

Chapter-7

Generation of High Test Voltages

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Objectives

- Design features of high voltage ac test equipment
- Tuned resonant test set
- Generation of high dc voltages
- High impulse test voltage generation

Generation of Power Frequency High AC Voltages

- High Voltage *power frequency* test transformers are required to produce single phase very high voltages
- Their continuous current ratings are *very low*, usually $\approx 1\text{A}$.
- Even 1A is a very high current rating. This is because a HV test transformer has to supply *only the capacitive charging current* to the capacitance formed by the dielectric of the test object.
- However, since the voltage rating requirements are high, the test transformers are required to be produced with very high insulation level. This *increases the size of the test sets* tremendously.
- Hence, single units of test transformers are produced maximum upto 700 kV.

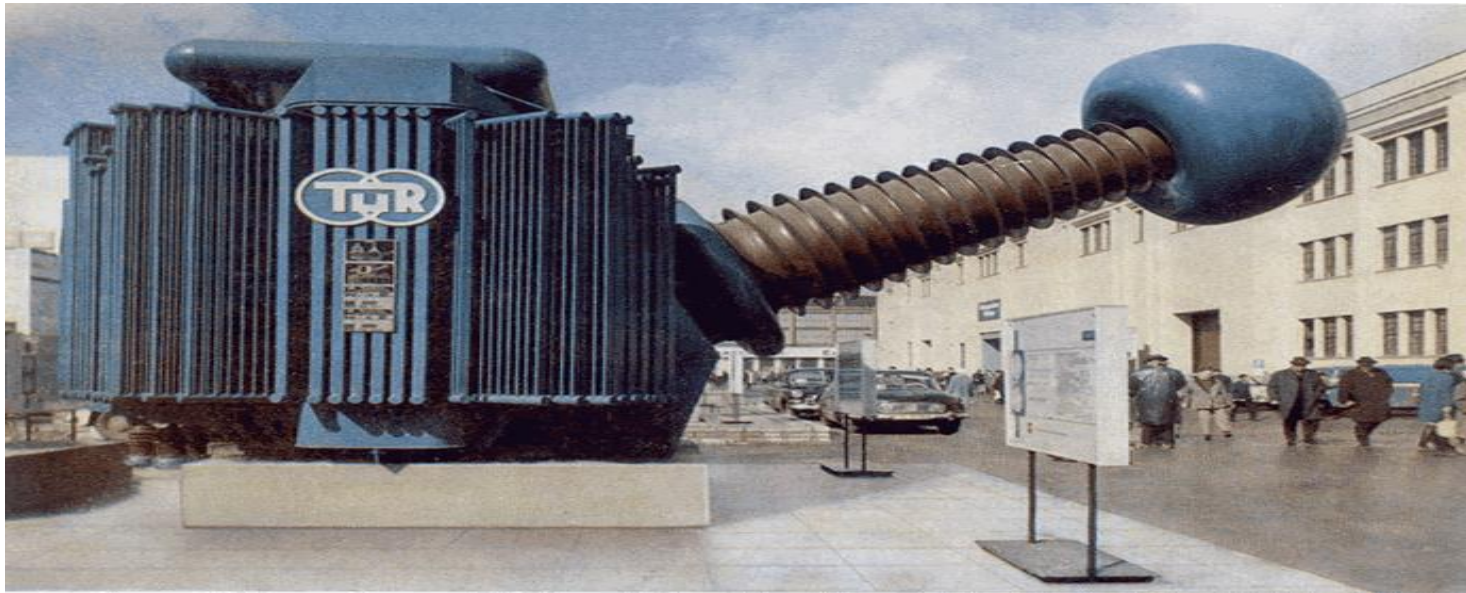


Fig. 1 A 600 kV, 3.33 A, Oil filled Testing Transformer for continuous operation [Courtesy TüR Dresden, Germany]

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Fig. 2 An SF₆ gas filled 1000 kV, 0.6 A, single unit ac power frequency test transformer, courtesy Himalayal Test Systems, China.

Cascaded Power Frequency Transformer Set

- For the production of higher voltages, a number of *identical units are put in cascade* to add up their voltages as shown in Fig. 3.

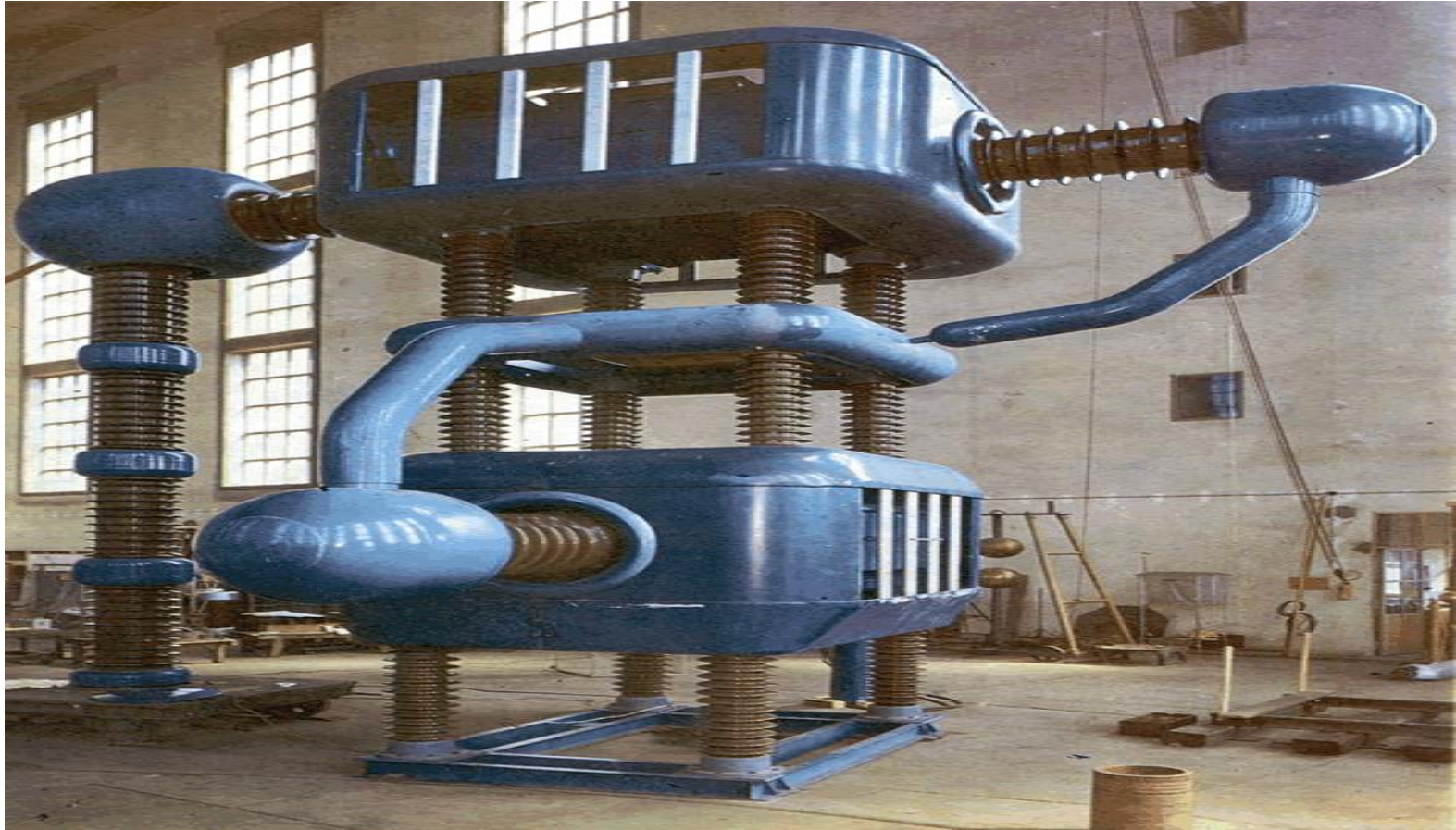


Fig. 3 A two-stage ac Testing Cascade, 1.2 MV (2 x 600 kV), 1.25 A, short-time operation of four hours at an ambient temperature of 35° C. Transformer tanks are made of sheet aluminum, courtesy TüR Dresden, Germany

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- Cascading a number of single identical units makes *transportation, production and erection simpler*.
- The cascading principle is illustrated with the basic scheme shown in Fig. below in which it can be seen that *output of a stage transformer becomes input for the next stage*.

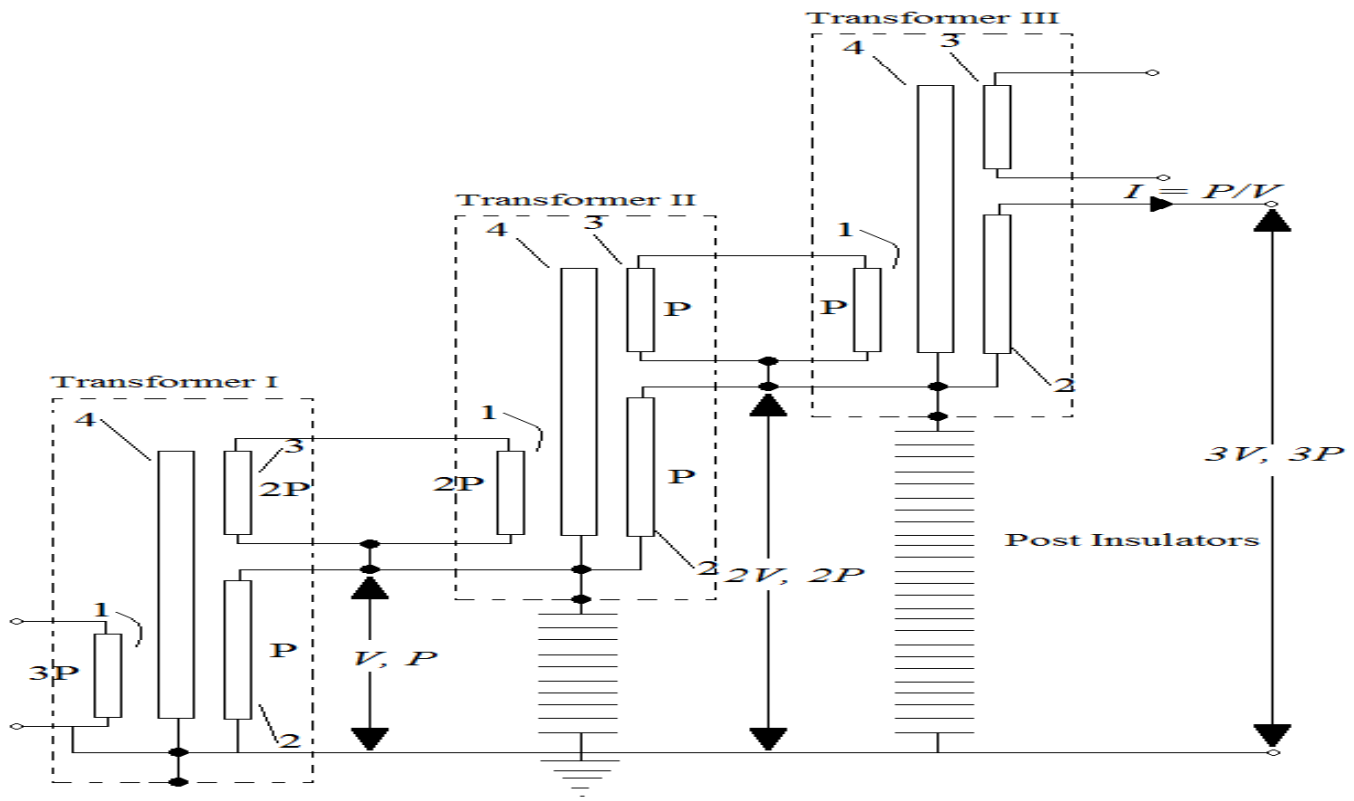


Fig. 4 Schematic of three transformers in cascade,(1) Primary windings,(2) Secondary, HV, windings, (3) Tertiary/ excitation windings (4) Core

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- The HV supply is connected to the primary winding "1" of transformer I, designed for a HV output of V . The other two transformers too are connected in the same fashion.
- The excitation winding "3" of Transformer I supplies the primary voltage for the second transformer unit II; both windings are dimensioned for the same low voltage, and the potential gain is fixed to the same value V .
- The HV or secondary windings "2" of both units are connected in series, so that a voltage of $2V$ is produced at the output of 2nd unit. The unit III is added in the same way.
- The tanks or vessels containing the active parts (core and windings) are indicated by dashed lines.
- For a metal tank construction and the HV windings shown in this basic scheme, the core and the tank of each unit would acquire the HV level of the previous unit as indicated. Only the tank of transformer I is earthed.
- The tanks of transformers II and III are at high potentials, namely V and $2V$ above earth, and must therefore be suitably insulated, hence raised above the ground on solid post insulators.
- Through HV bushings the leads from the excitation windings "3", as well as the tapings of the HV windings "2", are brought to the next transformer.
- ✓ For voltages higher than about 600 kV, the cascade of such transformers is a big advantage. The *weight and the size of the testing set is sub-divided into single units of smaller size and lower weight*. The *transportation and erection* of the test set in cascade *becomes simpler*. However, there is a *disadvantage* that the *primary windings of the lower stages are more heavily loaded with higher current in such sets*.

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- There are several methods of designing the cascade test sets. In Fig. 5 schematic diagram of another power frequency test set cascade of $3 \times 750 = 2250$ kV rating is shown.
- This circuit has a third winding, known as "Balancing Winding".
- These windings are designed to acquire the intermediate potentials between two stages.
- In this circuit, the transformers of the upper stages have their excitation windings arranged over the HV windings of the transformers of the lower potential.

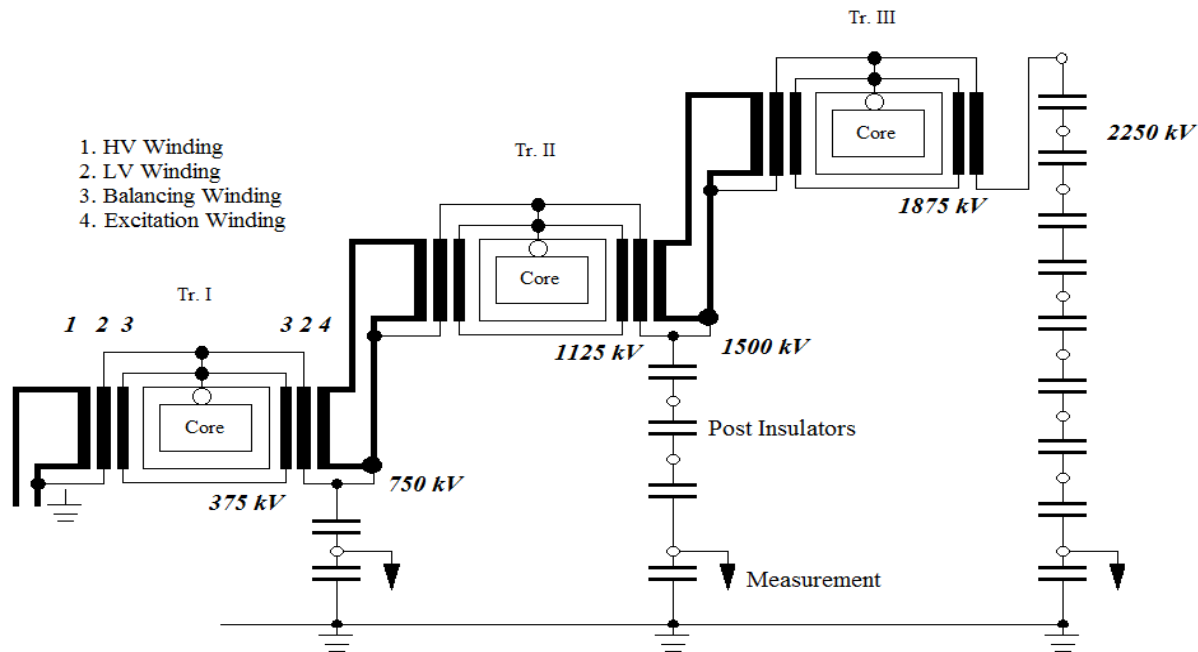


Fig. 5 Schematic of an ac 2250 kV test set circuit in cascade

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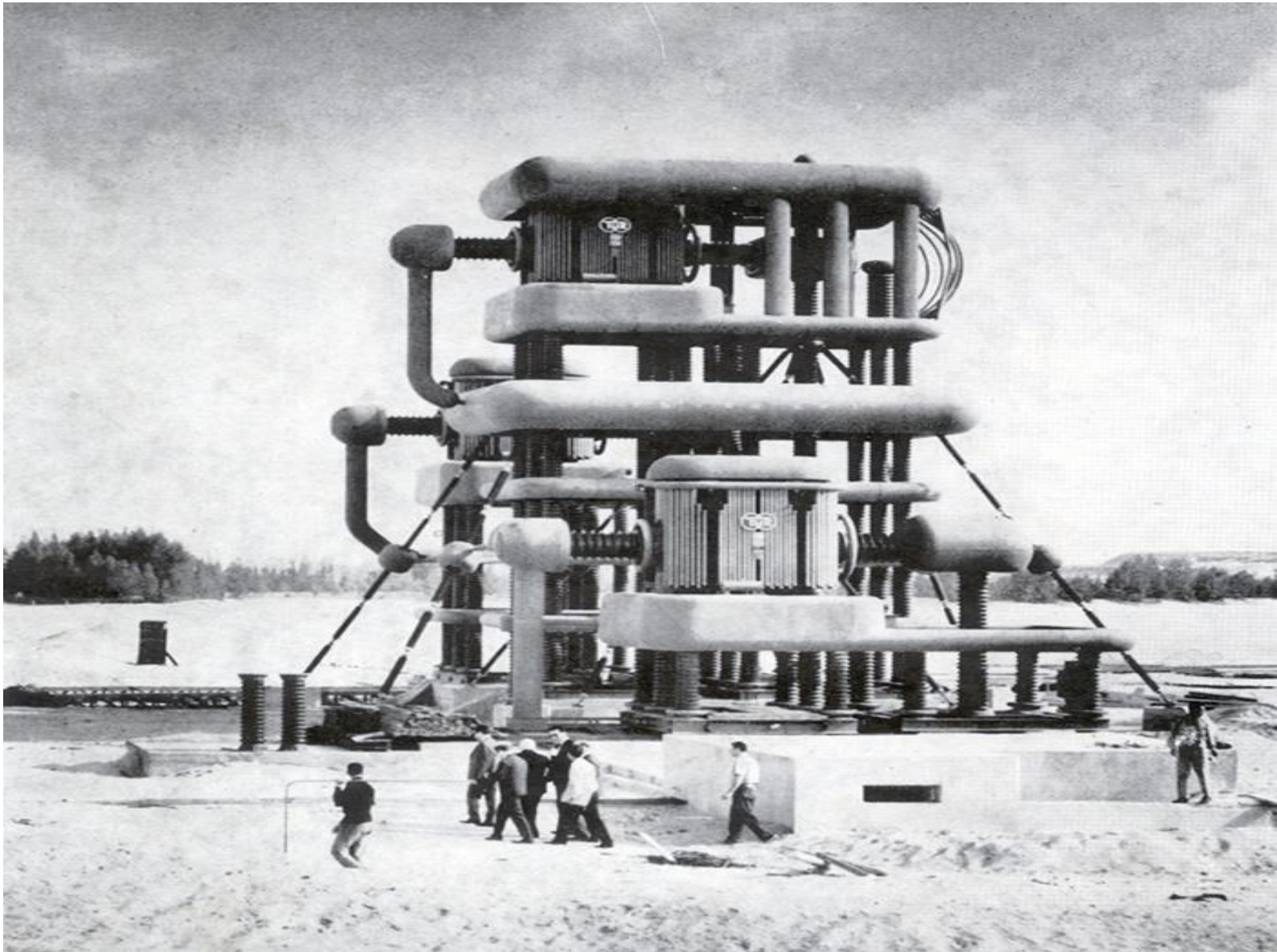
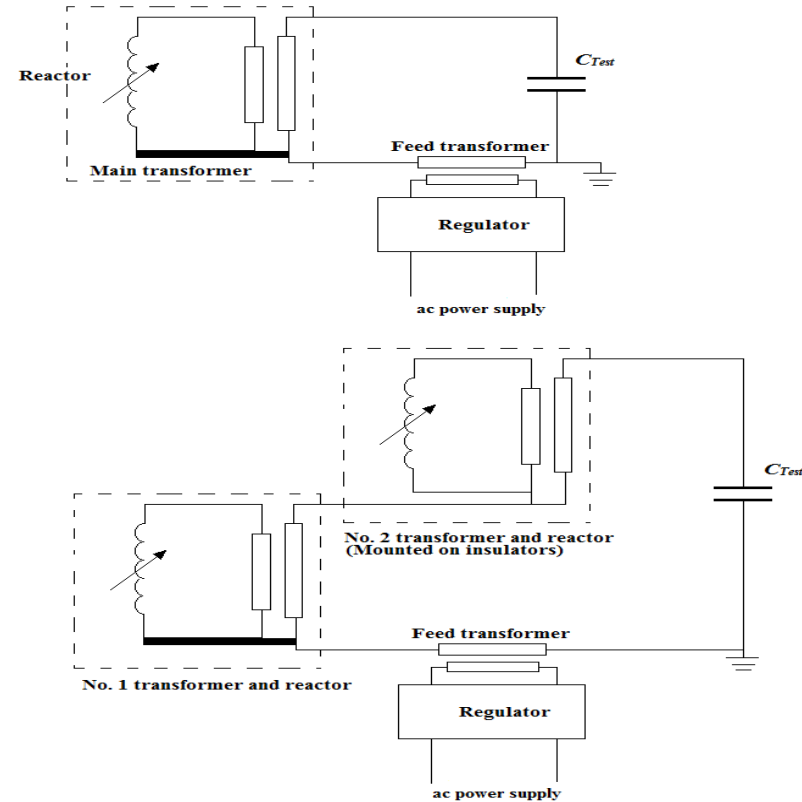


Fig. 6 Photograph of an ac test set of 2250 kV, 3 x 750 kV in cascade, 2250 kVA installed outdoors in open air, courtesy TüR Dresden, Germany

Tuned Resonant High-Voltage AC Test Equipment

- Testing of HV equipment having high capacitance, for example, long length of HV power cables, power capacitors, GIS etc. *may draw excessive capacitive charging current.*
- Necessity for "*Tuned series resonant HV power frequency test equipment*" arose in particular by the *cable manufacturing* industry when they required to test *long lengths of HV cables* drawing large capacitive current on the HV side.
- The capacitance C_t represents the capacitance of the test object. A variable reactor is connected on the LV (primary) winding of the test transformer. If the inductance of this reactor is tuned to match the impedance of the capacitive load, the capacitive power can be completely compensated.



**Fig. 7 Series resonant circuit for transformer/reactor (a)
Single transformer/reactor
(b) Two or more units in series**

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- The equivalent circuit diagram for this is a low damped series resonant circuit. The high output voltage can be controlled by a variable ac supply, i.e. a voltage regulator transformer (Feed Transformer) if the circuit was tuned before.
- The Feed Transformer is rated for the nominal current of the inductor and its voltage rating could be very low.
- It may be seen that it is possible to have series resonance at power frequency. With this condition, the current in the test object is very large and is limited only by the resistance of the circuit. The waveform of the voltage across the test object will be purely sinusoidal.
- The magnitude of the voltage across the capacitance C of the test object will be

$$V_c = \left| \frac{-jVX_c}{R + j(X_L - X_c)} \right| = \frac{V}{R} X_c = \frac{V}{\omega CR}$$

where R is the total series resistances of the circuit.

- The factor X_c/R is the Q factor of the circuit and gives the magnitude of the voltage multiplication across the test object under resonance conditions.
- Therefore, the input voltage required for excitation is reduced by a factor $1/Q$, and the output kVA required is also reduced by a factor $1/Q$. the secondary power factor of the circuit is unity.

Cont...

- For high capacitance and ohmic loads (loads with high real power losses), the parallel resonant circuit shown in Fig is more suitable.
- Both these series and parallel circuits can be made at the same system by changing the connections of the variable reactor 'L'. Right hand side Fig shows a HV variable reactor which is tuned automatically to the desired value of the capacitive load.

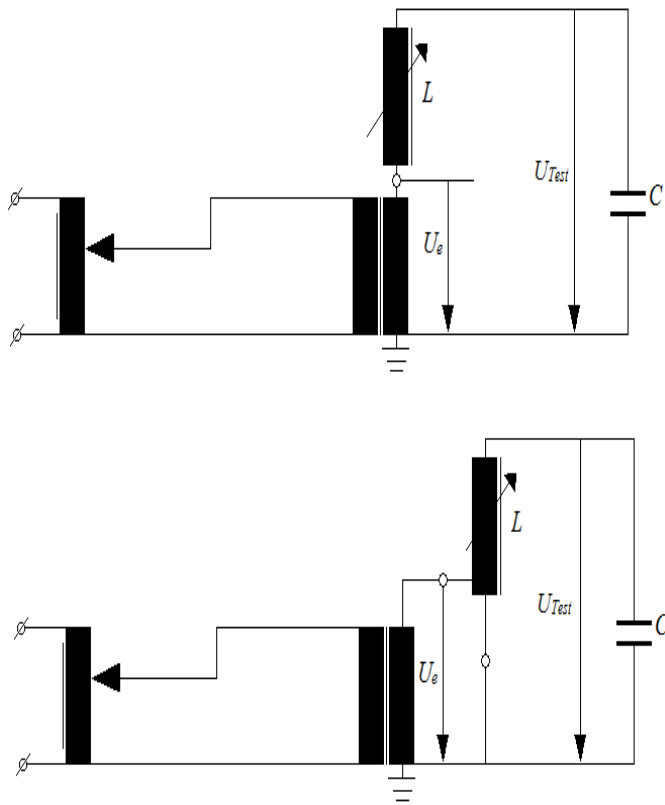


Fig. 8 Tuned variable reactor circuits, series and parallel connected inductor



(a)

(b)

Fig. 9 (a) An automatic tuned variable reactor and AC resonant test system of 400 kV , (b) A cable drum length under test showing variable reactor at the back, courtesy Power HV, China

Resonance Transformer: Advantages

- Dimensions and weight of such test sets are much smaller.
- 100% compensation of capacitive reactive power is possible. Under this condition, the *only power drawn* from the mains is the *active power required*.
- The magnitudes of the short circuit currents, in case of insulation failure, are minimized.
- The voltage wave shape is improved by attenuation of harmonic components already in the power supply. A practical figure for the *amplification of the fundamental voltage* amplitude at resonance is between *20 and 50 times*. Higher harmonic voltages are divided in the series circuit to a decreasing proportion across the capacitive load. Good wave shape helps accurate HV measurement and it is very desirable for Schering Bridge measurements.
- The power required from the supply is lower than the kVA in the main test circuit. It represents only about 5% of the main kVA with a unity power factor.
- The *disadvantages* are the requirements of additional variable chokes capable of withstanding the full test voltage and the full current rating.

Generation of High DC Voltage, Voltage Multiplier Circuits

- In HV technology direct voltages are mainly used for *pure scientific research work* and for testing equipment used in *HVDC transmission systems*. HVDC test sets are also suitable as mobile test units for testing the equipment at site after installation since these are very light weight.
- High dc voltages are even more *extensively used in physics* (accelerators, electron microscopy, etc.), electromedical equipment (x-rays), industrial applications (precipitation and filtering of exhaust gases in thermal power stations and cement industry; electrostatic painting and powder coating, etc.), or communications electronics (TV; broadcasting stations). Very high static voltages, produced by electrostatic generators, are used in nuclear physics.
- Therefore, the *requirements of voltage shape, voltage level, current rating, short - or long-term stability for every HVDC generating system may differ strongly* from each other. With the knowledge of fundamental generating principles, it is possible, however, to select proper circuits for any special application.
- The high dc voltages are generally obtained by means of rectifying circuits applied to ac voltage. Voltage doubler circuits in desired number are then used in cascade for the multiplication of the dc voltage. These are described in the following:

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- *Voltage doubler* circuits in desired number are then *used in cascade* for the multiplication of the dc voltage. These are described in the following:

➤ Half Wave rectifier circuit

(where: D - Diode, C - smoothing capacitor, R_L - the resistive load)

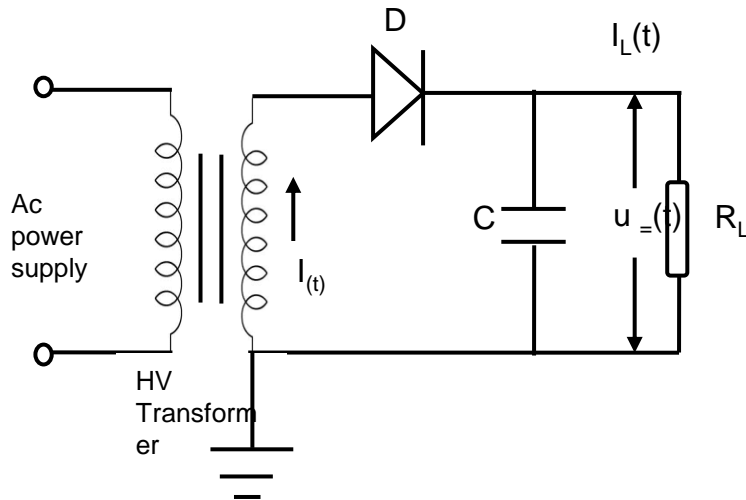


Fig. 10 Half-wave rectifier circuit

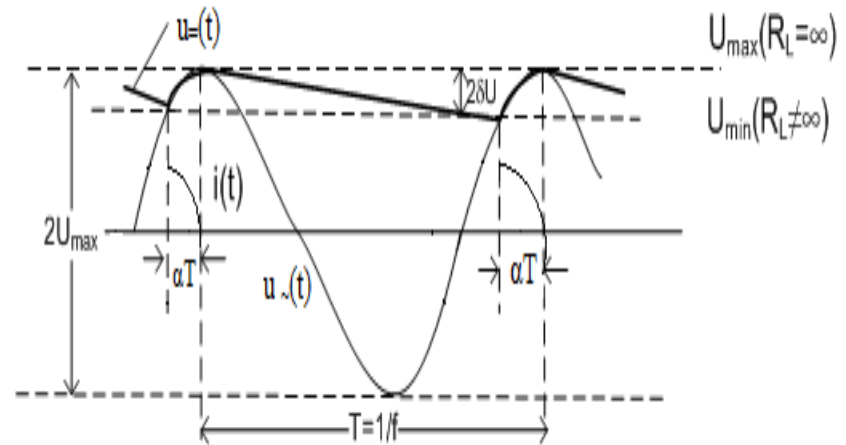


Fig. 11 Voltage output of half-wave rectifier circuit

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If \bar{U} is the arithmetic mean value of the dc output voltage

$$\bar{U} = \frac{1}{T} \int_0^T u_{dc}(t) dt$$

where T represents the periodic time required for the ac power supply cycle, given by:

$$T = \frac{1}{f}$$

Let the amplitude of the ripple be δU , then,

$$\delta U = 0.5(U_{max} - U_{min})$$

and the ripple factor is given by $\delta U / \bar{U}$

the charge Q transferred to the load R_L is given by:

$$Q = \int_{\alpha T} i(t) dt = \int_T i_L(t) dt = \frac{1}{R_L} \int_T u_{dc}(t) dt$$

$$Q = IT = I/f$$

$$i_L(t) \cong I, \quad \text{and } Q = 2\delta UC$$

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

When $R_L \rightarrow 0$, it means failure of the insulation

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➤ Voltage Doubler Circuit in Cascade

- Both full wave and half wave rectifier circuits produce a d.c. voltage less than the a.c. maximum voltage. When higher d.c. voltages are needed, a voltage doubler or cascaded rectifier doubler circuits are used.

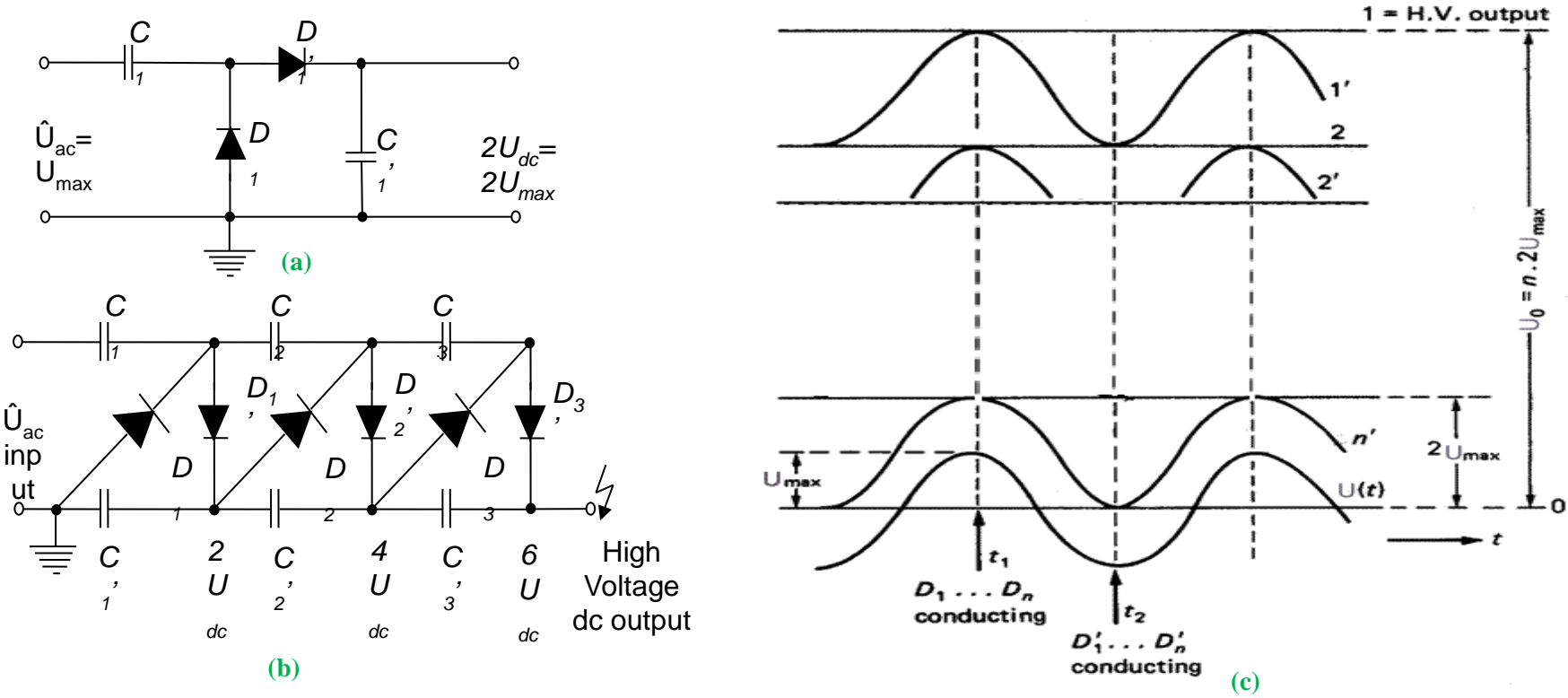


Fig. 12 (a) A simple voltage doubler circuit (b) Cascade circuit according to Cockcroft & Walton or Greinacher (c) Waveform and potentials at the nodes of the first cascade circuit at no load

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Fig. 13 A 2000 kV HVDC test set, courtesy TüR Dresden, Germany

Impulse Voltage Generator

- The impulse voltage generators were designed to produce the standard lightning impulse, li, waveshape up till a few decades ago.
- Impulse voltage generator to produce standard waveforms of ‘switching surge’ became a necessity.

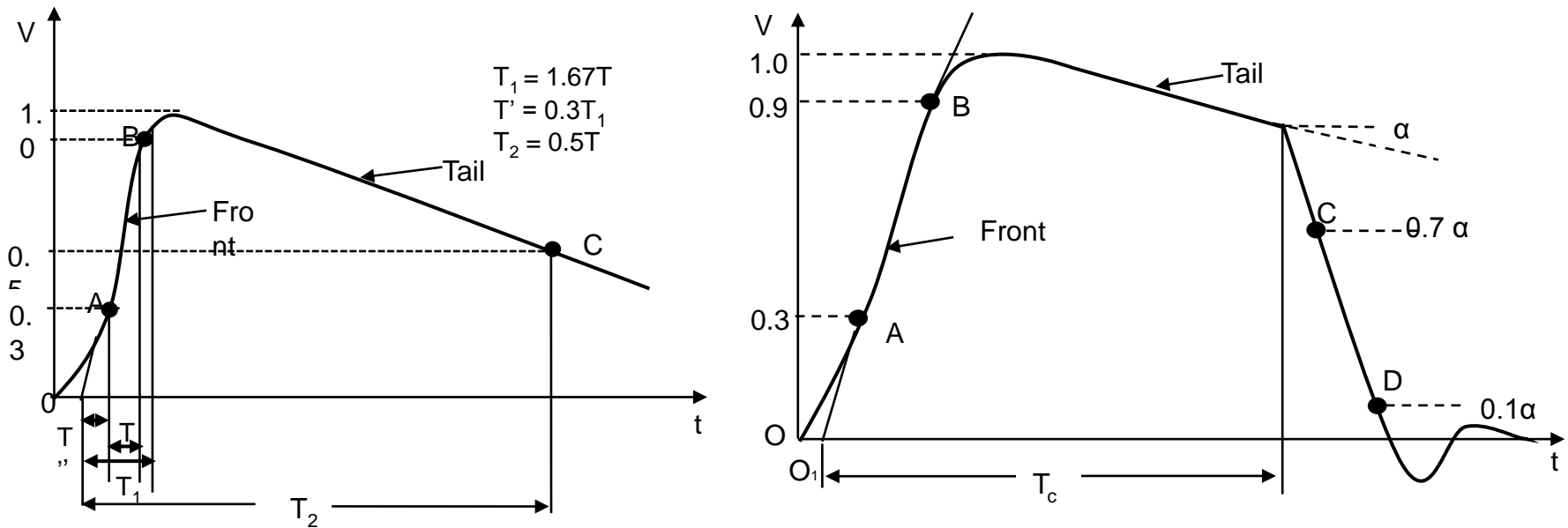


Fig. 14 General shape and definitions of lightning impulse voltage. (a) Full wave (b) Wave chopped at its tail, IEC 60060-1, *High Voltage Test Techniques—Part 1: General Definitions and Test Requirements*

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Figure illustrates the wave shape of one of the standard switching impulse. Impulse wave shapes of 100/2500, **250/2500** and 500/2500 μs are recommended. Permissible tolerance in the case of si for T_{cr} is $\pm 20\%$ and for T_2 it is $\pm 60\%$.

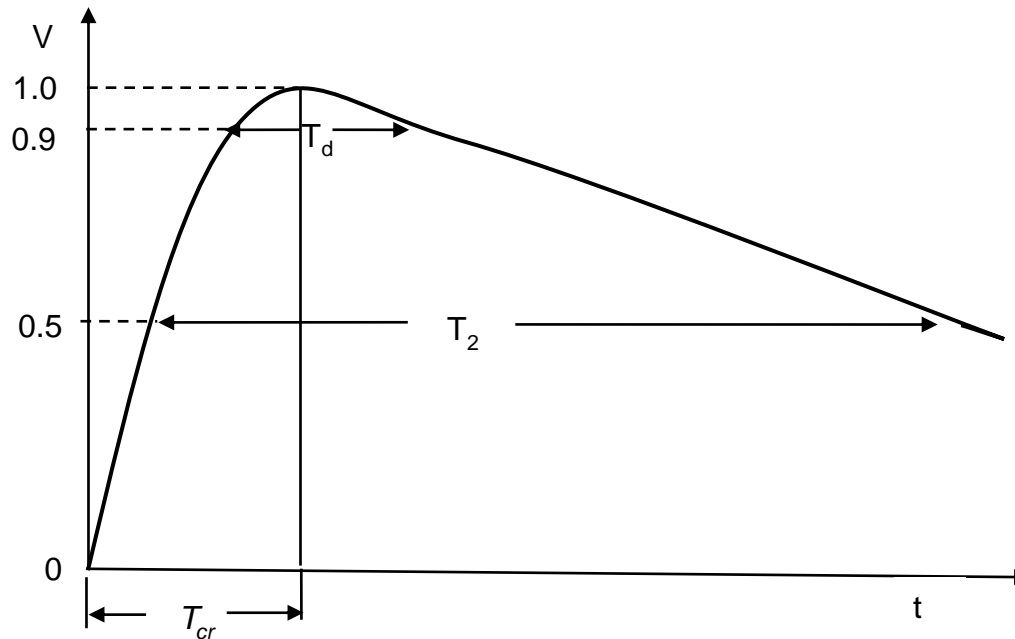
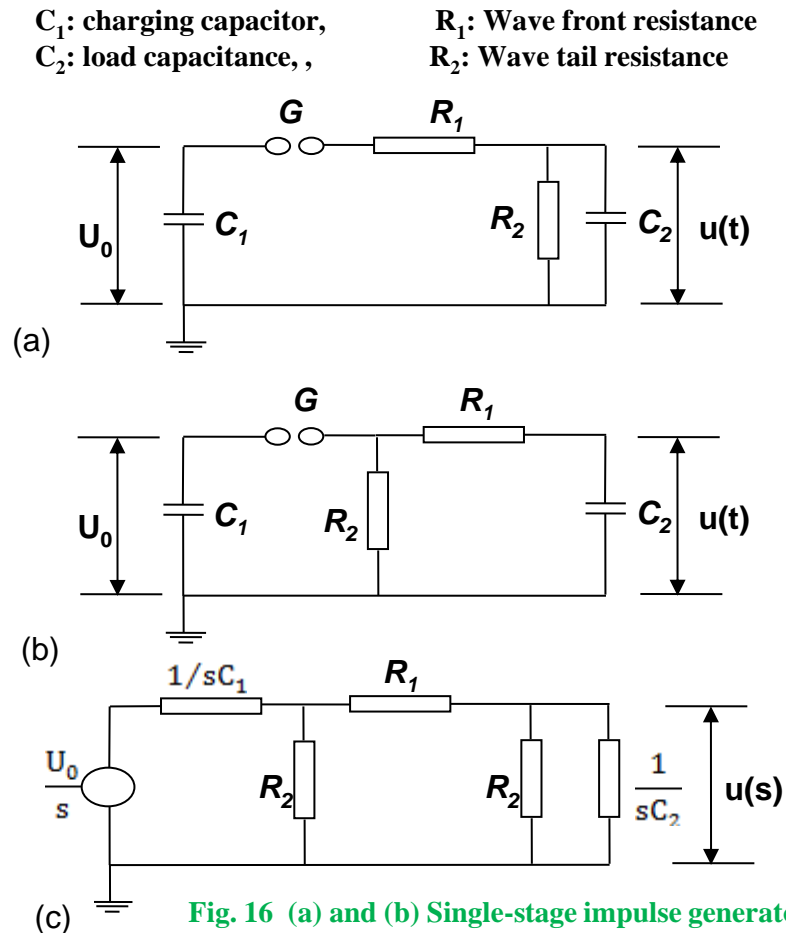


Fig. 15 General shape of switching impulse voltages. T_{cr} : Time to crest. T_2 : Virtual time to half value. T_d : Time above 90%, IEC 60060-1, *High Voltage Test Techniques—Part 1: General Definitions and Test Requirements*

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➤ Single-Stage Impulse Voltage Generator Circuit Analysis

- The capacitor C_1 is charged slowly from a dc source until the spark gap G breakdown and discharges upon C_2 , the load capacitor over the resistors R_1 and R_2 .
- This spark gap acts as a voltage-limiting and voltage sensitive switch.



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The energy rating of the impulse generator, $W = \frac{1}{2} C_1 (U_{0max})^2$ (1)

The output voltage is given by $u(s) = \frac{U_0}{s} \frac{Z_2}{Z_1 + Z_2}$ (2)

where

$$Z_1 = \frac{1}{C_1 s} + R_1 \quad \text{and} \quad Z_2 = \frac{R_2 / C_2 s}{R_2 + 1 / C_2 s} \quad \dots(3)$$

By substitution we find,

$$u(s) = \frac{U_0}{k} \frac{1}{s^2 + as + b} \quad \dots(4)$$

Where

$$a = \left(\frac{1}{R_1 C_1} + \frac{1}{R_1 C_2} + \frac{1}{R_2 C_1} \right) \quad b = \left(\frac{1}{R_1 R_2 C_1 C_2} \right) \quad \text{and} \quad k = R_1 C_2 \quad \dots(5)$$

From the transform tables the following expression in the time domain can be obtained:

$$u(t) = \frac{U_0}{k} \frac{1}{(\alpha_2 - \alpha_1)} [\exp(-\alpha_1 t) - \exp(-\alpha_2 t)] \quad \dots(6)$$

where α_1 and α_2 are the roots of the equation $s^2 + as + b = 0$, given by,

$$\alpha_1, \alpha_2 = \frac{a}{2} \mp \sqrt{\left(\frac{a}{2}\right)^2 - b} \quad \dots(7)$$

$$\eta = \frac{U_p}{U_0} \quad \dots(8)$$

$$C_2 \ll C_1 \quad \eta = \frac{C_1}{(C_1 + C_2)} = \frac{1}{1 + (C_2 / C_1)}$$

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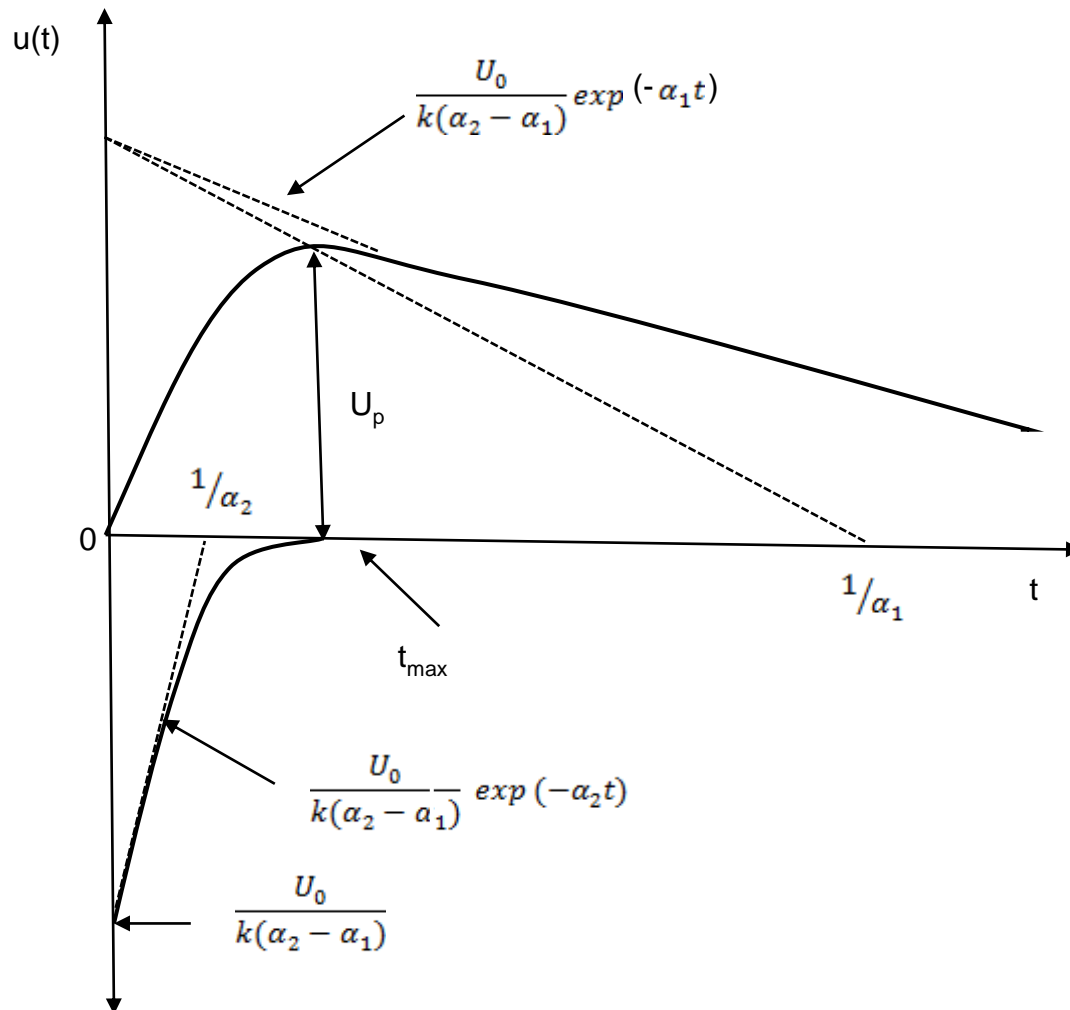


Fig. 17 The impulse voltage wave shape and its components according to the derived circuit equation (6)

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➤ Dimensioning of Single-Stage Impulse Generator Circuit

- An impulse voltage generator circuit consists of capacitors and resistors.
- With an appropriate choice of the combination of the wave front and the wave tail resistors, R_1 and R_2 respectively, desired shape of the output voltage, both lightning and switching impulse voltages, can be produced.

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

$$R_2 = \frac{1}{2(C_1 + C_2)} \left[\left(\frac{1}{\alpha_1} + \frac{1}{\alpha_2} \right) + \sqrt{\left(\frac{1}{\alpha_1} + \frac{1}{\alpha_2} \right)^2 - \frac{4(C_1 + C_2)}{\alpha_1 \alpha_2 C_1}} \right] \Omega \quad \dots(2)$$

- Both the equations Eq. (1) and Eq. (2) contain the time constants $1/\alpha_1$ and $1/\alpha_2$, which depend upon the desired waveshape.

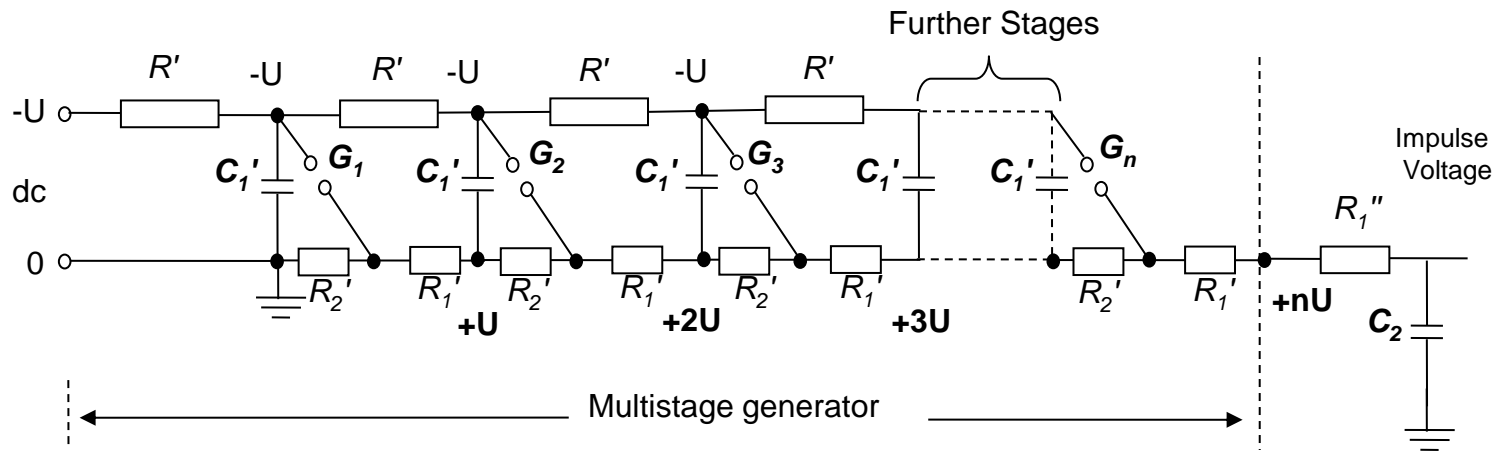
Table I Time constants for some selected impulse voltage wave shapes

T_1/T_2 (μs)	T_{cr}/T_2 (μs)	$1/\alpha_1$ (μs)	$1/\alpha_2$ (μs)
1.2 / 50	-	68.2	0.405
250/2500	-	2877	104
-	250/2500	3155	62.5

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- **Multistage Impulse Generator and Their Triggering Methods**
- The schematic diagram of Marx circuit and its modification are shown in Figs respectively.
- Usually the charging resistance R_s is chosen to limit the charging current to about 50 to 100 mA, and the generator capacitance C is chosen such that the product CR_s is about *10 s to 1 min*.
- The gap spacing is chosen such that the breakdown voltage of the gap G is greater than the charging voltage V . Thus, all the capacitances are charged to the voltage V in about 1 minute.
- When the impulse generator is to be discharged, the gaps G are made to spark over simultaneously by some external means. Thus, all the capacitors C get connected in series and discharge into the load capacitance or the test.
- *The discharge time constant CR/n (for n stages) will be very very small (microseconds), compared to the charging time constant CR_s which will be few seconds.*
- Hence, no discharge takes place through the charging resistors R_s . In the Marx circuit is of Fig. a the impulse wave-shaping circuit is connected externally to the capacitor unit.

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R_2' : stage wave tail resistors, R_1' : stage wave front resistors
 R_1'' : external wave front resistor, R' : charging resistors

Fig. 18 Multistage impulse generator with wave tail and front resistors in each stage

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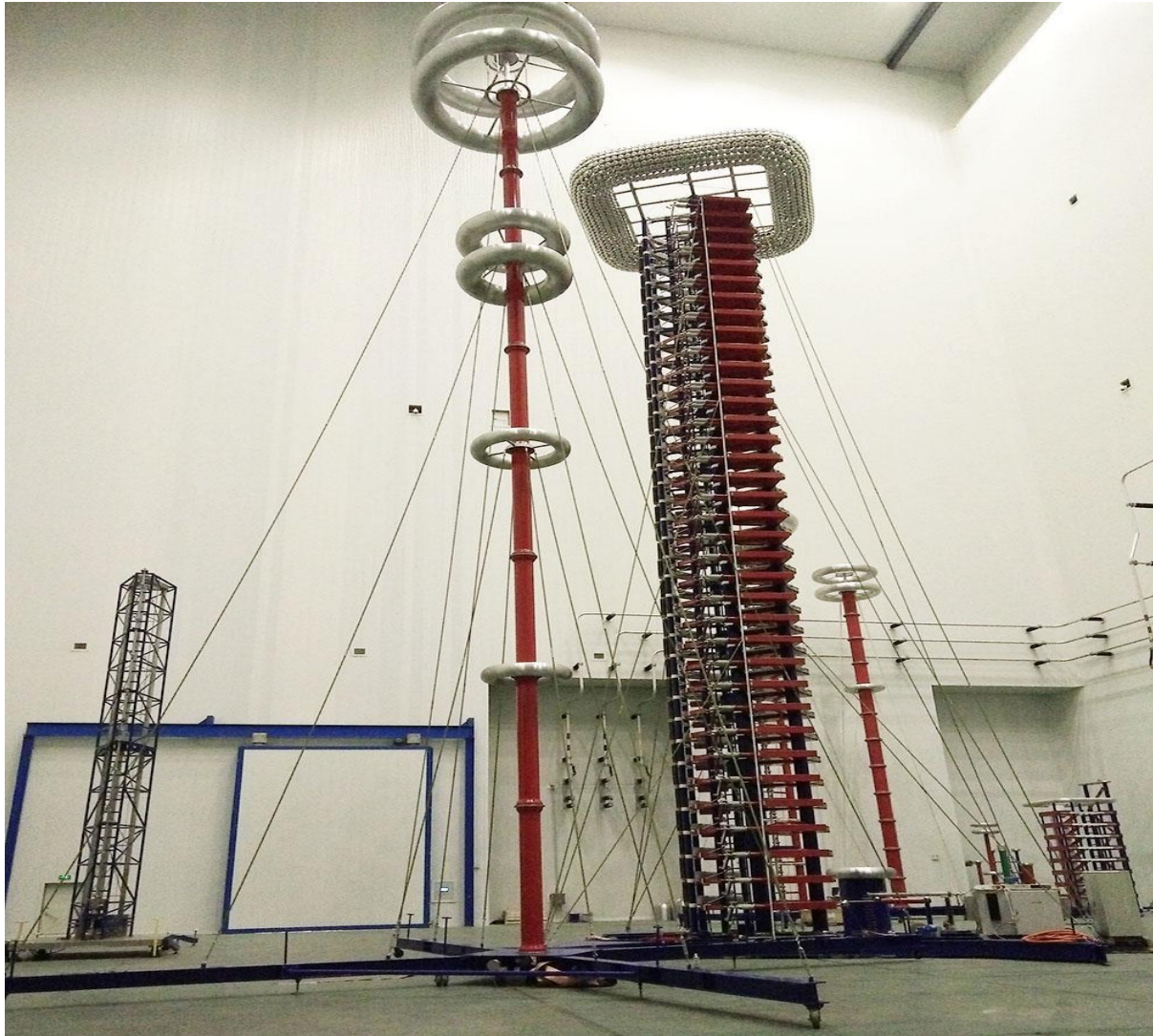


Fig. 19 A 7200 kV, 720 kJ, 36 stage impulse voltage generator, courtesy Fivestar HV Testing Equipment, China

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- **Triggering of Impulse Generator**

Three ways of triggering an impulse generator

- Fix the gap distances between the stage spheres in increasing order and increase the applied dc stage voltage till the flashover occurs.
- Set the gap distance between the spheres large enough, apply a desired charging dc voltage across them, and then reduce the gap distance till flashover takes place.
- Provide a trigatron at the first stage. Fix both, the desired stage voltage (charging voltage) and also corresponding stage sphere gaps in increasing order gap distances, within prescribed limits. Then apply the trigger pulse on the 'trigatron' to initiate the flashover which continues in sequence in all stages of the generator.

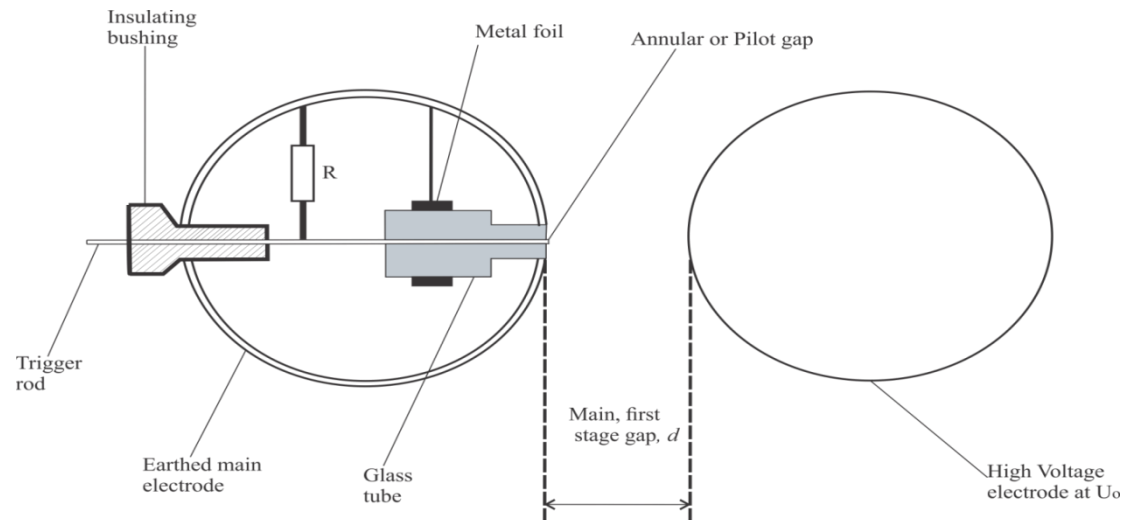


Fig. 20 The Trigatron spark gap

High Impulse Current Generator

➤ Sources of overcurrents and generation of overvoltages

- The high power frequency short circuit current in the power system network keeps flowing and clears only when the circuit is opened with the help of the operation of a circuit breaker.
- The flow of high current results in storage of high energy in the inductance of the network.
- This energy is released in developing excessive overvoltage across the circuit breaker contacts on opening, which travels towards the still energised healthy part of the network in the form of a 'traveling wave'.
- It is defined as 'switching overvoltage transient'
- The overvoltage, transient in nature, depends upon the instant at which the short circuit current is interrupted.

➤ Damaging effects of high currents

- The damage caused by direct injection of high impulse form of current accompanied with lightning strikes are multi-faced.
- The damage caused by the continuous power frequency short circuit currents are well known.

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➤ Design and construction of impulse current generator

- The main capacitor C in this circuit is charged with high voltage dc power supply over a charging resistor R' to a voltage magnitude U_0
- This capacitor is discharged on the test object, $R_2 L_2$, over damping resistance and inductance, $R_1 L_1$, with the help of a 'spark gap' .
- For producing higher magnitudes of impulse currents, a bank of discharge capacitors connected in parallel.

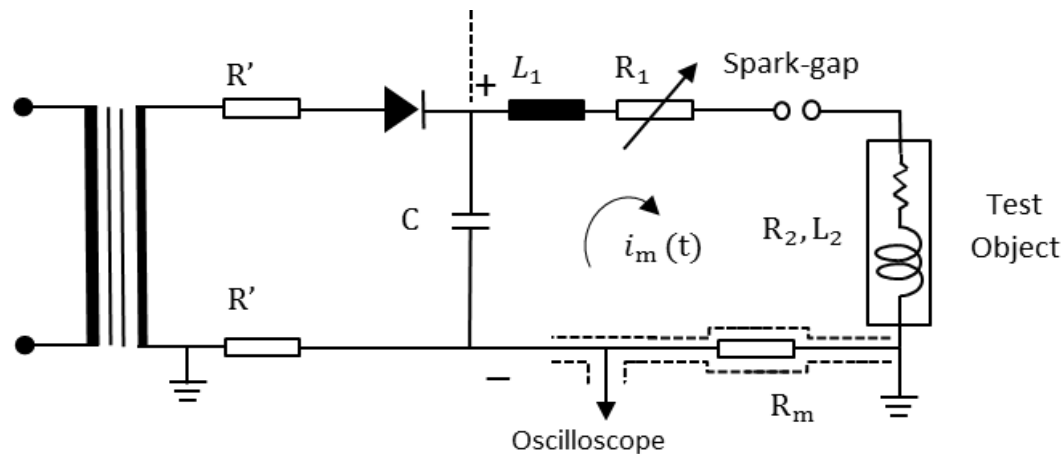


Fig. 21 Basic circuit of Impulse Current Generator with single discharge capacitor

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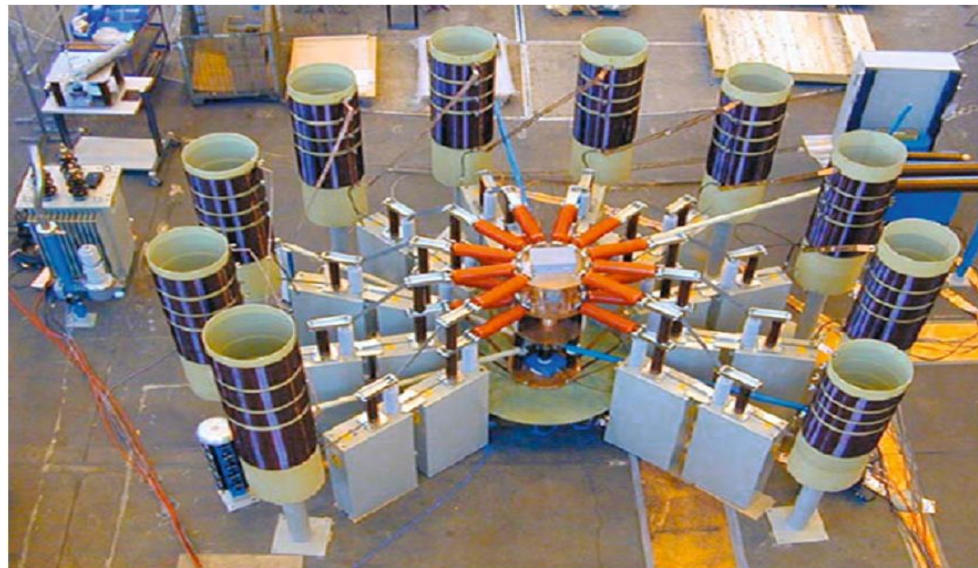
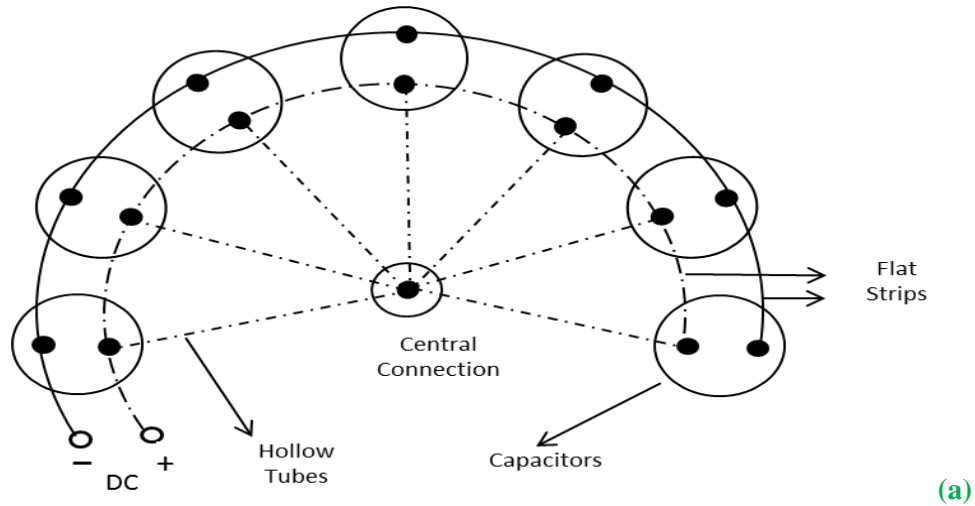


Fig. 22 (a) An Impulse Current Generator circuit with multi-discharge capacitors, (b) A 200 kA impulse current generator (100 kV, 250 kJ) in modular construction with 10 discharge capacitors, courtesy HIGHVOLT Prüftechnik GmbH, Dresden, Germany.

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■ Analysis of the circuit-producing impulse current

- The potential equation for the discharge circuit can be written as

$$U_0 = R i_m(t) + L \frac{di_m}{dt} + \frac{1}{C} \int i_m(t) dt$$

- The effective impedance Z of the discharge loop can be given as;

$$Z = \sqrt{R^2 - (2\sqrt{L/C})^2}$$

When $R^2 < 4L/C$

- The time varying current in the discharge circuit is given by the relation;

$$i_m(t) = 2 \frac{U_0}{Z} e^{-\frac{R}{2L}t} \sin(\omega t)$$

- Where ω is the angular frequency of the oscillating current given by;

$$\omega = \frac{Z}{2L} = \sqrt{\left[\frac{1}{LC} - \frac{R^2}{4L^2} \right]}$$

$$t_1 = t_f = \frac{1}{\omega} \sin^{-1} \frac{\omega}{\sqrt{LC}} \quad \text{or} = \frac{2}{\omega} \arctan \frac{\{\sqrt{[R^2 + (2\omega L)^2]} - R\}}{2\omega L}$$

- The peak value of the output impulse current can be calculated by putting $t = t_1$

$$I_{max} = 2 \frac{U_0}{Z} e^{-\frac{R}{2L}t_1} \sin(\omega t_1)$$

- The time taken for the impulse current to decay to its 50 % value from the peak, ' t_2 ' or t_h is estimated by the expression;

$$t_2 = t_h = \pi/\omega$$

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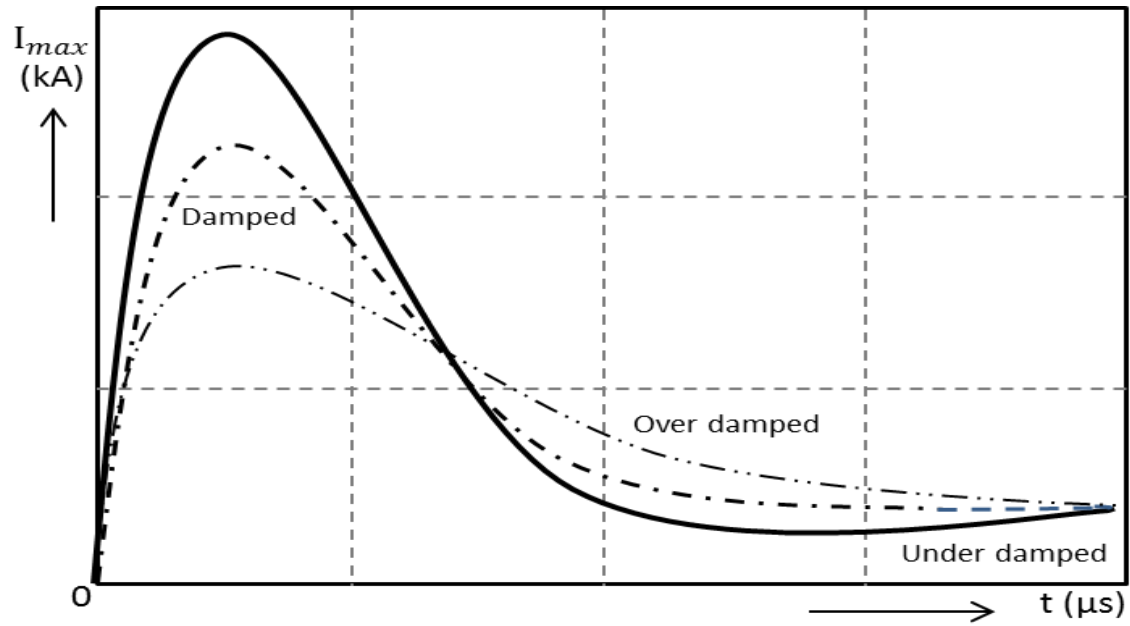


Fig. 23 (a) Output current wave forms for under, over and critically damped circuit conditions.

Summary

- All the high voltage equipment need to go through test with higher voltage than their rated voltage during the manufacturing process.
- The test voltages are two to three times higher than their line to ground working voltage.
- The equipment are also required to undergo tests with high impulse voltages to ensure their withstand capability against the possible over voltages in the system.
- The power ratings of the high voltage test equipment is quite low since the current requirement under the test is only to charge the capacitance formed by the insulation.
- Special techniques for the measurement of high voltage power frequency, dc and impulse, in laboratory are described in detail.
- Special instruments for the measurement of dielectric properties have been introduced, for example, $\tan\delta$, IR, PB etc.
- For a well-equipped high voltage laboratory such measuring instruments become an integral part for non-destructive quality control testing.

Thank You & References

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