Generation of High Voltages

Alternating Current Voltages (ac)

Electric power transmission with high ac voltage predominates transmission and distribution systems.

HVAC supplies are in common use in HV labs, ranging from 10 kV r.m.s. to 2 MV r.m.s.

All ac voltage tests are made at the working frequency (50 Hz) of the test objects.

Voltage control is performed by a control of the primary or low voltage input of voltage step-up systems.
Testing voltages are usually single-phase voltage to ground. The waveshapes must be nearly pure sinusoidal.

The ratio of peak to r.m.s. values should be equal to $\sqrt{2}$ within $\pm5\%$. The r.m.s. value is for a cycle of T

$$V_{r.m.s.} = \sqrt{\frac{1}{T} \int_0^T V^2(t)dt}$$

The nominal value of the test voltage is defined by its peak divided by $\sqrt{2}$ i.e. $V_{\text{max}}/\sqrt{2}$

Testing of high voltage apparatus or insulation always involves an application of high voltage to capacitive loads with little power dissipation.
The nominal KVA rating $P_n$ is given by

$$P_n = kV_n^2 \omega C_t$$

where $k \geq 1$ accounts for additional capacitances and safety factor. $V_n$ is the nominal voltage and $C_t$ the capacitance of the testing object.

$C_t$ changes considerably for different apparatus and typical values are:

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<td>Bushing</td>
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<td>Power transformers</td>
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Testing transformer

Faraday’s law:

\[
\frac{V_1}{N_1} \approx \frac{V_2}{N_2}
\]
With a single coil it becomes difficult if the output of 100 kV or more is required.
Cascaded transformer

Transformer 1

Transformer 2

Transformer 3

I = P/V
Disadvantages of cascading transformer

(i) Heavy loading of primary windings for the lower stages.

(ii) Bulky and heavy

Series resonant circuits

Equivalent circuit of transformer and test capacitance
If by chance resonance occurs

$$\omega(L_1 + L_2) = \frac{1}{\omega C}$$

Accidental resonance is extremely dangerous but controlled resonance can be used for onsite test

A series resonant circuit

Equivalent circuit of series resonant circuits
Direct current voltages (dc)

HV dc voltages have wide applications (accelerators, electron microscopy, x-rays precipitation and filtering, electrostatic painting)
Various types of hvdc generators available
IEC Publication 60-2: the value of a direct voltage is defined as:

\[ \bar{V} = \frac{1}{T} \int_{0}^{T} V(t) dt \]

where T is a certain period of time if V(t) is not constant. The deviation from the mean value is described by the ripple \( \delta V \)
The ripple factor is the ratio of the ripple amplitude to the mean value \[ \frac{\delta V}{V} \]

For a typical dc source this ripple factor should not exceed 5%.

The rectification from ac is the most efficient means of obtaining hvdc supplies.

\textbf{ac to dc conversion}

The theory of rectifier circuits for low voltage and high power output is similar.
Simple rectifier circuit (single-phase half-wave rectifier)
The ripple $\delta V$ in this case is given by

$$\delta V = \frac{T}{2R_L C} \int_0^T V(t) = \frac{IT}{2C} = \frac{I}{2fC}$$

It affects by the load current and circuit parameter $C$ and ac frequency $f$.

A sudden voltage breakdown at the load ($R_L \to 0$) may lead to an excessive current (protection is required)

-- switching device at transformer input

-- resistance insertion

Half-wave rectifier circuits have been built up to voltages in MV range
Cascade circuits (Cockcroft-Walton type)
Cascade circuits (Cockcroft-Walton type)

HV output open circuited \((I=0)\)
0-n’-V(t) – half-wave rectifier
\(C_n’\) charges up to \(+V_{\text{max}}\)
when \(V(t)=-V_{\text{max}}\)
\(D_n\) conducts as soon as \(V(t)\uparrow\)
Point n’ swings up to \(+2V_{\text{max}}\)
and point n attains a steady potential \(+2V_{\text{max}}\) when \(V(t)\) reaching \(+V_{\text{max}}\). The part n’-n-0 is a half-wave rectifier in which the voltage across \(D’_n\) can be assumed to be the ac source.
The current through $D_n$ that charged $C_n$ was not provided by $D'_n$ but from $V(t)$ and $C'_n$.

Assume that $C'_n$ was not discharged and the voltage across $C_n$ is not reduced if $n'$ oscillates between zero and $+2V_{\text{max}}$.

If the potential of $n'$ is zero, $C'_{n-1}$ is also charged to the potential of $n$ ($+2V_{\text{max}}$).

The next oscillation of $V(t)$ will force $D_{n-1}$ to conduct $\Rightarrow C_{n-1}$ will be charged to a voltage of $+2V_{\text{max}}$.

Similar charging processes take place in the rest of the circuit.
Voltage profiles (for zero load conditions):

Stage \((n-2)\) to 3

\[ V(t) = \pm 2nV_{\text{max}} \]

\[ V_0 = 2nV_{\text{max}} \]

\[ V_{\text{max}} \]

\[ 0 \]
the potential at the nodes 1’, 2’ …n’ are oscillating due to the voltage oscillation of V(t);
the potentials at the nodes 1, 2,…n remain constant with reference to ground potential;
the voltages across all capacitors are of dc type, the magnitude of which is \(2V_{\text{max}}\) across each capacitor stage, except the capacitor \(C'_n\) which is stressed with \(V_{\text{max}}\) only
every rectifier \(D_1, D'_1…D_n, D'_n\) is stressed with \(2V_{\text{max}}\); and
the hv output will reach a maximum voltage of \(2nV_{\text{max}}\)
HV output loaded ($I>0$)  
The output voltage will never reach $2nV_{\text{max}}$  
There will be also ripple on the voltage  
Two important quantities:  
the voltage drop $\Delta V$  
and the peak-to-peak ripple $2\delta V$  

$$
\Delta V_0 = \frac{I}{fC} \left( \frac{2n^3}{3} - \frac{n}{6} \right)
$$

$$
\delta V = \frac{I}{fC} \cdot \frac{n(n+1)}{4}
$$
Impulse voltages

Two kinds of overvoltages (transient voltages) are often encountered in transmission and distribution systems.

Lightning: high amplitude (1000 kV) and current injection (100 kA).

Switching: amplitude depends on the operating voltage and the shape on impedance of the system.

The actual shape of both overvoltage varies strongly, it became necessary to stimulate these transient voltages by relatively simple means for testing purpose. The international standards define the impulse voltages as a unidirectional voltage which rises more or less rapidly to a peak and then decays relatively slowly to zero.
**Lightning**: impulse voltages with front durations varying from less than one up to a few tens of µs.

Rise time (front time) is defined as $t_1 = 1.25(T_2 - T_1)$ and tail time as $t_2 = T_4$. Impulse voltages are referred to as a $t_1/t_2$ wave. 1.2/50µs wave is the accepted standard lightning impulse voltage. (Permit tolerance ±30% for $t_1$ and ±20% for $t_2$)
Switching: impulse voltages with front durations varying from a few tens to a few hundreds of μs.

The standard switching impulse has time values of $t_1 = 250 \, \mu s \pm 20\%$ and $t_2 = 2500 \, \mu s \pm 60\%$.
Single Stage Impulse Generator

$C_1$ is charged from a dc source until the spark-gap G breaks down.

A voltage is impressed upon the object under test of capacitance $C_2$.

$R_1$ and $R_2$ control the front and tail of the impulse voltage across $C_2$. 
Analysis of the circuit can be done using the Laplace transform of the impulse circuit.

The output voltage

\[ V(s) = \frac{V}{s} \frac{Z_2}{Z_1 + Z_2} \]

where

\[ Z_1 = \frac{1}{C_1s} + R_1 \]

and

\[ Z_2 = \frac{R_2 / C_2s}{R_2 + 1/C_2s} \]

By substitution:

\[ V(s) = \frac{V}{s} \frac{R_2 / (R_2C_2s + 1)}{R_1 + 1/C_1s + R_2 / (R_2C_2s + 1)} \]

where

\[ a = \frac{1}{R_1C_1} + \frac{1}{R_2C_2} + \frac{1}{R_1C_2} \]

\[ b = \frac{1}{R_1R_2C_1C_2} \]

\[ = \frac{V}{s} \frac{R_2}{(R_1 + 1/C_1s)(R_2C_2s + 1) + R_2} \]

\[ = \frac{V}{R_1C_2} \frac{1}{s^2 + as + b} \]
\[ V(s) = \frac{V}{R_1C_2(s_1 - s_2)} \frac{1}{(s - s_1)(s - s_2)} \]

where \( s_1 \) and \( s_2 \) are the root of the equation \( s^2 + as + b = 0 \) (both \( s_1 \) and \( s_2 \) will be negative)

From the transform tables

\[ v(t) = \frac{V}{R_1C_2(s_1 - s_2)} [\exp(s_1t) - \exp(s_2t)] \]

In practice \( R_2 \gg R_1 \) and \( C_1 \gg C_2 \), an approximate solution is obtained for \( s_1 \) and \( s_2 \) via

\[ s^2 + \frac{1}{R_1C_2} s + \frac{1}{R_1R_2C_1C_2} = 0 \]
The roots are

\[ s_1 = -\frac{1}{R_1 C_2} \quad \text{and} \quad s_2 = -\frac{1}{R_2 C_1} \]

The equation for the output voltage becomes

\[ v(t) = V \left[ \exp\left(-\frac{t}{R_2 C_1}\right) - \exp\left(-\frac{t}{R_1 C_2}\right) \right] \]

The wave shape depends on the values of generator the load capacitance and the wave-control resistances.
Multistage Impulse Generator

The one stage generator is not suitable for HVs (HV dc is required). Marx suggested an arrangement:

A number of capacitors are charged in parallel through resistances and discharged in series through spark gaps.
A dc voltage charges the stage capacitors $C'_1$ in parallel via $R'$ and $R'_2$ ($<<R'$). The points A, B, C and D will be at the potential of $-V$ and the points E, F, G, H and I at the earth potential.

Firing of the generator is initiated by the b/d of the gap $G_1$ which is followed by a nearly simultaneous b/d of all the remaining gaps.

Intuitively, $G_2$ can be twice wide of $G_1$ and $G_3$ three times of $G_1$ etc.

In practice, it has been noted that the gap $G_2$ must set to a gap distance only slightly greater than $G_1$; otherwise it does not operate.

Front resistance of $R_1$ is distributed.