Notes on

High Voltage Engineering

by

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Testing voltages in Laboratories:

Power systems equipment must withstand not only the rated voltage (V_m), which corresponds to the highest voltage of a particular system, but also over-voltages. Accordingly, it is necessary to test h.v. equipment during its development stage and prior to commissioning. The magnitude and type of test voltage varies with the rated voltage of a particular apparatus. The standard methods of measurement of high-voltage and the basic techniques for application to all types of apparatus for alternating voltages, direct voltages, switching impulse voltages and lightning impulse voltages are laid down in the relevant national and international standards.

Testing with power frequency voltages:

To assess the ability of the apparatus's insulation withstand under the system's power frequency voltage, the apparatus is subjected to the 1-minute test under 50 Hz or 60 Hz depending upon the country. The test voltage is set at a level higher than the expected working voltage in order to be able to simulate the stresses likely to be encountered over the years of service. For indoor installations the equipment tests are carried out under dry conditions only. For outdoor equipment tests may be required under conditions of standard rain as prescribed in the appropriate standards.

Testing with lightning impulse voltages:

Lightning strokes terminating on transmission lines will induce steep rising voltages in the line and set up travelling waves along the line and may damage the system's insulation. The magnitude of these over-voltages may reach several thousand kilovolts, depending upon the insulation. Exhaustive measurements and long experience have shown that lightning over-voltages are characterized by short front duration, ranging from a fraction of a microsecond to several tens of microseconds and then slowly decreasing to zero. The standard impulse voltage has been accepted as an aperiodic impulse that reaches its peak value in 1.2 μs and then decreases slowly (in about 50 μs) to half its peak value. In addition to testing equipment, impulse voltages are extensively used in research laboratories in the fundamental studies of electrical discharge mechanisms, notably when the time to breakdown is of interest.

Testing with switching impulses:

Transient over-voltages accompanying sudden changes in the state of power systems, e.g. switching operations or faults, are known as switching impulse voltages. It has become generally recognized that switching impulse voltages are usually the dominant factor affecting the design of insulation in HV power systems for rated voltages of about 300 kV and above. Accordingly, various international standards recommend that equipment designed for voltages above 300 kV be tested for switching impulses. Although the waveshape of switching over-voltages occurring in the system may vary widely, experience has shown that for flashover distances in atmospheric air of practical interest the lowest withstand values are obtained with surges with front times between 100 and 300 μs. Hence, the recommended switching surge voltage has been designated to have a front time of about 250 μs and half-value time of 2500 μs. For GIS (gas-insulated substation) on-site testing, oscillating switching impulse voltages are recommended for obtaining higher efficiency of the impulse voltage generator.

Testing with D.C. voltages:

In the past, DC voltages have been chiefly used for purely scientific research work. Industrial applications were mainly limited to testing cables with relatively large capacitance, which take a very large current when tested with AC voltages, and in testing insulations in which internal discharges may lead to degradation of the insulation under testing conditions. In recent years, with the rapidly growing interest in HVDC transmission, an increasing number of industrial laboratories are being equipped with sources for producing DC high voltages. Because of the diversity in the application of DC high voltages, ranging from basic physics experiments to industrial applications, the requirements on the output voltage will vary accordingly.

Ref: High Voltage Engineering by W.S.Zaengl

<u>GENERATION OF HIGH A.C. VOLTAGE</u>

High a.c. voltages are required to be generated in the laboratory for testing and research purposes. Major equipments that are used for generation of high a.c. voltage are

i) Testing Transformer
ii) Series Resonance Circuit.

A) Testing Transformer:

The power frequency single-phase transformer is the most common form of AC HV testing apparatus. It is designed for operation at the same frequency as the normal working frequency of the test object, i.e. 50 or 60 Hz. From the consideration of thermal rating, the kVA output and the fundamental design, a single-phase testing transformer may be compared to a single-phase power transformer as detailed below.

➢ Power Transformer vs. Testing Transformer:

i) Power transformers deal with bulk power, whereas the power rating of testing transformers is comparatively low, e.g. power rating of testing transformer is of the order of a few hundred kVA, while that for power transformers is of the order of several MVA.

ii) Voltage rating of testing transformer is normally very high but the current rating is low. On the other hand, the voltage rating of power transformers may or may not be very high but the current rating is generally very high.

iii) Power transformers are normally of continuous rating, although some may have intermediate ratings such as 60 min, 30 min etc. Usually a testing transformer has a rating of 30 min. But, if used for much shorter period of time, say for 1 min, then currents much larger than the rated value can be drawn.

iv) The short circuit impedance of power transformers is kept within 4-5%, while that for testing transformers is kept within 14-20%.

v) Unlike a power transformer a testing transformer is subjected to regular switching on and off operations, which results in transients and hence over voltages in the windings. These over voltages develop stresses that may result in breakdown of winding insulation. Thus testing transformers necessitate more reinforcement of insulation compared to power transformers.

vi) For power transformers, voltage regulation is generally positive. On the other hand, a testing transformer is generally subjected to capacitive load, which results in a negative voltage regulation, i.e. output voltage becomes greater than the input voltage. As a result, it becomes very difficult to measure the output terminal voltage with the help of a voltmeter connected to the primary side, but calibrated in terms of the secondary.

- **Voltage Regulation of a Testing Transformer:**

It is important to note here that most of the loads of a testing transformer are capacitive in nature as shown in Fig.1.

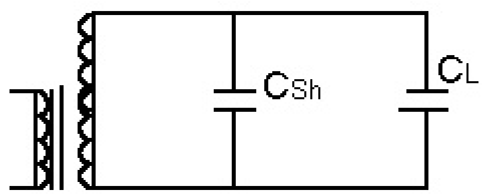


Fig.1

where, C_{Sh} = Equivalent shunt capacitance of the transformer.
C_L = Load capacitance.

Approximate Equivalent Circuit referred to hv side is shown in Fig.2.

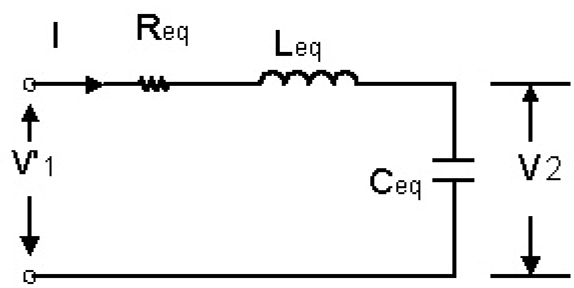


Fig.2

where, R_{eq} = Equivalent resistance
L_{eq} = Equivalent leakage inductance
C_{eq} = $C_{Sh} + C_L$ = Equivalent capacitance
V'_1 = Input voltage referred to hv side
V_2 = Output terminal voltage.

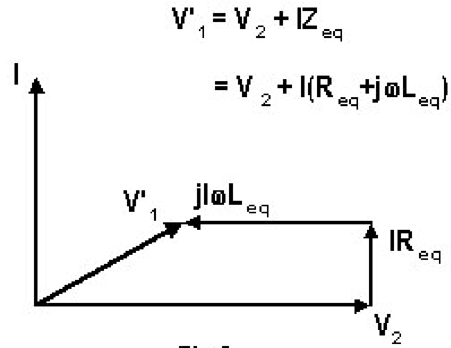


Fig.3

Normally in the case of testing transformers, short circuit impedance is made very high, so that

$$\omega L_{eq} >> R_{eq} \qquad \therefore\ V'_1 \approx V_2 + j\, I\, \omega L_{eq}$$

Again,

$$I = \frac{V_2}{1/j\omega C_{eq}} = j\omega C_{eq}\, V_2$$

$$\therefore V_1' = V_2 - \omega^2 L_{eq} C_{eq} V_2$$

$$\text{or, Voltage Regulation} = \frac{V_1' - V_2}{V_2} = -\omega^2 L_{eq} C_{eq}$$

$$\text{Again, p.u. impedance (Z)} = \frac{|I|\,|Z_{eq}|}{|V_2|} = \frac{\omega C_{eq} V_2 \cdot \omega L_{eq}}{V_2}$$

$$= \omega^2 L_{eq} C_{eq}$$

Thus, if a testing transformer has a p.u. impedance of 0.2, then the output terminal voltage is given as follows

$$\text{Voltage Regulation} = \frac{V_1' - V_2}{V_2} = -Z$$

$$or, \quad V_1' = (1 - Z)V_2$$

$$or,\ V_2 = \frac{V_1'}{1 - 0.2} = 1.25 V_1'$$

Prob. A 500V/250kV testing transformer is required to test a cable. The test voltage level is 150kV and the short-circuit impedance of the transformer is 16%. Calculate the voltage to be applied to the primary to conduct the test.

Slon. Given $V_2 = 150kV$ and $Z = 0.16$

$\therefore V'_1 = 150\ (1 - 0.16) = 126kV.$
(primary voltage referred to secondary)

So, the actual voltage that is to be applied to the primary $= 126 \times \frac{500}{250} = 252V.$

- **Potential Distribution along Transformer Winding:**

In power transformer, the effect of winding capacitance is normally neglected because of two reasons, viz. (a) the winding capacitances are low and (b) power frequency is low. Hence, the capacitive reactances are very high. But, under transient voltages, frequency becomes very high. As frequency increases, capacitive reactance decreases and inductive reactance increases. Hence, currents drawn by the capacitances become comparable to that drawn by other components.
In a transformer winding there are mainly two types of capacitances, viz. i) inter-turn capacitance (C_S) and ii) capacitance between hv and lv windings. When one particular winding is considered, then the capacitances are arranged in the manner shown in Fig.4.

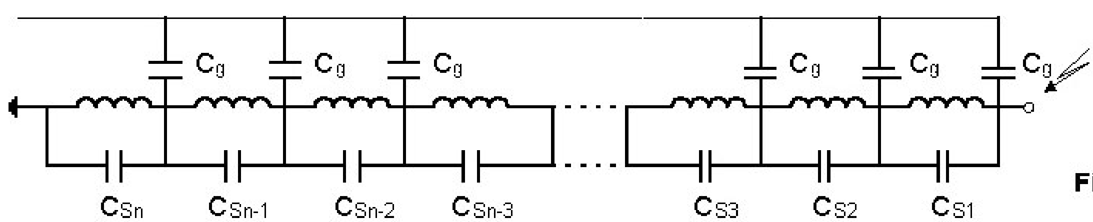


Fig.4

From the above circuit it is obvious that the current through C_{S1} is more than that through C_{S2},, because of the current drawn by C_g. Similarly, the current through C_{S2} will be more than that through C_{S3} and so on. So, current through C_{S1} is maximum and hence voltage drop across it is also maximum.

For high frequency equivalent circuit, series R & L are often neglected in comparison to C_S and C_g. Hence, the potential distribution is governed by a capacitive ladder circuit as shown in Fig.5. Then following the discussion mentioned above, it becomes clear that the potential distribution along a transformer winding will be non-linear.

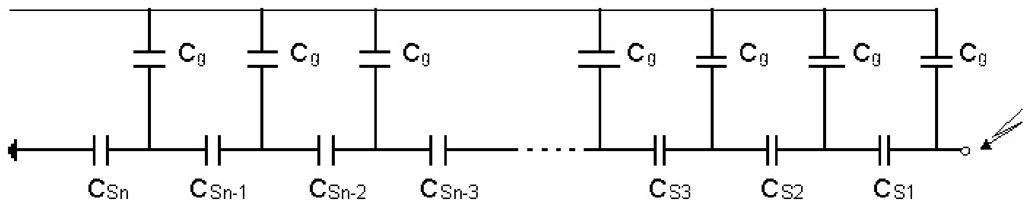


Fig.5

From the potential distribution shown in Fig.6, it may be seen that the part of the winding near to hv terminal is stressed most. It had been observed that only 2.5% of the winding is sometimes made to support 80% of the total voltage applied.

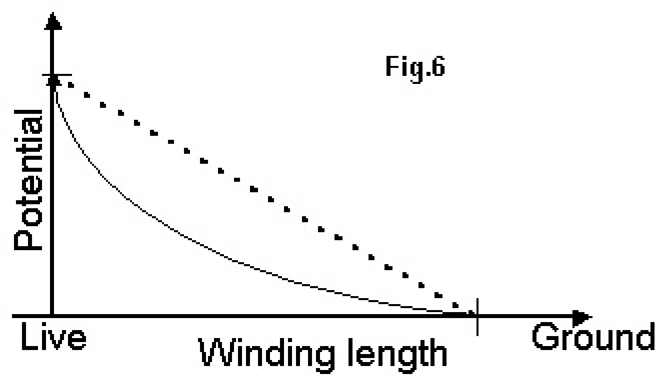


Fig.6

Had there been no shunt capacitor the potential distribution would have been linear as in the case of only resistances or capacitances in series shown in Fig.7.

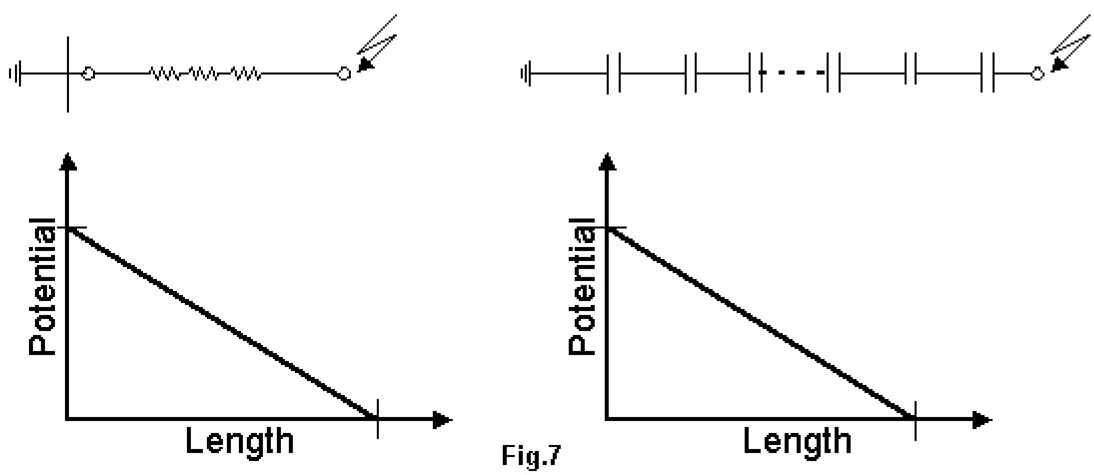
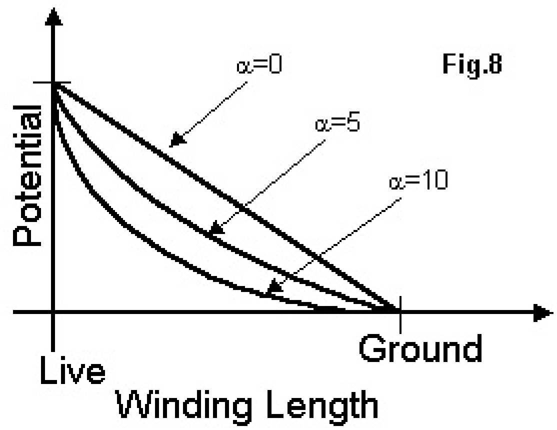


Fig.7

Let, C_g = Equivalent shunt capacitance.
C_S = Equivalent series capacitance.

Potential distribution depends upon α, where α is defined as $\sqrt{(C_g/C_S)}$. As α decreases, potential distribution approaches linear distribution. In other words,



the higher the value of α, the more non-uniform is the potential distribution as shown in Fig.8

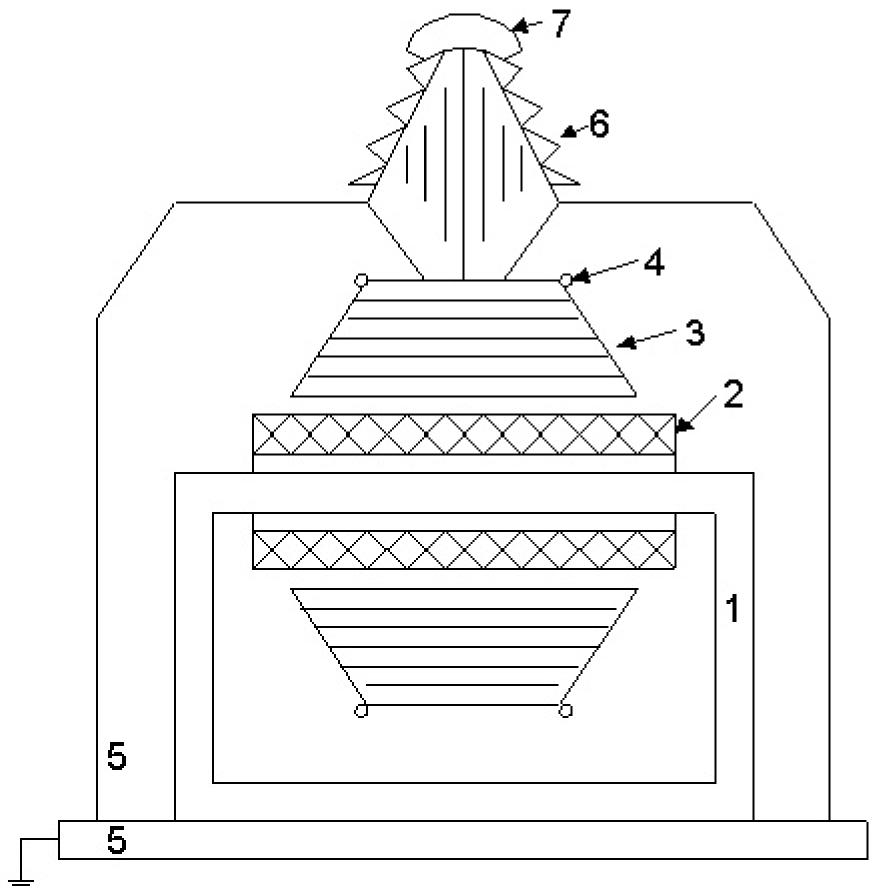


Fig. 9 Single–Unit Testing Transformer.

1. Iron Core
2. Primary LV or exciting winding
3. Secondary HV winding
4. Field Grading Shield
5. Grounded Tank or Base
6. HV Bushing
7. HV Electrodes with Corona Shield

Linearisation of Potential Distribution:

The following techniques are commonly adopted to linearise the potential distribution.

A) Use of Trapezoidal Windings:

Trapezoidal winding is a special form of helical winding. The inter-layer capacitances (series capacitances) between different layers of winding are formed by the layers acting as electrodes and the insulation between them as the dielectric.

Now, it is well known that $C = \frac{\in_r \in_o A}{d}$

Relative permittivity of winding insulation and the distance between two successive layers (d) are same for all the different layers. But, the overlapping area (A) for the outer layers is more than the inner layers. Hence, capacitances are higher for the outer layers than the inner layers.
In order to keep the interlayer capacitance constant, the condition that is needed to be satisfied is given by

$$\frac{\in .2\pi r_1 l_1}{d} = \frac{\in .2\pi r_2 l_2}{d} \ldots\ldots\ldots\ldots\ldots\ldots = \frac{\in .2\pi r_n l_n}{d}$$

where, r_n = radius of the nth layer
and l_n = axial length of the nth layer.

So, the necessary condition is $r_1 l_1 = r_2 l_2 = \ldots\ldots\ldots\ldots\ldots = r_n l_n$

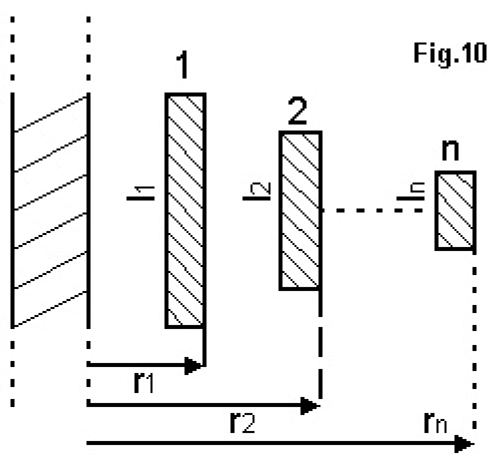


Fig.10

If the above condition is satisfied as shown in Fig.10, then inter layer or series capacitance becomes constant and the potential distribution becomes less non-uniform.

B) Use of Static Shield:

It has already been discussed that the non-linearity of potential distribution decreases as α decreases. Now, increase of C_S will lower α and will result in better potential distribution.

For this purpose, a static shield made of copper sheet is placed at the top of the windings and electrically connected to the HV terminal as shown in Fig.11. In this way capacitances will be formed between the shield and the different turns. The capacitive network then looks like what is shown in the figure. Since, the capacitances C_{Sa}, C_{Sb}, C_{Sc} etc. come in parallel to series capacitances, the effective series capacitances of the turns located near the hv terminal are increased. This results in improved potential distribution along the transformer winding.

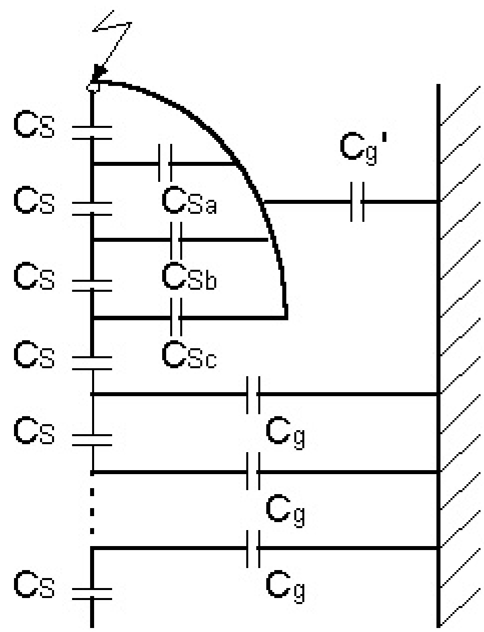


Fig.11

C) Use of Inter-leaved Winding:

Consider, ten sections of a transformer winding connected in continuous manner as shown in Fig.12.

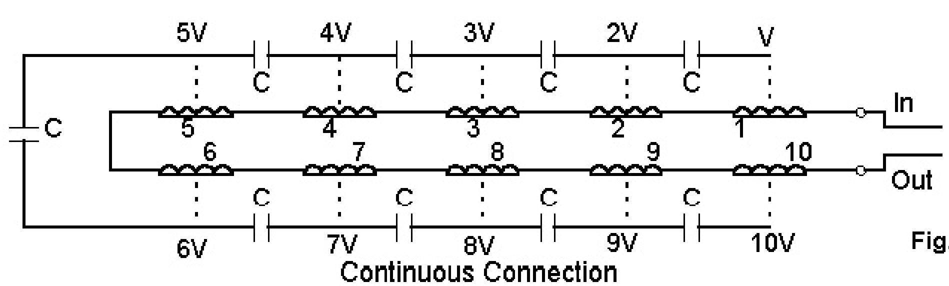


Fig.12

In this continuous connection, since all the nine series capacitances are connected in series, hence the equivalent series capacitance

$$C_{eq1} = \frac{C}{9}$$

The connection of the same winding in interleaved manner is shown in Fig.13.

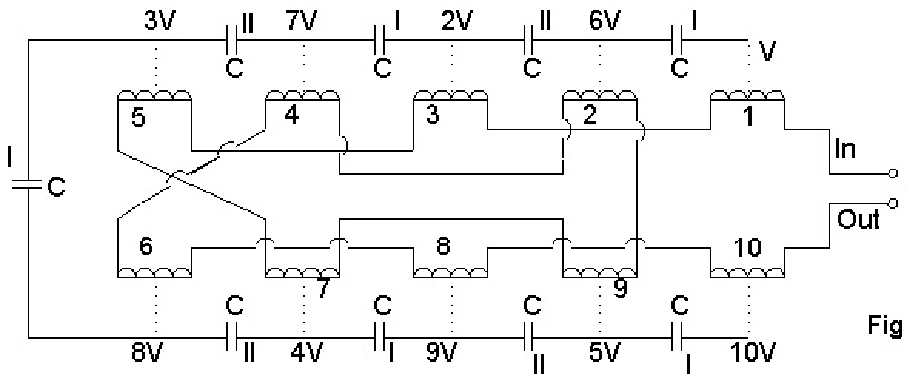


Fig.13

From the connection diagram shown in Fig.13, it may be seen that the capacitors can be divided into two groups. Capacitors in Group – I have a potential difference of 5V across each of them and the capacitors in Group – II have a potential difference of 4V across each of them. In Group – I, there are 5 capacitors and in Group – II, there are 4 capacitors. The potential difference between turns 1 and 10 is 9V. So, the total energy stored in all the capacitors

$$= \frac{1}{2}C(5V)^2 \times 5 + \frac{1}{2}C(4V)^2 \times 4$$

$$= \frac{1}{2} \times 189 \times CV^2$$

Let, the equivalent capacitance be C_{eq2}.

Then,

$$\frac{1}{2}C_{eq2}(9V)^2 = \frac{1}{2} \times 189 \times CV^2$$

$$\text{or } C_{eq2} = \frac{7}{3}C$$

Comparison of C_{eq2} with C_{eq1} gives

$$\frac{C_{eq2}}{C_{eq1}} = \frac{\frac{7}{3}C}{C/9} = 21$$

or, $$C_{eq2} = 21\ C_{eq1}$$

Thus the series capacitance increases by 21 items when interleaved winding is used as compared to continuous disc winding. This enhancement of equivalent series capacitance lowers the magnitude of α and linearises the potential distribution along the winding.

In practice interleaving of discs is not carried out over the entire length of the winding, as it is very expensive. Normally interleaving is done only at the line ends where the stresses are very high and need to be controlled.

Bushings:

Bushings are used for making connection of the transformer winding with the external objects. The transformer tank is normally earthed. So when the connection from the transformer winding is taken out of the tank, then flashover may occur between the windings and the tank. Bushings are used to insulate the tank from the live conductor to prevent only flashover.

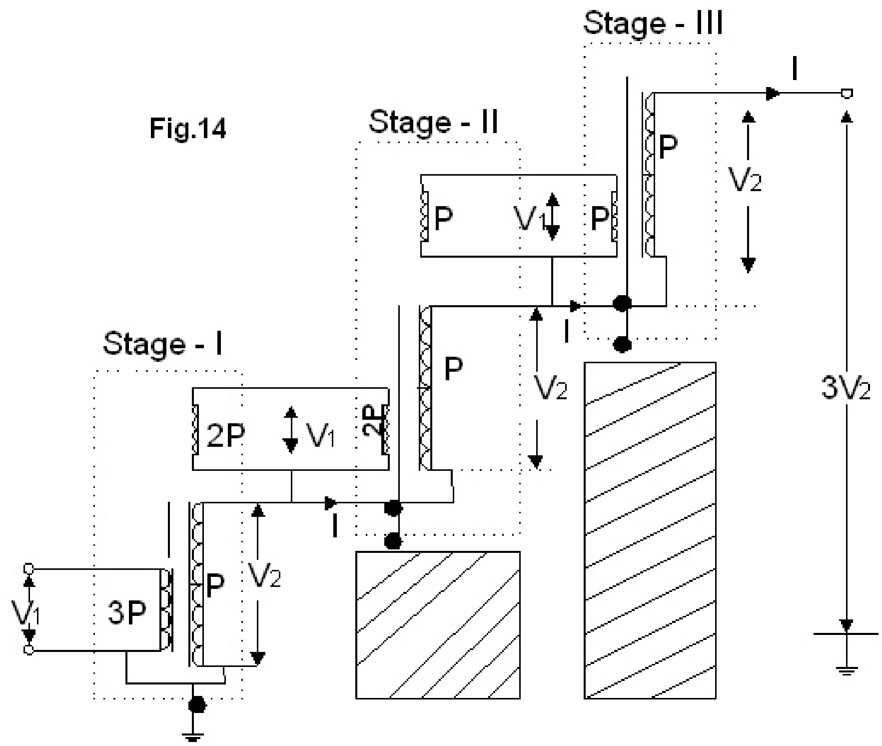
Sometimes instead of bushings, insulated tanks are used, where the tanks are insulated from the ground at appropriate voltage level. But this design is not common in use.

Cascade Connection of Testing Transformers:

Cascade connection of testing transformers is advantageous for voltages higher than 500kV, as the weight of a whole testing set can be subdivided into separate units and therefore transport and erection becomes easier. A prerequisite of cascade connection is a tertiary winding within each testing transformer unit as shown.

In the Fig.14 shown, three identical testing transformers are connected in cascade. All three units have the same voltage ratio, i.e. V_1:V_2. The units in stage – I and II are provided with a tertiary winding of required kVA rating.

Fig.14



Primary Voltage of Testing Transformer

The primary voltage of a testing transformer is generally rated at 300V to 500V (continuously variable). As per specifications, the output voltage of a testing transformer must have a peak factor of $\sqrt{2} \pm 5\%$, i.e. the output should contain as low harmonics as possible. To assure this the input voltage should also be free from harmonics. For this purpose often wave generators are employed to feed the primary of stage – I with sinusoidal input voltage. Such generators have their pitch factor and distribution factor suitably designed to eliminate harmonics. However, in modern times the feeding technique is to use buck-boost transformers as voltage regulators.

Operation of Cascaded Units:

The output of the stage – I unit is V_2 kV wrt earth at the secondary while the tertiary winding develops a voltage of V_1 volts to feed the primary of stage – II. As shown in the figure, the lowermost terminals of primary and secondary of stage – I unit are earthed. It is necessary because otherwise a capacitance will be formed between the secondary that is at a potential of V_2 kV wrt earth and the grounded tank. As a result a potential difference of 5–10 kV may develop between the terminal A and earth as shown in Fig.15. Thus the terminal A becomes floating which in turn will make the output voltage floating wrt earth.

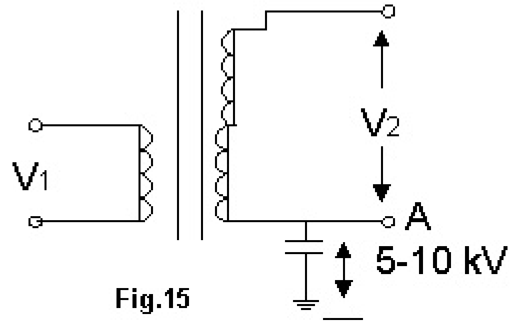


Fig.15

Now the primary winding of stage – II that is fed from the tertiary of stage – I will develop a potential difference of V_2 kV between the secondary terminals of stage – II unit. To avoid any stray capacitance between the secondary and tank of stage – II unit, the lowermost terminal of stage – II secondary is connected to its tank. Thus the tank of stage – II is at V_2 kV wrt earth and needs be insulated for V_2 kV by designing suitable insulating support. Hence, the output of stage – II secondary is at $2V_2$ kV wrt earth.

The tertiary of stage – II develops a potential difference of V_1 volts and feeds the primary of stage – III. This produces a potential difference of V_2 kV between the secondary terminals of stage – III unit. Since the lowermost secondary terminal of stage – III is connected to its tank, the tank of stage – III is at $2V_2$ kV wrt earth and is placed over a support designed to withstand $2V_2$ kV. The output of stage – III secondary is thus at $3V_2$ kV wrt earth.

It is to be noted here that V_2 for practical testing transformer units is in the range of 250kV to 300kV. It should also be mentioned here that in cascade connection of testing transformers, the secondary windings of all the units are connected in series.

kVA Grading of Cascaded Testing Transformer Units:

A major disadvantage of cascading of testing transformers is the heavy loading of primary windings for the lower stages.

Let, the output current of the cascaded transformer units be I amperes at a voltage of $3V_2$ kV.

So, kVA supplied to the load = $3V_2 I$

This current I flows through the secondary of the stage – III unit, the potential difference across which is V_2 kV.

So, kVA rating of the secondary of stage – III = $P = V_2 \; I$

It receives this power from its primary winding.

So, the kVA rating of the primary of stage – III = P.

The tertiary of stage – II supplies this power to the primary of stage – III.

So, the kVA rating of the tertiary of stage – II = P.

Now, the secondary of stage – II carries the output load current I and the potential difference between the secondary terminals of stage–II is V_2 kV.

So, the kVA rating of secondary of stage – II = V_2 I = P.

The primary of stage – II supplies the power to its secondary as well as its tertiary.

So, the kVA rating of primary of stage – II = P + P = 2P.

Following the same logic as discussed for stage – II,

The kVA rating of tertiary of stage – I = 2P

& the kVA rating of secondary of stage – I = V_2 I = P

So, the kVA rating of primary of stage – I = P + 2P = 3P.

So, total installed capacity for the three units

= 3P + 2P + P = 6P kVA

whereas the output to load is 3P kVA.

$$\text{Hence, utilisation of installed capacity } = \frac{3P}{6P} \times 100 = 50\%.$$

3 Cascaded Testing Transformer Units
Output = 3P kVA, $3V_2$ kV

Stage No.	Insulation level of tank wrt earth	Primary winding rating	Tertiary winding rating	Secondary winding rating
I	0	V_1, 3P kVA	V_1, 2P kVA	V_2 kV P kVA
II	V_2 kV	V_1, 2P kVA	V_1, P kVA	V_2 kV P kVA
III	$2V_2$ kV	V_1, P kVA	--	V_2 kV P kVA

Increase in the number of stages is not advisable because of the following reasons:

i) Inept utilization of installed capacity.
ii) Overloading of the lower stage transformers.
iii) Relatively high internal impedances of the whole cascaded circuit that causes poor voltage regulation.

Series Resonance Circuit

High voltage insulation under test normally offers capacitive load to the test circuit. This results in a series R-L-C circuit in conjunction with the resistance and inductance of the test circuit. In such circuits, unwanted resonance may take place that will give rise to exceptionally high voltage causing insulation damage and even severe explosions, particularly in the case of cables. In such tests, series resonant circuits can be used to avoid such accidental resonance.

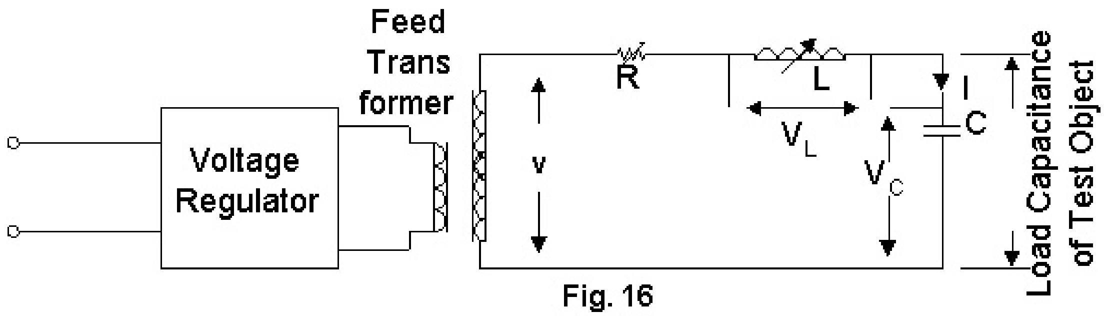


Fig. 16

A) Let, $C = 10^3$ pF. Then $L \cong 10^5$ H (Impractical)

Hence, this method cannot be used for testing very low capacitance objects, such as insulators, porcelain bushings, small length of cables etc.

B) Let, $R = 0.1\Omega$ & $X_C = 1000\Omega$ ($C \approx 3\mu F$)
and $v = 1000V$

$$\therefore \text{ Current at resonance} = \frac{1000}{0.1} = 10^4 A$$

$$\text{At series resonance } \omega L = \frac{1}{\omega C}$$

and voltage across test capacitance (V_C) = Voltage across in inductor (V_L) = $10^4 \times 10^3 = 10^7$V.

$\therefore$ Output VA = $10^7 \times 10^4 = 10^{11}$ VA
Input VA = $10^3 \times 10^4 = 10^7$ VA.

Hence, with the series resonance circuit, large voltage and large output kVA is obtained with a small amount of input voltage and input kVA.

C) Capacitance of the test object is normally low and hence, L should be higher.

D) Capacitance is dependent on the test object and hence, cannot be controlled. So, L should be adjusted to achieve resonance.

Series Resonance Circuit with Transformer/ Reactor

While changing L, step variation is not allowed as unwanted high voltage spikes may occur due to L(di/dt). This will adversely affect paper insulation of the test object.

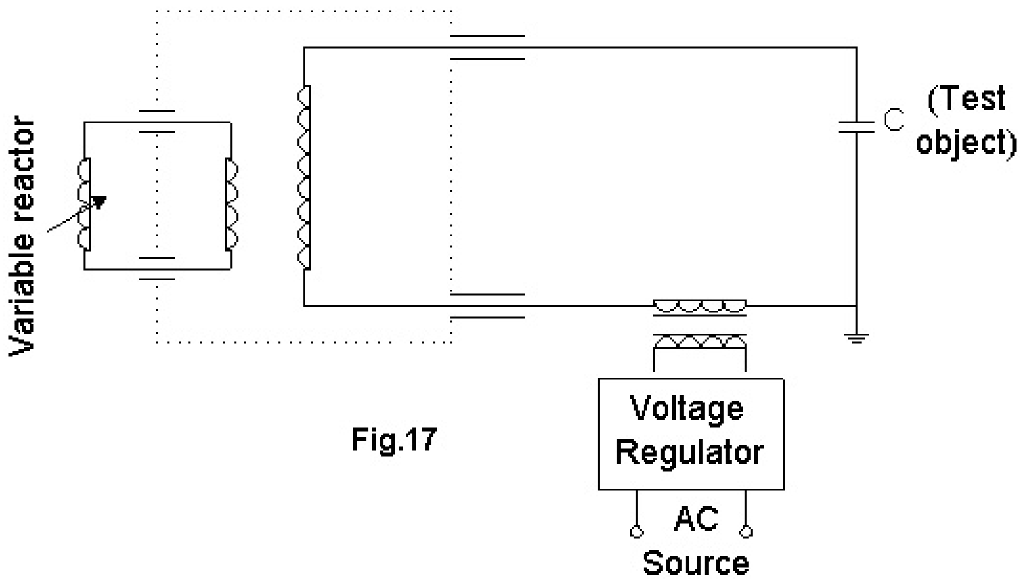


Fig.17

The voltage across the inductor is high at resonance. The variation of reactance at high voltage is difficult from the operation point of view. Hence, the variable reactor is connected to the LV side of a step down transformer connected in series with the test object. This allows smooth variation of inductor at lower voltage.

The function of the feed transformer is to inject current into the series circuit by varying the input voltage with the help of a voltage regulator. Initially, a small current is injected into the circuit by applying a low voltage. The reactor is varied to achieve resonance. When series resonance is achieved, more current is injected into the circuit till the desired voltage appears across the test object.

Note: Breakdown of solid dielectric is more severe for ac voltage than the same value of dc voltage. So capacitors and other objects with solid insulating media are always tested by ac voltage application.

Multiple Transformer / Reactor units in Series

The voltage across the test object is high at resonance and it has to be supported by the HV side of the reactor-transformer. Again, the current at series resonance is also high. So, the kVA rating of the reactor-transformer becomes very high for higher test voltages. In such cases, instead of using a single reactor-transformer, a no. of such units can be connected in series in a multi-stage circuit.

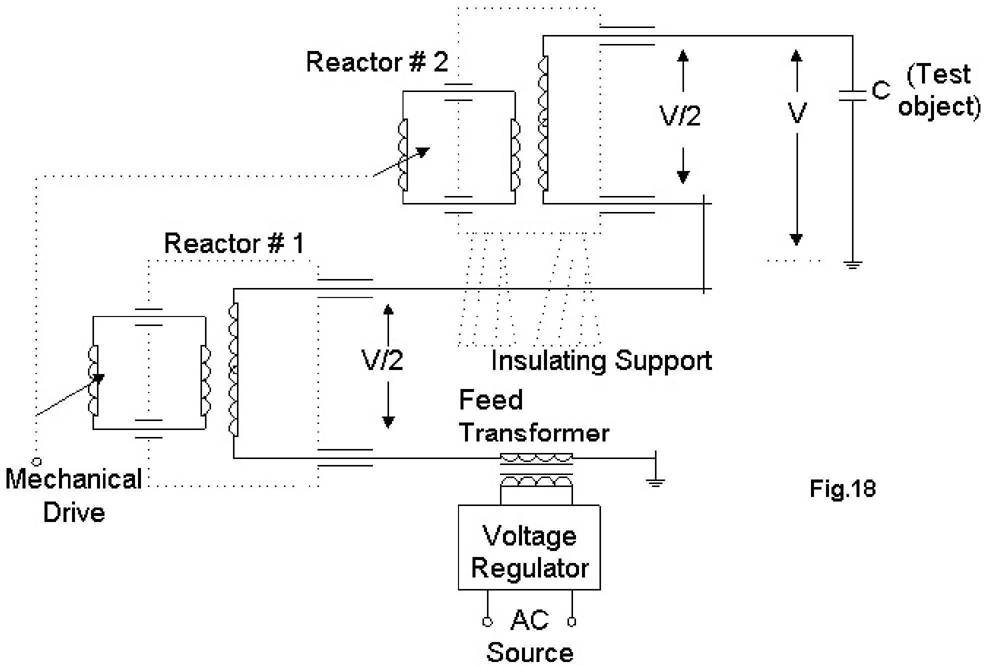


Fig.18

In this circuit, the total voltage across the test object is supported equally by the different units. In this way the kVA rating of individual reactor-transformers can be kept comparatively lower. The reactors in the different units are normally placed on the same shaft so that all the reactors are varied identically by a motorized drive. This helps in maintaining uniform voltage distribution across the different units.

Cable testing by Testing Transformer

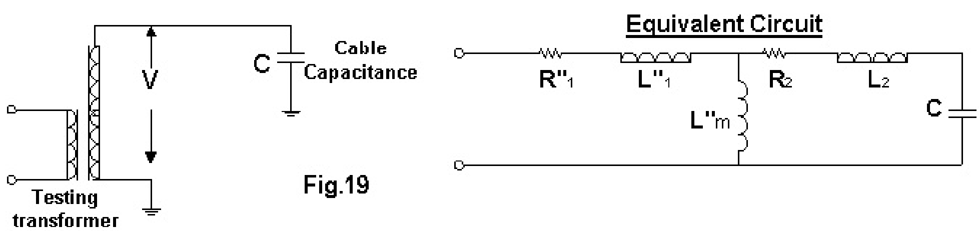


Fig.19

R_L'' & L_1'' = Equivalent resistance and leakage inductance of testing transformer primary (LV) side w.r.t. secondary (HV) side.

R_2 & L_2 = Resistance and leakage inductance of testing transformer secondary (HV) side.

L_m'' = Equivalent magnetizing inductance of testing transformer w.r.t. secondary (HV) side

In practice, $\omega L_m'' >> \omega (L_1'' + L_2)$

Hence, the approximate equivalent circuit becomes:

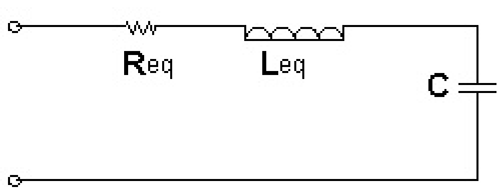


Fig.20

Thus it becomes a series R-L-C circuit, where resonance may occur.

i) As harmonics are present due to transformer iron-core, resonance due to harmonics may occur.
ii) Even for fundamental frequency resonance may occur occasionally depending upon the cable length and cable type and rating.

Consequences of Resonance:

Because of the accidental resonance, the circuit becomes resistive and a large current flow through the circuit. Hence, the voltage across the cable capacitance becomes very large of the order of 20 – 50 times the rated test voltage. This results in puncture of the cable insulation causing short-circuit across the cable capacitance. The testing transformer continues to feed this short circuit current at a very high voltage. Hence, a large amount of energy is drawn from the supply and transferred to the cable. This causes severe explosion of the cable. Even though a protective relay is connected to the primary of the testing transformer, the cable gets damaged within the operating time of the relay because of the huge amount of energy involved.

Advantages of Series Resonance Circuit:

i) In the case of series resonance circuit, if the cable insulation breaks down under test condition, then the cable capacitance is shorted and the resonance is lost. The impedance of the circuit increases from R to $Z=(R+jX_L)$. Hence, the circuit current is greatly reduced and hence energy drawn from the source is also reduced. Again, as the cable capacitance is shorted, the voltage across the cable capacitance becomes very small. Such a low voltage is unable to sustain an arc. In this way, explosion of the cable is totally avoided.
ii) The power required from the supply is lower than the kVA in the main circuit. Normally, it is only about 5% of the main kVA at unity power-factor.
iii) The test voltage waveshape is improved compared to input voltage due to attenuation of harmonics present in the input supply.
iv) Any number of units may be put in series without the problem of high impedance and hence poor regulation associated with a cascaded testing transformer group.
v) Higher sophistication is possible employing auto-tuning devices.

Measurement of "tanδ" using Series Resonance Circuit:

Dielectric Dissipation Factor (tanδ) of a capacitor is generally measured using Schering Bridge. In this bridge measurement tanδ is calculated from an expression that includes ω. If a testing transformer is used to generate the high voltage for bridge measurement, then harmonic frequencies will be present due to iron core. Hence, the value of tanδ obtained will not represent the true value at fundamental frequency.

In the case of series resonance circuit, the effect of harmonics in tanδ measurement is significantly reduced.

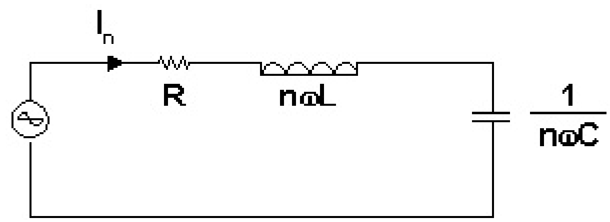


Fig.21

Circuit impedance for any harmonic frequency

$$Z_n = R + j\left(n\omega L - \frac{1}{n\omega C}\right)$$

The circuit is made resonant only for fundamental frequency. For all other frequencies, the current will not be purely resistive. As frequency increases, inductive reactance increases and capacitive reactance decreases. Hence, Z_n increases as n increases and hence, harmonic current decreases as n increases.

Again, the voltage drop across the inductance will be much higher than that across the capacitor for higher harmonics as $X_{Ln} >> X_{Cn}$. Thus the fundamental component of voltage across the capacitor will be very high compared to harmonic components. Hence, the deviation of the voltage waveform from pure sinusoid will not be pronounced across the capacitor. So measurement of tanδ will reflect the true value corresponding to fundamental frequency more closely.

Disadvantages:

i) Series resonant circuit can only be used to test objects having large capacitance, viz. cables.

ii) The current in the circuit at resonance is very high compared to the current drawn from the source. So, heavy bus bars and conductors are required to be used in the circuit.

Variable Voltage Source of 0-500V:

0-500V smoothly varying voltage source is necessary for the primary of the testing transformer and also for the feed transformer of the series resonance circuit. The commonly used methods are

i) Motor-Generator Set.
ii) Induction Regulator.
iii) Automatic Voltage Regulator.

i) Motor-Generator Set:

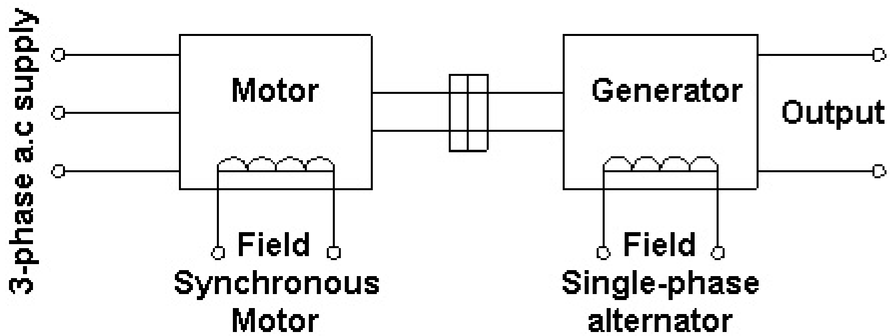


Fig.22

This arrangement draws balanced power from the supply. Supply harmonics are eliminated. Output voltage could be made nearly sinusoidal by properly designing the alternator.
The output voltage is never zero because of residual magnetism. Overall system efficiency is poor, as $\eta_{overall} = \eta_m \times \eta_G$. It is also very expensive.

ii) Induction Regulator:

The stator and rotor of an induction motor are connected in series. Output voltage varies with the position of the rotor. The rotor is locked at different positions using gear assembly.

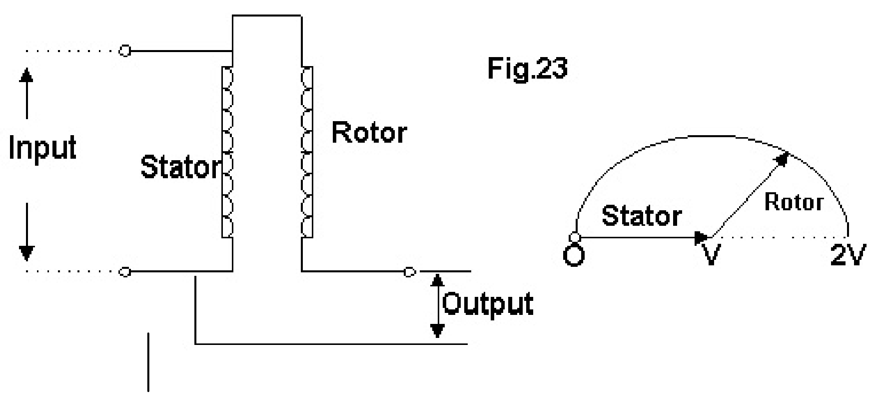


Fig.23

Smooth variation of voltage starting from zero.

iii) Automatic Voltage Regulator (Buck-Boost Method):

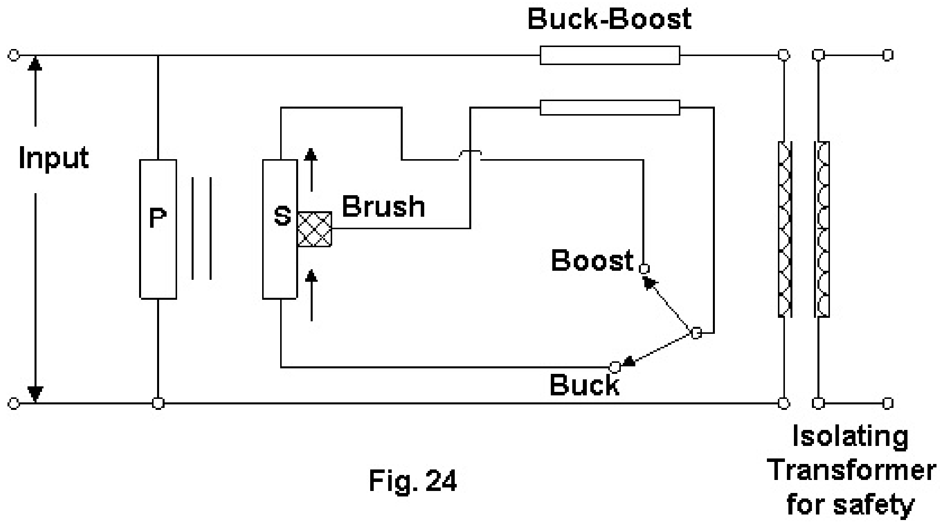


Fig. 24

Smooth variation of voltage starting from zero is obtained by varying the brush position with the help of a motor and gearing arrangement. Very commonly used now-a-days.

Generation of High DC Voltage

High DC voltages are extensively used for scientific research work, electromedical equipment, electrostatic precipitators, electrostatic painting etc. It is also used for testing equipment related to HVDC transmission lines. Another major use is in testing HVDC power cables of long lengths to circumvent the problem of high charging current to be fed to the cables under test.

Earlier HVDC was generated with the help of electrostatic generators. But now-a-days HVDC is generated by means of rectifying circuits in conjunction with a.c. voltage source. There are two rectification schemes in use, viz. a) Asymmetric and b) Symmetric.

Asymmetric Rectifier Circuit:

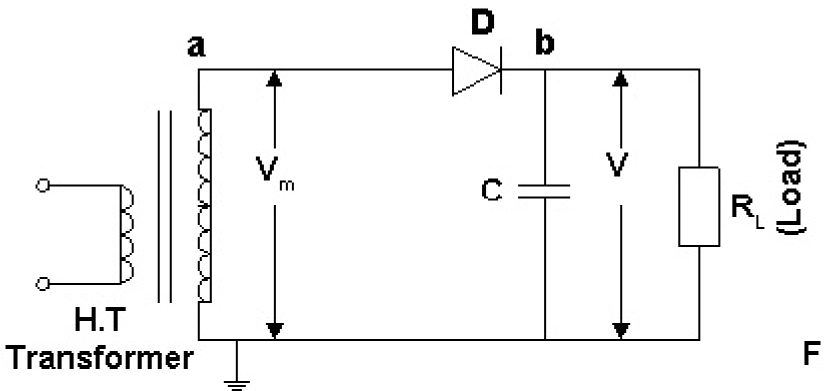


Fig.25

Neglecting leakage reactance of the transformer and the forward drop of the diode, the capacitor C is charged to $+V_m$ of the a.c. voltage when the diode D conducts. If the output load current is zero ($R_L \rightarrow \alpha$), then the potential of 'b' remains constant at $+V_m$. But, the potential of "a'' oscillates between $\pm V_m$. So, the diode D must be able to withstand a PIV of $2V_m$.

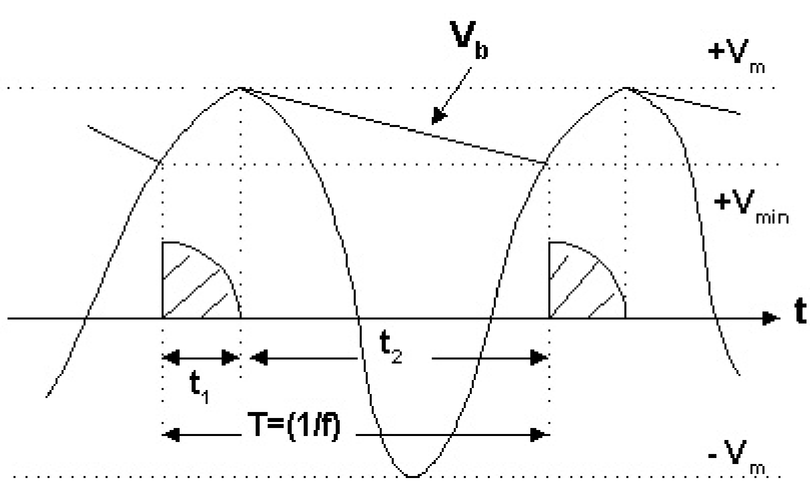


Fig.26

The output voltage V does not remain constant if the circuit is loaded. After the condenser is charged upto $+V_m$, the potential of 'b' becomes less than $+V_m$ during the period t_2 so that the diode D gets reverse biased. In this period the capacitor C discharges some amount of charge to the load and the output voltage gradually decreases depending upon the time constant of the load circuit in series with capacitor C. During the period t_1, the diode again becomes forward biased and the capacitor again gets charged to $+V_m$. The charge lost by the capacitor C during t_2 is gained during t_1. Since $t_1 << t_2$, the current supplied by the transformer is pulsed in nature. The output ripple is given by

$$\Delta V = \frac{V_m - V_{\min}}{2}$$

Disadvantages:

i) Since half-wave rectification is employed, the voltage generation is asymmetric.

ii) The rectifier and the HT transformer need to be robust and hence expensive.

iii) The current supplied by the transformer to charge the capacitor C introduces a dc component on the secondary side. Hence, no mmf balance takes place between the primary and secondary. This may cause saturation of the transformer core with the increase of load current.
To avoid core saturation following steps could be taken:
   a) Core cross-section is to be increased.
   b) Special transformers are to be used.
   c) The existing transformers have to be operated at a relatively low voltage compared to its rating. So that the operating point lies will below the knee point.

One way of solving all these problems is to use single-phase full-wave rectifier circuits.

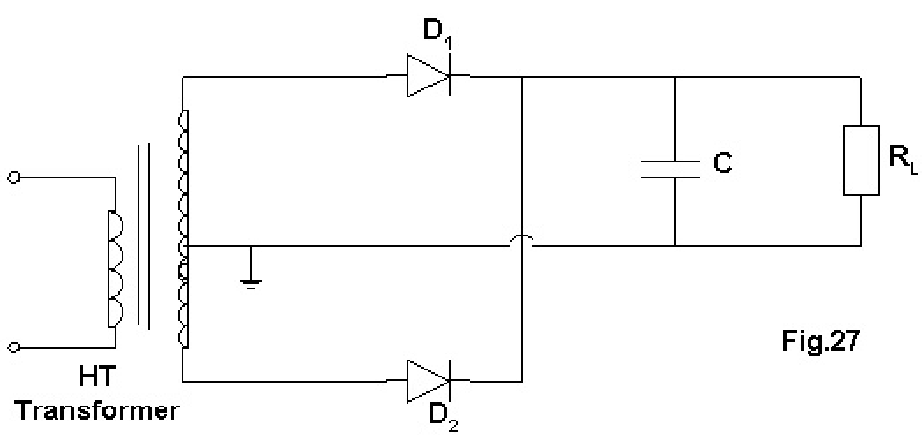


Fig.27

However, such full-wave rectifier circuits can only be used for the cases where the HV winding of the transformer can be earthed at its midpoint.

Hence, more commonly used method is single-phase voltage doubler.

Single – Stage Voltage Doubler Circuit:

Such voltage doubler circuits are also known as Cockcroft – Walton Voltage doubler circuits (1932).

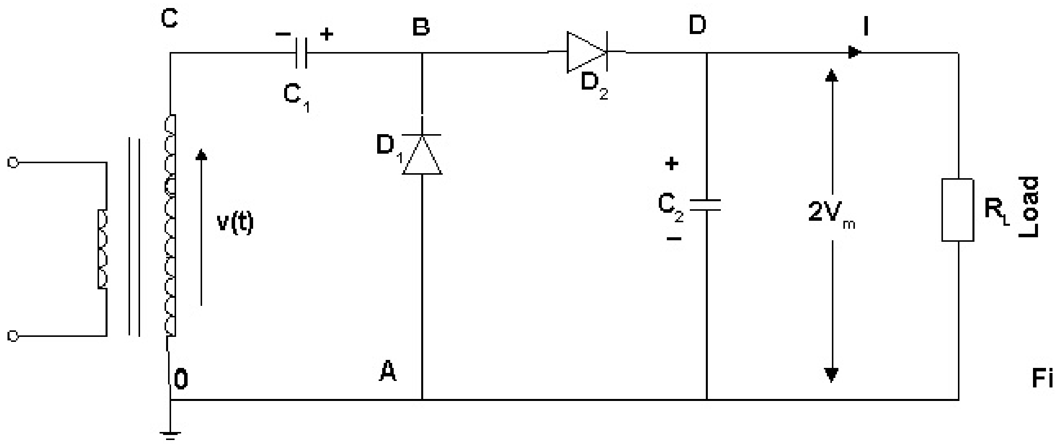


Fig.28

Open – Circuited HV Output: (I = 0)

In the loop 0–A–B–C, the capacitor C_1 charges upto a voltage of $+V_m$, when v(t) reaches the lowest potential $–V_m$. If C_2 is uncharged, then the diode D_2 conducts as soon as v(t) increases from $–V_m$ and D_1 gets reverse biased. During the period, when (dv/dt) is positive, the potential across C_1 remains constant at $+V_m$ as it has no path to discharge. Thus, the potential across diode D_1 during this period is $V_{BA} = V_{BC} + V_{CO}$ and is an oscillating voltage varying between 0 to $+2V_m$. But V_{BA} is unidirectional in nature. During this period when D_2 conducts, capacitor C_2 gets charged upto the maximum value of V_{BA}, i.e. $2V_m$. Hence, a steady dc voltage whose value is double the peak value of transformer secondary voltage is obtained across the capacitor C_2 as output.

HV Output when loaded: (I > 0)

If the generator supplies a load current I, then the output voltage will never reach the value $2V_m$ and there will also be a ripple on the output voltage.

The peak value of V_D is reached when V_C is at $+V_m$ and D_2 just stopped conduction. After that the current I continuously discharges C_2. There is a sudden drop in V_D during the period when D_1 conducts to charge C_1. V_D reaches its minimum value at the instant when D_2 starts to conduct and C_2 gets charged. During the period of conduction of D_2, C_2 again gets charged upto V_{Dmax}. During the period t_2, q amount of charge is transferred to load from C_2 and during the period t_1 the same amount of charge q is replenished by C_1 to C_2.

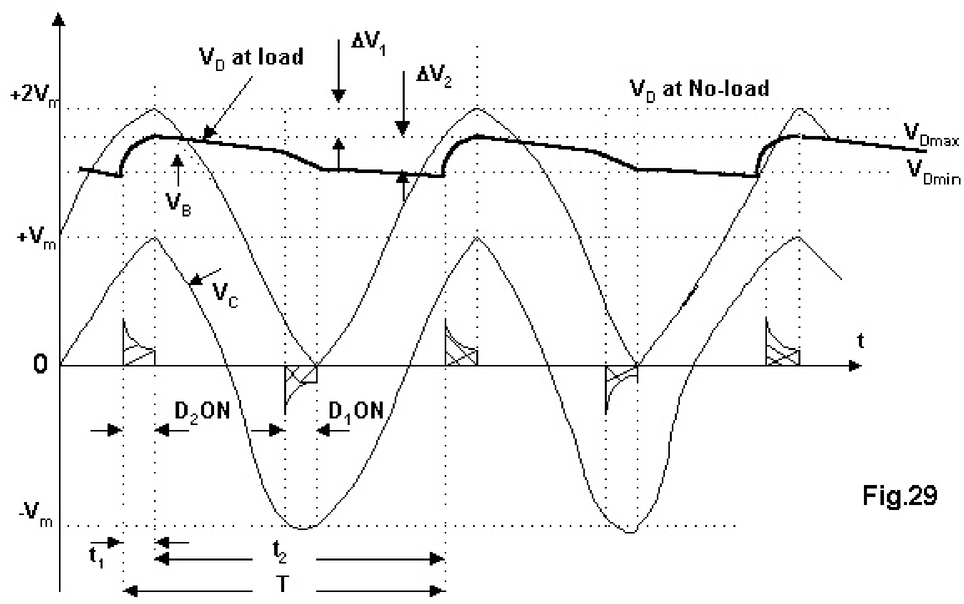


Fig.29

Voltage Regulation:

$V_{D\,max}$ = Maximum output voltage
V_{Dmin} = Minimum output voltage

$$\text{Average DC output voltage} = V_{DC} = \frac{V_{D\max} + V_{D\min}}{2}$$

a) Let, I be the load current. Then the amount of energy transferred to the load is as follows.

$$\frac{1}{2}C_2\ V_{D\max}^2 - \frac{1}{2}C_2\ V_{D\min}^2 = V_{DC} \cdot I \cdot t_2$$

$$\text{or, } C_2 \cdot \left(\frac{V_{D\max} + V_{D\min}}{2}\right)\left(V_{D\max} - V_{D\min}\right) = V_{DC} \cdot I \cdot t_2$$

$$\text{or, } C_2 \cdot V_{DC} \cdot \Delta V_2 = V_{DC} \cdot I \cdot t_2$$

$$\text{or, } \Delta V_2 = \frac{I.t_2}{C_2}$$

$$\text{Again, } T = t_1 + t_2 \text{ and } t_2 >> t_1$$

$$\text{So, } T \approx t_2$$

$$\therefore \Delta V_2 = \frac{I \cdot T}{C_2} = \frac{I}{fC_2}$$

b) C_1 supplies the charge to C_2 when D_2 conducts. Moreover, some charge is drained from C_1 to C_2 through D_2 even when it is turned off. As a result, V_B is decreased from $2V_m$ by an amount ΔV_1.

$$\text{so, } I = \frac{dq}{dt} = C_1 \frac{dv}{dt} = C_1 \frac{\Delta V_1}{T}$$

$$\text{or, } \Delta V_1 = \frac{IT}{C_1} = \frac{I}{fC_1}$$

$$\text{so, } Av\,DC \text{ output voltage } (V_{DC}) = \frac{V_{D\max} + V_{D\min}}{2}$$

$$= 2V_m - \Delta V_1 - \frac{\Delta V_2}{2}$$

$$= 2V_m - \frac{I}{fC_1} - \frac{I}{2fC_2}$$

$$= 2V_m - \frac{I}{f}\left(\frac{1}{C_1} + \frac{1}{2C_2}\right)$$

Thus the output voltage depends on – i) the load current, ii) frequency and iii) stage capacitances. Higher the frequency, lesser the voltage drops. Hence, often Cockcroft–Walton voltage doubler circuits are fed at a higher frequency from oscillators.

Problem:

A Cockcroft – Walton voltage doubler circuit is used to test a cable at 170kV. The insulation resistance of the cable is 6×10^9 Ω/m and the length of the cable is 12m. Stage capacitances are both 0.1μF. The generator is supplied from a 230V/250kV testing transformer. Calculate the voltage to be applied to the input of the transformer at 50Hz.

Solution:

$$\text{Given: } C_1 = C_2 = 0.1\mu F$$

$$R_L = 6 \times 10^9 \, \Omega / m$$

$$\therefore \text{Total } R_L = \frac{6 \times 10^9}{12} = 5 \times 10^8 \, \Omega$$

$$\text{Test Voltage} = 170\text{kV}$$

$$\therefore \text{Load current (I)} = \frac{170 \times 10^3}{5 \times 10^8} = 3.4 \times 10^{-4} A$$

$$\text{Now}: \; V_{DC} = 2V_m - \frac{I}{f}\left(\frac{1}{C_1} + \frac{1}{2C_2}\right)$$

$$\text{or,} \quad 2V_m = 170 \times 10^3 + \frac{3.4 \times 10^{-4}}{50}\left(\frac{1}{0.1 \times 10^{-6}} + \frac{1}{2 \times 0.1 \times 10^{-6}}\right)$$

$$= 170.102\,\text{kV}$$

$$\therefore V_m = 85.051\,\text{kV}$$

$$\therefore \text{Transformer primary } V_{\max} = \frac{85.051}{250} \times 230 = 78.25\,V$$

$$\therefore \text{Transformer primary } V_{rms} = \frac{78.25}{\sqrt{2}} = 55.33\,V \; \text{(Ans)}$$

Multistage Cockcroft – Walton Voltage Multiplier Circuit:

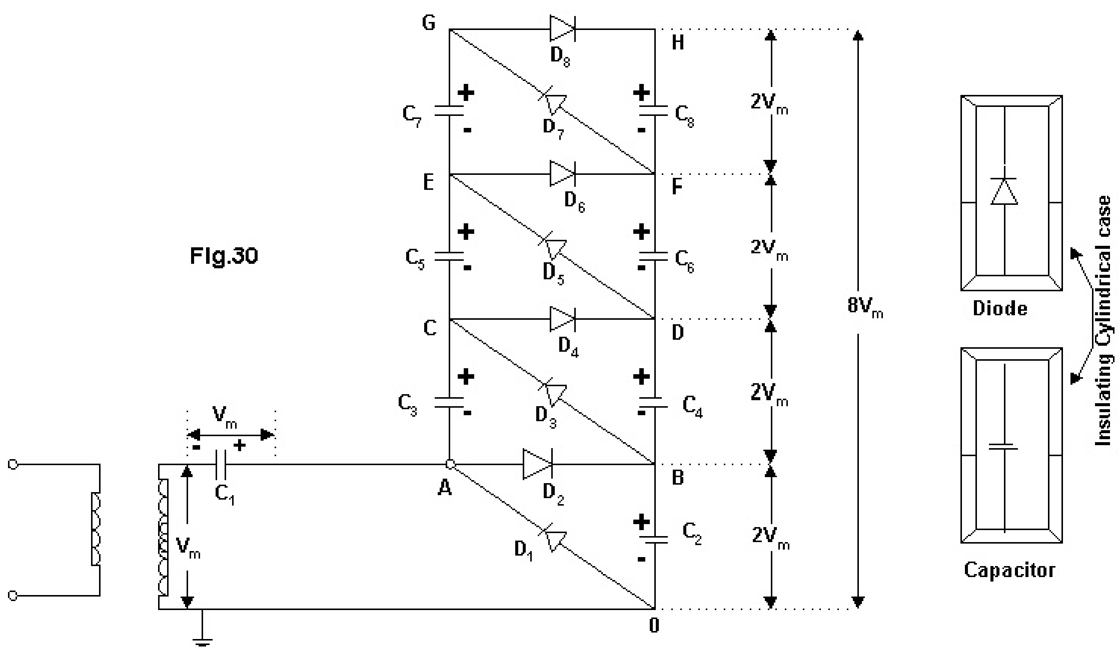


Fig.30

Terminal	Potential w.r.t earth	Nature of waveform
A	$0 – 2V_m$	Oscillatory
B	$2V_m$	DC
C	$2V_m – 4V_m$	Oscillatory
D	$4V_m$	DC
E	$4V_m – 6V_m$	Oscillatory
F	$6V_m$	DC
G	$6V_m – 8V_m$	Oscillatory
H	$8V_m$	DC

Let, V_m be the maximum value of the transformer secondary voltage. When the diode D_1 conducts, C_1 is charged to + V_m. When D_1 is turned off, the potential of A oscillates between 0 to $2V_m$ as transformer secondary voltage varies from $–V_m$ to $+V_m$. When D_1 is off, D_2 will turn on and C_2 will be charged upto $+2V_m$. When D_3 is on, then D_1 is on and D_2 is off. Then the potential of A is zero and thus C_3 gets charged to $2V_m$ from C_2. When D_1 and D_3 are off and D_2 and D_4 are on. Then the potential of C oscillates between $2V_m$ to $4V_m$ and C_4 gets charged upto $2V_m$. Since, the potential of B is $2V_m$ w.r.t. earth, hence, the potential of D is $4V_m$ w.r.t earth. In this way C_6 and C_8 are also charged to $2V_m$ each and so $8V_m$ may be obtained as the output DC voltage.

Practically, number of stage more than 4 is not used because (i) very high insulation is required for higher stages and (ii) the diodes are not ideal and identical which causes many problems.

Symmetric Voltage Doubler Circuit:

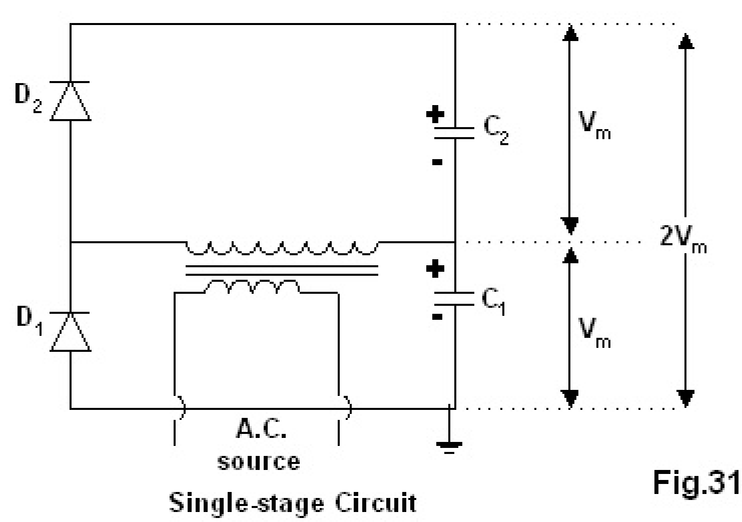


Fig.31

The symmetric voltage doubler circuit was proposed by Allibone in 1934. The HV transformer feeds two half-wave rectifiers and two storage capacitors are connected in series. When the diode D_1 conducts in one half-cycle, then C_1 is charged to $+V_m$ w.r.t. earth, where V_m is the peak value of the transformer secondary voltage. In the other half cycle, D_2 conducts and D_1 is off. Then C_2 is charged to $+V_m$, so that $+2V_m$ is obtained as output. When the diodes are turned off, then potential across the diodes vary from 0 to $2V_m$. Hence, the PIV of the diodes must be $2V_m$. As the diodes conduct identically in the two half cycles it is called symmetric voltage doubler circuit and there is no problem of transformer core saturation. In this circuit neither terminal of the transformer secondary could be earthed and the potential of one terminal of transformer secondary is a steady DC of magnitude $+V_m$. Hence, the insulation between the primary and the secondary of the transformer should be for a dc voltage $+V_m$.

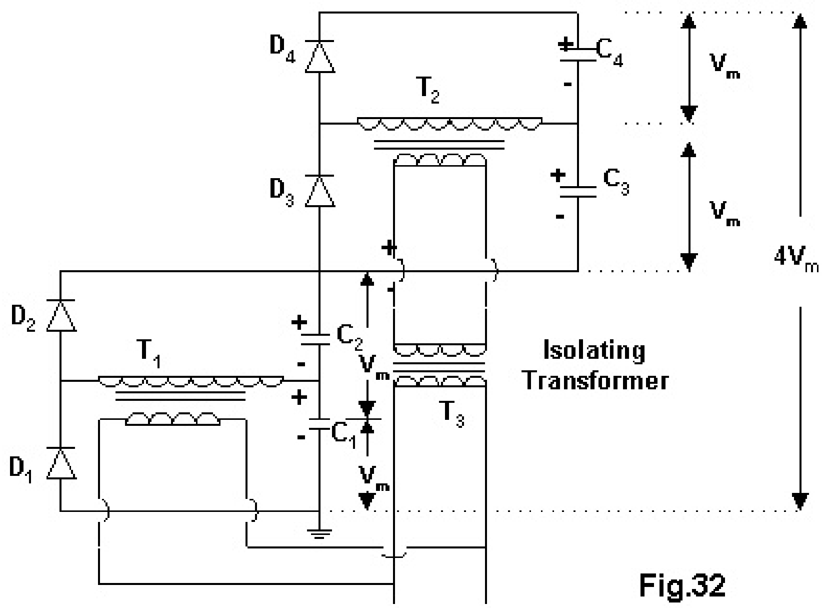


Fig.32

Multi-stage Circuit:

In one half cycle, D_1 and D_3 conduct and C_1 and C_3 are charged to $+V_m$ each. In the other half cycle, D_2 and D_4 conduct and C_2 and C_4 are charged to $+V_m$ each. Since, all the four storage capacitors are connected in series, $+4V_m$ is obtained as output. Since, one terminal of the secondary of transformer T_2 is at a steady DC potential $+3V_m$, insulation for $3V_m$ need to be provided between the primary and secondary of T_2. As it would be difficult to provide such high insulation within a single transformer, an isolating transformer T_3 is used that feeds T_2. Thus, this need for additional isolating transformers makes the use of more than two stages uneconomical.

Improved Symmetric Voltage Multiplier Circuit:

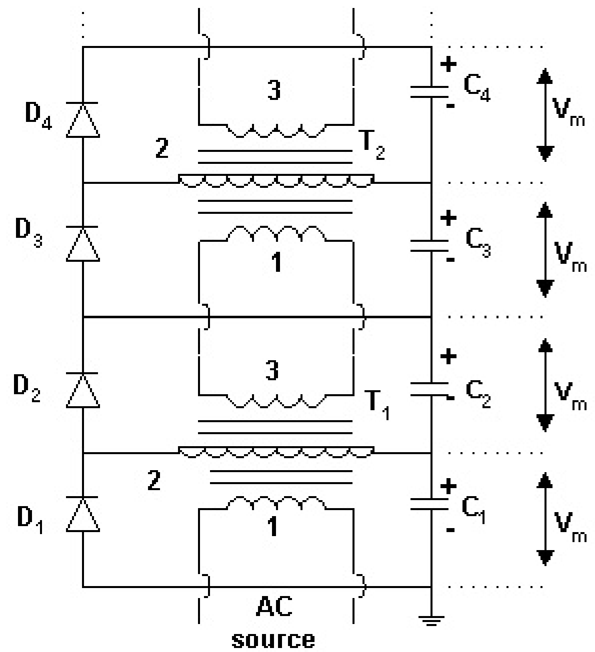


Fig.33

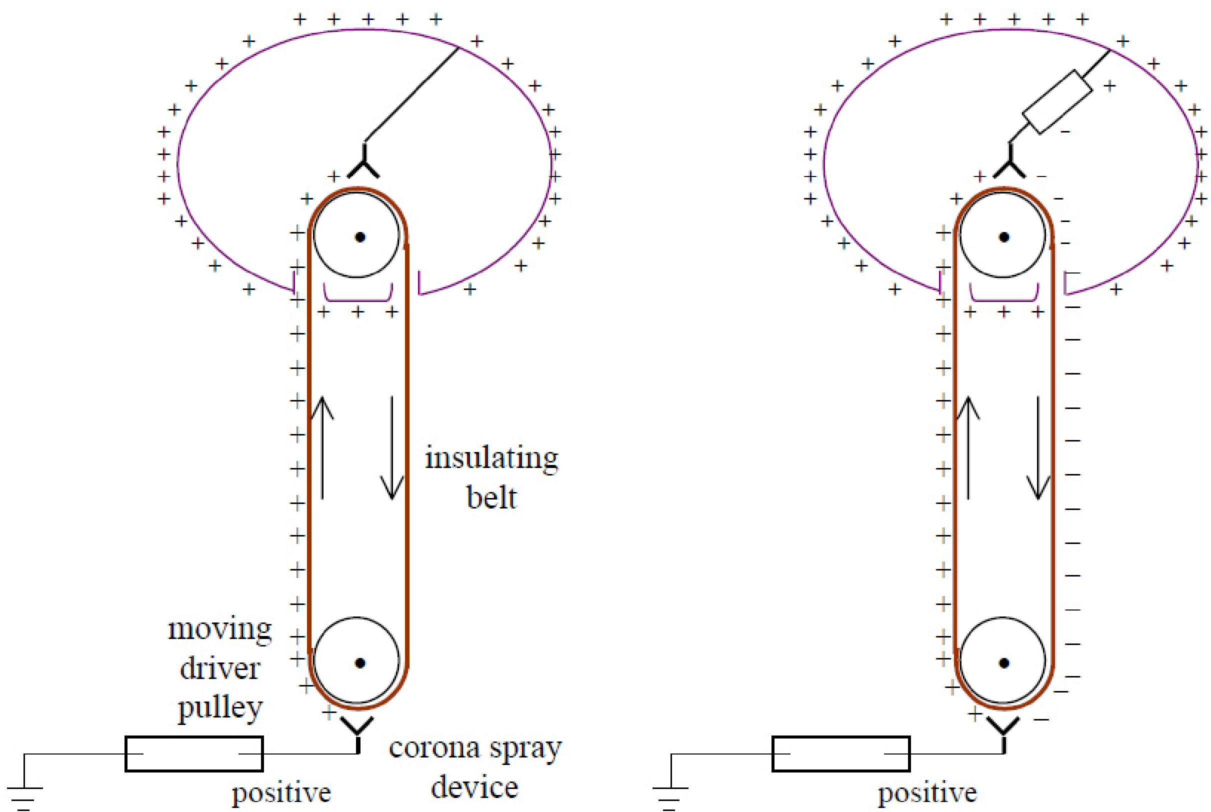
An essential improvement is made when the different stages are excited by specially designed cascaded transformer. Every transformer per stage consists of a LV primary (1), HV secondary (2) and LV tertiary (3) winding. The tertiary winding feeds the primary of the transformer in the next higher stage. The necessary dc insulation within each transformer T_1, T_2 etc can be subdivided within the transformers. However, a problem with this circuit is that the lower stage transformers have to supply the energy to the upper stage units.

Electrostatic Generators

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

Van de Graaff Generator

The Van de Graaff generator is one of the methods used to obtain very high voltages. However they cannot supply much currents and the power output is restricted to a few kilowatt, and their use is restricted to low current applications.
The American physicist Robert Jemison Van de Graaff invented the Van de Graaff generator in 1931. The device that bears his name has the ability to produce extremely high voltages -- as high as 20 million volts. Van de Graaff invented the generator to supply the high energy needed for early particle accelerators.



The Van de Graaff generator uses an insulating belt as the carrier of charge. The generator consists of a low direct voltage source, with corona discharge taking place at the positive end of the source. In the case of lower voltage output, separate low voltage source is not needed. The corona formation (spray) is caused by a comb like structure with sharp points (corona spray device). Charge is sprayed onto the belt at the bottom by corona discharges at a potential of 10 to 100 kV above earth and carried to the top of the column and deposited at a collector. The upper electrode at which the charge is collected has a high radius of curvature and the edges should be curved. The higher voltage of the upper electrode arises from the fact that for the same charge, a smaller capacitance gives a larger voltage ($V=Q/C$). The upper electrode has a smaller capacitance to earth on account of the larger spacing involved.

The potential of the high voltage electrode rises at a rate of $\frac{dV}{dt} = \frac{1}{C}\frac{dQ}{dt} = \frac{I}{C}$ where, I is the net charging current.

A steady potential will be reached by the high voltage electrode when the leakage currents are equal to the charging current. The edges of the upper electrode are so rounded as to avoid corona and other local discharges. With a single source at the lower end, the belt moves upwards with a positive charge and returns uncharged. Charging can be made more effective by having an additional charge of opposite polarity sprayed onto the belt by a self inducing arrangement (negative corona spray) using an ingenious method. This arrangement effectively doubles the charging rate.

Charging of generator:

When two materials are rubbed together, a flow of electrons can take place depending on the triboelectric properties. When such a transfer occurs, the material that lost electrons will become positively charged and the one that gained electrons becomes negatively charged. This basically how static electricity is generated.
A Van de Graaff generator creates static electricity. The current generated by a Van de Graaff generator remains the same, while the voltage changes according to the applied load. A very simple Van de Graaff generator is made of the following:

- A motor
- Rollers, two in number
- Insulated belt
- Brush assemblies, two in number
- Metal sphere as the output terminal

The motor is required to turn the belt at a constant speed around the two rollers as depicted in Fig. 3.

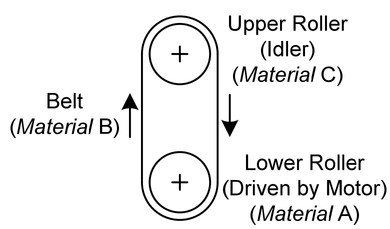


Fig. 3. Basic Structure of a Van de Graaff generator.

Let us examine if the upper roller (Material C) is made up of acrylic and the belt (Material B) is made up of rubber. When the belt is driven by a motor, due to friction between the belt and the upper acrylic roller, the roller will always acquire positive charge by loosing electron (according to the effect due to triboelectric series materials). Thus, the acrylic roller will acquire positive charge and the inside of the belt will acquire negative charge.

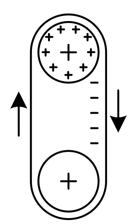


Fig. 4. Accumulation of charge in the roller and inside of belt.

Now, usually, the lower roller (Material A) is built up of a metal. Thus, the metal roller, in touch with the inner surface of the belt, develops a negative potential. Here comes the role of the lower metal comb. This comb has sharp points. Due to induction from negative charge of the lower roller, the lower comb develops a high electric field at its sharp tips that gradually becomes large enough to ionize air molecules. In this case, the electrons jumps to the comb by corona discharge and positive ions become attached to the outside surface of the belt.

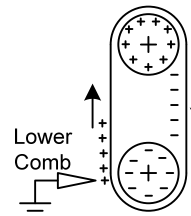


Fig. 5. Lower comb injecting positive charge on outside of the belt.

The positive charges, which are attached to the outside surface of the belt, gradually travel towards the top and enter into the isolated top metal sphere. Here, another metal comb, similar to the lower comb, is placed inside the sphere. Due to the positive charge on the outer surface of the belt, a strong field is developed at the sharp tips of the upper comb. After sometime, the field becomes high enough to ionize air molecules, and the electrons are attracted and jumps to the outside surface of the belt to neutralize the charge. Since the upper comb is directly connected with the upper sphere, the sphere looses electrons continually and develops excess positive charge. Since a metallic sphere can have no charge inside it, the excess positive charge is accumulated on the outer surface of the isolated sphere. Electrostatic induction by this method continues, building up very large amounts of charge on the outer surface of the sphere.

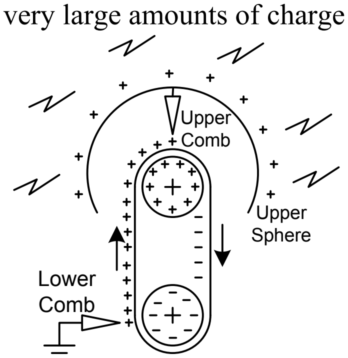


Fig. 6. The upper comb extracting the charge; the isolated sphere developing excess positive charge on its outer surface.

It is this simple electrostatic effect that allows the Van de Graaff generator to output very high voltages continuously. The maximum achievable potential is approximately equal to the sphere's radius (R) multiplied by the electric field (E_{max}) where corona discharges begin to form within the surrounding gas. For air at STP the breakdown field is about 30 kV/cm. Therefore, a polished spherical electrode 30 cm in diameter could be expected to develop a maximum voltage of about 450 kV. This explains why the upper spheres in Van de Graaff generators are often made with the largest possible diameter.

When negative charge is required, the material B of the belt in Fig. 3 is replaced with polypropylene and the top roller (Material C) is replaced by polyvinyl chloride. For even higher voltages, a separate high voltage supply unit is attached with the lower comb, which directly sprays a large amount of charge by corona discharge on the outer surface of the belt. This helps the top sphere of the generator to accumulate a very high charge within a short time.

Generation of Impulse Voltage

Overvoltages in electrical power system can be classified into two categories, viz. a) Internal Overvoltage and b) External Overvoltage.

Internal overvoltages are generated due to several events such as switching operations, load disturbances etc. But, external overvoltages are generated primarily due to natural phenomenon such as lightning. Lightning overvoltages are again generated in two different ways: i) Direct Stroke and ii) Indirect Stroke.

a) **Direct Lightning Stroke:**

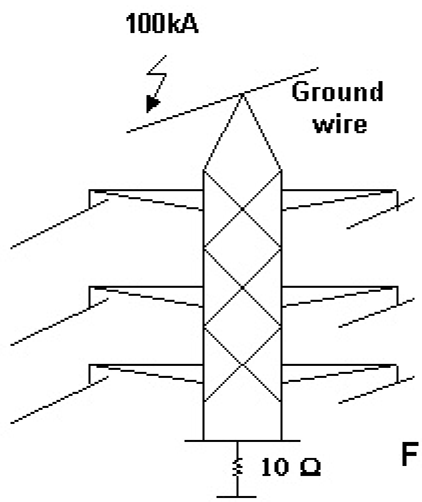


Fig.38

The transmission line towers also carry a ground wire in addition to the live conductors mainly for protection against lightning strikes, so that lightning cannot strike a live wire directly. But, a lightning can strike the ground wire directly and then the very high lightning current flows to ground through the tower. The tower has a finite grounding resistance, even though it is low. Say, the grounding resistance is of the order of 10Ω and the lightning is about 100kA. Then, the potential of tower becomes 1000kV w.r.t. earth. This causes flashover of insulators from tower to conductor and is called "Back-flashover". But, it may be noted that direct strokes occur infrequently.

b) **Indirect Lightning Stroke:**

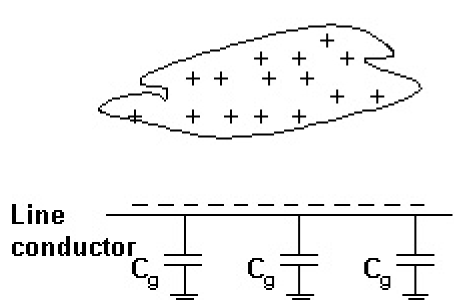


Fig.39

When a charged cloud comes close to an overhead transmission line, charges of polarity opposite to that of the cloud were induced on the section of the transmission line near the cloud. These induced charges in effect charge the ground capacitances of the line. When charge balancing between the cloud and the line is complete, the charged ground capacitances discharge to other ground capacitances of the line lying further away. This generates a travelling wave on the line moving in either direction.

Both direct and indirect lightning strokes generate transient voltages in overhead transmission lines, the magnitude of which are many times greater than the normal operating voltage.

Lightning Impulse Voltage:

A lightning impulse voltage has the following characteristics: i) Non-repetitive, ii) Aperiodic and iii) it rises sharply to its peak value and then falls gradually. It is characterized by – i) Polarity, ii) Peak value and iii) Waveshape represented by wave front and wave tail times.

As per IS-2071, the waveshape of a standard lightning impulse voltage is – i) wave front time = 1.2μs (± 30%) and ii) wave tail time = 50μs (± 20%).

Switching Impulse:

t_f = 250μs ± 20%
t_t = 2500μs ± 60%

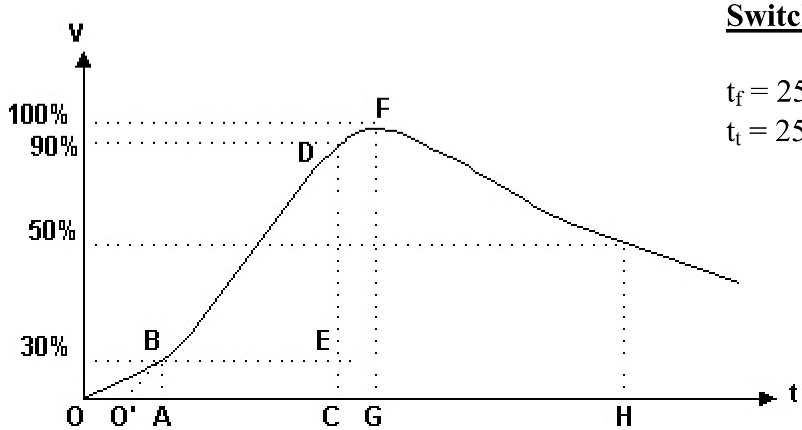


Fig.40

Practically, it is very difficult to identify the actual origin O, because of imperfect synchronization of measuring circuit and also due to ringing at a high frequency near the origin. So, the waveshape is measured from the virtual origin O′, which is the point on the time axis, where the straight line joining the points of 30% and 90% of the peak voltage cuts the time axis. Then

Wave-front time (t_f) = O′G

and Wave-tail time (t_t) = O′H, where H corresponds to the point on the voltage wave when the voltage has fallen to 50% of its peak value.

Determination of Wave-front time:

In the Fig. 40, $\Delta O'FG$ and ΔBDE are similar. So,

$$\frac{FG}{DE} = \frac{O'G}{BE}$$

$$\text{or, } O'G = \frac{FG}{DE} \times BE$$

$$\therefore \text{ Wave front time } (t_f) = \frac{100}{60} \times t_1 = 1.67 t_1$$

where, t_1 = time taken to rise to 90% of peak value from 30%.

Principle of Impulse Voltage Generation:

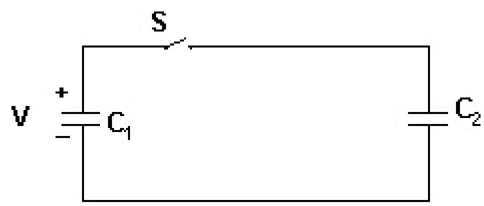


Fig.41

Let, the condenser C_1 is charged upto a voltage V. Now, if the switch is closed then the condenser C_2 of Fig.41 will be charged upto a steady voltage V_1 ($V_1 < V$) depending upon the magnitudes of C_1 and C_2. If $C_1 = C_2$, then $V_1 = (V/2)$.

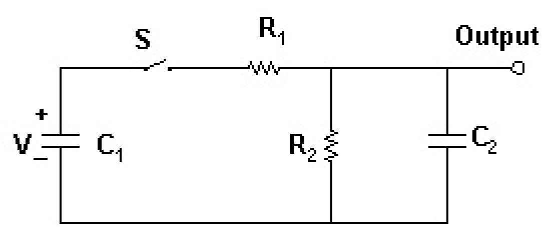


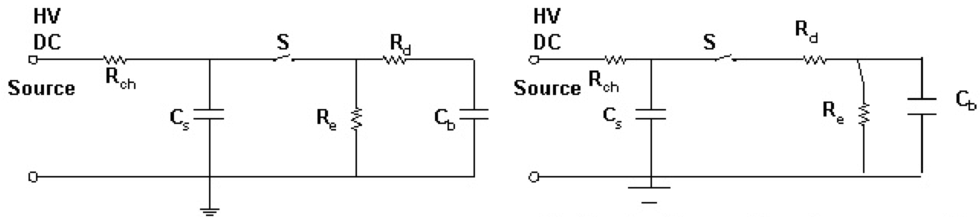
Fig.42

If two resistances are added in the circuit as shown in Fig.42, then time delays are incorporated in charging and discharging of C_2. As a result an impulse voltage wave is obtained as output. The polarity of the output impulse can be simply reversed by reversing the charging polarity of C_1.

Fast-acting Switch:

For automatic and fast switching action, mechanical switches are not suitable and hence, SCRs may be used as an alternative. But, the PIV of a single SCR is of the order of 3kV and impulse voltages are about million volts in magnitude. So, large numbers of SCRs are needed to be connected in series. In that case it becomes very difficult to obtain exact synchronization of all the SCRs, which distorts the impulse waveform. Hence, sphere gap is used as a switch, the breakdown time of which is about a microsecond only.

Basic Impulse Generator Circuit:



A) Source end connection of discharge resistor

B) Load end connection of discharge resistor

Fig.43

C_s = Source / Stage Capacitor
C_b = Load Capacitor
R_{ch} = Charging resistor

R_d = Damping resistor
R_e = Discharge resistor

Normally, $R_d \leq 0.1R_e$ and $C_b \leq 0.1C_s$.

i) Charge transfer from C_s to C_b

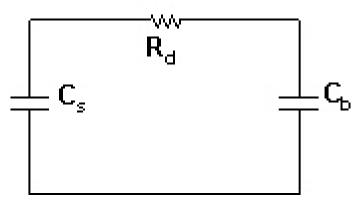


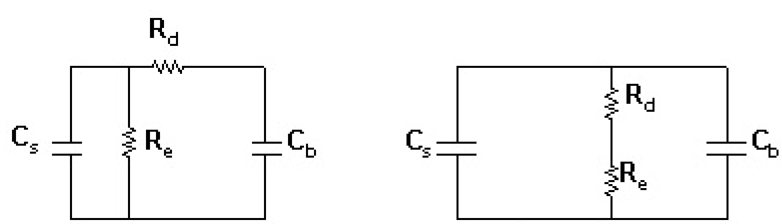
Fig.44

$$C_{eq} = \frac{C_s C_b}{C_s + C_b}$$

$$\text{so, Time constant } (\tau_1) = R_d C_{eq} = R_d C_{eq} = R_d \frac{C_s C_b}{C_s + C_b}$$

As C_b gets charged, the front of the impulse wave is generated. After the capacitor C_b attains its peak voltage V_P, both the capacitors starts discharging.

ii) Discharging of Capacitors C_s and C_b



(approx)

Fig.45

$$\text{Time constant } (\tau_2) = (R_d + R_e)(C_s + C_b)$$

Transform Circuit:

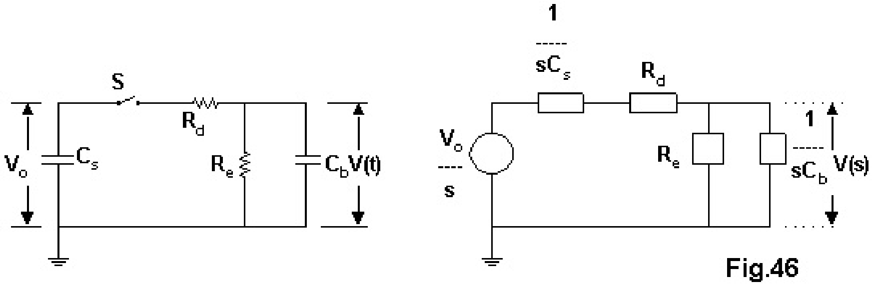


Fig.46

so, $V(s) = \frac{V_o}{s} \cdot \frac{Z_2}{Z_1 + Z_2}$

where, $Z_1 = R_d + \frac{1}{sC_s}$ and $Z_2 = \frac{R_e \cdot \frac{1}{sC_b}}{R_e + \frac{1}{sC_b}}$

By substitution one gets

$$V(s) = \frac{V_o}{k} \cdot \frac{1}{s^2 + as + b}$$

where, $a = \frac{1}{R_d C_s} + \frac{1}{R_d C_b} + \frac{1}{R_e C_b}$

$b = \frac{1}{R_d R_e C_s C_b}$

and $k = R_d C_b$

In time domain it yields

$$V(t) = \frac{V_o}{k} \frac{1}{(k_2 - k_1)} \left[e^{-k_1 t} - e^{-k_2 t} \right]$$

where, $k_1, k_2 = \frac{a}{2} \mp \sqrt{\left(\frac{a}{2}\right)^2 - b}$

The output impulse voltage is therefore superposition of two exponential functions of opposite polarity.

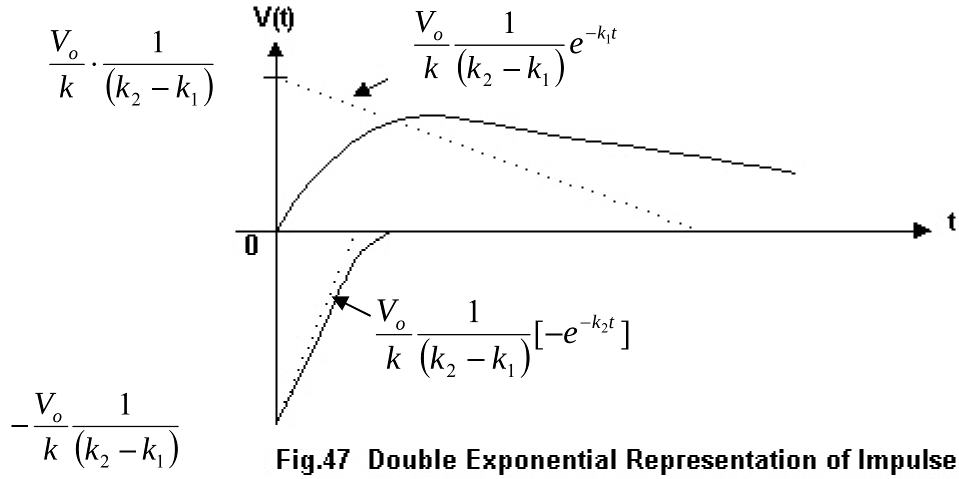


Fig.47 Double Exponential Representation of Impulse Wave

Wave shape	$1/k_1$	$1/k_2$
1.2/50μs	68.2	0.405
250/2500μs	2877	104

Voltage Efficiency:

It is defined as $\eta_v = \frac{V_P}{V_o}$

where, V_P is the peak value of the output impulse wave.

In many respects the two basic circuits of single-stage impulse generator are equivalent. But, they differ significantly in terms of voltage efficiency.

Maximum Stored Energy:

A very important parameter of impulse generator is the maximum stored energy, which is given by

$$W = \frac{1}{2}C_s(V_{o\max})^2$$

This energy primarily determines the size and the cost of a generator.

Significance of R_d:

In practice some inductance, however, small it may be, is always present in all the branches of the impulse generator circuit. Combining all the inductances into a lumped inductor, the charging circuit of C_b can be represented as

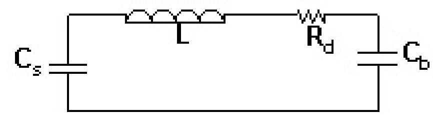


Fig.48

For this circuit to be non-oscillatory.

$$R_d \geq 2\sqrt{\frac{L}{C}}, \quad \text{where,} \quad C = \frac{C_s C_b}{C_s + C_b}$$

The discharge circuit of C_s and C_b is always non-oscillatory due to the presence of R_e, which increases the resistance beyond the critical resistance.

Multi-Stage Impulse Generator Circuit:

Following problems are generally encountered, if peak voltages higher than 200kV are to be generated using single-stage impulse generator circuit.

i) increase of the physical size of the circuit elements
ii) difficulty in obtaining high dc voltages for charging C_s
iii) difficulty in using spark gaps for switching at very high voltages and
iv) difficulties in suppressing corona discharges from the structure and leads.

In order to over come these difficulties, in 1923 Marx proposed a circuit where a number of source capacitors are charged in parallel and then discharged in series through spark gaps.

Marx Generator Circuit:

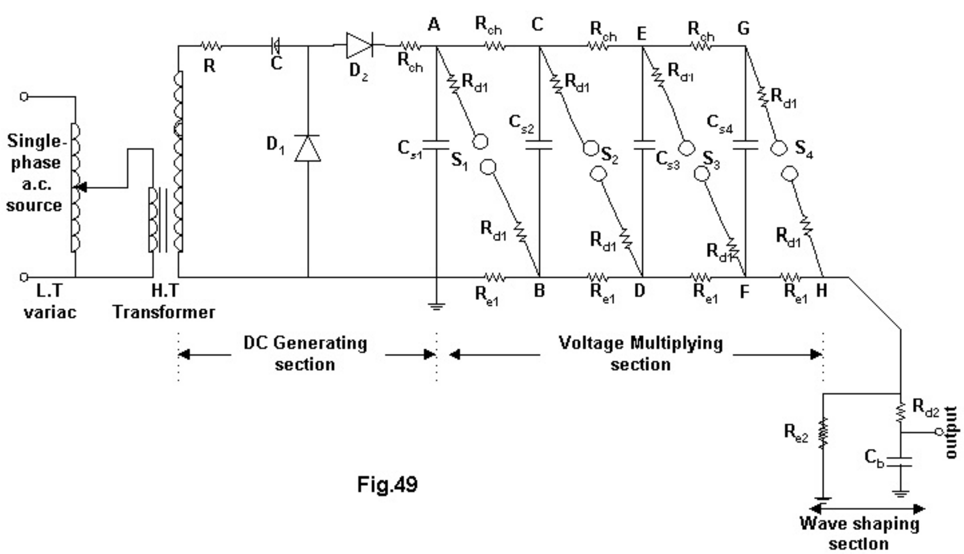


Fig.49

A multi-stage Marx generator circuit can be divided into three sections.

i) D.C. generating section
ii) Voltage multiplying section.
iii) Wave shaping section.

i) **D.C. Generating Section:**

Conventional Cockcroft-Walton Voltage doubler circuit is used in this section that utilises power frequency input at 50Hz. The output DC voltage is normally kept between 100kV – 200kV.

ii) **Voltage Multiplier Circuit:**

During charging all the source capacitances C_{s1}, C_{s2}, C_{s3} and C_{s4} are charged to a voltage V over the resistances R, R_{ch} and R_{e1}. The resistances are incorporated in the circuit to limit the charging current drawn by the capacitors. As the sphere gap S_4 is not in conducting mode, the load capacitor C_b is not charged. The gap distances of S_1, S_2, S_3 and S_4 are kept in ascending order such that $S_1 < S_2 < S_3 < S_4$. The gap of S_1 is so set that it does not break down at the voltage V. When all the source capacitors are charged to the voltage V, the sphere gap S_1 is triggered to break down. With the break down of S_1, $V_B = V_A = V$ and hence $V_C = 2V$ as C_{s2} is charged to a potential of V. The potential difference across the sphere gap S_2 is therefore 2V, which results in the break down of S_2. Then, $V_D = 2V$ and $V_E = 3V$. Thus the voltage appearing across sphere gap S_3 is 3V and it breaks down. Consequently, $V_F = 3V$ and $V_G = 4V$ which causes breakdown of sphere gap S_4. It leads to charging of C_b followed by discharging of source and load capacitors. Thus the required impulse voltage wave is generated across C_b.

iii) **Wave Shaping Circuit:**

To achieve standard impulse waveshape, the resistances R_{d2} and R_{e2} are commonly changed. The equivalent R_d and R_e is partially distributed within the impulse generator as R_{d1} and R_{e1}. The rest are placed as lumped parameters as R_{d2} and R_{e2} externally. While testing objects of low surge impedance, standard waveshapes are difficult to achieve. In that case along with lumped R_{d2} and R_{e2}, R_{e1} and R_{d1} might also be changed.

Representation of Multistage Generator by an Equivalent Single-Stage Generator:

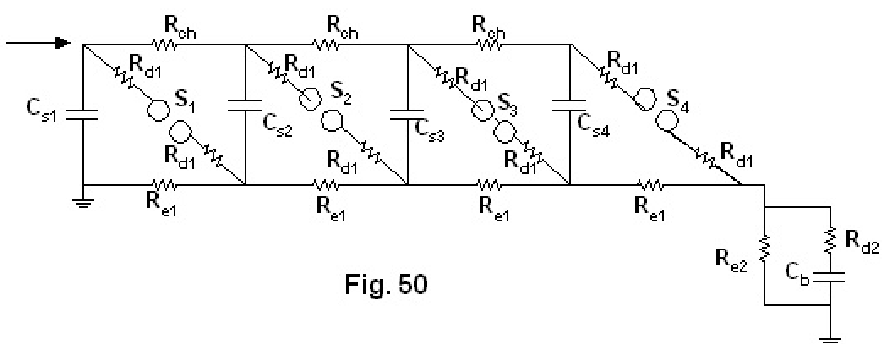


Fig. 50

When all the spark-gaps, viz. S_1, S_2 and S_3 break down, then all the stage capacitors are connected in series.

Let, $C_{s1} = C_{s2} = C_{s3} = C_{s4} = C_s$.

$$\text{Hence, } C_{eq} = \frac{C_s}{4}$$

$$\therefore \text{ In general, } C_{eq} = \frac{C_s}{n}$$

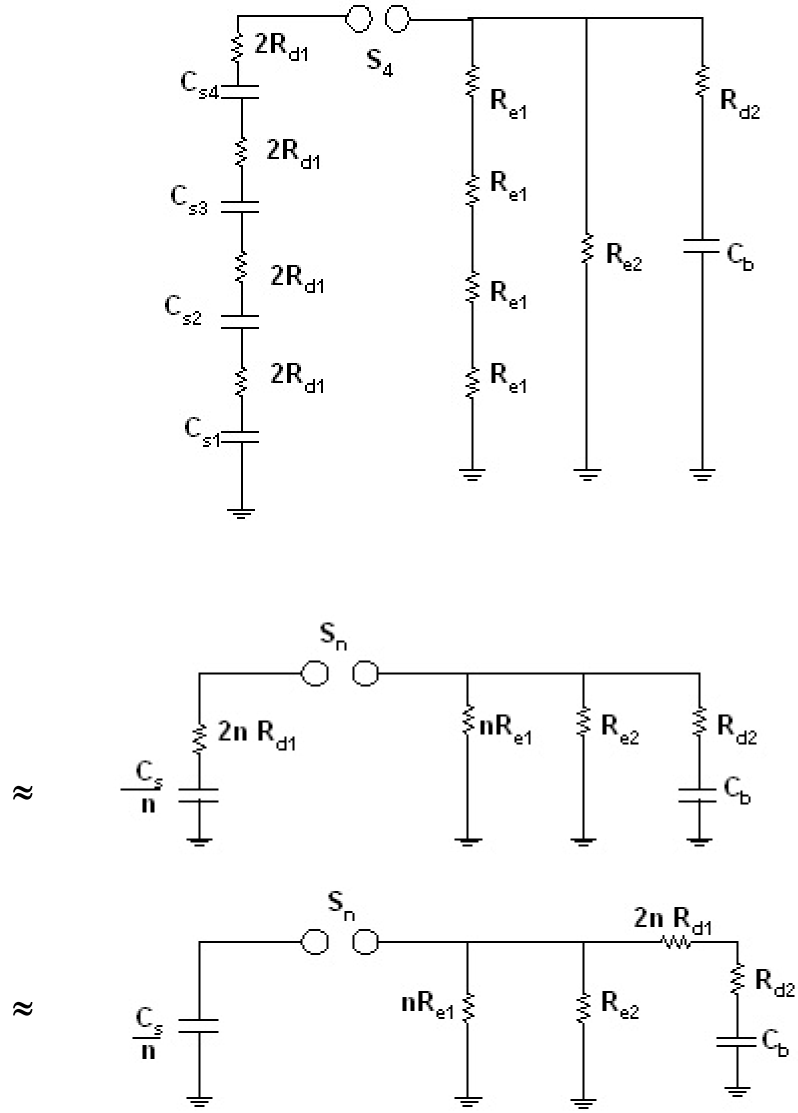


Fig.51

If this circuit is compared to a single – stage circuit, then it may be said that both R_e and R_d have been divided into two groups: One placed within the generator and the other in the wave shaping section.

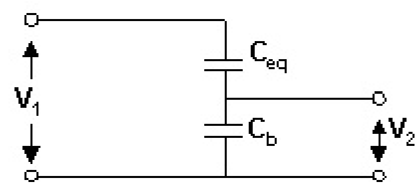
Problem:

Design an eight-stage impulse generator to generate 1400kV with voltage efficiency of 96%. The energy stored in the impulse generator is 16kJ and the input dc voltage is 175kV.

Solution:

When the sphere-gap S_n breaks down, then the capacitors C_{eq} and C_b are connected in series. Neglecting R_{d1} and R_{d2} the output voltage

Fig.52



$$V_2 = \frac{C_{eq}}{C_{eq}+C_b}\cdot V_1$$

$$\text{Given, Voltage efficiency}\,(\eta_v) = \frac{V_2}{V_1} = 0.96$$

$$\text{or, } \frac{C_{eq}}{C_{eq}+C_b} = 0.96$$

Again, energy stored in an impulse generator
= Energy stored in the stage capacitors.

For the eight stages, there are eight stage capacitors, each of which is charged to 175kV.

So,

$$\frac{1}{2}\cdot C_s\cdot\left(175\times10^3\right)^2\times 8 = 16\times10^3$$

$$\text{or, } C_s = 0.1306\mu F.$$

$$\therefore C_{eq} = \frac{C_s}{8} = 16.32nF.$$

Again,

$$\frac{C_{eq}}{C_{eq}+C_b} = 0.96$$

$$\text{or, } C_b = 0.68nF.$$

Now, the wave-front time is determined by the charging time of C_b, when all the C_s are in series.

$$1.2\times10^{-6} = \frac{3.243\left(C_{eq}\times C_b\right)}{C_{eq}+C_b}\times R_d$$

$$\text{or, } R_d = 566.8\Omega$$

This is because of the following:

$$\because v = V\,(1-e^{-\frac{t}{\lambda}})$$

$$\text{So, } t_{30} = \lambda\ln\left(\frac{1}{1-0.3}\right) \text{ and } t_{90} = \lambda\ln\left(\frac{1}{1-0.9}\right)$$

$$\therefore t_f = \frac{t_{90}-t_{30}}{0.9-0.3} = \frac{\lambda}{0.6}\left[\ln\left(\frac{1}{1-0.9}\right)-\ln\left(\frac{1}{1-0.3}\right)\right]$$

$$= 3.243\,\lambda$$

The tail time is determined by the discharging time of C_b through both R_e and R_d. During this discharge, C_{eq} and C_b are connected in parallel.

$$\therefore \left(50\times10^{-6} - 1.2\times10^{-6}\right) = 0.693\left(C_{eq} + C_b\right)\left(R_e + R_d\right)$$

or $\quad R_e + R_d = 4142.2$

or, $\quad R_e = 3575.3\Omega$

$$\because v = V e^{-\frac{t}{\lambda}},\ \text{So, } t_{50} = \lambda \ln\frac{1}{v/V} = \lambda \ln\frac{1}{0.5} = 0.693\lambda$$

Triggering of Impulse Generator

The following problems are generally associated with the breakdown of the 1st stage sphere gap:

i) If the gap is too large, then no breakdown occurs.

ii) If the gap is too small, then breakdown occurs before the capacitors are charged to the desired voltage.

So, for proper operation of the impulse generator at a desired voltage, it is required that the sphere gap in the 1st stage breaks down at the desired voltage and desired instant. The mechanism by which the initiation of the breakdown of the 1st stage gap occurs is called triggering.

Triggering may be manual or electronic. In manual triggering, the spark gaps are so set that they do not breakdown at the voltage to which the stage capacitors are charged. When all the capacitors are charged to the desired voltage level, the sphere gap spacings are reduced by mechanical means. The reduction of distance between the spheres results in breakdown and thus triggering is achieved. However, for impulse generators with higher number of stages, mechanical triggering is very inefficient and hence is not used. So in practice electronic triggering is employed.

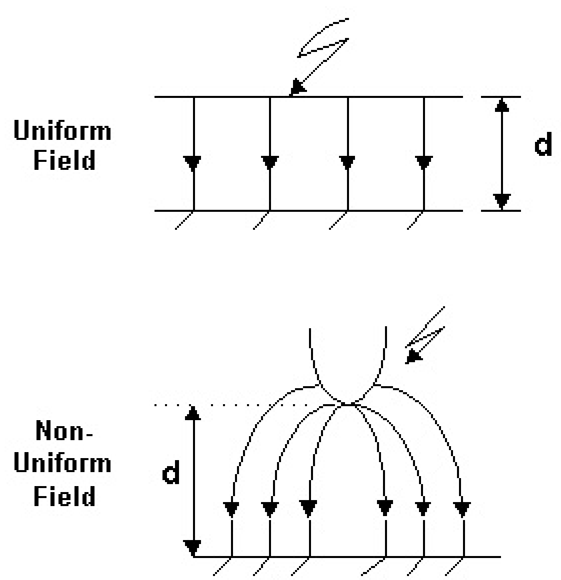


Fig.53

For uniform field, e.g. parallel plate capacitor, air breakdown occurs at $30kV_p$/cm at normal temperature and pressure that is same everywhere.

For non-uniform field, the potential distribution is non-linear and hence electric field intensity is not same everywhere. Hence, for the same spacing non-uniform field will breakdown at an applied voltage that is much lower than that required to break uniform field gap.

For electronic triggering the concept of breakdown in non-uniform field is utilized.

Trigatron Gap

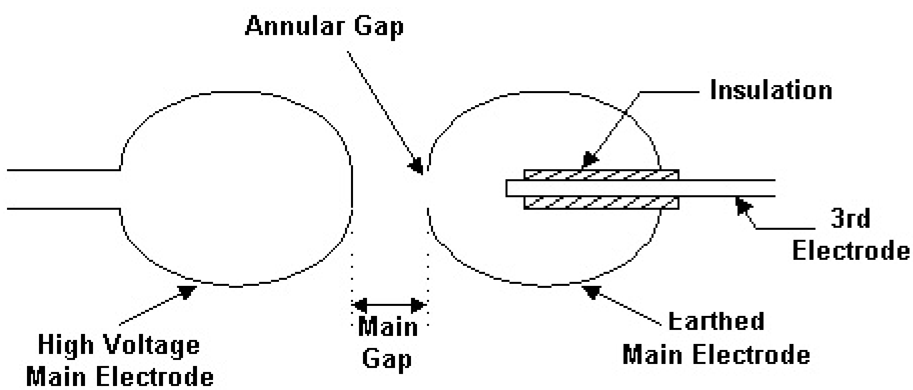


Fig.54

The three-electrode sphere gap arrangement used for triggering is known as Trigatron Gap and is used in the 1st stage of the impulse generator circuit. When triggering is required, a pulse of about 10-12 kV is applied at the 3rd electrode causing breakdown of the annular gap between the earthed main electrode and the 3rd electrode. The charge particles thus produced accumulate in the main gap and distorts the main field between the high voltage and earthed spheres. In this process the field in the main gap becomes non-uniform and as a result field intensity increases. This causes breakdown of the main gap and triggering is achieved.

The 3rd electrode is always housed in the earthed sphere of the 1st stage and is insulated from the earthed sphere. It is normally made of brass or copper.

Generation of Trigger Pulse

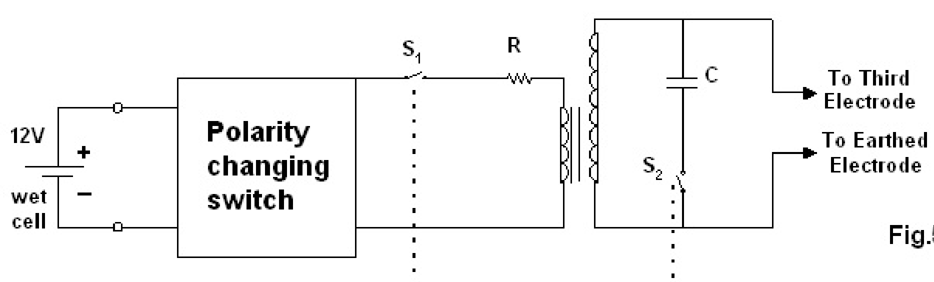


Fig.55

The transformer having a high turns ratio is connected to a dc source through a polarity reversal switch. The switches S_1 and S_2 operate simultaneously. When S_1 is closed S_2 is also closed and hence, the secondary is short-circuited by the capacitor C. A dc current is established on the primary side that is governed by the resistance R. When S_1 and S_2 are opened, then due to breaking of current on the primary side, a voltage is induced in the primary winding due to L(di/dt), which is reflected to the secondary side with amplified magnitude. This high voltage pulse is applied between the third electrode and the earthed main electrode to achieve triggering.

Delay Cable:

While recording an impulse signal by CRO, it has to be ensured that the CRO is properly synchronized with the impulse signal. Otherwise the entire impulse signal will not be recorded. For this purpose, the time-base of the CRO is activated first and the impulse signal is made to arrive at the vertical plates with a small delay. This is achieved with the help of delay cable as shown in the Fig.56.

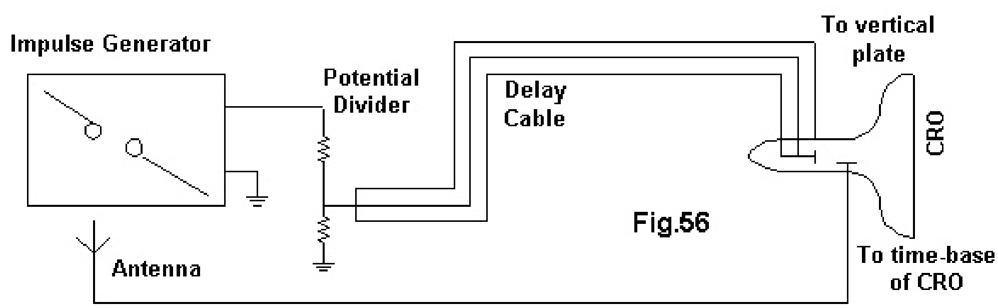


Fig.56

The antenna picks up the signal generated due to discharge of the sphere-gap within the impulse generator and fires the time-base of CRO, as soon as the impulse generator is triggered. The impulse signal arrives at the vertical plates after passing through a delay cable, which introduces a delay of about 0.1 – 0.5μs depending upon the insulating medium and length of the delay cable. This ensures that the complete impulse signal is recorded by the CRO.

The propagation velocity of a signal along a transmission line is

$$v = \frac{c}{\sqrt{\varepsilon_r \mu_r}}$$

For normal signal cables $\mu_r = 1$, so that the above equation can be simplified to

$$v = \frac{c}{\sqrt{\varepsilon_r}}$$

The relative velocity is defined as the ratio of the actual velocity in the cable to the velocity of light

$$v_{rel} = \frac{v}{c} \times 100\%$$

In standard signal cables using solid polyethylene or Teflon as a dielectric, the propagation velocity is about 60 – 70% of the velocity of light.

The reciprocal of propagation velocity is the transit time per unit length

$$T = \frac{1}{v},$$

which is normally given in μs/cm. The absolute transition time and the appropriate cable length necessary to delay a signal by a specified amount can be calculated from

$$\tau = T.L = \frac{L}{c}\sqrt{\varepsilon_r}$$

Switching Impulse Voltages

During tests with switching impulse voltages, the stressing of the power apparatus by internal overvoltages consequent to switching operations in the supply network is simulated. The idealised waveform of an aperiodic switching impulse voltage is, like that of a full lightning impulse voltage, defined by superposition of two exponential functions; however, the time constants here are appreciably larger.
Besides the test voltage value (peak value), switching impulse voltages are characterised by two time parameters, which, in contrast to lightning impulse voltages, are with reference to the true origin O of the waveform (Fig. 1).The truly existing deviation in the initial part of the switching impulse voltage is negligible on account of the larger values of the time parameters. The time to peak T_p is defined as the time between the true origin O and the instant of the peak, the time to half-value as the time between O and the point at $0.5\hat{u}$ on the tail of the switching impulse voltage.

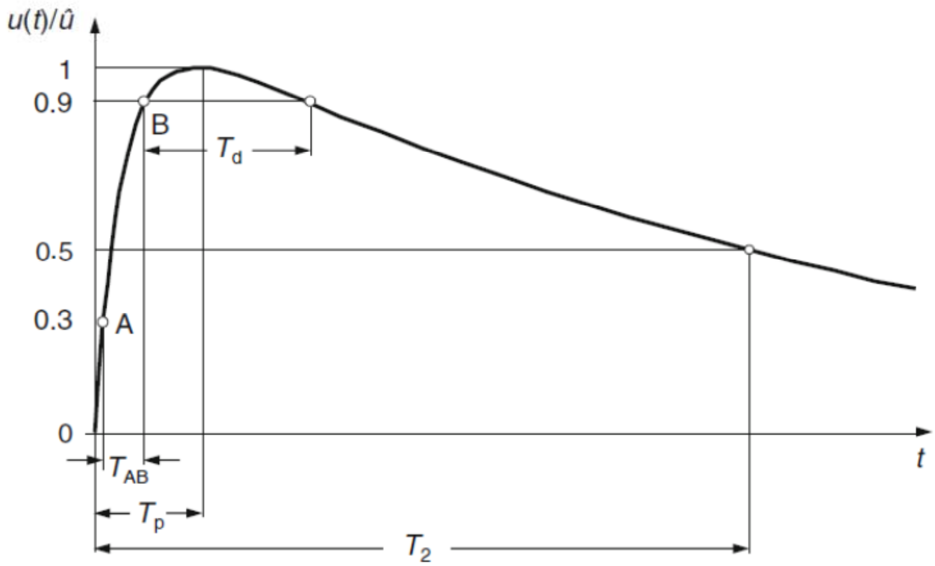


Fig. 1. Switching impulse voltage and its impulse parameters.

In addition to T_p and T_2, a few other time parameters are also defined. The time duration T_d is fixed as the time above 90 % during which the voltage is greater than $0.9\hat{u}$. In special cases, switching impulse voltages can also swing below the zero line in the tail region. It may therefore be necessary to specify the time to zero "T_z" between the true origin O and the instant of the first zero-crossing of the tail of the switching impulse voltages (not shown in the figure).
The front time T_1 as per Eqn. (1) is defined for switching impulse voltages. It serves as a criterion for distinguishing between lightning impulse voltages and switching impulse voltages. The latter have a front time of at least 20 µs.

$$T_1 = \frac{1}{0.6} T_{AB} \qquad (1)$$

wherein T_{AB} is the time interval between the points A at $0.3\hat{u}$ and B at $0.9\hat{u}$ on the front of the impulse voltage.
Switching impulse voltages are identified by the numerical values of T_p and T_2. The standard switching impulse voltage 250/2500 has a time to peak of 250 µs (tolerance: ±20 %) and a time to half-value of T_2 = 2500 µs (tolerance: ±60 %). The large tolerances permit the testing of various types of high-voltage apparatus without having to adjust the elements of the

impulse voltage generator each time to match the varying loads. The permissible uncertainties of measurement agree with those for lightning impulse voltages and amount to 3% for the test voltage value (peak value) and 10 % for the time parameters. The uncertainty comprises of the uncertainty of the approved measuring system and, wherever necessary, other uncertainty components during the impulse voltage test.

The time to peak T_p, on the basis of its definition, appears to be a measurement parameter simple to determine. However, during automatic data processing, small digitising errors of the recorder or superimposed oscillations in the extended time duration of the peak region can lead to erroneous values of the time to peak. Then the uncertainty for T_p prescribed in the test standards cannot be maintained. Since due to its significance in testing practice, the time to peak must be maintained as a time parameter, its determination is done, not directly but as the time interval T_{AB} between 0.3 and 0.9$\hat{u}$, multiplied with the factor K:

$$T_p = K \times T_{AB} \qquad (2)$$

For the switching impulse voltage 250/2500 with double exponential waveform as per Eqn. (2), the calculation results in T_{AB} = 99.1 μs and thus K = 2.523. For other values of T_p and T_2 within the permissible tolerance limits of the standard switching impulse voltage 250/2500, K can be calculated approximately from the numerical Eqn:

$$K = \{2.42 - (3.08 \times 10^{-3} T_{AB})\} + \{1.51 \times 10^{-4} T_2\} \qquad (3)$$

in which, for T_{AB} and T_2, the measured numerical values in microseconds are to be substituted. The error during calculation of T_p with K as per Eqn. (3) lies within ±1.5 %, which, as a rule, might be negligible during tests. For other switching impulse voltages, Eqn. (3) is invalid. The factor $K = T_p/T_{AB}$ is then obtained from the waveform of a switching impulse voltage calculated as per Eqn. (21), which has the same time T_{AB} as the measured waveform. For on-site tests with switching impulse voltages, a value of K = 2.4 is uniformly defined.

Generators for Switching Impulse Voltages

For the generation of lightning and switching impulse voltages, essentially there are two basic circuits available.

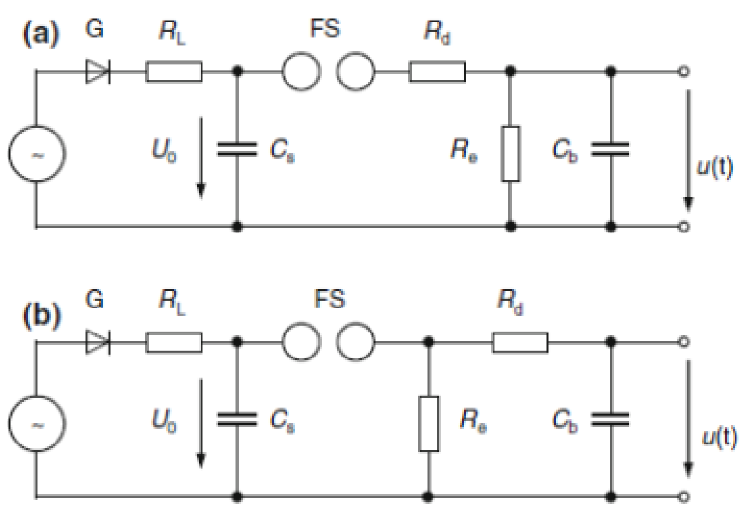


Fig. 2. Single-stage basic circuits for the generation of impulse voltages. (a) basic circuit Type-A, (b) basic circuit Type-B

Common to both circuits is the impulse capacitor C_s, which is charged to the voltage U_0 relatively slowly by a rectified alternating current via the charging resistor R_L. When U_0 reaches the firing voltage of the sphere gap FS, it breaks down and C_s discharges in a very short time through the discharge circuit, which consists of the damping resistor R_d, the load capacitor C_b and the discharge resistor R_e. Unavoidable inductances of the circuit elements as well as their leads are not indicated. They can be combined in the equivalent circuit and taken into account by an inductance connected in series with R_d. The impulse voltage u(t) can be obtained at the terminals of C_b and fed to the test object. Its impedance in turn affects the circuit and influences the waveform of the generated impulse voltage more or less. While R_d is primarily responsible for the charging of C_s, and thereby for the front time T_1 of the impulse voltage, R_e affects the discharge of C_b, and thereby the time to half-value T_2. Both the circuits in Fig. 2 differ from one another in the location of the discharge resistor R_e. in circuit *A* it is located behind the damping resistor R_d and in circuit B in front of it. The firing voltage of the sphere gap is adjusted by varying the spacing between the spheres, which also specifies the peak value of the generated impulse voltage u(t). The ignition spark is extinguished after the discharge of C_s and C_b, the switching sphere gap FS opens and C_s can be charged again from the direct voltage source through R_L. The magnitude of the direct voltage U_0 or the charging current amplitude determines the ignition repetition rate of the switching sphere gap and thereby the impulse rate. In small impulse generators up to 10 kV, instead of the sphere gap, electronic switches are preferred.

The maximum energy stored in the impulse capacitor C_s is given by Eqn. (4).

$$W=1/2\ C_s U_0^2 \quad (4)$$

which identifies the output capacity of the impulse voltage generator. The utilisation efficiency η is defined as the quotient of the peak value $\hat{u}$ of the generated impulse voltage and the charging voltage U_0:

$$\eta = \frac{\hat{u}}{U_0} = f\left(\frac{C_s}{C_b}\right) \quad (5)$$

For achieving a high utilisation efficiency and thereby a high peak value, $C_s >> C_b$.

Switching impulse voltages can also be generated with testing transformers which are excited by a voltage jump. In one circuit, the network alternating voltage at its peak value and in the other, the charge of a capacitor is switched on to the low-voltage winding. The switching impulse voltages appearing at the high-voltage terminals of the transformer have waveforms mostly other than the standard ones—especially, the time to peak and time to half-value are longer. By proper layout of the testing transformers, oscillating switching impulses will appear.

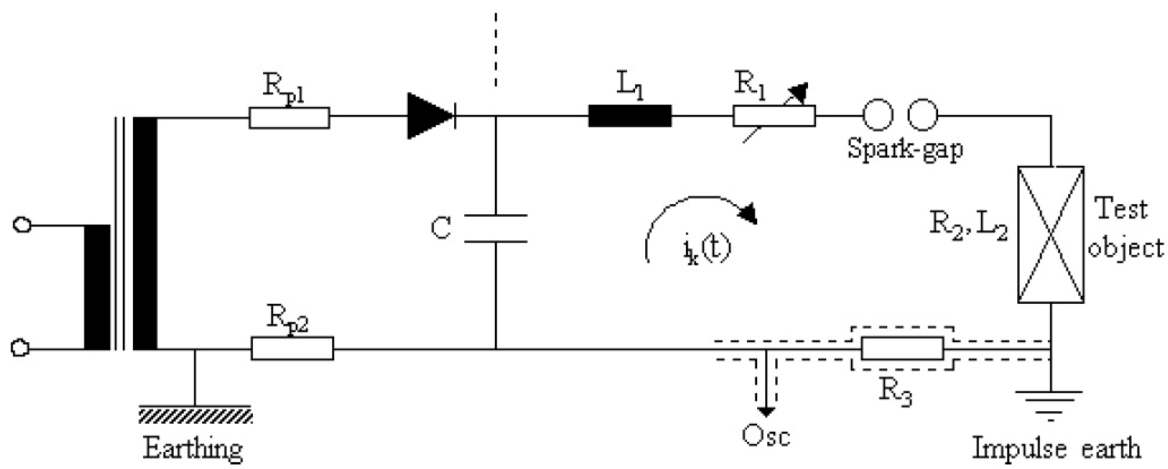
Oscillating switching impulses for on-site tests are, as a rule, generated with impulse voltage generators in which the damping resistor R_d in the basic circuit of Fig. 2(b) is either replaced or extended by an inductance. Due to the superimposed oscillation, the maximum value is nearly double that of an aperiodic impulse voltage which is generated with the same value of the charging voltage.

Impulse Current Generation:

Telecommunication, navigation and electrical power systems suffer most from lightning currents. Many lightning current tests, which simulate the real lightning conditions, are conducted on these systems in order to assess their performance. The production of such impulse currents requires impulse current generators with the ability to produce impulses of definite amplitude and waveshape. Therefore, it is well understood that the careful and correct design of impulse current generators plays an important role in the systems lightning protection.
The values of the time parameters of the impulse and the elements of the generator are expressed with analytical and arithmetic expressions ensuring that the characteristics of the generated current are in accordance with the limitations of the international standard IEC 60060-1.

Impulse Current Generator Circuit:

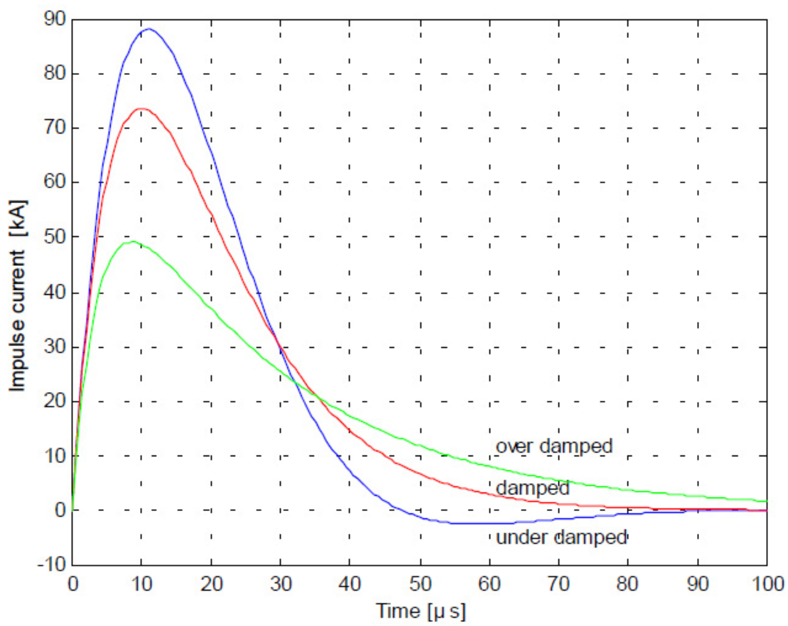
Discharging a capacitor to the test object through an inductive circuit performs impulse current tests. The capacitor, or a row of capacitors, is charged by a DC high voltage supply U_O. The total capacitance C of the circuit includes also the capacitive component of the test object. The inductance L includes an inductive air-core coil L_1 that is added to the circuit for the regulation of the damped oscillation, the inductance L_2 of the test object and the stray inductance of the circuit conductors.



Generally, the resistance of the discharge loop is very low. However, the resistive components of the circuit elements should be determined. The total resistance R of the loop includes the measuring resistor R_3, the resistance R_2 of the test-object and the circuit conductors as well as any other resistance R_1 that is added to the circuit for the attenuation of oscillations. The charging resistances R_{p1} and R_{p2} of the circuit do not contribute to the resistance of the discharge loop. Although the circuit is very simple, it is not flexible and independent to regulate the shape of the current waveform.
The generator consists also of a variable spark-gap which, when fired, discharges the capacitor to the test object loop resulting in the formation of the impulse current. The discharge current $i_k(t)$ can be determined from the system equation at the instant of triggering of the spark gap:

$$U_0 = Ri_k(t) + L\frac{di_k(t)}{dt} + \frac{1}{C}\int i_k(t)\, dt$$

This equation has three solutions, which, correspond to three distinct discharge conditions of the impulse current. The type of the discharge condition is determined by the value of the term (R^2-4L/C). If the resistance R is adjusted exactly to nullify the term, then the oscillation is damped. With smaller resistance, the term takes negative values and the oscillation in the current is under-damped. For higher magnitude of the resistance, the term becomes positive and the oscillation is over-damped. These types of discharge of the impulse current generator are shown in Fig. The resistance R is the varying element of the generator while the capacitance C and the inductance L are assumed to be constant.



The front-time t_f of the impulse current is defined as 1.25 times the interval between the instants when the impulse is 10% and 90% of peak value. The time to half-value t_h of the current is defined as the time interval between the virtual origin and the instant at which the current has decreased to half the peak value. The time parameters t_f/t_h of the four standard exponential impulse currents, according to IEC 60060-1, are the following: 1/20μs, 4/10μs, 8/20μs and 30/80μs. A ±10% tolerance is accepted between the specified values for these standard impulse currents. The front-time and the time to half-value of the impulse current can be controlled for a given capacitance with the simultaneous variation of the R and L values. The front-time can be determined with suitable selection of the inductive coil, while the time to half-value with the added resistance.

Analysis and design of an impulse current generator

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Abstract: - This paper presents an analytical method for the design and analysis of impulse current generators according to the requirements of the international standard IEC 60060-1. The circuit of the generator is analyzed and mathematical expressions for the most important circuit and impulse current parameters are included. The analytical expression of the impulse current waveform in the distinct operation conditions of the generator, as well as expressions for the calculation of the time constants of the waveform are computed. Moreover arithmetic expressions concerning the range of the generator element values are derived, ensuring that the characteristics of the generated current are in accordance with the limitations of IEC 60060-1. These expressions can well facilitate the correct design of the impulse current generator taking under consideration the international standard. A computer programme has been also developed to support the complex calculations in the impulse current generator circuit. The programme has the ability to calculate the desired configuration and the characteristics of the generated current.

Key words: - Impulse current, impulse current generator, IEC 60060-1

1 Introduction

Lightning as an electrical phenomenon has got very disturbing and destroying consequences for human lives and installations. Telecommunication, navigation and electrical power systems are mainly these, which suffer most from lightning currents. Many lightning current tests, which simulate the real lightning conditions, are conducting on these systems in order to observe their performance. The production of such impulse currents requires impulse current generators with the ability to produce impulses of definite amplitude and waveshape. Therefore, it is well understood that the careful and correct design of impulse current generators plays an important role in the systems lightning protection.

The performance of impulse current tests requires the design of generators that will produce impulses of the correct amplitude and waveshape. In this paper a mathematical analysis of the generator circuit is performed and the distinct operation conditions of the generator are analysed. Analytical expressions concerning the impulse current waveform are stated and the peak value as well as the time to peak are estimated.

The values of the time parameters of the impulse and the elements of the generator are expressed with analytical and arithmetic expressions ensuring that the characteristics of the generated current are in accordance with the limitations of the international standard IEC 60060-1 [1].

A computer programme has been also developed in order to combine the mathematical analysis with the limitations of the international standard. It introduces flexible solutions, which take advantage the laboratory equipment and maximize the efficiency of the generator. At the same time, it gives the opportunity the configuration of the generator to be freely designed according to the demands of the experiment, ignoring the limitations of the standard. The computer programme analyses the defined configuration or alternatively proposes possible configurations, which offer the desired characteristics. Finally a sensitivity analysis of the generator characteristics for all possible operation conditions is included in this paper.

This work forms a useful tool in the development of impulse current generators considering that the international bibliography is quite limited in this particular subject [2, 3, 4]. It must be mentioned that computational approaches to this problem has also been performed in the past [5, 6, 7].

2 Analysis of the generator circuit

Discharging a capacitor to the test object through an inductive circuit (Fig.1) performs impulse current tests. The capacitor, or a row of capacitors, is charged by a DC high voltage supply U_o. The total capacitance C of the circuit includes also the capacitive component of the test object. The inductance L includes an inductive air-core coil L_1

that is added to the circuit for the regulation of the damped oscillation, the inductance L_2 of the test-object and the stray inductance of the circuit conductors.

Generally, the resistance of the discharge loop is very low. However, the resistive components of the circuit elements should be determined. The total resistance R of the loop includes the measuring resistor R_3, the resistance R_2 of the test-object and the circuit conductors as well as any other resistance R_1 that is added to the circuit for the attenuation of oscillations. The charging resistances R_{p1} and R_{p2} of the circuit do not contribute to the resistance of the discharge loop. Although the circuit of Fig.1 is very simple, it is not flexible and independent to regulate the shape of the current waveform.

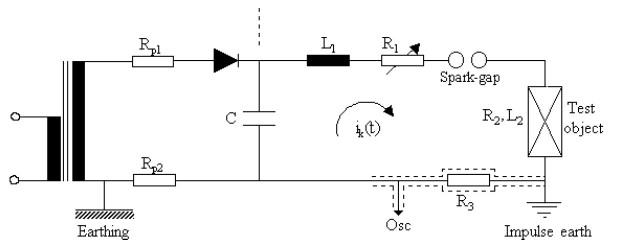

Fig.1 Current generator for exponential impulses (C: capacitor, L_1: inductance, L_2: inductance of the test object, R_1: damping resistance, R_2: resistance of the test object, R_3: measuring resistance, R_{p1}, R_{p2}: charging resistances, Osc: impulse oscilloscope).

The generator consists also of a variable spark-gap which, when fired, discharges the capacitor to the test object loop resulting in the formation of the impulse current. The discharge current $i_k(t)$ can be determined from the system equation at the instant of triggering of the spark gap:

$$U_0 = R i_k(t) + L\frac{di_k(t)}{dt} + \frac{1}{C}\int i_k(t)dt \qquad (1)$$

This equation has three solutions, which, correspond to three distinct discharge conditions of the impulse current. The type of the discharge condition is determined by the value of the term R^2-4L/C. If the resistance R is adjusted exactly to nullify the term, then the oscillation is damped. With smaller resistance, the term takes negative values and the oscillation in the current is under-damped. For higher magnitude of the resistance, the term becomes positive and the oscillation is over-damped. These types of discharge of the impulse current generator are shown in Fig.2. The resistance R is the varying element of the generator while the capacitance C and the inductance L are assumed to be constant.

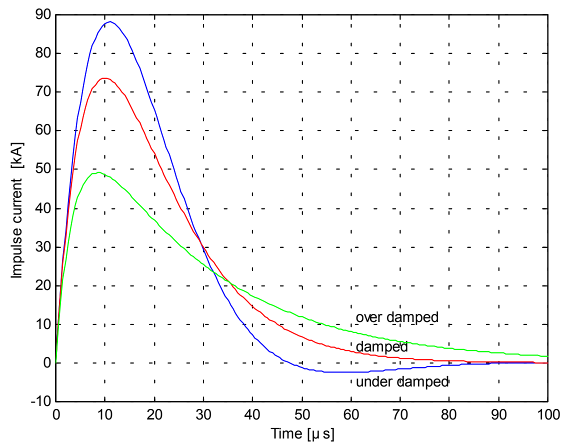

Fig.2 Distinctive discharge conditions of the exponential impulse current generator (over-damped: R=1.5 Ω, damped: R=1 Ω, under-damped: R=0.75 Ω, U_o=100kV, C=20μF, L=5μH).

Solving Eq.(1) by putting:

$$Z = \sqrt{\left|R^2 - 4L/C\right|} \qquad (2)$$

results in three solutions that correspond to the three types of the discharge.

If the resistance is adjusted to damp the oscillation, R^2=4L/C, then the impulse waveform is given by the relation:

$$i_k(t) = \frac{U_0}{L} t e^{-\frac{R}{2L}\cdot t} \qquad (3)$$

The time taken for the damped oscillating current to rise from zero to the peak is:

$$T = \frac{2L}{R} \qquad (4)$$

The amplitude of the current at peak is calculated as follows:

$$I_{\max} = \frac{2U_0}{eR} \qquad (5)$$

If R^2>4L/C, the oscillation is over-damped and the current waveform is given by the formula:

$$i_k(t) = \frac{U_0}{Z}\left(e^{-\frac{R-Z}{2L}\cdot t} - e^{-\frac{R+Z}{2L}\cdot t}\right) \qquad (6)$$

The time taken for the current to rise from zero to the peak is:

$$T = \frac{L}{Z}\ln\left(\frac{R+Z}{R-Z}\right) \qquad (7)$$

Thus, the amplitude of the current is calculated as:

$$I_{\max} = \frac{U_0}{Z}\left(e^{-\frac{R-Z}{2L}\cdot T} - e^{-\frac{R+Z}{2L}\cdot T}\right) \qquad (8)$$

If $R^2<4L/C$, the oscillation is under-damped and the current can be shown to vary with time according to the relation:

$$i_k(t) = \frac{2U_0}{Z} e^{-\frac{R}{2L}\cdot t} \sin(\omega \cdot t) \quad (9)$$

where ω is the angular frequency of the oscillation:

$$\omega = \frac{Z}{2L} \quad (10)$$

Since the current waveform is oscillating it will show more peaks than one, some of them with inverse polarity. The time taken for the oscillating current to rise from zero to the first peak is given by the expression:

$$T = \frac{2}{\omega} \arctan \frac{\sqrt{R^2 + (2\omega L)^2} - R}{2\omega L} \quad (11)$$

The amplitude I_{max} of the current wave at this peak is calculated as:

$$I_{\max} = \frac{2U_0}{Z} e^{-\frac{R}{2L}\cdot T} \sin(\omega \cdot T) \quad (12)$$

The respective time T′ from zero to the first peak of the inverse polarity is:

$$T' = T + \frac{\pi}{\omega} \quad (13)$$

Putting t= T′ in Eq.(9) results the minimum amplitude I_{min} of the current waveform.

$$I_{\min} = -I_{\max} \cdot e^{-\pi \frac{R}{Z}} \quad (14)$$

3 Design considerations

The front-time t_f of the impulse current is defined as 1.25 times the interval between the instants when the impulse is 10% and 90% of peak value. The time to half-value t_h of the current is defined as the time interval between the virtual origin and the instant at which the current has decreased to half the peak value. The time parameters t_f/t_h of the four standard, exponential impulse currents, according to IEC 60060-1, are the following: 1/20μs, 4/10μs, 8/20μs, 30/80μs. A ±10% tolerance is accepted between the specified values for these standard impulse currents.
The front-time and the time to half-value of the impulse current can be controlled for a given capacitance with the simultaneous variation of the R and L values. The front-time can be determined with suitable selection of the inductive coil, while the time to half-value with the added resistance.

Solving Eq.(3) for the pairs of values of the damped oscillating current at the points of 10%, 90% and 50% of peak value, the following expressions for the time parameters are derived:

$$t_f = 1.43 \frac{L}{R} \quad (15)$$

$$t_h = 5.42 \frac{L}{R} \quad (16)$$

Thus, the ratio of those parameters for the damped oscillation, results to be independent from the circuit elements R, L and C:

$$\frac{t_f}{t_h} = 0.26 \quad (17)$$

Considering the ±10% tolerance for t_f and t_h, the upper and lower limit of the ratio t_f/t_h for the standard, exponential impulse currents of IEC60060-1 may lie in the intervals of Table 1. It is obvious that the determined value for the ratio t_f/t_h in Eq.(17) lies outside the defined limits. This means that critical damping of the oscillation in the standard impulse currents is impossible. Inevitably, tests with the standard impulses have to be performed either with under-damped oscillating currents or with over-damped ones. A disadvantage of over-damping of the oscillation is the decrease of the current amplitude and, consequently, of the utilisation factor I_{max}/U_o of the impulse generator.

Table 1 Limits for the time parameters of standard impulse current waveforms.

Impulse	1/20μs	4/10μs	8/20μs	30/80μs
t_f/t_h	0.04-0.06	0.33-0.49	0.33-0.49	0.31-0.46

The under-damped oscillation maximises the utilisation factor but attention should be paid to the amplitude of the oscillation. According to IEC 60060-1, any polarity reversal after the current has fallen to zero shall not be more than 20% of the peak value. Thus, the ratio of the peak value I_{min} of the inverse polarity to the value I_{max} of the first peak must be:

$$\left| \frac{I_{\min}}{I_{\max}} \right| \leq 0.2 \quad (18)$$

Putting the values of I_{min}, I_{max} from Eq.(12), (14) results:

$$Z \leq \frac{\pi}{\ln 0.2} R \quad (19)$$

Substituting Z from Eq.(2) results the minimum magnitude of the resistance:

$$R \geq 1.1 \cdot \sqrt{L/C} \quad (20)$$

This is the lower limit for the magnitude of the resistance of the discharge loop in order to meet the requirement of IEC 60060-1 referring to the amplitude of the oscillation in the impulse current.

4. Computer design of the generator

The computer programme of this paper has been developed for the analysis and design of impulse current generators. The computation algorithm runs either for the calculation of the impulse current if the elements of the generator are given or for the calculation of the elements of the generator if the user defines the constants of the current. Following the first procedure, the initial conditions of the impulse generator are entered and the programme calculates the full waveform of the impulse current. For a pre-defined test current waveform, the programme follows the inverse procedure to calculate the elements of the generator.

In the first procedure, the user defines the impulse capacitance C, the inductance L and the total resistance R of the discharge unit of the generator as well as the D.C. charging voltage U_o. From these, result the impulse current waveform and the respective voltage waveform across the test-object.

The programme calculates all the parameters of the impulse current waveform like the front-time t_f, the time to half-value t_h and the ratio t_f/t_h. If the wave-front is oscillating, it is smoothed using a mathematical routine embedded in the programme. Then, the time parameters of the modified waveform are determined.

If either the front-time or the time to half-value fall outside the ±10% limits of the pre-selected standard waveform, then the user is warned to change the values of R, L and C. The divergences are displayed and modified values of the electrical elements are recommended. The same fine-tuning is performed if the inverse peak of the oscillating current exceeds the specified limits of 20%.

Other parameters, which are also calculated are the maximum and minimum value I_{max}, I_{min} of the current waveform and the time to maximum T, as well as the ratio I_{min}/I_{max} that is an important parameter for the under-damped oscillation.

Following the inverse procedure, the programme calculates the elements R, L and C of the generator using as input the front-time and the time to half-value. The user is also asked to enter the values of the available impulse capacitors. This facilitates the design because the number of available capacitors in the high voltage laboratories is always limited. The capacitors are bulky equipment and more expensive than the widely available spare resistances.

The designer may also control the oscillation in the current by putting a limit to the amplitude of the inverse peak. In this way, he directs the programme to a more desirable configuration and restricts the number of solutions. All the acceptable solutions give impulses with front-time and time to half-value within the permissible limits of ±10%. The optimised configurations are displayed, together with the impulse parameters, giving the ability to the user to select the most suitable and economical solution.

On the other hand, the user may select an impulse other than the standard ones. This procedure requires more input data since there are no limitations. Generally, the designer has the freedom to pre-define any desirable characteristic of the generator or of the impulse. These characteristics could be either the charging energy generator, the charge voltage of the impulse capacitor, the peak amplitude of the impulse current or even any one of the front-time and the time to half-value.

Finally the programme displays the results i.e. the resistance R, the inductance L and the capacitance of the impulse capacitor. It also displays the front-time and the time to half-value, the current peak, the charge voltage of the impulse capacitor, the charging energy of the generator and draws the current waveform, which obtained for each solution.

5. Sensitivity analysis

The utilisation factor I_{max}/U_o of the impulse generator for over-damped oscillating currents is maximised with large capacitance and small inductance (Fig.3a). Very important parameter is also the resistance of the discharge loop; increase of the resistance attenuates the impulse current (Fig.3b). Moreover, variations in the magnitude of the inductance and of the capacitance slightly affect the impulse current when the resistance is higher than 6 Ohm (Fig.3c). However, the current is too small. In this case it is quite unlikely to operate the generator at so low utilisation factor. On the other hand, the cost and the size of the construction in this case increase significantly.

It has been observed that by increasing the resistance, the front-time decreases while the time to half-value increases. The opposite results arise increasing the inductance i.e. the front-time increases and the time to half-value decreases. Finally both of these time parameters increase by increasing the impulse capacitance.

When operating the generator with under-damped oscillations, the utilisation factor is maximised for high values of the impulse capacitance and for low values of the inductance (Fig.4a). The impulse current in this condition is more sensitive to the magnitude of the elements of the generator, especially to the resistance of the discharge loop that is very small. Slight increase of the resistance causes a significant attenuation of the impulse current (Fig.4b).

of the time to half-value similar as in the over-damped oscillation. On the other hand increment of either the inductance or the capacitance of the generator will result not only in the increase of the front-time but in the increase of the time to half-value as well.

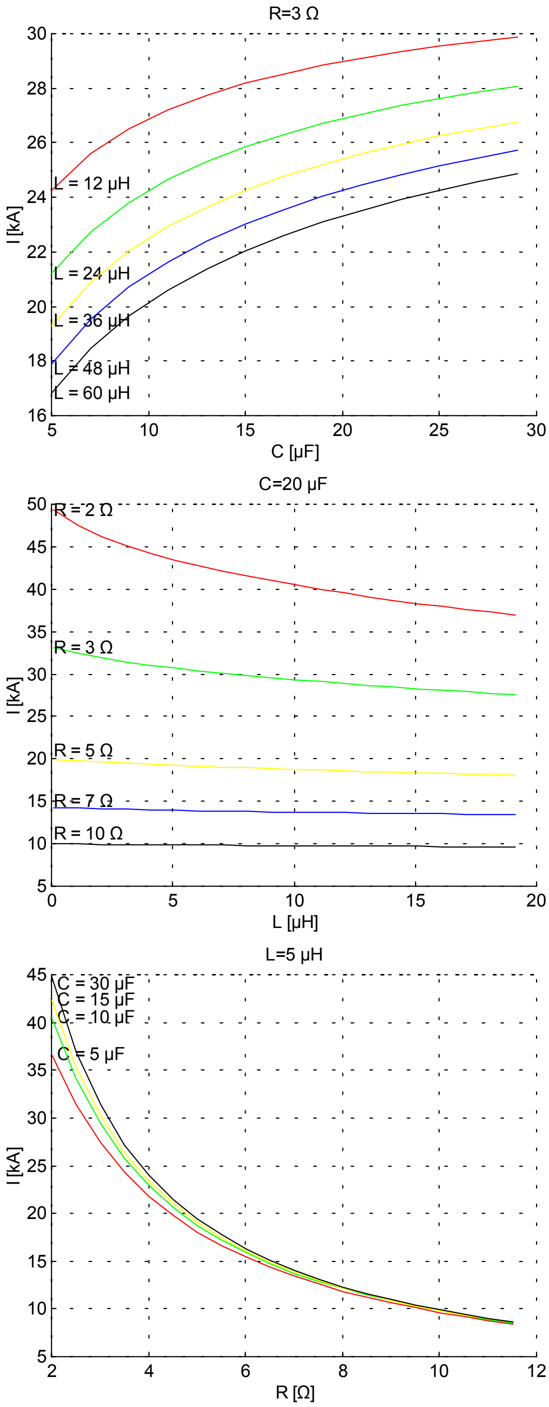

Fig.3 Sensitivity of the peak of impulse current in the over-damped oscillation.

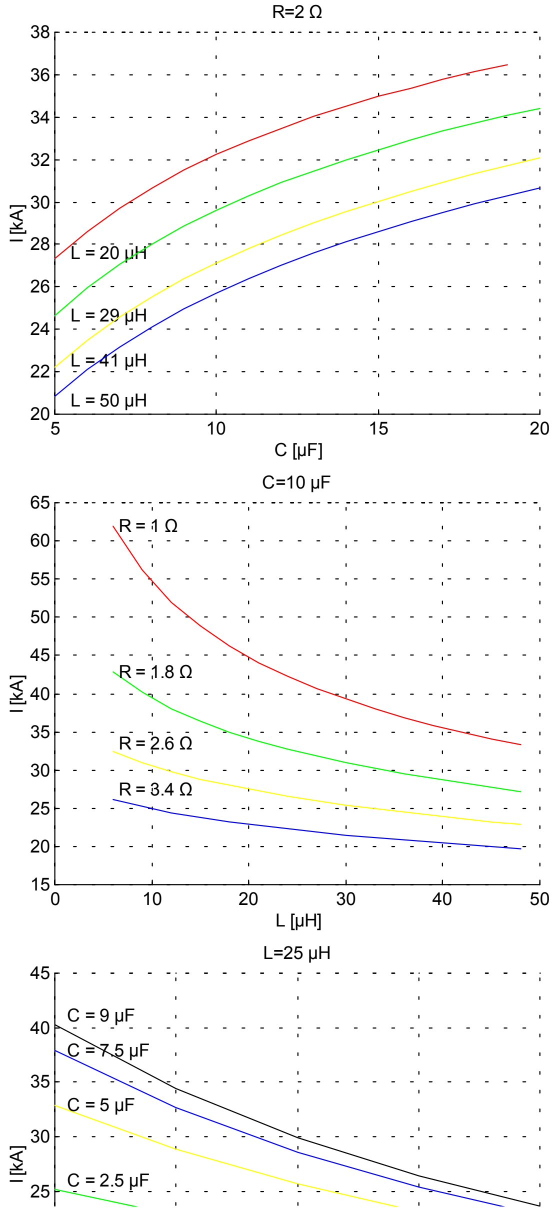

Fig.4 Sensitivity of the peak of impulse current in the under-damped oscillation.

It seems that with a high resistive component, the current is not affected by variations of the magnitude of the inductance and the capacitance (Fig.4c). This is rather unlikely to occur because the utilisation factor of the generator is very low and the size of the elements as well as their cost is increasing significantly.

When the generator is operating in the under-damped oscillation, increment of the total resistance results in the decrease of the front-time and increase

The condition $R^2=4L/C$ for critical damping of the oscillating current restricts the possibility of changing the elements of the generator. Therefore, it is not possible to obtain the desirable values of the front-time and of the time to half-value by varying one and only element (R, L, C) of the generator. When changing one element it is required to change at least one of the others in order to meet the requirements for damped oscillation, otherwise the current tends to the over-damped oscillation ($R^2>4L/C$) or to the under-damped ($R^2<4L/C$). In order to retain the damped oscillation, it is required to change the magnitude of two elements simultaneously. Such a modification tends to alter the time parameters t_f and t_h. Consequently, a modification to the generator elements is restricted by the upper and lower limit of the time parameters of the required current waveform.

The determination of the optimum combination between L, C and R, under the condition for critical damping, results to a higher value of the current and, therefore, to a better utilisation factor. The computer programme optimises the circuit configuration even after restrictions have been applied to some elements.

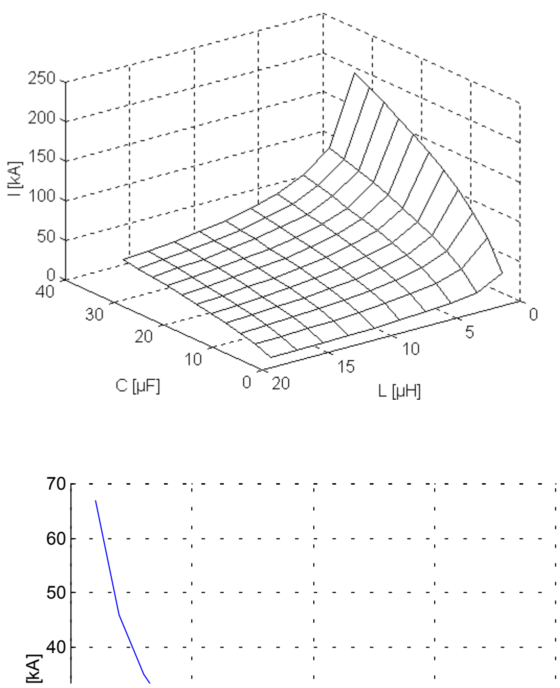

Fig.5 Sensitivity of the peak of impulse current in the damped oscillation.

6. Conclusions

The paper presented an analytical method in conjunction with a computer programme for the design of an impulse current generator. With the proposed method the parameters of the impulse current and the elements of the generator are calculated and several considerable conclusions concerning the configuration of the system are extracted. With the computer programme, which is very flexible and user friendly, the designer determines the circuit elements, entering the desired waveform. Inversely, given all or some of the circuit elements, the impulse current waveform, as well as the time parameters are evaluated. The limits defined by the international standards and the permissible tolerances are taken in account through the calculations something, which makes the method very accurate. Conclusions are also extracted testing the developed method and using several element values. The method can greatly assist to the construction and use of impulse current generators in research, work and testing.

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