THE SYMMETRICAL CASCADE RECTIFIER AN ACCELERATOR POWER SUPPLY IN THE MEGAVOLT AND MILLIAMPERE RANGE

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This paper describes the Symmetrical Cascade Rectifier and compares it with the standard Cockcroft-Walton generator.

The authors compare the formulas for voltage drops of both types of generators and thus make clear the advantages of the symmetrical type rectifier over the Cockcroft-Walton type and illustrate its higher voltage capabilities.

The realization of a 4 MeV accelerator based on the symmetrical cascade rectifier is presented.

The basic principle of the cascade rectifier circuit was discovered by Greinacher, a Swiss physicist, shortly after World War I.[1,2] Though two articles appeared on the so-called Greinacher circuit in 1920 and 1921, Greinacher's discovery remained unnoticed for a long period of time, thereafter. The cascade rectifier became known only when Cockcroft and Walton, using the same principle, succeeded in performing the first nuclear disintegration experiment in 1932 with protons accelerated in a Cockcroft-Walton generator.[3]

The circuit diagram of the Greinacher cascade rectifier is shown in figure 1. It consists of a high voltage transformer, a column of coupling capacitors, a column of smoothing capacitors and a series-connection of rectifiers. Generally, one stage of the cascade rectifier is made up of one coupling capacitor, one smoothing capacitor and a pair of rectifiers. The bottom stage has a voltage doubling effect resulting in a dc voltage of twice the peak value of the ac supply voltage V_o, namely $2V_o$. This same dc voltage appears across the smoothing capacitors of all other stages, so that a cascade generator with N stages produces a total dc voltage of

$$V = N\ (2V_o) \qquad (1)$$

This formula explains that a large number of stages and a high ac input voltage have to be chosen in order to achieve a high dc output voltage.[4] However, the maximum dc output voltage obtained in practical applications did not exceed 2 MV due to the fact that the voltage efficiency of the cascade circuit decreases rapidly with the number of stages. The voltage efficiency of the circuit is determined by various voltage drops which are due to the electrical performance of the rectifier components.

Even under no-load conditions, the cascade rectifier does not reach its theoretical output voltage. The practical construction of the cascade rectifier introduces considerable stray capacitances between the coupling and the smoothing column and to ground. Reactive currents are created, in particular at the usual operating frequencies of several hundred cycles per second. The effect of the stray capacitances was studied by Everhart and Lorrain by applying the theory of iterative networks to the cascade circuit.[5] The result is shown in figure 2 in form of a curve representing the ratio F of the reduced no-load voltage to the ideal output voltage $2NV_o$. F is the voltage efficiency of the cascade circuit when the capacitive voltage drop alone, caused by the reactive currents, is taken into consideration. F_{opt} is the curve of the improved voltage efficiency if a choke of suitable inductance is connected between the top terminals of the coupling and the smoothing column as suggested by Everhart and Lorrain. The voltage efficiency is a function of $\sqrt{2\ N\ C_S/C}$, where C_S = total stray capacitance between the smoothing and the coupling column, and C = capacitance of one smoothing or coupling capacitor.

The reactive currents, in addition to causing an undesirable voltage drop, also produce a ripple voltage which can be computed by applying the theory of iterative networks to the cascade circuit :

$$\delta V_{react} = V_o \left(1 - \frac{1}{\cosh \sqrt{2NC_S/C}} \right) \qquad (2)$$

The ripple voltage δV is generally measured from peak to peak.

The capacitive ripple voltage δV_{react} is independent of the load current, but proportional to the peak value of the ac input voltage V_o.

Additional voltage drops will appear as soon as a load current is drawn from the cascade rectifier. An exact mathematical theory of the performance of the cascade rectifier has not yet been developed because of the non-linear behaviour of the main components.[6] However, approximate formulae, giving a sufficiently good approximation for the design of a cascade rectifier, are available. The following formulae are normally used :

The voltage drop of the rectifiers is given by Baldinger's formula [6] :

$$\Delta V_{react} = 2\,N\,\sqrt[3]{\pi^2 I^2 R^2 V_o} \qquad (3)$$

where

I = dc mean value of the load current
R = resistance per rectifier in the forward direction

The voltage drop of the coupling and smoothing capacitors is given by [4] :

$$\Delta V_{cap} = \frac{I}{fC}\left(\frac{2}{3}N^3 - \frac{1}{6}N\right) \qquad (4)$$

where

f= operating frequency

The load dependent ripple voltage is a function of the square of the number of stages N :

$$\delta V_{load} = \frac{I}{fC}\left(\frac{N\,(\,N+1\,)}{2}\right). \qquad (5)$$

In the actual design, the voltage drop of the input transformer must also be considered. It should be emphasized that all these voltage drops cannot simply be added in order to obtain the total voltage drop, as the internal impedance of the cascade generator has a complex nature. For a general discussion of the performance of the cascade generator it is sufficient to consider only the voltage drop caused by the capacitors of the rectifier stack. This voltage drop is a function of N^3, and it can be shown that with a large number of stages N, the voltage drop will become equal to the ideal output voltage $2NV_o$. This is the reason why the Greinacher or Cockcroft-Walton circuit in practice is limited to 2 MV. When higher dc voltages are to be generated, methods have to be found in order to reduce the voltage drop caused by the capacitors. The formula (4) for ΔV_{cap} suggests some ways in which this could be achieved. One method would be to reduce the number of stages, i.e. to increase the voltage per stage. At present, the voltage per stage is limited to 500 kV because of the limitations of the rectifiers and capacitors now available. Another method would be to increase the capacitance per stage. This would, however, result in larger capacitors and thus higher amounts of stored energy causing the cascade rectifier to become an impulse generator of medium size. Yet a third method for reducing the voltage drop would be to increase the operating frequency of the Greinacher circuit. This method has its limitations because of the difficulties involved in designing and constructing high voltage transformers in the medium frequency range and the maximum frequency at which solid state rectifiers can operate.

In 1954 the difficulties of generating higher dc voltages with cascade rectifiers were overcome by the development of the so-called symmetrical cascade generator, shown in figure 3.[7,8] This cascade circuit is symmetrical with respect to the smoothing column. A second high voltage transformer, stack of rectifiers, and coupling column have been added. The advantages of this circuit become immediately apparent when comparing the respective formulae for voltage drop and ripple of the standard and the symmetrical generator.

The symmetrical cascade generator does not produce any capacitive ripple voltage as the reactive currents through the coupling columns are automatically compensated in the smoothing column. Moreover, the reactive currents are reduced by compensation chokes connected to each stage of the rectifier circuit.[9] The load dependent ripple voltage is much smaller than before and given by the formula :

$$\delta V_{load} = \frac{I}{fC}\left(\frac{N}{2}\right) \qquad (6)$$

With two rectifier stacks connected in parallel, the rated current has been doubled while maintaining the same voltage drop across the coupling capacitors.[10]

$$\Delta V_{cap} = \frac{I}{fC}\left(\frac{N^3}{6} + \frac{N}{3}\right) \qquad (7)$$

shows that a reduction has been achieved by a factor of 4 in comparison with the standard circuit.

The symmetrical cascade generator allows the generation of dc voltages equal or exceeding the output voltages of electrostatic machines and at the same time offers much larger current capabilities. The principle of the symmetrical generator was used in the design and construction of several positive ion accelerators up to 4 MV.

A 4 MV cascade generator is shown in figure 4. The cascade rectifier consists of 20 stages of 200 kV each. The number of stages is identical with the number of hoops which are provided for the electrostatic shielding of the machine. A pair of high voltage transformers energized from a frequency converter at 10 kcps, is mounted at the bottom part of the pressure tank. The ion source and the auxiliary equipment are covered by a high voltage terminal made of highly polished stainless steel. Auxiliary voltage for the ion source is provided from a 400 cps generator mounted on top of the cascade rectifier. The ac generator is driven by a motor on ground potential through an insulating shaft made of araldite. Smaller auxiliary shafts equipped with servomotors are provided for the remote control of the electrical equipment at 4 MV potential.

Best results with respect to insulating properties were obtained with a mixture of 90 percent nitrogen, 8 percent carbon dioxyde and 2 percent sulfurhexafluoride under a pressure of 165 psi.

The accelerating tube is of the uniform field type and is composed of 80 stages. A bleeder chain provides uniform potential distribution across the accelerating column. Other types of accelerating tubes were also developed and tested in the symmetrical generator.[11]

The symmetrical cascade generator in addition allows for the simple connection of a stabilizing system. Figure 5 explains the performance of the supply and stabilization circuits. The frequency converter set is stabilized against variations of the mains supply voltage. The dc output voltage of the generating voltmeter is compared with an adjustable reference voltage source, and any error signals are applied through amplifiers to the field excitation of the 10 kcps generator. This loop is called coarse or slow stabilization. The fine stabilization is connected to the analyzing magnet and consists of ac and dc amplifiers for the amplification of the error signals from the analyzing magnet and a special stabilization rectifier (bouncer rectifier) which is connected between the center point at the bottom of the cascade rectifier and ground. The bouncer rectifier will move the potential of the center point and the whole generator with respect to ground in order to compensate for the fluctuations of the accelerating voltage.

The first positive ion accelerators of this type were designed for a rated voltage of 4 MV and a rated current of 5 mA. These cascade rectifiers were operated at 4 MV and 5 mA without interruption for many weeks. A load resistor with an oil cooling system was installed instead of the accelerating tube in order to obtain the load current.

The symmetrical cascade generator offers a high current capability and for this reason a large amount of stored energy will be discharged in case of breakdowns in the accelerator column. This stored energy will damage the surfaces of the accelerating electrodes thus reducing the maximum dc voltage. At the same time, large ion currents will normally increase the electron loading of the accelerating tube, yielding extremely high X ray levels which have a negative effect upon the insulating properties of the pressurized gas.

An accelerator of this type is operating at present at the Institute of Physics of the University of Basel (Switzerland). This installation is used for advanced research in postgraduate study. For the time being, the limit of safe operation of the accelerating tube is 3.2 MV. Ion currents up to 1 mA have been produced, although normally only about 100 μA are used. A proton beam of 100 μA upon the target can be obtained with about 250 μA at the entrance slit of the analyzing magnet. At 3 MV and 100 μA protons on the target, the dc voltage fluctuations are less than 1 kV, i.e. less than 1 part in 3000. Generally, the ripple voltage is in the order of 200 volts per milliampere load current at the rated voltage of 4 MV. Experiments performed with different types of accelerating tubes have shown that it is easier to obtain large ion currents than higher accelerating voltages if the problem of heat dissipation from the targets is not taken into consideration. At present, work is in progress aimed at overcoming this problem.

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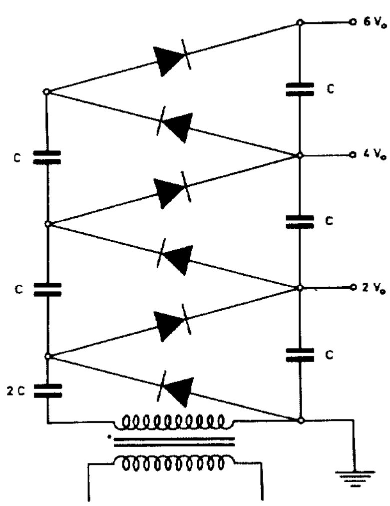

Fig. 1. Circuit of a Cockcroft-Walton cascade rectifier.

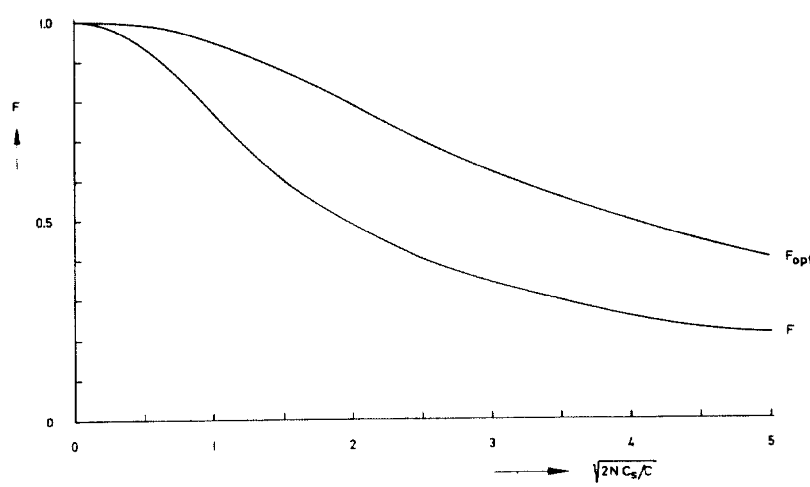

Fig. 2. Influences of stray capacitances on voltage efficiency of a cascade rectifier under no-load.

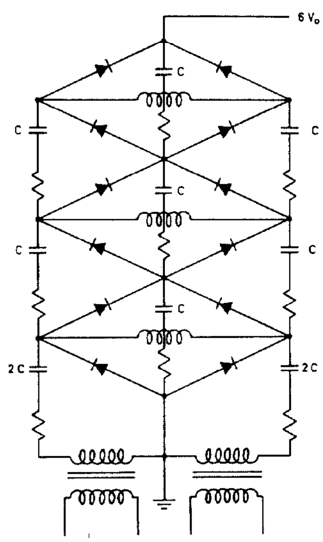

Fig. 3. Circuit of a symmetrical cascade rectifier.

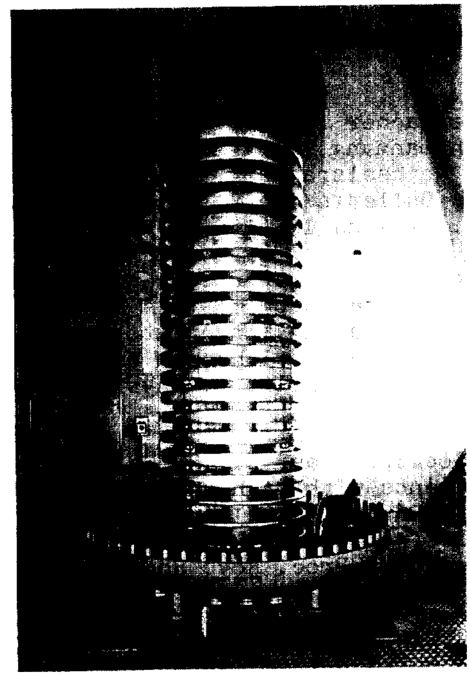

Fig. 4. The 4 MeV Ion accelerator of the University of Basel, Switzerland.

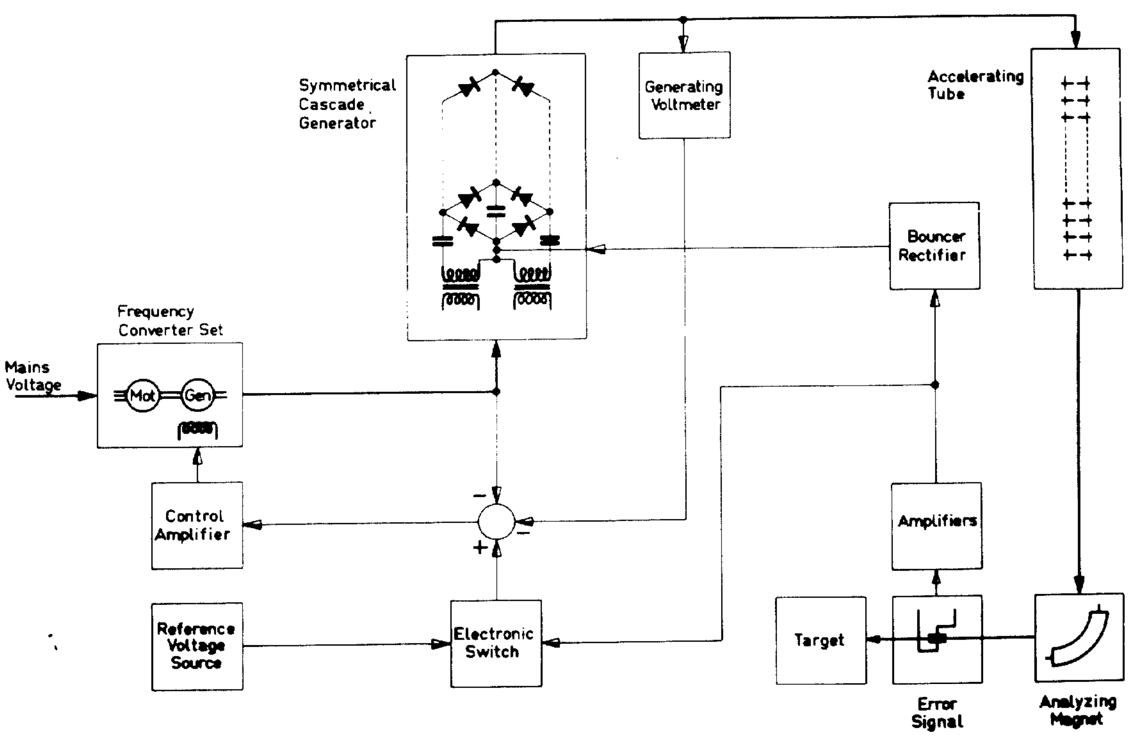

Fig. 5. Block diagram of a symmetrical 4 MeV ion accelerator.