicates that a contribution to the capacitive voltage drop at the smoothing column only occurs in only every other filter section. It is international practice to measure ripple between peak values and to indicate it in percent of the dc voltage:

$$\delta V'_o = \frac{2\sqrt{2}}{j\omega C}\left(i_1 + i_3 + \dots + i_{2N-1}\right) \qquad (10)$$

Since the reactive current in filter section k is given by

$$i_k = \frac{v_0 \sinh (2N-k)\, g}{Z \cosh 2Ng} \qquad (11)$$

we obtain for the ratio of the capacitive ripple $\delta V'_o$ to the actual open-circuit dc voltage V'_o the sum equation

$$\frac{\delta V'_o}{V'_o} = \frac{2g^2}{\sinh 2Ng} \sum_{n=1}^{N} \sinh (2n-1)\, g \qquad (12)$$

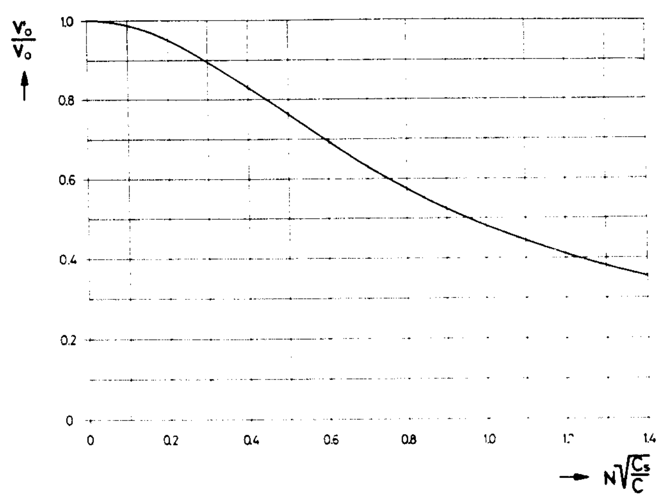

Figure 3. Relative Reduction of the Ideal No-Load Voltage V'_o/V'_o in Function of $N\sqrt{C_s/C}$

The sum included in equation (12) can be converted and rewritten as:

$$\sum_{n=1}^{N} \sinh (2n-1)\, g = \frac{1}{2} \cdot \frac{\cosh 2Ng - 1}{\sinh g} \tag{13}$$

With (4), we finally obtain

$$\frac{\delta V_o'}{V_o'} = \frac{C_s}{C} \cdot \frac{\cosh 2N\sqrt{\frac{C}{C_s}} - 1}{\sinh \sqrt{\frac{C_s}{C}} \cdot \sinh 2N\sqrt{\frac{C_s}{C}}} \tag{14}$$

This important relation (14) is evaluated on the graph in Figure 4 as a function of the ratio C_s/C for various numbers of stages N as the parameter.

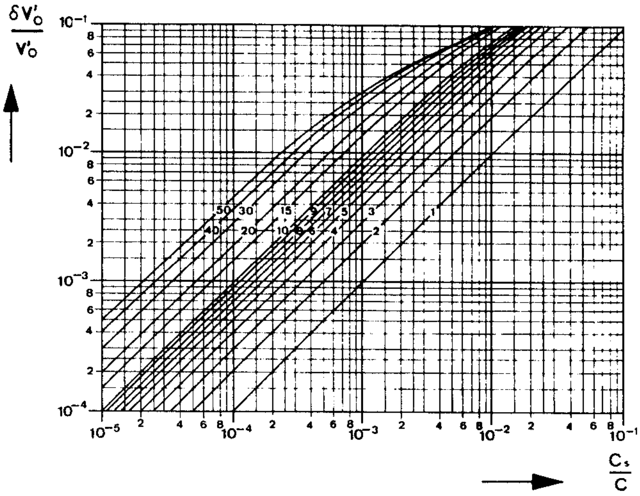

Figure 4. Relative Capacitive Ripple $\delta V_o'/V_o'$ in Function of the Capacitance Ratio C_s/C for Various Numbers of Stages

Load-Dependent Voltage Drop and Load-Dependent Ripple
If the cascade rectifier is loaded with a dc current, the resultant load-dependent voltage drop ΔV_{01} can be calculated according to the approximation

$$\Delta V_{01} = \frac{I}{fC} \cdot \frac{N}{3} (2N^2 + 1) \tag{15}$$

wherein I = dc current

f = operating frequency.

Indices 1 and 2 indicate the simple or symmetrical cascade generator. This paper will not discuss the voltage drop over the high-voltage transformer with its substantial stray inductance.

Since the load-dependent voltage drop is proportional to the third power of the number of stages, a stage number threshold is obtained for which the voltage obtained by increasing the number of stages is offset by the higher load-dependent voltage drop over the coupling and smoothing capacitors. This is the reason that a multiple-stage cascade rectifier cannot generate an arbitrarily high voltage.

Apart from the voltage drop which occurs due to the charge transport over the coupling and smoothing capacitors, it is also necessary to consider the voltage drop at the high-voltage rectifiers. Baldinger derived an equation to compute the voltage drop over the high-ohmic selenium rectifiers [6]. In modern high-voltage rectifiers which are composed of silicon diodes, the voltage drop is small enough to be ignored.

The reasons indicated above show that it is impossible to obtain a voltage in the order of several megavolts with the simple cascade generator; therefore, the symmetrical cascade rectifier illustrated in Figure 5 was developed.

Capacitive ripple does not occur with symmetrical cascade rectifiers because the capacitive currents compensate each other in the smoothing column. Due to the stray capacitances between the coupling columns, substantial capacitive currents may flow through the coupling capacitors. It is possible to compensate these capacitive currents with chokes in the individual stages of the symmetrical cascade generator and thus prevent additional supply-transformer loading.

The load-dependent ripple δV_{01} of the simple cascade generator is derived according to the equation

$$\delta V_{01} = \frac{I}{fC} \cdot \frac{1}{2} N (N+1) \tag{16}$$

In contrast, ripple δV_{02} in the symmetrical cascade rectifier is computed according to the equation

$$\delta V_{02} = \frac{I}{fC} \cdot \frac{1}{2} N \tag{17}$$

whereby ripple is again measured between the peaks. The stray capacitance of the high-voltage terminal against ground must be added to the total capacity C/N of the smoothing column which is of approximately the same magnitude.
An approximation can be given for the load-dependent voltage drop ΔV_{02}:

$$\Delta V_{02}' = \frac{I}{fC} \cdot \frac{N}{3} \left(\frac{N^2}{2} + 1 \right) \tag{18}$$

Empirical Data

Physical Limits
The analysis of Equation (18) is the point of attack for conceivable improvements applicable to the symmetrical cascade rectifier to achieve higher currents and/or higher voltages. It is obvious that, when the current I or the number of stages N is enlarged, the frequency or the capacitance of the coupling capacitors in the denominator of the equation must be increased to keep the load-dependent voltage drop within reasonable limits.

Fifteen years ago, pressurized gas-insulated symmetrical cascade rectifiers with 20 stages were built to generate high dc voltages up to 4 MV to power particle accelerators for nuclear research; they supplied dc currents of up to 10 mA with a supply frequency of 10 kHz [7].

Pressurized gas-insulated cascade generators for the mA range seem to be technically feasible for voltages of up to 10 MV.

In this context, it is important to note that the selection of the critical parameters, i.e., the operating frequency, the capacitance of the coupling capacitors, and the number of stages cannot be arbitrary in the symmetrical cascade rectifier, but that limit values must be observed. The operating frequency of the cascade rectifier cannot be increased randomly, because no frequency converter sets and high-voltage transformers are available for high outputs and frequencies of over 10 kHz. In practice, this means that a maximum operating frequency of 2 kHz must be considered. At this frequency, it is still possible to use standard transformer laminations even for high-performance high-voltage supply transformers. The capacitance of the coupling and smoothing capacitors is also restricted, because, otherwise, the cascade rectifier would have the potential of an impulse voltage generator with significant amounts of stored energy. The energy stored in the cascade rectifier can cause serious damage to the test object in the event of internal breakdowns or flashovers. Experience shows that the energy stored in the cascade generator should not exceed 30 kWs. The number of stages N, which is especially critical and which is included in the equation in the third power, can also not be too low; because this would lead to excessive per-stage voltages. Deliberations must be based on the fact that a per-stage voltage of 400 kV is the maximum value both for the coupling and smoothing capacitors, as well as for the individual rectifiers. For higher per-stage voltages, it is possible to ascertain that a nonlinear voltage distribution occurs along the capacitors and along the high-voltage rectifiers and can initiate flashovers.

Critical Rectifier Components

Tangible progress in the construction of high voltage dc power supplies was not made until high-voltage rectifiers were designed with silicon diodes instead of the conventional selenium diodes. The fact that silicon diodes were not introduced for such a long time was due to their well-known susceptibility to overvoltages and overcurrents. It is obvious that even modern avalanche diodes are not suitable for series circuits with high inverse voltages or overcurrents. To protect the still relatively sensitive silicon diodes, the diode network must include damping resistors which limit the short-circuit current to a reasonable magnitude. Furthermore, the diode network must be controlled with capacitors to obtain a linear distribution of the inverse voltage. High-voltage rectifiers with silicon diodes therefore represent a network which must be carefully computed. The damping resistors should have as high an ohmic rating as possible to obtain a good protection effect with the series resistors. However, this would cause very significant heating of the rectifiers during operation since the diodes carry high rms current values during the conductive phase. For this reason, the damping resistors must be selected in such a manner that the permissible operating temperature of the rectifiers, which is in the vicinity of 80° C. to 90° C., is not exceeded under the maximum operating conditions of the rectifier. The control, or protective, effect of the capacitive voltage divider parallel to the rectifier network increases with increasing shunt capacitance. However, high capacitances between the coupling columns of the symmetrical cascade rectifier cause high capacitive currents, as also indicated by the observations according to Everhart and Lorrain. Therefore, a compromise must be made.

A special problem in designing cascade generators and rectifiers is the calculation of the rms value of the rectifier current, because the ratio between the rms and the dc current in practice may vary between 1.5 and 2.5. Just like the important conduction angle, this critical ratio depends on the ratio of the complex impedance of the entire rectifier circuit to the load resistance.

Many years ago, it became common practice to include damping resistors in the coupling and smoothing capacitors whose values were such that at least an aperiodic damping was attained in the event of a short-circuit discharge of the capacitors (Figure 5). In practice, resistances between 10 Ohm and some 100 Ohm are used. The damping resistors limit the short-circuit current of the cascade generator in the event of an internal or external flashover.

The diagram of the cascade rectifier shows that the currents in the capacitors are added in such a manner that the current which flows in the bottom coupling capacitor is N times the current in the topmost capacitor. If excessive resistance values are selected for the damping resistors in the coupling capacitors for better protection of the rectifier components, the capacitors are heated up too much.

In this connection, it should be observed that the capacitive currents mentioned previously are also added from top to bottom in the coupling capacitors.

A design problem in conjunction with the high-voltage transformer which powers the cascade rectifier involves sufficient protection of the secondary winding against breakdowns or flashovers at the cascade rectifier or at the test object. In the event of a direct breakdown from the high-voltage terminal of the generator to ground, as occasionally occurs in practical operations, an overvoltage may build up over the secondary winding in the form of an impulse wave with a peak value equal to the full dc voltage. To avoid these extreme stresses to the high-voltage transformer, it is necessary to protect the secondary terminals with discharge spark gaps and to include damping resistors in the feed line to the generator (Figure 5). In this manner, it is possible to reduce incoming impulse waves to a reasonable magnitude of steepness and amplitude.

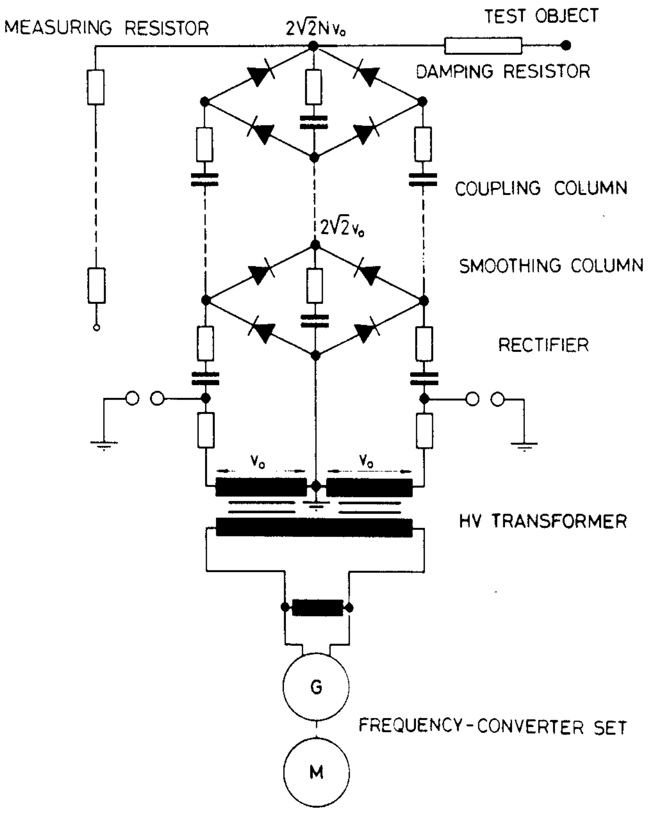

Figure 5. Block Diagram of a Complete Symmetrical Cascade Generator.

Design Details

Polarity Reversal and Grounding Facilities

If the standard or the symmetrical cascade rectifier is to be equipped with a remote-control polarity-reversal device, the V-shaped high-voltage rectifiers located on the individual stages (Figure 6) are supported on a rotating horizontal shaft. The horizontal rotating shafts are driven through miter gears by a vertical insulated shaft. Polarity reversal occurs when the bottom valve is rotated in the position of the upper valve and vice versa.

As long as the cascade rectifier is energized, this polarity reversal would be equivalent to a direct short circuit. For this reason it is necessary to discharge the cascade rectifier before this operation is performed; i.e., to ground it. This is achieved with the grounding device with which the individual stages of the generator are short-circuited over remote-control resistance arms which causes a strongly attenuated discharge. Polarity reversal is not carried out until the cascade generator is discharged either completely or to a small residual voltage value. False actuation of the polarity-reversal sequence is prevented by a corresponding lock device.

Damping Resistor

The test object is connected to the high-voltage terminal of the cascade rectifier through a damping resistor whose value is such that the current through the rectifiers will not exceed the rated current by a factor 50 to 100 (Figure 5) in the event of a short circuit at the test object.

Practical experience has shown that a damping resistor of this size is sufficient to restrict the short-circuit current, not only to protect the cascade generator and, particularly, the high-voltage rectifiers, but also the test object. If the output voltage of the cascade rectifier is measured in a conventional manner with a measuring resistor at the high-voltage electrode, the voltage drop over the damping resistor to the test object is, of course, ignored, since the relatively low impedance of the damping resistor makes it insignificant. Measuring accuracy is normally about ±2 percent.

Modern Installation Concepts

Very recently, test rectifiers for 2.5 MV, 200 mA (dc output, 500 kW), and for 2.2 MV, 200 mA and a pressurized gas-insulated injector power supply for 1.0 MV, 120 mA for plasma experiments (Figure 7) were built on the basis of the theoretical deliberations and experience described above.

The most powerful test rectifier for 2.5 MV (no-load voltage, 2.8 MV), shown in Figure 8, includes 7 stages and is equipped with a remote-control polarity-reversal installation.

Future Prospects

Voltages up to 10 MV seem to be feasible for pressurized gas-insulated high-voltage dc power supplies with currents in the mA range (for particle accelerators, supply of high-voltage electron microscopes).

Further voltage increases with air-insulated test rectifiers are approaching a threshold due to the rapidly increasing dimensions and costs of high-voltage laboratories. It is necessary to gain more experience with the insulation clearances required for dc voltages over 2.5 MV. On the other hand, it seems to be easier to increase dc currents to the order of amperes. Whereas the development of high-voltage dc power supplies for even higher outputs has been previously limited by the absence of suitable high-voltage rectifiers, the geometrical dimensions of high-voltage installations with dc outputs in the megawatt range now represent the basic problem. Although building costs are still a focal point for air-insulated installations, the physical dimensions represent a boundary for encapsulated SF_6-insulated high-voltage dc power supplies.

For high-output injectors, it is possible to divide the dc power supply into several pressure-vessel units or to weld the vessel together on the spot. Connecting several rectifier units in parallel has also been proposed; of course, this would give rise to problems related to protection.

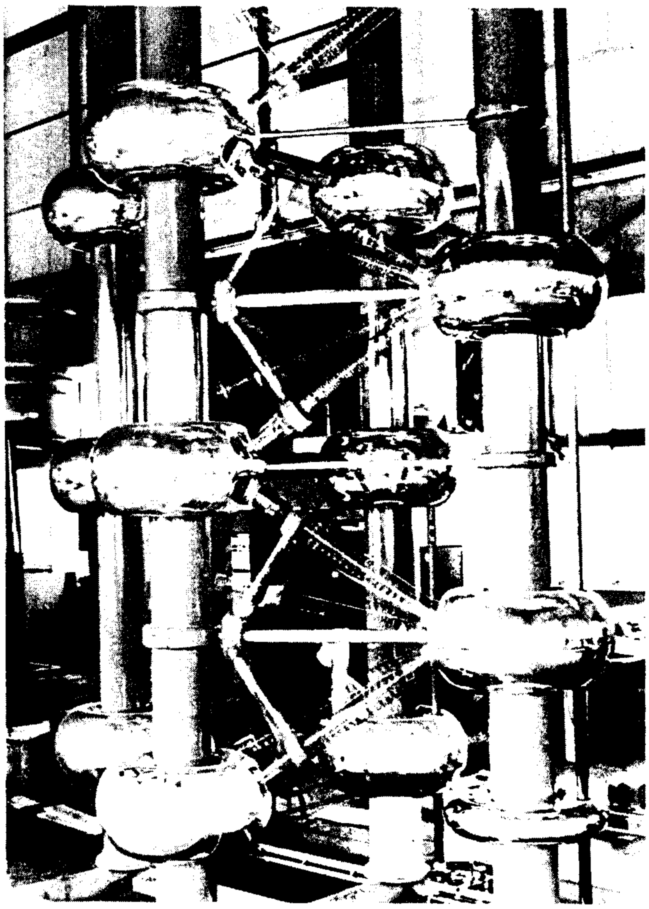

Figure 6. Cascade Generator with Polarity-Reversal Device

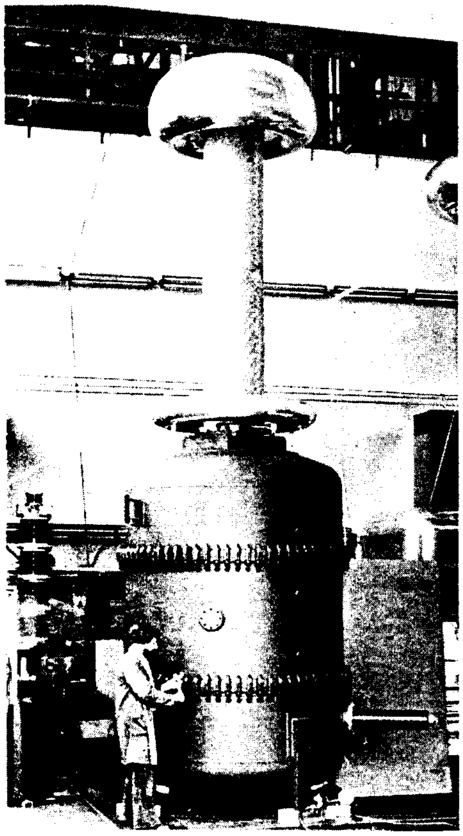

Figure 7. Pressurized Gas-Insulated Injector Power Supply, 1,0 MV/120 mA, for Vertical or Horizontal Operation with Top-Mounted 1 MV Feedthrough

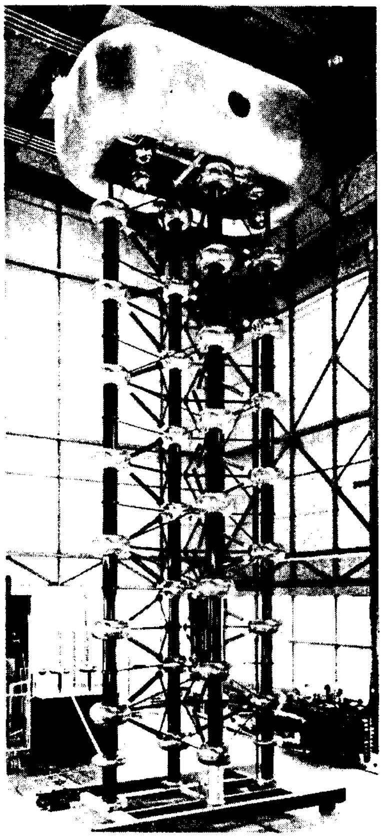

Figure 8. Seven-Stage Symmetrical Cascade Rectifier for 2.5 MV/200 mA (delivered in 1974)

References

1)	H. Greinacher:	Erzeugung einer Gleichspannung vom vielfachen Betrage einer Wechselspannung ohne Transformator. Bull. Schweiz. Elektrotechn. Ver. 11 (1920)
2)	J. D. Cockcroft & E. T. S. Walton:	Experiments with high velocity positive ions. Proc. Soc. Lond., Ser. A 136 (1932)
3)	R. Minkner:	Untersuchungen an Hochspannungsgleichrichtern zur Erzeugung konstanter Gleichspannungen. Diss. T. U. Berlin (1965)
4)	F. Heilbronner:	Transientverhalten mehrstufiger Hochspannungsprüfanlagen. ETZ-Report 11, VDE-Verlag Berlin (1973)
5)	E. Everhart & P. Lorrain:	The Cockcroft – Walton Voltage Multiplying Circuit. Rev. Sci. Instrum. 24 (1953)
6)	E. Baldinger:	Kaskadengeneratoren. Handbuch der Physik Band XLIV, Springer-Verlag (1959)
7)	G. Reinhold, J. Seitz & R. Minkner:	Die Weiterentwicklung des Kaskadengenerators. Zeitschr. f. Instrumentenkunde 67 (1959)

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