High Voltage Engineering

Unit-I

Generation of High DC and AC Voltages

Different forms of High Voltages

(i) High D.C. Voltages

(ii)High A.C Voltages of Power Frequency

(iii) High A.C Voltages of High Frequency

(iv) High transient or impulse voltages of very short duration such as lightning over voltages

(iv) High transient voltages of longer short duration such as switching surges

GENERATION OF HIGH D.C VOLTAGES

- Mainly required in research work in the areas of pure and applied physics

- High direct voltages are needed in insulation tests on cables, capacitors and impulse generator charging unit(100kV to 200kV)

- The most efficient method of generating high D.C voltages is through the process of rectification employing voltage multiplier circuits.

The value of a direct test voltage is defined by its arithematic mean value *Vd* and is expressed mathematically as

$$V_d = \frac{1}{T}\int_0^T \upsilon(t)\,dt$$

The magnitude of the ripple voltage denoted by δ*V* is defined as half the difference between the maximum and minimum values of voltage *i.e.,*

$$\delta V = \frac{1}{2}[V_{max} - V_{min}]$$

HALF-WAVE RECTIFIER CIRCUIT

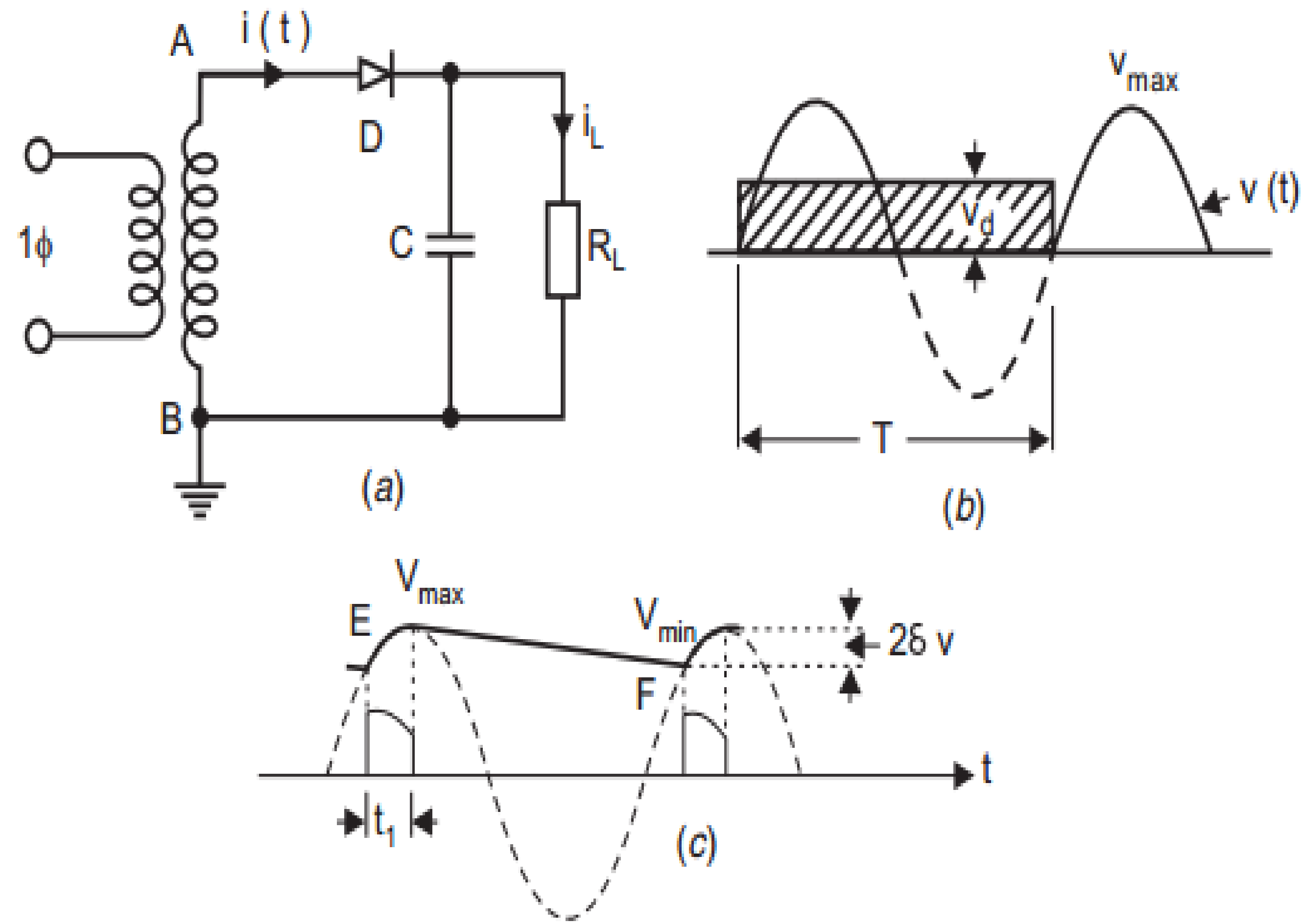


Fig. (*a*) Single Phase rectifier (*b*) Output voltage without *C* (*c*) Output voltage with *C*

During one period $T = 1/f$ of the a.c voltage, a charge Q is transferred to the load RL and is given as

$$Q = \int_T i_L(t)\,dt = \int_T \frac{V_{RL}(t)}{R_L}\,dt = IT = \frac{I}{f}$$

charge delivered by the capacitor during this time is

$$dQ = CdV$$

Therefore, if voltage changes from *Vmax* to *Vmin,* the charge delivered by the capacitor

$$\int dQ = \int_{V_{max}}^{V_{min}} CdV = -C\left(V_{max} - V_{min}\right)$$

Or the magnitude of charge delivered by the capacitor

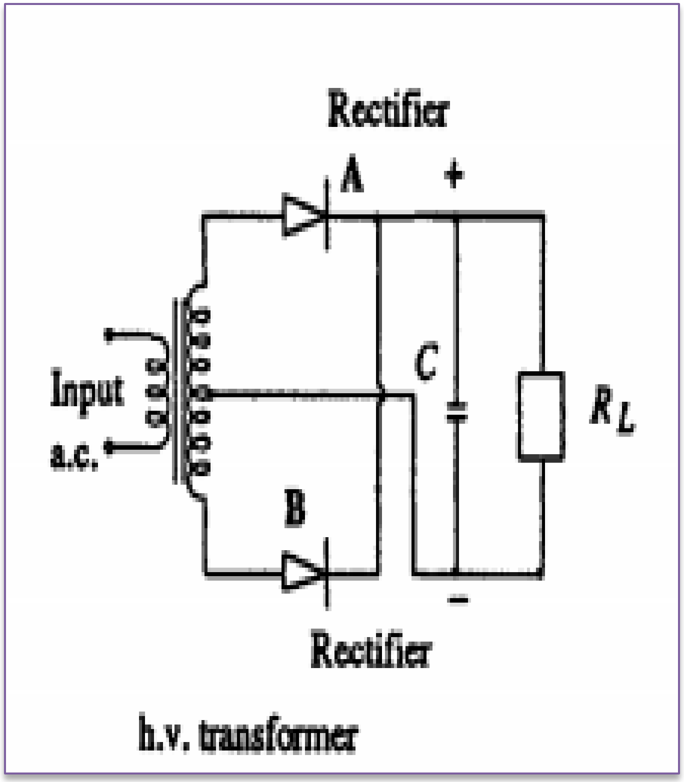
$$Q = C\,(V_{max} - V_{min})$$

$$Q = 2\delta VC$$

$$2\delta VC = IT$$

$$\delta V = \frac{IT}{2C} = \frac{I}{2fC}$$

Full Wave Rectifier Circuit



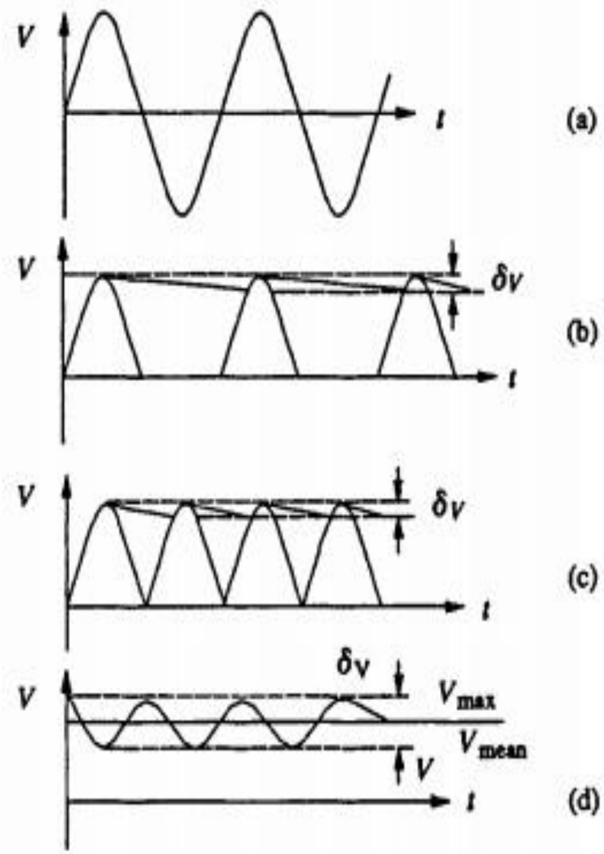


Fig. Input and output waveforms of half and full wave rectifiers

(a) Input sine wave
(b) Output with half wave rectifier and condenser filter
(c) Output with full wave rectifier and condenser filter
(d) V_{max}, V_{mean} and ripple voltage and δV with condenser filter of a full wave rectifier

Voltage doubler or cascaded voltage multiplier circuits

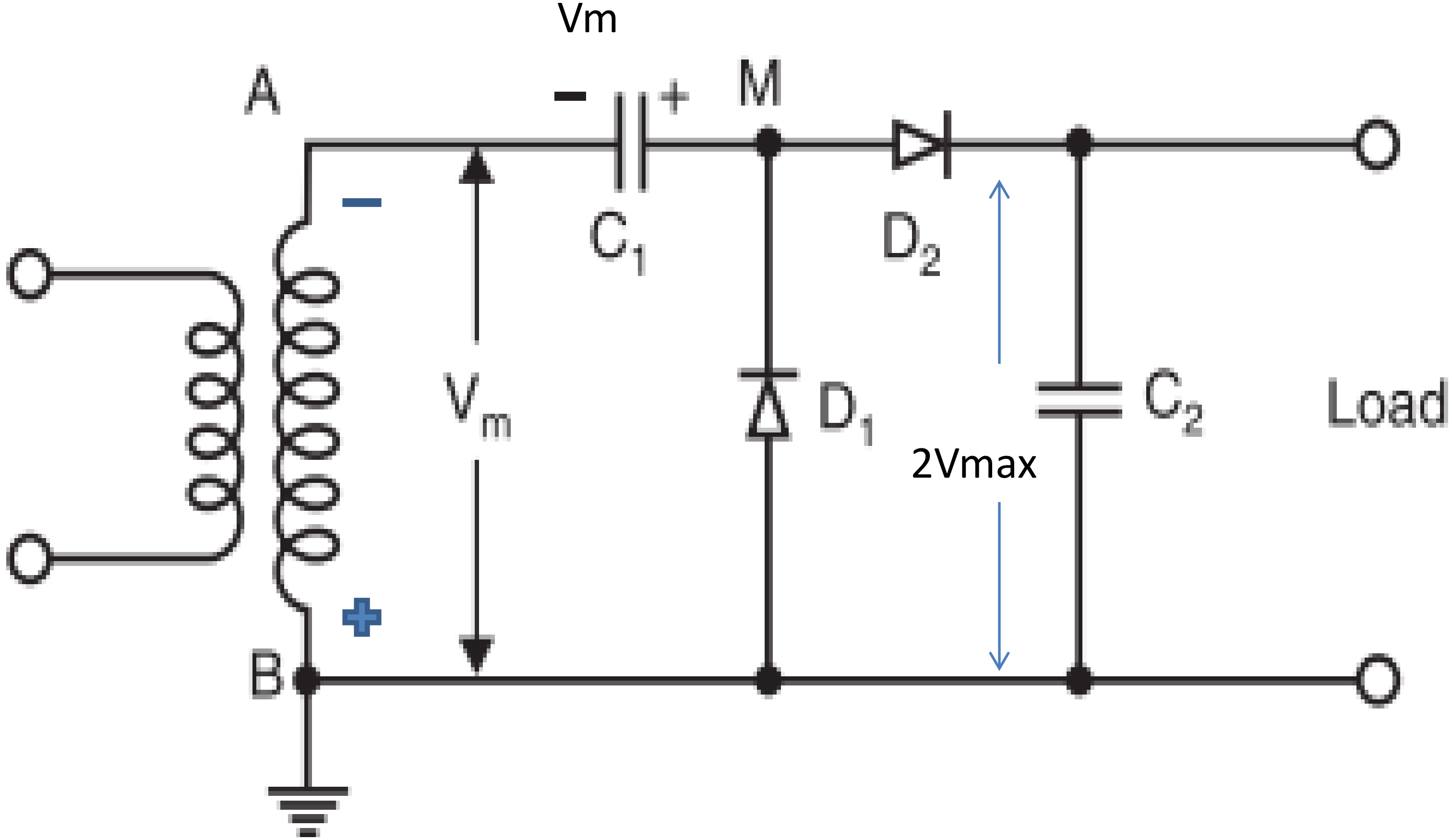


Fig. Greinacher voltage doubler circuit

COCKROFT-WALTON VOLTAGE MULTIPLIER CIRCUIT

Peak to Peak Ripple

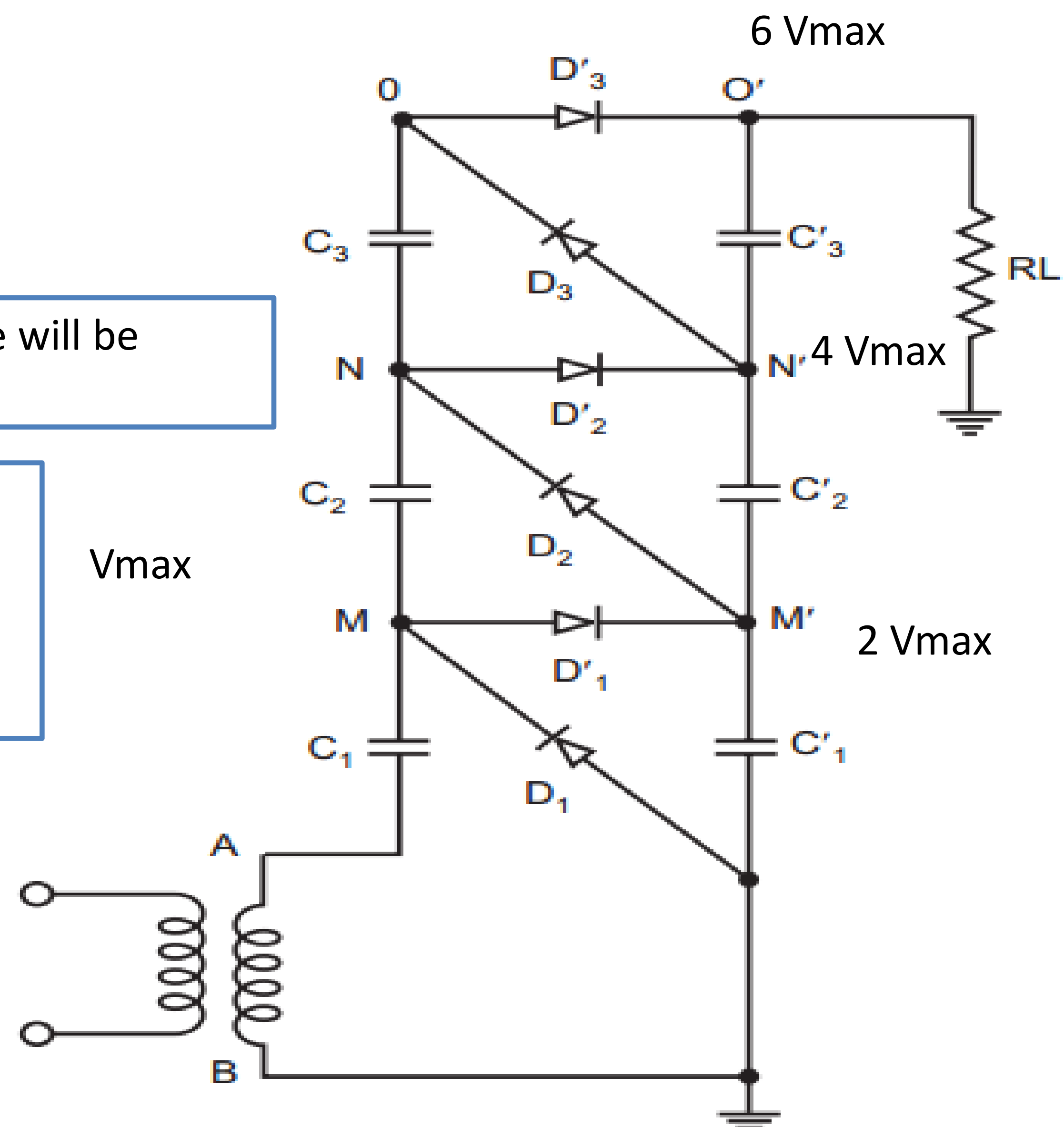
$$2\delta V = IT\sum_{n=0}^{n}\frac{1}{C'_i}$$

For *n*-stage circuit, the total ripple will be

$$2\delta V = \frac{I}{f}\left(\frac{1}{C'_n}+\frac{2}{C'_{n-1}}+\frac{3}{C'_{n-2}}+\ldots+\frac{n}{C'_1}\right)$$

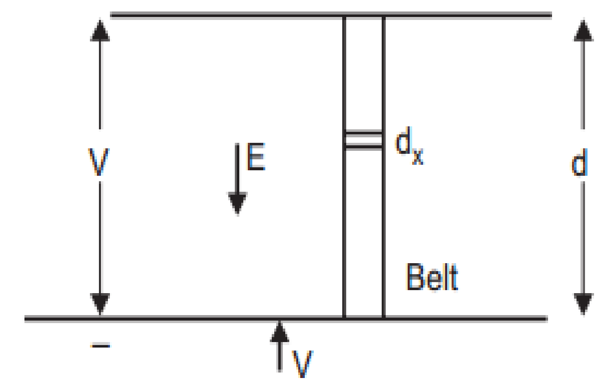
$$\delta V = \frac{I}{2f}\left(\frac{1}{C'_n}+\frac{2}{C'_{n-1}}+\frac{3}{C'_{n-2}}+\ldots+\frac{n}{C'_1}\right)$$

$$\delta V = \frac{I}{2fC}\,\frac{n(n+1)}{2} = \frac{In(n+1)}{4fC}$$



ELECTROSTATIC GENERATOR

In electromagnetic generators, current carrying conductors are moved against the electromagnetic forces acting upon them. In contrast to the generator, electrostatic generators convert mechanical energy into electric energy directly. The electric charges are moved against the force of electric fields, thereby higher potential energy is gained at the cost of mechanical energy.



An insulated belt is moving with uniform velocity v in an electric field of strength $E(x)$. Suppose the width of the belt is b and the charge density σ consider a length dx of the belt, the charge $dq = \sigma\, bdx$.

The force experienced by this charge (or the force experienced by the belt).

$$dF = Edq = E\,\sigma\, bdx$$

or $$F = \sigma b \int E dx$$

Normally the electric field is uniform

$\therefore$ $$F = \sigma b V$$

The power required to move the belt

$$= \text{Force} \times \text{Velocity}$$

$$= Fv = \sigma b V v$$

Now current $$I = \frac{dq}{dt}\,\sigma b\,\frac{dx}{dt} = \sigma b v$$

$\therefore$ The power required to move the belt

$$P = Fv = \sigma b V v = VI$$

Assuming no losses, the power output is also equal to VI.

Electrostatic Generator or Van deGraaf Generator

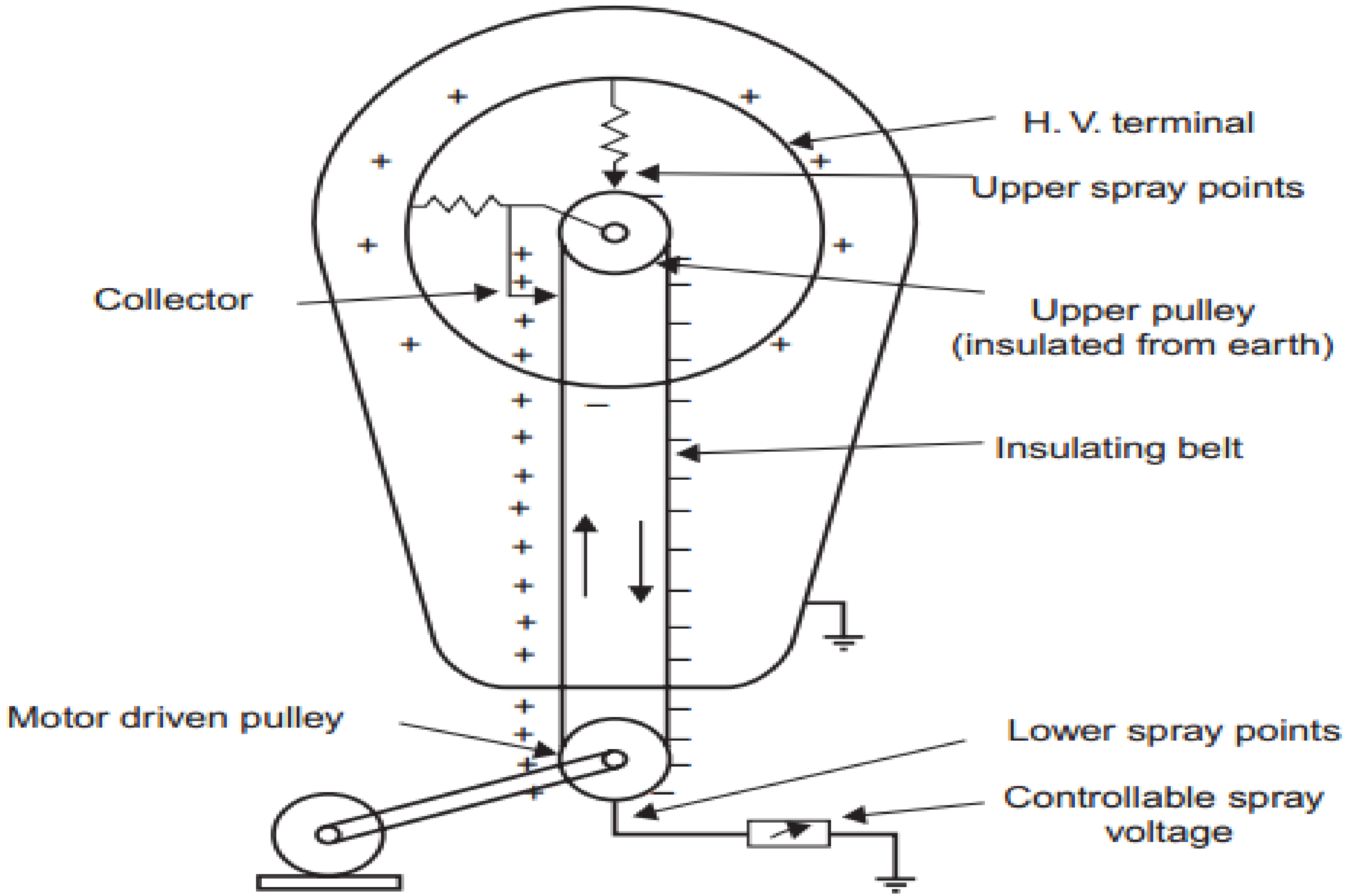


Fig. Van de Graaf generator

The potential at any instant is given as $V = q/C$ where q is the charge collected at that instant

Equilibrium is established at a terminal voltage which is such that the charging current

$$\left(I = C\frac{dV}{dt}\right)$$

The advantages of the generator are:

(*i*) Very high voltages can be easily generated

(*ii*) Ripple free output

(*iii*) Precision and flexibility of control

The disadvantages are:

(*i*) Low current output

(*ii*) Limitations on belt velocity due to its tendency for vibration. The vibrations may make it difficult to have an accurate grading of electric fields

GENERATION OF HIGH A.C. VOLTAGES

most of the testing equipments relate to high A.C. voltages

Cascaded Transformers:

For voltages higher than 400 KV

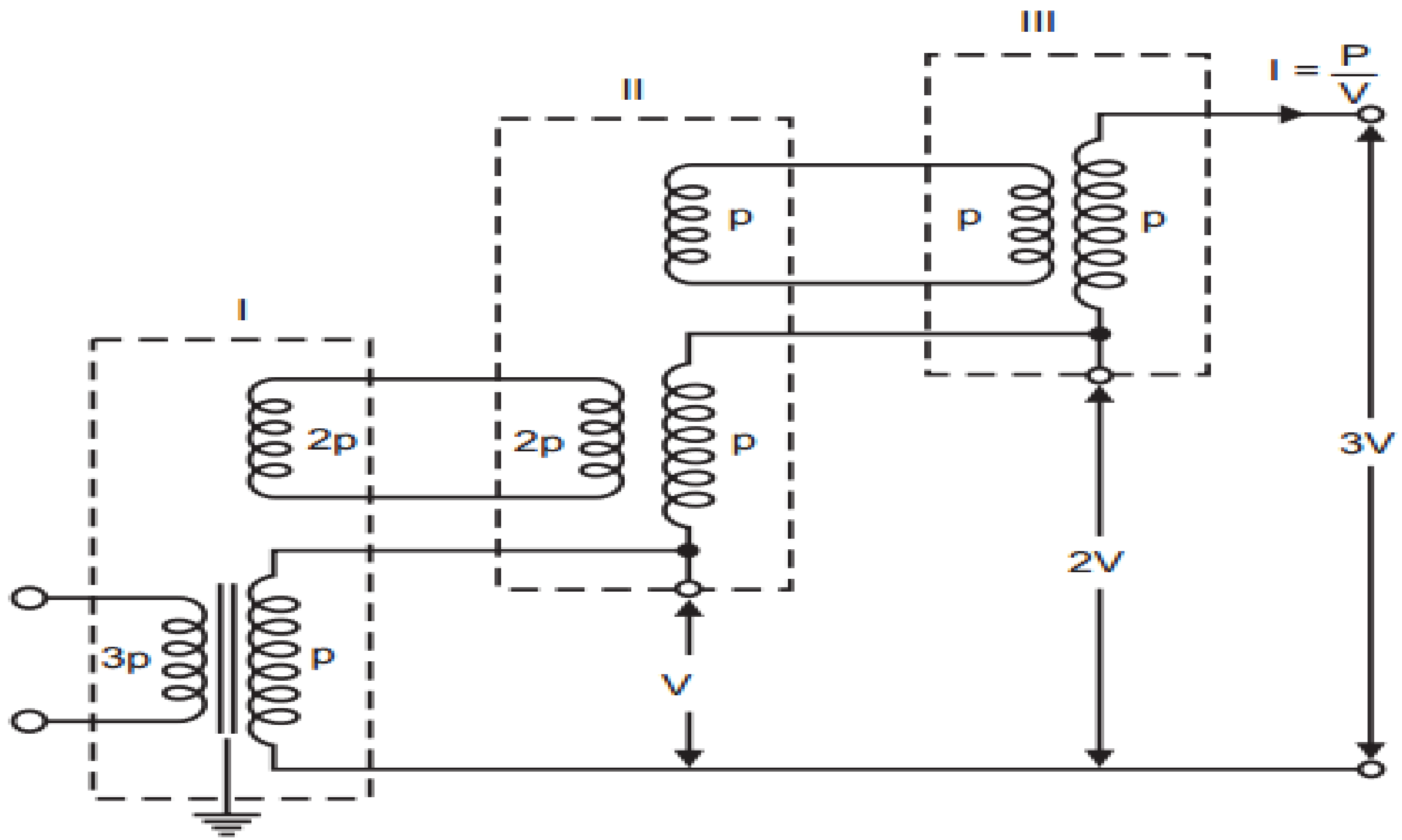


Fig. Basic 3 stage cascaded transformer

Insulators, C.B., bushings, Instrument transformers	= 0.1– 0.5 A
Power transformers, h.v. capacitors.	= 0.5–1 A
Cables	= 1 A and above

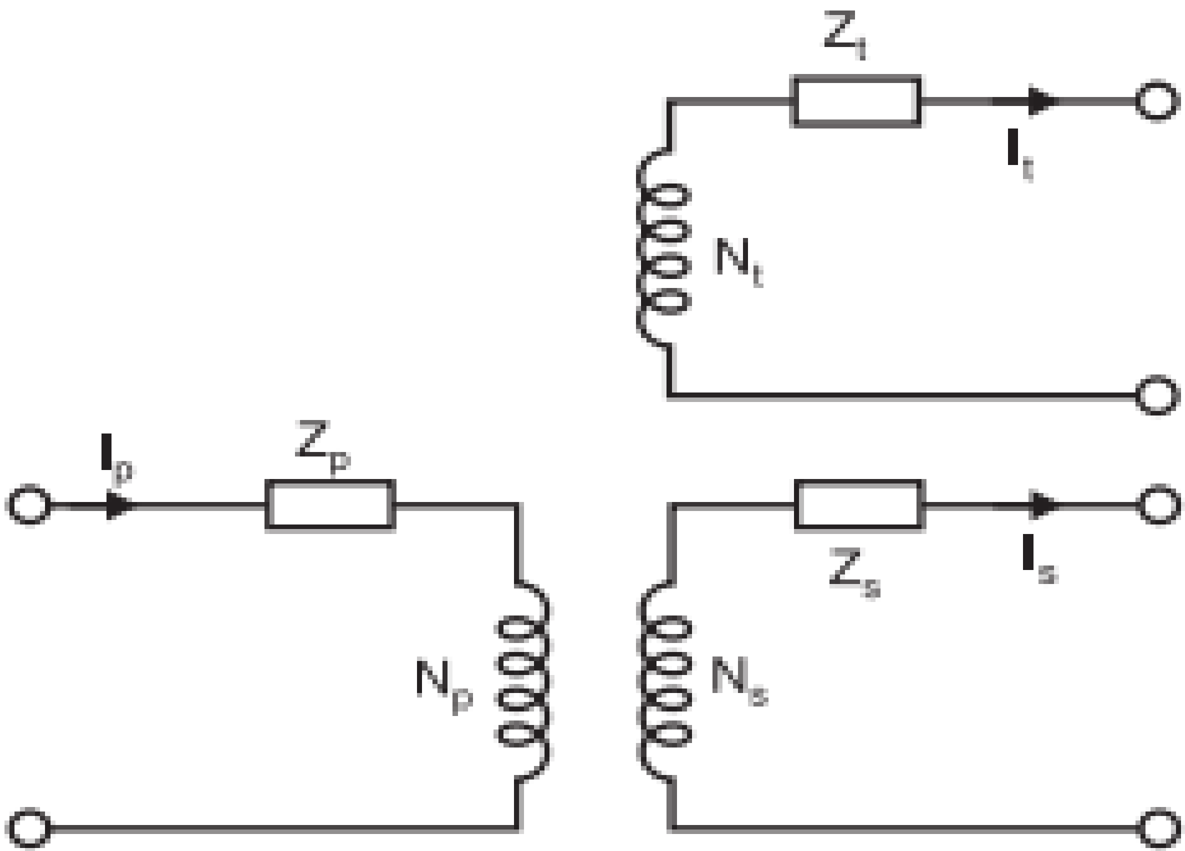


Fig. 2.10 Equivalent circuit of one stage

Let Z_{ps} = leakage impedance measured on primary side with secondary short circuited and tertiary open.

Z_{pt} = leakage impedance measured on primary side with tertiary short circuited and secondary open.

Z_{st} = leakage impedance on secondary side with tertiary short circuited and primary open.

If these measured impedances are referred to primary side then

$$Z_{ps} = Z_p + Z_s, \; Z_{pt} = Z_p + Z_t \quad \text{and} \quad Z_{st} = Z_s + Z_t$$

Solving these equations, we have

$$Z_p = \frac{1}{2}(Z_{ps} + Z_{pt} - Z_{st}), \; Z_s = \frac{1}{2}(Z_{ps} + Z_{st} - Z_{pt})$$

and
$$Z_t = \frac{1}{2}(Z_{pt} + Z_{st} - Z_{ps}) \tag{2.19}$$

Assuming negligible magnetising current, the sum of the ampere turns of all the windings must be zero.

$$N_p I_p - N_s I_s - N_t I_t = 0$$

Assuming lossless transformer, we have,

$$Z_p = jX_p, \quad Z_s = jX_s \quad \text{and} \quad Z_t = jX_t$$

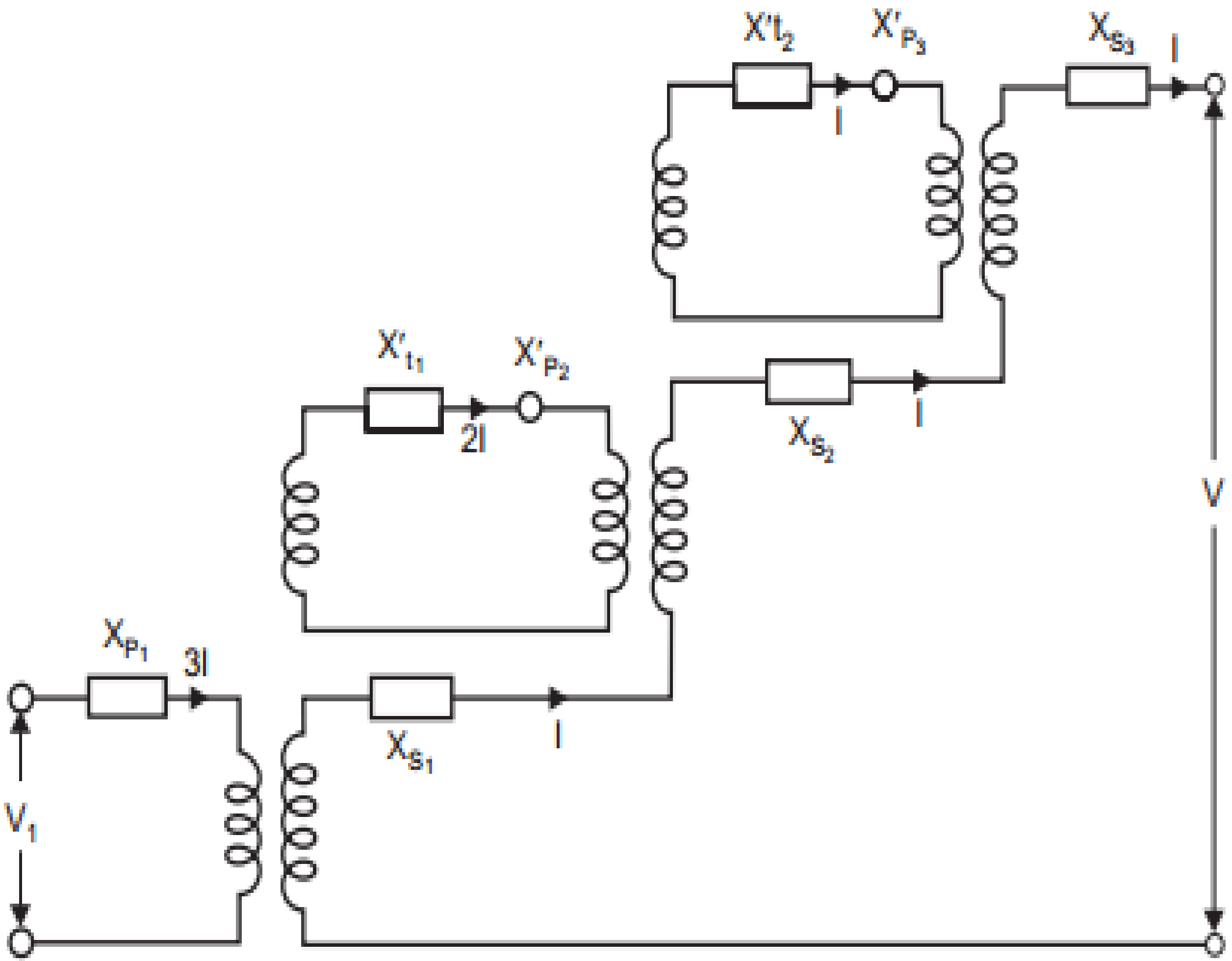
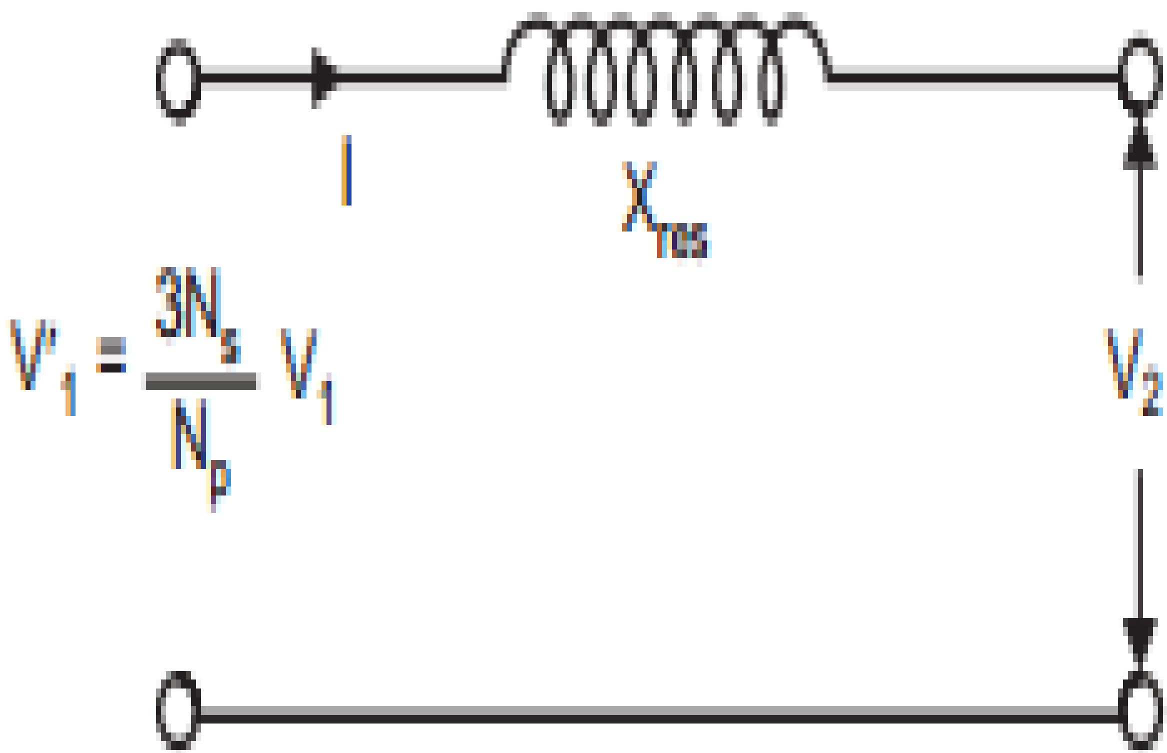


Fig. 2.11 Equivalent circuit of 3-stage transformer


I
X_{res}
$V'_1 = \frac{3N_s}{N_p} V_1$
V_2

$$I^2 X_{res} = (3I)^2 X_p + (2I)^2 X_p + I^2 X_p + I^2 X_s + I^2 X_s + I^2 X_s + (2I)^2 X_t + I^2 X_t$$

$$X_{res} = 14X_p + 3X_s + 5x_t \tag{2.20}$$

instead of $3(X_p + X_s + X_t)$ as might be expected. Equation (2.20) can be generalised for an n-stage transformer as follows:

$$X_{res} = \sum_{i=1}^{n}\left[(n-i+1)^2 X_{pi} + X_{si} + (i-1)^2 X_{ti}\right]$$

DC voltage test set 2000 kV, 10 mA for testing power cables, including a HV measuring resistor and automatic grounding system (foreground)

Three-stage cascade transformer 3 x 600 kV, 2 A cont. outdoor type with AC voltage divider 1500 kV

IMPULSE VOLTAGE

An impulse voltage is a unidirectional voltage which, without appreciable oscillations, rises rapidly to a maximum value and falls more or less rapidly to zero

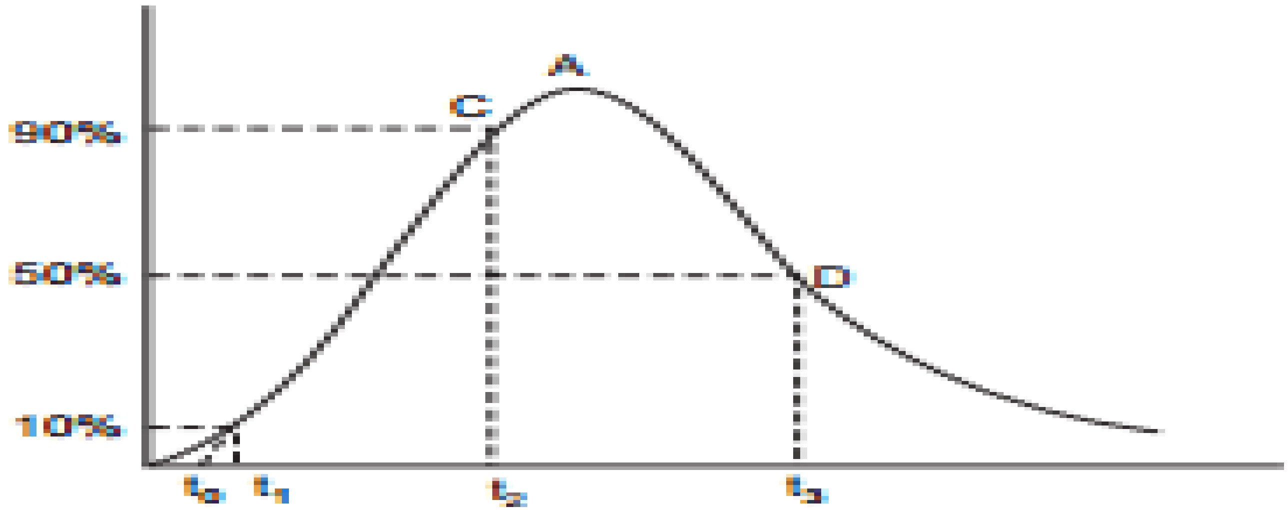


Fig. Full impulse wave

IMPULSE GENERATOR CIRCUITS

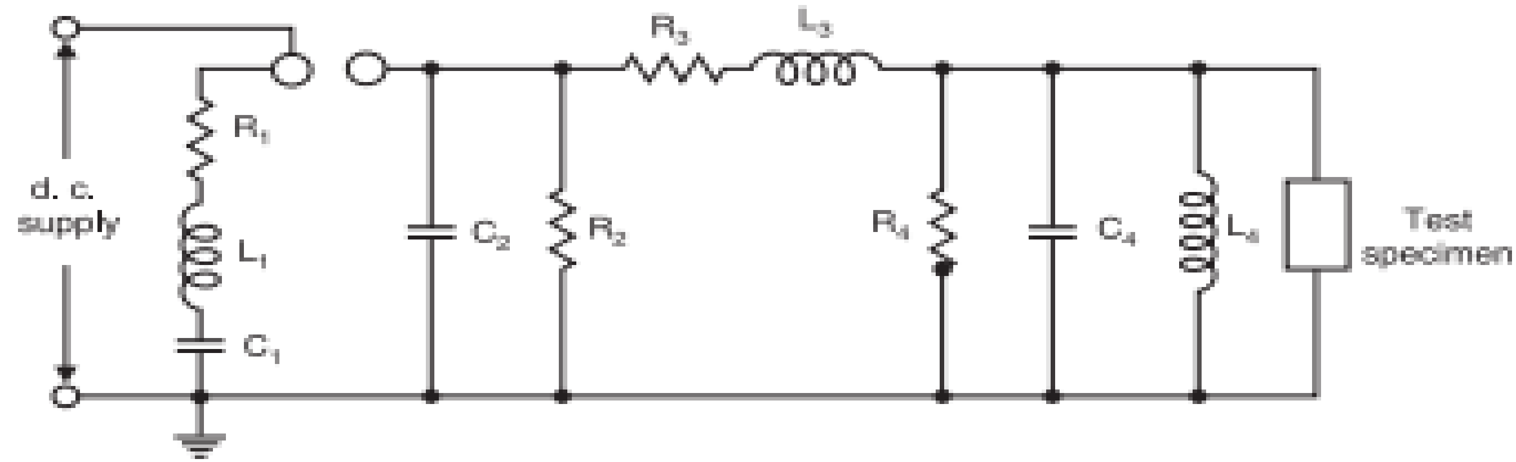


Fig. Exact equivalent circuit of a single stage impulse generator with a typical load

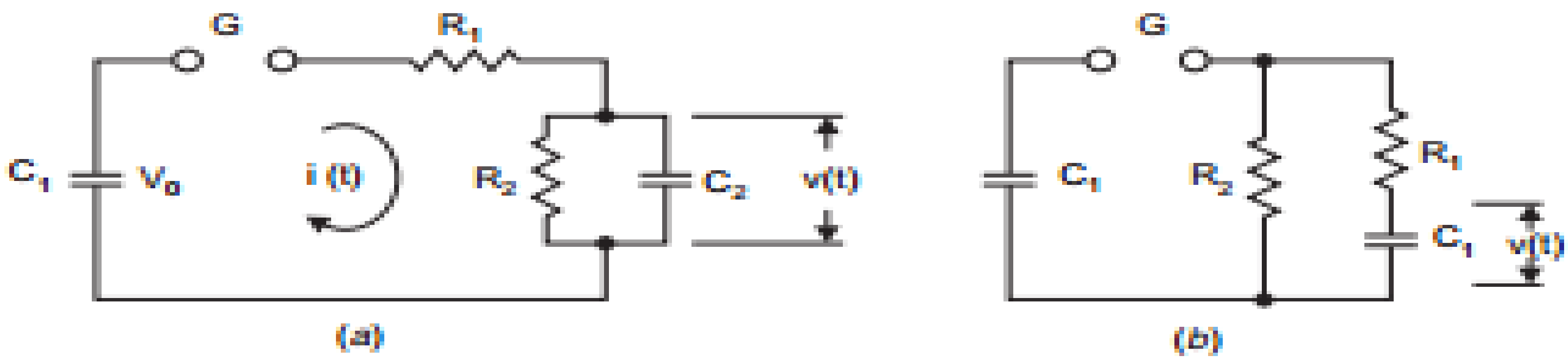


Fig. Simplified equivalent circuit of an impulse generator

MULTISTAGE IMPULSE GENERATOR CIRCUIT

(*i*) The physical size of the circuit elements becomes very large.
(*ii*) High d.c. charging voltage is required.
(*iii*) Suppression of corona discharges from the structure and leads during the charging period is
difficult.
(*iv*) Switching of vary high voltages with spark gaps is difficult.

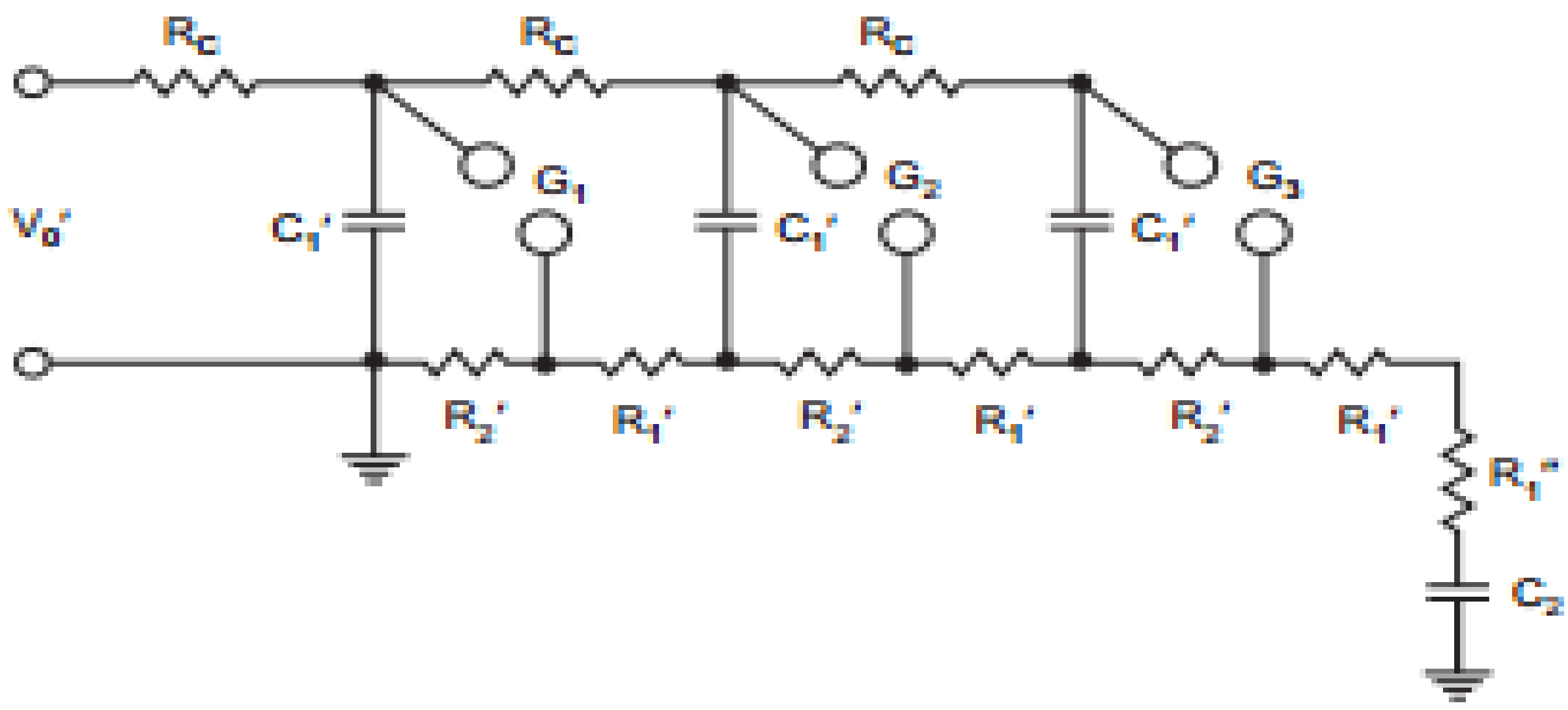
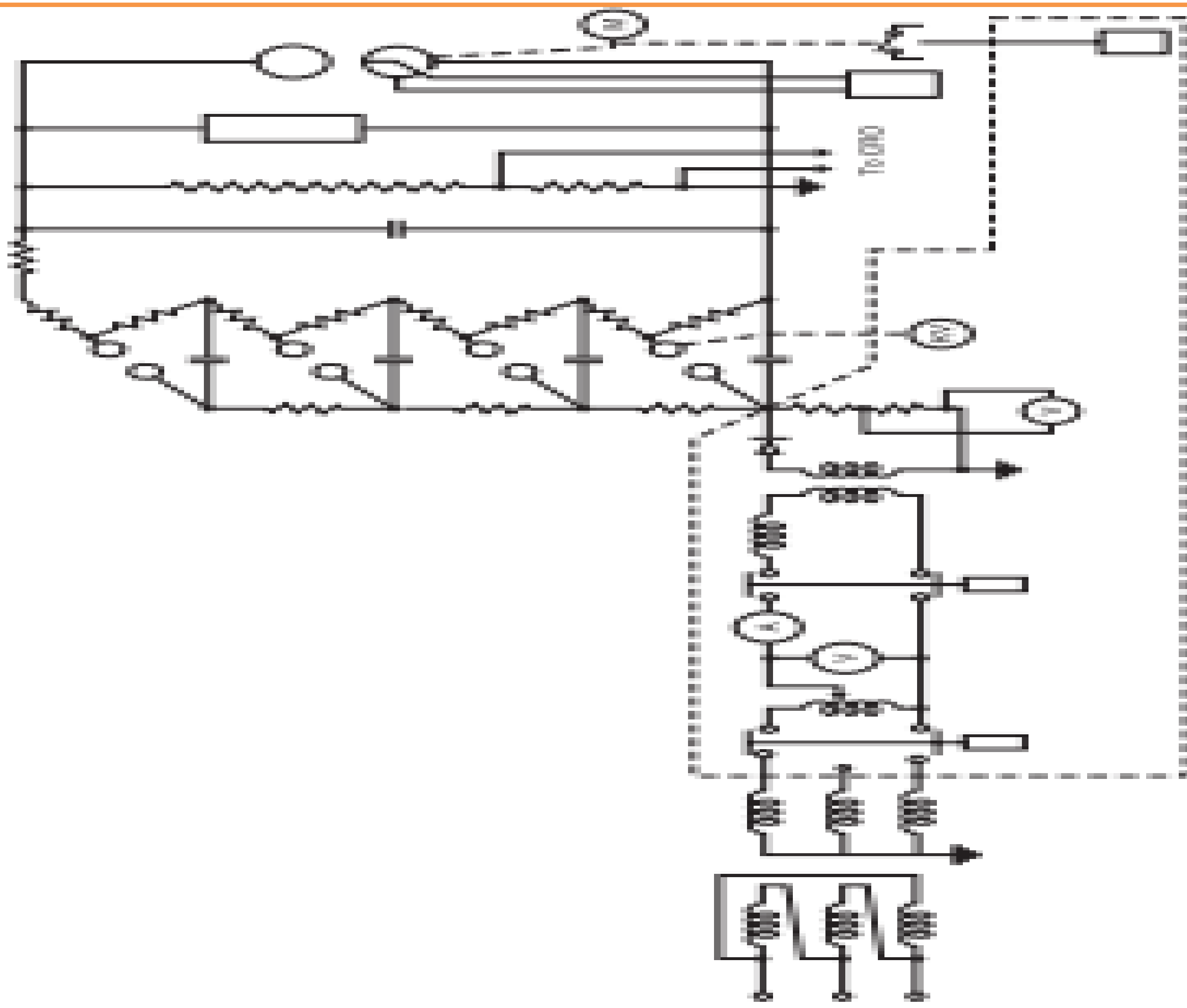


Fig. : A 3-stage Marx impulse generator in circuit '*b*' connections.

CONSTRUCTION OF IMPULSE GENERATOR



IMPULSE CURRENT GENERATION

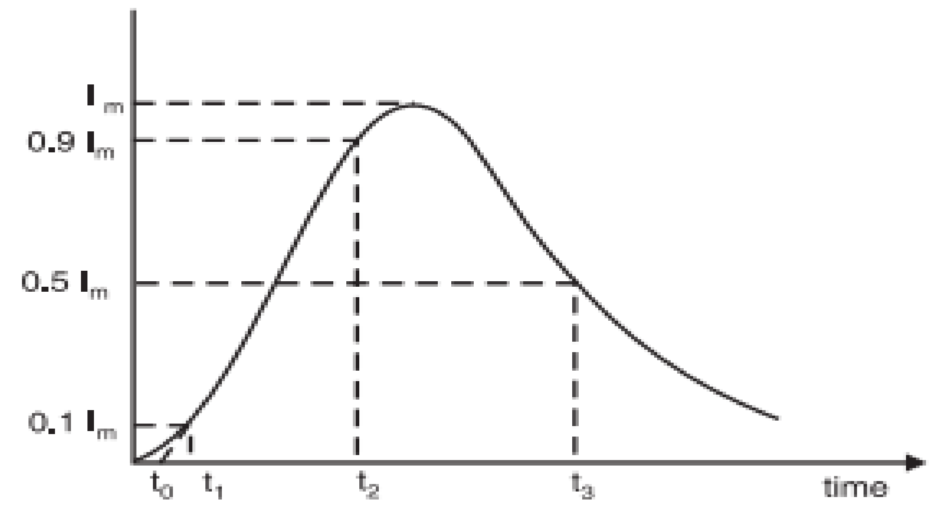


Fig. A typical impulse current wave

Analysis of Impulse Current Generator

$$i(t) = \frac{V}{\omega L} e^{-\alpha t} \sin \omega t$$

$$I_{\max} = V_0 \sqrt{\frac{C}{L}} f(\nu) = \sqrt{\frac{2W}{L}} f(\nu)$$

$$W = \frac{1}{2} C V_0^2$$

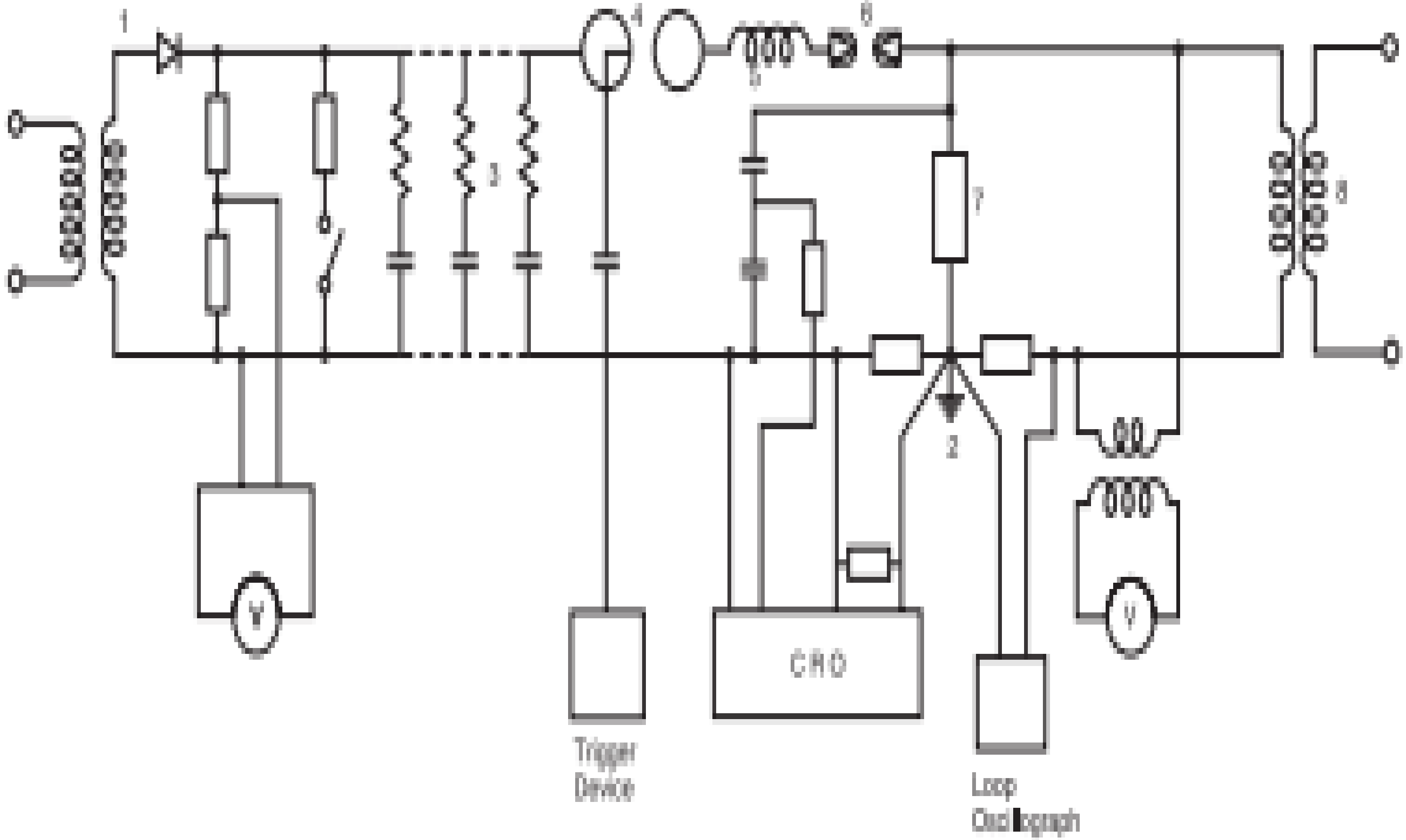


Fig. A typical impulse current generator circuit. 1. Charging unit 2. Earthing device 3. Capacitors with damping resistors 4. Firing sphere gap. 5. Reactor coil 6. Protective sphere gap 7. Test specimen (LA) 8. Test transformer for power frequency.

IMPULSE CURRENT GENERATION

High current impulse generators usually consist of a large number of capacitors connected in parallel to the common discharge path.

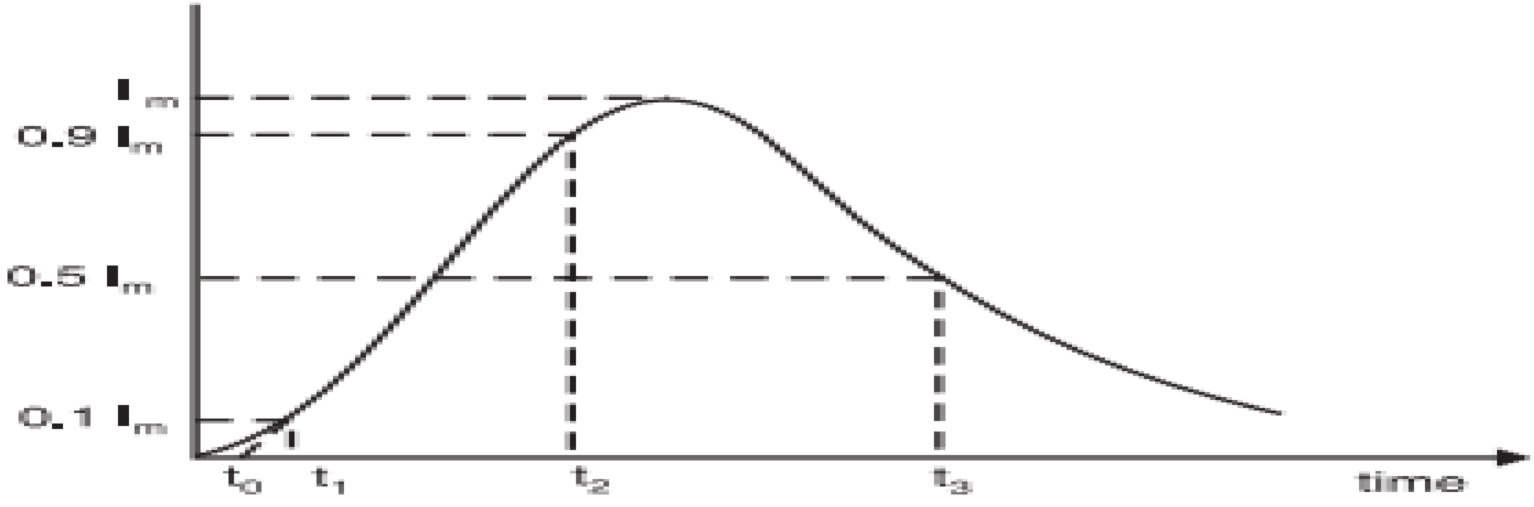


Fig. A typical impulse current wave

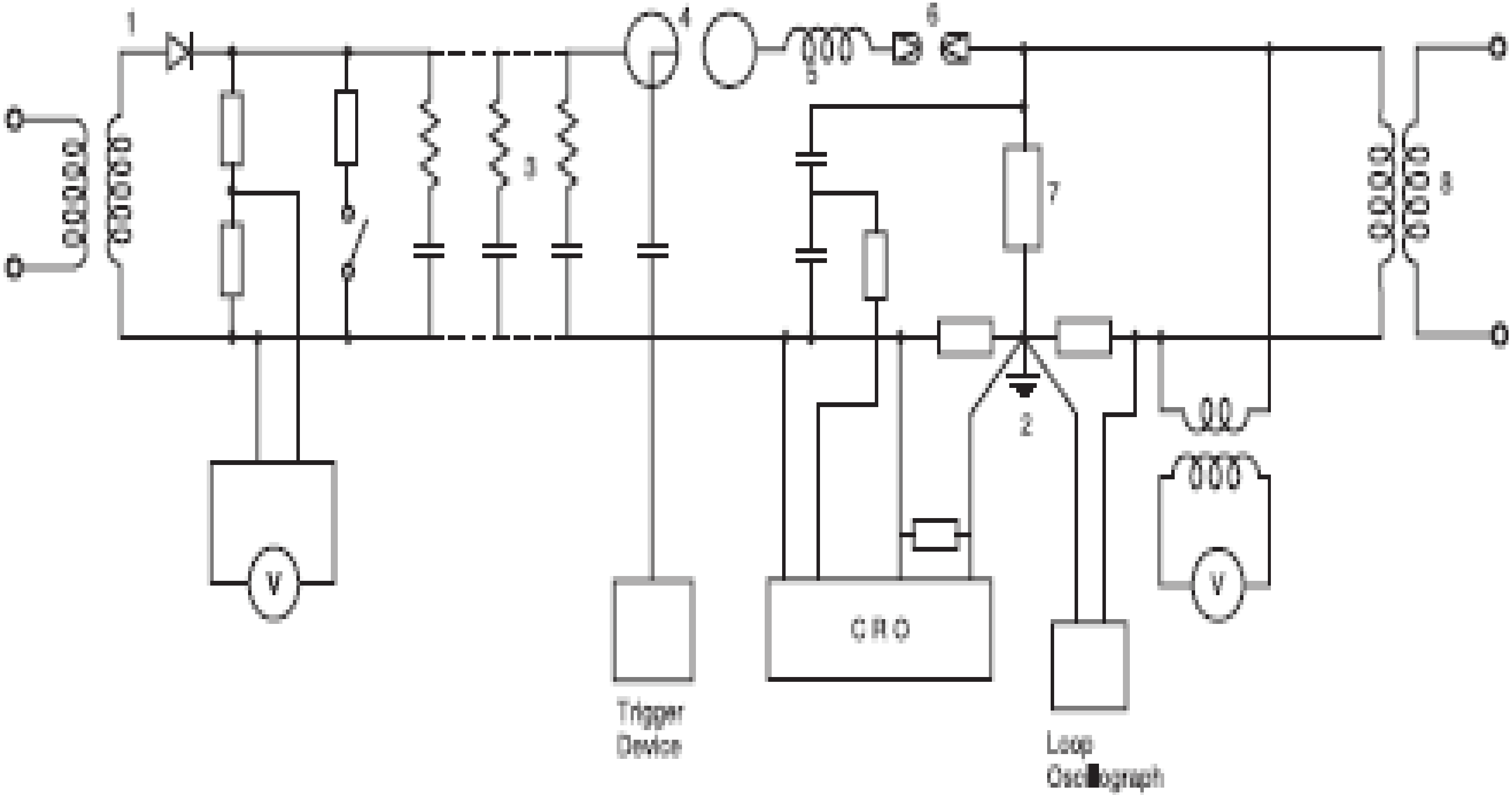


Fig. 3.14 A typical impulse current generator circuit. 1. Charging unit 2. Earthing device 3. Capacitors with damping resistors 4. Firing sphere gap. 5. Reactor coil 6. Protective sphere gap 7. Test specimen (LA) 8. Test transformer for power frequency.

Analysis of Impulse Current Generator

After the gap S is triggered, the Laplace transform current is given as

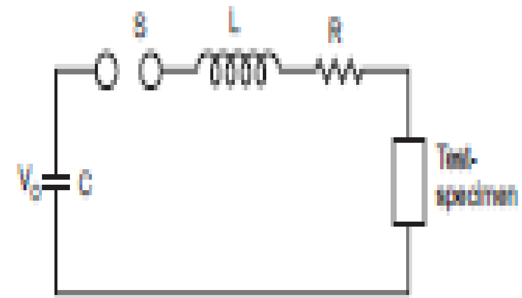


Fig. 3.15

$$I(s) = \frac{V_0}{s} \frac{1}{R + sL + 1/Cs}$$

$$= \frac{V}{L} \cdot \frac{1}{s^2 + R/Ls + 1/LC}$$

$$= \frac{V}{L} \cdot \frac{1}{(s+\alpha)^2 + \omega^2}$$

where $\alpha = \dfrac{R}{2L}$ and $\omega = \left(\dfrac{1}{LC} - \dfrac{R^2}{4L^2}\right)^{1/2}$

or
$$\omega = \frac{1}{\sqrt{LC}}\left(1 - \frac{R^2 C}{4L}\right)^{1/2} = \frac{1}{\sqrt{LC}}(1 - \nu^2)^{1/2}$$

where
$$\nu = \frac{R}{2}\sqrt{\frac{C}{L}}$$

Taking the inverse Laplace we have the current

$$i(t) = \frac{V}{\omega L} e^{-\alpha t} \sin \omega t$$

For current $i(t)$ to be maximum $\dfrac{di(t)}{dt} = 0$

$$\frac{di(t)}{dt} = \frac{V}{\omega L}[\omega e^{-\alpha t} \cos \omega t - \alpha e^{-\alpha t} \sin \omega t] = 0$$

$$= \frac{V}{\omega L} e^{-\alpha t}[\omega \cos \omega t - \alpha \sin \omega t] = 0$$

or $$\frac{\omega}{\sqrt{\alpha^2+\omega^2}}\cos\omega t - \frac{\alpha}{\sqrt{\alpha^2+\omega^2}}\sin\omega t = 0$$

or $$\sin\theta\cos\omega t - \cos\theta\sin\omega t = 0$$

or $$\sin(\theta - \omega t) = 0$$

or $$\omega t = \theta$$

or $$t_{max} = \frac{\theta}{\omega}$$

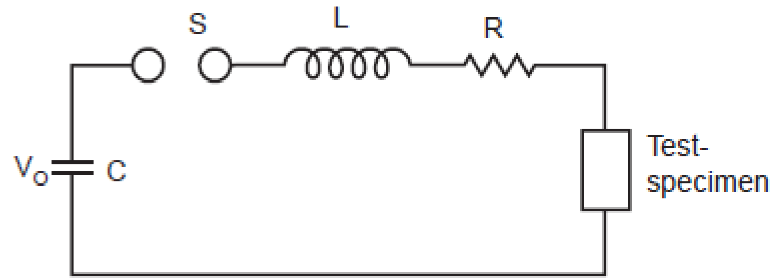


Fig. 3.15

where t_{max} is the time when the first maximum value of current occurs and

$$\theta = \sin^{-1}\frac{\omega}{\sqrt{\alpha^2+\omega^2}}$$

$$= \sin^{-1}\frac{\omega}{\left[\frac{R_2}{4L^2}+\frac{1}{LC}-\frac{R^2}{4L^2}\right]^{1/2}}$$

$$= \sin^{-1}\sqrt{LC\,\omega}$$

or $$t_{max} = \frac{\sin^{-1}\sqrt{LC\omega}}{\omega} = \frac{\sin^{-1}\sqrt{LC}\,.\,\frac{1}{\sqrt{LC}}(1-\nu^2)^{1/2}}{\frac{1}{\sqrt{LC}}(1-\nu^2)^{1/2}}$$

or $$t_{max} = \sqrt{LC}(1-\nu^2)^{-1/2}\sin^{-1}(1-\nu^2)^{1/2} = \sqrt{LC}.\frac{\sin^{-1}(1-\nu^2)^{1/2}}{(1-\nu^2)^{1/2}}$$

Substituting the value of $t = t_{\max}$ in (3.25) the first maximum value of current is given as

$$I_{\max} = \frac{V_0 \sqrt{LC}}{(1-\nu^2)^{1/2} L} . \operatorname{Exp}\left[- \frac{R\sqrt{LC}}{2L} \frac{\sin^{-1}(1-\nu^2)^{1/2}}{(1-\nu^2)^{1/2}} \right]$$

$$\sin \left\{ \frac{(1-\nu^2)^{1/2}}{\sqrt{LC}} . \sqrt{LC}\,(1-\nu^2)^{-1/2} \sin^{-1}(1-\nu^2)^{1/2} \right\}$$

$$= \frac{V_0}{(1-\nu^2)^{1/2}} . \sqrt{\frac{C}{L}} . \operatorname{Exp}\left[\frac{-\nu \sin^{-1}(1-\nu^2)^{1/2}}{(1-\nu^2)^{1/2}} \right] . \sin\left\{ \sin^{-1}(1-\nu^2)^{1/2} \right\}$$

$$= V_0 \sqrt{\frac{C}{L} \operatorname{Exp}\left[\frac{-\nu \sin^{-1}(1-\nu^2)^{1/2}}{(1-\nu^2)^{1/2}} \right]}$$

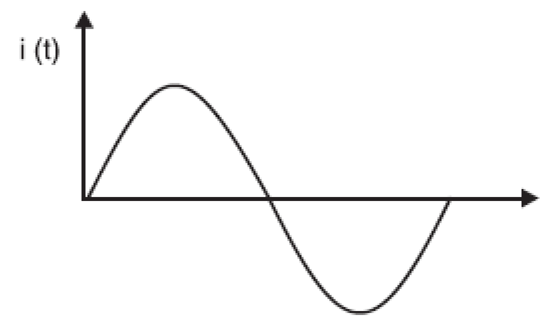


Fig. Current response of circuit .

Equation (3.26) can be rewritten as

$$I_{\max} = V_0 \sqrt{\frac{C}{L}} f(\nu) = \sqrt{\frac{2W}{L}} f(\nu)$$

where $$W = \frac{1}{2} C V_0^2$$

the initial energy stored by the generator.

If $R = 0$, $\nu = 0$ then from equation (3.26) it is clear that $I = V_0 \sqrt{C/L}$ and from equation :

$$i(t) = V_0 \sqrt{\frac{C}{L}} \sin \frac{t}{\sqrt{LC}}$$