7

High Voltage Generators for Testing

7.0 Generation of High Voltages

The power systems engineers is interested in high voltages primarily for power transmission, and secondly for testing of his equipment used in power transmission. In this chapter we are interested in generating high voltages for testing of insulation. Thus generation has to be carried out in the testing laboratory. In many testing laboratories, the primary source of power is at low voltage (400 V three phase or 230 V single phase, at 50 Hz). Thus we need to be able to obtain the high voltage from this. Since insulation is usually being tested, the impedances involved are extremely high (order of MΩ) and the currents small (less than an ampere). Therefore high voltage testing does not usually require high power. Thus special methods may be used which are not applicable when generating high voltage in high power applications.

7.1 Generation of High Alternating Voltages

Single transformer test units are made for high alternating voltages up to about 200 kV.
However, for high voltages to reduce the cost (insulation cost increases rapidly with voltage) and make transportation easier, a cascade arrangement of several transformers is used.

7.1.1 Cascade arrangement of transformers

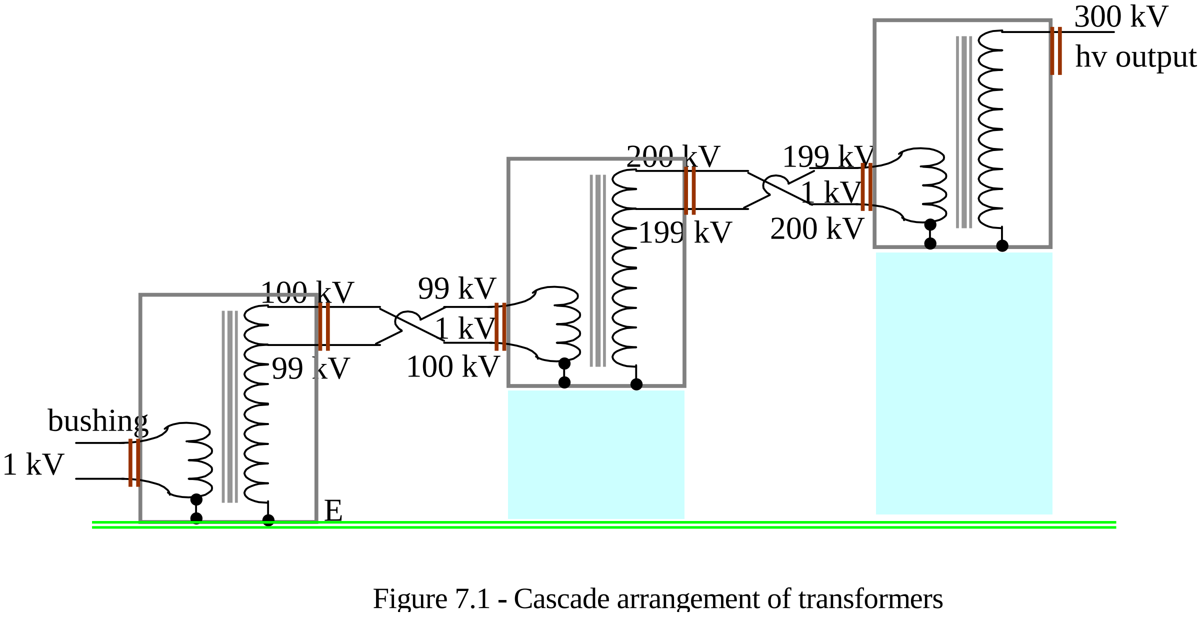


Figure 7.1 - Cascade arrangement of transformers

Figure 7.1 shows a typical cascade arrangement of transformers used to obtain up to 300 kV from three units each rated at 100 kV insulation. The low voltage winding is connected to the primary of the first transformer, and this is connected to the transformer tank which is earthed. One end of the high voltage winding is also earthed through the tank. The high voltage end and a tapping near this end is taken out at the top of the transformer through a bushing, and forms the primary of the second transformer. One end of this winding is connected to the tank of the second transformer to maintain the tank at high voltage. The secondary of this transformer too has one end connected to the tank and at the other end the next cascaded transformer is fed.
This cascade arrangement can be continued further if a still higher voltage is required.

In the cascade arrangement shown, each transformer needs only to be insulated for 100 kV, and hence the transformer can be relatively small. If a 300 kV transformer had to be used instead, the size would be massive. High voltage transformers for testing purposes are designed purposely to have a poor regulation. This is to ensure that when the secondary of the transformer is short circuited (as will commonly happen in flash-over tests of insulation), the current would not increase to too high a value and to reduce the cost. In practice, an additional series resistance (commonly a water resistance) is also used in such cases to limit the current and prevent possible damage to the transformer.

What is shown in the cascade transformer arrangement is the basic principle involved. The actual arrangement could be different for practical reasons.

7.1.2 Resonant Transformers

The resonance principle of a series tuned **L-C** circuit can be made use of to obtain a higher voltage with a given transformer.

Let **R** represent the equivalent parallel resistance across the coil and the device under test. The current **i** would be given by

$$i = \frac{E}{\dfrac{1}{j\omega C} + \dfrac{j\omega L R}{R + j\omega L}}$$

$$\text{so that} \quad v = i.\frac{j\omega L R}{R + j\omega L}$$

$$\text{i.e.} \quad v = \frac{-\omega^2 L C R . E}{R + j\omega L - \omega^2 L C R} = -\frac{E.R}{j\omega L} \quad \text{at resonance}$$

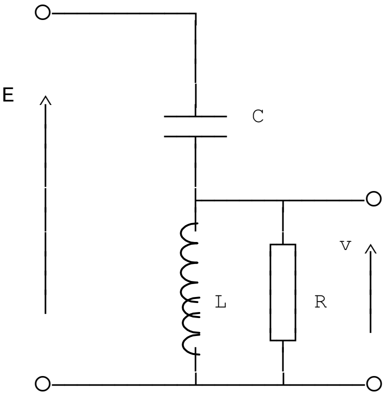


Figure 7.2 - Resonance circuit

Since **R** is usually very large, the **Q** factor of the circuit (Q = R/Lω) would be very large, and the output voltage would be given by

$$|v| = E.\frac{R}{L\omega} = E.Q$$

It can thus be seen that a much larger value that the input can be obtained across the device under test in the resonant principle.

$$\text{at resonance} \quad \omega = 2\pi f = \frac{1}{\sqrt{L C}}$$

Figure 7.3 shows the application of the resonance principle at power frequency.

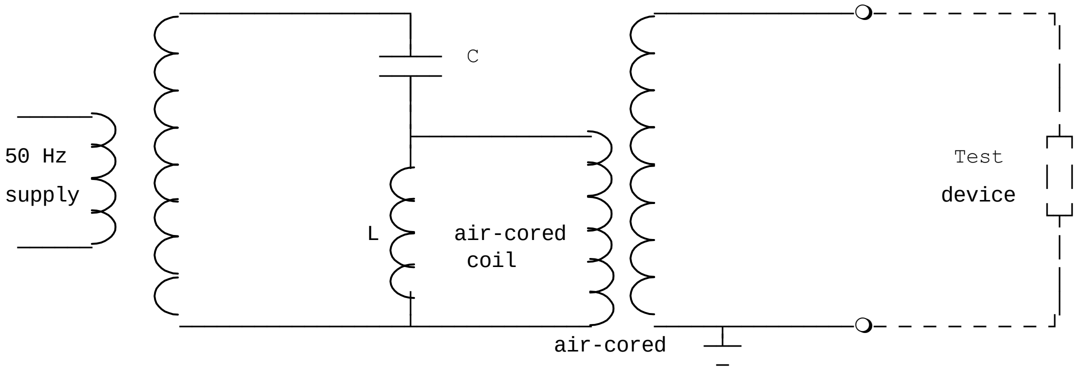


Figure 7.3 - resonant transformer

For certain applications, particularly when the final requirement is a direct voltage, it is an advantage to select a frequency higher than power frequency (50 Hz). This would result in a smaller transformer having fewer turns, and also simplifies the smoothing after rectification. High voltage high frequency voltages are not readily available, and the following is sometimes used to obtain a supply at three times power frequency. It makes use of the fact that the magnetising current of a transformer has a high third harmonic component. Thus if an open delta secondary is used, no power frequency voltage would remain and only the third harmonic component would be present. Figure 7.4 shows the circuit arrangement.

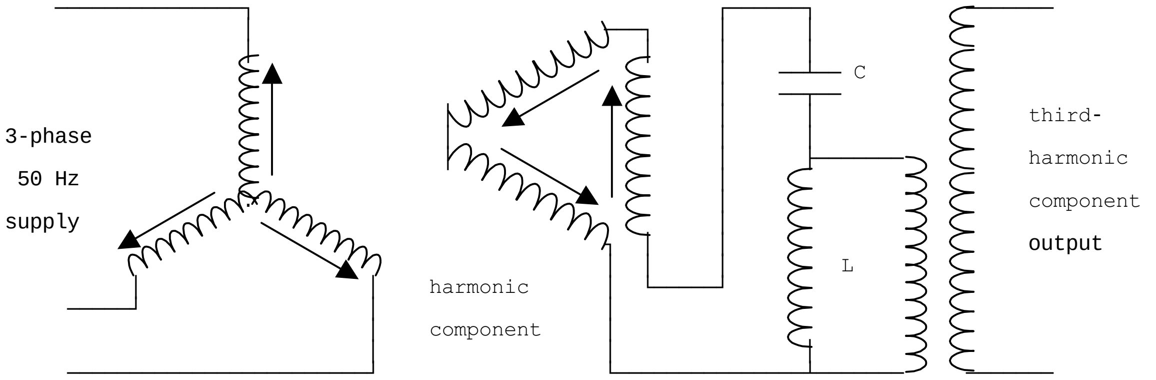


Figure 7.4 - Resonant transformer with third harmonic

Air-cored coils are used to simplify the construction and the insulation.

7.1.3 High frequency high voltages

High frequency (few kHz to Mhz) high voltages are required in testing apparatus for behaviour with switching surges, insulation flashover etc. The importance of testing with high frequency is that high frequency oscillations cause failure of insulator at comparatively low voltage due to high dielectric los and consequent heating. Thus it is necessary to produce damped high frequency voltages.

The damped oscillations are obtained by the use of a Tesla coil, together with a circuit containing a quenched spark gap. The tesla coil constitutes the high voltage transformer. It consists of two air-cored coils which are placed concentrically. The high voltage secondary coil has a large number of turns, and is wound on a frame of insulating material, the insulation between turns being air, or in some cases, oil. The primary winding has only a few turns wound on an insulating frame.

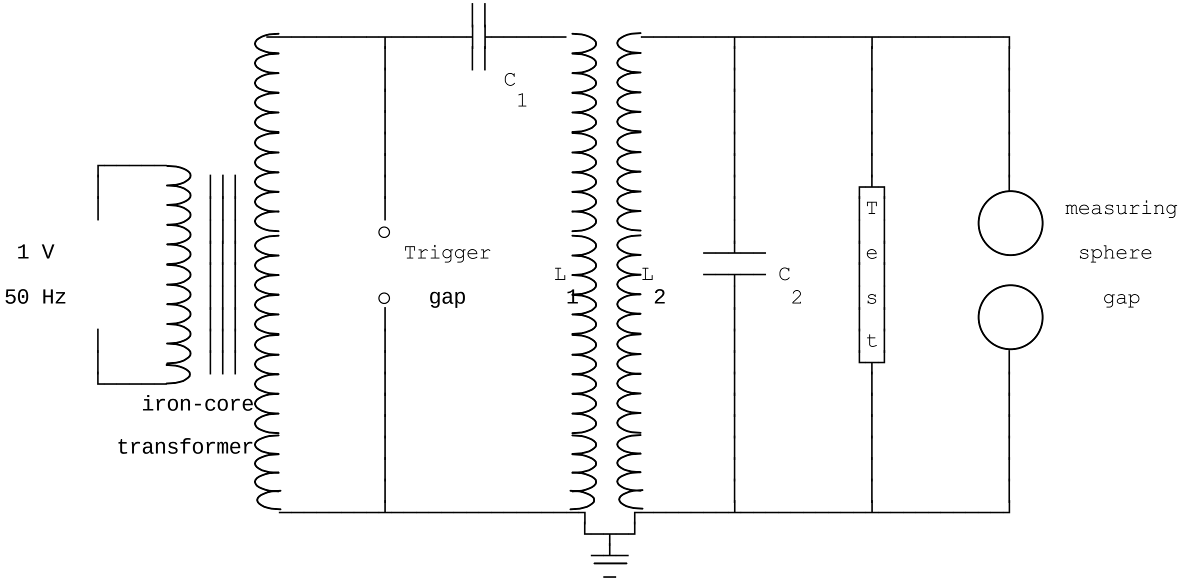


Figure 7.5 - Tesla coil circuit for high frequency generation

The supply is usually 50 Hz to the primary of the high voltage testing transformer. [In the circuit shown, C_2 includes the capacitance of the sphere gap used for measurement.] The primary circuit of the tesla transformer also contains a trigger spark gap. Since the supply to the primary of the tesla transformer is alternating, the capacitor C_1 is charged up to some maximum voltage, which depends upon the secondary side of the supply transformer, and upon the setting of the trigger gap.
At this voltage, the trigger gap breaks down, the capacitor C_1 discharges, and a train of damped oscillations of high frequency is produced in the circuit containing C_1, the spark gap and the primary winding of the tesla transformer. During the time taken for this train of oscillations to die away, the spark gap is conducting, due to the formation of an arc across it. This charge and discharge of capacitor C_1 takes place twice in one voltage cycle. Thus there will be a hundred of these trains of damped oscillations per second. The frequency of oscillations themselves is very high (about 100 kHz usually), its actual value depending upon the inductance and capacitance of the oscillatory circuit.

The circuit parameters are generally such that the resonant frequencies of the two sides are the same.

$$C_1 L_1 = C_2 L_2 \approx \frac{1}{\omega^2}$$

The expression for the voltage variation being obtained as the solution to a fourth order differential equation.

$$v = A e^{-\alpha_1 t} + B e^{-\alpha_2 t} + C e^{-\alpha_3 t} + D e^{-\alpha_4 t}, \quad \text{where } \alpha \text{ is complex}$$

The solution to the differential equation will generally be in conjugate pairs.

$$\alpha_1 = a + j\,\omega, \quad \alpha_2 = a - j\,\omega; \quad \ldots .etc$$

Thus the solution can be written in the form

$$v = A_1 e^{-a_1 t} \sin(\omega_1 t + \phi_1) + A_2 e^{-a_2 t} \sin(\omega_2 t + \phi_2)$$

$$\text{where} \quad a_1, a_2, A_1, A_2, \omega_1, \omega_2, \phi_1, \phi_2 \ \text{are constants}$$

If the two undamped frequencies are equal (corresponding to $L_1C_1 = L_1C_1$), then the damped resonant frequencies are nearly equal ($\omega_1 \approx \omega_2$).

The exponential decays of the components of the voltage depends on the resistance values.

If amplitudes A_1 and A_2 are equal, and the decays also equal, then the summation in **v** would have the form

$$\sin(\omega_1 t + \phi_1) + \sin(\omega_2 t + \phi_2) = 2 \sin \frac{(\overline{\omega_1 + \omega_2}\,.t + \phi_1 + \phi_2)}{2} . \cos \frac{(\overline{\omega_1 - \omega_2}\,.t + \phi_1 - \phi_2)}{2}$$

If $\omega_1 \approx \omega_2$, then $(\omega_1 + \omega_2)/2 \approx \omega$, so that the sum of the two sine terms represents a product of terms, one of which is of very nearly the resonant frequency, and the other with a frequency equal to the difference frequency between the primary and the secondary resonance frequencies. If the magnitudes and decays were not considered equal, the above result will be modified by the constants A_1 and A_2, and the exponential decays $e^{-a1\,t}$ and $e^{-a2\,t}$.

The energy tends to get transferred from primary to the secondary and vice versa, so that the voltage of primary is minimum when the secondary voltage is maximum and vice versa. Oscillation would occur which would be damped out due to the resistance in the circuit.

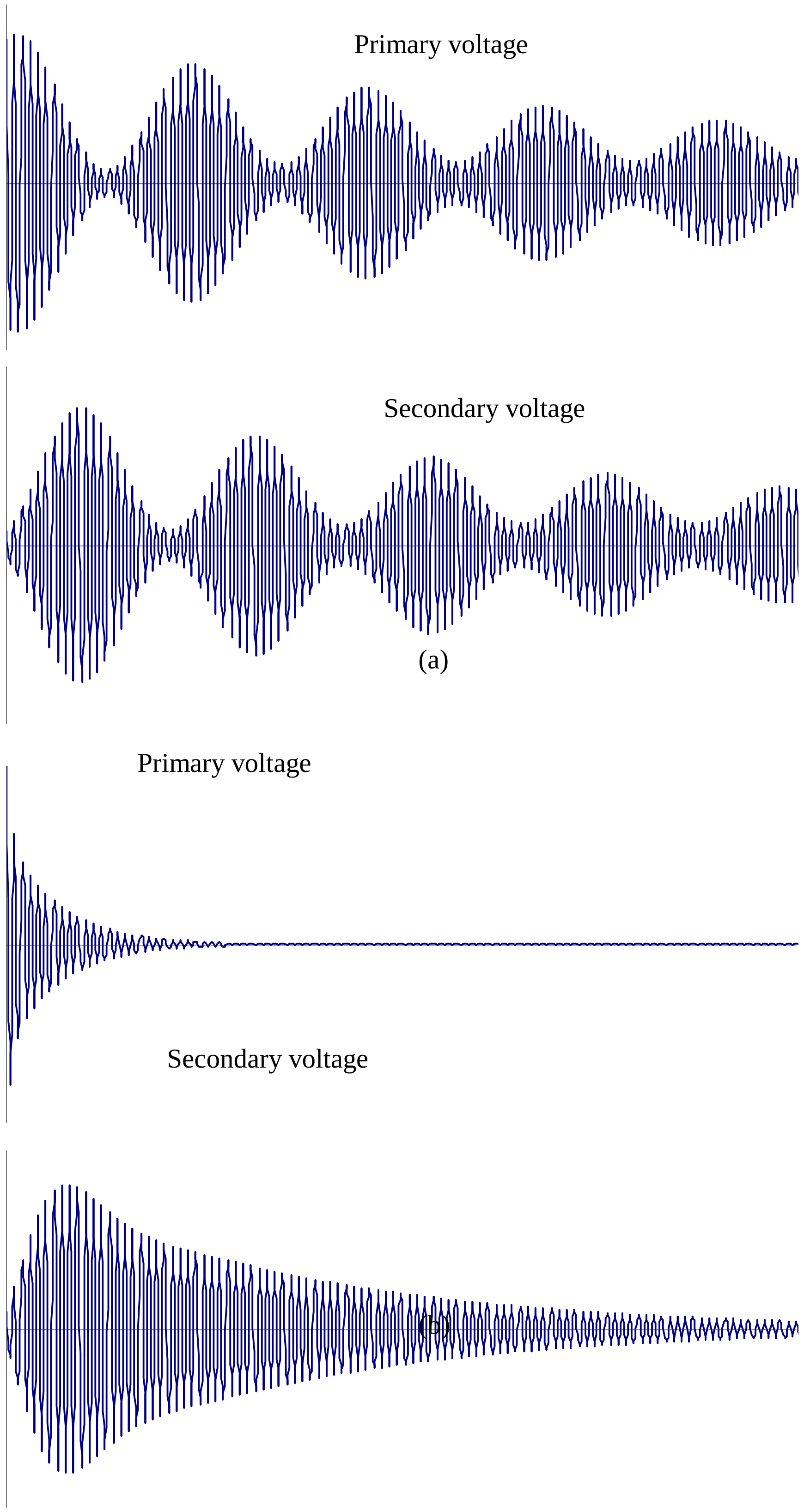


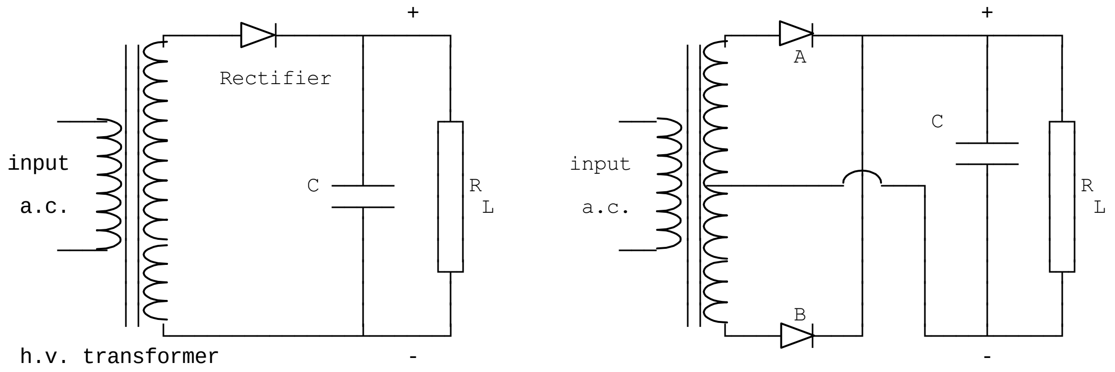
Figure 7.6 - Voltage waveforms across tesla transformer

What we require is a single series of short duration pulses. This can be done by preventing the energy from travelling backwards and forwards in the tesla transformer by quenching the trigger gap by air blast cooling. When the primary voltage is zero, the blast of air removes the spark in the primary gap so that the energy is confined to the secondary. Figure 7.6 (a) shows the primary and secondary voltage waveforms without quenching and figure 7.6 (b) shows the corresponding waveforms with quenching.

7.2 Generation of High Direct Voltages

Generation of high direct voltages are required in the testing of high voltage direct current apparatus as well as in testing the insulation of cables and capacitors where the use of alternating voltage test sets become impractical due to the steady high charging currents. Impulse generator charging units also require high direct voltages as their input.

7.2.1 Rectifier circuits



(a) half-wave rectifier (b) full-wave rectifier

Figure 7.7 - Half-wave and full-wave rectifier circuits

One of the simplest methods of producing high direct voltages for testing is to use either a half-wave for full-wave rectifier circuit with a high alternating voltage source. The rectifiers used must be high voltage rectifiers with a peak inverse voltage of at least twice the peak value of the alternating voltage supply. In theory, a low pass filter may be used to smooth the output, however when the test device is highly capacitive no smoothing is required. Even otherwise only a capacitance may be used across the test device for smoothing. Figure 7.7 shows the half-wave and the full wave arrangements.

In testing with high voltage direct current care must be taken to discharge any capacitors that may be present before changing connections. In certain test sets, automatic discharging is provided which discharges the capacitors to earth.

7.2.2 Voltage Multiplier Circuits

Both full-wave as well as half-wave circuits can produce a maximum direct voltage corresponding to the peak value of the alternating voltage. When higher voltages are required voltage multiplier circuits are used. The common circuits are the voltage double circuit and the Cockroft-Walton Circuit.

Voltage Doubler Circuit

The voltage doubler circuit makes use of the positive and the negative half cycles to charge two different capacitors. These are then connected in series aiding to obtain double the direct voltage output. Figure 7.8 shows a voltage doubler circuit.

In this case, the transformer will be of small rating that for the same direct voltage rating with only simple rectification. Further for the same direct voltage output the peak inverse voltage of the diodes will be halved.

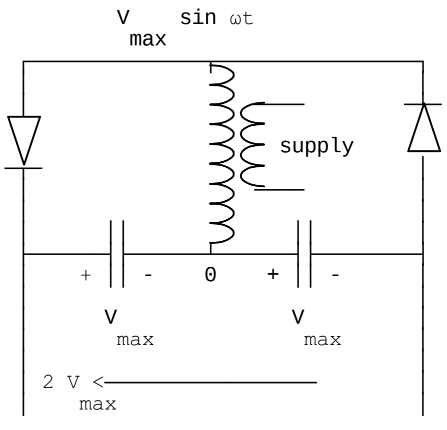


Figure 7.8 - Voltage doubler circuit

Cockroft-Walton Circuit

When more than doubling of the voltage is required, the Cockroft-Walton voltage multiplier circuit is commonly used. The circuit is shown in figure 7.9.

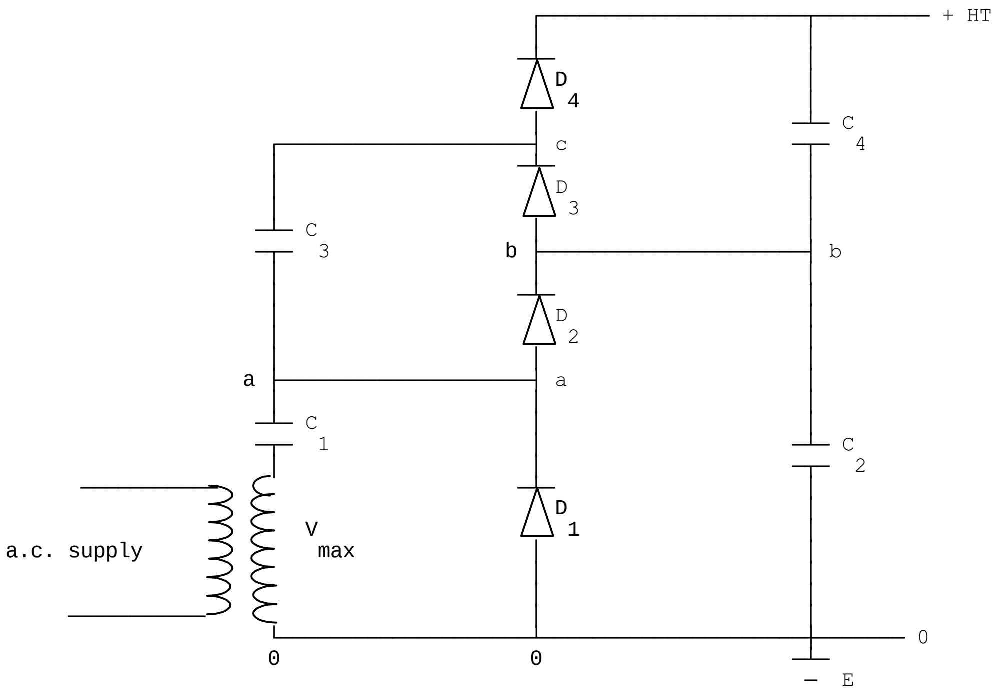


Figure 7.9 - Cockroft-Walton Circuit

Let $\mathbf{V_{max}}$ be the peak value of the secondary voltage of the high voltage transformer. To analyze the behaviour, let us consider that charging of capacitors actually takes place stage by stage rather than somewhat simultaneously. This assumption will not invalidate the result but will make analysis easier to follow. Consider the first part of the circuit containing the diode $\mathbf{D_1}$, the capacitor $\mathbf{C_1}$, and the secondary winding. During the first negative half cycle of the applied voltage, the capacitor $\mathbf{C_1}$ charge up to voltage $\mathbf{V_{max}}$. Since during the positive half cycle which follows, the diode $\mathbf{D_1}$ is reverse biassed, the capacitor $\mathbf{C_1}$ will not discharge (or will not charge up in the other direction) and the peak of this half cycle, the point **a** will be at **2** $\mathbf{V_{max}}$. During the following cycles, the potential at **a** will vary between **0** and **2** $\mathbf{V_{max}}$, depending on whether the secondary voltage and the capacitor voltage are opposing or assisting.

Initially, capacitor C_2 would be uncharged, and the voltage at **b** would be zero. Thus as the voltage at **a** varies between 0 and 2 V_{max}, the diode D_2 is forward biassed, and the capacitor C_2 would charge to 2 V_{max}. Once the voltage at **b** has reached 2 V_{max}, the voltage at **a** would be less than or equal to the voltage at **b**. Thus once C_2 has charged up, this diode too would be reverse biassed and the capacitor C_2 would not discharge. The voltage at **b** would now remain constant at 2 V_{max}. C_3 is also initially assumed uncharged. Since the voltage at **a** varies between 0 and 2 V_{max}, the diode D_3 would initially be forward biassed for almost the whole cycle. Thus the capacitor C_3 charges until it reaches 2 V_{max} when **b** is 2 V_{max} and **a** is 0. As the voltage at **a** again increases to 2 V_{max}, the voltage at **c** increases, and thus the diode D_3 is reverse biassed and C_3 would not discharge. Now as **a** reaches 2 V_{max} the voltage at **c** rises to 4 V_{max}, as C_3 has not discharged.

Thus after charging up has taken place, the voltage at **c** varies between 2 V_{max} and 4 V_{max}. Assuming C_4 also to be initially uncharged, since the voltage at **b** is a constant at 2 V_{max} and the voltage at **c** varies between 2 V_{max} and 4 V_{max} initially, during most of the cycle, the diode D_4 is forward biassed and C_4 charges up to the maximum difference between **d** and **b** (i.e. to 2 V_{max}). This occurs when the voltage at **c** is 4 V_{max} and the voltage at **d** would now be 4 V_{max}. As the voltage at **c** falls from 4 V_{max} to 2 V_{max}, since the capacitor C_4 has charged up it would not discharge, since there is no discharge path. Thus once the capacitors are charged up the voltage at **d** remains constant at 4 V_{max}.

This sequence of voltages gained is shown in Table 7.1.

Cycle	0	T/2	T	3T/2	2T	5T/2	3T	7T/2	4T
Location	-	+	-	+	-	+	-	+	-
a	0	2 Vm	0	2 Vm	0	2 Vm	0	2 Vm	0
b	0	2 Vm	2 Vm	2 Vm	2 Vm	2 Vm	2 Vm	2 Vm	2 Vm
c	0	0	2 Vm	4 Vm	2 Vm	4 Vm	2 Vm	4 Vm	2 Vm
d	0	0	0	4 Vm	4 Vm	4 Vm	4 Vm	4 Vm	4 Vm

Table 1

When the generator is used for a test, or when it is loaded, a current is drawn from the generator, and the capacitors lose some of their charge to the load, and the voltage falls slightly depending on the load. As the voltage across any of the capacitors drops, then at some point in the applied alternating voltage cycle, the corresponding diode would become forward biassed and charging up of the capacitor would once again result. Thus when a load is connected, there would be a small ripple in the output voltage.

7.2.3 Electrostatic generators

Electrostatic generators using the principle of charge transfer can give very high direct voltages. The basic principle involved is that the charge is placed on a carrier, either insulating or an isolated conductor, and raised to the required potential by being mechanically moved through the electrostatic field.

Van de Graeff generator

The Van de Graeff generator is one of the methods used to obtain very high voltages. However they cannot supply much currents and the power output is restricted to a few kilowatt, and their use is restricted to low current applications.

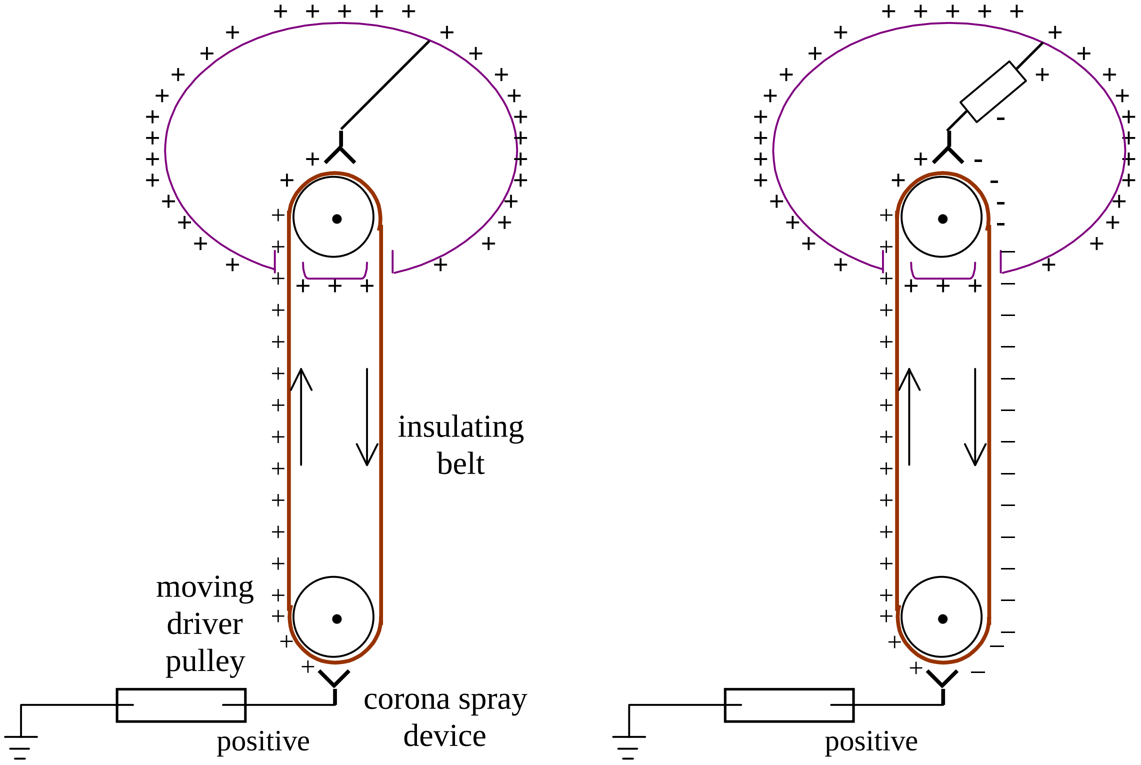


Figure 7.10 - Van de Graeff Generator

The Van de Graeff generator uses an insulating belt as the carrier of charge. The generator consists of a low direct voltage source, with corona discharge taking place at the positive end of the source. The corona formation (spray) is caused by a core like structure with sharp points (corona spray device). Charge is sprayed onto the belt at the bottom by corona discharges at a potential of 10 to 100 kV above earth and carried to the top of the column and deposited at a collector. The upper electrode at which the charge is collected has a high radius of curvature and the edges should be curved so as to have no loss. The generator is usually enclosed in an earthed metallic cylindrical vessel and is operated under pressure or in vacuum.

The higher voltage of the upper electrode arises from the fact that for the same charge, a smaller capacitance gives a larger voltage. The upper electrode has a smaller capacitance to earth on account of the larger spacing involved.

$$V = \frac{Q}{C}$$

The potential of the high voltage electrode rises at a rate of

$$\frac{dV}{dt} = \frac{1}{C}\frac{dQ}{dt} = \frac{I}{C}$$

where I is the net charging current

A steady potential will be reached by the high voltage electrode when the leakage currents na the load current are equal to the charging current. The edges of the upper electrode are so rounded as to avoid corona and other local discharges.

With a single source at the lower end, the belt moves upwards with a positive charge and returns uncharged. Charging can be made more effective by having an additional charge of opposite polarity sprayed onto the belt by a self inducing arrangement (negative corona spray). using an ingenious method. this arrangement effectively doubles the charging rate.

Sames Generator

This is a more recent form of the electrostatic generator. In this the charge is carried on the surface of an insulating cylinder. A two pole of this kind is shown in figure 7.11, but other number of poles are also possible. In this the power output will depend on the size of rotor. The number of poles will determine the current and the voltage. For example, a four pole rotor will produce twice the current at half the voltage of that of a two pole machine of the same size.

In the Sames generator, the rotor is a hollow cylinder made of an insulating material. Electric charges are deposited on the surface of the rotor which is driven by an electric motor to effect the transfer of charges in the field. The whole unit is sealed in a pressure unit and insulated ith hydrogen at a pressure of 10 to 25 atmospheres.

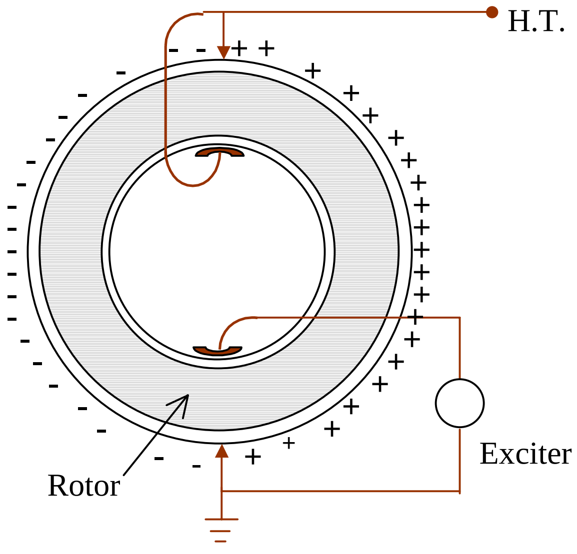


Figure 7.11 - Sames Generator