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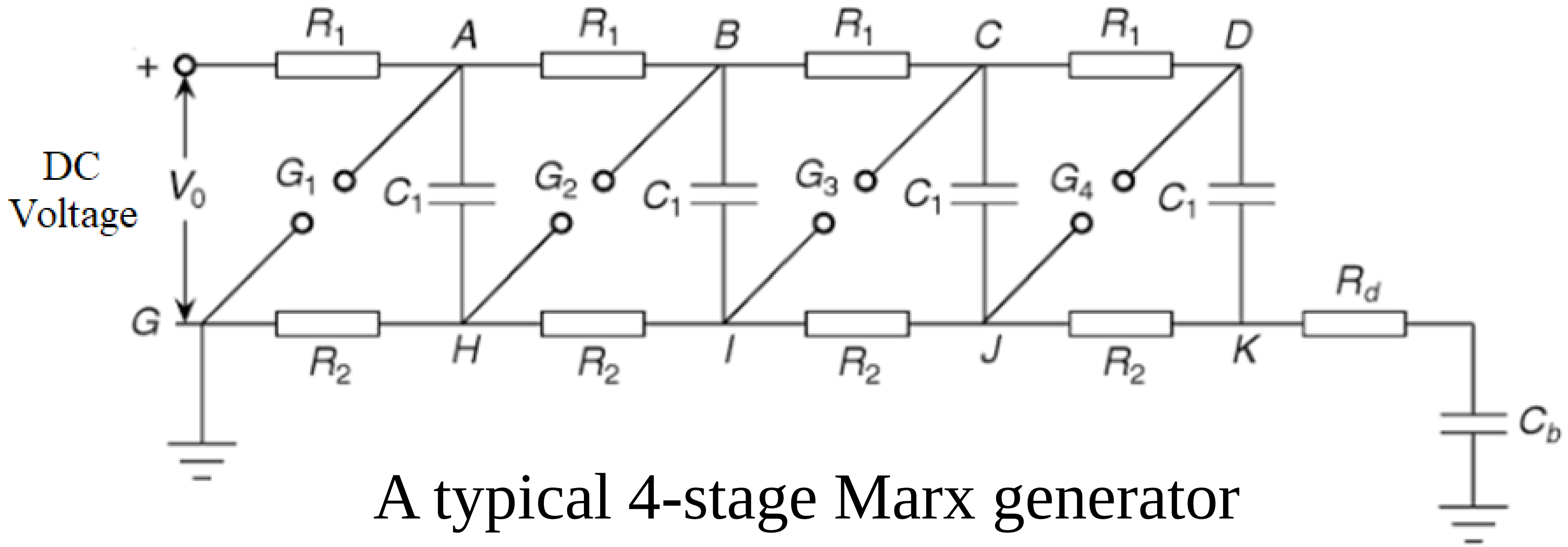
Generation of high voltages 'Impulse Voltage, Marx Generator'

- In order to obtain higher and higher impulse voltage, a single stage circuit is inconvenient for the following reasons:
  - The physical size of the circuit elements becomes very large.
  - High d.c. charging voltage is required.
  - Suppression of corona discharges from the structure and leads during the charging period is difficult.
  - Switching of very high voltages with spark gaps is difficult.

Generation of high voltages
'Impulse Voltage, Marx Generator'

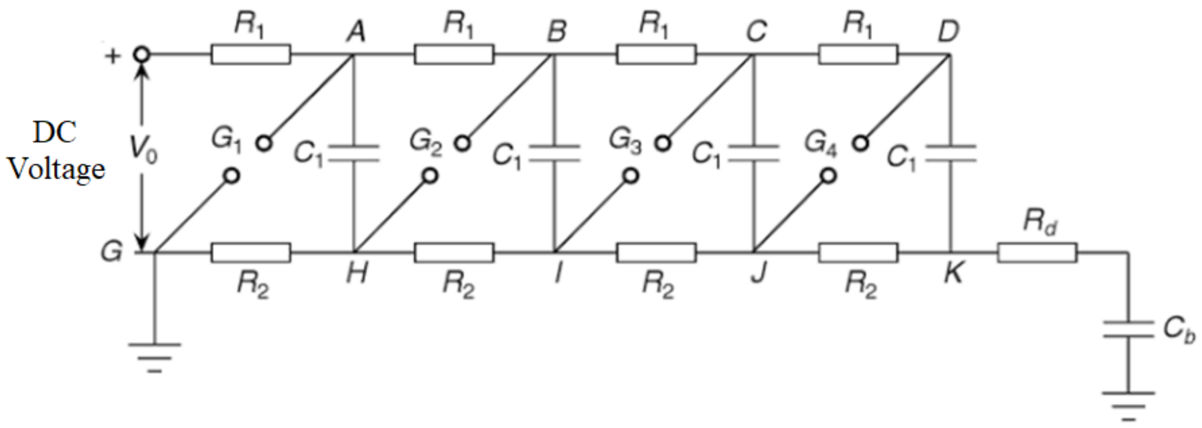
- In order to overcome these difficulties, in 1923 Marx suggested an arrangement where a number of capacitors are charged in parallel through a high ohmic resistances and then discharged in series through spark gaps.



A typical 4-stage Marx generator

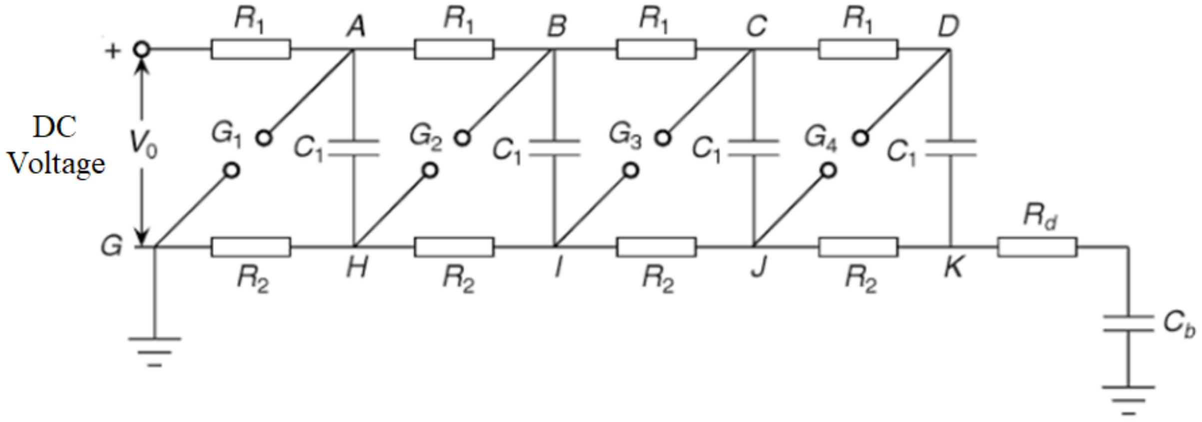
Generation of high voltages
‘Impulse Voltage, Marx Generator’

- The DC voltage V_0 charges the stage capacitor C_1 (four in number in parallel) through the high value charging resistors R_1 as well as through resistors R_2 which are much smaller than R_1
- After a long time period, which may be as high as 1 minute, the points *A*, *B*, *C*, *D* will acquire the potential of the DC source V_0 with respect to earth point *G*.



Generation of high voltages ‘Impulse Voltage, Marx Generator’

- The points *H*, *I*, *J*, *K* will remain at earth potential as the voltage drops across the resistors R_2 are negligible during charging. Therefore, the load capacitance C_b remains at earth potential during charging of stage capacitors.
- Suppose that the gaps G_1, G_2, G_3, G_4 are set to spark one after the other, the gap G_1 leading when the charging voltage attains a value of $+V_0$.



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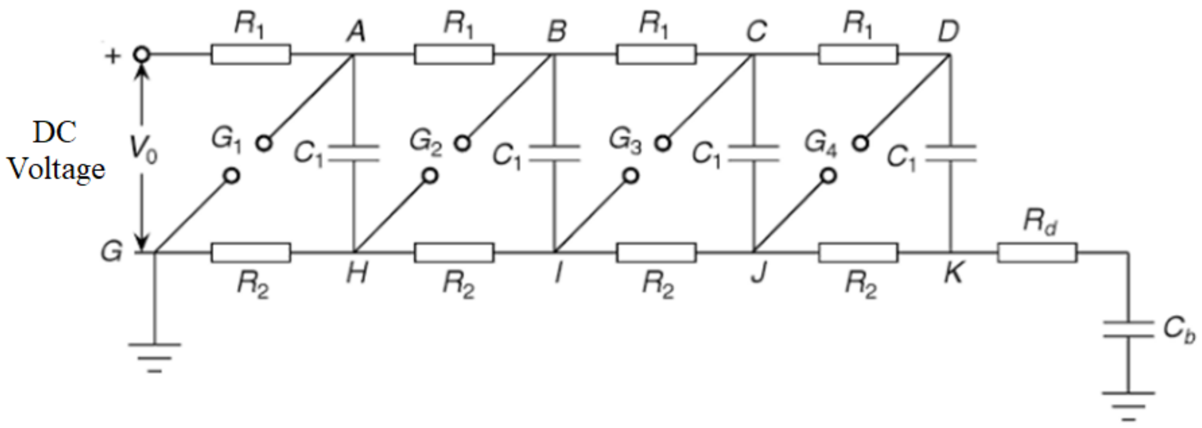
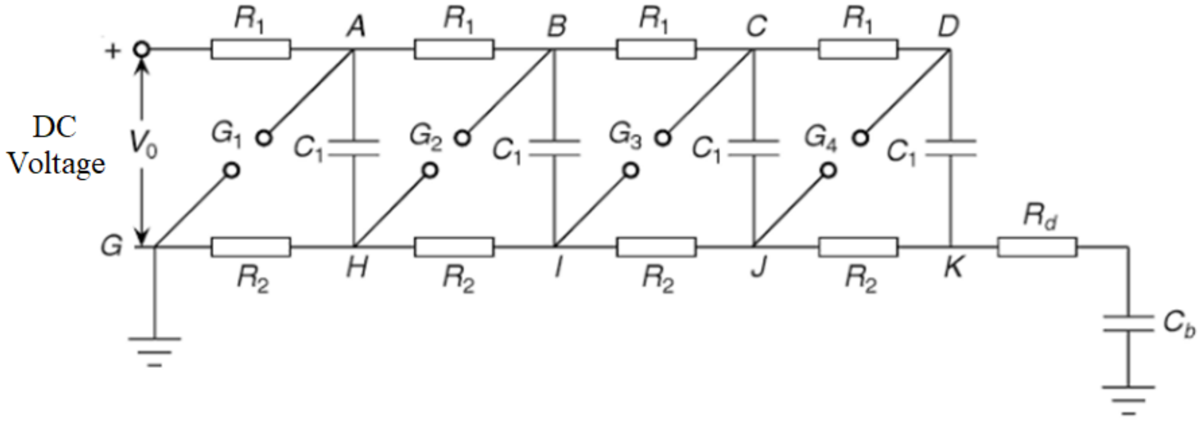
Generation of high voltages 'Impulse Voltage, Marx Generator'

- When G_1 breaks down there will be a momentary redistribution of charge potential on C_1 connected across AH. Its top plate falls to zero potential while its lower plate potential suddenly changes to $-V_0$. This is because the total charge of capacitor remains unchanged during the transient period.
- Therefore, suddenly there appears a potential of $2V_0$ across the gap G_2 ($-V_0$ to $+V_0$) and this gap then instantly breaks down.



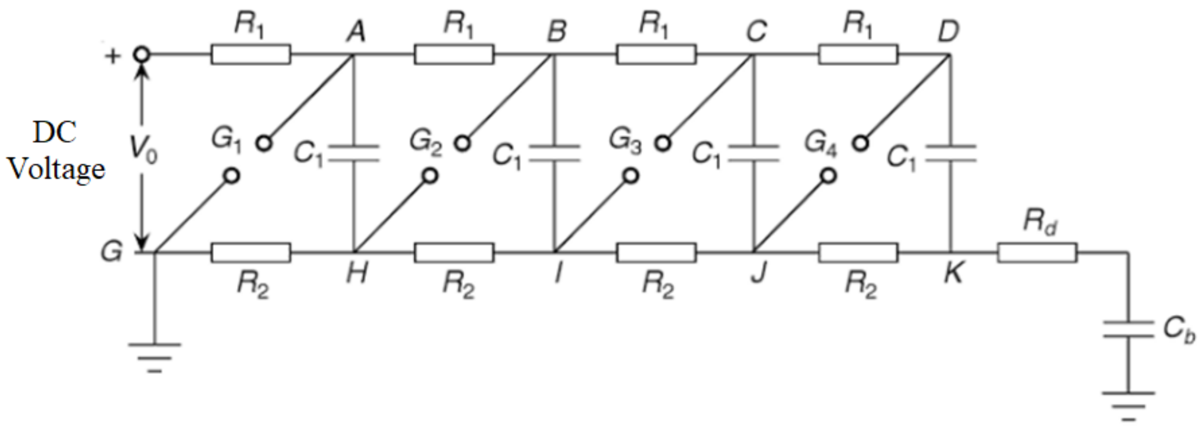
Generation of high voltages
‘Impulse Voltage, Marx Generator’

- The process is repeated , the lower plates successfully attain
  - $-1V_0$ (point H),
  - $-2V_0$ (point I),
  - $-3V_0$ (point J),
  - $-4V_0$ (point K).
- If the charging potential is positive then a negative potential with respect to earth will appear on the negative plate of the last stage capacitor.



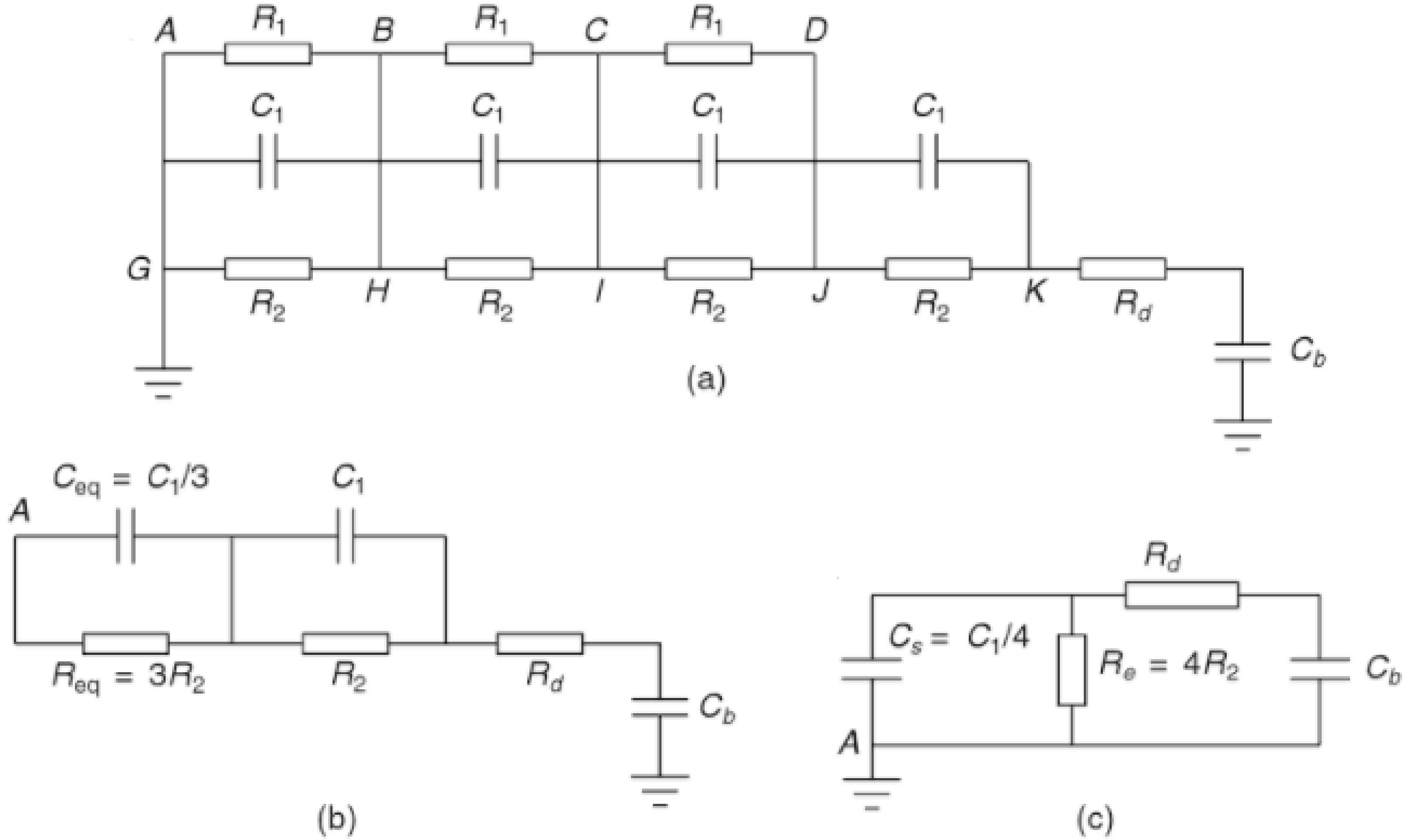
Generation of high voltages
'Impulse Voltage, Marx Generator'

- For obtaining a positive voltage with respect to earth, we need to charge the capacitors to $-V_0$
- For an *n*-stage impulse circuit the output impulse voltage across C_b will be $-n\eta V_0$ where η is the voltage efficiency.



Generation of high voltages
‘Impulse Voltage, Marx Generator’

Analysis of 4-stage impulse generating circuit



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Generation of high voltages
'Impulse Voltage, Marx Generator'

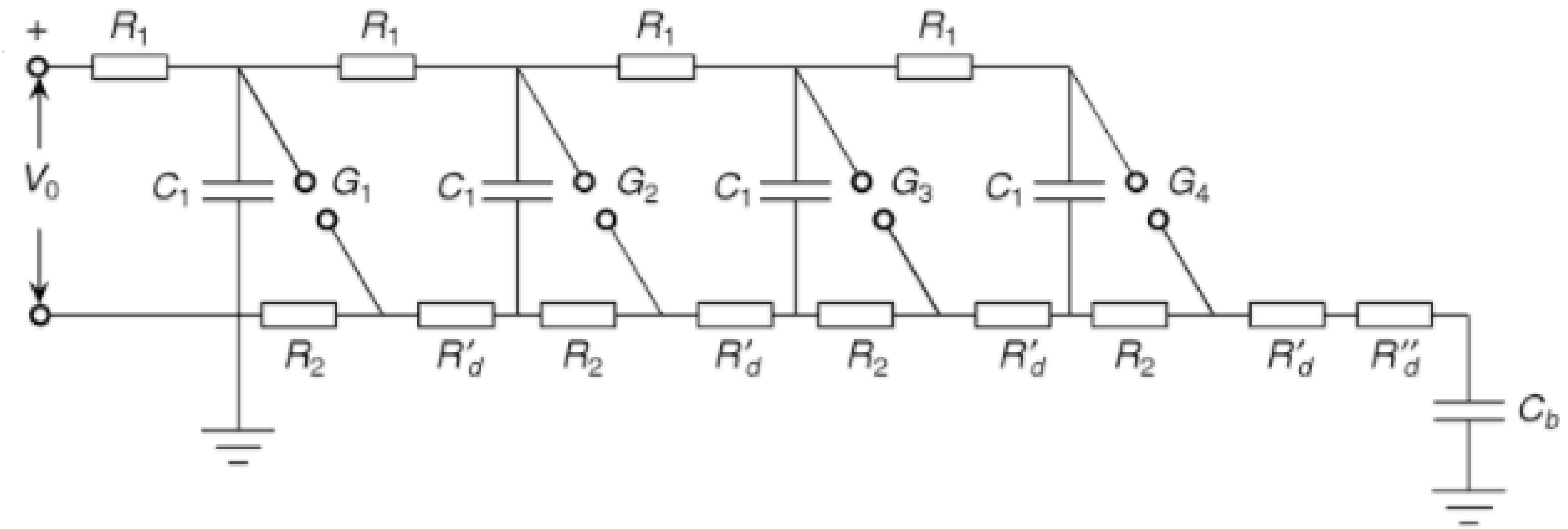
- The resistor $4R_2$ is equivalent to the discharge resistance and is responsible for the wave-tail shape.
- For n stage impulse generator:

$$C_s = \frac{C_1}{n}; \quad R_e \approx nR_2$$

where R_2 is the wave-tail resistor and R_d is the wave-front resistor

Generation of high voltages
‘Impulse Voltage, Marx Generator’

- The wave-front resistor R_d has to withstand for a small time the full rated voltage. Hence, it occupies more space.
- This is can be avoided if a part of R_d is distributed within the generator.



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Generation of high voltages ‘Impulse Voltage, Marx Generator’

- When this n-stage generator fires, the total discharge capacitance C_s, the effective front resistance R_d, and the effective discharge resistance R_e are given by:

$$C_s = \frac{C_1}{n};$$

$$R_d = R_d'' + nR_d'$$

$$R_e \approx nR_2$$

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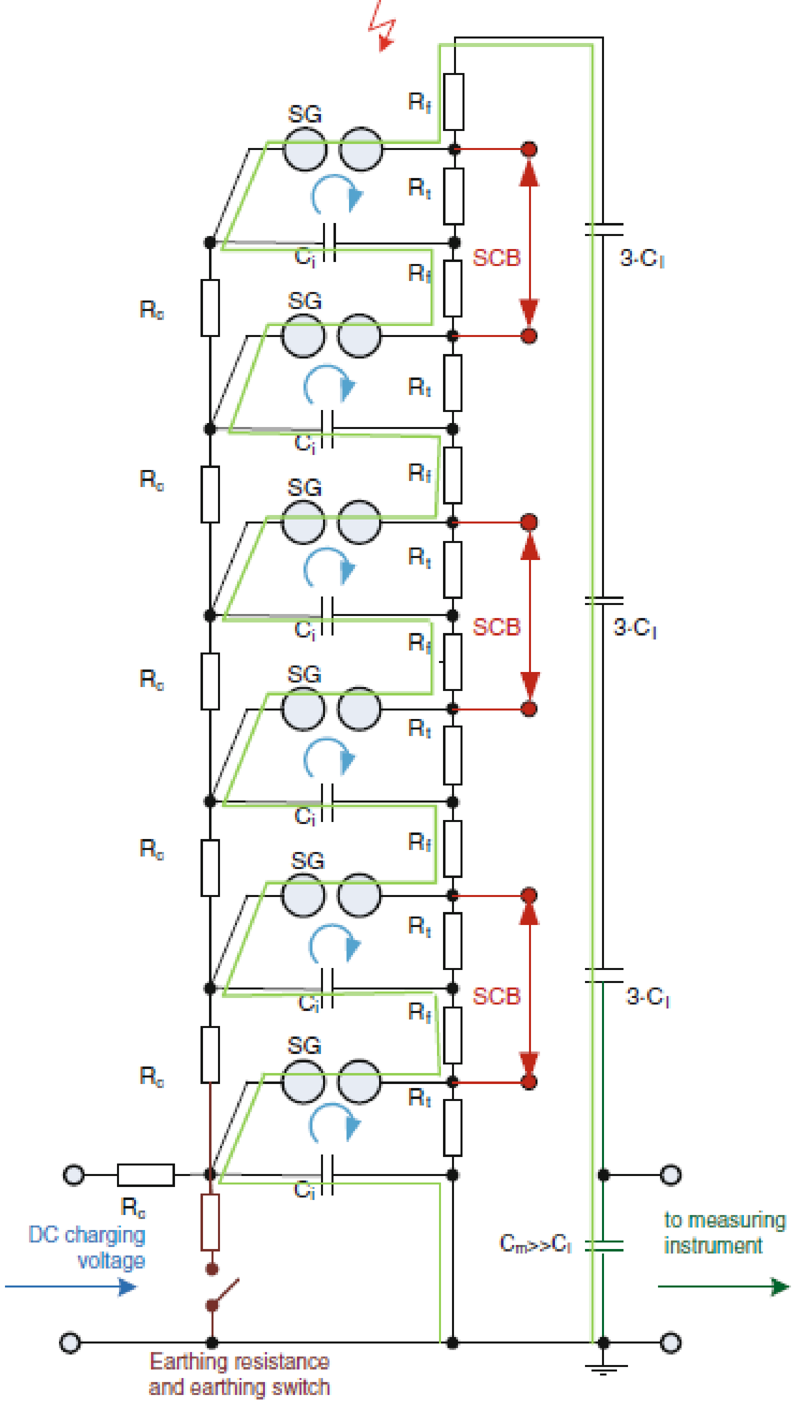

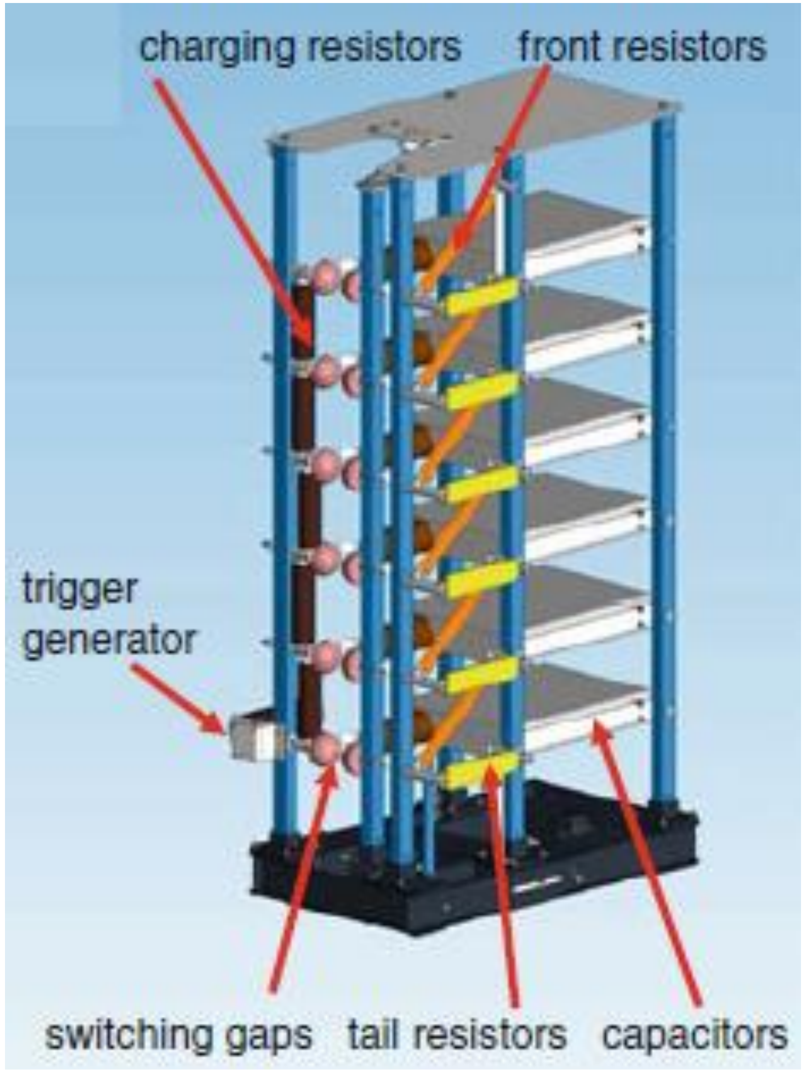

Generation of high voltages
‘Impulse Voltage, Marx Generator’

Example

A ten-stage impulse generator has 0.250 μF condensers. The wave front and wave tail resistances are 75 ohms and 2600 respectively. If the load capacitance is 2.5 nF, determine the wave front and wave tail times of the impulse wave.

Generation of high voltages
‘Impulse Voltage, Marx Generator’

$$R_1 = 75; R_2 = 2600; C_1 = \frac{0.25}{10}\times10^{-6}; C_2 = 2.5\times10^{-6};$$

$$a = \frac{1}{R_1C_1} + \frac{1}{R_1C_2} + \frac{1}{R_2C_1} = 7.0256\times10^{5}$$

$$b = \frac{1}{R_1R_2C_1C_2} = 8.2051\times10^{10}$$

$$k = R_1C_2 = 6.5\times10^{-6}$$

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Generation of high voltages
‘Impulse Voltage, Marx Generator’

$$\alpha_1 = \frac{a}{2} - \sqrt{\left(\frac{a}{2}\right)^2 - b} = 1.48\times 10^5; \quad \alpha_2 = \frac{a}{2} + \sqrt{\left(\frac{a}{2}\right)^2 - b} = 5.55\times 10^5$$

$$t_{\max} = \frac{\ln(\alpha_2/\alpha_1)}{\alpha_2 - \alpha_1} = 3.2494\times 10^{-6}$$

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Generation of high voltages ‘Impulse Voltage, Marx Generator’

$$V(t_{max}) = \frac{nV_0}{k}\frac{1}{\alpha_2-\alpha_1}\left(e^{-\alpha_1 t_{max}} - e^{-\alpha_2 t_{max}}\right) =$$

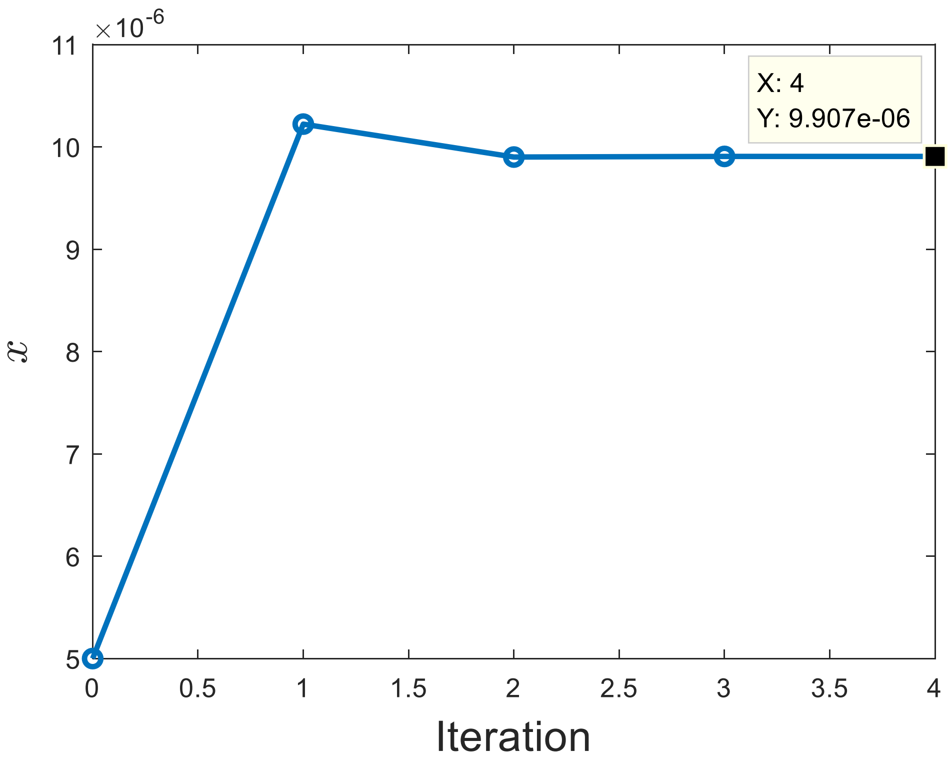
$$= 0.4534\frac{nV_0}{k}\frac{1}{\alpha_2-\alpha_1}$$

$$V(t_2) = 0.5V(t_{max})$$

$$\frac{nV_0}{k}\frac{1}{\alpha_2-\alpha_1}\left(e^{-\alpha_1 t_2} - e^{-\alpha_2 t_2}\right) = 0.5\times 0.4534\frac{nV_0}{k}\frac{1}{\alpha_2-\alpha_1}$$

$$\left(e^{-\alpha_1 t_2} - e^{-\alpha_2 t_2}\right) = 0.2267 \Rightarrow t_2 = 9.9\times 10^{-6}$$

Generation of high voltages
‘Impulse Voltage, Marx Generator’




```matlab
alpha1=1.48e5;
alpha2=5.55e5;
f = @(x) exp(-alpha1*x)-exp(-alpha2*x)-0.2267; % Equation definition!
fp = @(x) -alpha1*exp(-alpha1*x)+alpha2*exp(-alpha2*x); % First-order derivative of f!
x0 = 5e-6; % Initial guess!
N = 10; % Maximum number of iterations!
tol = 1E-6; % Convergence tolerance!
x = zeros(N + 1,1); % Preallocate solution vector where row => iteration!
x(1) = x0; % Set initial guess
% Newton's Method algorithm!
n = 2;
nfinal = N + 1; % Store final iteration if tol is reached before N iterations!
while (n <= N + 1)
    fe = f(x(n - 1));
    fpe = fp(x(n - 1));
    x(n) = x(n - 1) - fe/fpe;
    if (abs(fe) <= tol)
        nfinal = n; % Store final iteration!
        break;
    end
        n = n + 1;
end
% Plotevolution of the solution!figure('Color','White')!
plot(0:nfinal - 1,x(1:nfinal),'o-')
title('Newton''sMethod Solution: $f(x)','FontSize',20,'Interpreter','latex')
xlabel('Iteration','FontSize',16)
ylabel('$x$','FontSize',16,'Interpreter','latex')
```

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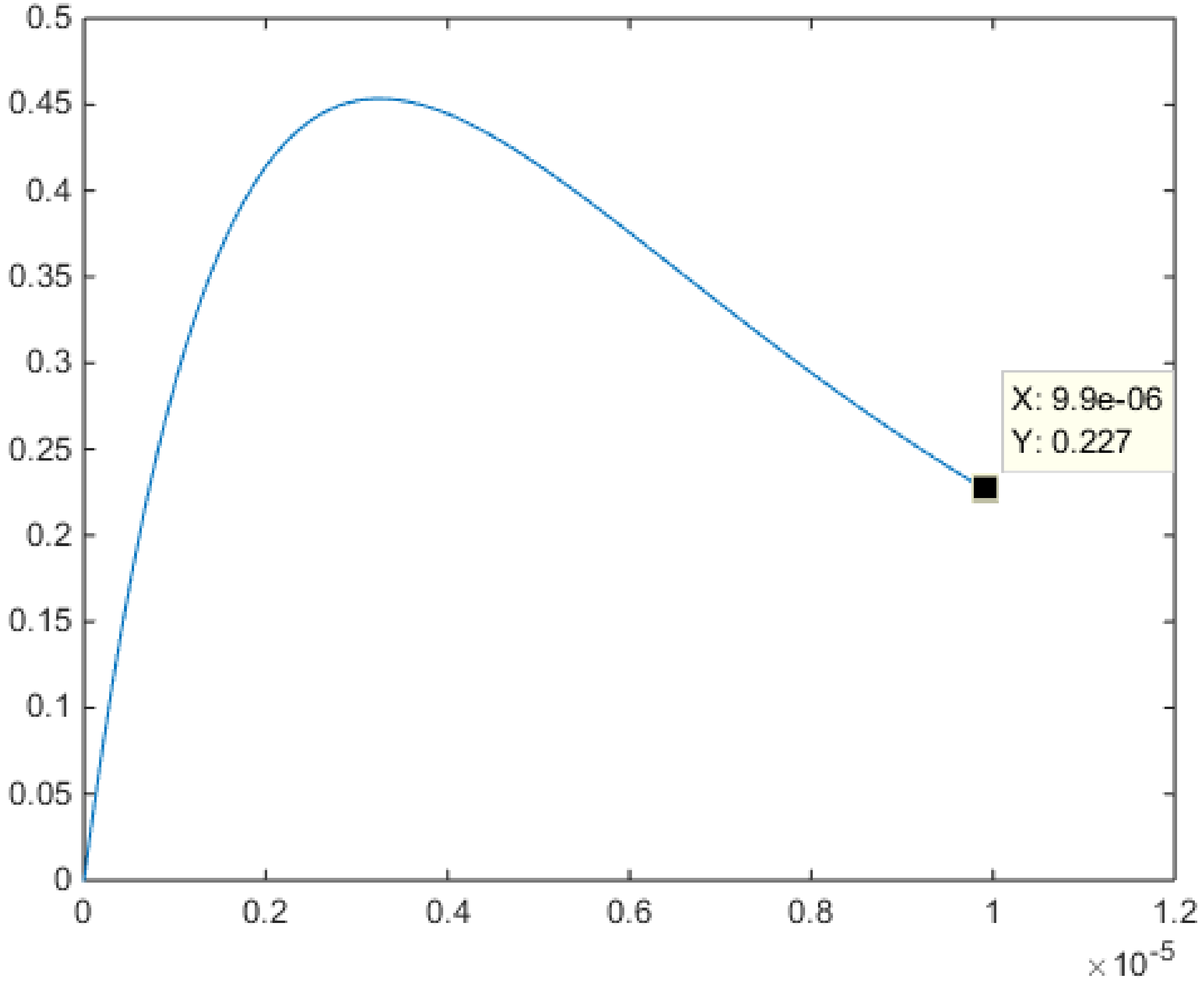
Generation of high voltages
‘Impulse Voltage, Marx Generator’



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Generation of high voltages
‘Impulse Voltage, Marx Generator’

Example

A 12-stage impulse generator has capacitors each rated at 0.3 µF, 150 kV. The capacitance of the test object is 200 nF. Determine the wave front and wave tail resistance to produce at 1.2/50 µsec impulse wave. Also determine the maximum output voltage if the charging voltage is 125 kV.

Generation of high voltages
'Impulse Voltage, Marx Generator'

$$C_1=\frac{0.3}{12}\times 10^{-6};C_2=200\times 10^{-9};\alpha_1=10^6/68.2;\alpha_2=10^6/0.405$$

$$R_1=\frac{1}{2C_2}\left[\left(\frac{1}{\alpha_1}+\frac{1}{\alpha_2}\right)-\sqrt{\left(\frac{1}{\alpha_1}+\frac{1}{\alpha_2}\right)^2-\frac{4(C_1+C_2)}{\alpha_1\alpha_2C_1}}\right]=29.3007$$

$$R_2=\frac{1}{2(C_1+C_2)}\left[\left(\frac{1}{\alpha_1}+\frac{1}{\alpha_2}\right)+\sqrt{\left(\frac{1}{\alpha_1}+\frac{1}{\alpha_2}\right)^2-\frac{4(C_1+C_2)}{\alpha_1\alpha_2C_1}}\right]=1.5083\times 10^3$$

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Generation of high voltages
‘Impulse Voltage, Marx Generator’

$$t_{\max} = \frac{\ln(\alpha_2 / \alpha_1)}{\alpha_2 - \alpha_1} = 2.0886\mathrm{e}\times 10^{-6}$$

$$k = R_1 C_2 = 5.8601\times 10^{-7}$$

$$V(t_{\max}) = \frac{nV_0}{k}\frac{1}{\alpha_2 - \alpha_1}\left(e^{-\alpha_1 t_{\max}} - e^{-\alpha_2 t_{\max}}\right) = 1.0054\times 10^{6}$$

Generation of high voltages
‘Alternating Voltage’

- Testing of h.v. apparatus or h.v. insulation always involves an application of high voltages to capacitive loads with low or very low power dissipation only.
- In general, power dissipation can be completely neglected if the nominal power output of the supply is determined.
- If C_t is the capacitance of the equipment or sample under test, and V_n the nominal r.m.s. voltage of the h.v. testing supply, the nominal kVA rating S_n may be calculated from the design formula

$$S_n = kV_n^{\,2}\omega C_t\,;$$

in which the factor $k > 1$ accounts for additional capacitances within the whole test circuit and some safety factor

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Generation of high voltages ‘Alternating Voltage’

- The capacitance of test equipment C_t may change considerably, depending upon the type of equipment.
- Typical values are:
  - Simple post or suspension insulators some 10 pF
  - Bushings, simple and graded 100 –1000 pF
  - Potential transformers 200 –500 pF
  - Power transformers
    <1000 kVA 1000 pF
    >1000 kVA 1000 –10 000 pF
  - H.V. power cables:
    Oil-paper impregnated .250–300 pF/m
    Gaseous insulated .60 pF/m
  - Metal clad substation, SF6 insulated .1000 – >10 000 pF

Generation of high voltages ‘Alternating Voltage’

- One may calculate the nominal currents $I_n = S_n/V_n$ for different test voltages, different C_t values, and proper safety factors k.
- From such estimations it may be seen that these currents may range from some 10 mA for testing voltages of 100 kV only, up to amperes in the megavolt range.
- The currents required for tests on various equipments are:

  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

Generation of high voltages ‘Alternating Voltage’

- Main methods for the generation of high a.c. testing voltages
  - Transformers
  - Resonant circuits
  - Tesla Coil

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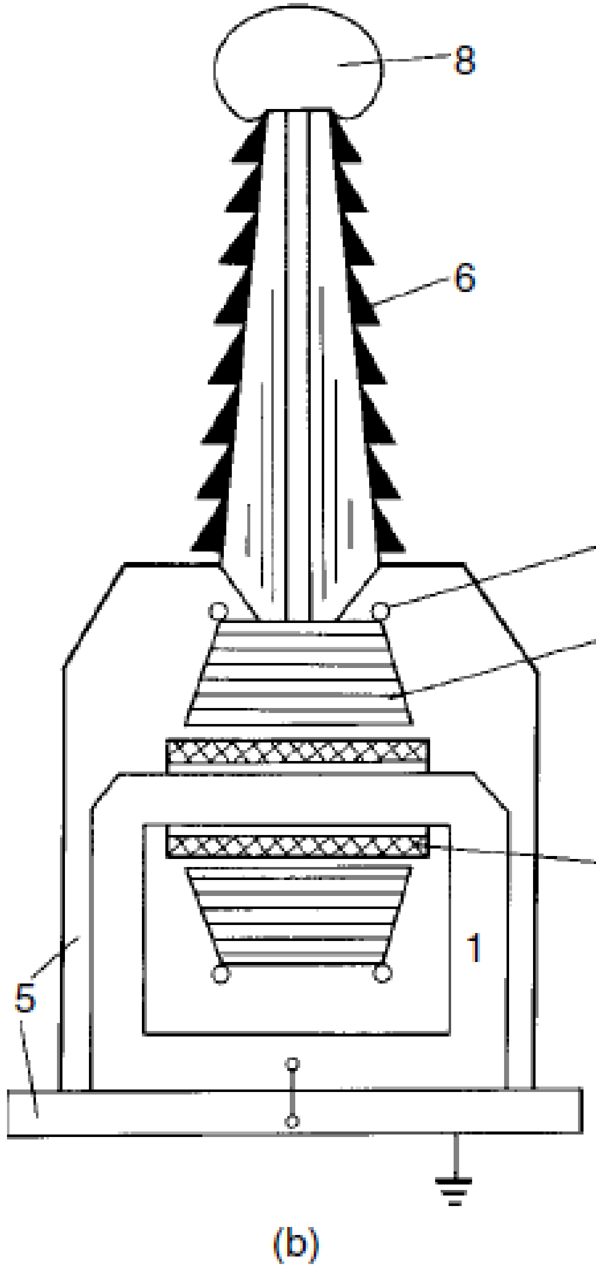
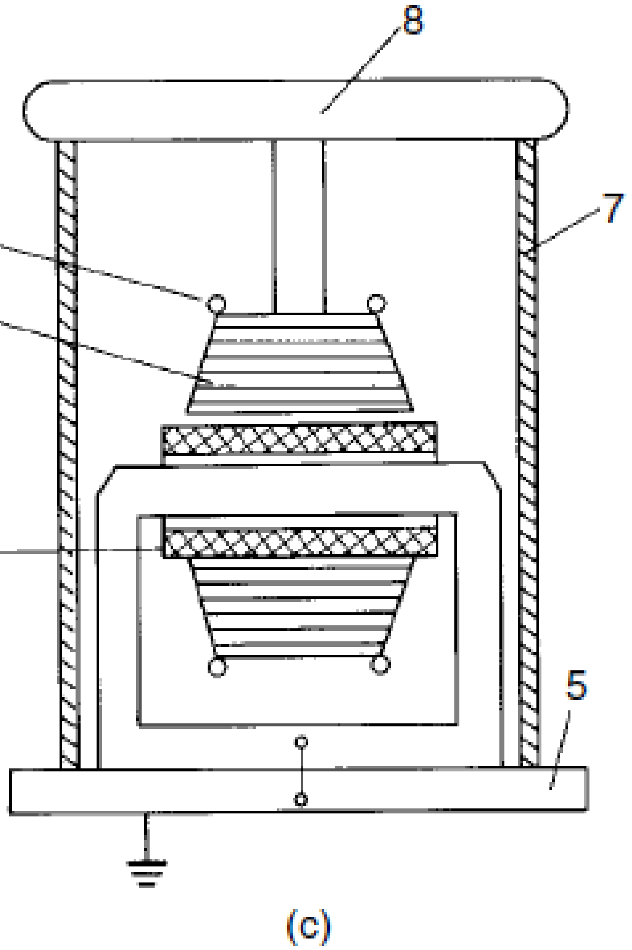
Generation of high voltages ‘Alternating Voltage, Transformers, ’

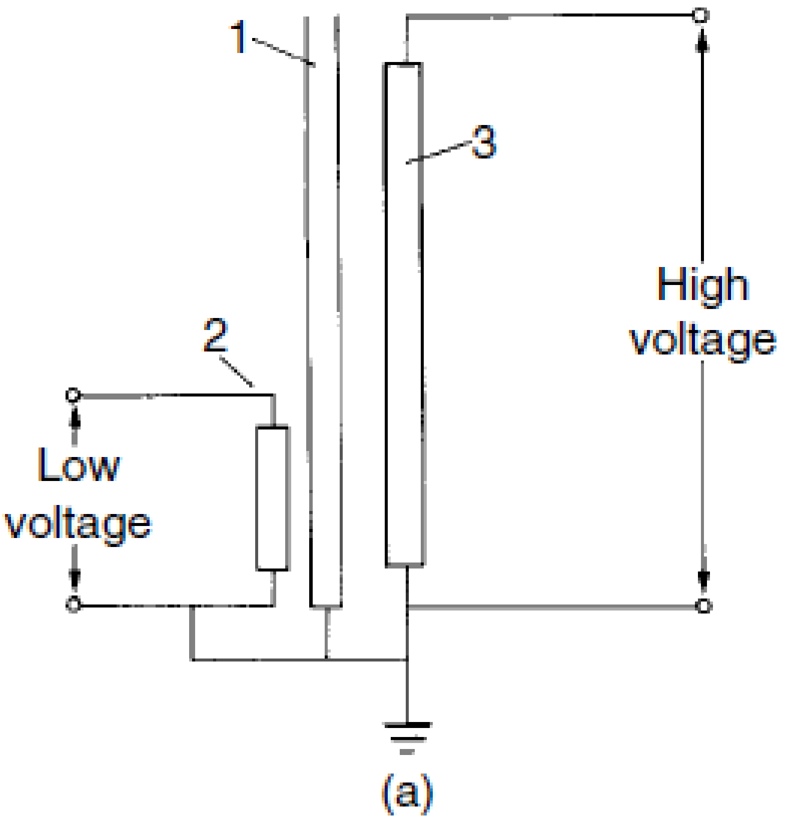
Single unit testing transformer

- The design of a test transformer is similar to a potential transformer used for the measurement of voltage and power in transmission lines.
- The flux density chosen is low so that it does not draw large magnetising current which would otherwise saturate the core and produce higher harmonics.



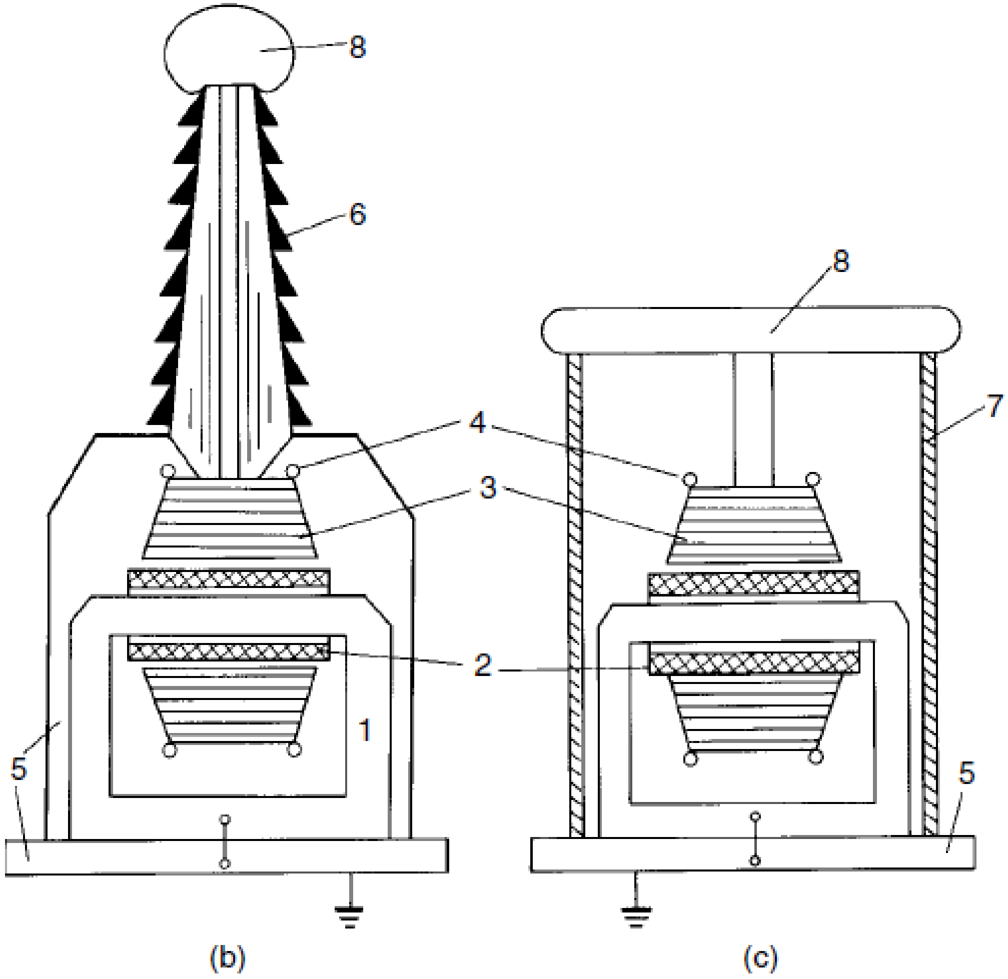
Single unit testing transformers. (a) Diagram. (b & c) different construction units. (1) Iron core. (2) Primary l.v. or exciting winding. (3) Secondary h.v. winding. (4) Field grading shield. (5) Grounded metal tank and base. (6) H.V. bushing. (7) Insulating shell or tank. (8) H.V. electrode





Generation of high voltages
'Alternating Voltage, Transformers'

- The primary winding '2' is usually rated for low voltages of 1 kV, but might often be split up in two or more windings which can be switched in series or parallel (not shown here) to increase the regulation capabilities.
- The iron core '1' is fixed at earth potential as well as one terminal of each of the two windings.
- Simplified cross-sections of two possible constructions for the unit itself are given in Figs (b) and (c).
- In both cases the layout arrangement of core and windings is basically the same.



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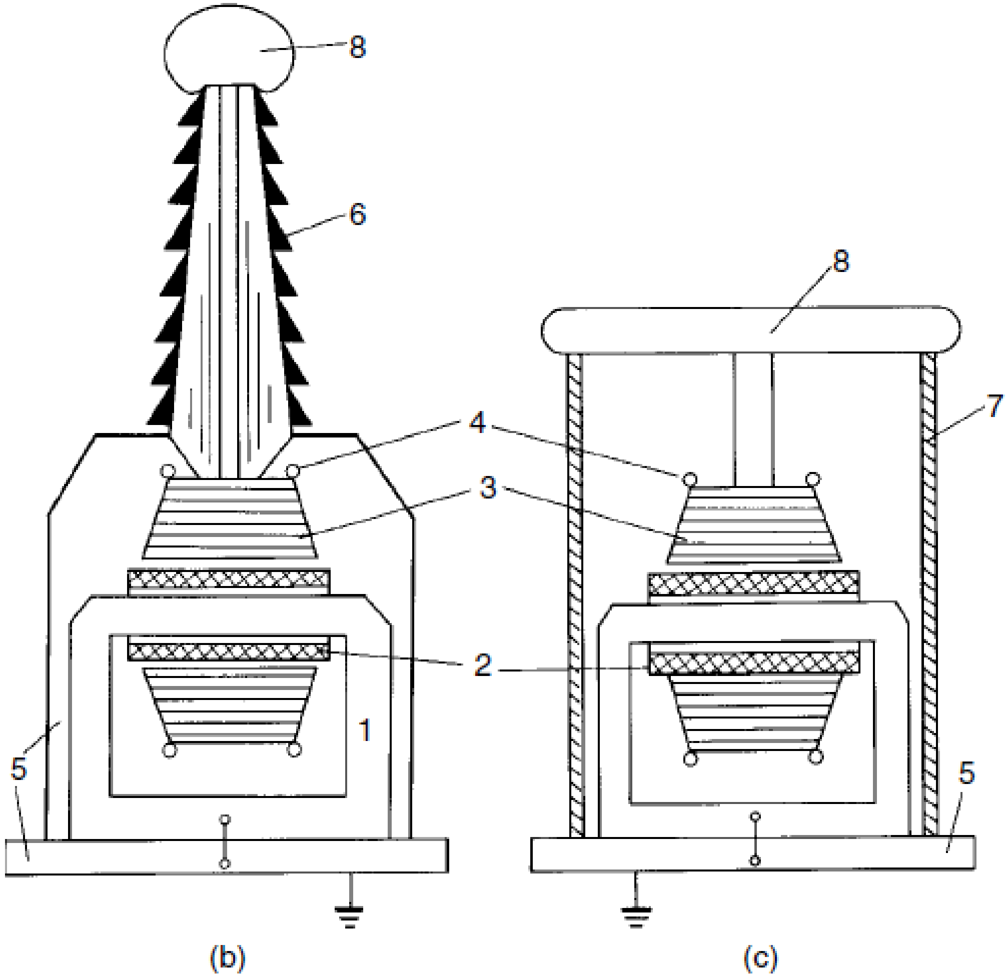
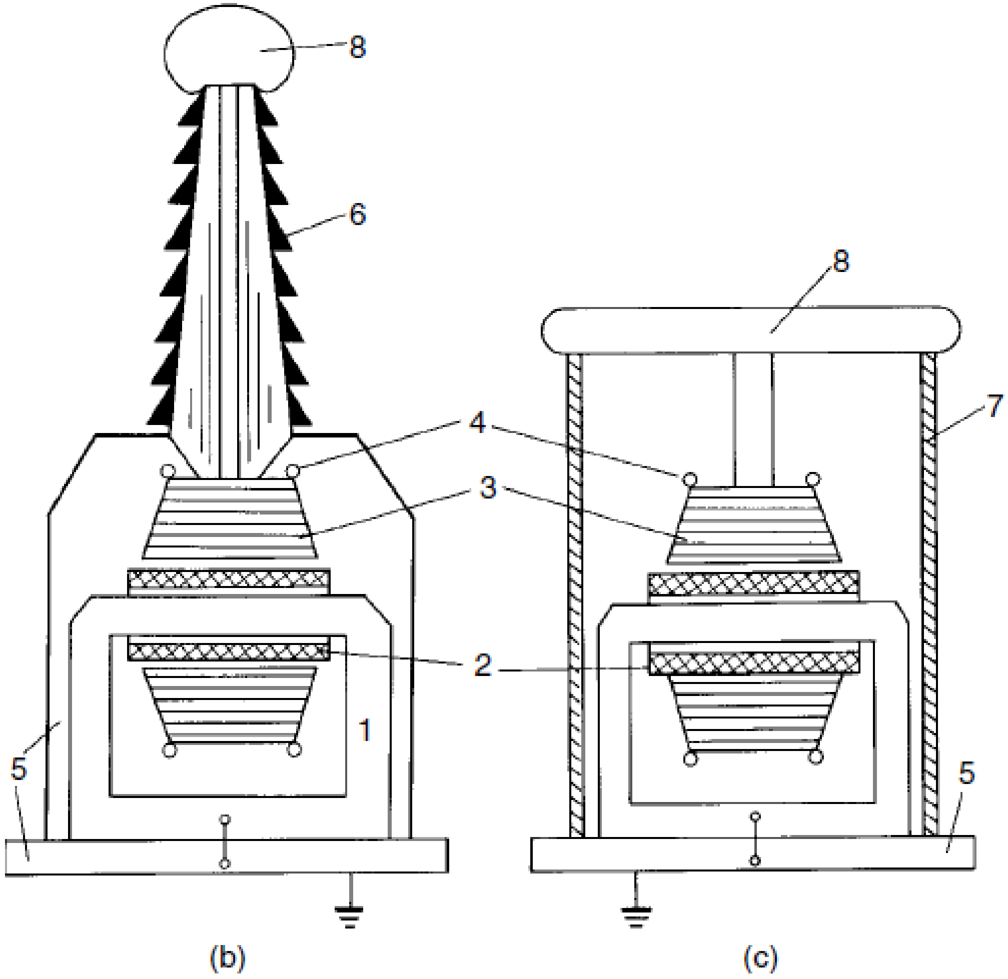
Generation of high voltages
‘Alternating Voltage, Transformers’

- Figure (b), however, shows a grounded metal tank unit, for which an h.v. bushing ‘6’ is necessary to bring the high voltage out of the tank ‘5’.
- Instead of a bushing, a coaxial cable could also be used if this improves the connection between testing transformer and test object.
- In Fig. (c), the active part of the transformer is housed within an isolating cylinder ‘7’ avoiding the use of the bushing. This construction reduces the height, although the heat transfer from inside to outside is aggravated.
- In both cases the vessels would be filled with high-quality transformer oil, as most of the windings are oil-paper insulated.



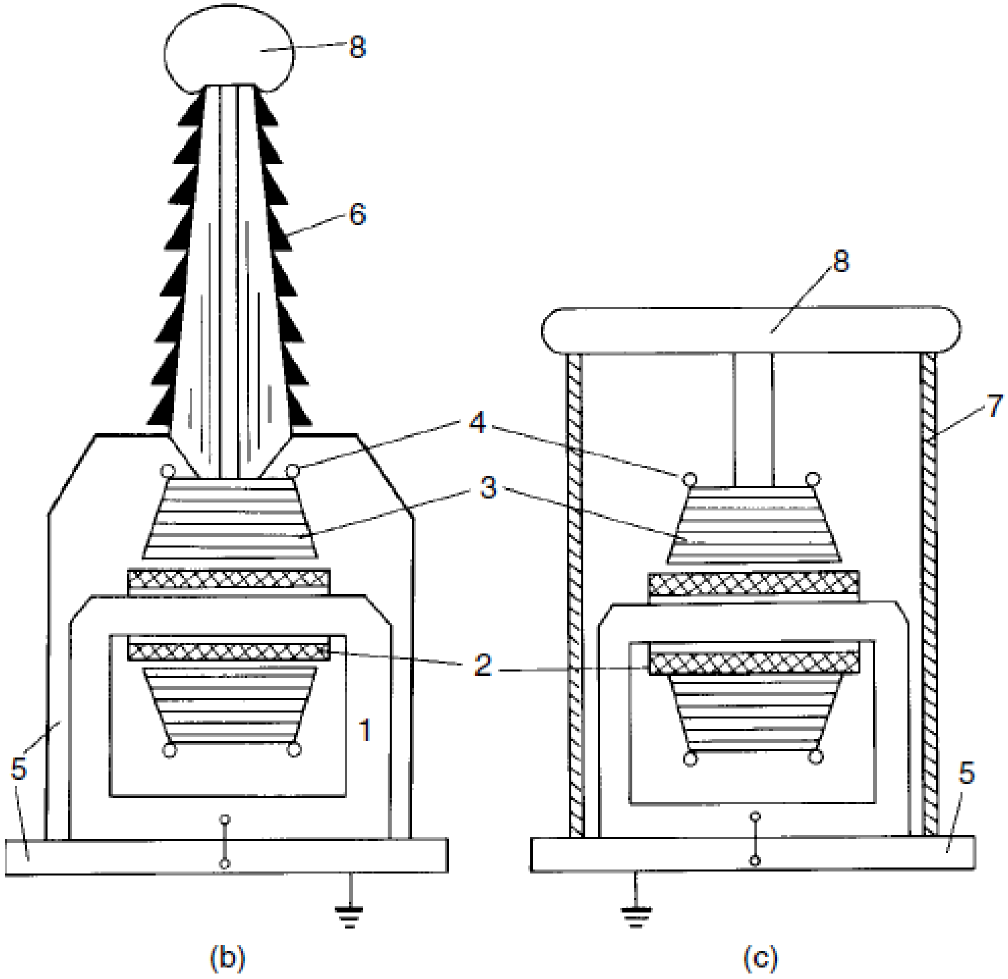
Generation of high voltages ‘Alternating Voltage, Transformers’

- The sectional view of the windings shows the primary winding close to the iron core and surrounded by the h.v. winding ‘3’.
- This coaxial arrangement reduces the magnetic stray flux and increases, therefore, the coupling of both windings.



Generation of high voltages
'Alternating Voltage, Transformers'

- The shape of the cross-sectional view of winding no. 3 is a hint to the usual layout of this coil: the beginning (grounded end) of the h.v. winding is located at the side close to the core, and the end close to a sliced metal shield, which prevents too high field intensities at h.v. potential.
- Between both ends the single turns are arranged in layers, which are carefully insulated from each other by solid materials (Kraft paper sheets for instance).



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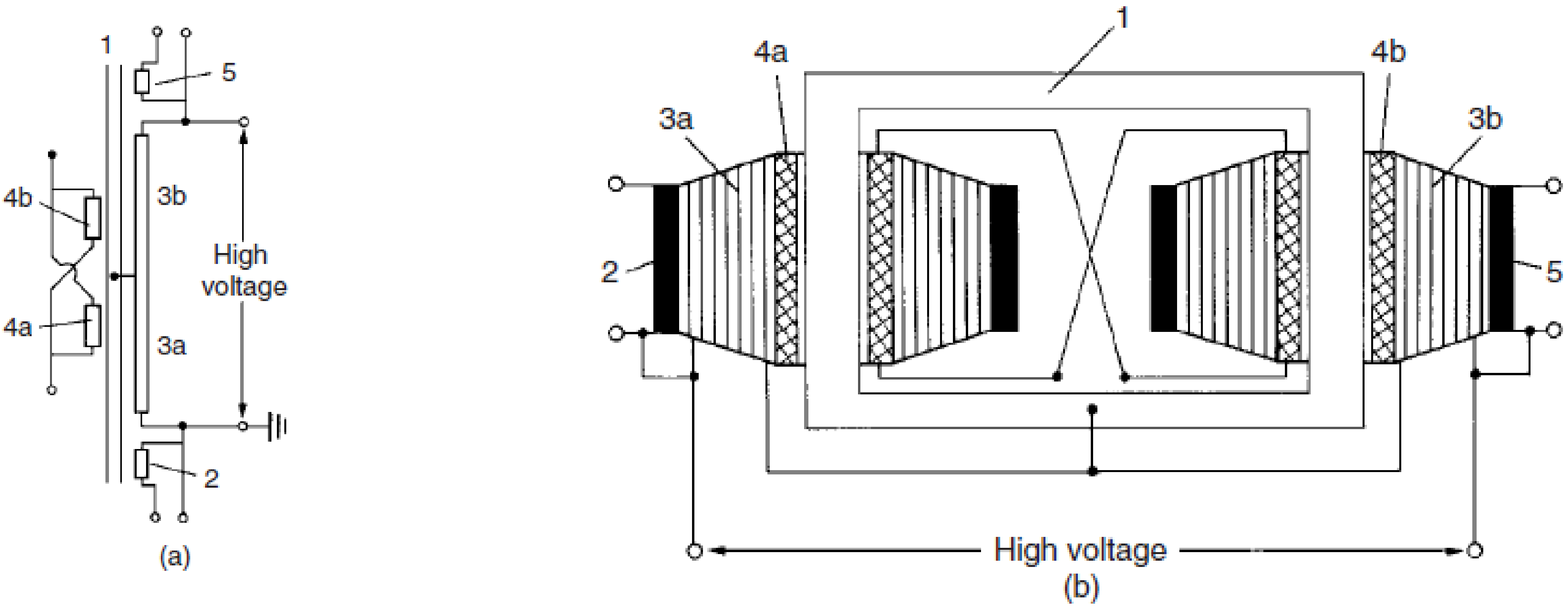
Generation of high voltages ‘Alternating Voltage, Transformers’

<u>Single unit testing transformer with mid-point core potential</u>

- It may well be understood that the design of the h.v. winding becomes difficult if voltages of more than some 100 kV must be produced within one coil.
- Better constructions are available by specialized techniques, mainly by ‘cascading’ transformers.



Single unit testing transformer with mid-point potential at core: Diagram (a) and cross-section (b). (1) Iron core. (2) Primary winding. (3a & b) High-voltage windings. (4a & b) compensating windings. (5) Exciting winding

Generation of high voltages ‘Alternating Voltage, Transformers’

- The first step in this technique is to place two h.v. windings on one iron core, to join both windings in series and to connect this junction with the core.
- The arrangement could still be treated as a single unit transformer, as only one core exists. The mid-point of the h.v. winding is connected to the core and to a metal tank, if such a tank is used as a vessel.
- The cross-section shows that the primary winding ‘2’ is, however, placed now around the first part ‘3a’ of the whole h.t. winding, whose inner layer, which is at half-potential of the full output voltage, is connected to the core.
- There are two additional windings, ‘4a’ and ‘4b’, rated for low voltages, which act as compensating windings.
- These are placed close to the core and reduce the high leakage reactance between ‘3b’ and the primary ‘2’.

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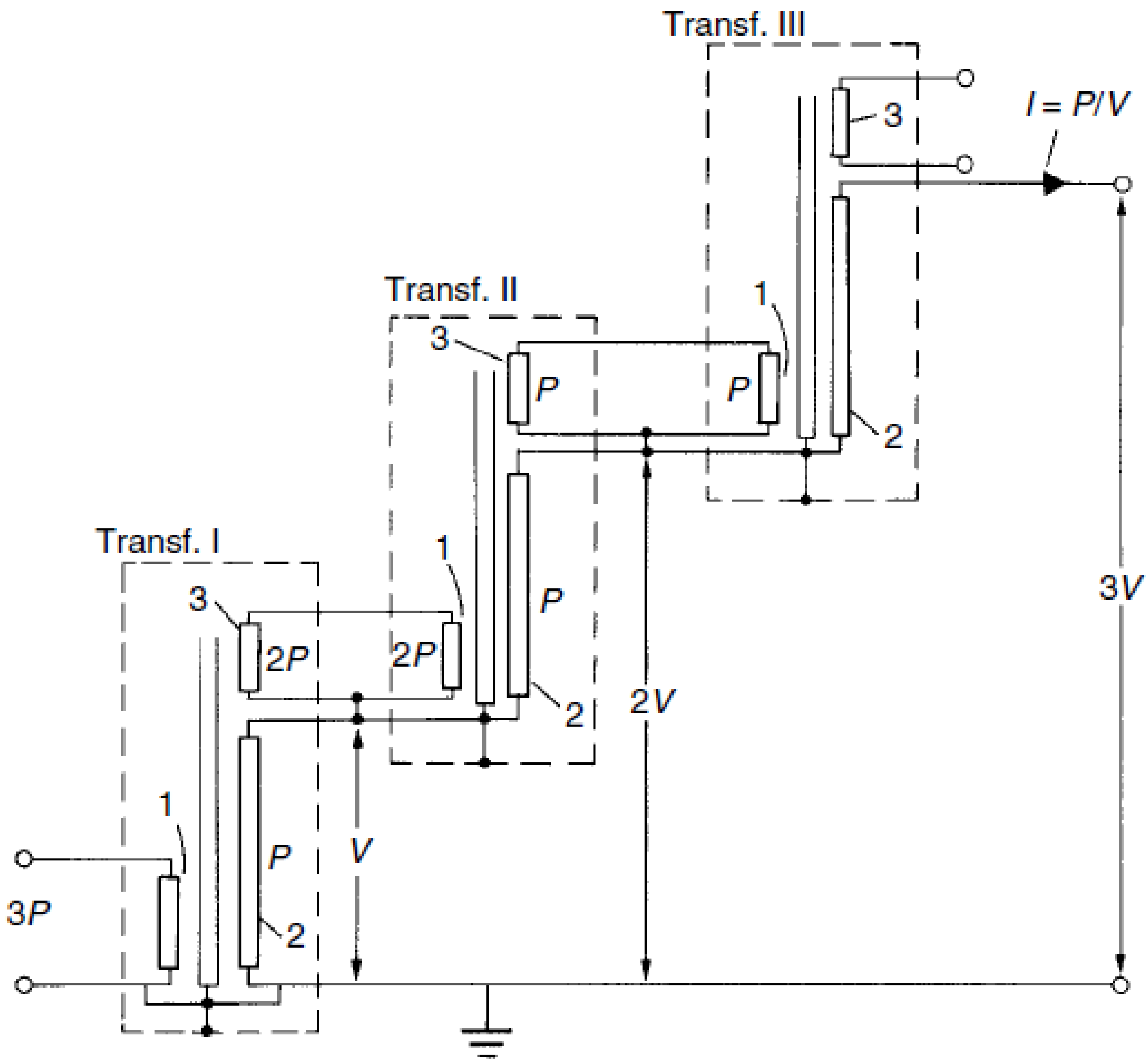
Generation of high voltages
‘Alternating Voltage, Transformers’

- Often an exciting winding ‘5’, again a winding rated for low voltages as the primary winding, is also available.
- This exciting winding is introduced here as it will be needed for the cascading of transformers.
- Note that this winding is at the full output potential of the transformer. Although no vessel is shown in which such a unit would be immersed, it can easily be understood that for metal tank construction two h.v. bushings are now necessary.
- The tank itself must be insulated from earth for half-output voltage.

Generation of high voltages
'Alternating Voltage, Transformers'

Cascading testing transformer

- For voltages higher than about 300 to 500 kV, the cascading of transformers is a big advantage, as the weight of a whole testing set can be subdivided into single units and therefore transport and erection becomes easier.
- A prerequisite to apply this technique is an exciting winding within each transformer unit.
- The l.v. supply is connected to the primary winding '1' of transformer I, designed for an h.v. output of *V* as are the other two transformers.
- The exciting winding '3' supplies the primary of the second transformer unit II; both windings are dimensioned for the same low voltage, and the potential is fixed to the high potential *V*.
- The h.v. or secondary windings '2' of both units are series connected, so that a voltage of 2V is produced hereby.
- The addition of the stage III needs no further explanation.



Basic circuit of cascaded transformers.

(1) Primary windings.

(2) Secondary h.t. windings.

(3) Tertiary exciting windings

Generation of high voltages
'Alternating Voltage, Transformers'

- The tanks or vessels containing the active parts (core and windings) are indicated by dashed lines only.
- For a metal tank construction and the non-subdivided h.v. winding assumed in this basic scheme, the core and tank of each unit would be tapped to the l.v. terminal of each secondary winding as indicated.
- Then the tank of transformer I can be earthed; the tanks of transformers II and III are at high potentials, namely V and $2V$ above earth, and must be suitably insulated.
- Through h.t. bushings the leads from the exciting coils '3' as well as the tappings of the h.v. windings are brought up to the next transformer.
- If the h.v. windings of each transformer are of mid-point potential type, the tanks are at potentials of 0.5V, 1.5V and 2.5V respectively.
- Again, an insulating shell could avoid the h.t. bushings, rendering possible the stacking of the transformer units.

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Generation of high voltages 'Alternating Voltage, Transformers'

- The disadvantage of transformer cascading is the heavy loading of primary windings for the lower stages.
- In the previous figure this is indicated by the letter *P*, the product of current and voltage for each of the coils.
- For this three-stage cascade the output kVA rating would be 3*P*, and therefore each of the h.t. windings '2' would carry a current of $I = P/V$.
- Also, only the primary winding of transformer III is loaded with *P*, but this power is drawn from the exciting winding of transformer II. Therefore, the primary of this second stage is loaded with 2P.
- Finally, the full power 3*P* must be provided by the primary of transformer I.

Generation of high voltages ‘Alternating Voltage, Transformers’

- Thus an adequate dimensioning of the primary and exciting coils is necessary. As for testing of insulation, the load is primarily a capacitive one, a compensation of this capacitive load by l.v. reactors, which are in parallel to the primary windings, is possible.
- As these reactors must be switched in accordance to the variable load, however, one usually tries to avoid this additional expense.
- It might also be necessary to add tuned filters to improve the waveshape of the output voltage, that is to reduce higher harmonics