High Voltage and Insulation Engineering

Topics to be discussed

- Generation of High voltage
  - ❖ High dc voltages
  - ❖ High ac voltages
  - ❖ High transient or impulse voltages

- Measurement of High voltage

- Behavior of Insulation
  - ❖ How we can design the insulation apparatus for High voltage.
  - ❖ Test the apparatus before installation.
  - ❖ Test the apparatus before operation.
  - ❖ Conduction phenomenon in Solids, liquids and Gaseous.

Generation of High voltages

- Generation of High Voltages: In the fields of electrical engineering and applied physics, high voltages (d.c, a.c and impulse) are required for several applications.
- A.C generation: High a.c voltages are required for testing power apparatus.
- D.C generation: Electrostatic precipitators, particle accelerators in nuclear physics and X-rays etc. require high voltages(d.c) of several kilovolts.
- Impulse generation: High voltages are required for testing purposes to simulate overvoltages that occur in in power systems due to lightning and switching action.

Optimum insulation level

- Three categories of Tests
  - ❖ Type - Design
  - ❖ Routine - Open Circuit and Short Circuit tests
  - ❖ Special - Unique tests.

- Air (Gaseous)at atmospheric pressure is the most gaseous insulation.
- Paper/cloth tape (solid)is the insulation for Rotating machine.
- Oil (liquid) acts as insulation for Transformer.
- Conducting phenomenon depends on peak value.
- Tests: Life tests, Aging tests and Accelerated Aging tests.

Test Sources

The important properties required for Test transformers are:

- ❖ Reproducibility
- ❖ Repeatability
- ❖ Portable
- ❖ High voltage Test devices are low current
- ❖ Reduces volume when it makes single phase

- In test Transformer ,occurrence of S.C is more than Power Transformer.
- High Voltage Test Centers: CPRI(Hyd), BHEL(Bhopal).
- IISC Bangalore – 3 Million Volt Impulse generation.
- Innumerable High voltage's are used but in major cases 100KV limited.

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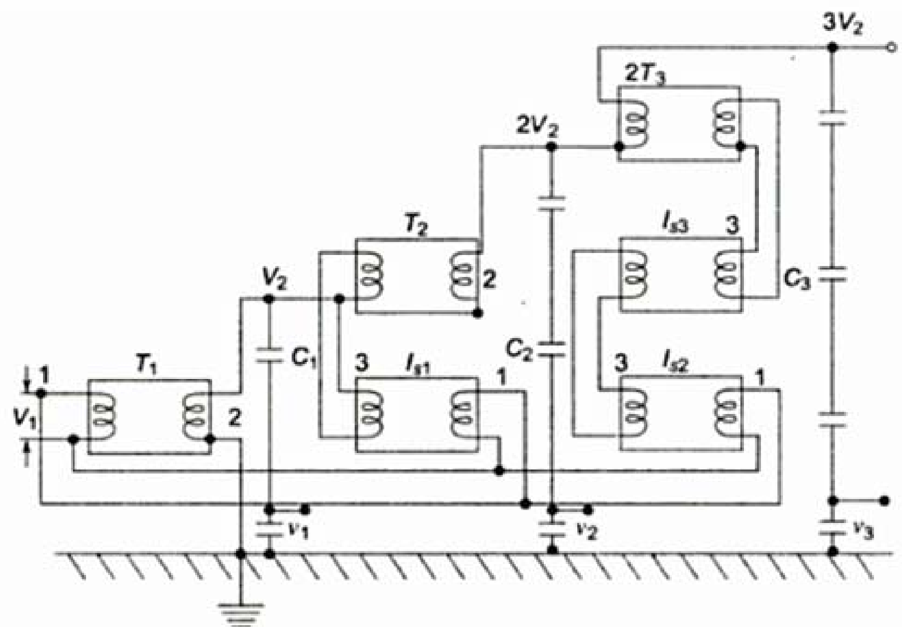
- Required amount of current depends on the equipment we are testing.
- Above 300KV, we will use the cascading of the transformers.
- Sinusoidal property must not be altered.

Cascade Transformers



T_1, T_2, T_3 — Cascade transformer units
I_{s1}, I_{s2}, I_{s3} — Isolation transformer units
C_1, C_2, C_3 — Capacitance voltage dividers for hv measurement after 1st, 2nd and 3rd stages
V_1, V_2, V_3 — For metering after 1st, 2nd and 3rd stages
1. Primary (lv winding), 2. hv winding, 3. Excitation winding

fig.1 Cascade transformer unit with isolating transformers for excitation

- First Transformer is at the ground potential along with its tank.
- Second transformer is kept on insulators and maintained at a potential of V_2, the output voltage of the first unit above the ground.
- The High voltage winding of the first unit is connected to the tank of the second unit. The low-voltage winding of this unit is supplied from the excitation winding of the first transformer, which in series with the high voltage winding of the first transformer at its high-voltage end.
- The rating of excitation winding is almost identical to that of the primary or the low-voltage winding.
- In a similar manner, the third transformer is kept on insulators above the ground at a potential of $2V_2$ and is supplied from the second transformer.

fig.2. Cascaded testing transformers with metal tanks and coolers
Total voltage 3000 kV, 4A (courtesy HIGH-VOLT Dresden, Germany)

Problem#1

Q1.A cascade transformer of 3 stages each having 350KV/stage and 1A current rating. Find

a)The ratings of each unit.

b)Total Output voltage.

Sol. At 3rd stage rating of the secondary winding = 350KVx1A=350KVA(P)

At 3rd stage :

Secondary Winding rating : P

Primary Winding rating:P

At 2nd stage:

Secondary Winding rating: P

Excited Winding rating: P

Primary Winding rating : 2P

At 1st stage:

Secondary Winding rating:P

Excited Winding rating :2P

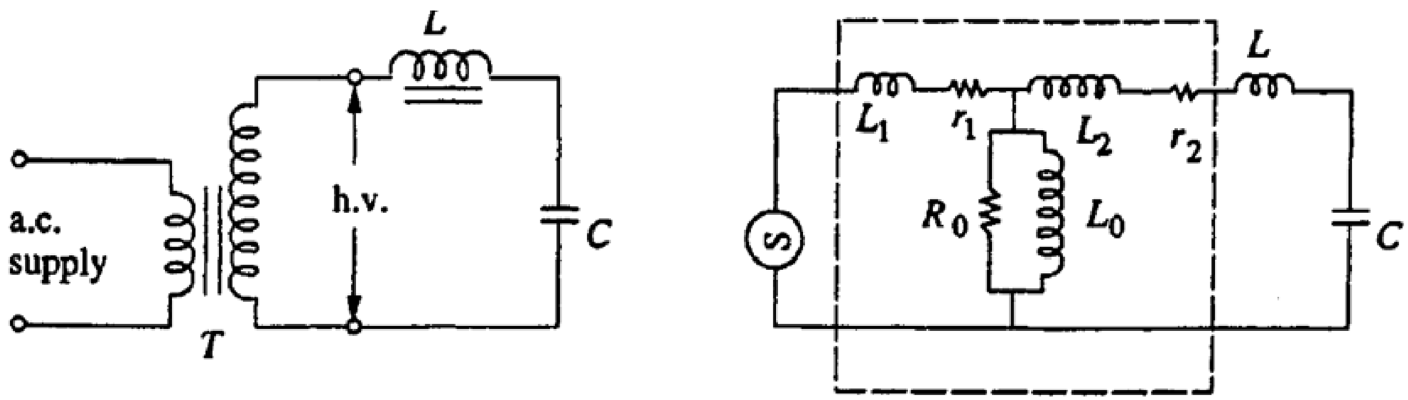
Primary Winding rating :3P

- Multiple rated ones are having more cost than Same rated ones.

Input to the units can be obtained from

- Motor-generator set
- Induction Regulator
- Auto-Transformer (Complete Control)

Resonant Transformers



(a) Transformer

(b) Equivalent circuit

T — Testing transformer
L — Choke
C — Capacitance of h.v. terminal and test object

L_1, L_2 — Leakage inductances of the transformer
r_1, r_2 — Resistances of the windings
R_0 — Resistance due to core loss

fig.3 Resonant Transformers

Resonance

- Resonance of a circuit involving capacitors and inductors occurs because magnetic field of the inductor generates an electric current in its windings that charges the capacitor, and then the discharging capacitor provides an electric current that builds the magnetic field in the inductor.

- It may be seen that it is possible to have series resonance at power frequency ω, if

$$\omega(L_1 + L_2) = 1 / \omega C$$

- With this condition, the current in the test object is very large and is limited only by the resistance of the circuit.

- The waveform of the voltage across the test object will be purely sinusoidal.

- Resonance of a harmonic can similarly occur, as harmonic currents are present due to the transformer iron core. Resonances are not quite so disastrous, but third harmonics have been observed of greater amplitude than the fundamental, and even the thirteenth harmonic can give a 5% ripple on the voltage waveform. This form of harmonic resonance causes greater voltage distortion .

- The factor $X_C/R = 1/\omega CR$ is the Q factor of the circuit and gives the magnitude of the voltage multiplication across the test object under resonance condition.

- Therefore , the input voltage required for excitation is reduced by a factor 1/Q, and the Output KVA is also reduced by a factor of 1/Q.

- This principle is utilized in testing at very high voltages and on occasions requiring large current outputs such as cable testing, dielectric loss measurements, partial discharge measurements etc.

- The chief advantages of the above principle are:
  - ❖ It gives an output of pure sine wave
  - ❖ Power requirements are less (5 to 10% of total KVA required)
  - ❖ No high-power arcing and heavy current surges occur if the test object fails as resonance ceases at the failure of the test object.
  - ❖ Cascading is also possible for very high voltages
  - ❖ Simple and compact test arrangement.

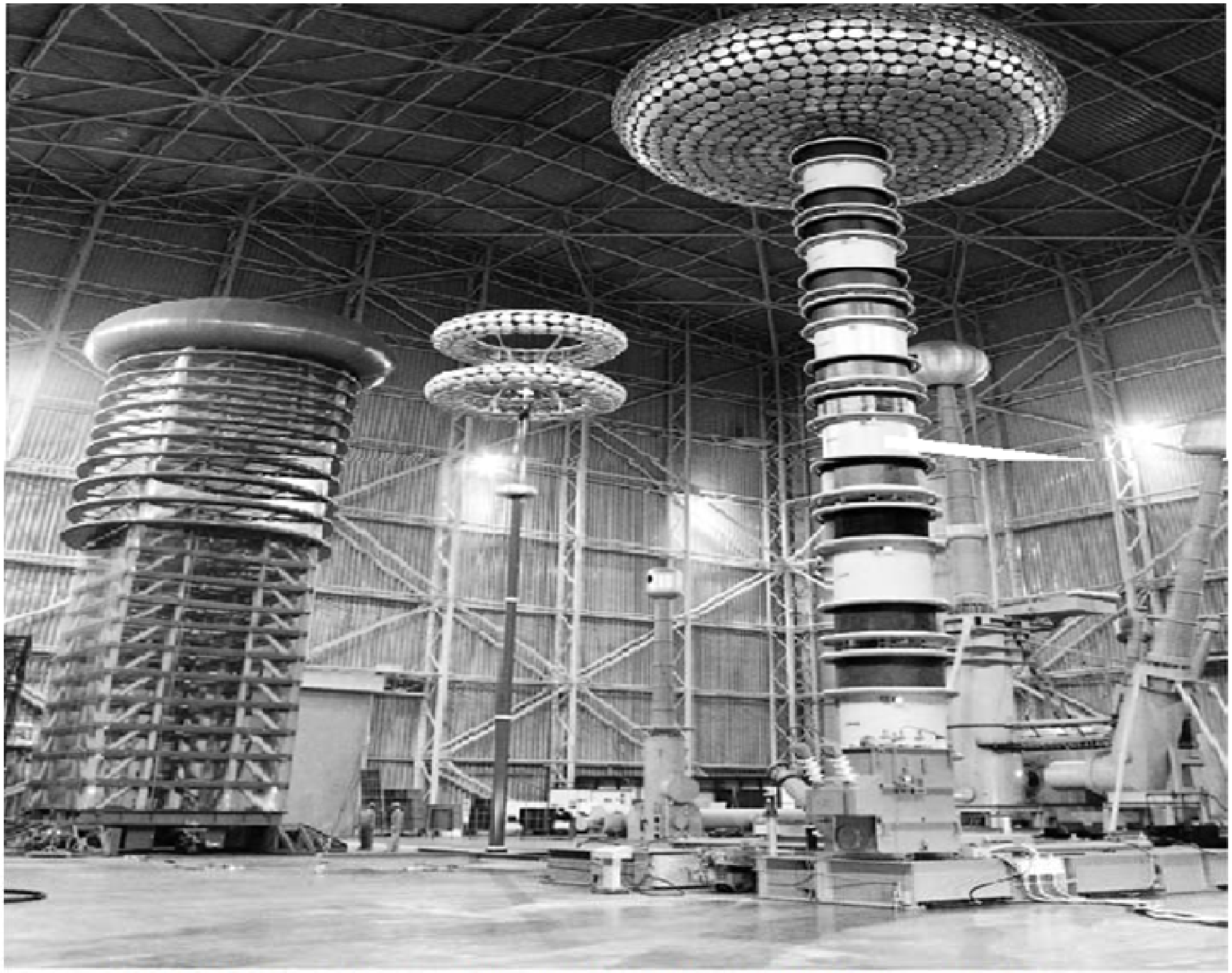


fig.4 2.2 MV Series Resonant Circuit (Hitachi Research Lab, Brewster, USA)

Contd..

- Resonance test source is used for a.c but not for d.c

- Resonance based test sources reduces stress on the test source. Additional Inductor has to be added for resonance.

- Cables are predominantly capacitive in nature.(Increase in capacitance is proportional to the cable length).For field testing of cables, large rotating machines or metal-clad gas insulated substations(GIS), a still further reduction of weight and size of the testing equipment is very desirable.

- An insulation based Industry uses often the resonant based test sources.

- By resonance, the decrease in the weight of transformer

  10-35 Kg/KVA to 1-10 Kg/KVA

Problem#2

- A test transformer 0.400/400KVA ,40KVA, leakage reactance is 8%.Input Excitation is 300V. Test object capacitance is 3000PF.
  a) Determine the voltage applied to the test object.
  b) Determine the test voltage if C_{stray} = 5000PF is added in parallel.
  c) Find at what condition, the source will resonate @ 60hz and find the output voltage.

Solution

- Given the input excitation voltage =300V =0.75(p.u)

  Leakage reactance = 0.08 (p.u)

  Test object capacitance $X_c = 1/j\omega C = -10.61 \times 10^5 j$

  $Z_{base} = (400k)^2/40k = 4M\Omega$

  Therefore, the test object capacitance in p.u is $X_c / Z_{base} = -0.265j$

a) The voltage across the test object is

$$V_0 = ((-.265j)*(0.75)/(0.08-0.265)j) * 400k = 430kV$$

b) $C_{eq} = C_1 + C_2$

$$X_{eq} = 1/j\omega(C_1+C_2) = -9.09\times10^5 j = -0.227j \text{ (p.u)}$$

$$V0 = ((-0.227j)(0.75)/(0.08-0.227)j) * 400k = 464kV$$

c) $L_p = 0.32/(2*3.14*50)$

$L_{sec} = Lp \times 10^6$

At resonance, $\omega L = 1/\omega C$

$C = 6.9nF$

$X_c = -3.83x105j = -0.1152j$ (p.u)

Current in the circuit is i = V/R = 0.75/0.01 = 75 (p.u)

Output voltage = i * X_c = 75* 0.1152

= 8.64 p.u

= 8.64*400K = 3.456MV

Problem#3

- A 100 KVA, 400v/250kv test transformer has 8% reactance, 2% resistance on 100KVA base. A cable is to be tested at 500kv using this transformer as a resonant transformer at 50hz. Given the charging current of cable to be 0.4A at 500kv.

  a)Determine the inductance required.

  b)Resistance of Inductor assumed to be 2%.Determine the i/p voltage of transformer.

Solution

- a) Reactance of the Cable = X_c =V/I = 500k/0.4 =1250kΩ.
  where as Reactance of transformer(leakage) = 50kΩ.
  Hence Inductance reactance required will be 1200kΩ.
  The value of Inductance required will be 3820H.

  b) Total resistance in the circuit= 4%= 25kΩ.
  At resonance, the excitation voltage on the secondary side is 10kV
  Primary voltage = Input voltage applied = 16V.

Rectifiers

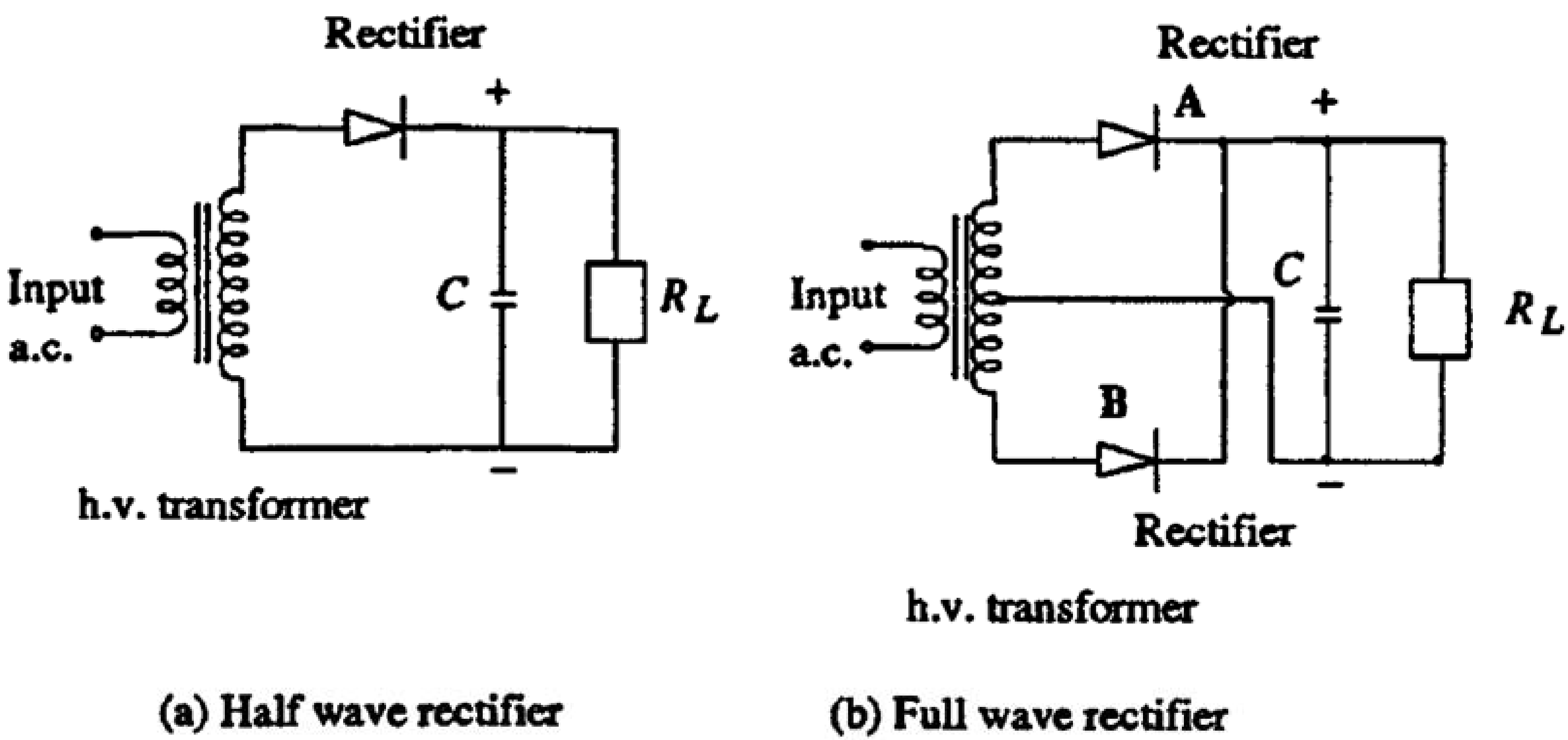


fig.5 Rectifiers

Ripple

- When on load, the capacitor gets charged from the supply voltage and discharges into load resistance R_L whenever the supply voltage varies from peak value to zero value.
- A fluctuation in the output dc voltage δV appears and it is called Ripple.
- Ripple voltage δV is larger for a half-wave rectifier than that for a full-wave rectifier.
- The ripple δV depends on
  a) Supply voltage frequency f
  b) Time constant CR_L
  c) Reactance of the supply transformer X_L.
- For half-wave rectifiers, the ripple frequency is equal to the supply frequency and for full-wave rectifiers, it is twice that value.

Voltage Doubler

- During the Negative half cycle, the capacitor C_1 is charged through rectifier R_1 to a voltage of $+V_{max}$.
- As the voltage of the transformer rises to positive $+V_{max}$ during the next half cycle, the potential of the other terminal of C1 rises to a voltage of $+2V_{max}$.Capacitor C_2 is charged through R_2 to $2V_{max}$.
- Rectifiers are rated to PIV of $2V_{max}$ and the Capacitors must also have the same rating.

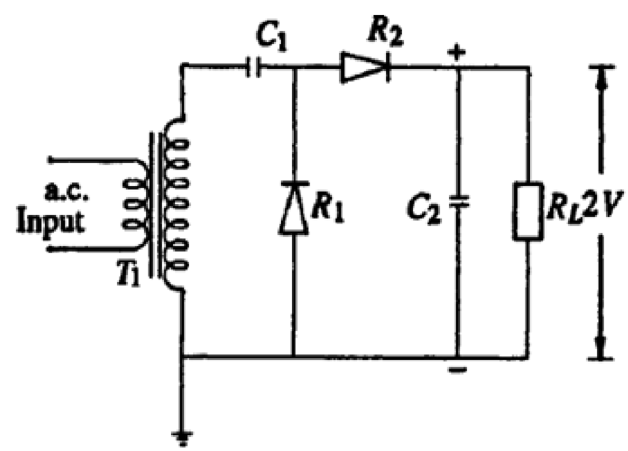


fig. 6 Voltage Doubler

Cascaded Voltage Doubler

- The rectifiers R_1 and R_2 with transformer T_1 and capacitors C_1 and C_2 produces an output voltage of 2V in the similar way.
- Connected in series or cascade to obtain a further voltage doubling to 4V.
- T is an isolating transformer to give an insulation for $2V_{max}$ since the transformer T_2 is at a potential of $2V_{max}$ above the ground.
- This arrangement becomes cumbersome if more than 4V is needed with cascaded steps.

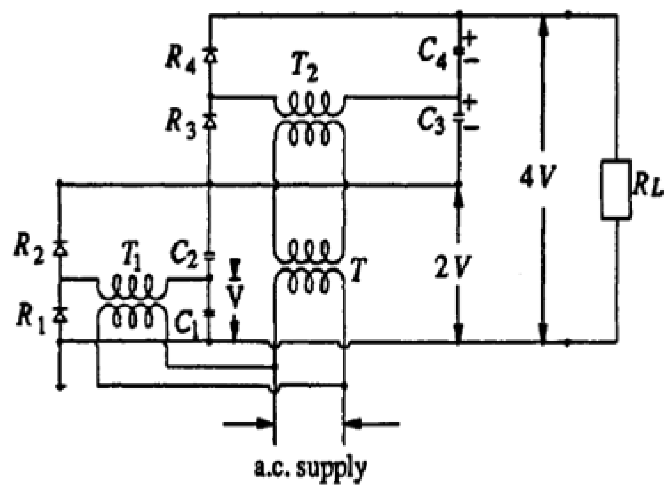
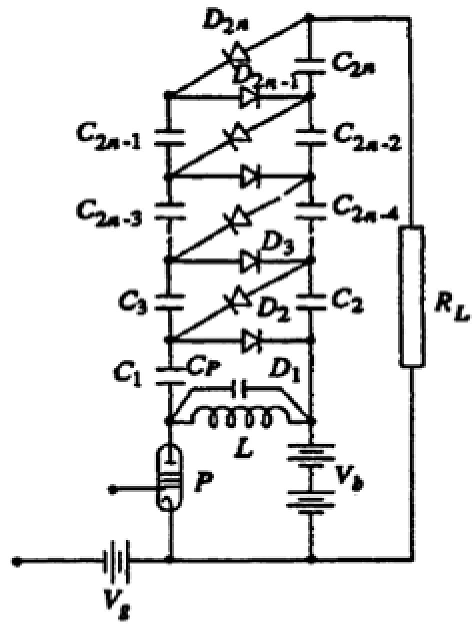


fig.7 Cascaded Voltage Doubler

Voltage Multiplier

- Pulses generated in the anode circuit of the valve P are rectified and the voltage is cascaded to give an output of $2nV_{max}$ across the load R_L.
- A trigger voltage pulse of triangular waveform (ramp) is given to make the valve switched on and off.
- A dc power supply of about 500 V applied to the pulse generator, is sufficient to generate a high voltage dc of 50 to 100kV with suitable number of stages.
- The pulse frequency is high (about 500 to 1000 Hz) and the ripple is quite low(<1%).



Cascaded rectifier unit with pulse generator

P—Pulse generator

V_b—D.C. supply to pulse generator

V_g—Bias voltage

fig. 8 Voltage Multiplier

Cockcroft-Walton Voltage Multiplier

- The first stage, D_1,D_2, C_1,C_2, and the transformer T are identical as in voltage doubler.
- The rectifiers D_1, D_3, … D_{2n-1} conduct during the positive half cycles while the rectifiers conduct during the negative half cycles.
- The voltage on C_2 is the sum of the input ac voltage, V_{ac} and the voltage across the capacitor C_1.
- The voltage across other capacitors C_2 to C_{2n} can be derived from the difference between voltage across the previous capacitor and the charging voltage.

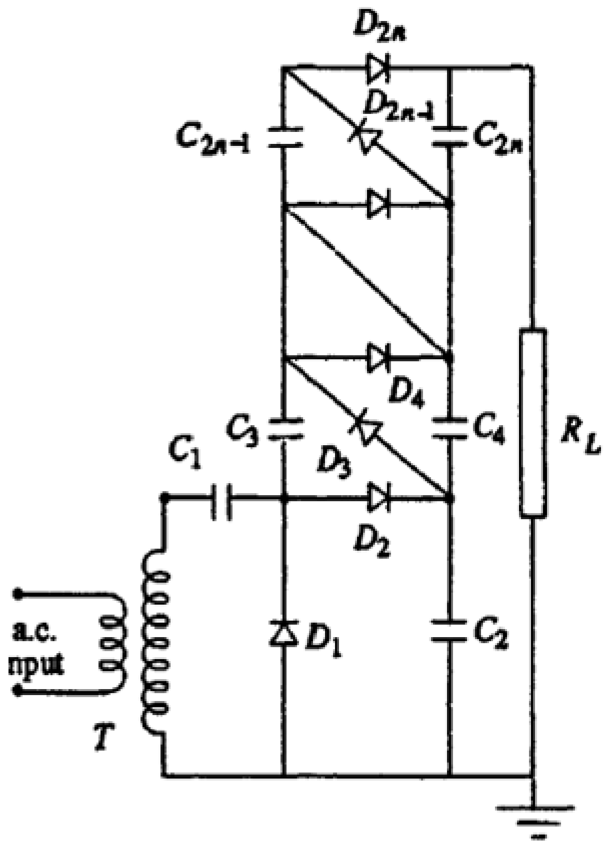


fig.9 Cockcroft-Walton Voltage Multiplier

Ripple in Cascaded Voltage Multiplier

- With load, the output voltage of the cascaded rectifiers is less than $2nV_{max}$.
- The charge transferred per cycle from the capacitor C_2 to the load during the non-conducting period t_2 is q and it is related to load current I_1 as

$$I_1 = \frac{dq}{dt} \approx \frac{q}{t_2}$$

t_1- conduction period of the rectifiers

t_2- non-conduction period of rectifiers

since $t_1 << t_2$ and $t_1 + t_2 = \frac{1}{f}$

$t_2 = 1/f$

$q = C_2 \delta V$

Hence, δV = the ripple = I_1 / fC_2.

Contd..

- At the same time a charge q is transferred from C_1 to C_2 during each cycle is I_1/fC_2. Thus total voltage drop will be $I_1/fC_1 + 2I_1/fC_2$.

Hence, regulation = mean voltage drop from 2Vmax

$$= \frac{I_1}{f}[\frac{1}{C_1} + \frac{2}{C_2}]$$

Therefore, the mean output voltage = $2V_{max} - \frac{I_1}{f}[\frac{1}{C_1} + \frac{2}{C_2}]$

- Assume that all capacitances $C_1, C_2, \ldots.. C_{2n}$ be equal to C.
- Let q be the charge transferred from C_{2n} to the load per cycle, then the ripple at the capacitor C_{2n} will be $I_1/2C$.
- Simultaneously, C_{2n-2} transfers charge q to the load and C_{2n-1}.Hence the ripple at the capacitor C_{2n-1} is $2I_1/fC$.
- Similarly, C_{2n-4} transfers a charge q to the load, to C_{2n-3} and to C_{2n-2}, therefore the ripple at capacitor C_{2n-4} is $3I_1/fC$
- Hence for n stages the total ripple(peak to peak) will be

$$\delta V_{total} = I_1(1+2+3+\ldots+n)/fC = \frac{I_1(n)(n+1)}{fC}$$

- The major contribution to the ripple is from the lowest or ground end capacitors C_1, C_2, C_3 etc. Ripple can be reduced if the capacitance of these capacitors is increased proportionally i.e., C_1, C_2 are made nC, C_3,C_4 are made (n-1)C and so on so that the total ripple will become nI_1/fC.

Voltage Regulation

- Regulation is the change of average voltage across the load from the no load theoretical value expressed as a percentage of no load voltage.
- The capacitor C_{2n} is charged to $2V_{max} - (nI_1 / fC)$ instead of nI_1/fC because charge given through C_{2n-1} in one cycle is equal to voltage drop of nI_1/fC.
- Similarly, capacitor C_{2n-2} is charged to only $[2V_{max} - (2nI_1 / fC) - ((n-1)I_1 / fC)]$

$$\Delta V_{2n} = \frac{nI_1}{fC} = \frac{I_1}{fC}[2n - n]$$

$$\Delta V_{2n-2} = \frac{nI_1}{fC} + \frac{nI_1}{fC} + \frac{(n-1)I_1}{fC} = \frac{I_1}{fC}[2n + n - 1]$$

$$= \frac{I_1}{fC}[2n + 2(n-1) - (n-1)]$$

....

$$\Delta V_4 = \frac{I_1}{fC}[2n + 2(n-1) + ... + 2]$$

$$= \frac{I_1}{fC}[2n + 2(n-1) + ... + 2.2 - 2]$$

$$\Delta V_2 = \frac{I_1}{fC}[2n + 2(n-1) + ... + 2.1 - 1]$$

Summing up all voltage drops

$$\Delta V = \frac{I_1}{fC}\sum_{n=1}^{n}\Delta V_{2n} = \frac{I_1}{fC}\left\{\sum_{n=1}^{n} n.2n - \sum_{n=1}^{n} n\right\} = \frac{I_1}{fC}[\sum_{1}^{n} 2n^2 - \sum_{1}^{n} n]$$

$$\Delta V = \frac{I_1}{fC}[\frac{2n^3}{3} + \frac{n^2}{2} - \frac{n}{6}]$$

- Optimum number of stages for the minimum voltage drop is($n^2/2$ and $n/6$ terms will become small compared to $(2/3)n^3$ and may be neglected for larger values of n(n>6))

$$n_{optimum} = \sqrt{\frac{V_{\max} fC}{I}}$$

In a single pulse voltage multiplier it has only one rectified wave or pulse per cycle. Hence its ripple content is high. In order to reduce the ripple as well as regulation and to improve the efficiency and power output, two or more pulse units are preferred.

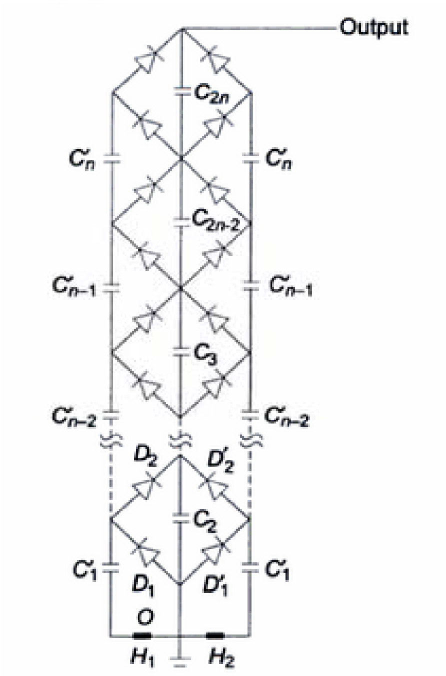


fig. 10 One phase, two pulse, voltage Multiplier

Ripple = nI/2fC

Voltage Regulation = $\frac{nI}{3fC}\left(\frac{n^2}{2}+1\right)$

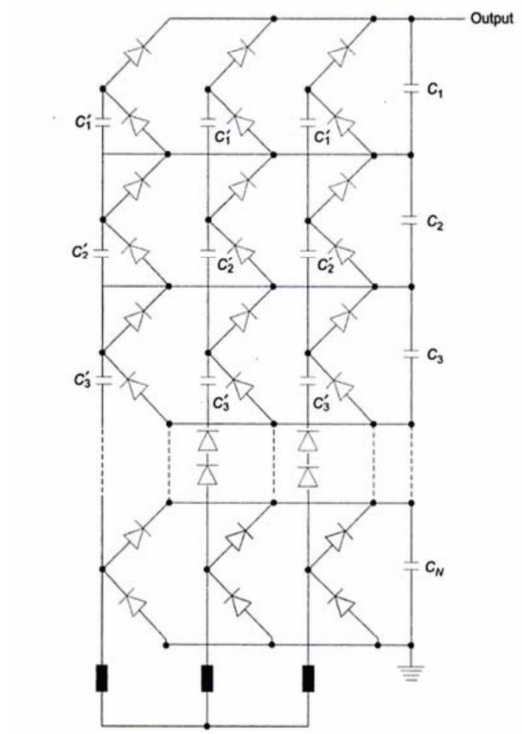


fig.11 Three phase, six-pulse, voltage multiplier circuit

Ripple = nI/6fC

Voltage Regulation = $\frac{nI}{3fC}\left(\frac{n^2}{6}-\frac{n}{4}+\frac{1}{3}\right)$

Electrostatic Machine Principles

- Force on insulated belt with a charge density δ moves in an electric field E(x) between two electrodes with separation 's'

$$F = \int_0^s E(x).dq = \int_0^s \delta.b.E(x)dx$$

- Mechanical power required to move the belt is

$$P = F.v = \delta.b.v\int_0^s E(x)dx$$

- Current in the system is $I = \dfrac{dq}{dt} = \delta b.\dfrac{dx}{dt} = \delta.b.v$

- In an electrostatic machine , the mechanical power required to move the belt at velocity v, P= F.v is converted into the electrical power, P=V.I

Van de Graaff Generators

- Generator is usually enclosed in an earthed metallic cylindrical vessel and is operated under pressure or in vacuum.
- Charge is sprayed onto an insulating moving belt by means of corona discharge points which are at some 10 kV from earth potential.
- The belt is driven at about 15-30 m/sec by means of motor and the charge is conveyed to the upper end where it is removed from the belt by discharging points connected to the inside of an insulated metal electrode through which the belt passes.

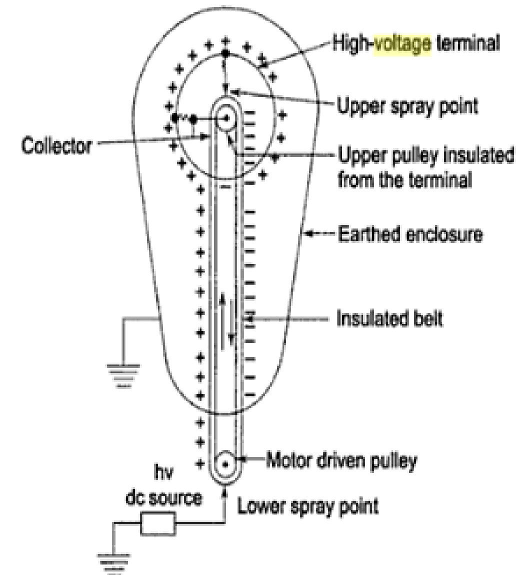


fig.12 Van de Graaff Generator

- The potential of the h.v terminal at any instant is V=Q/C

  where Q is charge stored

  C is capacitance of h.v electrode to ground.

- The potential of the terminal rises at a rate is given by dV/dt =I/C.

- The lower spray unit consist of a number of needles connected to the controllable d.c. source so that the discharge between the points and the belt is maintained. The controllable needle system is placed near the point where the belt enters the h.v terminal.

- A self-inducing arrangement is commonly used for spraying on the down-going belt charges of polarity opposite to that of h.v terminal. The rate of charging of the terminal, for a given speed of the belt, is therefore doubled. To obtain a self-charging system, the upper pulley is connected to the collector needle and is therefore maintained at a potential higher than that of h.v. terminal

- There is another system of points (upper stray points) which is connected to the inside of the h.v terminal and is directed towards the pulley. As the pulley is at a higher positive potential, the negative charges of the corona at the upper stray points are collected by the belt. This neutralizes any remaining positive charges on the belt and leaves any excess negative charges which travel down with it and are neutralized at the lower spray points.

- The main advantages of belt-driven electrostatic generators are the high d.c voltages which can be easily be reached, the lack of any fundamental ripple, and the precision and flexibility, though any stability of the voltage can only be achieved by suitable stabilizing devices. The voltages fluctuations and voltage stability may be in the order down to 10^{-5}.

- The shortcomings of these generators are the limited current output, as the limitations in belt velocity and its tendency for vibrations , which aggravates an accurate grading of electrical fields.

Electrostatic Generators

- Electrostatic Generators are duals of electromagnetic machines and are constant voltage variable capacitances machines.
- Principle :

  Current through variable capacitor is $I = \frac{dV}{dt} + V\frac{dC}{dt}$

  Power input into the circuit at any instant is $P = VI = CV\frac{dV}{dt} + V^2\frac{dC}{dt}$

If dC/dt is negative, mechanical energy is converted into electrical energy. With the capacitor charged with a d.c voltage V, Cdv/dt =0 and the power output will be

$$P = V^2\frac{dC}{dt}$$

- An electrostatic generator consists of a stator with interleaved rotor vanes forming a variable capacitor.

- The rotor to stator capacitance varies from C_m to $C_{0.}$ When the capacitance of the rotor is maximum(C_m), the rectifier B does not conduct and the stator is at ground potential. As the rotor rotates, the Capacitance C decreases and Voltage across C increases.

- The stator becomes more negative w.r.t ground. When the stator reaches line potential –E the rectifier **A** conducts and further movement of rotor causes current to flow from generator.

- Rectifier **B** will have E across it and charge left in generator will be $Q_0=C_0(V+E) + E\ (C_s+ C_r)$

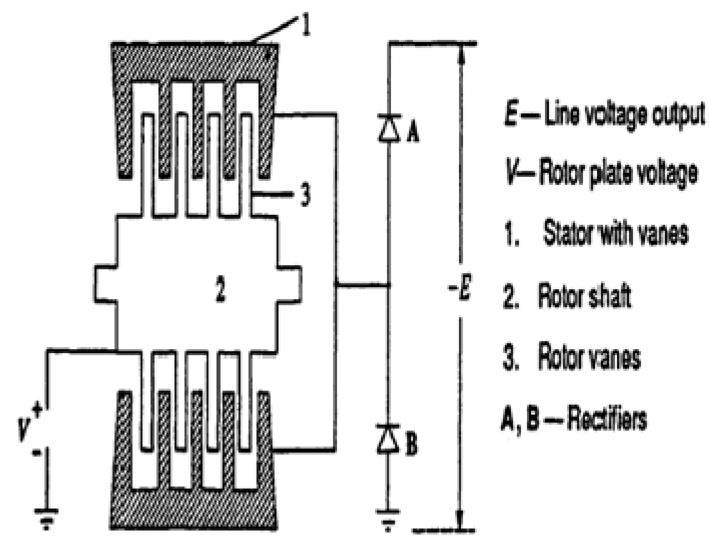


fig.13 Electrostataic Genertor

Impulse Voltages

- Transmission overvoltages due to lighting and switching surges cause steep buildup of voltage on transmission lines and other electrical apparatus.
- Transient disturbances on a transmission system due to lightning strokes and switching operations are followed by traveling waves of steep wave front. These waves cause unequal stress distribution along insulators and along the windings of a power transformer etc. and may lead to breakdown of the insulation system. It is therefore necessary to study the insulation behavior for both the impulse and switching test voltages.
- The magnitude of lightning voltages appearing on transmission lines does not depend on line design and hence lightning performance tends to improve with increasing insulation level, that is with system voltage. On the other hand, switching overvoltages are proportional to operating voltage. Hence, there is a system operating voltage at which the emphasis changes from lightning to switching surge design, this being important above 300kV.

- Lightning is probably the most common cause of flashover on overhead transmission lines. Two possibilities exist:

(i) The lightning stroke can either make a direct contact with a phase conductor producing a voltage on the line in excess of the impulse voltage level or

(ii) The stroke makes contact with an earth wire or tower. The combined effect of tower current and its impedance produces a voltage near the tower top sufficient to cause a back flashover.

In either case, the terminal equipment of high voltage transmission lines experience lightning impulses in service.

- Insulation is one of the most important constituents of a transformer and any weakness in insulation may result in the failure of the transformer. The effectiveness with which insulation performs, is measured in terms of dielectric strength.

- The power frequency tests alone are not adequate to demonstrate the dielectric strength of the transformer. The distribution of the impulse voltage stress along the transformer winding is very different from the power frequency voltage distribution.

- While the power frequency voltage distributes itself throughout the winding on a uniform volts per turn basis, the impulse voltage distributes initially based on the winding capacitances and finally on the inductances.

- Thus, it is necessary to ensure adequate dielectric strength of transformers for impulse conditions.

Switching Impulse

- Switching impulses occur during all kinds of switching operations in the system, for example by switching a transformer "ON" or "OFF" a system, or switching of a distribution line , circuit breakers etc. The magnitude and form of surges produced vary depending upon the nature of the switching event.

- The magnitude of switching impulses occurring in the network are proportional to the system voltage. The maximum voltage can attain a level of about 3.5 times the service voltage.

- Studies on network models and practical measurements have indicated that a transformer designed without taking switching impulses into account, can withstand switching impulse voltages equivalent to 83% of the corresponding basic impulse level (BIL).

Standard Lightning Impulse Wave

A lightning impulse voltage is a unidirectional voltage which rises rapidly to a maximum value and then decays slowly. Standard lightning impulse according to IEC 60060 is 1.2 µs ±30% / 50 µs±20%. The tolerance allowed in the peak value is ±3%. A lightning wave can be represented as double exponential wave, defined by the equation:

$$V = V_0[e^{-\alpha t} - e^{-\beta t}]$$

Where α & β are constants

The front or rise time T_1 is given by:

$$T_1 = 1.25(T_{90\%} - T_{10\%})$$

The tail or fall time T_2 is given by:

$$T_2 = T_{50\%}$$

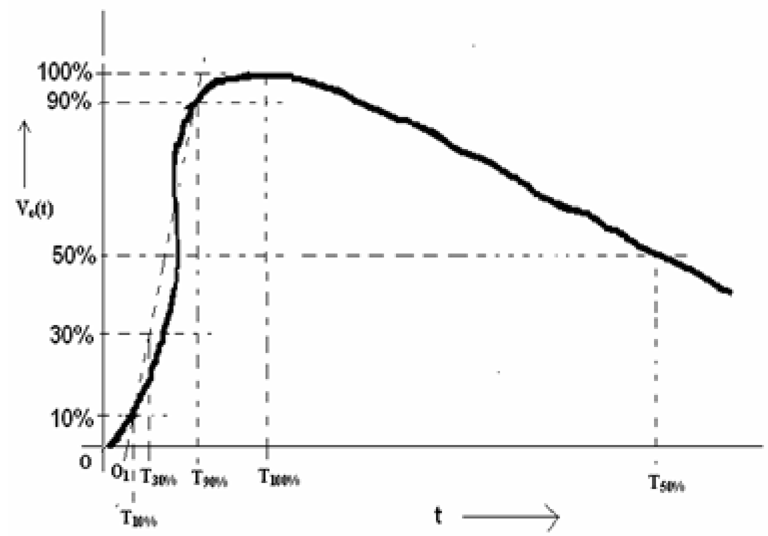


fig.14 Standard Lightning Impulse


LIGHTNING
IMPULSE
GENERATOR

Impulse Test Wave

- Impulse tests are made with wave shapes which simulate conditions that are encountered in service. From the data complied about natural lightning, it has been concluded that system disturbances from lightning can be represented by three basic wave shapes.
  - Full waves
  - Chopped waves or
  - Front of waves

- If a lightning disturbance travels some distance along the line before reaching the transformer, its wave shape approaches full wave generally referred to as 1.2/50 wave. A travelling wave causing a flashover across an insulator is simulated by a chopped wave. A case of a lightning stroke hitting directly at or very near to a transformer terminal, is represented by the front of wave.

Chopped Impulse Voltage

There are three types of chopped waves :

(i) Impulse voltage chopped on the front
(ii) Impulse voltage chopped on the tail
(iii) Linearly rising front chopped impulse

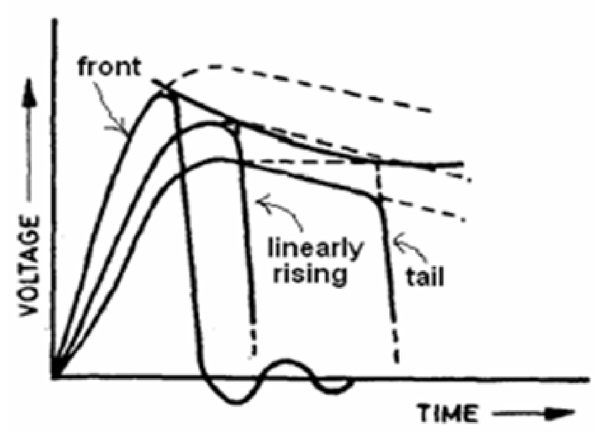


fig.15 Types of Chooped Impulse Voltges

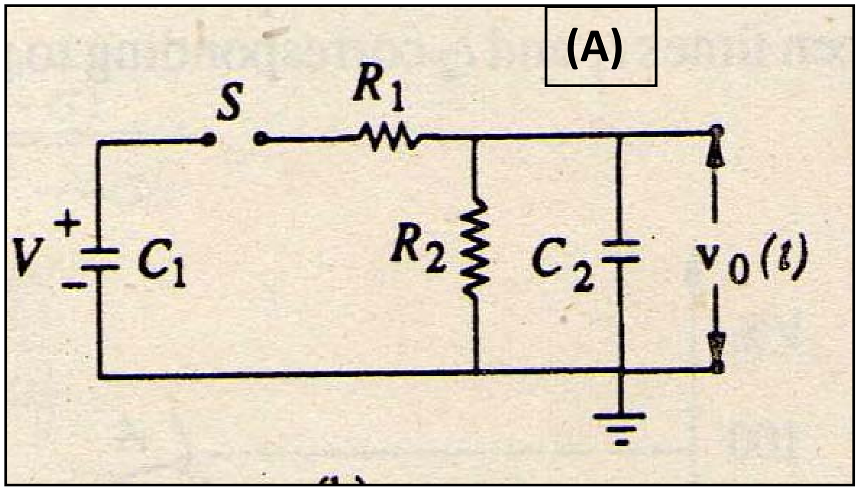
- A voltage rising with approximately constant steepness, until it is chopped by the occurrence of a disruptive discharge is described as a linearly rising impulse.

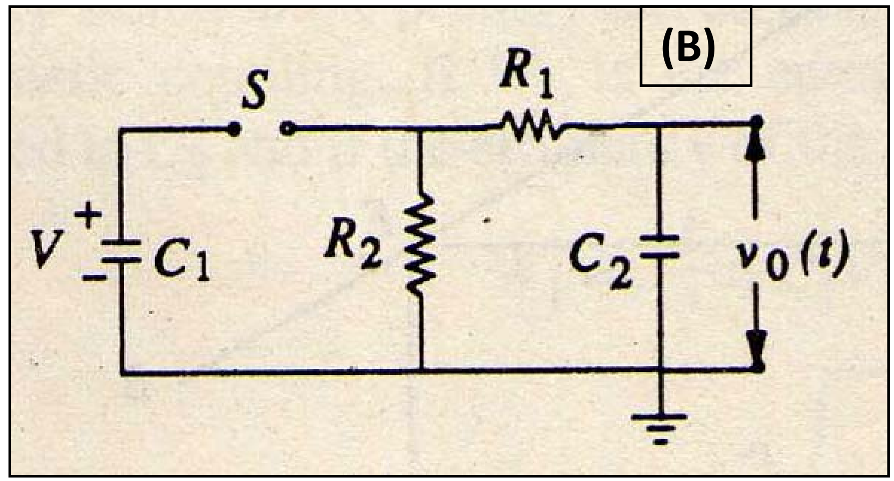
- Sometimes chopped impulse voltage waves are used for rigorous testing of the insulation of a system. For this purpose chopping gaps are used.

- The time to chopping between 2-6 μs is recommended in Standards.

Impulse Generator Circuits

A capacitor (C_1) previously charged to a particular DC voltage is suddenly discharged into the wave shaping network (R_1, R_2 & C_1 & C_2) by closing the switch S.





Where, ,C1 → charging or impulse capacitor ($C_1 >> C_2$)

C2 → load capacitor (test object + divider, etc.)

R1 → series resistor

R2 → parallel resistor ($R_2 >> R_1$)

S → spark gap

V → charging voltage

$V_o(t)$ → Output impulse voltage ($V_o \leq V$)

Analysis of the impulse circuits

The output voltage across C_2 is given by $v_0(t) = \frac{1}{C_2}\int_0^t i_2 dt$

Performing Laplace transformation and solving the eq. for output voltage after transforming back in time domain , we get

$$v_0(t) = \frac{V}{R_1 C_2(\alpha - \beta)}[\exp(-\alpha t) - \exp(-\beta t)]$$

Where α and β , are the roots of the Eq., which may be approximated as

$$\alpha \approx \frac{1}{R_1 C_2} and, \beta = \frac{1}{R_2 C_1}$$

Similarly solving the circuit given in (B), we get

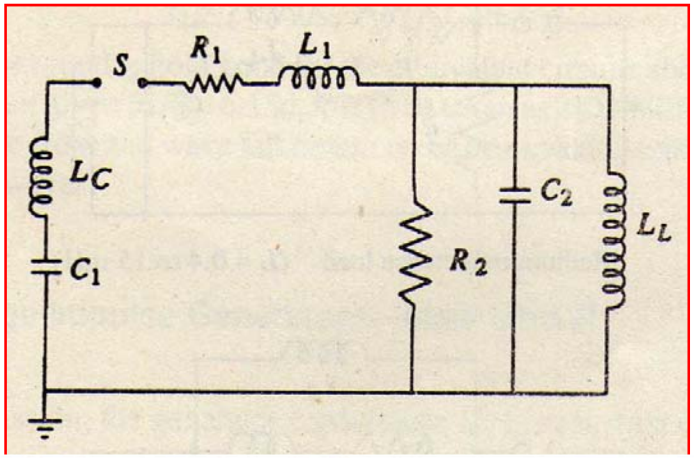
$$v_0(t) = \frac{V C_1 R_2 \alpha\beta}{(\beta - \alpha)}[\exp(-\alpha t) - \exp(-\beta t)]$$

Waveshape Control

- Generally, for a given generator, its capacitance C_1 and load capacitance C_2 will be fixed depending on the generator design and the test object. Hence desired wave shape is obtained by controlling R_1 and R_2.
- Since the resistance $R_2 >> R_1$, the simplified circuit can be used. Taking the circuit inductance to be negligible during charging, C_1 charges the load capacitance C_2 through R_1. Then the time taken for charging is apprx. 3 times the time constant of the circuit and is given by

$$t_1 = 3.0 R_1 \frac{C_1 C_2}{C_1 + C_2} = 3 R_1 C_e$$

Where, $C_e = C_1 C_2 / (C_1+C_2)$, R_1 in ohms, C_e in μF, then t_1 is obtained in μs.



(a) Series inductances in impulse generator circuit

L_C — Inductance of the generator capacitance C_1 and lead capacitances

L_1 — Inductance of the series resistance and the circuit loop inductance

L_L — Test object inductance

fig.16 Series Inductances in impulse genertor circuit

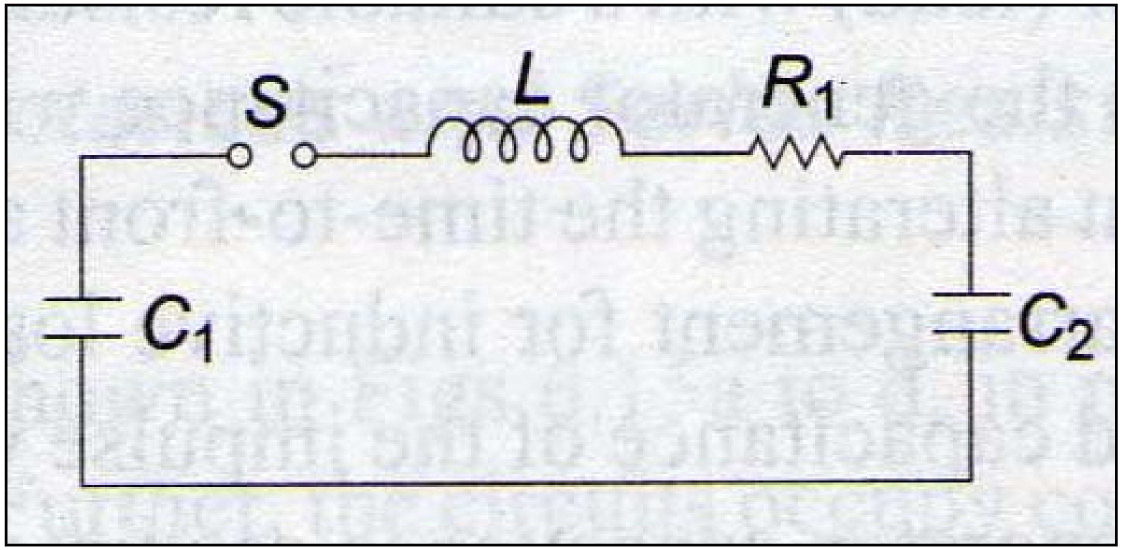


fig.17 Simplified circuit for calculation of wave front

- For calculating discharge or tail time, the capacitances C_1 and C_2 may be considered to be parallel, discharging through R_1 and R_2. Hence time for 50% discharge is apprx. given by

$$t_2 = 0.7(R_1 + R_2)(C_1 + C_2)$$

- The efficiency (V / V_0) depends upon the ratio of generator capacitance to the load capacitance (C_1 / C_2), generally > 10 . It also depends upon the position of R_1. When the circuit is so arranged that R_1 is on the generator side of R_2, the efficiency is highest in no load condition.

Effect of circuit inductance

- Each component has self inductance and some stray inductance in circuit. The actual inductance may vary from 10 μH to several hundreds of μH. The effect of inductance is to cause oscillations in the wave front and in the wave tail portions. All efforts are made in impulse generators to reduce the inductance value to the extent possible.

- Network simulation studies and field measurements have shown that the form of unipolar voltage generated due to switching is a periodically damped oscillatory one.

- Standard switching impulse voltage is defined, both by the Indian Standard and IEC (60060) as a wave having front time 250 μs and time to half value 2500 μs with a tolerance of ± 20 % in the front time and ±60% in the tail time.

- The American Standard recommends the total duration to the first zero passage of at least 500 μs . The Marx generator is used to produce switching impulse voltage also, but with a relatively low efficiency of 75%.

Switching Impulse Voltage Test

- The switching impulse voltages are of long duration and generally do not cause any non-uniform voltage distribution along the winding, but they affect the insulation to ground, between windings and phases and the electrical insulation of the bushings.

- During the switching impulse test, the open circuited low voltage winding on the same core limb, as the impulsed HV winding, is automatically subjected to impulse voltage stresses. These voltages are induced proportional to the transformation ratio. Further tests on low voltage windings are thus not essential.

- The dielectric strength of air shows a pronounced minimum for positive unipolar impulse in the range of 100-300 μs front time. Therefore, to avoid flashover on the external insulation of the transformer, it is preferred to conduct the test with negative polarity impulse.

Generation of Switching Surges

- Switching surges are an important factor in the design of insulation for extra high voltage transmission and power systems.

- A switching surge is a short duration transient voltage produced in the system as a result of sudden opening and closing of CBs or due to system faults.

- The switch waveform is not unique. Network simulation studies and field measurements have shown that the form of unipolar voltage generated due to switching is a periodically damped oscillatory wave of frequency ranging from a few hundred hertz to few kHz. It may also be considered as a slow rising impulse having a wave front of 0.1 to 10 ms and a tail time of one to several ms.

- Several circuits have been adopted for producing switching surges. Usually impulse generator circuit is modified to give longer duration wave shapes.

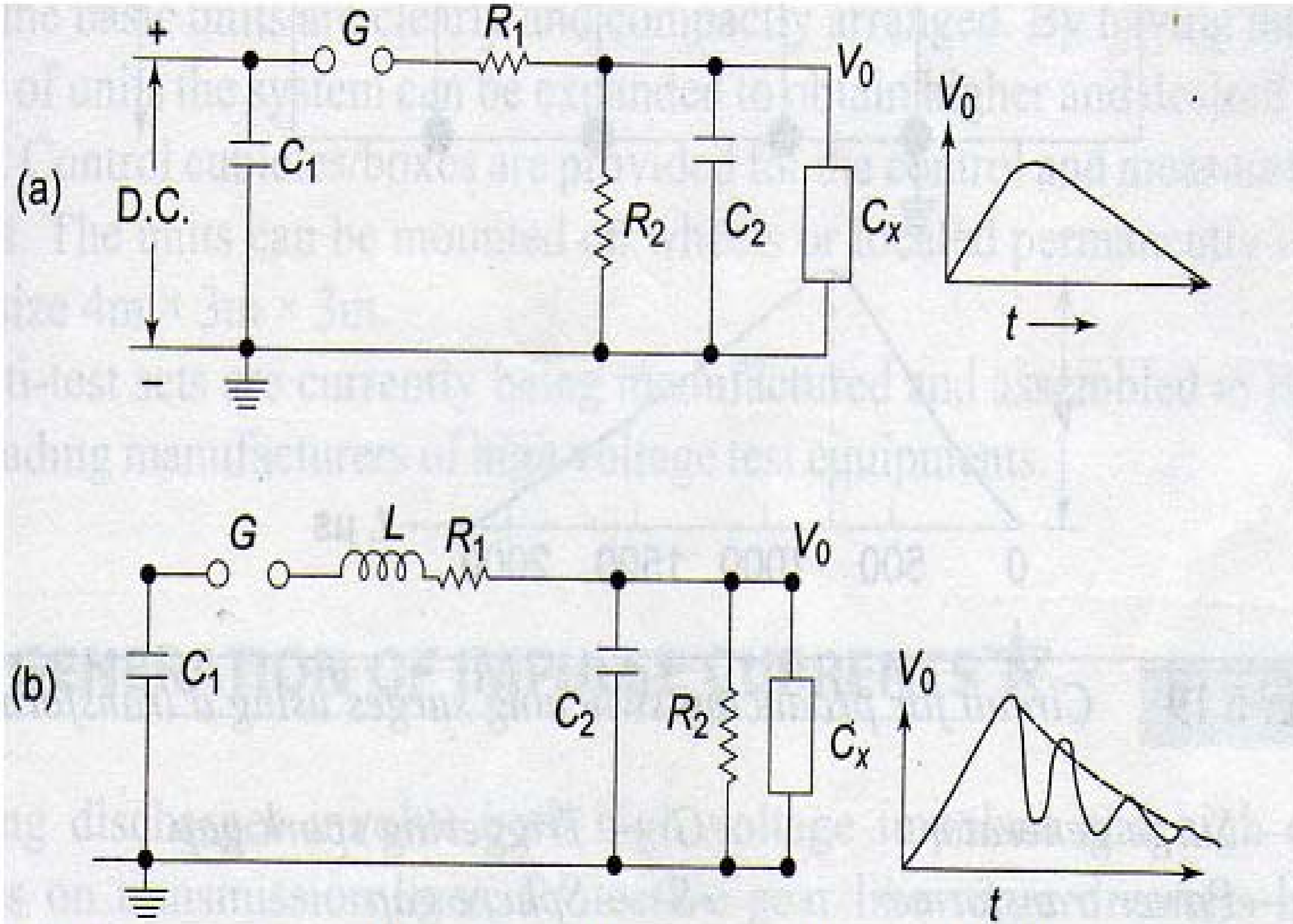


fig.18 Circuits for producing switching surge voltage. Also shown are the output waveshapes across the load C_x

Multistage Impulse Generator

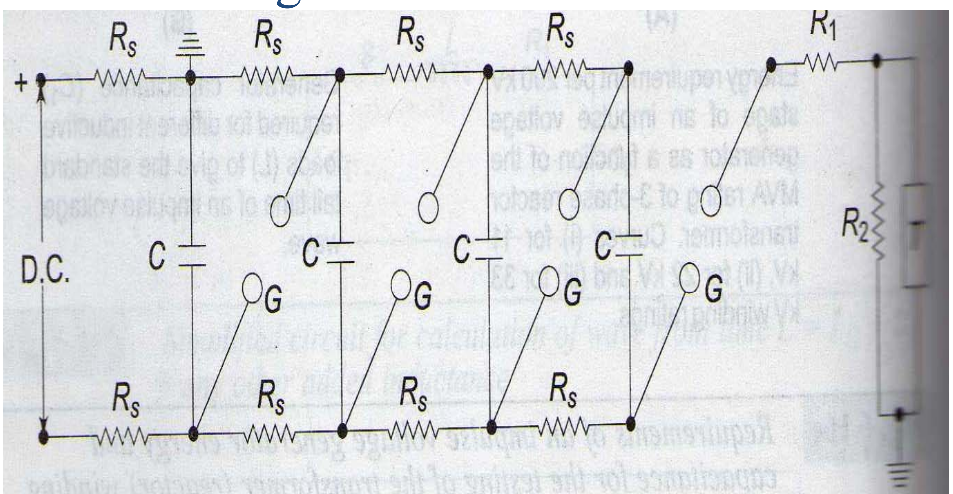
- Lightning and switching impulse test is conducted by direct application of voltage to the object under test, by means of an impulse generator. Impulse waves are generated by using an arrangement that charges a group of capacitors in parallel and then discharging them in series (Marx multiplier circuit) through a triggering system.

- The magnitude of the voltage is determined by initial charging voltage, number of capacitors in series at the time of discharge. The wave shape is determined largely by the Waveshaping elements of the generator and the impedance of the load.

- The impulse generator built on multi-stage Marx circuit is capable of generating both the lightning as well as switching impulse of required voltage level (ranging from hundreds of kV to several MV).

Marx Multiplier Circuit

- High impulse voltage can be generated by Marx generators where a bank of capacitors are charged in parallel and discharged in series through a resistor. Charging resistors are provided at each stage of The generator to maintain uniform voltage distribution. Figure shows the schematic diagram of Marx circuit arrangement.



Schematic diagram of Marx circuit arrangement for multistage impulse generator

C — Capacitance of the generator

R_s — Charging resistors

G — Spark gap

R_1, R_2 — Wave shaping resistors

T — Test object

fig.19 Schematic Diagram of Marx Circuit arrangement for Multistage Impulse Generator

- Usually the charging resistance R_s is chosen to limit the charging current to about 50-100 mA. The generator capacitance C_1 is chosen such that $C_1 R_s$ is about 10 sec to 1 min. The gap spacing is chosen such that the BDV of the gap G is greater than charging voltage V. For discharge, all gaps G are made to spark over by external trigger pulse with a very small time constant of C_1R_s/n (n stages).
- The modified Marx circuit is shown in figure 20, where in the resistances R_1 and R_2 are incorporated inside the generator at every stage.

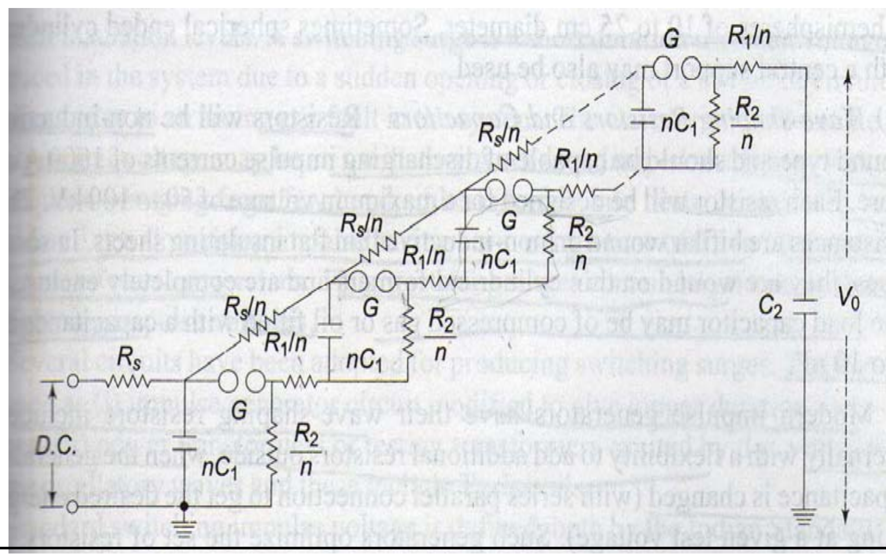


fig.20 Multistage impulse generator incorporating the series and wave tail resistors at every stage

- R_1 is divided into n equal parts of R_1/n and put in series with the gap G. R_2 is also divided into n parts and arranged across each stage capacitance unit after the gap G.

- By having this arrangement, the size of waveshape control resistor becomes smaller, This leads to saving in space and reduced cost. The efficiency of the generator (V_0 / nV) also becomes high.

Components of a Multistage Impulse Generator

- DC Charging Set

The charging set should be capable of giving a variable DC voltage of either polarity, Its current rating should be adequate enough to charge the generator capacitors to the required value.

- Charging Resistors

These are non inductive high value (10-100 kΩ) resistors, typically having voltage rating between 50 and 100 kV. They are used to limit the charging current from the DC set and control the charging time constant of generator capacitors.

- Generator Capacitors and Spark Gaps

These are arrange vertically one over the other with all the spark gaps aligned. The capacitors are designed for few hundred thousands of charging and discharging operations. They are basically energy storage capacitors having minimum self inductance and capable of withstanding voltage reversals to the specified value.

The spark gaps are usually spheres or hemispheres of 10-25 cm in diameter having a central support system. They are exposed to open air, but in some generator designs, they are enclosed in gas medium, provided with UV lamp irradiation from the bottom to all gaps to give better sparking consistency.

Waveshaping Resistors:

- They are essentially wire wound type and non inductive, capable of discharging high impulse currents. The resistors are usually resin cast. Each resistor is designed for a max. voltage of 50 to 100 kV.
- Modern impulse generators are provided with a number of sets of charging resistors having resistance value, voltage ratings and energy ratings varying over a wide range. The entire range of lightning and switching impulse voltages can be covered using these resistors either in series or in parallel combination.

Triggering System:

- To trip the generator at a predetermined time, the spark gaps are mounted on a movable frame and the gap distance is reduced by moving the movable electrode closer. This method, however, is difficult and does not ensure consistent and controlled tripping.

Triggering

- A simple method of controlling tripping consists of making the first stage gap, as what is called a trigatron. It consists of a high voltage spherical electrode of suitable size, an earthed main electrode of spherical shape and an insulated trigger electrode passing through the main gap. The trigger electrode is a metal rod with an annular clearance of 1 mm. The trigatron is connected to a trip pulse circuit, which produces a spark between the trigger electrode and the earthed sphere as shown in fig .21

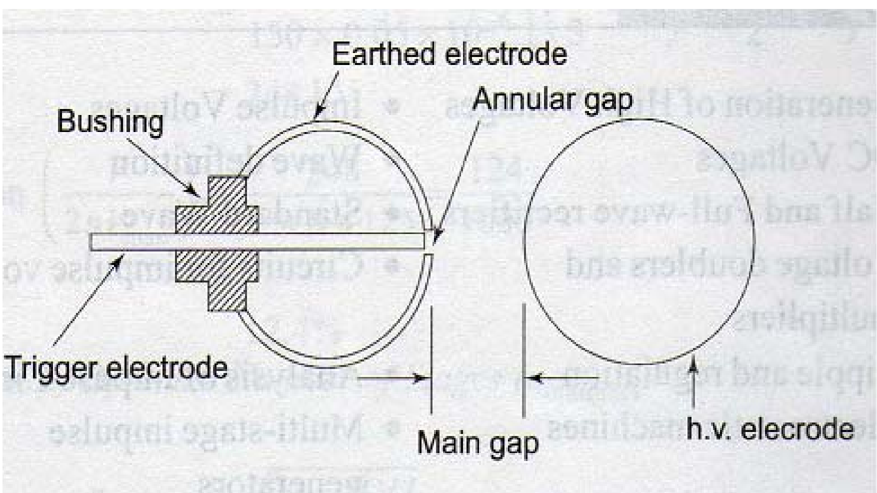
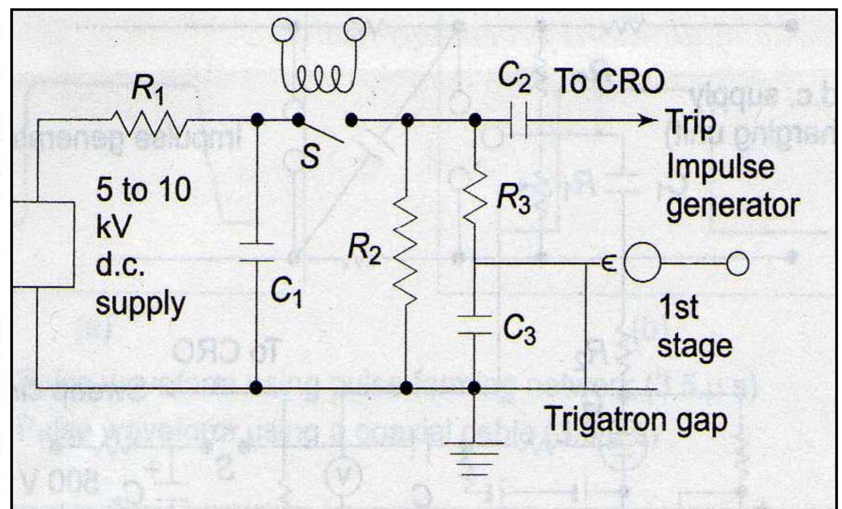


fig.21 Triggering Circuit and Tripping Circuit using Trigatron



(b) Tripping circuit using a trigatron

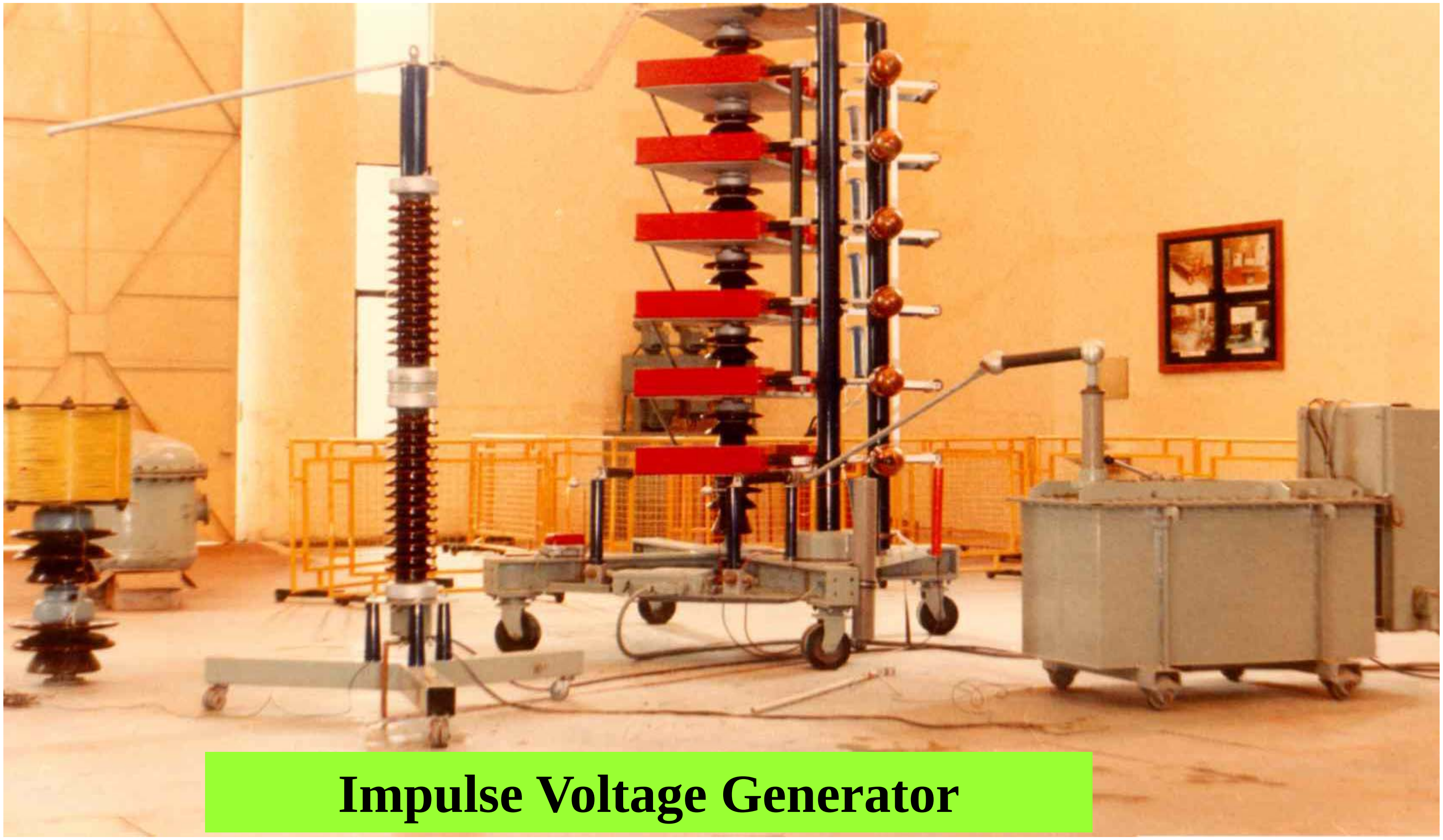
Voltage Dividers:

- Voltage dividers of either damped capacitor or resistor type and an oscilloscope with recording arrangement is provided for the measurement of the voltages across the test object. Sometimes a sphere gap or impulse peak voltmeter is also provided for calibration purpose.

Gas insulated Impulse Generators

- Impulse generators rated for 4 MV and above are very tall (30 m height) and require large space. Sometimes they need to located outdoor. In such cases, they are housed in an insulated enclosure. To make the unit compact, a compressed gas such as N_2 or SF_6 may be used as insulation.

- Impulse generators are needed to generate very fast transients having time duration of 0.5/5 or 0.1/1 μs waves. For testing Gas Insulated Systems (GIS), which may offer a load capacitance of say 1000 pF, may require energy of about 30 kJ or so.



Make: Haefley, Switzerland

Rating: 900 kV, 27 kJ

Applications :

Lightening & Switching Overvoltage Tests on HV Power Equipment & Modules & Insulation Systems

fig.22 Impulse Voltage Generator

fig.23 6 MV, 450 KJ IMPULSE VOLTAGE GENERATOR

fig.24 4 MV(4000 kV) IMPULSE GENERTOR

fig.25 5 MV, 500 kJ, Outdoor Type Impulse Generator with Capacitor Divider & Loading Capacitor

Courtesy :CPRI, UHV Lab. HYD

Some important definitions

Impulse Flash Over Voltage:

- Whenever an impulse voltage is applied to an insulation medium, flashover may or may not take place. If out of the total say 10 applications of impulse voltage, about 5 of them flashover, then the probability of flashover with that peak voltage of the applied impulse voltage is 50%.

- Therefore, a 50% impulse flash over voltage is its peak value, which causes flashover of the test object under test for about half the number of impulses. The flashover also depends upon the polarity, duration of wave front and wave tail of the applied impulse voltage.

- The impulse flashover voltage for the flashover on the wave front, is the value of the impulse voltage at the instant of flashover.

Impulse Puncture Voltage :

- It is defined as the peak value of the impulse voltage which causes the puncture of the material when puncture occurs on the wave tail and is defined as the value of the voltage at the instant of puncture when puncture occurs on the wave front.

Impulse Ratio for Flashover :

- The impulse ratio for flashover is the ratio of impulse flashover voltage to the peak value of power frequency flashover voltage. The impulse ratio is not a constant for any particular object, but depends upon the shape and polarity of the applied voltage.

Impulse Ratio for Puncture :

- The impulse ratio for puncture is the ratio of Impulse puncture voltage to the peak value of the power frequency puncture voltage.

STANDARD INSULATION LEVELS

Highest System Voltage kV rms	AC Withstand Voltage kV rms	Lightning Impulse Withstand Voltage kVp
12	28	75
17.5	170	95
24	50	125
36	70	170
52	95	250
72.5	140	325
123	185 (230)	450 (550)
145	230 (275)	550 (650)

The choice of reduced insulation levels supposes that the equipment is adequately protected against surges

STANDARD INSULATION LEVELS

Highest System Voltage kV rms	AC Withstand Voltage kV rms	Lightning Impulse Withstand Voltage kVp	Switching Impulse Withstand Voltage
170	275,325	650,750	--
245	360,395,460	850,950,1050	750
300	--	1175	850
362	570,630	1300,1425	950
420	630,630,680	1425,1550,1675	1050,1175,1175
525	790,790,830	1675,1800,1950	1300,1300,1300
765	830,830,880 880,975,975	1800,1950,2100 2250,2400,2550	1425,1425,1425 1425,1550,1550

The choice of reduced insulation levels supposes that the equipment is adequately protected against surges

Test sequence with impulses

The impulse of specified voltage magnitude is applied to the winding under test. To ensure that non-impulsed windings do not subjected to beyond 75% of BIL, their terminals are earthed directly or through resistors (Max. 400 Ω).

Full wave test sequence

--- A reduced full wave (between 50 to 75% of BIL)

--- Three full waves of 100% BIL

Sequence of impulse test with chopped

--- one reduced full impulse (between 50 to 75% of BIL)
--- one 100% full impulse
--- one reduced chopped impulse
--- two 100% chopped impulses
--- two 100% full impulses

Measurement and Recording of Impulses

- To measure the amplitude and shape of applied impulses which have values which have values ranging from a few tens of kV to over thousands of kV and duration 0.2 to 250 μs, special measuring equipment are used.

- To record transients, Impulse oscilloscopes with extremely high writing speeds, band width and fast response dividers are required. Digital peak voltmeters are employed to record voltage amplitudes.

- The chopping of impulse wave can be obtained with a rod gap, triggered sphere gap or a multiple chopping gap.

- The rod gap and triggered sphere gap lack consistency in chopping duration, which can be obtained with a multiple chopping gap.

Oscillographic recording of Voltage

- The preferred sweep time for wave front record is 1 μs
- For full wave, the sweep time should not be less than 10 μs
- The preferred sweep time for chopped wave is 1-10 μs
- For switching impulse wave front , sweep time of 100-200 μs is chosen
- For recording upto first zero passage of switching impulse wave,
- generally a sweep time of 1000-3000 μs is used.

Recording of Current

The impulse current measurements are the most sensitive parameters in failure detection and their Oscillographic record is the main criteria of the test result. The sweep time selected should be able to capture the high frequency components near the front of wave and also detect any discrepancies occurring late in time.

Recording of current at 10 μs and 100 μs sweep covers the above requirements in general.

Fault Detection

- The detection of faults is the most important phase of impulse testing. The detection of failure with CRO is most effective and sensitive. It is based on the fact that an insulation failure will change the impedance of transformer, causing a variation in the impulse current and in the voltage.

- Full wave oscillograms at reduced and full voltage levels are compared and taken as reference. Full wave oscillograms prior to and after the chopped wave application match when there is no dielectric failure in the winding.

- Current oscillograms almost always verify and magnify the small disturbances found on the voltage oscillograms. Major changes in current oscillograms indicate probable breakdown within the windings and earth.

- Thus, judgement and interpretation of current oscillograms is vital to avoid the possibility of a healthy transformer being judged unsound.

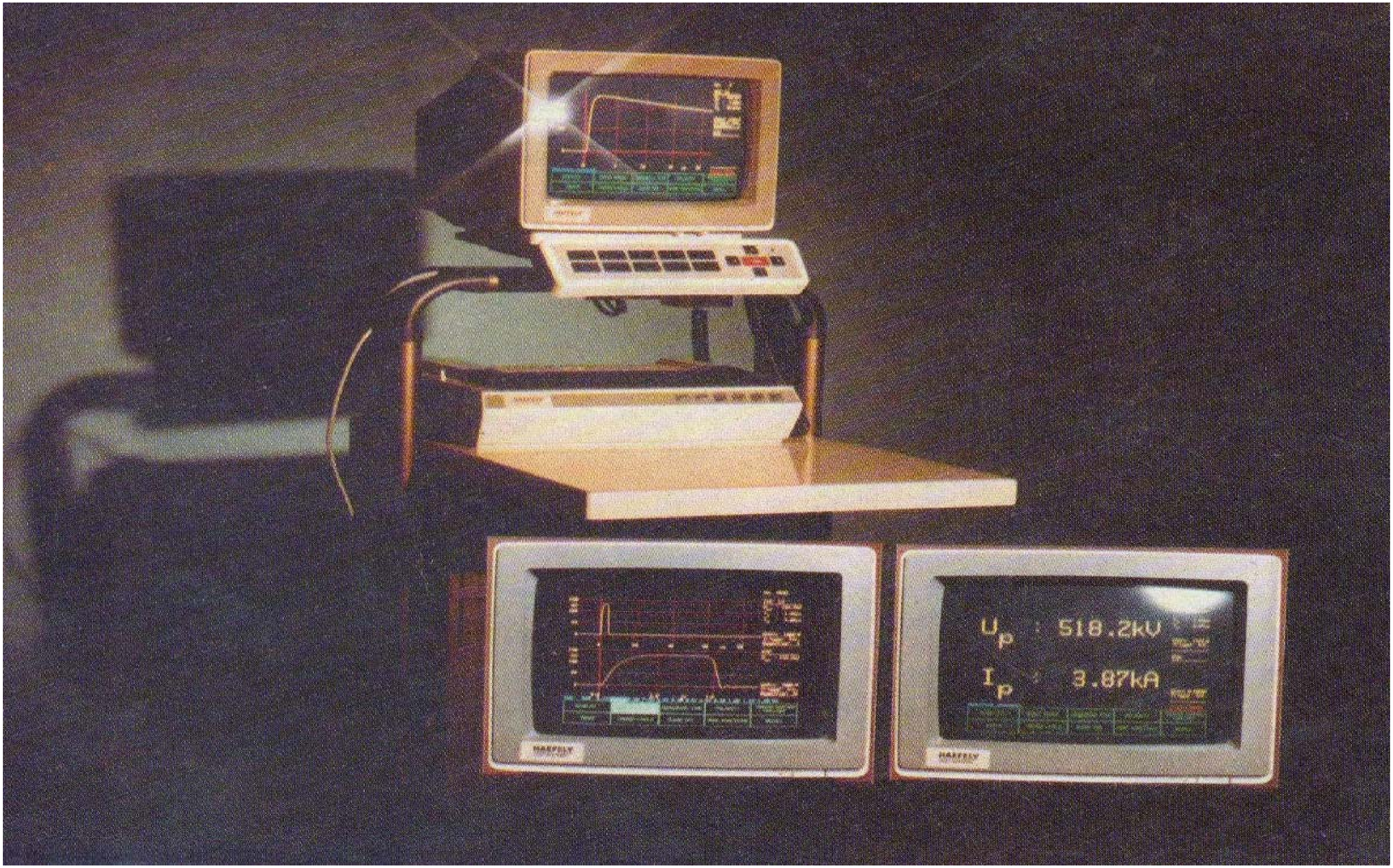


Fig.26 Digital Impulse Analysis System (DIAS) for measurement of impulse voltage and currents

Courtesy Haefely, Switzerland

Generation of Impulse Current

- For producing impulse current of large value, bank of capacitors connected in parallel are charged to a specific voltage and are discharged through a series R-L circuit as shown in fi30
- C represents a bank of capacitors connected in parallel which are charged from a dc source to a voltage up to 200 kV.
- R represents the dynamic resistance of the test object and the resistance of the circuit and the shunt.
- L is an air cooled current inductor, usually a spiral.

Wave shape : 4/10 μs & 8/20 μs

Tolerance : ± 10%

: + 20% & - 0% on peak value

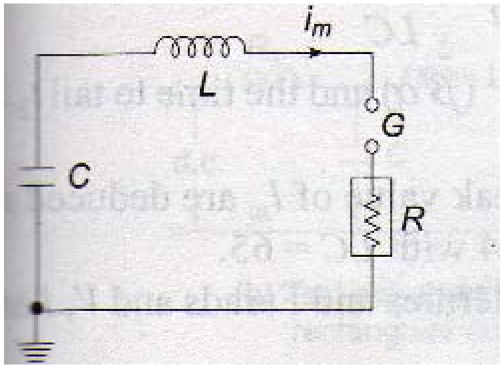


fig.27 Basic circuit of an impulse Current Generator

- If the capacitor is charged to a voltage V and discharged when the spark gap is triggered, the current i_m will be given by the equation

$$V = Ri_m + L\frac{di_m}{dt} + \frac{1}{C}\int_0^t i_m dt$$

The circuit is usually underdamped, so that $\frac{R}{2} < \sqrt{L/C}$

Hence, i_m is given by

$$i_m = \frac{V}{\omega L}[\exp(-\alpha t)]\sin(\omega t)$$

where $\alpha = \frac{R}{2L}$ and $\omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$

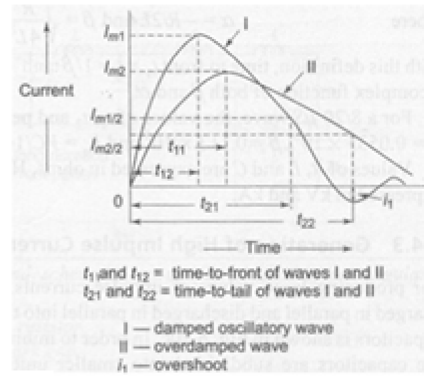


fig.28 Standard Impulse Current Waveforms

The time taken for the current i_m to rise from zero to the first peak value is

$$t_1 = t_f = \frac{1}{\omega}\sin^{-1}\frac{\omega}{\sqrt{LC}} = \frac{1}{\omega}\tan^{-1}\frac{\omega}{\alpha}$$

The duration for one half cycle of the damped oscillatory wave t_2 is

$$t_2 = \frac{\pi}{\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}}$$

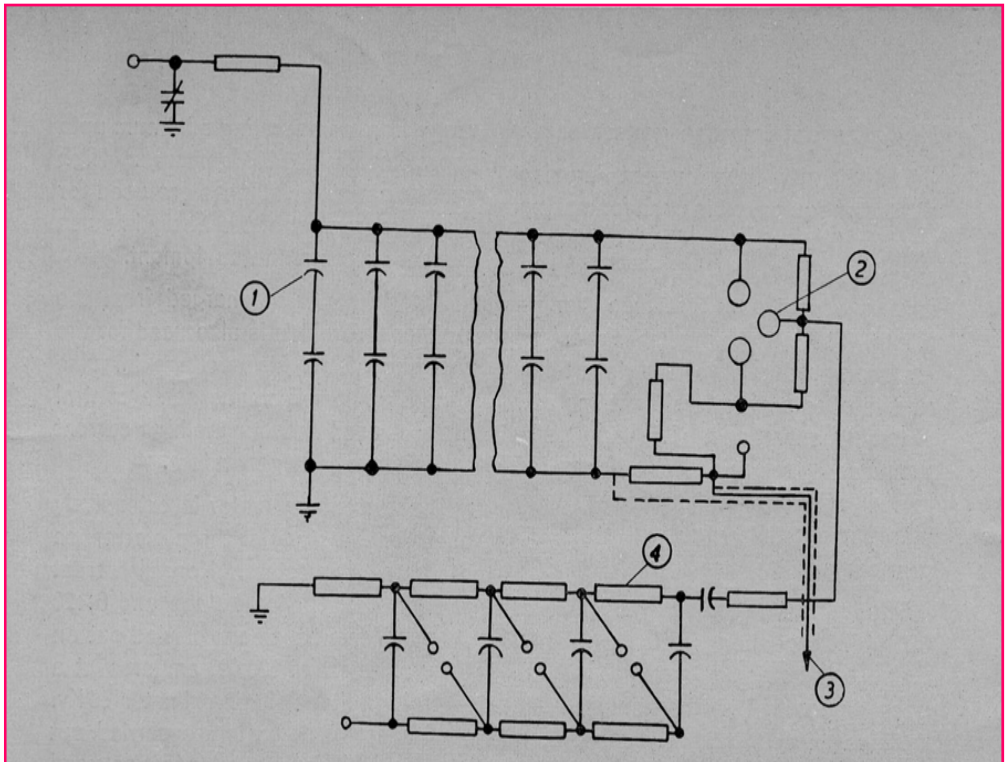


Fig. 6. Impulse current generator circuit

1. Capacitors
2. Tripping gaps
3. To oscilloscope
4. Trip generator

fig.29 200.000 Ampere Impulse Current Generator Circuit

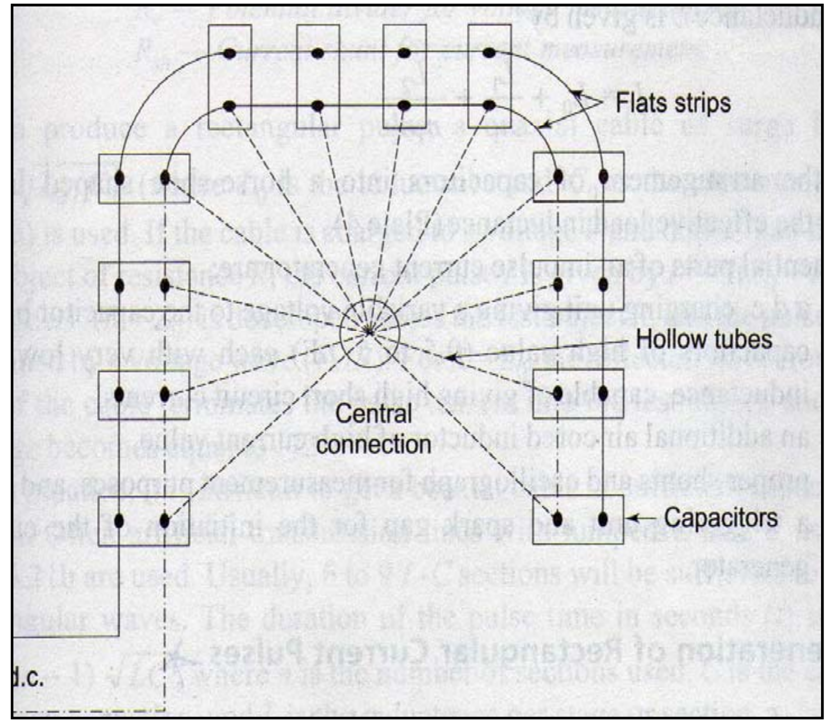


fig.30 Arrangement of capacitors for high impulse current generator

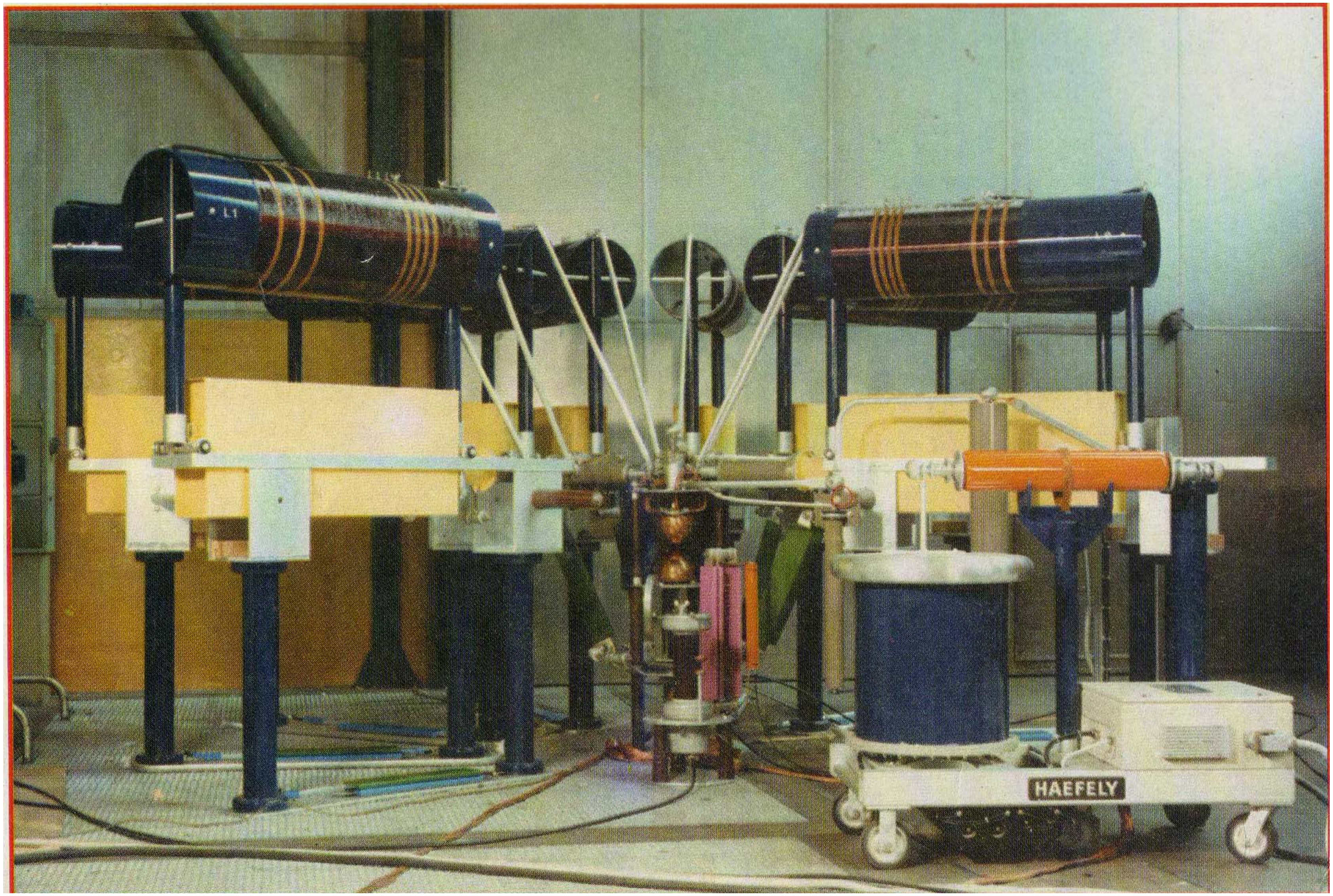


fig. 31 100 kA, 150 kJ, Impulse Current Generator

Generation of Rectangular Pulses

- Generation of rectangular current pulses of high magnitudes(few hundred amperes and duration upto 5 ms) can be done by discharging a pulse network or cable previously charged.

- The basic circuit for producing rectangular pulses is given in fig.32

- The length of the cable or an equivalent pulse forming network is charged to a specific dc voltage. When the spark gap is short-circuited, the cable or pulse network discharges through the test object.

- To produce a rectangular pulse, a coaxial cable of surge impedance $Z_0 = \sqrt{\frac{L_0}{C_0}}$

- If a cable is charged to a voltage V and discharged through the test object of resistance R, the current pulse I is given by

$$I = V/(Z_0+R)$$

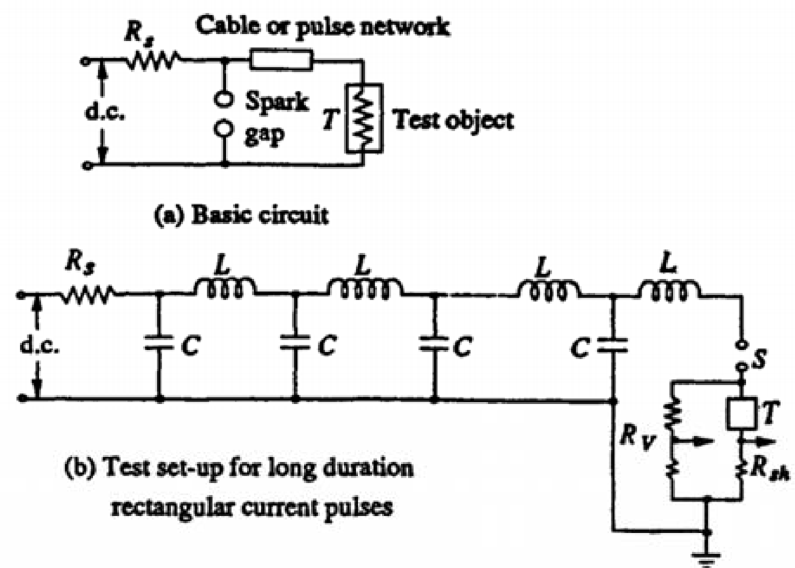


fig.32 Basic circuit and schematic set-up for producing rectangular current pulses

R_s — Charging resistor
S — Trigger spark gap
T — Test object
L-C — Pulse forming network
R_v — Potential divider for voltage measurement
R_{sh} — Current shunt for current measurement

GENERATION OF
HIGH VOLTAGE ALERTANATING CURRENT

The power frequency transformer is the most common form of HV testing apparatus. From the considerations of thermal rating, the regulation and kVA output, the design of a HV testing transformer doesn't differ from that of the power transformer. However, the former is often subjected to flashover of the object under test and its insulation must therefore be designed to withstand such surges.

The characteristic requirements of a testing transformer depend on the equipment to be tested

- For bushings and insulators, high current rating is not required as they have very low capacitance
- For transformers and generators, large currents with good regulation is required as they have high capacitance
- For cable tests, large current at low power factors over long periods of time
- For power factor & dielectric loss measurements, pure sinusoidal output at all loading conditions.