HV Testing

- HV Generation
- HV Measurement
- HV Testing Procedures
- Testing of insulation and HV plant items
- Commissioning test

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Learning objectives

- To appreciate the importance of HV generation, measurement and testing
- To learn how HVAC, HVDA and HV impulse are generated for HV testing
- To understand how HV voltage and currents can be measured, and how the measurement circuits are configured
- To understand how HV equipment and materials are tested for various purposes
- To analyse the results of HV testing
- To appreciate the procedures of commissioning new installations to power systems.

HV Generation

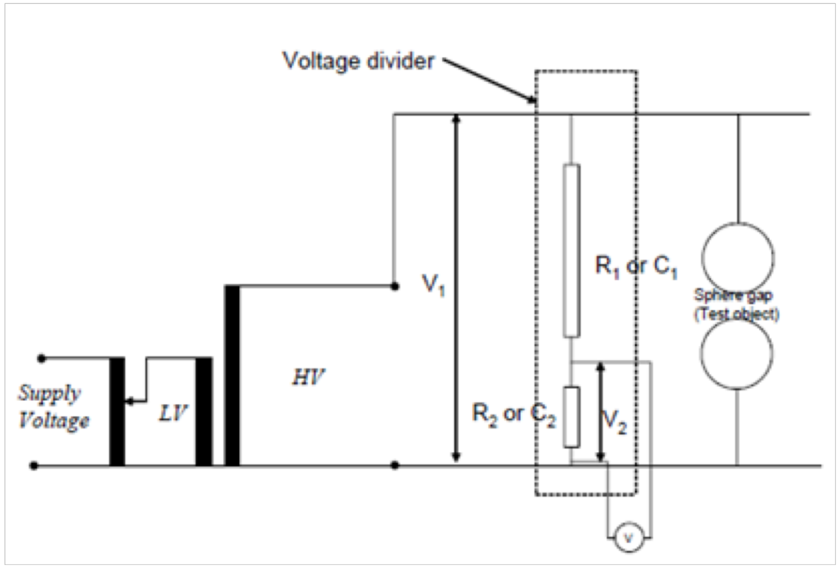
- It is necessary to carry out lab tests on HV plant items or insulation specimen before the design and commissioning, so there is always a market place for the HV generation.

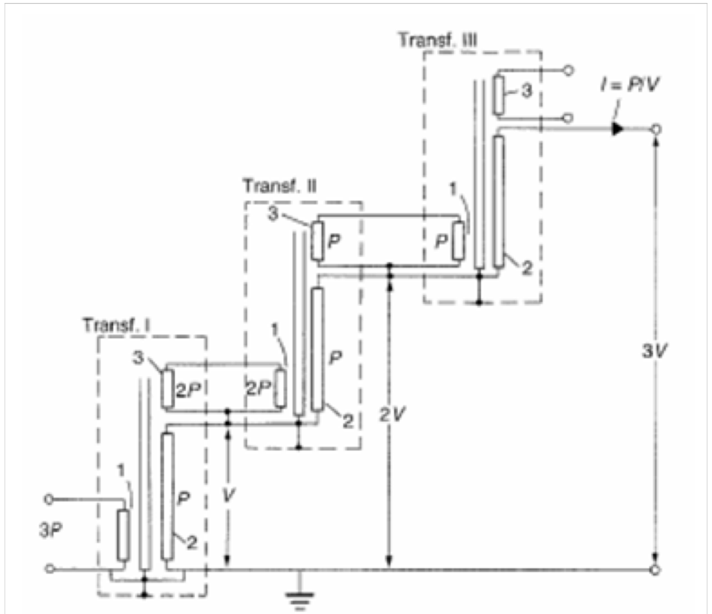
- In an AC network the equipment is continuously subjected to full power frequency voltage. The equipment should therefore be able to withstand power normal frequency voltage, allowing for some overvoltage.

- There are basic ways of A.C. voltage generations: high voltage transformers and resonant circuit.

AC test transformer and cascaded connections

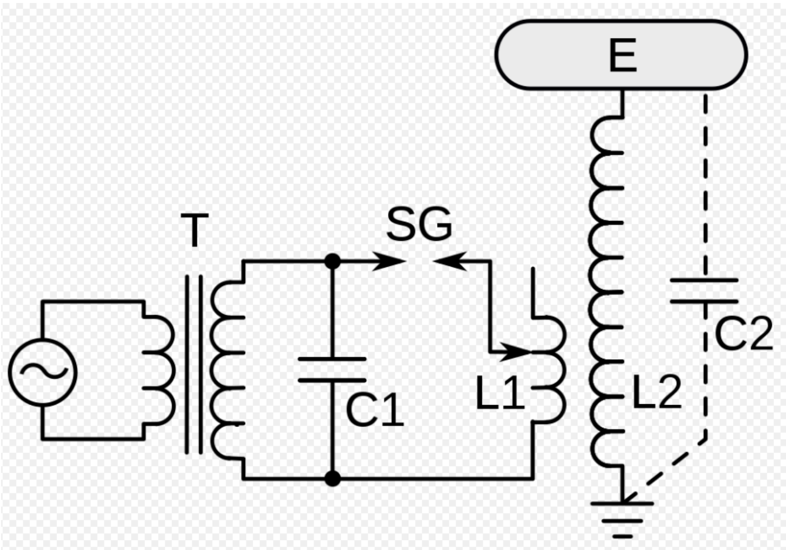
- In a high voltage laboratory the test transformers steps up the voltage from a lower voltage (230 V or 11 kV) to the desired voltage level.
- Figures below show the use of a single transformer and a cascaded transformer set for HV provision.





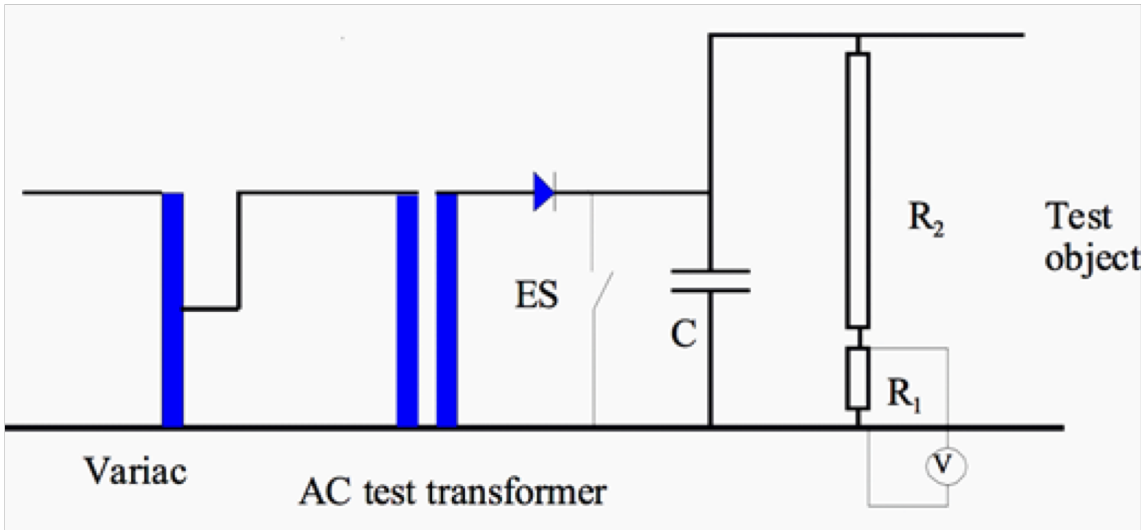
Resonant Circuit – Tesla coil

- A Tesla coil drives an air-core double-tuned resonant transformer to produce high voltages at low currents. Tesla's original circuits as well as most modern coils use a simple spark gap to excite oscillations in the tuned transformer. More sophisticated designs use transistor or thyristor switches or vacuum tube electronic oscillators to drive the resonant transformer.
- Tesla coils can produce output voltages from 50 kilovolts to several million volts for large coils



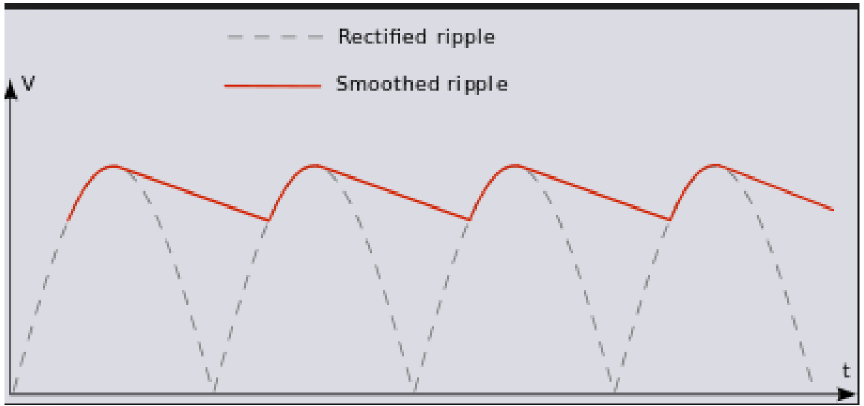
HV direct current

- DC tests are used mainly to do "pressure tests" on high voltage cables.
- Although the cables operate with AC, AC testing is not practical, due to he high capacitance of the cables
- In the case of DC, once the cable is charged, only the losses have to be supplied.
- DC test can leave space charge which changes the field or stress. This caused cable failures after being put back to service.



Consideration in DC supply setup

- Output voltage and duty
- Input/output voltages
- Output polarity
- Line and load regulation
- Efficiency
- Life time
- Ripple
- Stored energy
- Metering and control (remote programming)
- Protection and transient response
- RFI (radio frequency interference)
- Earthing



DC Test Design

- There are big advantages to have small capacitor rating for given values of required voltage ripples, as there is less stored energy, and thus safer operating environment.
- Example: for a given 10kV supply with a load current of 10mA and output ripple voltage (dV) of 1 V(pk to pk). At 50Hz, the half cycle period (dt = 1/100 secs).

  $I = C\ dv/dt$

  $10 \times 10^{-3} = C \times 100$, (dt = 1V/100 secs)

  $C = 100\ \mu F$

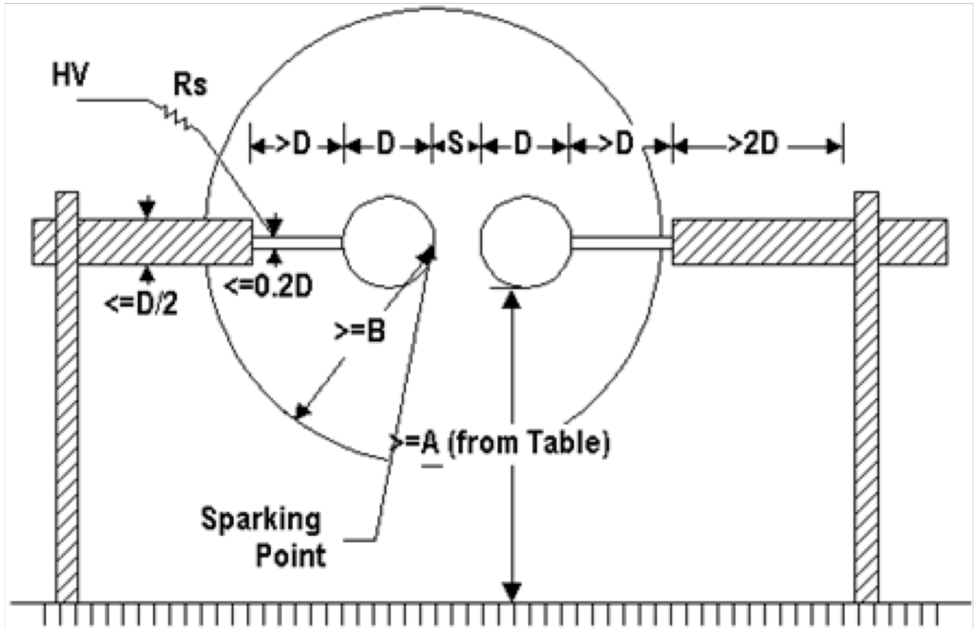
  At 30 kHz, $C = 0.167\ \mu F$.
- Control and protection are much easier, in addition to space saving and energy reduction. Safety circuit can collapse the output almost instantly when a load short circuit occurs.

Measurement of High Voltage

- In high voltage, due to safety reasons, the meters cannot be connected directly to the high voltage conductors.
- It is therefore necessary to use equipment to scale down the voltage signal to a safe value that can be displayed on instruments.
- On the power system, voltage and capacitive voltage transformers are used, while other techniques are used in the laboratory.
- Obviously, accuracy of the whole system is of the utmost importance.
- HV measurement techniques include:
  - DC measurement: sphere gap, electrostatic voltmeter, series resistance micrometer and resistance divider
  - AC measurement: sphere gap, electrostatic meter, series impedance ammeters, potential transformer and resistance or capacitance divider
  - Impulse or high frequency measurement: sphere gap, peak meter and potential dividers with oscilloscope

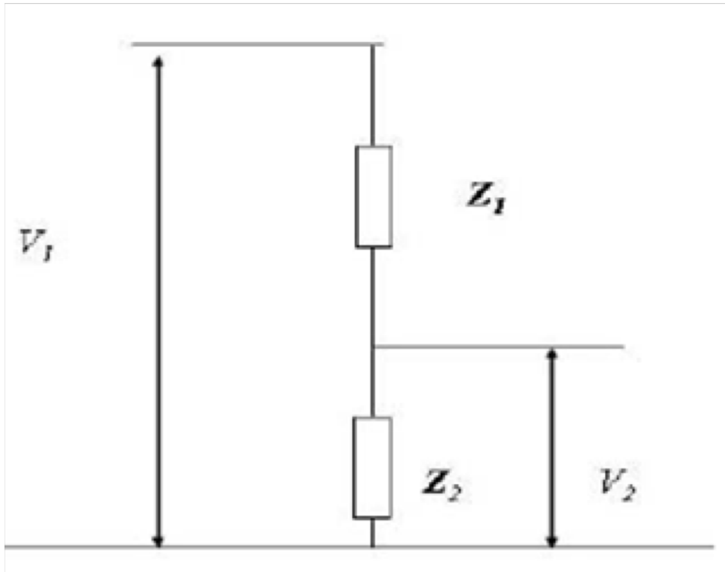
Sphere gap

- The relationship of the voltage to be measured and the length of the gap can be found from BS 358.



Voltage divider

- For DC measurement, the impedances take the form of resistors. Both resistors and capacitors can be used for AC and impulse measurement.



$$V_2 = \frac{Z_2}{Z_1 + Z_2} V_1$$

$$V_2 = \frac{C_1}{C_1 + C_2} V_1$$

$$V_2 = \frac{R_2}{R_1 + R_2} V_1$$

Voltage transformer

The voltage to be measured may not be sinusoidal – Fourier tranform

$$F_{rms} = \sqrt{\frac{1}{T}\int_{t_o}^{t_o+T} f(t)^2 dt} = \sqrt{\frac{1}{T}\int_{t_o}^{t_o+T} [a_v + \sum_{n=1}^{\infty} A_n \cos(n\omega_o t - \theta_n)]^2 dt}$$

The expression can be simplified as:

$$F_{rms} = \sqrt{a_v^2 + \sum_{n=1}^{\infty} (\frac{A_n}{\sqrt{2}})^2}$$

For example:

$$V = 10 + 20\cos(\omega_o t - \theta_1) + 30\cos(2\omega_o t - \theta_2) + 10\,cos(3\omega_o t - \theta_3)$$

$$= \sqrt{10^2 + (\frac{20}{\sqrt{2}})^2 + (\frac{30}{\sqrt{2}})^2 + (\frac{10}{\sqrt{2}})^2} = 28.3\text{K}$$

HV Testing Procedure

- Electrical equipment must be capable of withstanding working voltage and overvoltages. Suitable testing procedure required.

- High voltage testing can be classified into

  – testing of insulating materials (samples of dielectrics)
    - permittivity, dielectric loss per unit volume, and the dielectric strength of the material

  – tests on completed equipment.
    - capacitance, the power factor or the total dielectric loss, the ultimate breakdown voltage and the flash-over voltage.

General Tests on HV Equipment

- Sustained low-frequency tests (50Hz)
- High voltage DC test
- High frequency test
- Surge on impulse test
- Flash-over test

Sustained low-frequency tests (50Hz)

- the commonest of all tests--- determines the dielectric strength and dielectric loss.
- the tests are carried out at the highest ultimate stress possible.
- High voltage a.c. tests at 50 Hz are carried out as Routine tests on low voltage (230 or 400 V) equipment.

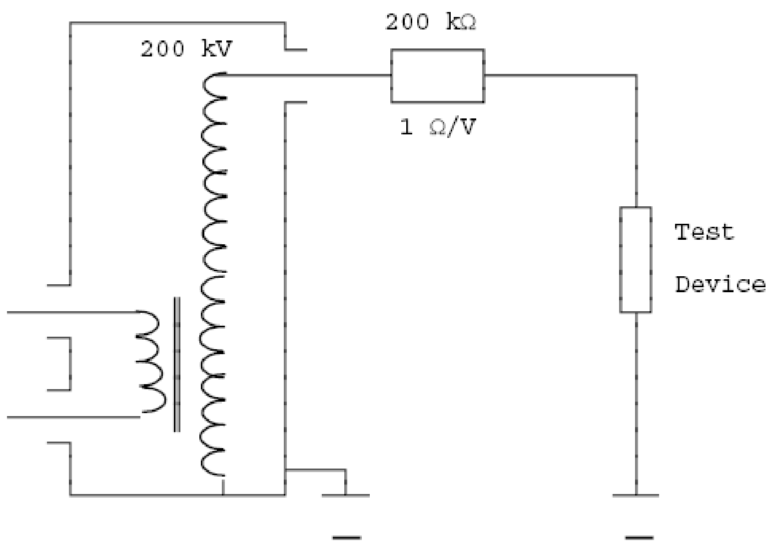


Figure 9.1 - a.c. generation test circuit

High Voltage DC Test

- These tests are done
  - on apparatus expected to operate under direct voltage conditions, and also where,
  - due to the inconvenience of the use of high capacity transformers required for extra high tension alternating voltage tests and
    - on cables to avoid high capacitive charging current
- This d.c test is not completely equivalent to the corresponding a.c. conditions

High Frequency Tests (kHz)

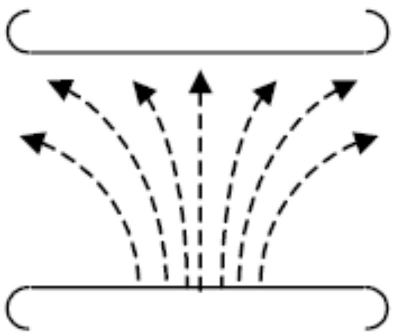
- Important --- if the HV lines etc., and insulators are expected to carry high frequency such as radio transmitting stations.

- In the case of porcelain insulators, breakdown or flashover occurs in most cases as a result of high frequency disturbances in the line.

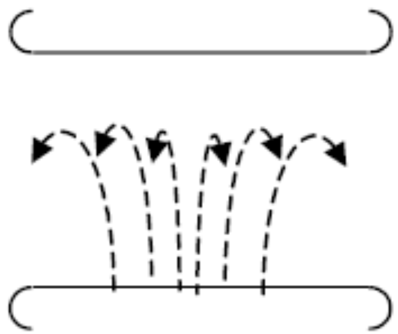
- It is also found that high frequency oscillations cause failure of insulation at a comparatively low voltage due to high dielectric loss and heating.

High Frequency Tests

- The behaviour of insulating materials at high frequencies are different to that at ordinary power frequency.
  - The dielectric loss per cycle is very nearly constant so that at high frequencies the dielectric loss is much higher
  - and the higher loss causes heating effects. The movements of charge carriers would be different.



Low Frequency



High Frequency

Surge or Impulse Tests

- To investigate the influence of surges in transmission lines, breakdown of insulators and of the end turns of transformer connections to line.
- The IEC Standard impulse wave of 1.2/50μs wave is generally used.
- Overvoltages of much higher duration arise due to line faults, switching operations etc, for which impulse waves such as 100/5000 μs duration may be used.
- The most general tests upon insulating materials are carried out at power frequencies

Flash-over tests

- Porcelain insulators are designed so that spark over occurs at a lower voltage than puncture, thus safeguarding the insulator.

- Tests
  - (i) 50 percent dry impulse flash-over test,
  - (ii) Dry flash-over and dry one-minute test
  - (iii) Wet flash-over and one minute rain test

- the voltage for puncture of a given thickness (ie. dielectric strength) is the most important under the test.

Factors for Dielectric Strength

- thickness of the sample tested
- shape of the sample
- previous electrical and thermal treatment of the sample
- shape , size , material and arrangement of the electrodes
- nature of the contact which the electrodes make with the sample
- waveform and frequency of the applied voltage (if alternating)
- rate of application of the testing voltage and the time during which it is maintained at a constant value .
- temperature and humidity when the test is carried out
- moisture content of the sample.

Testing of solid dielectric materials---d.l.

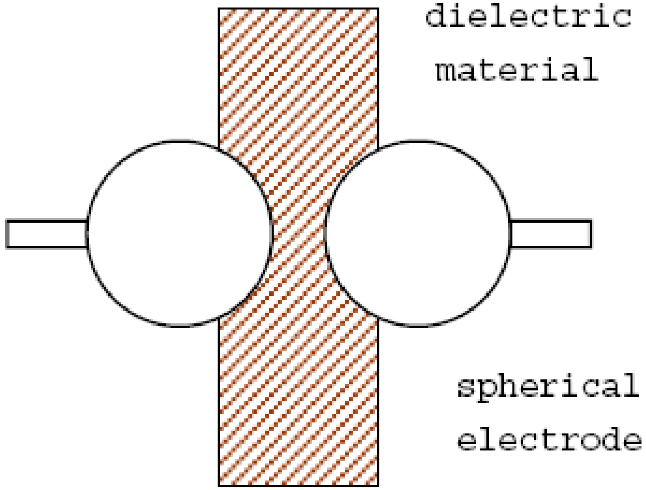
- Dielectric loss results in heat accumulation
- Insulants are usually bad in heat transfer
- Conductivity increases with temperature

- If the rate of temperature rise is higher than heat dissipating, breakdown occurs.

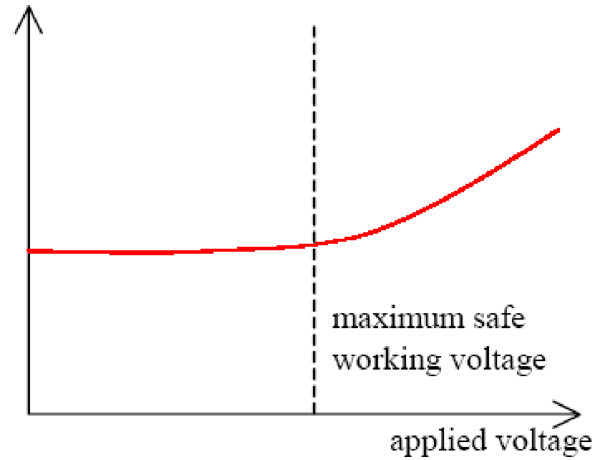
- Measurement of dielectric loss gives indication as to comparative dielectric strengths of insulants.

Determination of Dielectric strength of solid dielectrics

- The applied voltage is 50Hz, increasing from 1/3 of full rating to full value rapidly.
- Tests help identify weak spots in insulants.

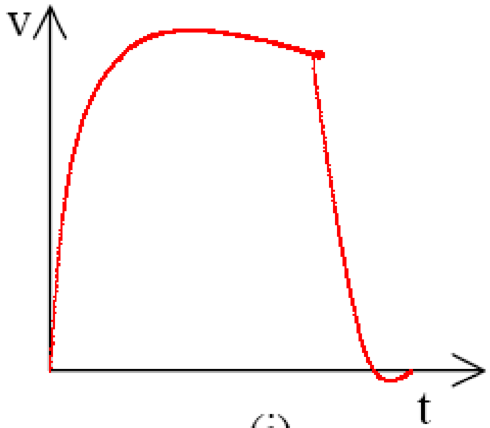


Dielectric loss

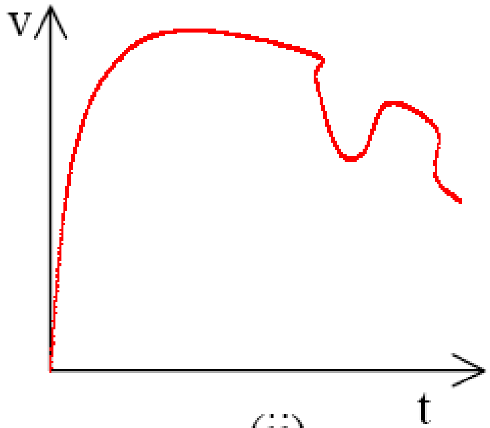


Impulse Testing

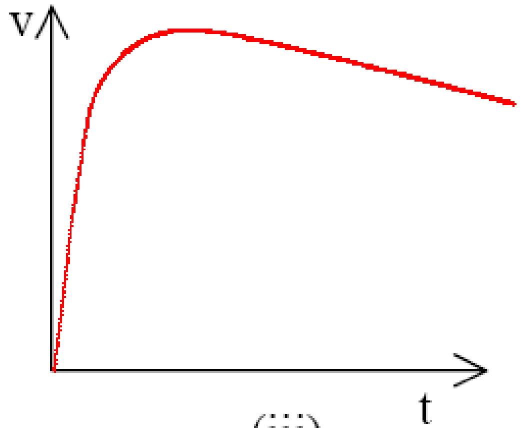
- These are done as tests on sample of apparatus. (4 to 5 times the normal operating value)
- Apply on to the sample a certain number (say 10) positive impulse and 10 negative impulses of this particular value. They should withstand this voltage without any destruction.
- (i) --- Complete damage, (ii) partial damage, (iii) no damage



(i)



(ii)



(iii)

Impulse withstand voltage

System Voltage	I.E.C. Impulse Withstand Voltage
11 kV	75 kV
33 kV	170 kV
66 kV	325 kV
132 kV	550 kV
275 kV	1050 kV

Tests on Insulators—type tests

- **Withstand Test**: A 1/50 μs wave of the specified voltage (corrected for humidity, air density etc.,) is applied. Flashover or puncture should not occur. Repeat five times for each polarity.
- **Flash-over test**: A 1/50 μs wave is applied. The voltage is gradually increased to the 50% impulse flashover voltage. The test is done for both polarities. No puncture of insulation during these tests.
- **Dry One-minute test**: The prescribed voltage (corrected for ambient conditions) should be gradually brought up (at power frequency) and maintained for one minute. No puncture or flash-over during the test.
  - **Dry flash-over test**: The voltage shall then be increased gradually until flash-over occurs. This is repeated ten times. There shall be no damage to the insulator.
- **One-minute Rain test**: The prescribed voltage is maintained for one minute
  - **Wet flash-over test**: The voltage shall then be increased gradually until flash-over occurs. This is repeated ten times. No damage to the insulator.
- **Visible discharge test**: This states that after the room has been darkened and the specified test voltage applied, after five minutes, there should be no visible signs of corona.

Tests on Insulators—sample tests

- **Temperature cycle test**: The complete test shall consist of five transfers (hot-cold-hot-....), each transfer not exceeding 30 s.
- **Mechanical loading test**: The insulator shall be mechanically loaded up to the point of failure. When failure occurs, check the load value.
- **Electro-mechanical test**: The insulator is simultaneously subjected to electrical and mechanical stress. (i.e. it shall be subjected to a power frequency voltage and a tensile force simultaneously. The voltage shall be 75% of dry flash-over voltage of the unit. There should be no damage caused.
- **Overvoltage test**: The insulator shall be completely immersed in an insulating medium (oil), to prevent external flashover occurring. The specified overvoltage must be reached without puncture. The voltage is then gradually increased until puncture occurs.
- **Porosity test**: Freshly broken pieces of porcelain shall show no dye penetration after having been immersed for 24 hours in an alcoholic mixture at a pressure of 2000 p.s.i. (1 atm = 14.7 psi)

Tests on Insulators—Routine tests

- These are to be applied to all insulators and shall be commenced at a low voltage and increased rapidly until flash-over occurs every few seconds.
  - The voltage shall be maintained at this value for a minimum of five minutes,
  - or if failures occur, for five minutes after the last punctured piece has been removed.

- **Mechanical Routine Test:** A mechanical load of 20% in excess of the maximum working load of the insulator is applied after suspending the insulator for one minute. There should be no mechanical failure of the insulator.

Tests on Transformers

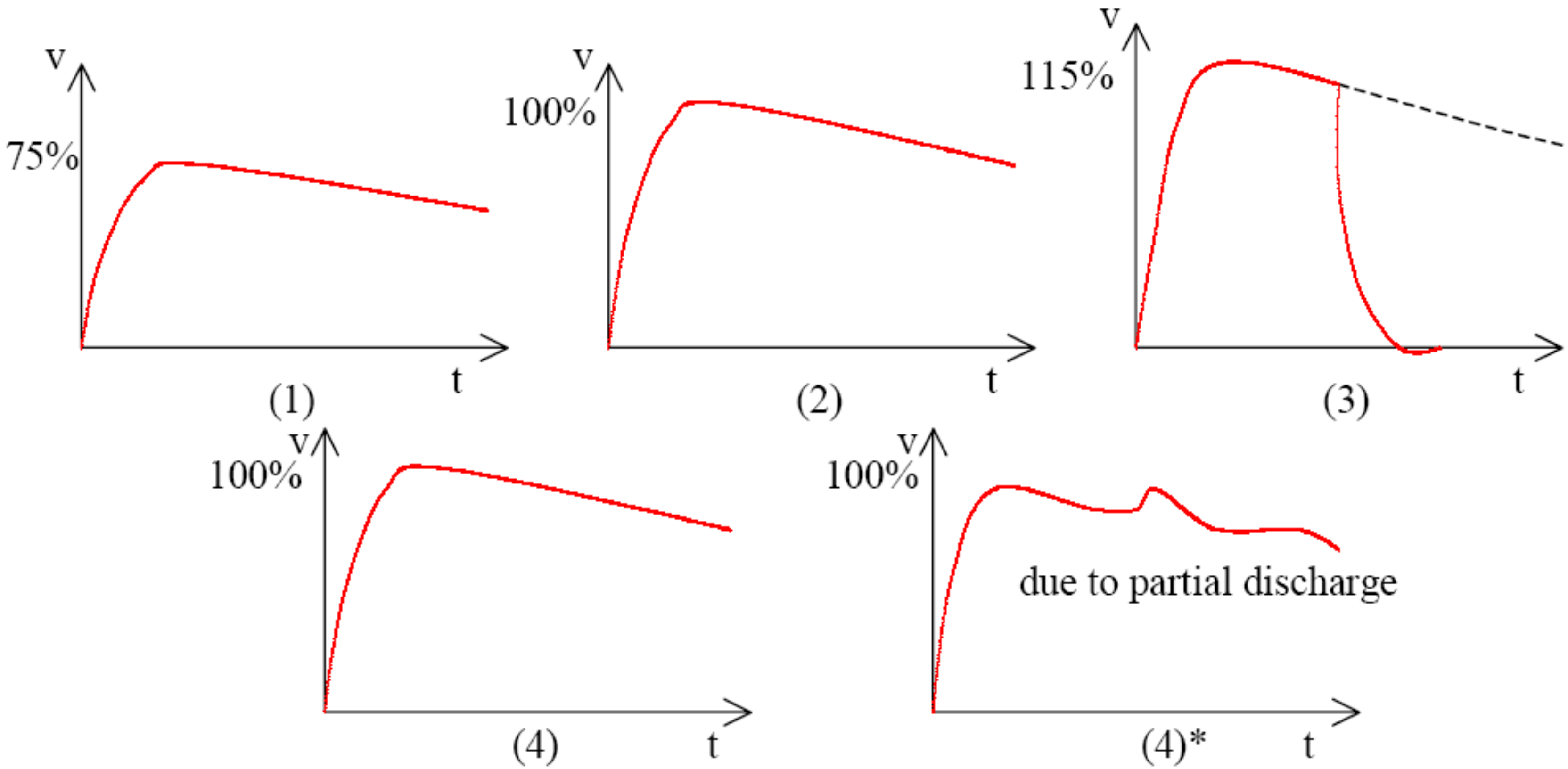
- Apply full wave impulse at 75% I.E.C. withstand value. Since the transformer should be able to withstand the I.E.C.voltage, there should be no damage to the transformer.

- Apply full wave at 100% I.E.C. withstand value and observe whether there is any breakdown. Then the device has passed the test.

- Chopped wave test at 115% fullwave amplitude : For this kind of test , the impulse generator would have to be fitted with a rod gap or controlled trigatron type gap.
  - Since there is no voltage across insulator after chopping takes place, from the waveform it is not possible to say whether any damage has taken place.

- Apply full wave test again and compare the wave and at 100% of I.E.C. voltage and see whether there is any distortion in the waveform indicating damage.

Tests Waveforms



Tests on Cables

- Conductor resistance
- Voltage test:---Test voltage (25Hz-100Hz). Maintained at full voltage for 15 min.

Voltage Designation	Belted Cables				Single-core, S.L. & Screened Cables	
	(i)		(ii)		(ii)	
	(1)	(2)	(1)	(2)	(1)	(2)
11 kV	24 kV	36 kV	14 kV	21 kV	15 kV	22 kV

where (i) Between conductors, (ii) Between any conductor and sheath
(1) Cable as manufactured, (2) After bending test

Tests on Cables

- **Dielectric power-factor / Voltage test (for 33 kV cables only)**
  - Each core of every drum of completed cable is tested for dielectric power factor at room temperature at the following a.c. single phase 50 Hz voltages : 9.5 kV , 19 kV , 28.5 kV, 38.0 kV.
  - The measured power-factor at normal working voltage shall not exceed the value declared by the manufacturer and shall in no case exceed 0.01-PILC, 0.002 for XLPE
  - The ionization - ie. the difference in power-factor between half the normal working voltage and the twice the normal working voltage

Tests on Pressurised Cables

- **Loading cycle test:** Cable subjected to 20 load cycles to a minimum conductor temperature 5^o C in excess of the design value, with the cable energised to 1.5 times the working voltage.

- **Thermal stability test (132 kV cables only):** the cable to be energised to 1.5 times working voltage and the loading current adjusted to give a maximum temperature 5^o C in excess of the design value. The current to be maintained at this value for a period of 6 hours,, to prove that the cable is thermally stable.

- **Impulse test:** to be subjected to 10 positive and 10 negative impulses at test voltage.

- **Cold power-factor/voltage test:** The power factor of a 100 m length of cable to be measured at 0.5, 1.0, 1.5 and 2 times the working voltage with the cable at the stipulated minimum internal pressure. The values not to exceed the makers' guaranteed values.

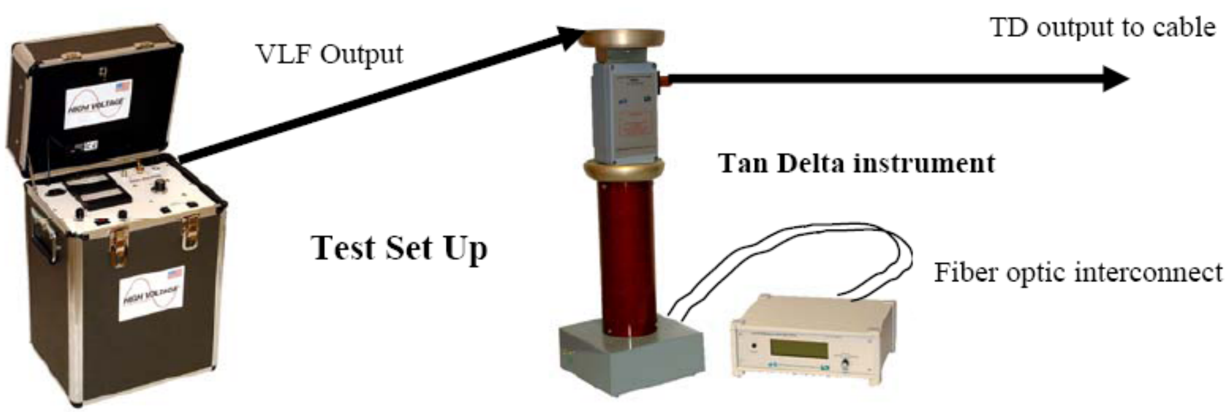
- **Dielectric thermal resistance test:** The thermal resistance of the cable is measured.

- **Mechanical Test of metallic reinforcement:** A sample of cable to withstand twice the maximum specified internal pressure for a period of seven days.

- **Binding test:** The cable to be subjected to three binding cycles round a drum of diameter 20 times the diameter of the pressure retaining sheath.

VLF & Tan Delta Testing

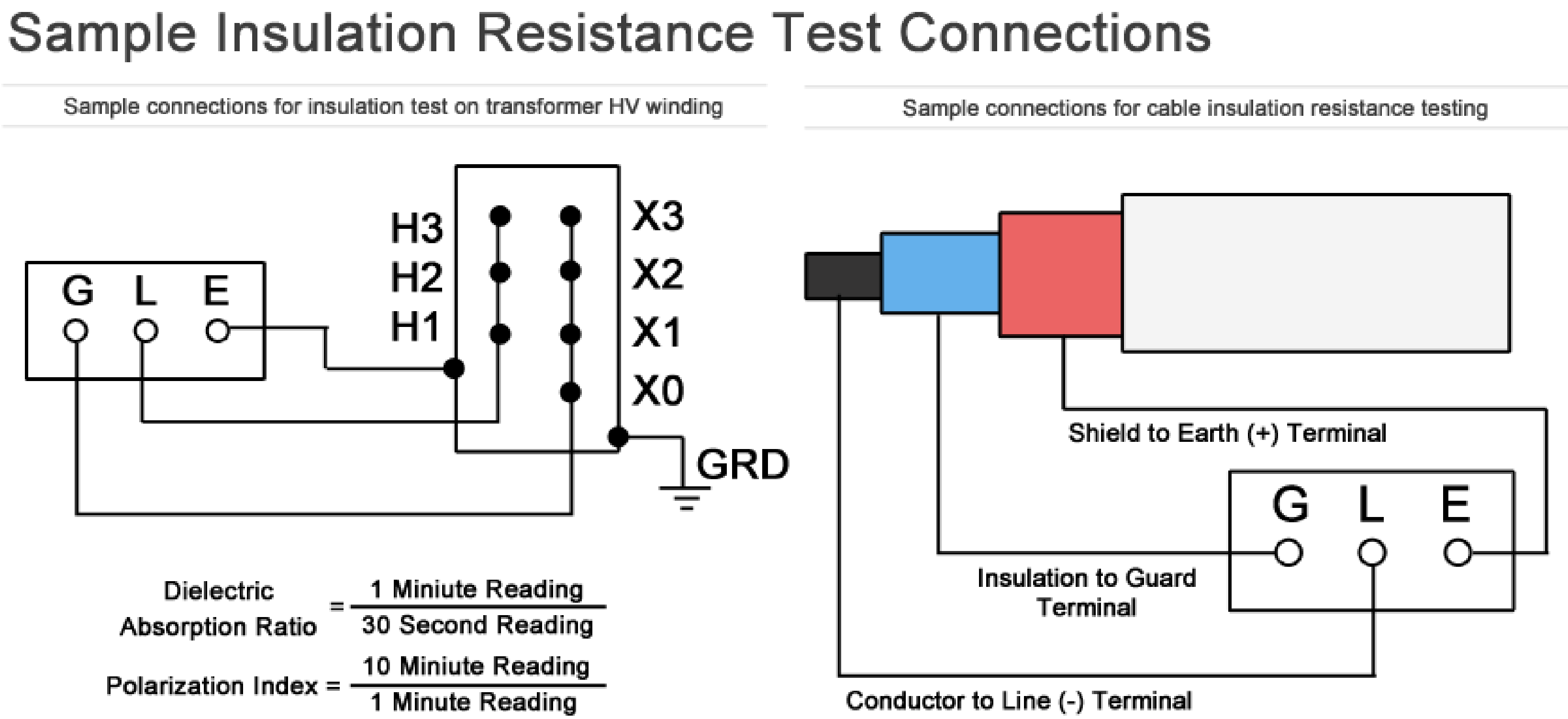
- Very Low Frequency (VLF) testing is performed to verify a cables AC voltage withstand capability. It is simply a pass/fail AC stress test using an instrument with a 0.1 Hz (or lower) output frequency rather than 50/60 Hz.
- If a cable can not hold 2 – 3 times normal voltage, find out during a controlled outage, locate the defect and make the repair or replacement, avoiding an in-service failure.
- A Tan Delta test permits the user to grade the deterioration level of many cables in order to prioritize replacement, rejuvenation, or to determine what additional tests may be useful.



Polarisation Index

- The index is calculated from measurements of the winding insulation resistance.
- Before measuring the insulation resistance, remove all external connections to the machine and completely discharge the windings to the grounded machine frame.
- Proceed by applying either 500 or 1000 volts dc between the winding and ground using a direct-indicating, power-driven megohmmeter.
- For machines rated 500 volts and over, the higher value is used. The voltage is applied for 10 minutes and kept constant for the duration of the test.
- The polarization index is calculated as the ratio of the 10-minute to the 1-minute value of the insulation resistance, measured consecutively.
- Polarization Index = $\dfrac{\text{Resistance after 10 minutes}}{\text{Resistance after 1 minute}}$
- The recommended minimum value of polarization index for ac and dc motors and generators is 2.0.
- Machines having windings with a lower index are less likely to be suited for operation.
- The polarization index is useful in evaluating windings for:
  - Buildup of dirt or moisture.
  - Gradual deterioration of the insulation (by comparing results of tests made earlier on the same machine).
  - Fitness for overpotential tests.
  - Suitability for operation.

Example application



DAR and PI Test Diagnosis

DAR	Insulation Condition
<1.25	Questionable
≤ 1.6	Adequate
>1.6	Good

PI	Insulation Condition
<1	Dangerous
<2	Questionable
<4	Good
>4	Excellent

What does a guard terminal do?

- During insulation testing, the resistance path on the outer surface of the insulation material often gets neglected. However, this resistance path is very much a part of the measurement and can dramatically affect the results.

- For example, if dirt is present on the outer surface of a bush, the surface leakage current can be up to ten times that flowing through the actual insulation.

- The surface leakage is essentially a resistance in parallel with the true insulation resistance of the material being tested. By using the guard terminal to perform a ‘three-terminal test’, the surface leakage current can be ignored.

Power plant commissioning management

- Definition------
  - Activities which demonstrate that an item of equipment is acceptable for service, including inspections, off-load and on-load commissioning tests
- Objectives:
  - Verifying that equipment has not been damaged, correctly installed, perform to spec.
  - Obtaining data for comparison with future.

Contractual responsibilities

Activity	Responsibility
1. Prepare design spec.	Elec. Supply Company (ESC)
2. Issue tender document, award contract	Elec. Supply company (ESC)
3. Manufacture equipment	Contractor
4. Erect equipment on site	Contractor or ESC
5. Pre-commissioning inspection	Contractor and/or ESC
6. Off-load commissioning test	Contractor or ESC
7. Pre-energisation inspection	Contractor and/or ESC
8. On-load commissioning test	Contractor and/or ESC
9. Post-commissioning inspection	Contractor and/or ESC

Commissioning panel

Chairman	Project manager, supply company technical engineer
Technical engineer	Defining tests required, analyse test results
Contractor’s representative	Oversee test and analyse test results
Operators	Check energisation procedure
Others	Connection with the system is ok.

Commissioning programme

- Pre-commissioning inspection
- Off-load commissioning test programme
- Pre-energisation inspection
- Energisation and on-load commissioning tests
- Post-commissioning inspection