POLLACHI INSTITUTE OF ENGINEERING AND TECHNOLOGY
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sky is the limit

Department of Electrical and Electronics Engineering

Regulation 2021

IV Year – VII Semester

EE3701- High Voltage Engineering

UNIT– I OVERVOLTAGESINELECTRICALPOWER SYSTEMS

NATURAL CAUSES OF OVER VOLTAGES

Introduction

Examination of over voltages on the power system includes a study of their magnitudes, shapes, durations, and frequency of occurrence. The study should be performed at all points along the transmission network to which the surges may travel **Types of Overvoltage**

• Thevoltagestressesontransmissionnetworkinsulationarefoundtohaveavarietyof Origins.
• InnormaloperationAC(orDC)voltagesdo notstresstheinsulation severely.
• Overvoltagestressingapowersystem can beclassified intotwo main types:

External overvoltage: generated by atmospheric disturbances of these disturbances, lightning is the most common and the most severe. Internal over voltages: generated by changes in the operating conditions of the network. Internal over voltages.

Lightning Over voltages Lightning is produced in an attempt by nature to maintain dynamic balance between the positively charged ionosphere and the negatively charged earth.

Over fair-weather areas there is a downward transfer of positive charges through the global air-earth current. This is then counteracted by thunderstorms, during which positive charges are transferred upward in the form of lightning. During thunderstorms, positive and negativecharges areseparatedby themovements ofaircurrents forming icecrystals in theupper layer of a cloud and rain in the lower part.

The cloud becomes negatively charged and has a larger layer of positive chargeat its top. As the separation of charge proceeds in the cloud, the potential difference between the centers of charges _increases and the vertical electric field along the cloud also increases. The totalpotentialdifferencebetweenthetwomainchargecentersmayvaryfroml00to1000MV.Onlya part of the total charge-several hundred coulombs is released to earth by lightning; the rest is consumed in inter cloud discharges. The height of the thundercloud dipole above earth may reach5 km in tropical regions.

Figure:1Overvoltage DueToArcingGround

TheLightning Discharge

The channel to earth is first established by a stepped dischargecalled a leader stroke. The leader is initiated by a breakdown between polarized water droplets at the cloud base caused by the high electric field, or a discharge between the negative charge mass in the lower cloud andthe positive charge pocket below it. (Figure 1.2) As the downward leader approaches the earth,an upward leader begins to proceed from earth before the former reaches earth. The upward leader joins the downward one at a point referred to as the striking point. This is the start of the return stroke, which progresses upward like a travelling wave on a transmission line

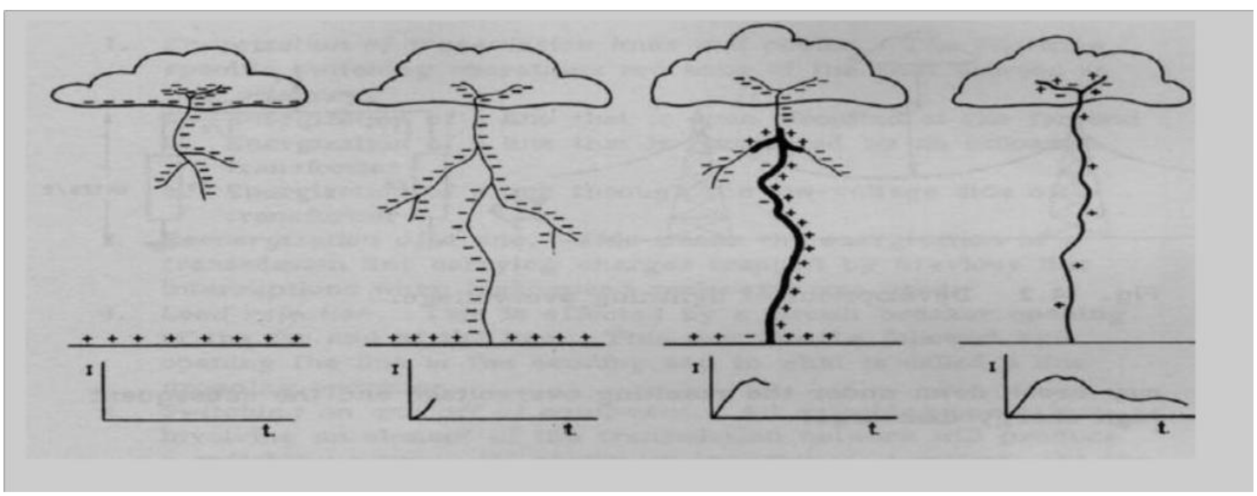

Figure:1.2DevelopmentalStagesOfALightingFlashAndThe Corresponding Current Surge

LIGHTNINGPHENOMENON

At the earthling point a heavy impulse current reaching the order of tens of kilo amperes occurs, which is responsible for the known damage of lightning. The velocity of progression of the return stoke is very high and may reach half the speed of light. The corresponding current heatsitspathtotemperaturesupto20,000°C,causingtheexplosiveairexpansionthatisheardas thunder. The current pulse rises to its crest in a few microseconds and decays over a period of tens or hundreds of microseconds.

Factsabout Lightning

- Astrikecanaverage100millionvoltsofelectricity

  Current of up to 100,000 amperes
- Cangenerate54,000
- LightningstrikessomewhereontheEartheverysecond

  Kills hundreds of people every year.
- UseTheFiveSecondRuleLighttravelsatabout186,291miles/second

  Sound travels at only 1,088 feet/second
- Youwillseetheflashof lightningalmostimmediately5280/1088=4.9
- About5secondsforsoundtotravel1mile1miles(statute)isequalto 1,609.34meters.1 Feet are equal to 0.30 meters.

LightningVoltageSurges

Themostseverelightningstrokeisthatwhichstrikesaphaseconductoronthetransmission line

- Itproducesthehighestovervoltageforagivenstroke current.
- The lightning stroke injects its current into a termination impedance Z, whichin this case
- ishalfthelinesurgeimpedanceZosincethecurrentwillflowinbothdirectionsasshown
- InFigure1.3.Therefore,thevoltagesurgemagnitudeatthestrikingpoints=(½) IZo The
- lightning current magnitude is rarely less than 10 kA.
- FortypicaloverheadlinesurgeimpedanceZoof300 Ω,thelightningsurgevoltagewill Probablyhaveamagnitudein excess of1500kV.

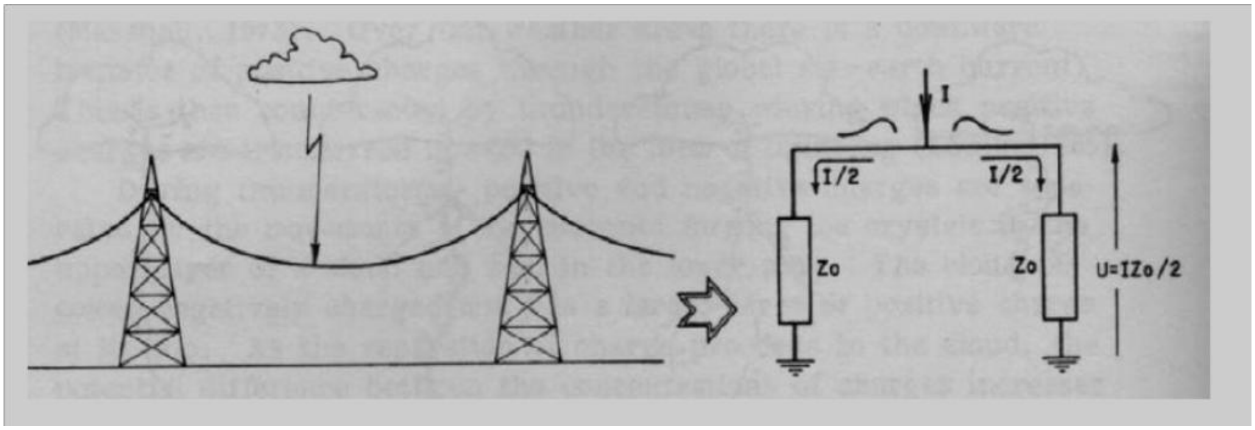

Figure:1.3DevelopmentalLightingovervoltage

EFFECT OF LIGHTNING

Theimpedanceofthelightningchannelitselfismuchlargerthan1/2Zo (itisbelievedto range from l00to 3000 Ω).

- Lightningvoltagesurgewill havethesame shapecharacteristics.
- Inpracticetheshapesandmagnitudesoflightningsurgewavesgetmodifiedbytheir Reflections at
- points of discontinuity as they travel along transmission lines.
- Lightningstrokesrepresenttruedangertolife,structures,powersystems,and Communication
- networks.
- Lightning is always a major source of damage to power systems where equipment
- Insulationmaybreakdown,undertheresultingovervoltageandthesubsequenthigh- Energy
- discharge.

Lightning has been a source of wonder to mankind for thousands of years. Scotland pointsoutthatanyrealscientificsearchforthefirsttimewasmadeintothephenomenonof lightning by Franklin in18th century. Before going into the various theories explaining the charge formation in a thunder cloud and the mechanism of lightning, it is desirable to review some of the accepted facts concerning the thunder.

CloudAndTheAssociated Phenomenon.

- The height of the cloud base above the surrounding ground level may vary from 160 to9,500m.Thecharged centerswhich areresponsibleforlightningareintherangeof 300 to 1500 m.
- The maximum charge on a cloud is of the order of 10 coulombs which is built up exponentially
- over a period of perhaps many seconds or even minutes. The maximum potential of a cloud lies approximately within the range of 10 MV to 100 MV.
- Theenergy in alightning strokemaybeof theorder of250kWhr.

- Raindrops:

Raindrops elongate and become unstable under an electric field, the limiting diameter being0.3 cm in a field of 100 kV/cm. A free falling raindrop attains a constant velocity with respecttotheairdependinguponitssize.Thisvelocityis800cms/sec.fordropsofthesize 0.25 cm dia. and is zero for spray. This means that in case the air currents are moving upwards with a velocity greater than 800 cm/sec, no rain drop can fall. Falling raindrops greater than 0.5 cm in dia become unstable and break up into smaller drops. When a drop is broken up by air currents, the water particles become positively charged and the air negatively charged. When ice crystal strikes with air currents, the ice crystal is negatively charged and the air positively charged.

Wilson’s Theory of Charge Separation Wilson‘s theory is based on the assumption that a large number of ions are present in the atmosphere. Many of these ions attach themselves to small dust particles and water particles. It also assumes that an electric field exists in the earth‘s atmosphere during fair weather which is directed downwards towards the earth (Figure.1.4 (a)). The intensity of the field is approximately 1 volt/cm at the surface of the earth and decreases gradually with height so that at 9,500 m it is only about 0.02 V/cm. A relativelylargeraindrop (0.1cmradius)fallinginthisfieldbecomespolarized,theupperside acquires a negative.

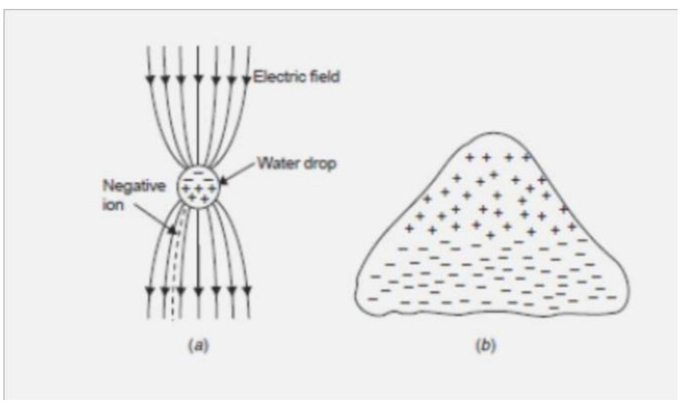

Figure:1.4 (a) Capture of negative ions by large falling drop; (b) Chargeseparationinathundercloudaccordingto Wilson’stheory.

Wilson’sTheoryofChargeSeparation

Wilson‘s theory is based on the assumption that a large number of ions are present in the atmosphere. Many of these ions attach themselves to small dust particles and water particles. It also assumes that an electric field exists in the earth‘s atmosphere during fair weather which is directeddownwardstowardstheearth(Figure.1.4 (a)).Theintensityofthefieldisapproximately 1 volt/cm at the surface of the earth and decreases gradually with height so that at 9,500 m it is only about 0.02 V/cm. A relatively large raindrop (0.1 cm radius) falling in this field becomes polarized, the upper side acquires a negative charge and the lower side a positive charge. Subsequently, the lower part of the drop attracts –ve charges from the atmosphere which are available in abundance in the atmosphere leaving a preponderance of positive charges in the air.

The upwards motion of air currents tends to carry up the top of the cloud, the +ve air and smaller drops that the wind can blow against gravity. Meanwhile the falling heavier raindrops which are negatively charged settle on the base of the cloud. It is to be noted that the selective action of capturing –vecharges from the atmosphereby thelowersurface ofthedrop is possible. No such selective action occurs at the upper surface. Thus in the original system, both the positive and negative charges which were mixed up, producing essentially a neutral spacecharge, are now separated.

Thus according to Wilson‘s theory since larger negatively charged drops settle on the base of the cloud and smaller positively charged drops settle on the upper positions of the cloud, the lower base of the cloud is negatively charged and the upper region is positively charged (Figure.1.4 (b)). **Simpson’s and Scarse Theory** Simpson‘s theory is based on the temperature variationsinthevarious regionsofthecloud.Whenwaterdropletsarebrokenduetoaircurrents, water droplets acquire positive charges whereas the air is negatively charged. Also when ice crystals strike with air, the air is positively charged and the crystals negatively charged. The theory is explained with the help of Fig. 1.5.

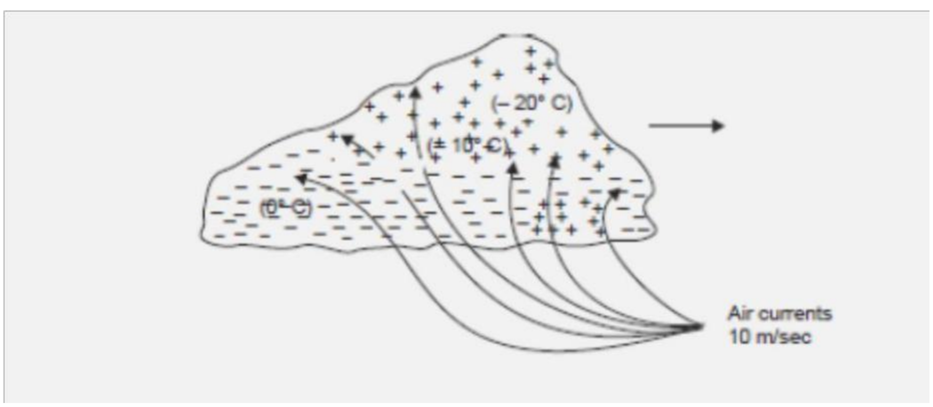

Figure:1.5Chargegenerationandseparationinathunder

cloudaccordingtoSimpson‘stheoryLetthecloudmoveinthedirectionfromlefttoright as shown by the arrow. The air currents are also shown in the diagram. If the velocity of the air currents is about 10 m/sec in the base of the cloud, these air currents when collide with the water particles in the base of the cloud, the water drops are broken and carried upwards unless they combine together and fall down in a pocket as shown by a pocket of positive charges (right bottom region in Fig. 7.23). With the collision of water particles we know the air is negatively charged and the water particles positively charged. These negative charges in the air are immediately absorbed by the cloud particles which are carried away upwards with the air currents. The air currents go still higher in the cloud where the moisture freezes into ice crystals.

The air currents when collide with ice crystals the air is positively charged and it goes in the upper region of cloud whereas the negatively charged ice crystals drift gently down in the lower region of the cloud. This is how the charge is separated in a thundercloud. Once the charge separation is complete, the conditions are now set for a lightning stroke.

Mechanism of Lightning Stroke Lightning phenomenon is the discharge of the cloud to the ground. The cloud and the ground form two plates of a gigantic capacitor and the dielectric medium is air. Since the lower part of the cloud is negatively charged, the earth is positively charged by induction. Lightning discharge will require the puncture of the air between the cloud andtheearth.ForbreakdownofairatSTPconditiontheelectricfieldrequiredis30kV/cmpeak. But in a cloud where the moisture content in the air is large and also because of the high altitude (lower pressure) it is seen that for breakdown of air the electric field required is only 10 kV/cm. The mechanism of lightning discharge is best explained with the help of Fig. 1.6. After agradient of approximately 10 kV/cm is set up in the cloud, the air surrounding gets ionized. At thisastreamer(Fig.1.6(a))startsfromthecloudtowardstheearthwhichcannotbedetectedwith the naked eye; only a spot travelling is detected.

Thecurrent inthe streamer isoftheorderof100amperesandthespeedofthestreameris 0.16 m/μ sec. This streamer is known as pilot streamer because this leads to the lightning phenomenon. Depending upon the state of ionization of the air surrounding the streamer, it is branched toseveralpathsandthisisknownassteppedleader(Fig.1.6(b)). Theleadersteps areof the order of 50 m in length and are accomplished in about a microsecond. The charge is brought fromthecloudthroughthealreadyionizedpathtothesepauses.Theairsurroundingthesepauses is again ionized and the leader in this way reaches the earth (Fig.1.6(c)).Once the stepped leader has made contact with the earth it is believed that a power return stroke(Fig. 1.6(c)) moves very fast up towards the cloud through the already ionized path by the leader. This streamer is very intense where the current varies between 1000 amps and 200,000 amps and the speed is about 10% that of light. It is herewherethe –ve charge of the cloud is being neutralized by the positive induced charge on the earth (Fig. 1.6 (d)).

It is this instant which gives rise to lightning flash which we observe with our naked eye. Theremay be another cell of charges in the cloud near the neutralized charged cell. This charged cell will try to neutralize through this ionized path. This streamers known as dart leader (Fig.1.6 (e)). The velocity of the dart leader is about 3% of the velocity of light. The effect of the dart leader is much more severe than that of the return stroke. The discharge current in the return streamer is relatively very large but as it lasts only for a few microseconds the energy contained in the streamer is small and hence this streamer is known as cold lightning stroke whereas the dart leader is known as hot lightning stroke because even though the current in this leader is relatively smaller but it lasts for some milliseconds and therefore the energy contained in this leader is relatively larger.

It is found that each thunder cloud may contain as many as 40 charged cells and a heavy lightning stroke may occur. This is known as multiple stroke. 1.2.3 Line Design Based On Lightning Theseverity ofswitching surges forvoltage400 kV and aboveis muchmore than that duetolightningvoltages.Allthesameitisdesiredtoprotectthetransmissionlinesagainst direct lightning strokes. The object of good line design is to reduce the number of outages caused by lightning. To achieve this following actions are required. (I) The incidence of stroke on to power conductor should be minimized. (ii) The effect of those strokes which are incident on the system should be minimized. To achieve (i) we know that lightning normally falls on tall objects; thus tall towers are more vulnerable to lightning than the smaller towers. In order to keep smaller tower height for a particular ground clearance, the span lengths will decrease which requires more number of towers and hence the associated accessories like insulators etc. The cost will go up very high. Therefore, a compromise has to be made so that adequate clearance is provided, at the same time keeping longer span and hence lesser number of towers.

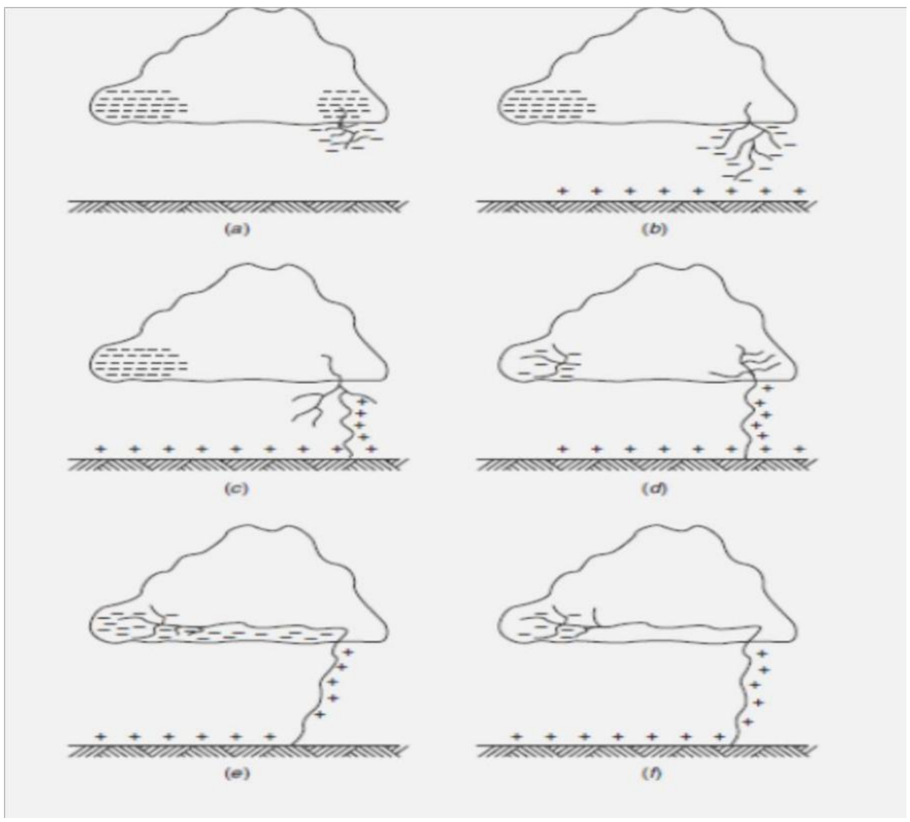

Figure:1.6Lightning mechanism

With a particular number of towers the chances of incidence of lightning on power conductor scan be minimized by placing a ground wire at the top of the tower structure. . The tower presents a discontinuity to the travelling waves; therefore they suffer reflections and refraction. Thesystem is, then,equivalent to alinebifurcatedat thetowerpoint.Weknowthat the voltage and current transmitted into the tower will depend upon the surge impedance of thetower and the ground impedance (tower footing resistance) of the tower. If it is low, the wave reflectedbackupthetowerwilllargelyremovethepotentialexistingduetotheincidentwave. In this way the chance of flashover is eliminated. If, on the other hand, the incident waveencounters high ground impedance, positive reflection will take place and the potential on the top of the tower structure will be raised rather than lowered. It is, therefore, desired that for good line design high surge impedances in the ground wire circuits, the tower structures and the tower footing should be avoided.

OVERVOLTAGESDUETOSWITCHINGSURGES

The increase in transmission voltages needed to fulfill the required increase in transmitted powers, switching surges have become the governing factor in the design of insulation for EHV and UHV systems. In the meantime, lightning over voltages come as a secondary factor in these networks. There are two fundamental reasons for this shift in relative importance from lightning to switching surges as higher transmission voltages are called for:

- Overvoltages produced ontransmission lines by lightning strokes are only slightly dependent onthepowersystemvoltages.Asaresult,theirmagnitudesrelativetothesystempeakvoltage decrease as the latter is increased.
- External insulation has its lowest breakdown strength under surges whose fronts fall in the range 50-500 micro sec.,which is typical for switching surges.
- According to the International Electro-technical Commission(IEC) recommendations, all equipment designed for operating voltages above 300 kV should be tested under switching impulses (i.e., laboratory-simulated switching surges).

Temporaryover voltages

The purpose of this Guide is to provide information on transient and temporary over voltages and currents in end-user AC power systems. With this information in hand, equipment designers and users can more accurately evaluate their operating environment to determine the need for surge protective devices (SPDs) or other mitigation schemes. The Guide characterizes electrical transmission and distribution systems in which surges occur, based upon certain theoreticalconsiderationsaswellasonthedatathathavebeenrecordedininteriorlocationswith particular emphasis on industrial environments. There are no specific mathematical models that simulate all surge environments; the complexities of the real world need to be simplified to produce a manageable set of standard surge tests. To this end, a scheme to classify the surge environment is presented.

This classification provides a practical basis for the selection of surge-voltage and surge-current waveforms and amplitudes that can be applied to evaluate the capability of equipment to withstand surges when connected to power circuits. The fundamental approach to electromagnetic compatibility (EMC) in the arena of surges is the requirement that equipment immunity and characteristics of the surge environment characteristics should be properly coordinated. By definition, the duration of the surges considered in this Guide do not exceed a one-half period of the normal mains waveform. They can be periodic or random events andmight appear in any combination of line, neutral, or grounding conductors. They include those surges with amplitudes, durations, or rates of change sufficient to cause equipment damage or operationalupset(seeFigure1.7).Surgeprotectivedevicesactingprimarilyonthevoltageare often applied to divert damaging surges, but the upset can require other remedies.

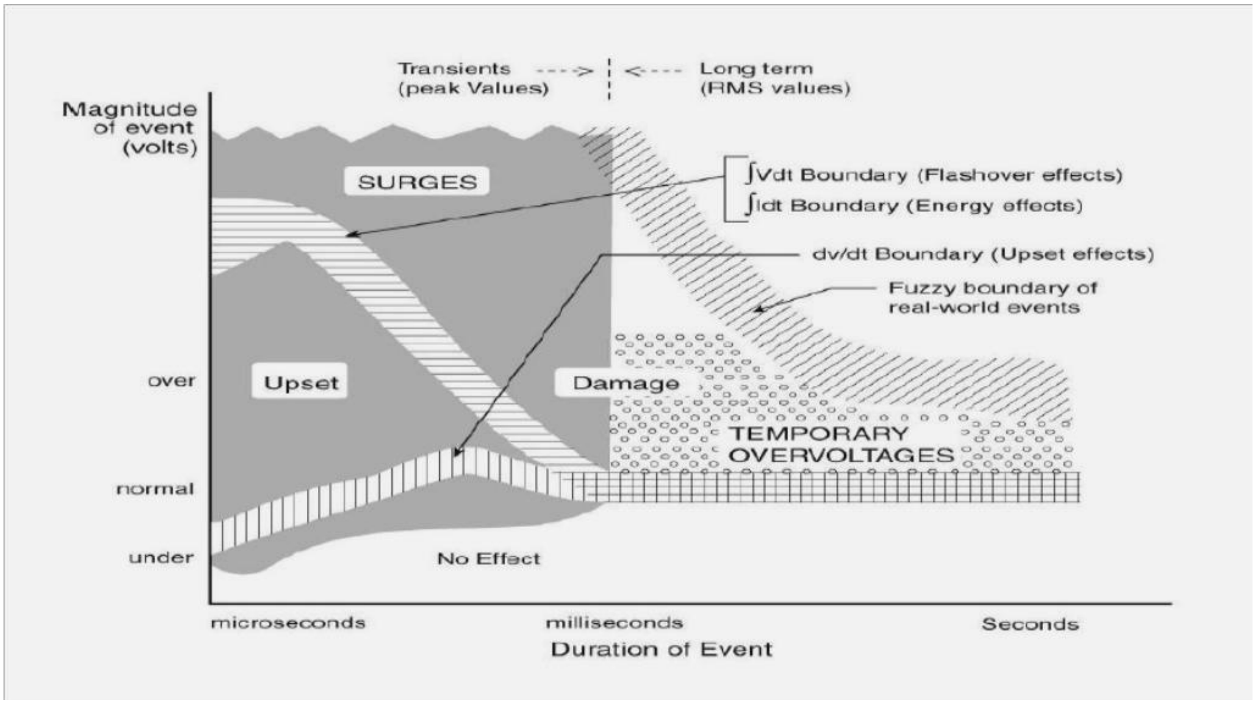

Figure:1.7Simplifiedrelationshipamongvoltage,duration,rateof change, and effect on equipment.

Temporary over voltages represent a threat to equipment as well as to any surge protective devices that may have been provided for the mitigation of surges. The scope of this Guide includes temporary over voltages only as a threat to the survival of SPDs, and therefore includes considerations on the selection of suitable SPDs. No equipment performance requirements are specified in this Guide. What is recommended is a rational, deliberate approach to recognizing the variables that need to be considered simultaneously, using the information presented here to define a set of representative situations. For specific applications, the designer has to take into consideration not only the rates of occurrence and the waveforms described in this Guide, but also the specific power system environment and the characteristics of the equipment in need of protection. As an example, the following considerations are necessary to reach the goal of practical surge immunity:

- Desiredprotection
- Hardwareintegrity
- Process immunity
- Specificequipmentsensitivities
- The power environment
- Surge characteristics

- Electricalsystem
- Performanceofsurgeprotectivedevices
- Protection
- Lifetime
- Thetest environment
- Costeffectiveness

Answers may not exist that address all of the questions raised by the considerations listed above. In particular, those related to specific equipment sensitivities, bothin terms of component failure and especially in terms of processing errors, might not be available to the designer. The goal of the reader may be simply selecting the most appropriate device from among the various surge protective devices available and meet the requirements of the equipment that they must protect. Subsets of the considerations in this section might then apply, and the goal of the reader may then be the testing of various surge protective devices under identical test conditions. The following can guide the reader in identifying parameters, seeking further facts, or quantifying a test plan.

DesiredLevelof Protection

The desired level of protection can vary greatly depending upon the application. For example, in applications not involving online performance, protection may only be needed to reduce hardware failures by a certain percentage. In other cases, such as data processing or critical medical or manufacturing processes, any interruption or upset of a process might be unacceptable. Hence, the designer should quantify the desired goal with regard to the separate questions of hardware failure and process interruption or upset.

Equipment Sensitivities

Specific equipment sensitivities should be defined in concert with the above-mentioned goals. The sensitivities (immunity) will be different for hardware failure or process upset. Such definitions might include: maximum amplitude and duration of the surge remnant that can be tolerated, wave-form or energy sensitivity, et cetera.

PowerEnvironment

The applicable test waveforms recommended in this Guide should be quantified on the basis of the location categories and exposure levels as explained in the corresponding clauses of the Guide. The magnitude of the rams voltage, including any anticipated variation, should be quantified. Successful application of surge protective devices requires taking into consideration occasional abnormal occurrences. It is essential that an appropriate selection of the SPD limiting voltage is based on actual characteristics of the mains voltage.

PerformanceofSurgeProtectiveDevices

Evaluation of a surge protective device should verify a long life in the presence of both the surge and electrical system environments described above. At the same time, its remnant and voltage levels should provide a margin below the immunity levels of the equipment in order to achieve the desired protection. It is essential to consider all of these parameters simultaneously. For example, the use of a protective device rated very close to the nominal system voltage might provide attractive remnant figures, but can be unacceptable when a broad range of occasional abnormal deviations in the amplitude of the mains waveform are considered. Lifetime or overall performance of the SPDs should not be sacrificed for the sake of a low remnant.

TestEnvironment

The surge test environment should be carefully engineered with regard to the preceding considerations and any other parameters that are important to the user. A typical description of the test-environment includes definitions of simultaneous voltages and currents, along with proper demonstrations of short-circuit.

It is important to recognize that the specification of an open-circuit voltage without simultaneousshort-circuitcurrentcapabilityismeaningless.CostEffectivenessThecostofsurge protectioncanbe small, compared tooverallsystemcost and benefitsinperformance. Therefore, added quality and performance in surge protection may be chosen as a conservative engineering approach to compensate for unknown variables in the other parameters. This approach can provide excellent performance in the best interests of the user, while not significantly affecting overall system cost.

Definitions

Thedefinitionsgivenherehavebeendevelopedby severalstandards-writing organizations and have been harmonized.

BackFlashover(Lightning):

A flashover of insulation resulting from a lightning strike to part of a network orelectrical installation that is normally at ground potential. Blind Spot: A limited range within the total domain of application of a device, generally at values less than the maximum rating. Operation of the equipment or the protective device itself might fail in that limited range despite the device's demonstration of satisfactory performance at maximum ratings.

ClampingVoltage:

Deprecatedterm.Seemeasuredlimitingvoltage.

Combination Surge (Wave): A surge delivered by an instrument which has the inherent capability of applying a 1.2/50 us voltage wave across an open circuit, and delivering an 8/20 us current wave into a short circuit. The exact wave that is delivered is determined by the instantaneous impedance to which the combination surge is applied.

Combined Multi-Port Spd: A surge protective device integrated in a single package as the means of providing surge protection at two or more ports of a piece of equipment connected to different systems (such as a power system and a communications system).

Coordination Of Spds (Cascade): The selection of characteristics for two or more SPDs to be connected across the same conductors of a system but separated by some decoupling impedance such that, given the parameters of the impedance and of the impinging surge, this selection will ensure that the energy deposited in each of the SPDs is commensurate with its rating.

Direct Strike: A strike impacting the structure of interest or the soil (or objects) within a few meters from the structure of interest. Energy Deposition: The time integral of the power dissipated in a clamping-type surge protective device during a current surge of a specified waveform. Failure Mode: The process and consequences of device failure.

Leakage Current: Any current, including capacitive coupled currents, that can be conveyed from accessible parts of a product to ground or to other accessible parts of the product.

Lightning Protection System (LPS): The complete system used to protect a space against the effects of lightning. It consists of both external and internal lightning protection systems.

Lightning Flash To Earth: An electrical discharge of atmospheric origin between cloud and earth consisting of one or more strikes.

LightningStrike: A singleelectricaldischargeinalightning flashto earth.

Mains: The AC power source available at the point of use in a facility. It consists of the set of electrical conductors (referred to by terms including service entrance, feeder, or branch circuit) for delivering power to connected loads at the utilization voltage level.

Maximum continuous operating voltage (MCOV): The maximum designated root-mean-square (rms) value of power-frequency voltage that may be applied continuously between the terminals of the arrester.

Measured limiting voltage: The maximum magnitude of voltage that appears across the terminals of the SPD during the application of an impulse of specified wave shape andamplitude.

Nearbystrike: Astrike occurring inthevicinityof thestructureof interest.

Nominal System Voltage: A nominal value assigned to designate a system of a given voltage class.

Nominal Arrestor voltage: The voltage across the arrestor measured at a specified pulsed DC current, IN(dc), of specific duration. IN(dc) is specified by the arrestor manufacturer.

One-Port SPD: An SPD having provisions (terminals, leads, plug) for connection to the AC power circuit but no provisions (terminals, leads, receptacles) for supplying current to theAC power loads.

Open-circuit voltage (OCV) : The voltage available from the test set up (surgegenerator, coupling circuit, back filter, connecting leads) at the terminals where the SPD under test will be connected.

Pointofstrike: Thepoint wherealightning strike contactstheearth, astructure, oran LPS.

Pulse life: The number of surges of specified voltage, current amplitudes, and wave shapes that may be applied to a device without causing degradation beyond specified limits. The pulse life applies to a device connected to an AC line of specified characteristics and for pulses sufficiently spaced in time to preclude the effects of cumulative heating.

Response time (arrestor): The time between the point at which the wave exceeds the limiting voltage level and the peak of the voltage overshoot. For the purpose of this definition, limitingvoltageisdefinedwitha8/20Itscurrentwaveformofthesamepeak Currentamplitude as the waveform used for this response time.

Short-Circuit Current (Scc): The current which the test set up (surge generator, coupling circuit, back filter, connecting leads) can deliver at the terminals where the SPD undertestwillbeconnected,withtheSPDreplacedbybondingthetwoleadterminals.(Also sometimes abbreviated as SCI).

SPD disconnect or: A device for disconnecting an SPD from the system in the event of SPDfailure.Itistopreventapersistentfaultonthesystemandtogiveavisibleindicationofthe SPD failure.

Surge Response Voltage: The voltage profile appearing at the output terminals of a protectivedeviceandappliedtodownstreamloads,duringandafteraspecifiedimpingingsurge, until normal stable conditions are reached.

SurgeProtectivedevice(SPD): Adevicethatisintendedtolimittransientovervoltages and divert surge currents. It contains at least one nonlinear component—a surge reference equalizer. A surge protective device used for connecting equipment to external systems whereby all conductors connected to the protected load are routed—physically and electrically—through a single enclosure with a shared reference point between the input and output ports of each system.

Swell: A momentary increase in the power frequency voltage delivered by themains,outsideofthenormaltolerances,withadurationofmorethanonecycleandlessthan a few seconds.

SwitchingSurgeTestVoltage Characteristics

Switching surges assume great importance for designing insulation of overhead lines operating at voltages more than 345 kV. It has been observed that the flashover voltage for various geometrical arrangements under unidirectional switching surge voltages decreases with increasing the front duration of the surge and the minimum switching surge corresponds to the rangebetween100 and500μsec.However,timetohalfthevaluehasno effect asflashovertakes place either at the crest or before the crest of the switching surge. Fig.1.8 gives the relationship between the criticalflashover voltage per meter as a function of time toflashover for on a 3 mrod-rod gap and a conductor-plane gap.

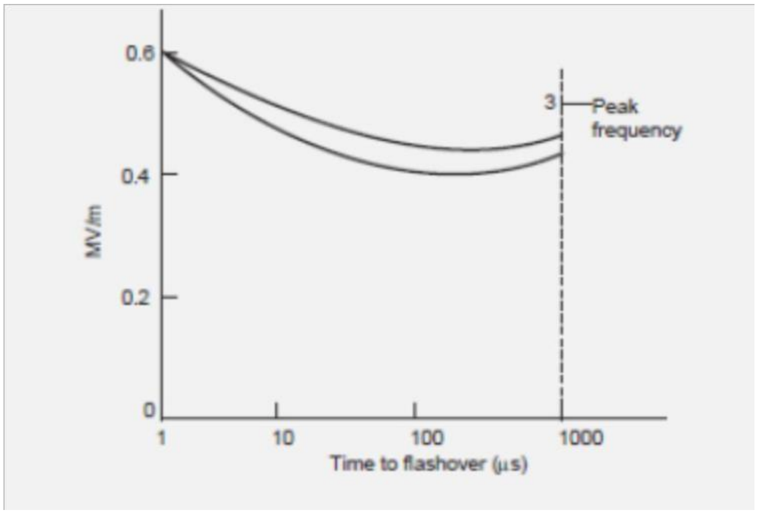

Figure:1.8 Variationof F.O.V/mas a functionoftimeto flashover

It can be seen that the standard impulse voltage (1/50 µ sec) gives highest flashover voltage and switching surge voltage with front time varying between 100 to 500 µ sec has lower flashover voltages compared to power frequency voltage. The flashover voltage not onlydepends upon the crest time but upon the gap spacing and humidity for the same crest time surges.

It has been observed that the switching surge voltage per meter gap length decreases drastically with increase in gap length and, therefore, for ultrahigh voltage system, costly design clearances are required. Therefore, it is important to know the behavior of external insulation with different configuration under positive switching surges as it has been found that for nearly all gap configurations which are of practical interest positive switching impulse is lower than the negative polarity switching impulse.

It has also been observed that if the humidity varies between 3 to 16 gm/m3, the breakdown voltage of positive and gaps increases approximately 1.7% for 1 gm/m3 increase in absolute humidity. For testing purposes the switching surge has been standardized with wave front time 250 µ deceit is known that the shape of the electrode has a decided effect on the flashover voltage of the insulation.

Lot of experimental work has been carried on the switching surge flash over voltage furlong gaps using rod-plane gap and it has been attempted to correlate these voltages with switching surge flash over voltage of other configuration electrodes. Several investigators have shownthatifthegaplengthvariesbetween2to8m,the50%positiveswitchingsurgeflashover for any configurations given by the expression

$$V_{50} = 500\ kd^{0.6}\ \text{kV}$$

where d is the gap length in meters, k is the gap factor which is a function of electrode geometry. Forrod-plane gaps K=1.0. Thus Krepresents aproportionality content and is equal to 50% flash overvoltage of any gap geometry to that of a rod-plane gap for the same gap spacing

$$k = \frac{V_{50}}{V_{50}\text{rod} - \text{plane gap}}$$

i.e., The expression for V50 applies to switching impulse of constant crest time. A more general expression which applies to longer times to crest has been proposed as follows :

$$V_{50} = \frac{3450\ K}{1 + \frac{8}{d}}\ \text{kV}$$

here K and d have the same meaning as in the equation above. The gap factor K depends mainly on the gap geometry and hence on the field distribution in the gap. Shown in Fig 1.9

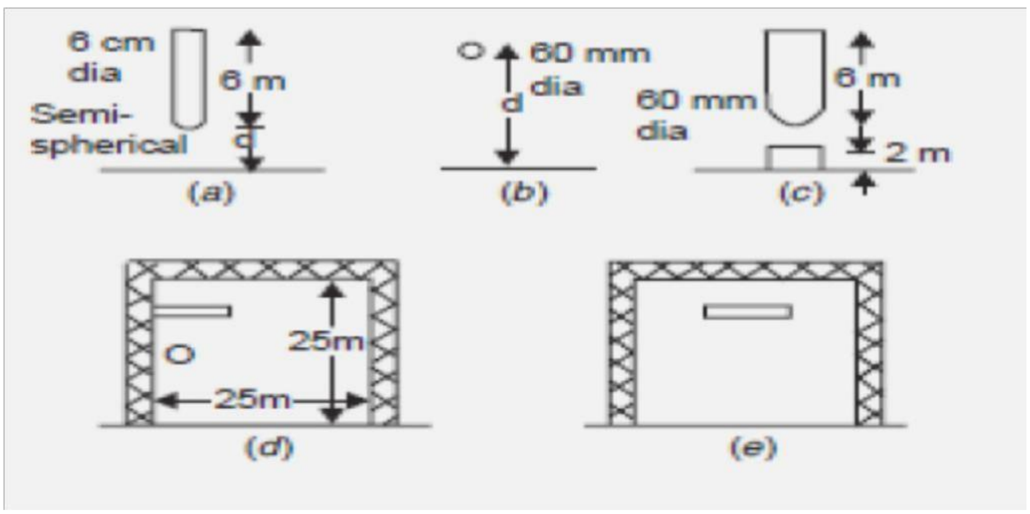

Figure:1.9Differentgap geometries

OvervoltageProtection

The causes of over voltages in the system have been studied extensively in previous sections. Basically, there are two sources: (i) external over voltages due to mainly lightning, and

(ii) internal overvoltage mainly due to switching operation. The system can be protected against external over voltages using what are known as shielding methods which do not allow an arcpath to form between the line conductors and ground, thereby giving inherent protection in the line design. For protection against internal voltages normally non-shielding methods are used which allow an arc path between the ground structure and the line conductor but means are provided to quench the arc. The use of ground wire is a shielding method whereas the use of spark gaps, and lightning arresters are the non-shielding methods. We will study first the non- shielding methods and then the shielding methods. However, the non shielding methods can also be used for external over voltages.

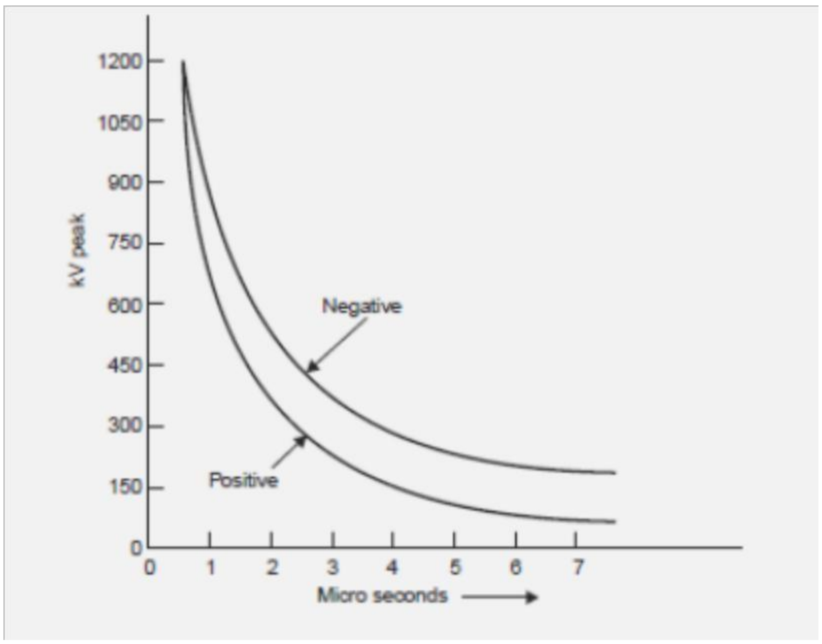

Figure:1.10Volt-timecurvesofgapsforpositive andnegative polarity

The non-shielding methods are based upon the principle of insulation breakdown as the Overvoltage is incident on the protective device; thereby a part of the energy content in the overvoltage is discharged to the ground through the protective device. The insulation breakdown is not only a function of voltage but it depends upon the time for which it is applied and also it depends upon the shape and size of the electrodes used.

The steeper the shape of the voltage wave, the larger will be the magnitude of voltage required for breakdown; this is because an expenditure of energy is required for the rupture of any dielectric, whether gaseous, liquid or solid, and energy involves time. The energy criterion for various insulations can be compared in terms of a common term known as Impulse Ratio which is defined as the ratio of breakdown voltage due to an impulse of specified shape to the breakdown voltage at power frequency. The impulse ratio for sphere gap is unity because thisgap has a fairly uniform field and the breakdown takes place on the field ionization phenomenon mainly whereas for a needle gap it varies between 1.5 to 2.3 depending upon the frequency and gap length. This ratio is higher than unity because of the non-uniform field between the electrodes.

The impulse ratio of a gap of given geometry and dimension is greater with solid than with air dielectric. The insulators should have a high impulse ratio for an economic design whereas the lightning arresters should have a low impulse ratio so that a surge incident on the lightning arrester may be-by passed to the ground instead of passing it on to the apparatus. The volt-time characteristics of gaps having one electrode grounded depend upon the polarity of the voltage wave. From Fig.1.10 it is seen that the volt-time characteristic for positive polarity is lowerthanthenegativepolarity,i.e.thebreakdownvoltageforanegativeimpulseis greaterthan forapositivebecauseofthenearnessofearthedmetalorofcurrent carryingconductors. Forpost insulators the negative polarity wave has a high breakdown value whereas for suspension insulators the reverse is true.

Horn Gap

The horn gap consists of two horn-shaped rods separated by a small distance. One end of this is connected to be line and the other to the earth as shown in Fig. 1.11, with or without a series resistance. The choke connected between the equipment to be protected and the horn gap serves two purposes: (i) The steepness of the wave incident on the equipment to be protected is reduced. (ii) It reflects the voltage surge back on to the horn.

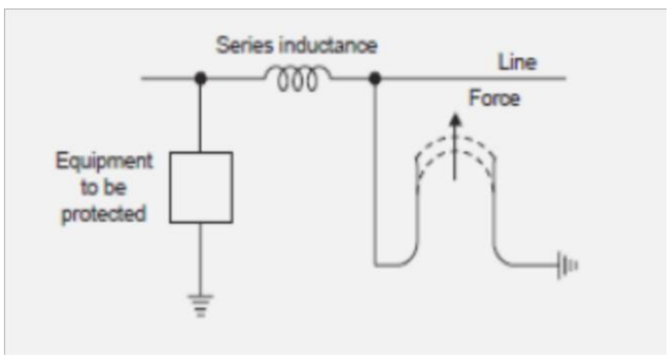

Figure:1.11Horngapconnected inthesystemforprotection

Whenever a surge voltage exceeds the breakdown value of the gap a discharge takesplace and the energy content in the rest part of the wave is by-passed to the ground. An arc is set upbetweenthegap,whichactslikeaflexibleconductorandrisesupwardsundertheinfluenceof the electro-magnetic forces, thus increasing the length of the arc which eventually blows out. There are two major drawbacks of the horn gap; (*i*) The time of operation of the gap is quitelargeascomparedtothemodern protectivegear.(*ii*)Ifusedonisolatedneutralthehorngapmay constitute a vicious kind of arcing ground. For these reasons, the horn gap has almost vanished from important power lines.

Surge Diverters

Thefollowing arethebasic requirements of asurge diverter:

- Itshouldnotpassanycurrentatnormalorabnormal(normally5%morethanthenormal voltage) power frequency voltage.
- Itshouldbreakdownasquicklyaspossibleaftertheabnormalhighfrequencyvoltage arrives.
- Itshouldnotonlyprotecttheequipmentforwhichitisusedbutshoulddischargethesurge current without damaging itself.
- Itshouldinterruptthepowerfrequencyfollowcurrentafterthesurgeisdischargedto ground.

There are mainly three types of surge diverters: (*i*) Rod gap, (*ii*) Protector tube or expulsion type of lightning arrester, (*iii*) Valve type of lightning arrester. **Rod gap** This type of surge diverter is perhaps the simplest, cheapest and most rugged one. Fig. 1.12 shows one such gap for a breaker bushing. This maytake the form of arcing ring. Fig. 1.13 shows the breakdown characteristics (volt-time) of a rod gap.

For a given gap and wave shape of the voltage, the time for breakdown varies approximately inversely with the applied voltage.

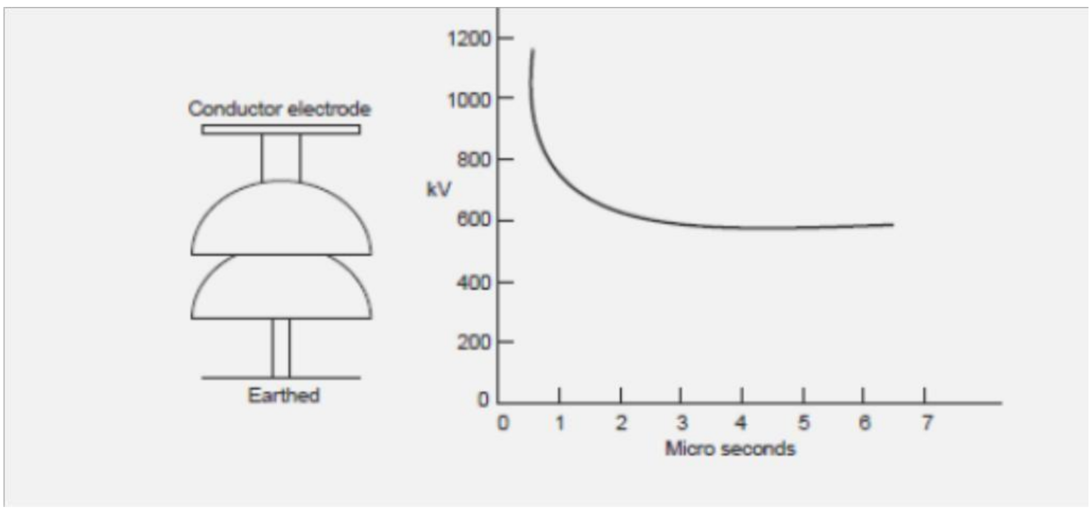

Figure:1.12A rodgap Figure.1.13 Volt-timecharacteristic ofrod gap

The time to flashover for positive polarity is lower than for negative polarities. Also it is found that the flashover voltage depends to some extent on the length of the lower (grounded) rod. For low values of this length there is a reasonable difference between positive (lower value) and negative flashover voltages. Usually a length of 1.5 to 2.0 times the gap spacing is good enoughtoreducethisdifferencetoareasonableamount.Thegap settingnormallychosen issuch that its breakdown voltage is not less than 30% below the voltage withstand level of the equipment to be protected. Even though rod gap is the cheapest form of protection, it suffersfrom the major disadvantage that it does not satisfy one of the basic requirements of a lightning arresterlistedat no. (*iv*)*i.e.*, it does not interrupt thepower frequency followcurrent. This means that every operation of the rod gap results in a *L*-*G* fault and the breakers must operate to de- energize the circuit to clear the flashover. The rod gap, therefore, is generally used as back up protection.

Expulsiontypeoflightningarrester

Animprovementoftherodgapis theexpulsiontubewhichconsistsof(i) aseriesgap(1) external to the tube which is good enough to withstand normal system voltage, thereby there isno possibility of corona or leakage current across the tube; (ii) a tube which has a fiber lining on theinnersidewhich isahighlygasevolvingmaterial;(iii)asparkgap(2)inthetube; and(iv)an open vent at the lower end for the gases to be expelled (Fig. 1.14). It is desired that the breakdown voltage of a tube must be lower than that of the insulation for which it is used. When

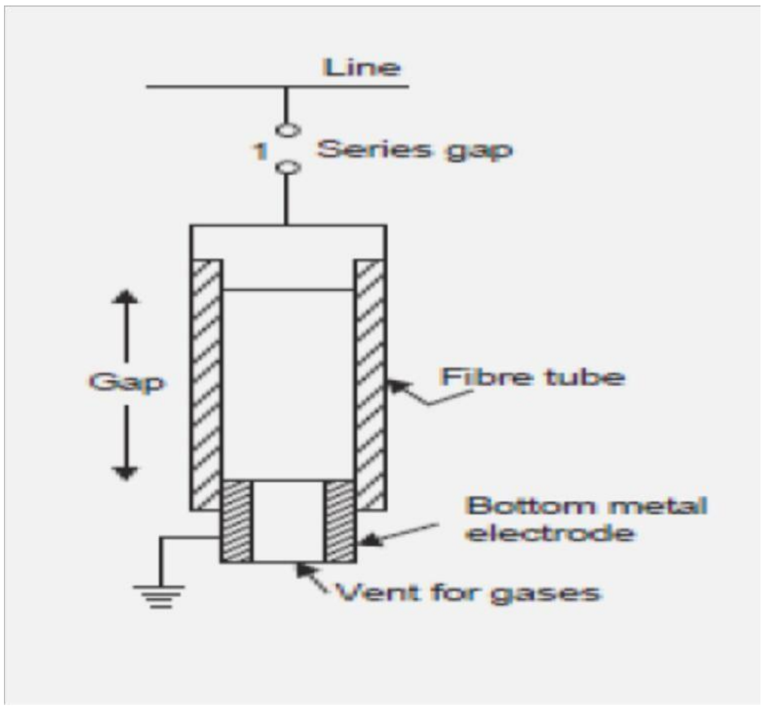

Figure:1.14Expulsiontype

SurgeProtectionofRotatingMachine

A rotating machine is less exposed to lightning surge as compared to transformers. Because of the limited space available, the insulation on the windings of rotating machines is kept to a minimum. The main difference between the winding of rotating machine and transformer is that in case of rotating machines the turns are fewer but longer and are deeply buried in the stator slots. Surge impedance of rotating machines in approx. 1000 Ω and since the inductance and capacitance of the windings are large as compared to the overhead lines the velocity of propagation is lower than on the lines. For atypical machine it is 15 to 20 metres/ μ sec. This means that in case of surges with steep fronts, the voltage will be distributed or concentrated at the first few turns. Since the insulation is not immersed in oil, its impulse ratio is approx. unity whereas that of the transformer is more than 2.0.

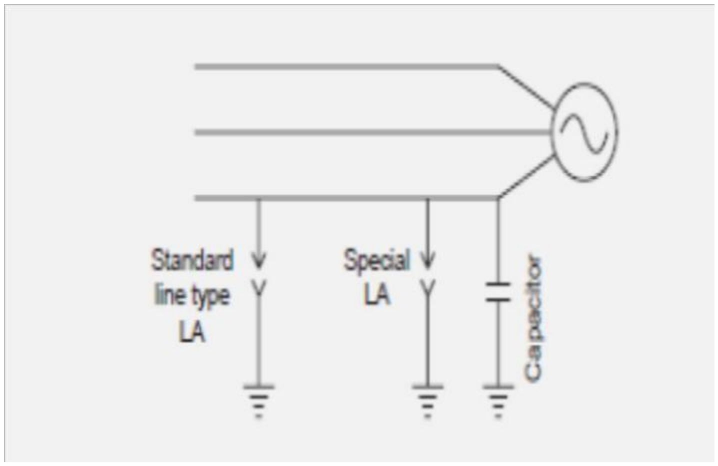

Figure:1.15SurgeProtectionofRotating Machine

The rotating machine should be protected against major and minor insulations. By major insulation is meant the insulation between winding and the frame and minor insulation means inter-turn insulation. Themajor insulation is normally determined by theexpectedline-to-ground voltage across the terminal of the machine whereas the minor insulation is determined by the rate of rise of the voltage. Therefore, in order to protect the rotating machine against surges requires limiting the surge voltage magnitude at the machine terminals and sloping the wavefront of the incoming surge. To protect the major insulation a special lightning arrester is connected at the terminal of the machine and to protect the minor insulation a condenser of suitable rating is connected at the terminals of the machine as shown in Fig. 1.15.

SYSTEMFAULTSANDOTHERABNORMALCONDITIONS

The shunt capacitances are also shown. Under balanced conditions and complete transposed transmission lines, the potential of the neutral is near the ground potential and the currents in various phases through the shunt capacitors are leading their corresponding voltages by 90°. They are displaced from each other by 120° so that the net sum of the three currents is zero (Fig. 1.16). Say there is line-to-ground fault on one of the three phases (say phase _c‘).The voltage across the shunt capacitor of that phase reduces to zero whereas those of the healthy phases become line-to-line voltages and now they are displaced by 60° rather than 120°. The net charging current now is three times the phase current under balanced conditions (Fig.1.16 (c)). These currents flow through the fault and the windings of the alternator. The magnitude of this current is often sufficient to sustain an arc and, therefore, we have an arcing ground. This could be due to a flashover of a support insulator. Here this flashover acts as a switch. If the arc extinguishes when the current is passing through zero value, the capacitors in phases a and b are charged to linevoltages. Thevoltageacrossthelineand thegrounded points ofthepost insulator will bethesuper-position ofthe capacitorvoltage and the generator voltageand this voltagemay be good enough to cause flashover which is equivalent to strike in a circuit breaker. Because of thepresenceoftheinductanceofthegeneratorwinding,thecapacitanceswillformanoscillatory circuit and these oscillations may build up to still higher voltages and the arc may reignite causing further transient disturbances which may finally lead to complete rupture of the post insulators.

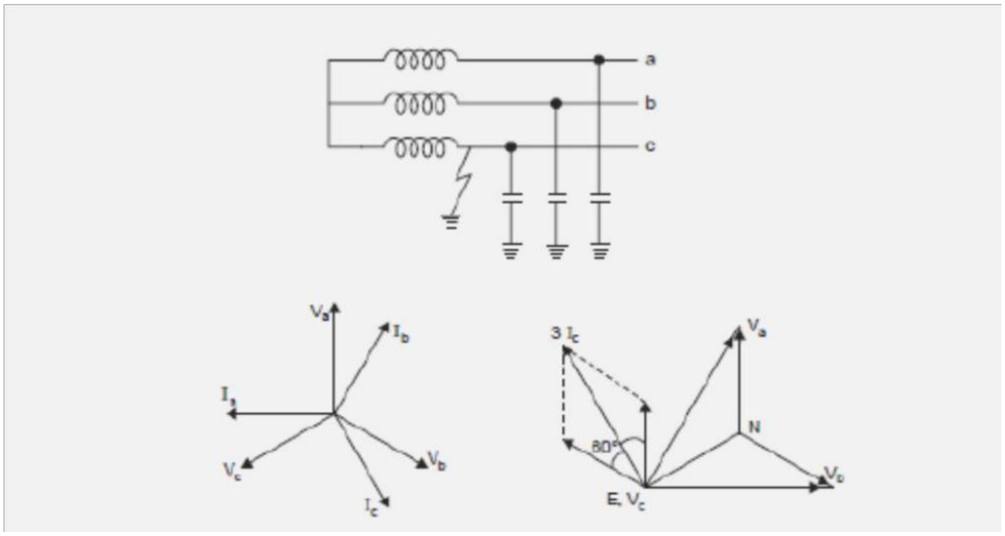

Figure:1.16(a)3-phasesystemwithisolatedneutral;(b)Phasordiagramunderhealthy condition; (c) Phasor diagram under faulted condition.

BewleyLattice Diagram

This is a convenient diagram devised by Bewley, which shows at a glance the position and direction of motion of every incident, reflected, and transmitted wave on the system at every instant of time. The diagram overcomes the difficulty of otherwise keeping track of the multiplicity of successive reflections at the various junctions.

Consideratransmissionlinehaving aresistance **r**, aninductance **l**,a conductance **g**anda capacitance **c**, all per unit length.

If _ is the propagation constant of the transmission line, and **E** is the magnitude of the voltage surge at the sending end, then the magnitude and phase of the wave as it reaches any section distance **x** from the sending end is **Ex** given by.

*E = E .e= E .e= E ee -x-(+ j) x-x-j xx*γ αβα β

where

e representstheattenuationinthelengthoflinex

e-j representsthephaseanglechangeinthelength of linex

Therefore,

attenuationconstantofthelineinneper/km phase angle constant of the line in rad/km.

Itisalsocommonforanattenuationfactorktobedefined correspondingtothelengthofa particular line. i.e.

k=efor alineof length l.

Whenavoltagesurgeofmagnitudeunityreachesajunctionbetweentwosectionswith surge impedances Z_1 and Z_2, then a part is transmitted and a part is reflected back. In traversing the second line, if the attenuation factor is k, then on reaching the termination at the end of the second line its amplitude would be reduced. The lattice diagram may now be constructed as follows. Set the ends of the lines at intervals equal to the time of transit of each line. If a suitable time scale is chosen, then the diagonals on the diagram show the passage of the waves.

IntheBewleylatticediagram,thefollowingpropertiesexist. All

- waves travel downhill, because time always increases.
- Thepositionofany wave atany timecanbededuced directlyfromthediagram.
- Thetotal potential at any point, at any instant oftimeis thesuperposition ofall thewaves which have arrived at that point up until that instant of time, displaced in position from each other by intervals equal to the difference in their time of arrival.
- The history of the wave is easily traced. It is possible to find where it came from and just what other waves went into its composition.
- Attenuation is included, so that the wave arriving at the far end of a line corresponds to the value entering multiplied by the attenuation factor of the line.

UNITII ELECTRICALBREAKDOWN INGASES, SOLIDSANDLIQUIDS

INTRODUCTION

With ever increasing demand of electrical energy, the power system is growing both in size and complexities. The generating capacities of power plants and transmission voltage are on the increase because of their inherent advantages. If the transmission voltage is doubled, the power transfer capability of the system becomes four times and the line losses are also relatively reduced.Asaresult,itbecomesastrongerandeconomicalsystem.In India,wealreadyhave400 kV lines in operation and 800 kV lines are being planned. In big cities, the conventional transmission voltages (110 kV–220 kV etc.) are being used as distribution voltages because of increased demand.

A system (transmission, switchgear, etc.) designed for 400 kV and above using conventional insulating materials is both bulky and expensive and, therefore, newer and newer insulating materials are being investigated to bring down both the cost and space requirements. The electrically live conductors are supported on insulating materials and sufficient airclearances are provided to avoid flashover or short circuits between the live parts of the system and the grounded structures. Sometimes, a live conductor is to be immersed in an insulating liquid to bring down the size of the container and at the same time provide sufficient insulation between the live conductor and the grounded container. In electrical engineering all the three media, viz. the gas, the liquid and the solid are being used and, therefore, we study here the mechanism of breakdown of these media.

CLASSICALGASLAWS

In the absence of electric or magnetic fields charged particles in weakly ionized gases participate in molecular collisions. Their motions follow closely the classical kinetic gas theory.

The oldest gas law established experimentally by Boyle and Mariotte states that for a givenamountofenclosedgasataconstanttemperaturetheproductofpressure(p)andvolume (V)isconstantor

$$pV = C = \text{const.} \qquad 2.1$$

Inthesamesystem,ifthepressureiskept constant,thenthevolumesVandV$_0$ are related to their absolute temperatures T and T0 (in K) by Gay–Lussac's law:

$$\frac{V}{V0} = \frac{T}{T_0} \qquad 2.2$$

Whentemperatures areexpressedindegreesCelsius, eqn(2.2)becomes;

$$\frac{V}{V0} = \frac{273+\theta}{273}$$

Equation(2.3) suggeststhat asweapproachΘ=-273°C thevolume ofgas shrinks to zero.Inreality,allgasesliquefybeforereachingthisvalue.

Accordingtoeqn(2.2)theconstantCineqn(2.1)isrelatedtoagiventemperatureT_0 for the volume V_0:

$$pV_0 = C_0 \qquad 2.4$$

SubstitutingV_0fromeqn(2.2)gives

$$pV_0 = \left(\frac{C_0}{T_0}\right) T \qquad 2.5$$

TheratioC_0/T_0_iscalledtheuniversalgasconstantandisdenotedbyR.

Equation(2.5)thenbecomes

$$pV = RT = C \qquad 2.6$$

Numerically R is equal to 8.314 joules/°Kmol. If we take n as the number of moles, i.e. themassmofthegasdividedbyit'smol-mass,thenforthegeneralcaseeqn(2.1)takestheform

$$pV = nC = nRT, \qquad 2.7$$

Equation(2.7)then describesthestateof anidealgas, sincewe assumedthat Ris a constantindependentofthenatureofthegas.Equation(2.7)maybewrittenintermsof gas density N in volume V containing N_1 molecules.

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PuttingN=$N_A$whereN_A=6.02*10 molecules/mole,$N_A$isknownasthe Avogadro's number.Theneqn(2.7)becomes

$$pV = \frac{N_1}{N_A} RT = N_1 kT \text{ or } p = NkT \qquad 2.8$$

Theconstantk=R/NAistheuniversalBoltzmann'sconstant(=1.3804*10^{23} joules/°K) and N is the number of molecules in the gas.

Thefundamentalequationforthekinetictheoryofgasisderivedwiththe following assumed conditions:

- Gasconsistsofmoleculesofthesamemasswhichareassumedspheres.
- Molecules are in continuous random motion.
- Collisionsareelastic – simple mechanical.
- Meandistancebetweenmoleculesismuchgreaterthantheirdiameter.

CORONADISCHARGES

Inuniformfieldandquasi-uniformfieldgapstheonsetofmeasurableionizationusually leads to complete breakdown of the gap. In non-uniform fields various manifestations of luminous and audible discharges are observed long before the complete breakdown occurs.These discharges may be transient or steady state and are known as ‘coronas’. An excellent review of the subject may be found in a book by Loeb.

The phenomenon is of particular importance in h.v. engineering where non-uniformfields are unavoidable. It is responsible for considerable power losses from h.v. transmissionlines and often leads to deterioration of insulation by the combined action of the discharge ions bombarding the surface and the action of chemical compounds that are formed by the discharge.

It may give rise to interference in communication systems. On the other hand, it has various industrial applications such as high-speed printing devices, electrostatic precipitators, paint sprayers, Geiger counters, etc. The voltage gradient at the surface of the conductor in air required to produce a visual a.c. corona in air is given approximately by the Peek’s expression. There is a distinct difference in the visual appearance of a corona at wires under differentpolarity oftheapplied voltage. Under positivevoltage, a coronaappearsin theform of auniform bluish-white sheath over the entire surface of the wire.

Onnegativewires thecoronaappearsas reddish glowing spots distributedalong thewire. The number of spots increases with the current. Stroboscopic studies show that with alternating voltages a corona has about the same appearance as with direct voltages. Because of thedistinctly different properties of coronas under the different voltage polarities it is convenient to discuss separately positive and negative coronas. In this section a brief review of the main features of corona discharges and their effect on breakdown characteristics will be included. For detailed treatment of the basic fundamentals of this subject the reader is referred to other literature sources.

Positive oranodecoronas

The most convenient electrode configurations for the study of the physical mechanism of coronas are hemi spherically capped rod-plane or point-plane gaps. In the former arrangement,byvaryingtheradiusoftheelectrodetip,different degreesof fieldnon-uniformitycanbereadily achieved. The point plane arrangement is particularly suitable for obtaining a high localized stress and for localization of dense space charge. In discussing the corona characteristics andtheir relation to the breakdown characteristics it is convenient to distinguish between the phenomena that occur under pulsed voltage of short duration (impulse corona), where no space charge is permitted to drift and accumulate, and under long lasting (d.c.) voltages (static field corona).

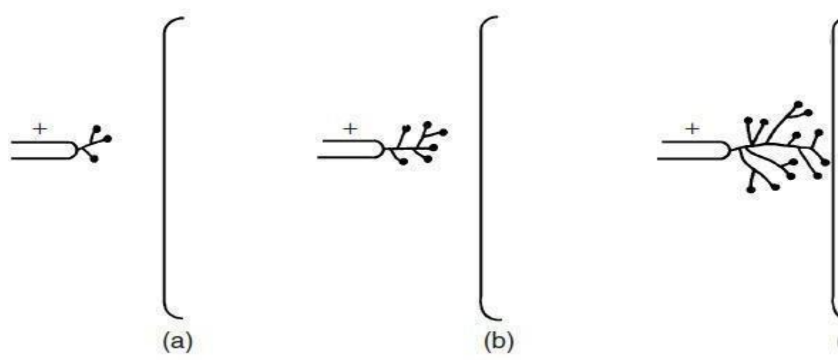

Figure:2.1Schematicillustrationoftheformationofstreamersunderimpulsevoltage- progressive growth with increasing pulse duration-positive rod-plane gap

Underimpulsevoltagesatalevel just above ionizationthreshold,because of thetransient development of ionization, the growth of discharge is difficult to monitor precisely. However, with the use of ‘Lichtenberg figures’ techniques, and more recently with high-speedphotographic techniques, it has been possible to achieve some understanding of the various discharge stages preceding breakdown under impulse voltages.

The observations have shown that when a positive voltage pulse is applied to a point electrode, the first detectable ionization is of a filamentary branch nature, as shown diagrammatically in Fig. 2.1(a). This discharge is called a streamer and is analogous to the case ofuniform fieldgapsathigherpdvalues.As theimpulsevoltagelevelisincreased,thestreamers grow both in length and their number of branches as indicated in Figs 2.1(b) and (c). One of the interesting characteristics is their large number of branches which never cross each other. The velocity of the streamers decreases rapidly as they penetrate the low field region.

Negativeorcathode corona

Withanegativepolaritypoint-planegapunderstaticconditionsabovetheonsetvoltage thecurrentflowsinvery regularpulses asshowninFig.2.2(b),whichindicatesthenatureofa single pulse and the regularity with which the pulses are repeated. The pulses were studied in detail by Trichel and are named after their discoverer as ‘Trichel pulses’.

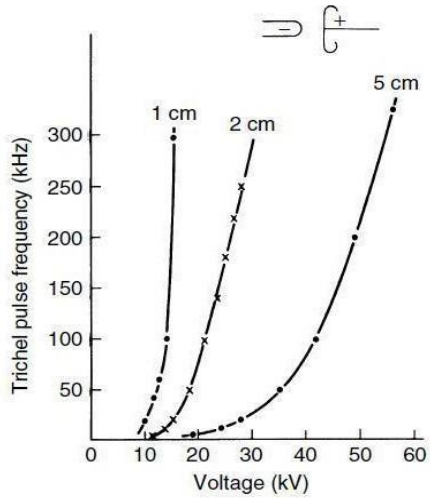

Figure:2.2Trichelpulsefrequency–voltagerelationshipfordifferentgaplengthsinair(r= 0.75mm)

The onset voltage is practically independent of the gap length and in value is close to the onset of streamers under positive voltage for the same arrangement.

Thepulsefrequency increases with thevoltage and depends upon theradius ofthe cathode, the gap length and the pressure. The relationship between the pulse frequency and the gapvoltage for different gap lengths and a cathode point of 0.75mm radius in atmospheric air is shown in Fig. 2.2. A decrease in pressure decreases the frequency of the Trichel pulses.

IONIZATIONANDDECAYPROCESSES

Atnormal temperatureandpressuregases areexcellent insulators. Theconduction in air atlowfieldisintheregion10^{-16} – 10^{-17} A/cm2.Thesecurrentresultsfromcosmicradiations

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andradioactivesubstancespresentinearthandtheatmosphere.Athigherfieldschargedparticles may gain sufficient energy between collisions to cause ionization on impact with neutral molecules.

It was shown in the previous section that electrons on average lose little energy in elastic collisionsandreadilybuilduptheirkineticenergywhichmaybesuppliedbyanexternalsource, e.g. an applied field. Ontheotherhand, duringinelasticcollisions alargefraction oftheirkinetic energy is transferred into potential energy, causing, for example, ionization of the struck molecule. Ionization by electron impact is for higher field strength the most important process leading to breakdown of gases. The effectiveness of ionization by electron impact depends upon the energy that an electron can gain along the mean free path in the direction of the field.

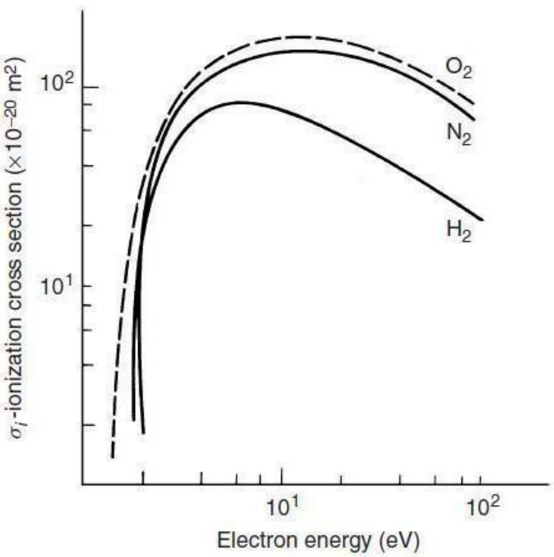


Figure: 2.3 Variation of ionization cross-sections for O2, N2, H2 with electron energy

Thissimplemodelisnotapplicableforquantitativecalculations,becauseionizationby collision, as are all other processes in gas discharges, is a probability phenomenon, and is generallyexpressedintermsofcross-sectionforionizationdefinedastheproductPiσ=σiwhere Pi is the probability of ionization on impact and σ is the molecular or atomic cross-sectional area for interception defined earlier. The cross-section &i is measured using monoenergetic electron beams of different energy. The variation of ionization cross-sections for H2, O2, and N2 with electron energy.

It is seen that the cross-section is strongly dependent upon the electron energy. At energies below ionization potential the collision may lead to excitation of the struck atom or molecule which on collision with another slow moving electron may become ionized. This process becomes significant only when densities of electrons are high. Very fast moving electrons may pass near an atom without ejecting an electron from it. For every gas there exists an optimum electron energy range which gives a maximum ionization probability.

TOWNSEND'SCRITERION

Townsendfirstionization coefficient

In the absence of electric field the rate of electron and positive ion generation in an ordinary gas is counterbalanced by decay processes and a state of equilibrium exists. This stateof equilibrium will be upset upon the application of a sufficiently high field. The variation of the gas current measured between two parallel plate electrodes was first studied as a function of the applied voltage by Townsend.

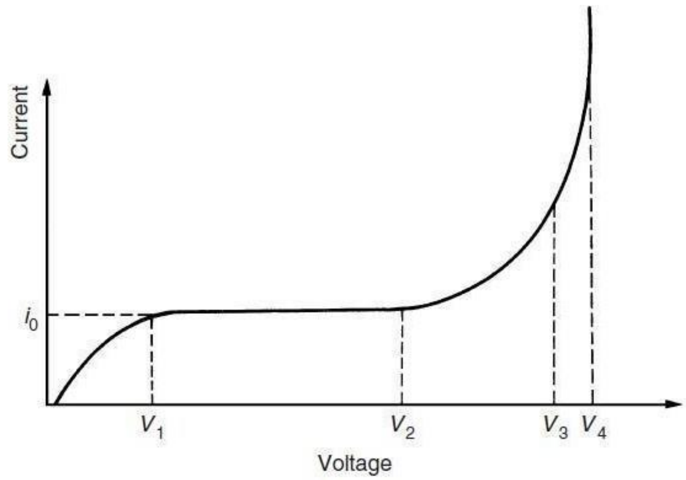


Figure:2.4Current–voltagerelationshipinpresparkregion

Townsend found that the current at first increased proportionately with the applied voltage and then remained nearly constant at a value i_0 which corresponded to the background current(saturationcurrent),orifthecathodewasirradiatedwithau.v.light,$i_0$gavetheemitted photocurrent. At still higher voltage the current increased above the value i_0 at an exponential rate. The general pattern of the current–voltage relationship is shown schematically in Fig. 2.4.

TheincreaseincurrentbeyondV$_2$ Townsendascribedtoionizationofthegasbyelectron collision. As the field increases, electrons leaving the cathode are accelerated more and more between collisions until they gain enough energy to cause ionization on collision with gas molecules or atoms.

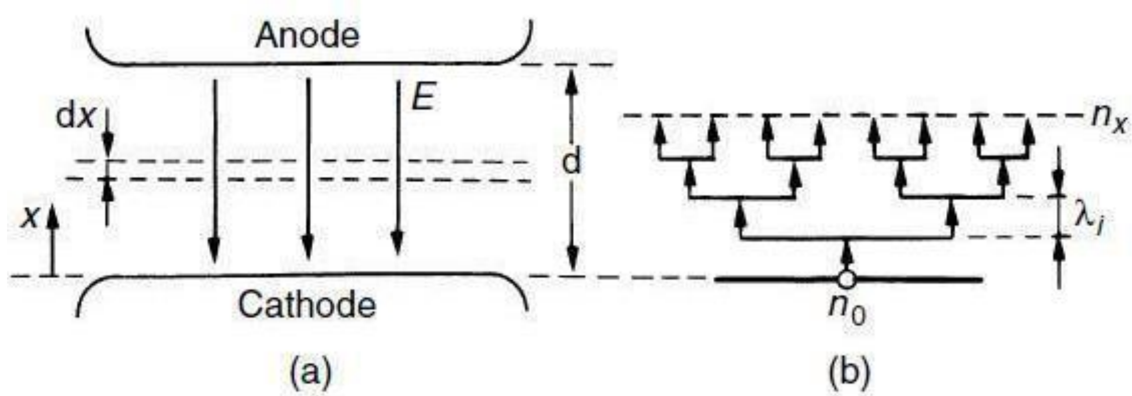


Figure:2.5Schematicrepresentationofelectronmultiplication(a)gap arrangement,(b) Electron avalanche

To explain this current increase Townsend introduced a quantity α, known as Townsend's first ionization coefficient, defined as the number of electrons produced by an electron per unit length of path in the direction of the field. Thus if we assume that n is the number of electrons at a distance x from the cathode in field direction (Fig. 2.5) the increase in electrons dn inadditional distancedx isgiven by

$dn = \alpha n dx$. 2.9

Integrationoverthedistance(d)

$n = n_0 e^{\alpha d}$ 2.10

wheren$_0$ isthenumberofprimaryelectronsgeneratedatthe cathode. In termsofcurrent, with I_0 the current leaving the cathode, eqn (2.10) becomes

$$I = I_0 e^{\alpha d} \quad 2.11$$

Theterme $^{\alpha d}$ iscalledtheelectron avalanche and itrepresentsthenumber ofelectrons producedbyoneelectronintravellingfromcathodetoanode.Theelectronmultiplicationwithin the avalanche is shown diagrammatically in Fig. 2.3.

$$\frac{\alpha}{p} = \frac{\sigma_i}{KT} e^{-(\sigma i/kT)[Vi/(E/p)]} = A(T) e^{-[B(T)/(E/p)]} \quad 2.12$$

Where

$$A(T) = \frac{\sigma_i}{kT};\ B(T) = \frac{V_i \sigma_i}{kT} \quad 2.13$$

WhereA& B arethe Ionization Constants.

It cannot be expected that the real dependence of α/p upon E/p agrees with measured values within the whole range of E/p, because phenomena which have not been taken into account are influencing the ionization rate. However, even with constant values of A and B, eqn (5.47) determines the ionization process within certain ranges of E/p. Therefore, for variousgases the ‘constants’ A and B have been determined experimentally and can be found in the literature.

Theconstants A and B in eqn (2.13),as derived from kinetictheory, rarely agree with the experimentally determined values. The reasons for this disagreement lies in the assumptions made in our derivations. We assumed that every electron whose energy exceeds eVi will automatically lead to ionization. In reality the probability of ionization for electrons with energy just above the ionization threshold is small and it rises slowly to a maximum value of about 0.5at 4 to 6 times the ionization energy. Beyond that it decreases. We have also assumed that the mean free path is independent of electron energy which is not necessarily true. A rigorous treatment would require taking account of the dependence of the ionization cross-section upon the electron energy.

TownsendSecondIonisation Coefficient

Fromtheequation

$I=I_0 e^{\alpha x}$ Wehave,taking log onboth the sides.

$$\ln I=\ln I_0+\alpha x \qquad 2.14$$

Thisisastraightlineequationwithslopeαandinterceptln I_0 asshowninFig.2.5iffor a given pressure p, E is kept constant.

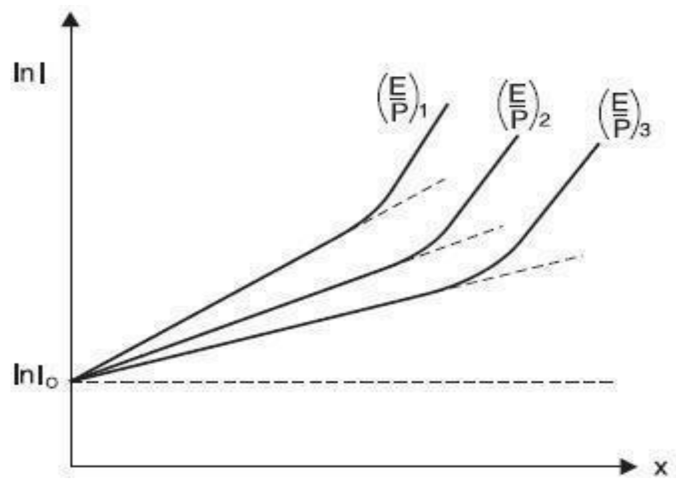


Figure: 2.6 Variation of gap current with electrode spacing in uniform E

Townsendinhisearlierinvestigationshadobservedthatthecurrentinparallelplategap increased more rapidly with increase in voltage as compared to the one given by the above equation.Toexplainthisdeparturefromlinearity,Townsendsuggestedthat asecondmechanism must be affecting the current. He postulated that the additional current must be due to the presence of positive ions and the photons. The positive ions will liberate electrons by collision with gas molecules and by bombardment against the cathode. Similarly, the photons will also release electrons after collision with gas molecules and from the cathode after photon impact.

Let us consider the phenomenon of self-sustained discharge where the electrons are released from the cathode by positive ion bombardment. Let n_0 be the number of electrons releasedfromthecathodebyultravioletradiation, n_+thenumberofelectronsreleased fromthe cathodeduetopositiveionbombardmentandnthenumberofelectronsreachingtheanode.Let ν, known as Townsend second ionization co-efficient be defined as the number of electrons released from cathode per incident positive ion, Then

$$n=(n_0+n_+)e^{\alpha d} \qquad 2.15$$

Nowtotalnumberofelectronsreleasedfromthecathodeis(n_0+n_+)andthosereachingthe anode are n, therefore, the number of electrons released from the gas = $n-(n_0+n_+)$, and corresponding to each electron released from the gas there will be one positive ion and assuming each positive ion releases ν effective electrons from the cathode then

$n_+ = \nu n^- \nu n_0^- \nu n^+$

Substitutingn+forn,we have

$$n = \frac{n_0 e^{\alpha d}}{1+\nu n(1-e^{\alpha d})} = \frac{n_0 e^{\alpha d}}{1-\nu(e^{\alpha d}-1)}$$

In practice positive ions, photons and metastable, all the three may participate in the process of ionization. It depends upon the experimental conditions. There may be more than one mechanism producingsecondaryionizationinthedischargegapand,therefore,itiscustomaryto express the net secondary ionization effect by a single coefficient ν and represent the current by the above equation keeping in mind that ν may represent one or more of the several possible mechanism.

$\nu = \nu_1 + \nu_2 + \nu_3 + ...$

It is to be noted that the value of ν depends upon the work function of the material. If the work function of the cathode surface is low, under the same experimental conditions willproduce more emission. Also, the value of ν is relatively small at low value of E/p and will increase with increase in E/p.

This is because at higher values of E/p, there will be more number of positive ions and photons of sufficiently large energy to cause ionization upon impact on the cathode surface. It is to be noted that the influence of ν on breakdown mechanism is restricted to Townsend breakdown mechanism i.e., to low-pressure breakdown only.

TownsendBreakdown Mechanism

When voltage between the anode and cathode is increased, the current at the anode is given by

$$I = \frac{I_0 e^{\alpha d}}{1-\nu(e^{\alpha d}-1)}$$

Thecurrentbecomesinfinite if

$$1-\nu(e^{\alpha d}-1)=0$$

or $\nu(e^{\alpha d} - 1) = 1$

or $\nu e^{\alpha d} \approx 1$

Sincenormally $e^{\alpha d} >> 1$

The current in the anode equals the current in the external cirrcuit. Theoretically the current becomes infinitely large under the above mentioned condition but practically it is limited by the resistance of the external circuit and partially by the voltage drop in the arc.

Theconditionve$^{\alpha d}$ =1definesthe conditionforbeginningofsparkandisknownasthe Townsendcriterionforsparkformationor Townsendbreakdowncriterion.Usingtheabove equations, the following three conditions are possible.

- $\nu e^{\alpha d} = 1$

  Thenumberof ionpairs produced inthegap bythepassageofarcelectronavalancheis sufficientlylarge andthe resultingpositiveionsonbombardingthecathode areableto relaseonesecondaryelectron and socausearepetition oftheavalancheprocess. The dischargeisthensaidtobeself-sustained asthedischargewillsustainitselfevenif the sourceproducingI_0isremoved.Therefore,theconditionve$^{\alpha d}$=1definesthe threshold sparkingcondition.

- $\nu e^{\alpha d} > 1$

  Hereionizationproducedbysuccessive avalanche iscumulative.Thespark discharge growsmorerapidlythemore $\nu e^{\alpha d}$ exceedsunity.

- $\nu e^{\alpha d} < 1$

  HerethecurrentIisnotself-sustainedi.e.,onremovalofthesourcethecurrentI_0 ceases to flow.

PASCHEN'SLAW

TheTownsend'sCriterion

$$\nu(e^{\alpha d} - 1) = 1$$

enables the evaluation of breakdown voltage of the gap by the use of appropriate values of α/p and ν corresponding to the values E/p when the current is too low to damage the cathode and also the space charge distortions are minimum. A close agreement between the calculated and experimentally determined values is obtained when the gaps are short or long and the pressure is relatively low. An expression for the breakdown voltage for uniform field gaps as a functionofgaplengthandgaspressurecanbederivedfromthethresholdequationbyexpressing the ionization coefficient α/p as a function of field strength E and gas pressure p i.e.,

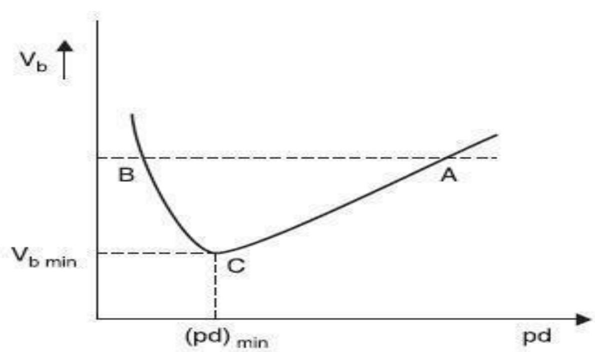


Figure:2.7Paschen'slaw curve

Substitutingthis,wehave

$$e^{f(E/p)pd} = \frac{1}{v} + 1$$

Takingln both thesides, wehave

$$f\left(\frac{E}{p}\right)pd = ln\left[\frac{1}{v} + 1\right] = K \text{ say}$$

Foruniform fieldE = $\frac{v_b}{d}$;

$$f\left(\frac{E}{p}\right)pd = K$$

or

$$f\left(\frac{E}{p}\right) = \frac{K}{pd}$$

or

$$V_b = F\,(p.d)$$

This shows that the breakdown voltage of a uniform field gap is a unique function of the product of gas pressure and the gap length for a particular gas and electrode material. This relation is known as Paschen's law. This relation does not mean that the breakdown voltage is directlyproportionaltoproductpdeventhoughitisfoundthatforsomeregionoftheproductpd the relation is linear i.e., the breakdown voltage varies linearly with the product pd.

STREAMERORKANALMECHANISM OFSPARK

Weknowthat the chargesin betweenthe electrodesseparatedby adistancedincreaseby afactor $e^{\alpha d}$ whenfieldbetweenelectrodesis uniform.Thisisvalidonly ifweassumethat the fieldE$_0$=V/d isnotaffected bythespacechargesofelectronsand positiveions.Raetherhas observedthatifthechargeconcentrationishigherthan10^6butlowerthan10^8thegrowthofan avalanche is weakened i.e., dn/dx < $e^{\alpha d}$.

Whenever the concentration exceeds 10^8, the avalanche current is followed by steep rise in current and breakdown of the gap takes place. The weakening of the avalanche at lower concentrationandrapidgrowthofavalancheathigherconcentrationhavebeenattributedtothe modificationoftheelectricfieldE$_0$ duetothespacechargefield. Fig.2.6showstheelectricfield aroundanavalancheasitprogressesalongthegapandtheresultantfieldi.e.,thesuperposition of the space charge field and the original field E$_0$. Since the electrons have higher mobility, the space charge at the head of the avalanche is considered to be negative and is assumed to be concentrated within a spherical volume. It can be seen from Fig. 2.6 that the filed at the head of the avalanche is strengthened.

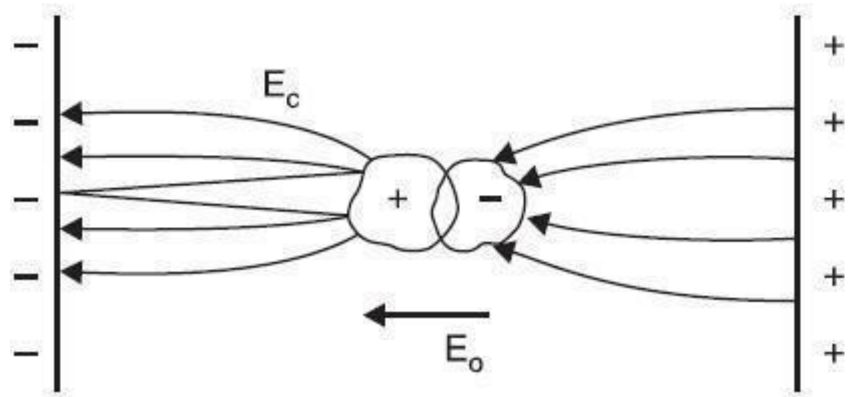


Figure:2.8Fieldredistributionduetospace charge

Thefieldbetweenthetwoassumedchargecentresi.e.,theelectronsandpositiveionsis decreased as the field due to the charge centres opposes the main field E_0 and again the field betweenthepositivespacechargecentreandthecathodeisstrengthenedasthespacecharge field aids the main field E_0 in this region. It has been observed that if the charge carrier number exceeds 10^6, the field distortion becomes noticeable. If the distortion of field is of 1%, it would lead to a doubling of the avalanche but as the field distortion is only near the head of the avalanche, it does not have significance on the discharge phenomenon. However, if the charge carrierexceeds10^8,thespacechargefieldbecomesalmostofthesamemagnitudeasthemain field E_0 and hence it may lead to initiation of a streamer. The space charge field, therefore, plays a very important role in the mechanism of electric discharge in a non-uniform gap.

Townsend suggested that the electric spark discharge is due to the ionization of gas molecule by the electron impact and release of electrons from cathode due to positive ion bombardmentat thecathode. Accordingto thistheory, theformativetimelag ofthespark should beatbestequaltotheelectrontransittimet_r.Atpressuresaroundatmosphericandabovep.d.> 10^3Torr-cm,theexperimentallydeterminedtime lagshavebeenfound tobemuchshorterthan t_r. Study of the photographs of the avalanche development has also shown that under certain conditions, the space charge developed in an avalanche is capable of transforming the avalanche into channels of ionization known as streamers that lead to rapid development of breakdown. It has also been observed through measurement that the transformation from avalanche to streamer generally takes place when the charge within the avalanche head reaches a critical value of

$n_0 e^{\alpha x} \approx 10^8$ or $\alpha X_c \approx 18$ to 20

whereXcisthelengthoftheavalancheparthinfielddirectionwhenitreachesthecritical size. If the gap length d < Xc, the initiation of streamer is unlikely.

The short-time lags associated with the discharge development led Raether and independently Meek and Meek and Loeb to the advancement of the theory of streamer of Kanal mechanismforsparkformation,inwhichthesecondarymechanismresultsfromphotoionization of gas molecules and is independent of the electrodes.

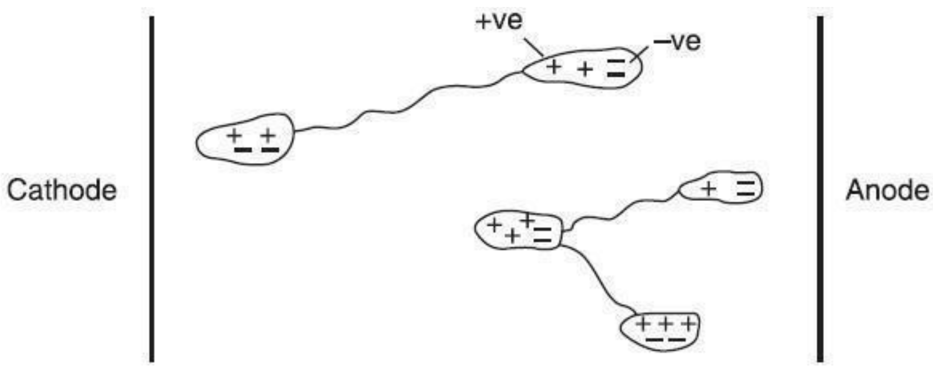


Figure:2.9Secondaryavalanche formationsbyphotoelectrons

RaetherandMeekhaveproposedthatwhentheavalancheinthegapreachesa certain critical size the combined space charge field and externally applied field E_0 lead to intense ionization and excitation of the gas particles in front of the avalanche head. There is recombination of electrons and positive ion resulting in generation of photons and these photons in turn generate secondary electrons by the photo ionization process. These electrons under the influence of the electric field develop into secondary avalanches as shown in Fig. 2.9. Since photons travel with velocity of light, the process leads to a rapid development of conduction channel across the gap.

Raether after thorough experimental investigation developed an empirical relation for the streamer spark criterion of the form

$$\alpha x_c = 17.7 + \ln x_c + \ln\frac{E_r}{E_0}$$

where$E_r$istheradialfieldduetospacechargeandE_0istheexternally

appliedfield.Nowfortransformationofavalancheintoastreamer$E_r \approx E$

Therefore, $\alpha x_c = 17.7 + \ln x_c$

For a uniform field gap, breakdown voltage through streamer mechanism is obtained on theassumptionthatthetransitionfromavalanchetostreameroccurswhentheavalanchehasjust crossed the gap. The equation above, therefore, becomes

$$\alpha d = 17.7 + \ln d$$

Whenthecriticallength$X_c \geq d$minimumbreakdownbystreamermechanismisbroughtabout. The condition $X_c = d$ gives the smallest value of α to produce streamer breakdown.

Meeksuggestedthatthetransitionfromavalanchetostreamertakesplacewhentheradial field about the positive space charge in an electron avalanche attains a value of the order of the externally applied field. He showed that the value of the radial field can be obtained by using the expression.

$$E_r = 5.3 \times 10^{-7} \frac{\alpha e^{\alpha x}}{(x/p)^{1/2}} \text{ volts/cm}$$

wherex isthedistanceincmwhich theavalanchehasprogressed, pthe gaspressureinTorr and

α the Townsend coefficient of ionization by electrons corresponding to the applied field E. The minimum breakdown voltage is assumed to correspond to the condition when the avalanche has crossed the gap of length d and the space charge field E_r approaches the externally applied field i.e., at x = d, E_r = E. Substituting these values in the above equation, we have

$$E_r = 5.3 \times 10^{-7} \frac{\alpha e^{\alpha d}}{(d/p)^{1/2}}$$

Takingln on boththesides, wehave

$$\ln E = -14.5 + \ln \alpha - \frac{1}{2}\ln\frac{d}{p} + \alpha d$$

$$\ln E - \ln p = -14.5 + \ln\alpha - \ln p - \frac{1}{2}\ln\frac{d}{p} + \alpha d$$

$$\ln\frac{E}{p} = -14.5 + \ln\frac{\alpha}{p} - \frac{1}{2}\ln\frac{d}{p} + \alpha d$$

The experimentally determined values of α/p and the corresponding E/p are used to solve the above equation using trial and error method. Values of α/p corresponding to E/p at a given pressure are chosen until the equation is satisfied.

BREAKDOWNINNON-UNIFORMFIELDS

Innon-uniformfields,e.g.inpoint-plane,sphere-planegapsorcoaxialcylinders,the field strength and hence the effective ionization coefficient $\bar{\alpha}$ vary across the gap. The electron multiplicationisgovernedbytheintegralof $\bar{\alpha}$ overthepath($\int \bar{\alpha}\, dx$).Atlowpressuresthe Townsend criterion for spark takes the form

$$\gamma\left[\exp\left(\int_0^d \bar{\alpha}\, dx\right) - 1\right] = 1$$

wheredisthegaplength.Theintegrationmustbetakenalongthelineofthehighestfield strength.

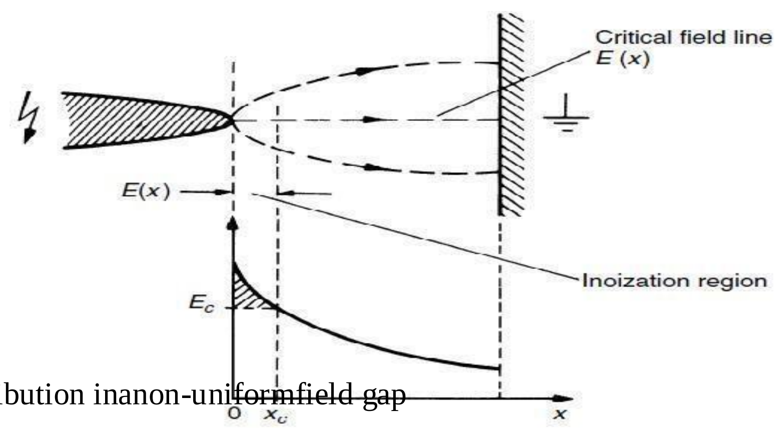


Figure:2.9Electricfielddistribution inanon-uniformfield gap

Theexpressionisvalidalsoforhigherpressuresifthefieldisonlyslightlynon-uniform. Instronglydivergentfieldstherewillbeatfirsta regionofhighvaluesof E/poverwhichα/p> 0.WhenthefieldfallsbelowagivenstrengthE$_c$theintegral$\int \overline{\alpha}$ dxceasestoexist.

Townsend mechanism then loses its validity when the criterion relies solely on the γ effect, especially when the field strength at the cathode is low.

In reality breakdown (or inception of discharge) is still possible if one takes into account photo ionization processes. The criterion condition for breakdown (or inception of discharge) for the general case may be represented to take into account the non-uniform distribution of$\overline{\alpha}$or

$$exp \int_0^{x_{c<d}} \overline{\alpha} dx = N_{cr}$$

8 whereN$_{cr}$isthecriticalelectronconcentrationinanavalanchegivingrisetoinitiation of a streamer (it was shown to be approx. 10), x$_c$is the path of avalanche to reach this size and d the gap length.

$$\int_0^{x_c<d} \overline{\alpha} dx = ln\, N_{cr} \approx 18 - 20 \qquad 2.15$$

Figure 2.9 illustrates the case of a strongly divergent field in a positive point plane gap. Equation (2.15) is applicable to the calculation of breakdown or discharge inception voltage, depending on whether direct breakdown occurs or only corona.

BREAKDOWN IN LIQUIDDIELECTRICS

Liquid dielectrics are used for filling transformers, circuit breakers and as impregnates in high voltage cables and capacitors. For transformer, the liquid dielectric is used both for providing insulation between the live parts of the transformer and the grounded parts besides carrying out the heat from the transformer to the atmosphere thus providing cooling effect. For circuit breaker, again besides providing insulation between the live parts and the grounded parts, the liquid dielectric is used to quench the arc developed between the breaker contacts. The liquid dielectrics mostly used are petroleum oils. Other oils used are synthetic hydrocarbons and halogenated hydrocarbons and for very high temperature applications sillicone oils and fluorinated hyrocarbons are also used.

The three most important properties of liquid dielectric are (i) The dielectric strength (ii) The dielectric constant and (iii) The electrical conductivity. Other important properties are viscosity, thermal stability, specific gravity, flash point etc. The most important factors which affect the dielectric strength of oil are the, presence of fine water droplets and the fibrous impurities. The presence of even 0.01% water in oil brings down the dielectric strength to 20%of the dry oil value and the presence of fibrous impurities brings down the dielectric strength much sharply. Therefore, whenever these oils are used for providing electrical insulation, these should be free from moisture, products of oxidation and other contaminants.

Table:2.1.Dielectricpropertiesofsomeliquids

S.No.	Property	Transformer Oil	Capacitor Oil	Cable Oil	Silicone Oil
1.	Relative permittivity 50 Hz	2.2 – 2.3	2.1	2.3 – 2.6	2.7 – 3.0
2.	Breakdown strength at 20°C 2.5 mm 1 min	12 kV/mm	18 kV/mm	25 kV/mm	35 kV/mm
3.	(*a*) Tan δ 50 Hz	10^{-3}	2.5×10^{-4}	2×10^{-3}	10^{-3}
	(*b*) 1 kHz	5×10^{-4}	10^{-4}	10^{-4}	10^{-4}
4.	Resistivity ohm-cm	$10^{12} – 10^{13}$	$10^{13} – 10^{14}$	$10^{12} – 10^{13}$	2.5×10^{14}
5.	Maximum permissible water content (ppm)	50	50	50	< 40
6.	Acid value mg/gm of KOH	NIL	NIL	NIL	NIL
7.	Sponification mg of KOH/gm of oil	0.01	0.01	0.01	< 0.01
8.	Specific gravity at 20°C	0.89	0.89	0.93	1.0–1.1

The main consideration in the selection of a liquid dielectric is its chemical stability. The other considerations are the cost, the saving in space, suptibility to environmental influences etc. The use of liquid dielectric has brought down the size of equipment tremendously. In fact, it is practicallyimpossibletoconstructa765kVtransformerwithair astheinsulatingmedium. Table 2.1.Showsthepropertiesofsomedielectricscommonlyusedinelectricalequipments.

Liquids which are chemically pure, structurally simple and do not contain any impurity even in traces of 1 in 109, are known as pure liquids. In contrast, commercial liquids used as insulating liquids are chemically impure and contain mixtures of complex organic molecules. In fact theirbehaviouris quiteerratic. Notwo samples ofoil taken out from thesamecontainerwill behave identically. The theory of liquid insulation breakdown is less understood as of today as compared to the gas or even solids. Many aspects of liquid breakdown have been investigated over the last decades but no general theory has been evolved so far to explain the breakdown in liquids. Investigations carried out so far, however, can be classified into two schools of thought.

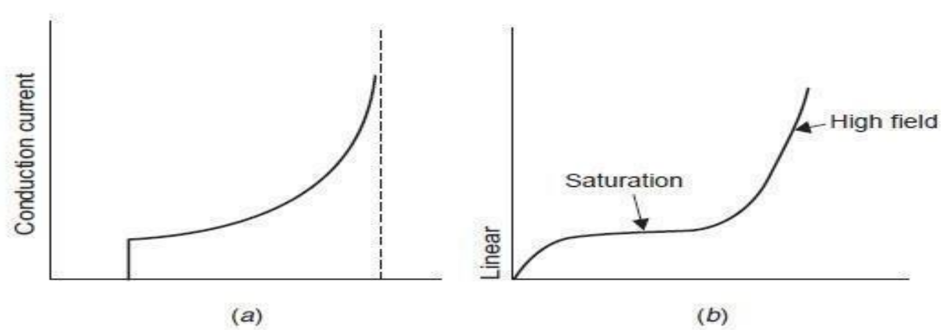


Figure:2.10Variationof currentasafunctionofelectric field
(a)Highfields(b)Lowfields

The first one tries to explain the breakdown in liquids on a model which is an extensionof gaseous breakdown, based on the avalanche ionization of the atoms caused by electon collisiron in the applied field. The electrons are assumed to be ejected from the cathode into the liquid by either a field emission or by the field enhanced thermionic effect (Shottky's effect). Thisbreakdownmechanismexplainsbreakdownonlyofhighlypureliquidanddoesnotapplyto explain the breakdown mechanism in commercially available liquids.

It has been observed that conduction in pure liquids at low electric field (1 kV/cm) is largely ionic due to dissociation of impurities and increases linearily with the field strength. At moderately high fields the conduction saturates but at high field (electric), 100 kV/cm the conduction increases more rapidly and thus breakdown takes place. Fig. 2.10 (a) shows the variation of current as a function of electric field for hexane. This is the condition nearer to breakdown. However, if the figure is redrawn starting with low fields, a current-electric field characteristic as shown in Fig. 2.10 (b) will be obtained.

The second school of thought recognises that the presence of foreign particles in liquid insulations has a marked effect on the dielectric strength of liquid dielectrics. It has been suggested that the suspended particles are polarizable and are of higher permittivity than the liquid. These particles experience an electrical force directed towards the place of maximum stress. With uniform field electrodes the movement of particles is presumed to be initiated by surface irregularities on the electrodes, which give rise to local field gradients. The particles thus get accumulated and tend to form a bridge across the gap which leads finally to initiation of breakdown. The impurities could also be in the form of gaseous bubbles which obviously have lower dielectric strength than the liquid itself and hence on breakdown of bubble the total breakdown of liquid may be triggered.

ElectronicBreakdown

Onceanelectronisinjectedintotheliquid,itgainsenergyfromtheelectricfieldapplied between the electrodes. It is presumed that some electrons will gain more energy due to fieldthan they would lose during collision.Theseelectrons areaccelerated under the electricfield and would gain sufficient energy to knock out an electron and thus initiate the process of avalanche. The threshold condition for the beginning of avalanche is achieved when the energy gained by the electron equals the energy lost during ionization (electron emission) and is given by

$$e\lambda E = Chv$$

where λ is the mean free path, hv is the energy of ionization and C is a constant. Table2.2givestypicalvaluesofdielectricstrengthsofsomeofthehighlypurifiedliquids.

The electronic theory whereas predicts the relative values of dielectric strength satisfactorily, the formative time lags observed are much longer as compared to the ones predicted by the electronic theory.

Table:2.2.Dielectricstrengths ofpure liquids

Liquid	*Strength (MV/cm)*
Benzene	1.1
Goodoil	1.0–4.0
Hexane	1.1–1.3
Nitrogen	1.6–1.88
Oxygen	2.4
Silicon	1.0–1.2

BREAKDOWN IN SOLID DIELECTRICS

Solid insulating materials are used almost in all electrical equipments, be it an electric heater or a 500 MW generator or a circuit breaker, solid insulation forms an integral part of all electrical equipments especially when the operating voltages are high. The solid insulation not only provides insulation to the live parts of the equipment from the grounded structures, it sometimes provides mechanical support to the equipment. In general, of course, a suitable combination of solid, liquid and gaseous insulations is used.

The processes responsible for the breakdown of gaseous dielectrics are governed by the rapid growth of current due to emission of electrons from the cathode, ionization of the gas particles and fast development of avalanche process. When breakdown occurs the gases regain their dielectric strength very fast, the liquids regain partially and solid dielectrics lose their strength completely.

The breakdown of solid dielectrics not only depends upon the magnitude of voltage applied but also it is a function of time for which the voltage is applied. Roughly speaking, the product of the breakdown voltage and the log of the time required for breakdown is almost a constant i.e,

$$V_b = 1nt_b = \text{constant}$$

The characteristics is shown in Fig. 2.11

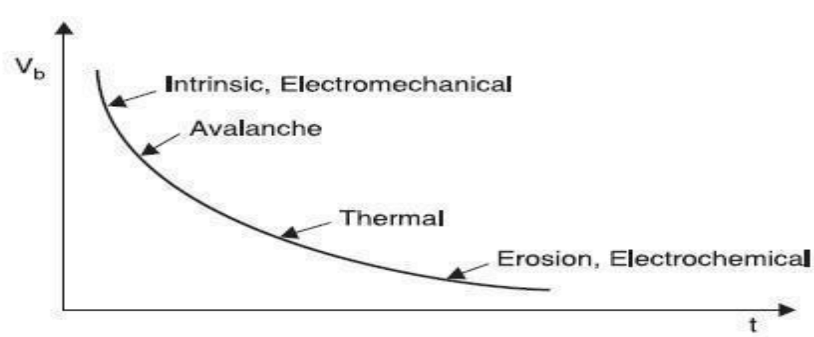


Figure:2.11Variation of $V_b$with timeof application

The dielectric strength of solid materials is affected by many factors viz. ambient temperature, humidity, duration of test, impurities or structural defects whether a.c., d.c. or impulse voltages are being used, pressure applied to these electrodes etc. The mechanism of breakdown in solids is again less understood. However, as is said earlier the time of application plays an important role in breakdown process, for discussion purposes, it is convenient to divide the time scale of voltage application into regions in which different mechanisms operate. The various mechanisms are:

- IntrinisicBreakdown
- ElectromechanicalBreakdown
- BreakdownDuetoTreeingandTracking
- Thermal Breakdown
- ElectrochemicalBreakdown

Intrinsicbreakdownin solids

If the dielectric material is pure and homogeneous, the temperature and environmental conditions suitably controlled and if the voltage is applied for a very short time of the order of 10–8 second, the dielectric strength of the specimen increases rapidly to an upper limit known as intrinsic dielectric strength. The intrinsic strength, therefore, depends mainly upon the structural design of the material i.e., the material itself and is affected by the ambient temperature as the structure itself might change slightly by temperature condition.

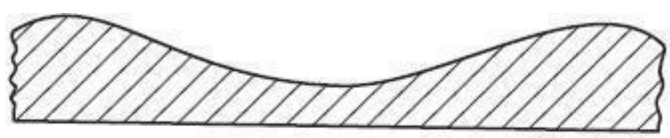


Figure:2.12Specimendesignedfor intrinsicbreakdown

In order to obtain the intrinsic dielectric strength of a material, the samples are so prepared that there is high stress in the centre of the specimen and much low stress at the corners asshowninFig.2.12.Theintrinsicbreakdownis obtainedintimesoftheorderof10^{-8}sec.and, therefore, has been considered to be electronic in nature.

The stresses required are of the order of one million volt/cm. The intrinsic strength is generally assumed to have been reached when electrons in the valance band gain sufficient energy from the electric field to cross the forbidden energy band to the conduction band. In pure andhomogenousmaterials,thevalence andthe conductionbandsareseparatedbyalargeenergy gap at room temperature, no electron can jump from valance band to the conduction band.

The conductivity of pure dielectrics at room temperature is, therefore, zero. However, in practice, no insulating material is pure and, therefore, has some impurities and/or imperfections in theirstructural designs. Theimpurity atoms mayact as traps forfreeelectrons in energylevels that lie just below the conduction band is small. An amorphous crystal will, therefore, always have some free electrons in the conduction band. At room temperature some of the trapped electrons will be excited thermally into the conduction band as the energy gap between the trapping band and the conduction band is small.

An amorphous crystal will, therefore, always have some free electrons in the conduction band.Asanelectricfieldisapplied,theelectronsgainenergyandduetocollisionsbetweenthem the energy is shared by all electrons. In an amorphous dielectric the energy gained by electrons from the electric field is much more than they can transfer it to the lattice. Therefore, the temperature of electrons will exceed the lattice temperature and this will result into increase in the number of trapped electrons reaching the conduction band and finally leading to complete breakdown. When an electrode embedded in a solid specimen is subjected to a uniform electric field, breakdown may occur.

An electron entering the conduction band of the dielectric at the cathode will move towards the anode under the effect of the electric field. During its movement, it gains energy and on collision it loses a part of the energy. If the mean free path is long, the energy gained due to motion is more than lost during collision. The process continues and finally may lead to formation of an electron avalanche similar to gases and will lead finally to breakdown if the avalanche exceeds a certain critical size.

ELECTROMECHANICALBREAKDOWN

When a dielectric material is subjected to an electric field, charges of opposite nature are induced on the two opposite surfaces of the material and hence a force of attraction is developed and the specimen is subjected to electrostatic compressive forces and when these forces exceed the mechanical withstands strength of the material, the material collapses. If the initial thickness ofthematerialis$d_0$andiscompressedtoathicknessdundertheappliedvoltageVthenthe compressive stress developed due to electric field is

$$F = \frac{1}{2}\varepsilon_0 \varepsilon_r \frac{V^2}{d^2}$$

where$\varepsilon_r$is therelativepermittivity ofthespecimen. If$\gamma$is theYoung's modulus, themechanical compressive strength is

$$\gamma \ln \frac{d_0}{d}$$

Equatingthetwounder equilibriumcondition,wehave

$$\frac{1}{2}\varepsilon_0 \varepsilon_r \frac{V^2}{d^2} = \gamma \ln \frac{d_0}{d}$$

$$V^2 = d^2 \frac{2\gamma}{\varepsilon_0 \varepsilon_r} \ln \frac{d_0}{d} = K\, d^2 \ln \frac{d_0}{d}$$

Differentiatingwithrespecttod,wehave

$$2V\frac{dV}{dd} = K\left[2d\ln\frac{d_0}{d} - d^2 \cdot \frac{d}{d_0} \cdot \frac{d_0}{d^2}\right] = 0$$

or $$2d\ln\frac{d_0}{d} = d$$

or $$\ln\frac{d_0}{d} = \frac{1}{2}$$

or $$\frac{d}{d_0} = 0.6$$

For any real value of voltage V, the reduction in thickness of the specimen cannot be more than 40%. If the ratio V/d at this value of V is less than the intrinsic strength of the specimen, a further increase in V shall make the thickness unstable and the specimen collapses.

The highest apparent strength is then obtained by substituting d = 0.6 d0 in the above expressions.

$$\frac{V}{d} = \sqrt{\frac{2\gamma}{\varepsilon_0\varepsilon_r}\ln 1.67} \quad \text{or} \quad \frac{V}{d_0} = E_a = 0.6\left\{\frac{\gamma}{\varepsilon_0\varepsilon_r}\right\}^{1/2}$$

The above equation is approximate only as γ depends upon the mechanical stress. The possibility of instability occurring for lower average field is ignored i.e., the effect of stress concentration at irregularities is not taken into account.

THERMAL BREAKDOWN

When an insulating material is subjected to an electric field, the material gets heated up due to conduction current and dielectric losses due to polarization. The conductivity of the material increases with increase in temperature and a condition of instability is reached when the heat generated exceeds the heat dissipated by the material and the material breaks down.

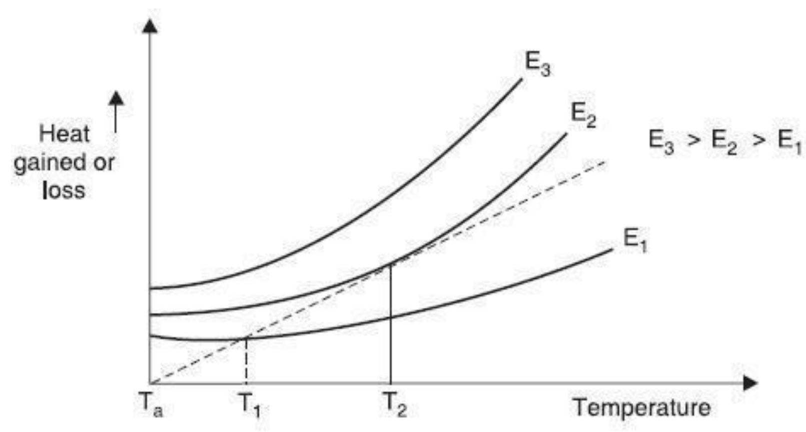


Figure2.13Thermalstabilityorinstabilityofdifferentfields

Fig. 2.13 shows various heating curves corresponding to different electric stresses as a function of specimen temperature. Assuming that the temperature difference between theambient and the specimen temperature is small, Newton's law of cooling is represented by a straight line.

The test specimen is at thermal equilibrium corresponding to field E_1 at temperature T_1 as beyond that heat generated is less than heat lost. Unstable equilibrium exists for field E_2 at T_2, and for field E_3 the state of equilibrium is never reached and hence the specimen breaks downthermally.

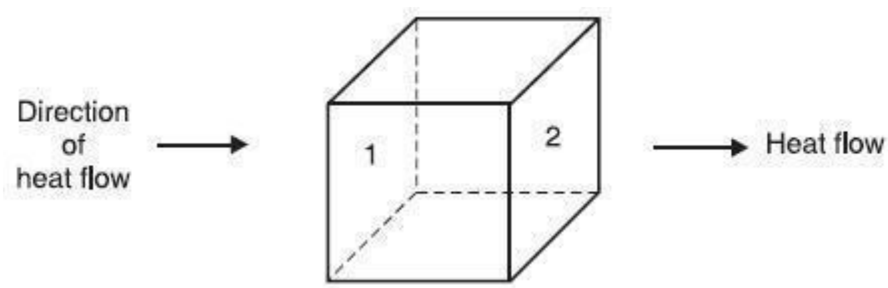


Figure:2.14.Cubicalspecimen—Heatflow

In order to obtain basic equation for studying thermal breakdown, let us consider a small cube(Fig.2.14)withinthedielectricspecimenwithsideΔxandtemperaturedifferenceacrossits faces in the direction of heat flow (assume here flow is along x-direction) is ΔT. Therefore, the temperature gradient is

$$\frac{\Delta T}{\Delta x} \approx \frac{dT}{dx}$$

LetΔx^2=A. Theheat flowacross face1

$KA\frac{dT}{dx}$ Joules

Heatflowacrossface 2

$$KA\frac{dT}{dx} - KA\frac{d}{dx}\left(\frac{dT}{dx}\right)\Delta x$$

Here the second term indicates the heat input to the differential specimen. Therefore, the heat absorbed by the differential cube volume

$$= \frac{KA\frac{d}{dx}\left(\frac{dT}{dx}\right)\Delta x}{\Delta V} = K\frac{d}{dx}\left(\frac{dT}{dx}\right)$$

Theheat inputto theblock willbepartly dissipatedinto thesurrounding andpartly it will raise the temperature of the block. Let CV be the thermal capacity of the dielectric, σ the electricalconductivity,Etheelectricfieldintensity.Theheatgeneratedbytheelectricfield= σE2watts,andsupposetheriseintemperatureoftheblockisΔT,intimedt,thepowerrequired to raise the temperature of the block by ΔT is

$$C_v \frac{dT}{dt} \text{ watts}$$

Therefore,

$$C_v \frac{dT}{dt} + K \frac{d}{dt}\left(\frac{dT}{dx}\right) = \sigma E^2$$

Thesolutionoftheaboveequationwillgive usthetimerequiredto reachthecritical temperatureTcforwhichthermalinstabilitywillreachandthedielectricwillloseitsinsulating properties.

However,unfortunatelytheequationcanbesolvedinitspresentfromCV,Kandσisall functions of temperature and in fact σ may also depend on the intensity of electrical field.

Therefore,toobtainsolutionoftheequation,wemakecertainpracticalassumptionsand we consider two extreme situations for its solution

Table:2.3Thermalbreakdownvoltage

Material		*Maximum thermal voltage in MV/cm*	
		d.c.	*a.c.*
Ceramics	HV Steatite	—	9.8
	LF Steatite	—	1.5
	High grade porcelain		2.8
Organic materials	Ebonite	—	1.45–2.75
	Polythene		3.5
	Polystyrene		5.0
	Polystyrene at 1 MHz		0.05
	Acrylic resins		0.3–1.0
Crystals	Mica muscovite	24	7–18
	Rock salt	38	1.4
Quartz	Perpendiculars to axis	12000	—
	Paralle to axis	66	—
	Impure	—	2.2

Table2.3givesforthick specimen,thermalbreakdownvaluesforsomedielectricunder a.c.andd.c.voltagesat20℃.

BREAKDOWNIN COMPOSITE DIELECTRICS

A vacuum system is one in which the pressure maintained is at a value below the atmosphericpressureandismeasuredintermsofmmofmercury.Onestandardatmospheric pressureat0°Cisequalto760mmofmercury.OnemmofHgpressureisalsoknownasone torr after the name of Torricelli who was the first to obtain pressures below atmosphere, with the help of mercury barometer. Sometimes 10^{-3} torr is known as one micron. It is now possible to obtain pressures as low as 10^{-8} torr.

In a Townsend type of discharge, in a gas, the mean free path of the particles is small and electrons get multiplied due to various ionization processes and an electron avalanche is formed. In a vacuum of the order of 10–5 torr, the mean free path is of the order of few meters and thus when theelectrodes areseparated by afewmm an electroncrosses thegap without any collision. Therefore, in a vacuum, the current growth prior to breakdown cannot take place due to formation of electron avalanches.

However, if it could be possible to liberate gas in the vacuum by some means, the discharge could take place according to Townsend process. Thus, a vacuum arc is different from the general class of low and high pressure arcs. In the vacuum arc, the neutral atoms, ions and electrons do not come from the medium in which the arc is drawn but they are obtained from the electrodes themselves by evaporating its surface material. Because of the large mean free pathfor the electrons, the dielectric strength of the vacuum is a thousand times more than when the gas is used as the interrupting medium.

Inthisrangeofvacuum,thebreakdownstrengthisindependentofthegasdensityand depends only on the gap length and upon the condition of electrode surface. Highly polished and thoroughly degassed electrodes show higher breakdown strength. Electrodes get roughened after use and thus the dielectric strength or breakdown strength decreases which can be improved by applyingsuccessivehighvoltageimpulseswhichofcoursedoesnotchangetheroughened surface but removes the loosely adhering metal particles from the electrodes which were deposited during arcing. It has been observed that for a vacuum of 10^{-6}torr, some of the metals likesilver,bismuth-copperetc.attaintheirmaximumbreakdownstrengthwhenthegapisslightly less than 3 mm. This property of vacuum switches permits the use of short gaps for fast operation.

ELECTRICDISCHARGEINVACUUM

The electric discharge in vacuum results from the neutral atoms, ions and electrons emitted from the electrodes themselves. Cathode spots are formed depending upon the current flowing. For low currents a highly mobile cathode spot is formed and for large currents a multiple number of cathode spots are formed. These spots constitute the main source of vapourin the arc. The processes involved in drawing the discharge will be due to high electric field between the contacts or resistive heating produced at the point of operation or a combination of the two. The cathode surfaces, normally, are not perfectly smooth but have many micro projections.

Due to their small area of cross-section, the projections will suffer explosive evaporation by resistive heating and supply sufficient quantity of vapour for the arc formation. Since in case of vacuum, the emission occurs only at the cathode spots and not from the entire surface of the cathode,thevacuumdischargeisalsoknownascoldcathodedischarge.Incoldcathodethe emission of electrons could be due to any of the combinations of the following mechanisms:

Field emission; (ii) Thermionic emission; (iii) Field and Thermionic emission; (iv) Secondary emission by positive ion bombardment; (v) Secondary emission by photons; and (vi) Pinch effect. The stability of discharge in vacuum depends upon: (i) the contact material and its vapour pressure, and (ii) circuit parameters such as voltage, current, inductance and capacitance. It has been observed that higher the vapour pressure at low temperature the better is the stability of the discharge. There are certain metals like Zn, Bi which show these characteristics and are better electrode materials for vacuum breakers. Besides the vapour pressure, the thermal conductivity of the metal also affects the current chopping level. A good heat conducting metal will cool its surface faster and hence its electrode surface temperature will fall which will result into reduction in evaporation rate and arc will be chopped because of insufficient vapour. On the other hand, a bad heat conductor will maintain its temperature and vaporization for a longer time and the arc will be more stable.

Theprocessofmultiplicationofchargedparticlesbythe processofcollisionisverysmall in the space between the electrodes in vacuum, electron avalanche is not possible. If somehow a gas cloud could be formed in vacuum, the usual kind of breakdown process can take place. This is the line of action adopted by the researchers to study mechanism of breakdown in vacuum. By finding the way, gas cloud could be created in a vacuum.

PROBLEMS

1. A steady current of 600 μA flows through the plane electrode separated by a distance of 0.5 cmwhenavoltageof10kVisapplied.DeterminetheTownsend'sfirstionizationcoefficient if acurrent of 60 μA flows when the distance of separation is reduced to 0.1 cm and the field is kept constant at the previous value.

Solution: Sincethefieldiskeptconstant(i.e.,ifdistanceofseparationisreduced,thevoltage is also reduced by the same ratio so that V/d is kept constant).

$$I = I_0 e^{\alpha x}$$

Substitutingtwodifferentsetsofvalues,

$$\text{we have } 600 = I_0 e^{0.5\alpha} \text{ and } 60 = I_0 e^{0.1\alpha} \quad \text{or}$$

$$10 = e^{0.4\alpha} \text{ or } 0.4\,\alpha = \ln 10$$

$$0.4\,\alpha = 2.3026$$

$\alpha = 5.75$ ionizing collisions/cm.

2. ThefollowingtablegivestwosetsofexperimentalresultsforstudyingTownsend's mechanism. The field is kept constant in each set:

I set 30 kV/cm Gap distance (mm)	II set kV/cm Observed current A	
	I set	II set
0.5	1.5×10^{-13}	6.5×10^{-14}
1.0	5×10^{-13}	2.0×10^{-13}
1.5	8.5×10^{-13}	4×10^{-13}
2.0	1.5×10^{-12}	8×10^{-13}
2.5	5.6×10^{-12}	1.2×10^{-12}
3.0	1.4×10^{-10}	6.5×10^{-12}
3.5	1.4×10^{-10}	6.5×10^{-11}
4.0	1.5×10^{-9}	4.0×10^{-10}
5.0	7.0×10^{-7}	1.2×10^{-8}

Themaximumcurrentobservedis6×10^{-14} A.DeterminethevaluesofTownsend's first and second ionization coefficients.

3. Thefollowingobservationsweremadeinanexperimentfordeterminationof dielectric strength of transformer oil. Determine the power law equation.

Gapspacing	4	6	8	10
BreakdownVoltage(kV)	88	135	165	212

UNIT– III GENERATIONOFHIGHVOLTAGESANDHIGHCURRENTS

GENERATIONOFHIGHVOLTAGESANDHIGHCURRENTS

There are various applications of high D.C. voltages in industries, research medical sciences etc. HVDC transmission over both overhead lines and underground cables is becoming more and more popular. HVDC is used for testing HVAC cables of long lengths as these have very large capacitance and would require very large values of currents if tested on HVAC voltages. Even though D.C. tests on A.C. cables are convenient and economical, these suffer from the fact that the stress distribution within the insulating material is different from thenormal operating condition. In industry it is being used for electrostatic precipitation of a sink in thermal power plants, electrostatic painting, cement industry, communication systems etc.

HVDC is also being used extensively in physics for particle acceleration and in medical equipments (X-Rays).The most efficient method of generating high D.C. voltages is through the process of rectification employing voltage multiplier circuits. Electrostatic generators have also beenusedforgeneratinghighD.C.voltages.AccordingtoIEEEstandards4-1978,thevalueof a direct test voltage is defined by its arithmetic mean value Vd and is expressed mathematically as

$$V_d = \int_0^T V(t)\,dt$$

Where T is the time period of the voltage wave having a frequency f = 1/T. Test voltages generated using rectifiers are never constant in magnitude. These deviate from the mean value periodically and this deviation is known as ripple. The magnitude of the ripple voltage denoted by δV is defined as half the difference between the maximum and minimum values of voltage i.e.,

$$\delta V = \frac{1}{2}[V_{max} - V_{min}]$$

andripplefactor isdefined astheratio ofripplemagnitudetothe meanvalue Vdi.e., δV/Vd.

The test voltages should not have ripple factor more than 5% or as specified in a specific standard for particular equipment as the requirement on voltage shape may differ for different applications.

Half-WaveRectifierCircuit

Thesimplestcircuitforgenerationofhighdirectvoltageis thehalfwaverectifiershown in Fig. 3.1 Here RL is the load resistance and C the capacitance to smoothen the dace. output voltage. If the capacitor is not connected, pulsating dace. voltage is obtained at the output terminals where as with the capacitance C, the pulsation at the output terminal are reduced. Assuming the ideal transformer and small internal resistance of the diode during conduction the capacitor C is charged to the maximum voltage Vmax during conduction of the diode D. Assuming that there is no load connected, the dace. Voltage across capacitance remains constant at Vmax whereas the supply voltage oscillates between ± Vmax and during negative half cycle the potential of point A becomes – Vmax and hence the diode must be rated for 2Vmax. This would also be the case if the transformer is grounded at A instead of B as shown in Fig. 3.1 (a). Such a circuit is known as voltage doublers due to Villard for which the output voltage would be taken across D. This dace. voltage, however, oscillates between zero and 2Vmax and is needed for the Cascade circuit.

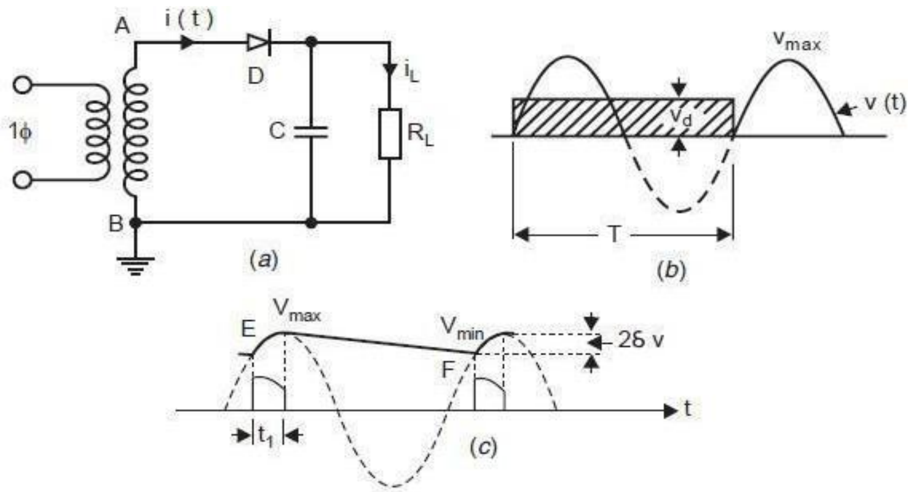


Figure: 3.1 (a) Single Phase rectifier (b) Output voltage without C (c) Output voltage with Cuff thecircuitisloaded,theoutputvoltagedoesnotremainconstantatVmax.AfterpointE(Fig.3.1 (c)), the supply voltage becomes less than the capacitor voltage, diode stops conducting.

Thecapacitorcannotdischargebackintothea.c.systembecauseofonewayactionofthe diode. Instead, the current now flows out of C to furnish the current ill through the load. While giving up this energy, the capacitor voltage also decreases at a rate depending on the time constant CR of the circuit and it reaches the point F corresponding to V min. Beyond F, the supply voltage is greater than the capacitor voltage and hence the diode D starts conducting charging the capacitor Cagain to Vmax and alsoduring this periodit supplies current to the load also. This second pulse of imp(ic + il) is of shorter duration than the initial charging pulse as it serve mainly to restore into C the energy that C meanwhile had supplied to load. Thus, while each pulse of diode current lasts much less than a half cycle, the load receives current more continuously from C. Assuming the charge supplied by the transformer to the load during the conduction period t, which is very small to be negligible, the charge supplied by the transformer to the capacitor during conduction equals the charge supplied by the capacitor to the load. Note that ic>> iL. During one period T = 1/f of the a.c voltage, a charge Q is transferred to the loadRL and is given as

$$Q = \int_T i_L(t)\,dt = \int_T \frac{V_{RL}(t)}{R_L}\,dt = IT = \frac{I}{f}$$

where I is the mean value of the dace output iL(t) and VRL(t) the dace. voltage which includes a ripple as shown in Fig. 2.1 (c). This charge is supplied by the capacitor over theperiod T when the voltage changes from Vmax to Vmin over approximately period T neglecting the conduction period of the diode. Suppose at any time the voltage of the capacitor is V and it decreases by an amount ofdVoverthetimedt then charge delivered by thecapacitor duringthis time is

$$dQ = CdV$$

Therefore,ifvoltagechangesfrom Vmaxto Vmin,the chargedelivered bythe capacitor

$$\int dQ = \int_{V_{max}}^{V_{min}} CdV = -C\left(V_{max} - V_{min}\right)$$

Orthe magnitudeofchargedelivered bythecapacitor

$$Q = C\,(V_{max} - V_{min})$$

Using equation

$$Q = 2\delta VC$$

$$2\delta VC = IT$$

Therefore,

Or

The above equation shows that the ripple in a rectifier output depends upon the load current and the circuit parameter like f and C. The product fC is, therefore, an important design factor for the rectifiers. The higher the frequency of supply and larger the value of filtering capacitor the smaller will be the ripple in the dace. output. The single phase half-wave rectifier circuits have the following disadvantages:

- The size of the circuits is very large if high and pure dace. output voltages are desired.
- Theh.t.transformermaygetsaturatediftheamplitudeofdirectcurrentiscomparable with the nominal alternating current of the transformer.

It is to be noted that all the circuits considered here are able to supply relatively low currents and therefore are not suitable for high current applications such as HVDC transmission. When high dace. voltages are to be generated, voltage doubler or cascaded voltage multiplier circuits are used. One of the most popular doubler circuit due to Greinacher is shown in Fig. 3.2. Suppose B is more positive with respect to A and the diode D1 conducts thus charging the capacitor C1 to Vmax with polarity as shown in Fig. 3.2. During the next half cycle terminal Aof the capacitor C1 rises to Vmax and hence terminal M attains a potential of 2 Vmax. Thus, the capacitor C2 ischarged to 2 Vmax through D2.Normally the voltage across the load will be less than 2 Vmax depending upon the time constant of the circuit C2RL.

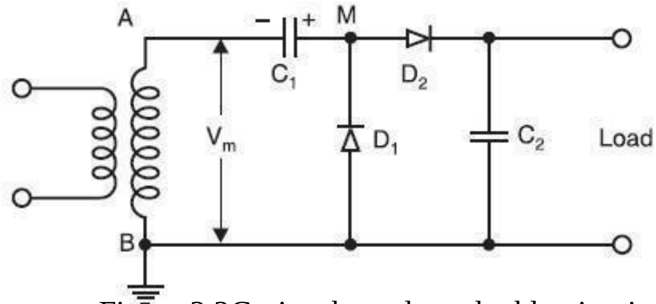


Figure:3.2Greinachervoltagedoublercircuit

Cockroft-WaltonVoltageMultiplier Circuit

In 1932, Cockroft and Walton suggested an improvement over the circuit developed by reinacher for producing high D.C. voltages. Fig. 3.3. Shows a multistage single phase cascade circuit of the Cockroft-Walton type. No Load Operation: The portion ABM′MA is exactly identical to Greinarcher voltage doublers circuit and the voltage across C becomes 2Vmax when M attains a voltage 2Vmax.During the next half cycle when B becomes positive with respect to A, potential of M falls and, therefore, potential of N also falls becoming less than potential at M′ henceC2ischargedthroughD2.NexthalfcycleAbecomesmorepositiveandpotentialofM andNrisethuschargingC′2throughD′2.FinallyallthecapacitorsC′1,C′2,C′3,C1,C2,andC3 are charged. The voltage across the column of capacitors consisting of C_1, C_2, C_3, keeps on oscillating as the supply voltage alternates.

Thiscolumn,therefore,isknownasoscillatingcolumn.However,thevoltageacrossthe capacitances C'_1, C'_2, C'_3, remains constant and is known as smoothening column. The voltages at M′, N′,and O′are2 Vmax4 Vmax and 6 Vmax. Therefore, voltageacross all thecapacitorsis 2 Vmax except for C1where it is Vmax only. The total output voltage is 2nVmax where n is the number of stages. Thus, the use of multistage arranged in the manner shown enables very high voltageto beobtained. Theequal stress ofthe elements (bothcapacitorsand diodes)used is very helpful and promotes a modular design of such generators.

Generator Loaded: When the generator is loaded, the output voltage will never reach the value 2n Vmax. Also, the output wave will consist of ripples on the voltage. Thus, we have to deal with two quantities, the voltage drop ΔV and the ripple δV.In 1932, Cockroft and Walton suggested an improvement over the circuit developed by Greinacher for producing high D.C. voltages. Fig. 2.3. shows a multistage single phase cascade circuit of the Cockroft-Walton type.

No Load Operation:

The portion ABM′MA is exactly identical to Greinarcher voltage doublers circuit and the voltage across *C* becomes 2*V*maxwhen *M* attains a voltage 2*V*max.During thenext half cycle when *B* becomespositivewithrespecttо*A*,potentialof*M*fallsand,therefore,potentialof*N*alsofalls becoming less than potential at *M*′ hence C_2 is charged throughD_2. Next half cycle *A* becomes more positive and potential of *M* and *N* rise thus charging C'_2 throughD'_2. Finally all the capacitors C'_1, C'_2, C'_3, *C*, C_2, and C_3 are charged. The voltage across the column of capacitors consisting of C_1, C_2, C_3, keeps on oscillating as the supply voltage alternates. This column, therefore, is known as oscillating column.

However, the voltage across the capacitances C'_1,C'_2, C'_3, remains constant and isknown as smoothening column. The voltages at M', N', and O are 2 Vmax 4 Vmax and 6 Vmax. Therefore, voltage across all the capacitors is 2 Vmax except for $C_1$where it is Vmax only. The total output voltage is $2nV$max where n is the number of stages. Thus, the use of multistage arranged in the manner shown enables very high voltage to be obtained. The equal stress of the elements (both capacitors and diodes) used is very helpful and promotes a modular design of such generators.

GeneratorLoaded:

When the generator is loaded, the output voltage will never reach the value $2n$ Vmax. Also, the output wave will consist of ripples on the voltage. Thus, we have to deal with two quantities, the voltage drop V and the ripple Suppose a charge q is transferred to the load per cycle.Thischargeisq=I/f=IT.Thechargecomesfromthesmootheningcolumn,theseries connectionofC′1,C′2,C′3,.IfnochargeweretransferredduringTfromthisstackviaD1,D2, D3, to the oscillating column, the peak to peak ripple would merely be But in practice charges are transferred.

Theprocessisexplained withthehelpofcircuitsinFig.3.4(a)and(b).Fig.3.4(a)shows arrangement when point A is more positive with reference to B and charging of smoothing column takes place and Fig. 3.4 (b) shows the arrangement when in the next half cycle Becomes positive with reference to A and charging of oscillating column takes place. Refer to Fig. 3.4(a). Say the potential of point O′ is now 6 Vmax. This discharges through the load resistance and say thechargelost is q =IT overthecycle. This must beregainedduringthechargingcycle (Fig. 3.4 (a)) for stable operation of the generator.

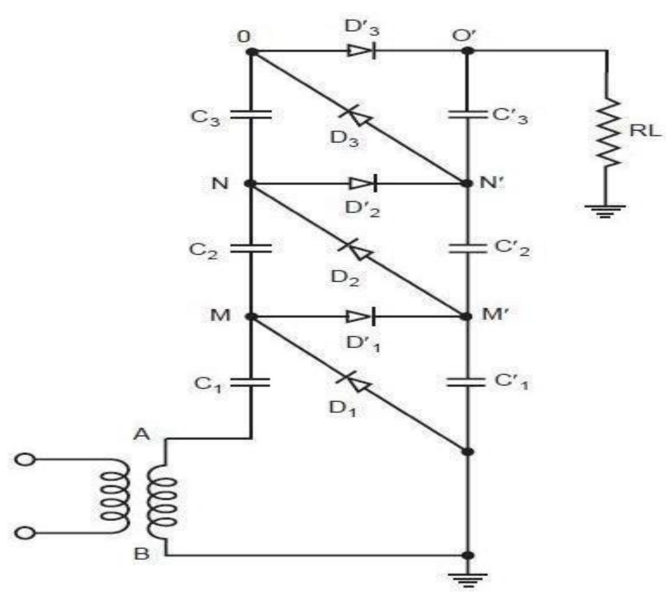


Figure:3.3multistagesinglephasecascadecircuit oftheCockroft-Walton type

$$2\delta V = IT\sum_{n=0}^{n}\frac{1}{C'_i}$$

.

$C_3$is,thereforesuppliedachargeqfromC_3.ForthisC_2mustacquirechargeof2qso that it can supply q charge to the load and q to C_3, in the next half cycle termed by cockloft and Waltonasthe transfer cycle (Fig.3.4(b)).Similarly C'_1must acquire forstabilityreasonscharge 3q so that it can supply a charge q to the load and 2q to the capacitor C_2 in the next half cycle (transfer half cycle). During the transfer cycle shown in Fig. 3.4 (b), the diodes D_1, D_2, D_3, conductwhenBispositivewithreferencetoA.HereC'_2transfersqchargetoC_3,C_1transfers charge 2q to C_2 and the transformer provides change 3q.For n-stage circuit, the total ripple will be

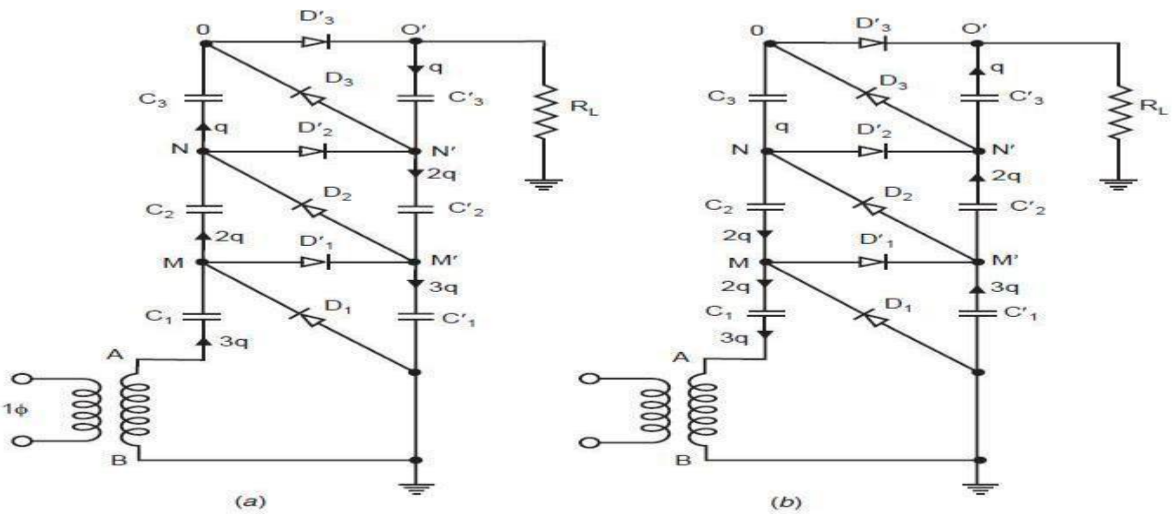


Figure:3.4 (a)Chargingofsmoothening Column(b)Chargingofoscillating column

$$2\delta V = \frac{I}{f}\left(\frac{1}{C'_n} + \frac{2}{C'_{n-1}} + \frac{3}{C'_{n-2}} + \ldots + \frac{n}{C'_1}\right)$$

$$\delta V = \frac{I}{2f}\left(\frac{1}{C'_n} + \frac{2}{C'_{n-1}} + \frac{3}{C'_{n-2}} + \ldots + \frac{n}{C'_1}\right)$$

From above equation, it is clear that in a multistage circuit the lowest capacitors are responsible for most ripples and it is, therefore, desirable to increase the capacitance in the lower stages. However, this is objectionable from the view point of High Voltage Circuit where if the load is large and the load voltage goes down, the smaller capacitors (within the column) wouldbe overstressed. Therefore, capacitors of equal value are used in practical circuits i.e., $C'n = C'n$

$-1 = C'_1 = C$ and theripple is given as

$$\delta V = \frac{I}{2fC}\frac{n(n+1)}{2} = \frac{In(n+1)}{4fC}$$

The second quantity to be evaluated is the voltage drop ΔV which is the difference between the theoretical no load voltage 2nVmax and the on load voltage. In order to obtain the voltage drop ΔV refer to Fig. 3.4 (a).Here C′1 is not charged up to full voltage 2Vmax but onlyto 2Vmax – 3q/C because of the charge given up through C1 in one cycle which gives a voltage drop of 3q/C = 3I/fC The voltage drop in the transformer is assumed to be negligible. Thus, C2is charged to the voltage.

$$\left(2V_{max} - \frac{3I}{fC}\right) - \frac{3I}{fC}$$

Ingeneralfor a*n*-stage generator

$$2V_{max} - \left(\frac{3I + 3I + 2I}{fC}\right)$$

$$\Delta V_1 = \frac{3I}{fC}$$

$$\Delta V_2 = \{2 \times 3 + (3 - 1)\} \frac{I}{fC}$$

$$\Delta V_3 = (2 \times 3 + 2 \times 2 + 1) \frac{I}{fC}$$

$$\Delta V_n = \frac{nI}{fC}$$

$$\Delta V_{n-1} = \frac{I}{fC} \{2n + (n - 1)\}$$

$$\Delta V_{n-2} = \frac{I}{fC} \{2n + 2(n - 1) + (n - 2)\}$$

.
.
.

$$\Delta V_1 = \frac{I}{fC} \{2n + 2(n - 1) + 2(n - 2) + \dots 2 \times 3 + 2 \times 2 + 1\}$$

$$\Delta V = \Delta V_n + \Delta V_{n-1} + \dots + \Delta V_1$$

Afteromitting I/fC,theseriescanberewrittenas:

$$T_n = n$$

$$T_{n-1} = 2n + (n - 1)$$

$$T_{n-2} = 2n + 2(n - 1) + (n - 2)$$

$$T_{n-3} = 2n + 2(n - 1) + 2(n - 2) + (n - 3)$$

.
.
.

$$T_1 = 2n + 2(n - 1) + 2(n - 2) + \dots + 2 \times 3 + 2 \times 2 + 1$$

$$T = T_n + T_{n-1} + T_{n-2} + \dots + T_1$$

Tosumupweaddthelasttermofalltheterms(*Tn*through*T*1)andagain addthelast term of the remaining term and so on, *i.e.*,

$$[n + (n-1) + (n-2) + \dots + 2 + 1]$$
$$+ [2n + 2(n-1) + 2(n-2) + \dots + 2 \times 2]$$
$$+ [2n + 2(n-1) + \dots + 2 \times 4 + 2 \times 3]$$
$$+ [2n + 2(n-1) + \dots + 2 \times 4]$$
$$+ [2n + 2(n-1) + 2(n-2) + \dots + 2 \times 5] + \dots [2n]$$

Rearrangingthe abovetermswehave

$$n + (n-1) + (n-2) + \dots + 2 + 1$$
$$+ [2n + 2(n-1) + 2(n-2) + \dots + 2 \times 2 + 2 \times 1] - 2 \times 1$$
$$+ [2n + 2(n-1) + 2(n-2) + \dots + 2 \times 3 + 2 \times 2 + 2 \times 1] - 2 \times 2 - 2 \times 1$$
$$+ [2n + 2(n-1) + 2(n-2) + \dots + 2 \times 4 + 2 \times 3 + 2 \times 2 + 2 \times 1]$$
$$- 2 \times 3 - 2 \times 2 - 2 \times 1$$

.
.
.

$$[2 \times n + 2(n-1) + \dots + 2 \times 2 + 2 \times 1] - [2(n-1)]$$
$$+ 2(n-2) + \dots + 2 \times 2 + 2 \times 1]$$

or $n + (n-1) + (n-2) + \dots + 2 + 1$

Plus $(n-1)$ number of terms of $2[n + (n-1) + \dots + 2 + 1]$

minus $2[1 + (1+2) + (1+2+3) + \dots + \dots \{1 + 2 + 3 + \dots (n-1)\}]$

The last term (minus term) is rewritten as

$$2[1 + (1+2) + \dots + \{1 + 2 + 3 + \dots (n-1)\} + \{1 + 2 + \dots + n\}]$$
$$-2[1 + 2 + 3 + \dots + n]$$

The *n*th term of the first part of the above series is given as

$$t_n = \frac{2n(n+1)}{2} = (n^2 + n)$$

Therefore, the above terms are equal to

$$= \sum (n^2 + n) - 2 \sum n$$
$$= \sum (n^2 - n)$$

Taking once again all the term we have

$$T = \sum n + 2(n-1) \sum n - \sum (n^2 - n)$$
$$= 2n \sum n - \sum n^2$$
$$= 2n \cdot \frac{n(n+1)}{2} - \frac{n(n+1)(2n+1)}{6}$$
$$= \frac{6(n^3 + n^2) - n(2n^2 + 3n + 1)}{6}$$
$$= \frac{6n^3 + 6n^2 - 2n^3 - 3n^2 - n}{6}$$
$$= \frac{4n^3 + 3n^2 - n}{6} = \frac{2}{3}n^3 + \frac{n^2}{2} - \frac{n}{6}$$

$$n \cdot \frac{nI}{2fC}$$

Hence $$\Delta V = \frac{I}{fC}\left(\frac{2}{3}n^3 - \frac{n}{6}\right)$$

Ifn≥4wefindthatthelineartermcanbeneglectedandtherefore,thevoltage term approximated to

$$\Delta V = \frac{I}{fC} \cdot \frac{2}{3} n^3$$

From above it is clear that for a given number of stages, a given frequency and capacitance of each stage, the output voltage decrease linearly with load current I. For a given load, however, V0= (V0max– V) may rise initially with the number of stages n, and reaches a maximum value but decays beyond on optimum number of stage. The optimum number ofstages assuming a constant Vmax, I, f and C can be obtained for maximum value of V0 max by differentiating above equation with respect to n and equating it to zero

$$\frac{dV_{max}}{dn} = 2V_{max} - \frac{2}{3}\frac{I}{fC}3n^2 = 0$$

$$= V_{max} - \frac{I}{fC}n^2 = 0$$

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

Substituting n_{opt} in equation (2.12) we have

$$(V_{0\,max})_{max} = \sqrt{\frac{V_{max} fC}{I}}\left(2V_{max} - \frac{2I}{3fC}\frac{V_{max} fC}{I}\right)$$

$$= \sqrt{\frac{V_{max} fC}{I}}\left(2V_{max} - \frac{2}{3}V_{max}\right)$$

$$= \sqrt{\frac{V_{max} fC}{I}} \cdot \frac{4}{3}V_{max}$$

It is to be noted that in general it is more economical to use high frequency and smaller value of capacitance to reduce the ripples or the voltage drop rather than low frequency and high capacitance. Cascaded generators of Cockroft-Walton type are used and manufacturedworldwide these days. A typical circuit is shown in Fig. 3.5. In general a direct current up to 20 mA is required for high voltages between 1 MV and 2 MV. In case where a higher value of current is required, symmetrical cascaded rectifiers have been developed. These consist of mainly two rectifiers in cascade with a common smoothing column. The symmetrical cascaded rectifierhasasmallervoltagedropand alsoasmallervoltageripplethanthesimplecascade.The alternating current input to the individual circuits must be provided at the appropriate high potential; this can be done by means of isolating transformer. Fig. 3.6 shows a typical cascaded rectifier circuit. Each stage consists of one transformer which feeds two half wave rectifiers.

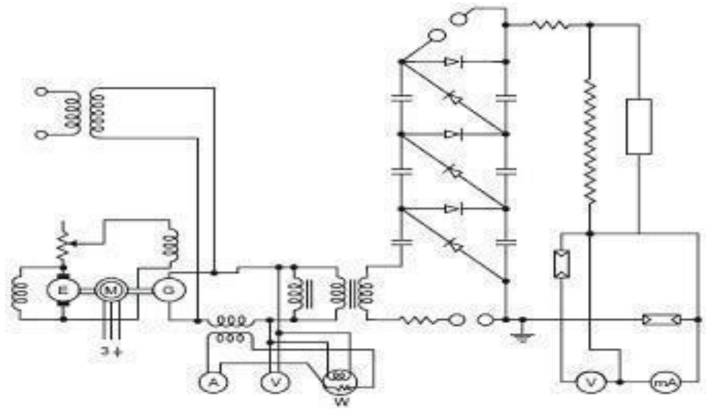


Figure:3.5ATypicalCockroft circuit

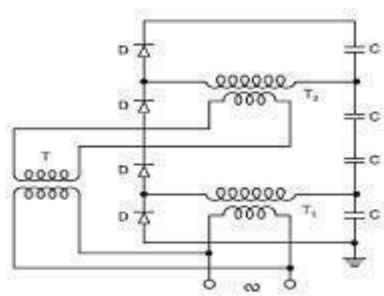


Figure:3.6Cascadedrectifiercircuit

As the storage capacitors of these half wave rectifiers are series connected even the h.v. winding ofT1cannot be grounded. This means that themain insulation between theprimaryand thesecondarywindingofT1hastobeinsulatedforadace.voltageofmagnitudeVmax,thepeak voltage of T1. The same is required for T2 also but this time the high voltage winding is at a voltage of 3Vmax. It would be difficult to provide the whole main insulation within this transformer, an isolating transformer T suppliesT2. The cascading of every stage would thus require an additional isolating transformer which makes this circuit less economical for more than two stages.

ElectrostaticGenerator

In electromagnetic generators, current carrying conductors are moved against the electromagnetic forces acting upon them. In contrast to the generator, electrostatic generators convert mechanical energy into electric energy directly. The electric charges are moved against the force of electric fields, thereby higher potential energy is gained at the cost of mechanical energy. The basic principle of operation is explained with the help of Fig. 2.7.An insulated beltis moving with uniform velocity ν in an electric field of strength E (x). Suppose the width of the belt is b and the charge density ζ consider a length dx of the belt, the charge dq = ζ bdx. The force experienced by this charge (or the force experienced by the belt).

$$dF = Edq = E\,\sigma\, bdx$$

$$F = \sigma b \int E dx$$

Normallytheelectricfieldis uniform

$$F = \sigma b V$$

$$= \text{Force} \times \text{Velocity}$$

$$= Fv = \sigma b V v$$

$$I = \frac{dq}{dt} \sigma b \frac{dx}{dt} = \sigma b v$$

Nowcurrent

Thepowerrequiredtomovethebelt $P = Fv = \sigma b V v = VI$

Assuming no losses, the power output is also equal to *VI*.

Fig. 3.8 shows belt driven electrostatic generator developed by Van de Graaf in 1931. An insulating belt is run over pulleys. The belt, the width of which may vary from a few cms to meters is driven at a speed of about 15 to 30 m/sec, by means of a motor connected to the lower pulley. The belt near the lower pully is charged electro statically by an excitation arrangement. The lower charge spray unit consists of a number of needles connected to the controllable dace. source (10 kV–100 kV) so that the discharge between the points and the belt is maintained. The charge is conveyed to the upper end where it is collected from the belt by discharging points connected to the inside of an insulated metal electrode through which the belt passes. The entire equipment is enclosed in an earthed metal tank filled with insulating gases of good dielectric strength viz. SF6 etc. So that the potential of the electrode could be raised to relatively higher voltage without corona discharges or for a certain voltage a smaller size ofthe equipment will result. Also, the shape of the h.t., electrode should be such that the surface gradient of electric field is made uniform to reduce again corona discharges, even though it is desirable to avoid corona entirely. An isolated sphere is the most favorable electrode shape and will maintain a uniform field *E* with a voltage of *Er* where *r* is the radius of the sphere.

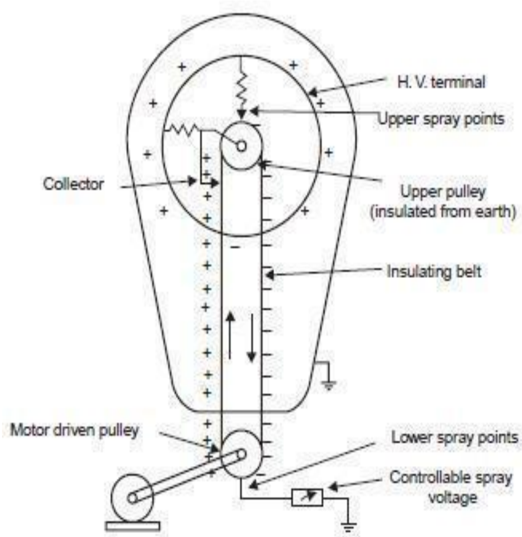


Figure:3.7Van deGraafgenerator

As the h.t. electrode collects charges its potential rises. The potential at any instant is given as $V = q/C$ where q is the chargecollected at that instant.It appears as though ifthe charge were collected for a long time any amount of voltage could be generated. However, as the potential of electrode rises, the field set up by the electrode increases and that may ionize the surrounding medium and, therefore, this would be the limiting value of the voltage. In practice, equilibrium is established at a terminal voltage which is such that the charging current

$$\left(I = C\frac{dV}{dt}\right)$$

equals the discharge current which will include the load current and the leakage and corona loss currents. The moving belt system also distorts the electric field and, therefore, it is placed within properly shaped field grading rings. The grading is provided by resistors and additional coronadischarge elements. The collector needle system is placed near the point where the belt enters the h.t. terminal. A second point system excited by a self-inducing arrangement enablesthedowngoing belt to becharged to thepolarity oppositeto thatoftheterminal and thus the rate of charging of the latter, for a given speed, is doubled. The self inducing arrangement requires insulating the upper pulley and maintaining it at a potential higher than that of the h.t. terminal by connecting the pulley to the collector needle system. The arrangement also consists of a row of points (shown as upper spray points in Fig. 3.7) connected to the inside of the h.t. terminal and directed towards the pulley above its points of entry into the terminal.

As the pulley is at a higher potential (positive), the negative charges due to corona discharge at the upper spray points are collected by the belt. This neutralizes any remaining positivecharge on the belt and leaves an excess of negative charges on the downgoing belt to be neutralized by the lower spray points. Since these negative charges leave the h.t. terminal, the potential of the h.t. terminal is raised by the corresponding amount. In order to have a rough estimate of the current supplied by the generator, let us assume that the electric field E is normal to the belt and is homogeneous.

We know that $D = \varepsilon_0 E$ where D is the flux density and since the medium surroundingtheh.t. terminal is say air $\varepsilon_r=1$ and $\varepsilon_0 = 8.854 \times 10^{-12}$ F/meter. According to Gauss law, $D = \zeta$ the surface charge density. From above equation it is clear that current I depend upon ζ, b and v. The belt width (b) and velocity being limited by mechanical reasons, the current can beincreased by having higher value of ζ. ζ can be increased by using gases of higher dielectric strengthsothatelectricfieldintensityEcouldbeincreasedwithouttheinceptionofionizationof the medium surrounding the h.t. terminal. However, with all these arrangements, the actual short circuit currents are limited only to a few mA even for large generators.

Theadvantages ofthegeneratorare:

- Veryhighvoltagescanbeeasilygenerated
- Ripple free output
- Precisionandflexibilityofcontrol

The disadvantages are:

- Low current output
- Limitations on belt velocity due to its tendency for vibration. The vibrations may make it difficult to have an accurate grading of electric fields. These generators are used in nuclear physics laboratories for particle acceleration and other processes in research work.

Generationofhigha.c. voltages

Most of the present day transmission and distribution networks are operating on a.c. voltages and hence most of the testing equipmentsrelate to high a.c. voltages. Even though most of the equipments on the system are 3-phase systems, a single phase transformer operating at power frequency is the most common from of HVAC testing equipment. Test transformers normally used for the purpose have low power rating but high voltage ratings. These transformers are mainly used for short time tests on high voltage equipments. The currents required for these tests on various equipments are given below:

- Insulators,C.B.,bushings,Instrument
- Transformers = 0.1– 0.5 A
- Powertransformers,h.v.capacitors.=0.5–1A
- Cables = 1 A and above

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

CascadedTransformers

For voltages higher than 400 KV, it is desired to cascade two or more transformers depending upon the voltage requirements. With this, the weight of the whole unit is subdivided into single units and, therefore, transport and erection becomes easier. Also, with this, the transformer cost for a given voltage may be reduced, since cascaded units need not individually possess the expensive and heavy insulation required in single stage transformers for highvoltages exceeding 345 kV. It is found that the cost of insulation for such voltages for a single unit becomes proportional to square of operating voltage. Fig. 3.9 shows a basic scheme for cascading three transformers. The primary of the first stage transformer is connected to a low voltage supply. A voltage is available across the secondary of this transformer. The tertiary winding (excitation winding) of first stage has the same number of turns as the primary winding, and feeds the primary of the second stage transformer. The potential of the tertiary is fixed to the potential V of the secondary winding as shown in Fig. 3.9.

The secondary winding of the second stage transformer is connected in series with the secondary winding of the first stage transformer, so that a voltage of 2V is available between the ground and the terminal of secondary of the second stage transformer. Similarly, the stage-III transformer isconnected inserieswiththesecond stagetransformer. Withthistheoutputvoltage between ground and the third stage transformer, secondary is 3V. it is to be noted that the individual stages except the upper most must have three-winding transformers. The upper most, however, will be a two winding transformer. Fig. 3.9 shows metal tank construction of transformers and the secondary winding is not divided. Here the low voltage terminal of the secondary winding is connectedto thetank. The tank ofstage-Itransformer is earthed. Thetanks of stage-II and stage-III transformers have potentials of V and 2V, respectively above earth and, therefore, these must be insulated from the earth with suitable solid insulation.

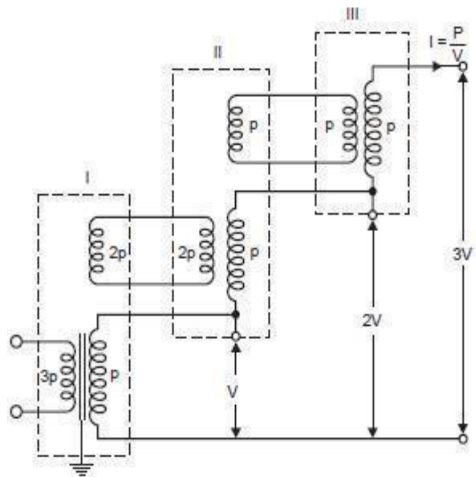


Figure:3.8Basic3stage cascadedtransformer

Through h.t. bushings, the leads from the tertiary winding and the h.v. winding are brought out to be connected to the next stage transformer. However, if the high voltage windings are of mid-point potential type, the tanks are held at 0.5 V, 1.5 V and 2.5 V, respectively. This connection results in a cheaper construction and the high voltage insulation now needs to be designed for V/2 from its tank potential. The main disadvantage of cascading the transformers is that the lower stages of the primaries of the transformers are loaded more as compared with the upper stages. The loading of various windings is indicated by P in Fig. 3.8. For the three-stage transformer, the total output VA will be 3VI = 3P and, therefore, each of the secondary winding of the transformer would carry a current of I = P/V.

Theprimarywindingofstage-IIItransformerisloadedwithPandsoalsothetertiary windingofsecondstagetransformer.Therefore,theprimaryofthesecondstagetransformer would be loaded with 2P.Extending the same logic; it is found that the first stage primary would be loaded with P. Therefore, while designing the primaries and tertiary's of these transformers, thisfactormustbetakenintoconsideration.Thetotalshortcircuitimpedanceofacascaded transformerfromdataforindividualstagescanbeobtained.Theequivalentcircuitofan individualstageisshowninFig.3.9.HereZp,Zs,andZt,aretheimpedancesassociatedwith eachwinding.Theimpedancesareshowninserieswithanideal3-windingtransformerwith correspondingnumberofturnsNp,NsandNt.Theimpedancesareobtainedeitherfrom calculatedorexperimentally-derivedresultsofthethreeshortcircuittestsbetweenanytwo windings taken at a time.

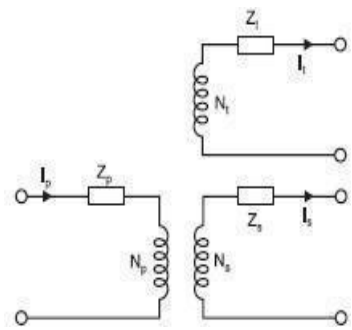


Figure:3.9Equivalent circuitofone stage

- Let*Zps*=leakageimpedancemeasuredonprimarysidewithsecondaryshortcircuited and tertiary open.
- *Zpt*=leakageimpedancemeasuredonprimarysidewithtertiaryshortcircuitedand secondary open.
- *Zst*=leakageimpedanceonsecondarysidewithtertiaryshortcircuitedandprimary open.

Ifthesemeasured impedancesarereferredto primarysidethen

$$Z_{ps} = Z_p + Z_s, \; Z_{pt} = Z_p + Z_t \quad \text{and} \quad Z_{st} = Z_s + Z_t$$

Solving these equations, we have

$$Z_p = \frac{1}{2}\left(Z_{ps} + Z_{pt} - Z_{st}\right), \; Z_s = \frac{1}{2}\left(Z_{ps} + Z_{st} - Z_{pt}\right)$$

$$Z_t = \frac{1}{2}\left(Z_{pt} + Z_{st} - Z_{ps}\right)$$

Assumingnegligiblemagnetizingcurrent,thesumoftheampereturnsofall the windings must be zero.

$$N_p I_p - N_s I_s - N_t I_t = 0$$

Assuming lossless transformer, we have,

$$Z_p = jX_p \quad Z_s = jX_s \quad \text{and} \quad Z_t = jX_t$$

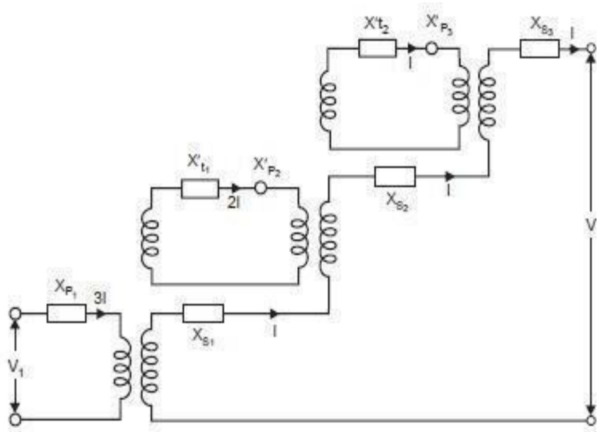


Figure:3.10Equivalent circuitof3-stage transformer

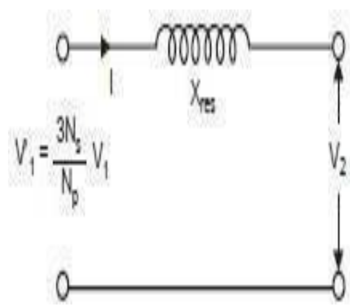


Figure:3.11Asimplified equivalentcircuit

It has been observed that theimpedanceofatwo-stagetransformeris about 3–4 timesthe impedance of one unit and three-stage impedance is 8–9 times the impedance of one unit transformer. Hence, in order to have a low impedance of a cascaded transformer, it is desirable that the impedance of individual units should be as small as possible.

ReactivePower Compensation

As is mentioned earlier, the test transformers are used for testing the insulation of various electrical equipments. This means the load connected to these transformers is highly capacitive. Therefore, if rated voltage is available at the output terminals of the test transformer and a test piece (capacitive load) is connected across its terminals, the voltage across the load becomes higher than the rated voltage as the load draws leading current. Thus, it is necessary to regulate the input voltage to the test transformer so that the voltage across the load, which is variable, depending on the test specimen, remains the rated voltage. Another possibility is that a variable inductor should be connected across the supply as shown in Fig. 3.11 so that the reactive power supplied by the load is absorbed by the inductor and thus the voltage across the test transformeris maintained within limits.

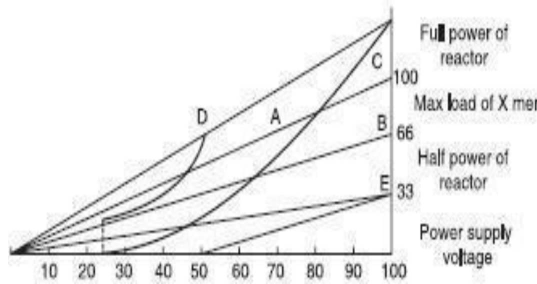


Figure:3.12Reactivepowercompensation

It should be noted that the test transformer should be able to supply the maximum value of load current for which it has been designed at all intermediate voltages including the rated voltage.Thepowervoltagecharacteristicis,therefore,astraightlineasshownbyline*A*inFig. 3.14.Thecompensatingreactivepowerabsorbedbytheair-coredinductorisshownonparabolas *B*, *C* and *D*. These will be parabolas as the reactive power = *V*2/*X*. Curve *B* corresponds to the condition when the transformer primary is connected in parallel and the reactor is connected at position 1 in Fig. 3.12.Similarly Curve *C*—Transformer primary connected in parallel andreactor at position 1 connected.

Curve *D*—Transformer primary connected in series and reactor at position 2.When the primary series is connected, for the same supply voltage, voltage per turn of primary becomes half its value when it is parallel connected and, therefore, the secondary voltage becomes 1/2of theratedvoltageand hencethecurvestarts at 50%oftheratedvoltage. Thepowerofthevoltage regulatorisproportionaltothesupplyvoltageand,therefore,isrepresented byline *E*inFig.3.12 and the maximum power at rated voltage is 33.3% of the maximum power requirement of the transformer. All possible operating conditions of the test transformer lie within the triangulararea enclosed by the line *A*, the abscissa and the 100% rated voltage line.

This area has been sub-divided into different parts, so that the permissible supply power (Here 33% of maximum transformer load) is never exceeded. The value of the highest voltage is always taken for the evaluation of the compensation arrangement. Since the impedance of thetest transformer is usually large (about 20–25%), the range under 25% of the rated voltage is not considered. It is clear from the above considerations that the design of the compensating reactor depends upon

- Thecapacitanceandoperatingvoltageoftestspecimen The
- power rating of the available regulator.
- Thepossibilityofdifferentconnectionsofthewindingoftesttransformer. The
- power rating of the test transformer.

In order that the test laboratory meets all the different requirements, every particular case must be investigated and a suitable reactor must be designed for reactive power compensation.In multistage transformers with large power output, it is desirable to provide reactive power Compensation at every stage, so that the voltage stability of the test transformer is greatly improved.

SeriesResonant Circuit

The equivalent circuit of a single-stage-test transformer along with its capacitive load is shown in Fig.3.14. Here $L1$ represents the inductance of the voltage regulator and thetransformer primary, L the exciting inductance of the transformer, $L2$ the inductance of the transformer secondary and C the capacitance of the load. Normally inductance L is very large as compared to $L1$ and $L2$ and hence its shunting effect can be neglected. Usually the load capacitance is variable and it is possible that for certain loading, resonance may occur in the circuit suddenly and the Current will then only be limited by the resistance of the circuit and the voltageacrossthetestspecimenmaygoup ashighas20to 40timesthedesiredvalue.Similarly, presence of harmonics due to saturation of iron core of transformer may also result in resonance. Third harmonic frequencies have been found to be quite disastrous. With series resonance, the resonance is controlled at fundamental frequency and hence no unwanted resonance occurs.

The development of series resonance circuit for testing purpose has been very widely welcome by the cable industry as they faced resonance problem with test transformer while testing short lengths of cables. In the initial stages, it was difficult to manufacture continuously variable high voltage and high value reactors to be used in the series circuit and therefore, indirect methods to achieve this objective were employed. Fig. 3.15 shows a continuously variable reactor connected in the low voltage winding of the step up transformer whose secondary is rated for the full test voltage. $C2$ represents the load capacitance. If N is the transformation ratio and L is the inductance on the low voltage side of the transformer, then it is reflectedwith $N2L$ valueonthesecondaryside(loadside)ofthetransformer.Forcertainsetting of the reactor, the inductive reactance may equal the capacitive reactance of the circuit, hence resonance will take place.

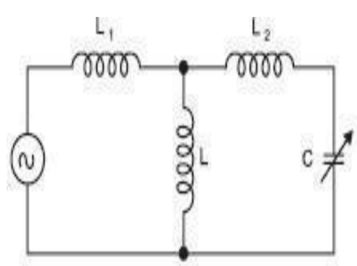


Figure:3.13Equivalentcircuit ofasinglestageloaded transformer

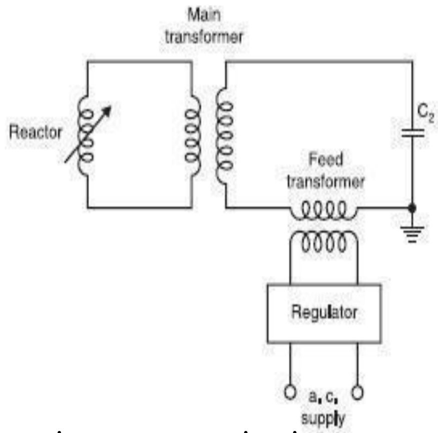


Figure:3.14Singletransformer/reactorseriesresonance circuit

Thus, the reactive power requirement of the supply becomes zero and it has to supply only the losses of the circuit. However, the transformer has to carry the full load current on the high voltage side. This is a disadvantage of the method. The inductor are designed for high quality factors $Q = \omega L / R$. The feed transformer, therefore, injects the losses of the circuit only. It has now been possible to manufacture high voltage continuously variable reactors 300 kV per unit using a new technique with split iron core. With this, the testing step up transformer can be omittedasshowninFig.3.15.Theinductanceoftheseinductorscanbevariedoverawiderange depend upon the capacitance of the load to produce resonance. Here R is usually of low value. After the resonance condition is achieved, the output voltage can be increased by increasing the input voltage. The feed transformers are rated for nominal current ratings of the reactor

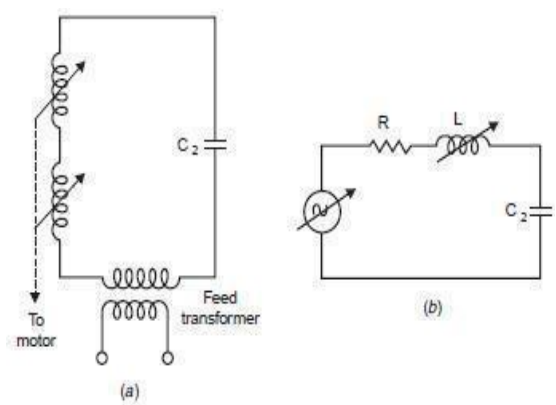


Figure: 3.15 (a) Series resonance circuit with variable h.t. reactors (b) Equivalent circuit of (a)Figure. 3.15 (b) represents an equivalent circuit for series resonance circuit.

Fig. 3.15 (b) represents an equivalent circuit for series resonance circuit. Here R is usually of low value. After the resonance condition is achieved, the output voltage can be increased by increasing the input voltage. The feed transformers are rated for nominal current ratings of the reactor. Under resonance, the output voltage will be

$$V_0 = \frac{V}{R}\frac{1}{\omega C_2}$$

$$\omega L = \frac{1}{\omega C_2}$$

WhereVisthesupplyvoltage.

Since at resonance

$$V_0 = \frac{V}{R}\omega L = VQ$$

$$\omega L = \frac{1}{\omega C_2}$$

Therefore $$V_0 = \frac{V}{R}\omega L = VQ$$

Where Q is the quality factor of the inductor which usually varies between 40 and 80. This means that withQ=40, theoutput voltageis40 timesthesupply voltage. It also means that the reactive power requirements of the load capacitance in kVA are 40 times the power to be provided by the feed transformer in KW. This results in a relatively small power rating for the feed transformer.

Thefollowing aretheadvantages ofseries resonancecircuit.

- The power requirements in KW of the feed circuit are (kVA)/Q where kVA is thereactive
- Power requirements of the load and Q is the quality factor of variable reactor usually greaterthan 40. Hence, the requirement is very small.
- The series resonance circuit suppresses harmonics and interference to a large extent. The near sinusoidal wave helps accurate partial discharge of measurements and is also desirable for measuring loss angle and capacitance of insulating materials using Schering Bridge. In case of a flashover or breakdown of a test specimen during testing on high voltage side, the resonant circuit is detuned and the test voltage collapses immediately. The short circuit
- Current is limited by the reactance of the variable reactor. It has proved to be of great value as the weak part of the isolation of the specimen does not get destroyed. In fact, since the arc flash over has very small energy, it is easier to observe where exactly the flashover is occurring by delaying the tripping of supply and allowing the recurrence of flashover.
- No separate compensating reactors (just as we have in case of test transformers) are required. This results in a lower overall weight.
- WhentestingSF6switchgear,multiplebreakdownsdonotresultinhightransients.
  Hence, no special protection against transients is required.

- Series or parallel connections of several units are not at all a problem. Any number of units can be connected in series without bothering for the impedance problem which is very severely associated with a cascaded test transformer. In case the test specimen requireslargecurrentfortesting,unitsmay beconnectedin parallelwithoutany problem.

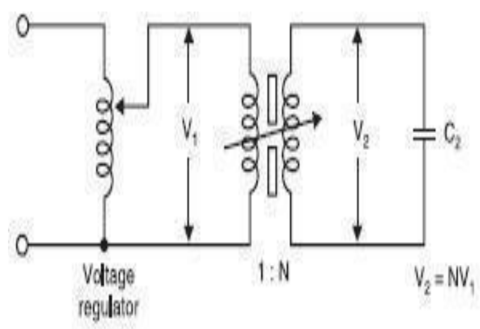


Figure:3.16Parallelresonance system

In an attempt to take advantage of both the methods of connections, i.e., series and parallel resonant systems, a third system employing series parallel connections was tried. This is basically a modification of a series resonant system to provide most of the characteristics of the parallel system. Fig. 3.17. Shows a schematic of a typical series parallel method.

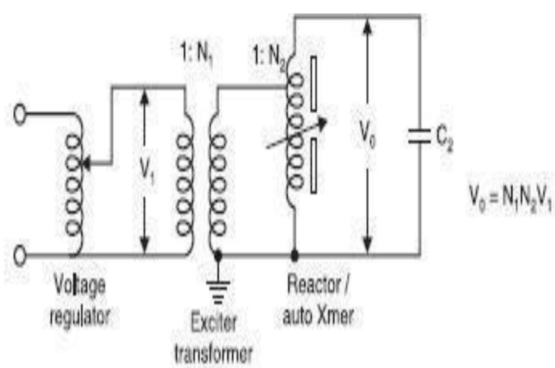


Figure:3.17Series-parallelresonant system

Here the output voltage is achieved by auto transformer action and parallel compensation is achieved by the connection of the reactor. It has been observed that during the process of tuning for most of the loads, there is a certain gap opening that will result in the parallel connected test system going into uncontrolled overvoltageof thetest sampleand ifthe test set is allowed to operate for a long time, excessive heating and damage to the reactor would result. Also, it has been observed experimentally that complete balance of ampere turns takes place when the system operates under parallel resonance condition.

Under all other settings of the variable reactor, an unbalance in the ampere turns will force large leakage flux into the surrounding metallic tank and clamping structure which will cause large circulating currents resulting in hot spots which will affect adversely the dielectric strength of oil in the tank.

In view of the above considerations, it has been recommended not to go in for series-parallel resonant mode of operation for testing purpose. If a single stage system up to 300 kV using the resonance test voltage is required, parallel resonant system must be adopted. For test voltage exceeding 300 kV, the series resonant method is strongly recommended. The specific weight ofa cascaded test transformer varies between 10 and 20 kg/kava where as for a series resonant circuit with variable high voltage reactors it lies between 3 and 6 kg/kava. circuit with variable frequency sources With the development of static frequency convertor, it has now been possible to reduce the specific weight still further. In order to obtain resonance in the circuit a choke of constantmagnitudecanbeusedandastheloadcapacitancechangesthesourcefrequencyshould be changed.

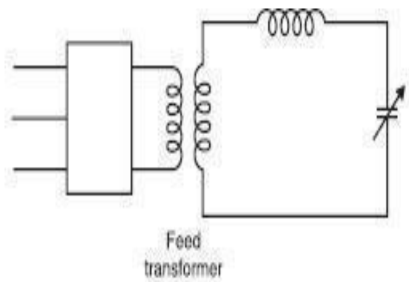


Figure:3.18Schematicdiagramofseriesresonant

Fig. 3.18 shows a schematic diagram of a series resonant circuit with variable frequency source. The frequency convertor supplies the losses of the testing circuit only which are usually of the order of 3% of the reactive power of the load capacitor as the chokes can be designed for very high quality factors.

A word of caution is very important, here in regard to testing of test specimen having large capacitance. With a fixed reactance, the frequency for resonance will be small as compared to normal frequency. If the voltage applied is taken as the normal voltage the core of the feed transformerwillgetsaturatedasV/fthenbecomes largeandthefluxinthecorewillbelarge.So, a suitable voltage must be applied to avoid this situation with the static frequency convertor circuits the specific weight has come down to 0.5 kg/kVA. It is to be noted that whereas the series resonant systems are quite popular for testing cables and highly loss free capacitive loads, cascaded transformers are more common in high voltage laboratories for testing equipment in MV range and also for relatively high loads.

ImpulseVoltages

As explained in detail in the above Chapter , disturbances of electric power transmission and distribution systems are frequently caused by two kinds of transient voltages whose amplitudes may greatly exceed the peak values of the normal a.c. operating voltage. The first kind are lightning overvoltage, originated by lightning stroke shitting the phase wires of overhead lines or the bus bars of outdoor substations. The amplitudes are very high, usually in the order of 1000 kV or more, as every stroke may inject lightningcurrents up to about 100 kA and even more into the transmission line;_27_ each stroke is then followed by travelling waves, whose amplitude is often limited by the maximum insulation strength of the overhead line. The rate of voltage rise of such a travelling wave is at its origin directly proportional to the steepness of the lightning current, which may exceed 100 kA/μsec, and the voltage levels may simply be calculated by the current multiplied by the effective surge impedance of the line. Too high voltage levels are immediately chopped by the breakdown of the insulation and therefore travelling waves with steep wave fronts and even steeper wave tails may stress the insulation of power transformers or other h.v. equipment severely. Lightning protection systems, surge arresters and the different kinds of losseswilldampanddistortthetravellingwaves, andthereforelightningovervoltage'swithvery different wave shapes are present within the transmission system.

Thesecond kind is causedby switching phenomena.Their amplitudes are always related to the operating voltage and the shape is influenced by the impedances of the system as well as by the switching conditions. The rate of voltage rise is usually slower, but it is well known that the wave shape can also be very dangerous to different insulation systems, especially to atmospheric air insulation in transmission systems with voltage levels higher than 245 kV. Both types of over voltages are also effective in the l V. distribution systems, where they are either producedby theusual,sometimescurrent-limiting,switchesorwheretheyhavebeentransmitted from the h.v. distribution systems.

Here they may often cause a breakdown of electronic equipment, as they can reach amplitudes of several kilovolts, and it should be mentioned that the testing of certain l V. apparatus with transient voltages or currents is a need today. Such tests also involve 'electromagnetic compatibility (EMC) tests', which will not be discussed here. Although the actual shape of both kinds of overvoltage varies strongly, it became necessary to simulate these transient voltages by relatively simple means for testing purposes. The various national and international standards define the impulse voltages as a unidirectional voltage which rises more or less rapidly to a peak value and then decays relatively slowly to zero.

In the relevant IEC Standard 60, widely accepted today through national committees, a distinction is made between lightning and switching impulses, i.e. according to the origin of the transients. Impulse voltages with front duration's varying from less than one up to a few tens of microseconds are, in general, considered as lightning impulses. Figure 3.19(a) shows the shape for such a 'full' lightning impulse voltage as well as sketches for the same voltage chopped atthe tail (Fig. 3.19(b)) or on the front (Fig. 3.19(c)), i.e. interrupted.

Tc: time to chopping. O1 : virtual origin disruptive discharge. Although the definitions are clearly indicated, it should be emphasized that the 'virtual origin' O1 is defined where the lineAB cuts thetimeaxis. The'fronttime'T1,again avirtual parameter,is defined as1.67times the interval T between the instants when the impulse is 30 per cent and90 per cent of the peak value for full or chopped lightning impulses. For front-chopped impulses the 'time to chopping' Tc is about equal to T1. The reason for defining the point A at 30 per cent voltage level can be found in most records of measured impulse voltages.

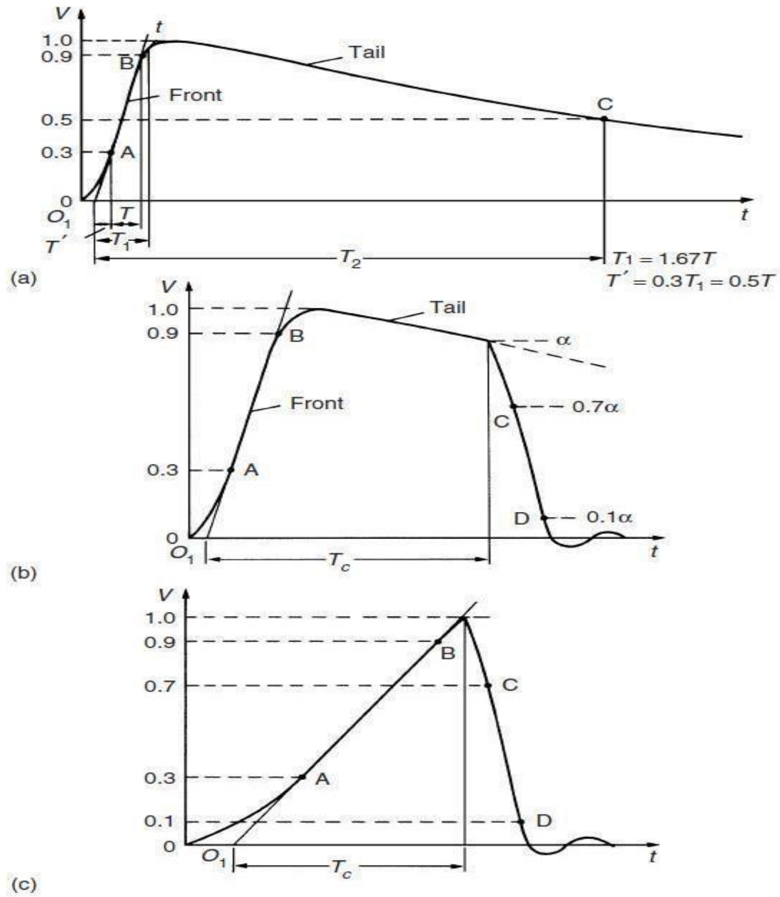


Figure: 3.19 General shape and definitions of lightning impulse (LI)voltages. (a) Full LI. (b) LI chopped on the tail. (c) LI chopped on the front.T1 : front time. T2 : time to half-value.

It is quite difficult to obtain a smooth slope within the first voltage rise, as the measuring systems as well as stray capacitances and inductances may cause oscillations. For most applications, the (virtual) front time T1 is 1.2 μs, and the (virtual) time to half-value T2 is 50 μs. In generalthespecificationspermitatoleranceofupto30percentforT1 and20percentforT2. Such impulse voltages are referred to as a T1/T2 impulse, and therefore the 1.2/50 impulse is the accepted standard lightning impulse voltage today. Lightning impulses are therefore of veryshort duration, mainly if they are chopped on front. Due to inherent measurement errors and uncertain tie-in the evaluation the ‘time parameters’ T1, T2 and Tc or especially the time difference between the points C and D (Figs 3.19 (b) and (c)) can hardly be quantified with high accuracy.

Figure 3.20 illustrates the slope of a switching impulse. Whereas the time to half-valueT2 is defined similarly as before, the time to peak Tp is the time interval between the actual origin and the instant when the voltage has reached its maximum value. This definition could be criticized, as it is difficult to establish the actual crest value with high accuracy. An additional parameteristhereforethetime Td,the timeat 90percentof crestvalue. Thedifferent definitions in comparison to lightning impulses can be understood if the time scale is emphasized: the standard switching impulse has time parameters (including tolerances) and is thereforedescribed as a 250/2500 impulse.

For fundamental investigations concerning the insulation strength of long air gaps or other apparatus, the time to peak has to be varied between about 100 and 1000 μs, as the breakdown strength of the insulation systems may be sensitive upon the voltage wave shape.

$$T_p = 250\,\mu s \pm 20\%$$
$$T_2 = 2500\,\mu s \pm 60\%$$

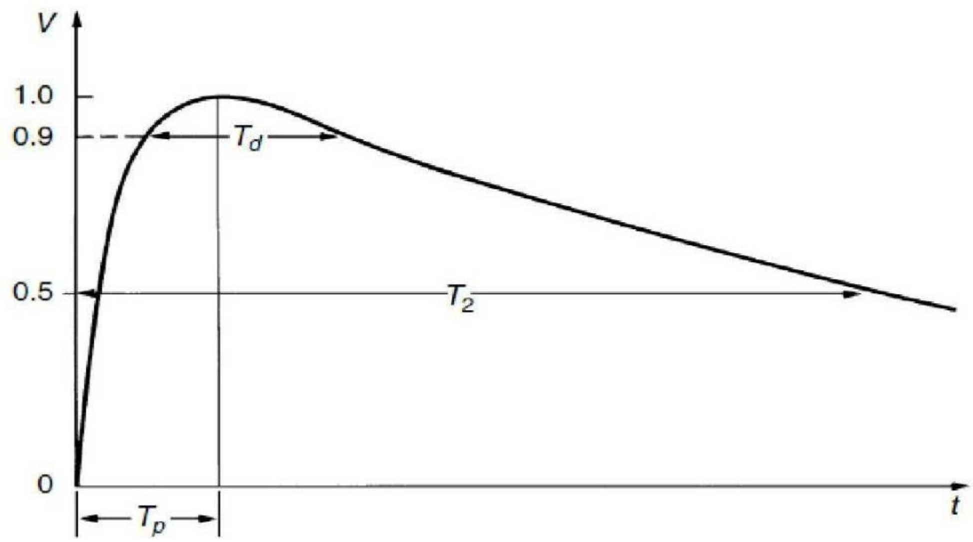


Figure:3.20Generalshapeofswitchingimpulsevoltages.Tp:timetopeak.T2 :timetohalf- value. Td: time above 90 per cent

Impulsevoltagegenerator circuits

The introduction to the full impulse voltages as defined in the previous section leads to simple circuits for the generation of the necessary wave shapes. The rapid increase and slow decay can obviously be generated by discharging circuits with two energy storages, as the wave shape may well be composed by the superposition of two exponential functions.

Again the load of the generators will be primarily capacitive, as insulation systems are tested. This load will therefore contribute to the stored energy. A second source of energy could be provided by an inductance or additional capacitor. For lightning impulses mainly, a fast discharge of pure inductor is usually impossible, as h.v. chokes with high energy content can never be built without appreciable stray capacitances. Thus a suitable fast discharge circuit will always consist essentially of two capacitors.

Single-stagegeneratorcircuitsTwobasiccircuitsforsingle-stageimpulsegeneratorsare shown in Fig. 3.21.The capacitor C_1 is slowly charged from a dace. source until the spark gap Gbreaksdown.Thissparkgapactsasavoltage-limitingandvoltage-sensitiveswitch,whose ignitiontime(timetovoltagebreakdown)isveryshort incomparisontoT$_1$.Assuch single-stage generators may be used for charging voltages from some kV up to about 1 MV, the sphere gaps) will offer proper operating conditions.

An economic limit of the charging voltage V0 is, however, a value of about 200 to 250 kV,astoolargediametersofthesphereswouldotherwiseberequiredtoavoidexcessivein homogeneous field distributions between the spheres. The resistors R_1, R_2 and the capacitance C_2 form the waveshaping network. R1 will primarily damp the circuit and control the front time T_1. R_2 will discharge the capacitors and therefore essentially control the wave tail.

The capacitance C_2 represents the full load, i.e. the object under test as well as all other capacitiveelementswhichareinparalleltothetestobject(measuringdevices;additionalload capacitor to avoid large variations of T_1/T_2, if the test objects are changed). No inductances are assumed so far, and are neglected in the first fundamental analysis, which is also necessary to understand multistage generators. In general this approximation is permissible, as the inductance of all circuit elements has to be kept as low as possible.

Within the 'discharge' capacitance C_1. As C1 is always much larger than C_2, this figure determines mainly the cost of a generator. For the analysis we may use the Laplace transform circuit sketched .which simulatestheboundarycondition, that fort 0 C1ischarged to V0 and for t >0 this capacitoris directly connectedto thewaveshaping network. For thecircuit Fig. 3.21(a) the output voltage is thus given by the expression.

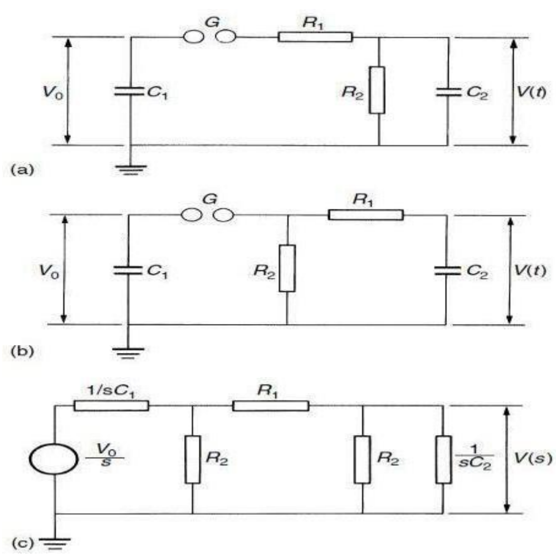


Figure: 3.21Single-stage impulse generator circuits (a) and (b). C1: discharge capacitance. C2:loadcapacitance.R1:frontordamping resistance.R2:dischargeresistance.(c)Transform circuitBeforestartingtheanalysis,weshouldmentionthemostsignificantparameterofimpulse generators.Thisisthemaximumstoredenergy

$$W = \tfrac{1}{2}C_1(V_{0_{\max}})^2$$

$$V(s) = \frac{V_0}{s}\frac{Z_2}{Z_1 + Z_2},$$

Where

$$Z_1 = \frac{1}{C_1 s} + R_1;$$
$$Z_2 = \frac{R_2/C_2 s}{R_2 + 1/C_2 s}.$$

Where

$$V(s) = \frac{V_0}{k}\frac{1}{s^2 + as + b}$$

where

$$a = \left(\frac{1}{R_1C_1} + \frac{1}{R_1C_2} + \frac{1}{R_2C_2}\right);$$
$$b = \left(\frac{1}{R_1R_2C_1C_2}\right);$$
$$k = R_1C_2.$$

ForcircuitFig.3.22(b)onefindsthesamegeneralexpressioneqn,withthe following constants; however,

$$a = \left(\frac{1}{R_1C_1} + \frac{1}{R_1C_2} + \frac{1}{R_2C_1}\right);$$
$$\left.\begin{array}{l} b = \left(\dfrac{1}{R_1R_2C_1C_2}\right); \\ k = R_1C_2. \end{array}\right\} \text{ as above}$$
$$\alpha_1, \alpha_2 = \frac{a}{2} \mp \sqrt{\left(\frac{a}{2}\right)^2 - b}.$$

Forbothcircuits,therefore,weobtainfromthetransformtablesthesameexpression in the time domain:

$$V(t) = \frac{V_0}{k}\frac{1}{(\alpha_2 - \alpha_1)}[\exp(-\alpha_1 t) - \exp(-\alpha_2 t)]$$

Althoughonemightassumethatbothcircuitsareequivalent,alargerdifferencemay occur if the voltage efficiency, 5, is calculated. This efficiency is defined as

$$\eta = \frac{V_p}{V_0};$$

Vpbeing thepeak valueoftheoutput voltageas indicated. Obviously thisvalueis always smallerthan1 or 100 per cent. It can be calculated by finding tmax from dVt/dt D0; this timefor the voltage Vt to rise to its peak value is given by

$$t_{\max} = \frac{\ln(\alpha_2/\alpha_1)}{(\alpha_2 - \alpha_1)}.$$

Substitutingthisequationinto eqnonemay find

$$\eta = \frac{(\alpha_2/\alpha_1)^{-[(\alpha_2/\alpha_1 - \alpha_1)]} - (\alpha_2/\alpha_1)^{-[(\alpha_2/\alpha_2 - \alpha_1)]}}{k(\alpha_2 - \alpha_1)}.$$

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

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

Circuit Fig. 2.25(b):

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

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

Alltheseequations containthetime constants1/˛1 and 1/˛2,which depend upon the waveshape.Thereis,however,nosimplerelationshipbetweenthesetimeconstantsandthetimes T_1, T_2 and Tp as defined in the national or international recommendations, i.e. in Figs 2.23 and 2.24. This relationship can be found by applying the definitions to the analytical expression for Vt,this meanstoequation.Therelationshipisirrationalandmustbecomputednumerically.Thefollowing table shows the result for some selected wave shapes: The standardized nominal values of T_1 and T_2 are difficult to achieve in practice, as even for fixed values of C_1 the load C_2 will vary and the exact values for R_1 and R_2 according to above equation in general not available.

These resistorshavetobe dimensionedforthe ratedhighvoltage ofthe generator andare accordinglyexpensive.ThepermissibletolerancesforT$_1$ andT$_2$ arethereforenecessaryandused to graduate the resistor values. According of the real output voltage V(t) will in addition be necessary if the admissible impulse shape has to be testified. Another reason for such a measurement is related to the value of the test voltage as defined in the recommendations. This magnitude corresponds to the crest value, if the shape of the lightning impulse is smooth.

However, oscillations or an overshoot may occur at the crest of the impulse. If the frequency of such oscillations is not less than 0.5MHz or the duration of overshoot not over 1 sec, a ‘mean curve’ (see Note below) should be drawn through the curve. The maximum amplitudeofthis‘meancurve’definesthevalueofthetestvoltage.Suchacorrectionisonly tolerated, provided their single peak amplitude is not larger than 5 per cent of the crest value.

Oscillation son the front of the impulse (below 50 per cent of the crest value) are tolerated, provided their single peak amplitude does not exceed 25 percent of the crest value.

It should be emphasized that these tolerances constitute the permitted differencesbetween specified values and those actually recorded by measurements. Due to measuring errors the true values and the recorded ones may be somewhat different. Note. With the increasing application of transient or digital recorders in recording of impulse voltages it became very obvious that the definition of a ‘mean curve’ for the evaluation of lightning impulse parameters of waveforms with oscillations and/or overshoot, as provided by the standards, is insufficient. Any software, written to evaluate the parameters, needs clear instructions which are not yet available. As this matter is still under consideration (by CIGRE Working Group 33.03) and a revision of the current standards may provide solutions, no further comments to this problem are given. The origin of such oscillations or the overshoot can be found in measuring errors as well as by the inductances within every branch of the circuit or the stray capacitances, which will increase with the physical dimensions of the circuit.

As far as inductances are concerned, a general rule for the necessary critical damping of single-stage or – with less accuracy of multistage generators can easily be demonstrated . If individual inductances L1, L2 are considered within the discharge circuit as indicated in Fig. 3.22(a), a second order differential equation determines the output voltage across the load capacitanceC2.However,suchanequivalentcircuitcannotbeexact,asadditionalcircuitsrelated to stray capacitances are not taken into account. Thus we may only combine the total inductance within the C1 –C2 circuit to single inductance L, as shown in Fig. 3.22 (b), and neglect the positions of the tail resistors, which have no big influence. This reduces the circuit to a simple damped series resonant circuit, and the critical resistance R D R1 for the circuit to beNon-oscillatory is given by the well-known equation

$$R_1 \cong R = 2\sqrt{\frac{L}{C}}$$

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$$

This equation is in general suitable for predicting the limiting values for the front resistor R1. The extremely tedious analytical analysis of circuits containing individual inductances is shown elsewhere. Computer programs for transients may also be used to find the origin of oscillations, although it is difficult to identify good equivalent circuits.

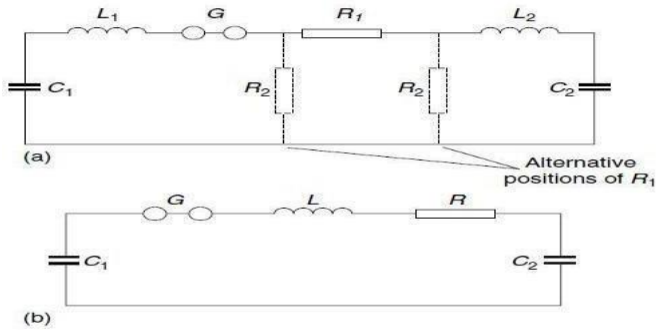


Figure: 3.22 Simplified circuit of impulse generator and load. Circuit showing alternativepositionsofthewavetailcontrolresistance.(b)Circuitforcalculationofwave front oscillations

Multistageimpulsegenerator circuits

The difficulties encountered with spark gaps for the switching of very high voltages, the increase of the physical size of the circuit elements, the efforts Generation of high voltages 61necessary in obtaining high dace. voltages to charge C1 and, last but not least, the difficulties of suppressing corona discharges from the structure and leads during the charging period make the one-stage circuit inconvenient for higher voltages. In order to overcome these difficulties, in 1923 Marx35 suggested an arrangement where a number of condensers are charged in parallel throughhighohmicresistancesandthendischargedinseriesthroughsparkgaps.Therearemany different, although always similar, multistage circuits in use. To demonstrate the principle of operation, a typical circuit is presented in Fig. 3.23 which shows the connections of a six-stage generator. The dace. Voltage charges the equal stage capacitors C01 in parallel through the high value charging resistors R0 as well as through the discharge (and also charging).

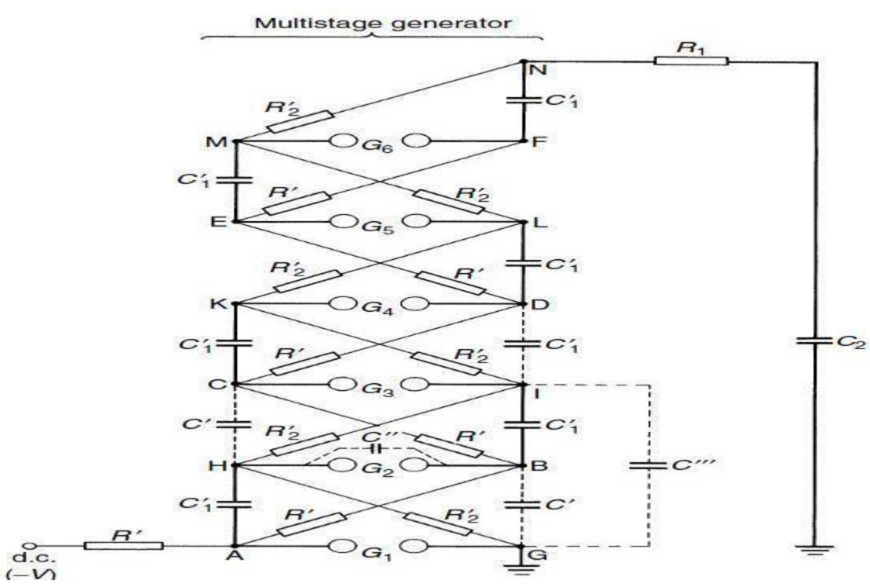


Figure:3.23Basiccircuitofasix-stageimpulsegenerator(Marxgenerator)resistances

R02whicharemuchsmallerthantheresistorsR0andarecomparablewithR2inFig. 3.25. At the end of the relatively long charging period(typically several seconds up to 1 minute), the points A, B, . . . ,F will be at the potential of the dace. source, e.g. _V with respect to earth, and the pointsG,H,, N will remain at the earth potential, as the voltage drop during charging across the resistors R02is negligible. The discharge or firing of the generator is initiated by the breakdown of the lowest gap G1 which is followed by a nearly simultaneous breakdown of allthe remaining gaps. According to the traditional theory, which does not take into account the stray capacitances Indicated by the dotted lines, this rapid breakdown would be caused by high overvoltages acrossthe second and furthergaps: when thefirst gap fires, thepotential at point A changes rapidly from _V to zero, and thus the point H increases its potential to CV.

As the point B still would remain at the charging potential, _V, thus a voltage of 2V would appear across G2. This high overvoltage would therefore cause this gap to break downand the potential at point I would rise to C2V, creating a potential difference of 3V acrossgapG3, if again the potential at point C would remain at the charging potential.

This traditional interpretation, however, is wrong, since the potentials B and C can – neglecting stray capacitances – also follow the adjacent potentials of the points A and B, as the resistors R0 are between. We may only see up to now that this circuit willgive an output voltage with a polarity opposite to that of the charging voltage. In practice, it has been noted that the gap G2 must be set to a gap distance only slightly greater than that at which G1 breaks down; otherwise it does not operate.

According to Edwards, Husbands and Perry_31_ for an adequate explanation one may assume the stray capacitances C0, C00 and C000 within the circuit. The capacitances C0 are formed by the electrical field between adjacent stages; C000 has a similar meaning across two stages. C00 is the capacitance of the spark gaps. If we assume now the resistors as open circuits, we may easily see that the potential at point B ismore or less fixed by the relative magnitudes of thestray capacitances.NeglectingC0between thepointsHandC andtakingintoaccountthatthe discharge capacitors C01 are large in comparison to the stray capacitances, point B can be assumed as mid-point of a capacitor voltage divider formed by C00 and C0/C000. Thus the voltage rise of point A from _V to zero will cause the potential B to rise from V to a voltage of

$$V_B = -V + V\left(\frac{C''}{C' + C'' + C'''}\right) = -V\left(\frac{C' + C'''}{C' + C'' + C'''}\right)$$

Hence the potential difference across G_2 becomes

$$V_{G2} = +V - (-V_B) = V\left(1 + \frac{C' + C'''}{C' + C'' + C'''}\right).$$

If C00 equals zero, the voltage across G2 will reach its maximum value 2V.This gap capacitance, however, cannot be avoided. If the stage capacitancesC0 and C000 are both zero, VG2 will equal V, and a sparking of G2 would not be possible. It is apparent, therefore, thatthese stray capacitances enhance favorable conditions for the operation of the generator. In reality, the conditions set by the above equations are approximate only and are, of course, transient, as the stray capacitances start to discharge via the resistors. As the values of C0 to C000 are normally in the order of some 10 pF only, the time constants for this discharge may be as low as 10_7 to 10_8 sec. Thus the voltage across G2 appears for a short time and leads to breakdown within several tens of nanoseconds. Transient over voltages appear across the further gaps, enhanced also by the fact that the output terminal N remains at zero potential mainly, and therefore additional voltages are built up across the resistor R02. So the breakdown continuesand finally the terminal N attains a voltage of C6V, or nV, if n stages are present.

The processes associated with the firing of such generators are even more sophisticated. They have been thoroughly analyzed and investigated experimentally.31,36,37_In practice for a consistent operation it is necessary to set the distance for the first gap G1 only slightly below the second and further gaps for earliest breakdown. It is also necessary to have the axes of the gaps in one vertical plane so that the ultraviolet illumination from the spark in the first gap irradiates the other gaps. This ensures a supply of electrons released from the gap to initiate breakdown during the short period when the gaps are subjected to the overvoltage.

If the first gap is not electronically triggered, the consistency of its firing and stability of breakdown and therefore output voltageis improved by providing ultraviolet illumination forthe firstgap.Theseremarksindicateonlyasmallpartoftheproblemsinvolvedwiththeconstruction of spark gaps and the layout of the generator. Before some of these additional problems are treated, we shall treat more realistic Marx circuits as used for the explanations so far.

In Fig. 3.24, the wave front control resistor R1 is placed between the generator and the load only. Such a single ‘external’ front resistor, however, has to withstand for a short time the full rated voltage and therefore is inconveniently long or may occupy much space. This disadvantage can be avoided if either a part of this resistance is distributed or if it is completely distributed within the generator. Such an arrangement is illustrated in Fig. 2.30, in which in addition the series connection of the capacitors C01 and gaps (as proposed originally byGoodlet_38_) is changed to an equivalent arrangement for which the polarity of the output voltage is the same as the charging voltage. The charging resistorsR0 are always large compared with the distributed resistors R01and R02, andR02is made as small as is necessary to give the required time to halve-valueT2. Adding the external front resistor R001 helps to damp oscillations otherwise

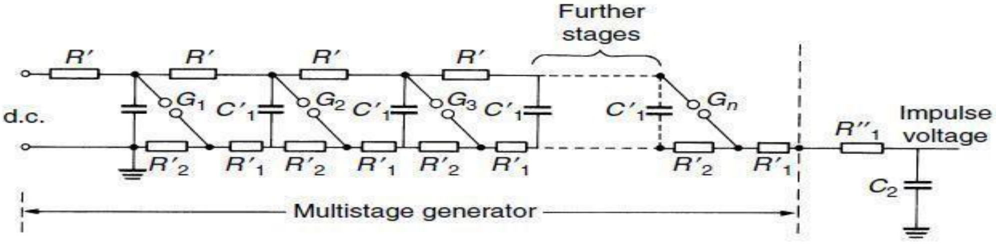


Figure:3.24Multistageimpulsegenerator withdistributeddischargeandfront resistors

R02: discharge resistors. R01: internal front resistors. R001: external front resistorexcited by the inductance and capacitance of the external leads between the generator and the load, if these leads are long. If the generator has fired, the total is charge capacitance C1 maybe calculated as where n is the number of stages. The consistent firing of such circuits could be explained as for the generator

$$\frac{1}{C_1} = \sum^{n} \frac{1}{C'_1};$$

the effective front resistance R_1 as

$$R_1 = R''_1 + \sum^{n} R'_1;$$

and the effective discharge resistance R_2 – neglecting the charging resistances R' – as

$$R_2 = nR'_2 = \sum^{n} R'_2;$$

of Fig. 3.24. For both generator circuits, the firing is aggravated if the resistancesR02 have relatively low values. According to equations such low values appear with generators of high energy content and/or short times to half-value, T2. Then the time constant for discharging the stray capacitances to ground C000 (Fig. 3.24) will be too low and accordingly the overvoltagefor triggering the upper stages too short. By additional means providing high resistance values within the firing period, this disadvantage can be avoided.

TRIPPINGANDCONTROLOFIMPULSE GENERATORS

In large impulse generators, the spark gaps are generally sphere gaps or gaps formed by hemispherical electrodes. The gaps are arranged such that sparking of one gap results in automatic sparking of other gaps as overvoltage is impressed on the other. In order to have consistency in sparking, irradiation from an ultra-violet lamp is provided from the bottom to all the gaps. To trip the generator at a predetermined time, the spark gaps may be mounted one movable frame, and the gap distance is reduced by moving the movable electrodes closer.

This method is difficult and does not assure consistent and controlled tripping. A simple method of controlled tripping consists of making the first gap a three electrode gap and firing it from a controlled source. Figure 3.25 gives the schematic arrangement of a three electrode gap The first stage of the impulse generator is fitted with a three electrode gap, and the central electrode is maintained at a potential in-between that of the top and the bottom electrodes with the resistors R\ and RL. The tripping is initiated by applying a pulse to the thyratron G byclosing the switch S. The capacitor C produces an exponentially decaying pulse of positive polarity the pulse goes and initiates the oscillograph time base. The thyratron conducts on receivingthepulsefromtheswitchSandproduces anegativepulsethrough thecapacitanceCiat the central electrode of the three electrode gap.

Hence, the voltage between the central electrode and the top electrode of the three electrode gap goes above its sparking potential and thus the gap conducts. The time lag required for the thyratron firing andbreakdown of the three electrode gap ensures that the sweep circuit of the oscillographbegins before the start of the impulse generator voltage. The resistance R^ ensures decoupling of voltage oscillations produced at the spark gap entering the oscilloscopethrough the common trip circuit. The three electrode gap requires larger space andanelaborateconstruction.Now-a-daysatrigatrongapshowninFig.3.26isused,andthisrequires much smaller voltage for operation compared to the three electrode gap

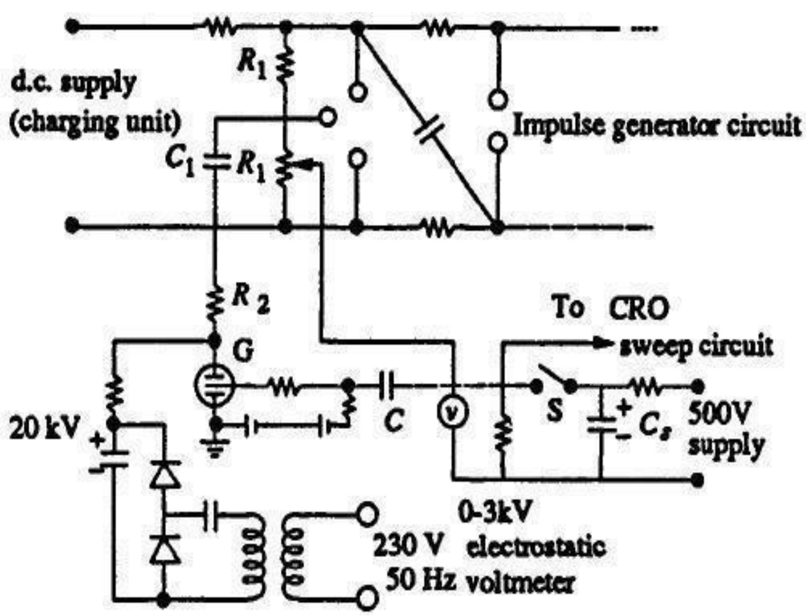


Figure:3.25Trippingof animpulsegeneratorwithathree electrodegap

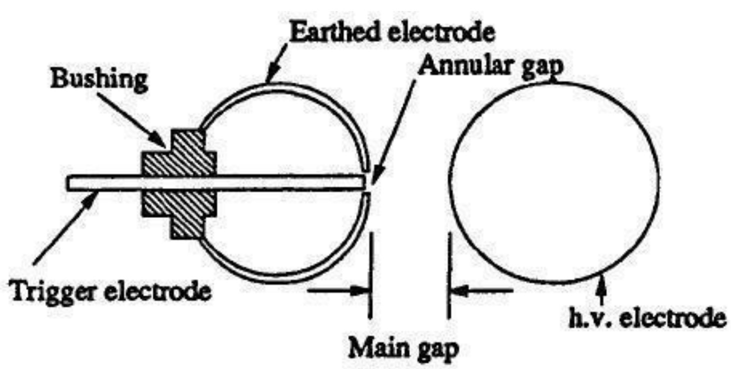
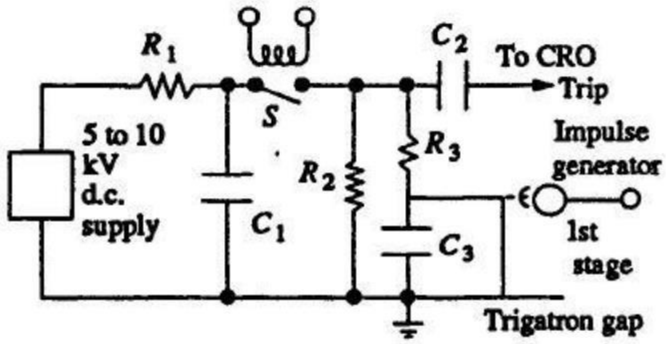
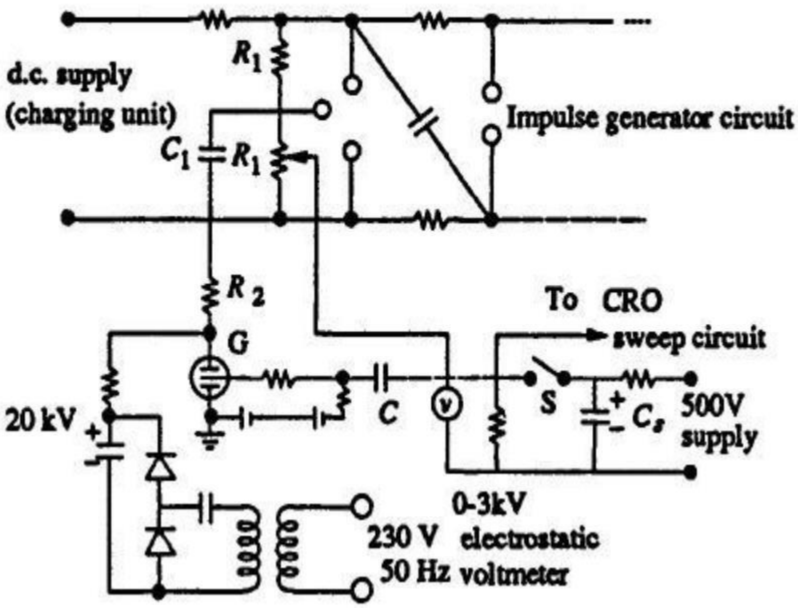


Figure:3.26(a)Trigatron gap





(b) TrippingcircuitusingatrigatronFigure:3.26

Trigatron gap and tripping circuit

A trigatron gap consists of high voltage spherical electrode of suitable size, an earthed main electrodeof spherical shape, and atrigger electrode throughthemain electrode. Thetrigger electrode is a metal rod with an annular clearance of about 1 mm fitted into the main electrode through a bushing. The trigatron is connected to a pulse circuit as shown in fig. 3.26 b. Tripping of the impulse generator is effected by a trip pulse which produces a spark between the trigger electrode and the earthed sphere. Due to space charge effects and distortion of the field in the main gap, spark over of the main gap Fig. 3.27 applied for correct operation.

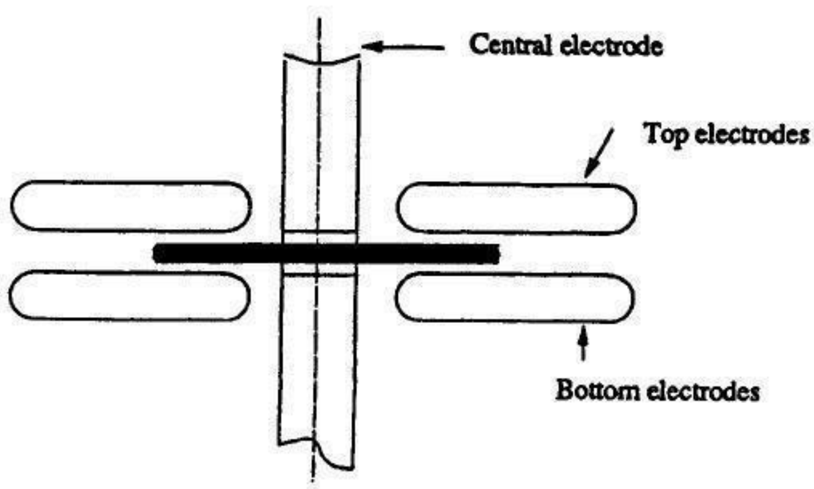


Figure:3.27Threeelectrodegapforhighcurrent switching

ThreeElectrodeGap forImpulseCurrentGenerator

In the case of impulse current generators using three electrode gaps for tripping and control, a certain special design is needed. The electrodes have to carry high current from the capacitor bank. Secondly, the electrode has to switch large currents in a small duration of time(in about a microsecond). Therefore, the switch should have very low inductance. The erosion rate of the electrodes should be low. For high current capacitor banks, a number of spark gap switches connected in parallel as shown in Fig. 3.27 are often used to meet the requirement. Recently, trigatron gaps are being replaced by triggered vacuum gaps, the advantage of the latter being fast switching at high currents (> 100 kA) in a few nanoseconds. Triggering of the spark gapsbyfocusedlaserbeamsisalsoadoptedsincetheperformanceisbetterthantheconventional triggering methods.

UNIT–IVMEASUREMENTOFHIGHVOLTAGEANDHIGHCURRENTS

INTRODUCTION

Transient measurements have much in common with measurements of steady state quantities but the Short-lived nature of the transients which we are trying to record introduces special problems. Frequently the transient quantity to be measured is not recorded directly because of its large magnitudes e.g. when a shunt is used to measure current, we really measure the voltage across the shunt and then we assume that the voltage is proportional to the current, a fact which should not be taken for granted with transientcurrents. Often the voltage appearingacrossthe shuntmay be insufficient to drivethemeasuring device it requires amplification. On the other hand, if the voltage to be measured is too large to be measured with the usual meters, it must be attenuated. This suggests an idea of a measuring system rather than a measuring device. Measurements of high voltages and currents involve much more complex problems which a specialist in common electrical measurement does not have to face. The high voltage equipments have large stray capacitances with respect to the grounded structures and hence large voltage gradients are set up. A person handling these equipments and the measuring devices must be protected against these over voltages. For this, large structures are required to control the electrical fields and to avoid flash over between the equipment and the grounded structures. Sometimes, these structures are required to control heat dissipation within the circuits. Therefore, the location and layout of the equipments is very important to avoid these problems. Electromagnetic fields create problems in the measurements of impulse voltages and currents and should be minimized. The chapter is devoted to describing various devices and circuits for measurement of high voltages and currents. The application of the device to the type of voltages and currents is also discussed.

UniformFieldSpark Gaps

Bruce suggested the use of uniform field spark gaps for the measurements of a.c., d.c and impulse voltages. These gaps provide accuracy to within 0.2% for a.c. voltage measurements an appreciable improvement as compared with the equivalent sphere gap arrangement.

Fig. 4.1 shows a half-contour of one electrode having plane sparking surfaces with edges of gradually increasing curvature

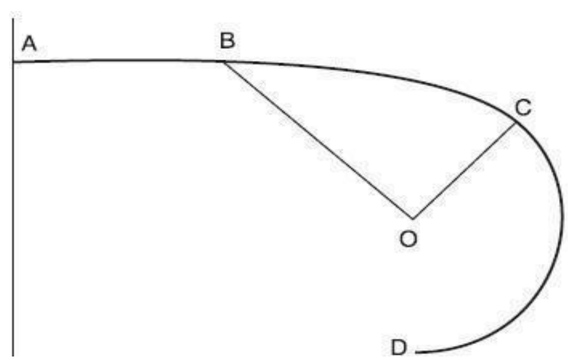


Figure:4.1Halfcontour ofuniformsparkgap

The portion AB is flat, the total diameter of the flat portion being greater than the maximum spacing between the electrodes. The portion BC consists of a sine curve based on the axes OB and OC and given by XY = CO sin (BX/BO . π/2). CD is an arc of a circle with centreat O.BruceshowedthatthebreakdownvoltageVofagapoflength Scmsinairat20°C and 760 mmHg. Pressure is within 0.2 per cent of the value given by the empirical relation.

$$V = 24.22S + 6.08\sqrt{S}$$

Thisisagreatadvantage,thatis,ifthespacingbetweenthespheresforbreakdownis known the breakdown voltage can be calculated.

Theotheradvantagesofuniformfield sparkgapsare

(i) Noinfluenceofnearbyearthedobjects

(ii) Nopolarity effect.

However,thedisadvantagesare

(i) Veryaccuratemechanicalfinishoftheelectrodeis required.

(ii) Carefulparallelalignmentofthetwo electrodes.

(iii) Influenceofdust bringsin erraticbreakdown ofthegap.

This is much more serious in these gaps as compared with sphere gaps as the highly stressed electrode areas become much larger. Therefore, a uniform field gap is normally not used for voltage measurements.

Rod Gaps

A rod gap may be used to measure the peak value of power frequency and impulse voltages. The gap usually consists of two 1.27 cm square rod electrodes square in section at their end and are mounted on insulating stands so that a length of rod equal to or greater than one half of the gap spacing overhangs the inner edge of the support. The breakdown voltages as found in American standards for different gap lengths at 25° C, 760 mm Hg. pressure and with water vapour pressure of 15.5 mm Hg. are reproduced here.

Table4.1

Gap Length in Cms.	Breakdown Voltage KV Peak	Gap Length in Cms.	Breakdown Voltage KV Peak
2	26	80	435
4	47	90	488
6	62	100	537
8	72	120	642
10	81	140	744
15	102	160	847
20	124	180	950
25	147	200	1054
30	172	220	1160

Thebreakdownvoltageisarodgapincreasesmoreorlesslinearlywithincreasing relative air density over the normal variations in atmospheric pressure. Also, the breakdownvoltage increases with increasing relative humidity, the standard humidity being taken as 15.5 mmHg.Becauseofthelargevariationinbreakdownvoltageforthesamespacingandthe uncertaintiesassociatedwiththeinfluenceofhumidity,rodgapsarenolongerusedformeasurementofa. c.orimpulsevoltages.However,morerecentinvestigationshaveshown thattheserodscanbeusedford.cmeasurementprovidedcertainregulationsregardingthe electrodeconfigurationsareobserved.Thearrangementconsistsoftwohemispherically capped rods of about 20 mm diameter as shown in Fig. 4.3.1.

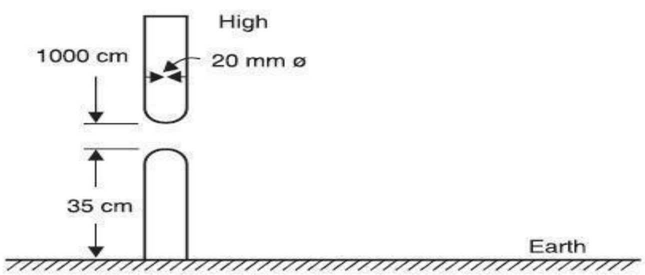


Figure:4.2Electrodearrangements fora rod gaptomeasureHVDC

The earthed electrode must be long enough to initiate positive breakdown streamers if the high voltage rod is the cathode. With this arrangement, the breakdown voltage will always be initiated by positive streamers for both the polarities thus giving a very small variation and being humidity dependent. Except for low voltages (less than 120 kV), where the accuracy is low, the breakdown voltage can be given by the empirical relation.

$$V = \delta(A + BS)4\sqrt{5.1 \times 10^{-2}(h + 8.65)}KV$$

Wherehis theabsolutehumidityingm/m3andvariesbetween4and20gm/m3intheabove relation. The breakdown voltage is linearly related with the gap spacing and the slope of the relation B

= 5.1kV/cmandisfoundtobeindependentofthepolarityofvoltage.HoweverconstantAispolarity dependent and has the values

A= 20 Kv for positivePolarity=15Kv for negative polarity

Theaccuracyoftheaboverelationisbetterthan±20%and,therefore,providesbetteraccuracy even as compared to a sphere gap.

ElectrostaticVoltmeter

The electric field according to Coulomb is the field of forces. The electric field is produced by voltage and, therefore, if the field force could be measured, the voltage can also be measured. Whenever a voltage is applied to a parallel plate electrode arrangement, an electric field is set up between the plates. It is possible to have uniform electric field between the plates with suitable arrangement of the plates. The field is uniform, normal to the two plates and directed towards the negative plate. If A is the area of the plate and E is the electric fieldintensity between the plates ε the permittivity of the medium between the plates, we know that the energy density of the electric field between the plates is given as,

$$w_d = \frac{1}{2} \in E^2 \quad (4.2)$$

Consider a differential volume between the plates and parallel to the plates with area Aand thickness dx, the energy content in this differential volume Adx i

$$dw = w_d A dx = \frac{1}{2} \in E^2 A dx \quad (4.3)$$

NowforceFbetweentheplatesisdefinedasthederivativeofstoredelectricenergy along the field direction i.e.,

$$F = \frac{dw}{dx} = \frac{1}{2} \in E^2 A \quad (4.4)$$

NowE=V/dwhereVisthevoltagetobemeasuredanddthedistanceofseparation between the plates. Therefore, the expression for force

$$F = \frac{1}{2} \in \frac{V^2 A}{d^2} \quad (4.5)$$

Since the two plates are oppositely charged, there is always force of attraction between the plates. If the voltage is time dependant, the force developed is also time dependant. In such a case the mean value of force is used to measure the voltage. ThusElectrostatic voltmeters measure the force based on the above equations and are arranged such that one of the plates is rigidly fixed whereas the

$$F = \frac{1}{T}\int_0^T F(t)dt = \frac{1}{T}\int \frac{1}{2} \in \frac{V^2}{d^2} A\, dt = \frac{1}{2}\frac{\in A}{d^2} \cdot \frac{1}{T}\int V^2(t)dt = \frac{1}{2} \in A \frac{V_{rms}^2}{d^2} \quad (4.6)$$

other is allowed to move. With this the electric field gets disturbed. For this reason, the movable electrode is allowed to move by not more than a fraction of a millimeter to a few millimeters even for high voltages so that the change in electric field is negligiblysmall.Astheforceisproportionaltosquareof Vrms,themetercanbeusedbothfor a.c.and d.cvoltagemeasurement.

The force developed between the plates is sufficient to be used to measure the voltage. Various designs of the voltmeter have been developed which differ in the construction of electrode arrangement and in the use of different methods of restoring forces required to balance the electrostatic force of attraction. Some of the methods are

- Suspensionofmovingelectrodeononearmofabalance.
- Suspension of the moving electrode on a spring.
- Penduloussuspensionofthemovingelectrode. Torsional
- suspension of moving electrode.

The small movement is generally transmitted and amplified by electrical or optical methods. If the electrode movement is minimized and the field distribution can exactly be calculated, the meter can be used for absolute voltage measurement as the calibration can be made in terms of the fundamental quantities of length and force. From the expression for the force, it is clear that for a given voltage to be measured, the higher the force, the greater is the precision that can be obtained with the meter. In order to achieve higher force for a given voltage, the areaof theplatesshould be large, the spacing between theplates (d) should be small and some dielectric medium other than air should be used in between the plates.

If uniformity of electric field is to be maintained an increase in area A must be accompanied by an increase in the area of the surrounding guard ring and of the opposing plate and the electrode may, therefore, become unduly large especially for higher voltages. Similarly the gap length cannot be made very small as this is limited by the breakdown strength of the dielectric medium between the plates. If air is used as the medium, gradients upto5 kV/cm has been found satisfactory. For higher gradients vacuum or SF6gas has been used. The greatest advantage of the electrostatic voltmeter is its extremely low loading effect as only electric fields arerequired to beset up. Becauseofhigh resistanceofthemedium between theplates, theactive power loss is negligibly small. The voltage source loading is, therefore, limited only to their active power required to charge the instrument capacitance which can be as low as a few pico farads for low voltage voltmeters.

The measuring system as such does not put any upper limit on the frequency of supply to be measured. However, as the load inductance and the measuring system capacitance form a series resonance circuit, a limit is imposed on the frequency range. For low range voltmeters, the upper frequency is generally limited to a few MHz. Fig. 4.4 shows a schematic diagram of an absolute electrostatic voltmeter. The hemispherical metal dome D encloses a sensitive balance B which measures the force of attraction between the movable disc whichhangs from one of its arms and the lower plate P. The movable electrode M hangs with a clearance of above 0.01 cm, in a central opening in the upper plate which serves as a guard ring. Thediameterofeachoftheplatesis1metre.Lightreflectedfromamirrorcarriedbythebalance beam serves to magnify its motion and to indicate to the operator at a safe distance when a condition of equilibrium is reached. As the spacing between the two electrodes is large (about

100 cms for a voltage of about 300 kV), the uniformity of the electric field is maintained by the guard rings G which surround the space between the discs M and P. The guard rings G are maintained at a constant potential in space by a capacitance divider ensuring a uniform spatial potential distribution. When voltages in the range10 to 100 kV are measured, the accuracy is of the order of 0.01 per cent. Hueter has used a pair of spheres of 100 cms diameter for the measurement of high voltages utilizing the electrostatic attractive force between them. The spheresarearrangedwithaverticalaxisandatspacingslightlygreaterthanthesparkingdistance for the particular voltage to be measured. The upper high voltage sphere is supported on a spring and the extension of spring caused by the electrostatic force is magnified by a lamp-mirror scale arrangement. An accuracy of 0.5 per cent has been achieved by the arrangement.

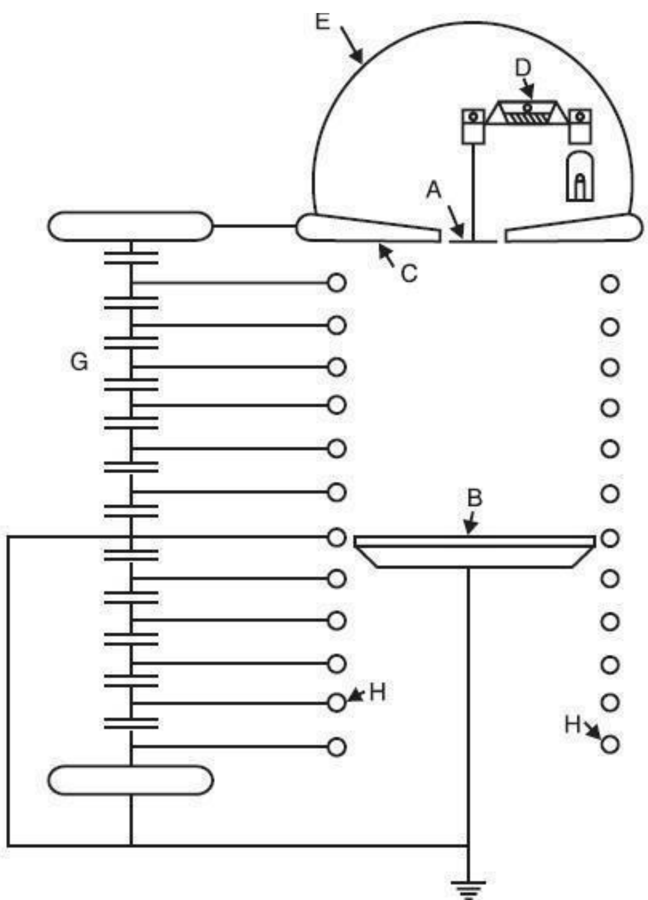


Figure:4.3Schematicdiagramofelectrostaticvoltmeter

Electrostatic voltmeters using compressed gas as the insulating medium have been developed. Here for a given voltage the shorter gap length enables the required uniformity of the field to be maintained with electrodes of smaller size and a more compact system can beevolved.OnesuchvoltmeterusingSF6gashasbeenusedwhichcanmeasurevoltagesupto1000 kV and accuracy is of the order of 0.1%. The high voltage electrode and earthed plane provide uniform electric field within the region of a 5 cm diameter disc set in a 65 cm diameter guard plane. A weighing balance arrangement is used to allow a large damping mass. The gap length can be varied between 2.5, 5 and10 cms and due to maximum working electric stress of 100 kV/cm, the voltage ranges can be selected to 250 kV, 500 kV and 100 kV. With 100 kV/cm as gradient, the average force on the disc is found to be0.8681 N equivalent to 88.52 gm wt. The disc movements are kept as small as 1 μm by the weighing balance arrangement. The voltmeters are used for the measurement of high a.c. and d.c voltages. The measurement of voltages lower than about 50 volt is, however, not possible, as the forces become too small.

PeakVoltmeterswithPotentialDividers

Passive circuits are not very frequently used these days for measurement of the peak value of a.c. or impulse voltages. The development of fully integrated operational amplifiers and other electronic circuits has made it possible to sample and hold such voltages and thus make measurements and, therefore, have replaced the conventional passive circuits. However, it is to be noted that if the passive circuits are designed properly, they provide simplicity and adequate accuracy and hence a small description ofthese circuits is in order. Passive circuits are cheap, reliable and have a high order of electromagnetic compatibility. However, in contrast, the most sophisticated electronic instruments are costlier and their electromagnetic compatibility (EMC)is low. The passive circuits cannot measure high voltages directly and use potential dividers preferably of the capacitance type. Fig. 4.4.1 shows a simple peak voltmeter circuit consisting of a capacitor voltage divider which reduces the voltage V to be measured to a low voltage Vm.

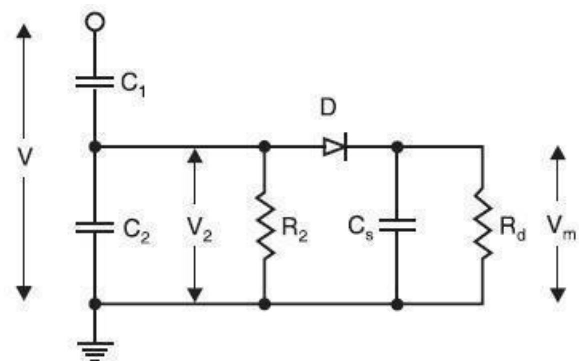


Figure:4.4Peakvoltmeter

SupposeR2andRdarenotpresentandthesupplyvoltageisV.Thevoltageacrossthe storage capacitor Cs will be equal to the peak value of voltage across C_2 assuming voltage drop across the diode to be negligibly small. The voltage could be measured by an electrostatic voltmeter or other suitable voltmeters with very high input impedance. If the reverse current through the diode is very small and the discharge time constant of the storage capacitor very large,thestoragecapacitorwillnotdischargesignificantlyforalongtimeandhenceitwillhold thevoltagetoitsvalueforalongtime.Ifnow,Visdecreased,thevoltageV_2decreases proportionately and since now the voltage across C_2 is smaller than the voltage across Cs to whichitisalreadycharged,therefore,thediodedoesnotconductandthevoltageacrossCsdoes notfollowthevoltageacrossC_2.Hence,adischargeresistor$R_d$mustbeintroducedintothe circuit so that the voltage across Cs follows the voltage across C_2. From measurement point of viewitisdesirablethatthequantitytobemeasuredshouldbeindicatedbythemeterwithina fewseconds and henceRd is so chosen that$R_dC_s \approx 1$ sec. Asaresult ofthis, following errorsare introduced. With the connection of R_d, the voltage across Cs will decrease continuously even when the input voltage is kept constant. Also, it will discharge the capacitor C_2 and the mean potentialofV2(t)willgainanegatived.ccomponent.HencealeakageresistorR2mustbe inserted in parallel with C_2 to equalize these unipolar discharge currents. The second error corresponds to the voltage shape across the storage capacitor which contains ripple and is due to the discharge of the capacitor Cs. If the input impedance of the measuring device is very high,the ripple is independent of the meter being used. The error is approximately proportional to the ripple factor and is thus frequency dependent as the discharge time constant cannot be changed.If RdCs = 1 sec, the discharge error amounts to 1% for 50 Hz and 0.33% for 150 Hz. The third sourceoferrorisrelatedtothisdischargeerror.Duringtheconductiontime(whenthevoltage acrossCsislowerthanthatacrossC2becauseofdischargeofCsthroughRd)ofthediodethe storage capacitor Cs is recharged to the peak value and thus Cs becomes parallel with C_2. If discharge error is ed, recharge error er is given by

$$e_r = 2e_d \frac{c_s}{c_1+c_2+c_s} \qquad (4.7)$$

Hence Cs should be small as compared withC_2 to keep down the recharge error. It has alsobeenobservedthatinordertokeeptheoverallerrortoalowvalue,itisdesirabletohavea high value of R_2. The same effect can be obtained by providing an equalizing arm to the low voltage arm of the voltage divider as shown in Fig. 4.4.2 This is accomplished by the addition of asecondnetworkcomprisingdiode,CsandRdfornegativepolarity currentstothecircuitshown inFig.4.4.3Withthis,thed.ccurrentsinbothbranchesareoppositeinpolarityandequalizeeach other.TheerrorsduetoR2arethuseliminated.Rabusdevelopedanothercircuitshownin Fig. 4.4.4 to reduce errors due to resistances. Two storage capacitors are connected by a resistor Rs within every branch and both are discharged by only one resistance Rd.

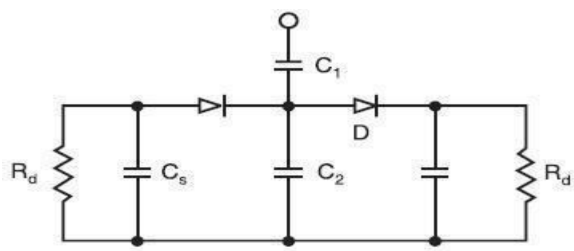


Figure:4.5Modifiedpeakvoltmeter circuit

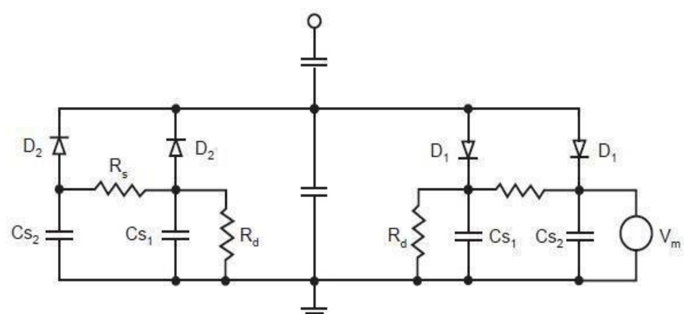


Figure:4.6Two-wayboostercircuitdesignedbyRabus

Here because of the presence of Rs, the discharge of the storage capacitor Cs_2 is delayed andhencetheinherentdischargeerrorisreduced.However,sincethesearetwostorage capacitors within one branch, they would draw more charge from the capacitor C_2 and hence the recharge error would increase. It is, therefore, a matter of designing various elements in the circuit so that the total sum of all the errors is a minimum. It has been observed that with the commonlyusedcircuitelementsinthevoltagedividers,theerrorcanbekepttowellwithin about1%evenforfrequenciesbelow20Hz.ThecapacitorC $_1$hastowithstandhighvoltageto be measured and is always placed within the test area whereas the low voltage arm C_2 including the peak circuit and instrument form a measuring unit located in the control area. Hence acoaxialcableisalwaysrequiredtoconnectthetwoareas.Thecablecapacitancecomesparallel with the capacitance C_2 which is usually changed in steps if the voltage to be measured is changed. A change of the length of the cable would, thus, also require recalibration of thesystem. The sheath of the coaxial cable picks up the electrostatic fields and thus prevents the penetration of this field to the core of the conductor. Also, even though transient magnetic fields will penetrate into the core of the cable, no appreciable voltage (extraneous of noise) is induced duetothesymmetricalarrangementandhenceacoaxialcableprovidesagoodconnection between thetwo areas. Whenever,adischargetakes placeat thehigh voltageend ofcapacitorC_1 tothecableconnectionwherethecurrentlooksintoachangeinimpedanceahighvoltageof short duration may be built up at the low voltage end of the capacitor C_1 which must be limited byusinganovervoltageprotectiondevice(protectiongap).Thesedeviceswillalsoprevent completedamage ofthe measuring circuitif theinsulationofC_1fails.

ImpulseVoltageMeasurementsUsingVoltage Dividers

If the amplitudes of the impulse voltage is not high and is in the range of a few kilovolts, itispossibletomeasurethemevenwhenthesesareofshortdurationbyusingCROS.However,if the voltages to be measured are of high magnitude of the order of megavolts which normally is the case for testing and research purposes, various problems arise. The voltage dividers required are of special design and need a thorough understanding of the interaction present in these voltage dividing systems. The voltage generator G is connected to a test object—T through alead L.

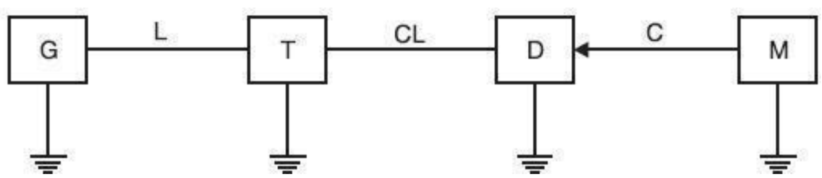


Figure:4.7Basicvoltage testingcircuit

Thesethreeelementsformavoltagegeneratingsystem.TheleadLconsistsofaleadwire andaresistancetodamposcillationortolimit short-circuitcurrentsifofthetestobjectfails.The measuring system starts at theterminals ofthetest object and consists ofaconnecting lead CLto thevoltagedividerD.Theoutput ofthedividerisfed to themeasuring instrument (CROetc.)M. The appropriate ground return should assure low voltage drops for even highly transient phenomena and keep the ground potential of zero as far as possible.

It is to be noted that the test object is a predominantly capacitive element and thus this forms an Oscillatory circuit with the inductance of the load. These oscillations are likely to be excited by any steep voltage rise from the generator output, but will only partly be detected by the voltage divider. A resistor in series with the connecting leads damps out these oscillations. The voltage divider should always be connected outside the generator circuit towards the load circuit (Test object) for accurate measurement. In case it is connected within the generator circuit and the test object discharges (chopped wave) the whole generator including voltage divider will be discharged by this short circuit at the test object and thus the voltage divider is loaded by the voltage drop across the lead L. As a result, the voltage measurement will be wrong. Yet for another reason, the voltage divider should be located away from the generator circuit. The dividerscannot beshieldedagainstexternalfields.Allobjectsin thevicinityofthedividerwhich may acquire transient potentials during a test will disturb the field distribution and thus the dividerperformance.Therefore,theconnectingleadCLisanintegralpartofthepotentialdivider circuit. In order to avoid electromagnetic interference between the measuring instrument M andC the high voltage test area, the length of the delay cable should be adequately chosen. Veryshort length of the cable can be used only if the measuring instrument has high level of electromagnetic compatibility (EMC). For any type of voltage to be measured, the cable should be co-axial type. The outer conductor provides a shield against the electrostatic field and thus prevents the penetration of this field to the inner conductor. Even though, the transient magnetic fields will penetrate into the cable, no appreciable voltage is induced due to the symmetrical arrangement. Ordinary coaxial cables with braided shields may well be used for d.c. and a.c. voltages. However, for impulse voltage measurement double shielded cables with predominantly two insulated braided shields will be used for better accuracy.

Duringdisruptionoftest object,very heavytransientcurrentflow and hencethe potential of the Ground may rise to dangerously high values if proper earthling is not provided. For this, large metal sheets of highly conducting material such as copper or aluminum are used. Most of themodernhighvoltagelaboratoriesprovidesuch groundreturnalongwithaFaradayCagefora complete shielding of the laboratory. Expanded metal sheets give similar performance. At least metal tapes of large width should be used to reduce the impedance.

Voltages dividers for a.c., d.c. or impulse voltages may consist of resistors or capacitors or a convenient combination of these elements. Inductors are normally not used as voltage dividing elements as pure inductances of proper magnitudes without stray capacitance cannot be built and also these inductances would otherwise form oscillatory circuit with the inherent capacitance of the test object and this may lead to inaccuracy in measurement and high voltages in the measuring circuit. The height of a voltage divider depends upon the flash over voltage and this follows from the rated maximum voltage applied.

Now, the potential distribution may not be uniform and hence the height also depends upon the design of the high voltage electrode, the top electrode. For voltages in the megavolt range,theheight ofthedividerbecomeslarge. As athumbrulefollowing clearancesbetween top electrode and ground may be assumed 2.5 to 3 meters/MV for d.c. voltages.2 to 2.5 m/MV for lightning impulse voltages. More than 5 m/MV rms for a.c. voltages. More than 4 m/MV for switching impulse voltage.The potential divider is most simply represented by two impedances Z1 and Z2 connected in series and the sample voltage required for measurement is taken from across Z2, FIG. 4.8.If the voltage to be measured is V1 and sampled voltage V2, then

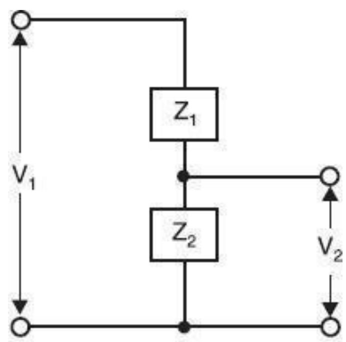


Figure:4.8Basicdiagramofapotentialdividercircuit

$$V2 = \frac{Z2}{Z1+Z2}V1 \quad (4.8)$$

Ifthe impedancesarepureresistances

$$V2 = \frac{R2}{R1+R2}V1 \quad (4.9)$$

Ifthe impedancesarepureresistances

$$V2 = \frac{C1}{C1+C2}V1 \quad (4.10)$$

The voltage V_2 is normally only a few hundred volts and hence the value of Z_2 is so chosen that V_2across it gives sufficient deflection on a CRO. Therefore, most of the voltage dropisavailableacrosstheimpedanceZ_1andsincethevoltagetobemeasuredisinmegavolt the length of Z_1 is large which result in inaccurate measurements because of the stray capacitances associated with long length voltage dividers (especially with impulse voltage measurements) unless special precautions are taken. On the low voltage side of the potential dividers where a screened cable of finite length has to be employed for connection to the oscillograph other errors and distortion of wave shape can also occur.

CROFORIMPULSEVOLTAGEANDCURRENTMEASUREMENT

The coupling impedance *Zm* is a parallel combination of *R*, *L* and *C* whose quality factor is low.The complex impedance *Zm* is given as

$$\frac{1}{Z_m} = \frac{1}{R} + \frac{1}{j\omega L} + j\omega C$$

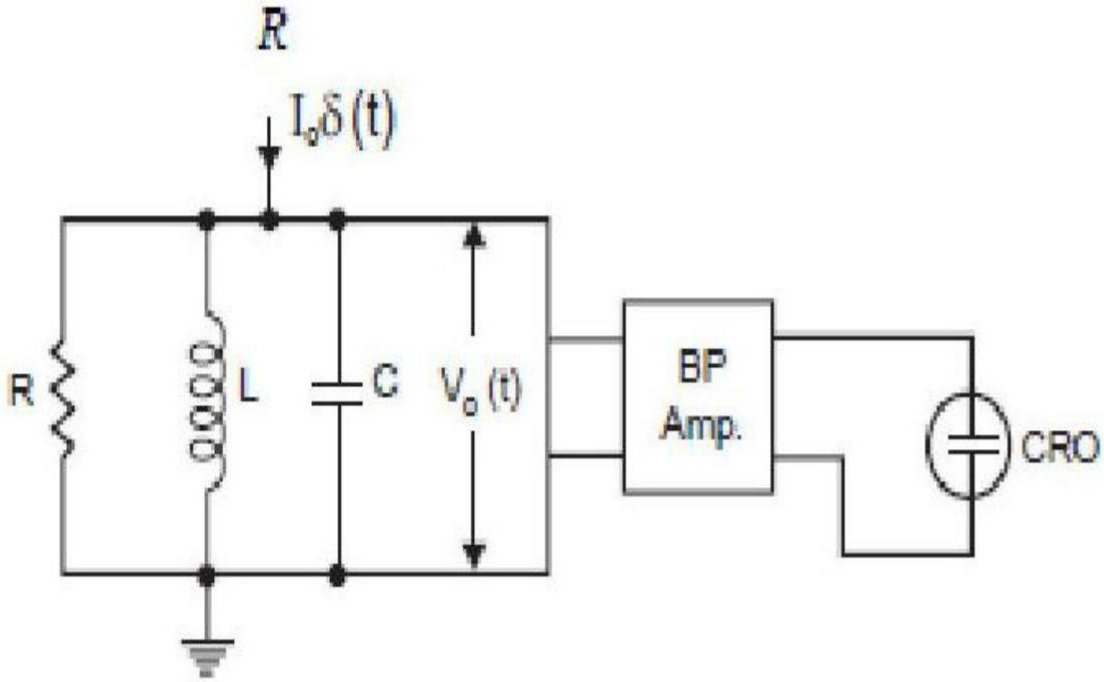


Figure:4.9CROforimpulsevoltageandcurrentmeasurement

The measuring impedance Zm is the impedance of a band pass filter which suppresses harmonic currents depending upon the selected circuit quality factor Q, below and above the resonance frequencyf0 i.e., Zm will suppress all frequency currents below and above its resonance frequency. The alternate is– 20 dB per decade if Q = 1 and can be greatly increased. Also, the measuring circuit Zm performs integration of the PD pulse currents i (t) = I0 δ (t).The above equation shows a damped oscillatory output voltage where amplitude is proportional tothe charge q. The charge due to the pulse i(t) is actually stored by the capacitor Cinstantaneously but due to the presence of inductance and resistance, Oscillations are produced. If these oscillations are not damped, the resolution time of the filter will be large and proper integration will not take place especiallyof the subsequent current pulses. There is a possibilityof over lapping and the results obtainedwill be erroneous. The resolution time as is said earlier shouldbesmallerthan thetimeconstantτ ofthecurrentpulse[*i*(*t*)*I*0*e*-*t*/τ].Theresolutiontimeor decay time depends upon the *Q*-factor and resonancefrequency *f*0 of the measuring impedance *Zm*.Let*Q*=1 =*R*/*LC*.Thevoltage*v*0(*t*)asshowninFig.6.28canbeobtainedbywritingnodal equation.

$$\frac{V_0(s)}{R} + \frac{V_0(s)}{sL} + V_0(s)\,Cs = I_0$$

$$V_0(s) = \frac{RsLI_0}{RLCs^2 + sL + R} = \frac{I_0 s/C}{s^2 + \frac{s}{RC} + \frac{1}{LC}}$$

$$= \frac{I_0 s/C}{\left(s + \frac{1}{2RC}\right)^2 + \frac{1}{LC} - \frac{1}{(4R^2C^2)}} = \frac{I_0 s/C}{(s+\alpha)^2 + \beta^2}$$

where $$\alpha = \frac{1}{2RC} \text{ and } \beta = \sqrt{\frac{1}{LC} - \alpha^2}$$

Therefore, $$V_0(s) = \frac{q}{C}\cdot\left[\frac{s}{(s+\alpha)^2 + \beta^2}\right]$$

$$V_0(s) = \frac{q}{C}\frac{s}{(s+\alpha)^2+\beta^2} = \frac{q}{C}\left[\frac{s+\alpha}{(s+\alpha)^2+\beta^2} - \frac{\alpha}{(s+\alpha)^2+\beta^2}\right]$$

$$= \frac{q}{C}\left[\frac{s+\alpha}{(s+\alpha)^2+\beta^2} - \frac{\alpha}{\beta}\cdot\frac{\beta}{(s+\alpha)^2+\beta^2}\right]$$

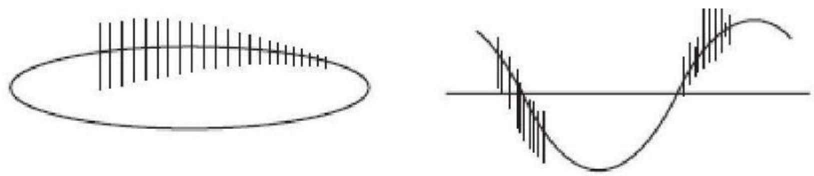
$$= \frac{q}{C}\left[e^{-\alpha t}\cos\beta t - \frac{\alpha}{\beta}e^{-\alpha t}\sin\beta t\right]$$

$$= \frac{q}{C}e^{-\alpha t}\left[\cos\beta t - \frac{\alpha}{\beta}\sin\beta t\right]$$

The resolution time is about 10 μ sec and for higher values of *Q*, *T* will be still larger.The resonance frequency is also affected by the coupling capacitance *Ck* and the capacitance *Ct* ofthetestspecimenasthesecontributetotheformationof *C*.Therefore,the*RLC* circuitshould bechosenorselectedaccordingtothetestspecimensothatadesiredresonancefrequencyis obtained. The desired central frequency f_0 or a band width around *f*0 is decided by the band pass amplifier connected to this resonant circuit

These amplifiers are designed for typically lower and upper cut off frequencies (– 3 *dB*) between 150 kHz and 100 kHz. This band of frequency is chosen as it is much higher than thepower supply frequency and also the frequency which are not used by broadcasting stations. Theresolution timebecomesless than10 μ sec. and henceproperintegration ofthecurrent pulse is made possible. However, the main job of the amplifier is to increase the sensitivity of the whole measuring system. The time dependency of the output voltage *v*0 (*t*) can be seen on the oscilloscope. In the usual ellipse representation, the individual pulse *v*0 (*t*) are practically only recognizable on vertical lines of different heights as one rotation of the ellipse corresponds toone period of the supply system 20 m sec. for 50 Hz and 16.7 m sec. for 60 Hz supplies.

The magnitude of the individual discharge is quantified by comparing the pulse crest value with the one obtained from the calibration circuit as shown in Fig. 6.30. The calibration circuit consists of a voltage step generator *V*0 and a series capacitor *C*0. The charge *q* is simulated with no normal voltage applied to the PD testing circuit. It is possible to suggest the location of the partial discharges in an insulating material by looking at the display on the CRO screen.



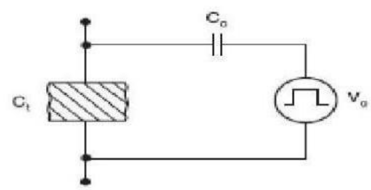


Figure:4.10Circuitforcalibrationofthe oscilloscope

DIGITALTECHNIQUESINHIGHVOLTAGEMEASUREMENT

ResistancePotentialDividers

The resistance potential dividers are the first to appear because of their simplicity of construction, less space requirements, less weight and easy portability. These can be placed near the test object which might not always be confined to one location.

The length of the divider depends upon two or three factors. The maximum voltage to be measured is the first and if height is a limitation, the length can be based on a surface flash over gradient in the order of 3–4 kV/cm irrespective of whether the resistance R1 is of liquid or wire wound construction. The length also depends upon the resistance value but this is implicitly bound up with thestray capacitance of the resistance column, the product of the two (RC) giving atimeconstantthevalueofwhichmustnotexceed thedurationofthewavefrontitisrequiredto record. It is to be noted with caution that the resistance of the potential divider should bematchedtotheequivalentresistanceofagivengeneratortoobtain agivenwaveshape.FIG. 4.11 (a)showsacommonformofresistancepotentialdividerusedfortestingpurposeswherethe wave front time of the wave is less than 1 micro sec.

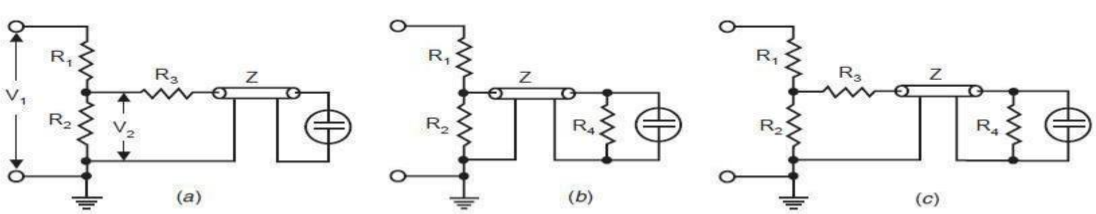


Figure:4.11variousformsofresistancepotentialdividersrecordingcircuits(a)Matchingat divider end (b) Matching at Oscillo graph end (c) Matching at both ends of delay cableHereR_3,the resistanceatthe divider endof the delay cableischosensuchthat$R_2 + R_3 = Z$whichputsanupperlimitonR2i.e.,R2<Z.Infact,sometimestheconditionformatchingis given as

(4.11)
$$Z = R3 + \frac{R1R2}{R1+R2}$$

But, since usually $R_1 >> R_2$, the above relation reduces to $Z = R_3 + R_2$. From Fig. 4.19 (a), the voltage appearing across R2 is

(4.12)

ofthecable beingrepresented byanimpedanceZ to ground.

Now

(4.13)

(4.14)
$$V2 = \frac{(Z+R3)R2}{2Z}\frac{V1}{Z1+R1}$$

$$V3 = \frac{V2}{Z+R3}Z = \frac{Z}{Z+R3}\frac{(Z+R3)R2}{2Z}.\frac{V1}{Z1+R1} = V1\frac{R2}{2(Z1+R1)}$$

(4.15) However,thevoltageenteringthedelaycableis

(4.16)

As this voltage wave reaches the CRO end of the delay cable, it suffers reflections as theimpedance offered by theCROis infinite and as a result the voltage wavetransmitted into the CROisdoubled.TheCRO,therefore,recordsavoltageThereflectedwave,however,asit reaches thelow voltagearmofthepotential dividerdoes not sufferany reflection as $Z=R_2 +R_3$ and is totally absorbed by $(R_2 + R_3)$. Since R_2 is smaller than Z and Z_1 is a parallel combination of R_2 and $(R_3 + Z)$, Z_1 is going to be smaller than R_2 and since $R_1 >> R_2$, R_1 will be much greater than Z_1 and, therefore to a first approximation $Z_1 + R_1 \approx R_1$.

Therefore,

(4.17)
$$V_3' = \frac{R2}{R1}V1 \approx \frac{R2}{R1+R2}V1 \text{ as } R2 << R1$$

Fig.4.11(b)and(c) arethevariantsofthepotentialdividercircuitof Fig.4.11(a). The cable Matching is done by a pure ohmic resistance $R_4 = Z$ at the end of the delay cable and, therefore, the voltage reflection coefficient is zero i.e. the voltage at the end of the cable is transmittedcompletelyintoR4andhence appearsacross the CRO plateswithoutbeingreflected.

Astheinput impedanceof thedelaycable is $R_4= Z$, this resistanceis a parallel to

R2 and forms an integral part of the divider's low voltage arm. The voltage of such a divider is, therefore, calculated as follows: Equivalent impedance

$$R1 + \frac{R2Z}{RZ+Z} = \frac{R1(R2+Z)+R2Z}{(R2+Z)} \quad (4.18)$$

Therefore,Current

$$I = \frac{V1(R2+Z)}{R1(R2+Z)+R2Z} \quad (4.19)$$

andvoltage

$$V2 = \frac{IR2Z}{R2+Z} = \frac{V1(R2+Z)}{R1(R2+Z)+R2Z}\frac{R2Z}{R2+Z} \quad (4.20)$$

$$= \frac{R2Z}{R1(R2+Z)+R2Z}V1 \quad (4.21)$$

orvoltage ratio

$$\frac{V2}{V1} = \frac{R2Z}{R1(R2+Z)+R2Z} \quad (4.22)$$

DuetothematchingattheCROendofthedelaycable,thevoltagedoesnot sufferany reflection at that end and the voltage recorded by the CRO is given as

(4.23)

Normallyforundistortedwaveshapethroughthecable

$$V2 = \frac{R2}{2R1+R2}V1 \quad (4.24)$$

For a given applied voltage V_1 this arrangement will produce a smaller deflection on the CROPlates as compared to theonein Fig. 4.19 (a).Thearrangement of Fig. 4.19 (c)provides for matching at both ends of the delay cable and is to be recommended where it is felt necessary to reduce to the minimum irregularities produced in the delay cable circuit. Since matching is provided at the CRO end of the delay cable, therefore, there is no reflection of the voltage at that end and the voltage recorded will be half of that recorded in the arrangement of Fig. 4.19 (a) viz

$$V2 = \frac{R2}{2(R1+R2)}V1 \quad (4.25)$$

It is desirable to enclose the low voltage resistance (s) of the potential dividers in a metal screening box. Steel sheet is a suitable material for this box which could be provided with a detachableclosefittinglidforeasyaccess.Iftherearetwolowvoltageresistorsatthedivider positionasinFig.4.11(a)and(c),theyshouldbecontainedinthescreeningbox,asclose together as possible, with a removable metallic partition between them. The partition serves two purposes(i)itactsasanelectrostaticshieldbetweenthetworesistors(ii)itfacilitatesthe changingoftheresistors.Thelengthsoftheleadsshouldbeshortsothatpracticallyno inductance is contributed by these leads. The screening box should be fitted with a largeearthlingterminal.Fig.4.12showsasketchedcross-sectionofpossiblelayoutforthelow voltage arm of voltage divider.

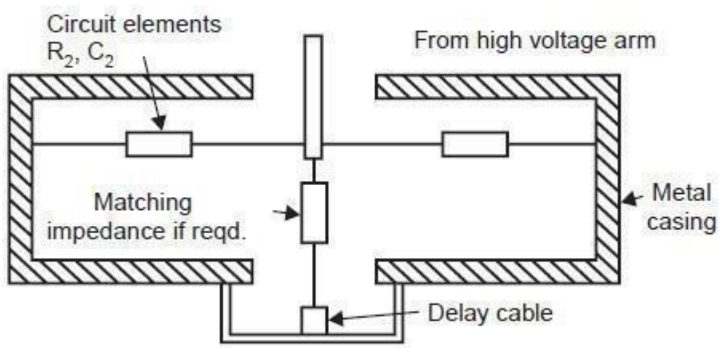


Figure:4.12Cross-sectionoflow voltagearmof a voltagedivider

CapacitancePotential Dividers

Capacitance potential dividers are more complex than the resistance type. For measurement of impulse voltages not exceeding 1 MV capacitance dividers can be both portable and transportable. In general, for measurement of 1 MV and over, the capacitance divider is a laboratory fixture. The capacitance dividers are usually made of capacitor units mounted one above the other and bolted together. It is this failure which makes the small dividers portable. A screeningboxsimilartothatdescribedearliercanbeusedforhousingboththelowvoltage capacitorunitC_2andthematching resistorif required.

The low voltage capacitor C_2 should be non-inductive. A form of capacitor which has givenexcellent results is ofmicaand tin foil plate, construction, each foil having connecting tags coming out at opposite corners. This ensures that the current cannot pass from the high voltage circuit to the delay cable without actually going through the foil electrodes. It is also important that the coupling between the high and low voltage arms of the divider be purely capacitive. Hence, the low voltage arm should contain one capacitor only; two or more capacitors in parallel mustbeavoidedbecauseofappreciableinductancethatwouldthusbeintroduced.Further,the tappings to thedelaycablemust betaken offas closeas possibleto theterminals ofC_2.Fig. 4.21 shows variants of capacitance potential dividers.

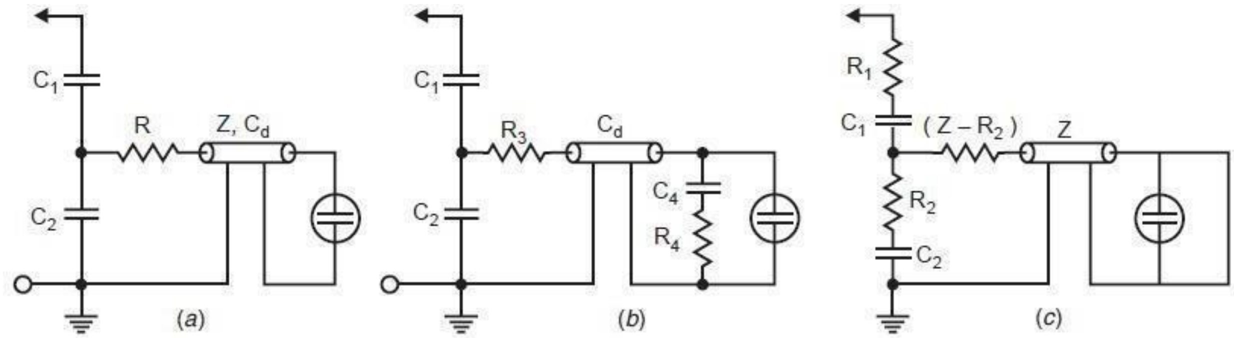


Figure: 4.13 Capacitor dividers (a) Simple matching (b) Compensated matching(c) Damped capacitordividersimplematchingForvoltagedividersinFIG.(b)and(c),thedelaycablecannot be matched at its end.

AlowResistorinparalleltoC2 wouldloadthelowvoltagearmofthedividertooheavily anddecreasetheoutputvoltagewithtime.SinceRandZformapotentialdividerandR=Z,the voltageinputtothecablewillbehalfofthevoltageacrossthecapacitorC2.Thishalved voltages travelstowardstheopenendofthecable(CROend)andgetsdoubledafterreflection.Thatis, the voltage recorded by the CRO is equal to the voltage across the capacitor C2. The reflected wave charges the cable to its final voltage magnitude and is absorbed by R (i.e. reflection takes place at R and since R = Z, the wave is completely absorbed as coefficient of voltage reflectionis zero) as the capacitor C2 acts as a short circuit for high frequency waves. The transformation ratio, therefore, changes from the value:

$$\frac{C_1 + C_2}{C_1}$$

forvery high frequencies to thevalue

$$\frac{C_1 + C_2 + C_d}{C_1}$$

forlow frequencies.

However,thecapacitanceofthedelaycableCdisusuallysmallascomparedwithC2.For capacitive divider an additional damping resistance is usually connected in the lead on the High voltage side as shown in FIG. 4.14 (c). The performance of the divider can be improved if damping resistor which corresponds to the a periodic limiting case is inserted in series with the individual element of capacitor divider. This kind of damped capacitive divider acts for high frequencies as a resistive divider and for low frequencies as a capacitive divider. It can,therefore, be used over a wide range of frequencies i.e. for impulse voltages of very different duration and also for alternating voltages.

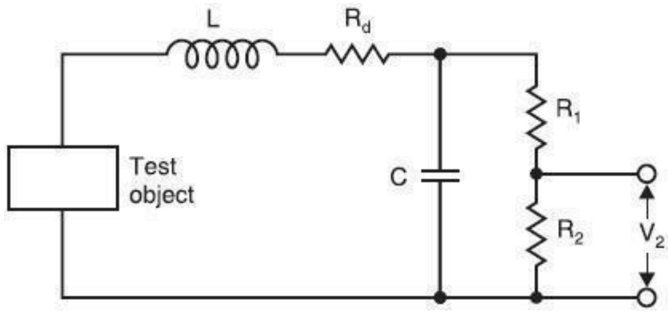


Figure:4.14Simplifieddiagramofaresistancepotentialdivider

Fig. 4.22 shows a simplified diagram of a resistance potential divider after taking into Considerations the lead in connection as the inductance and the stray capacitance as lumped capacitance. HereL represents the loop inductance of the lead-in connection for the high voltage arm. The damping resistance Rd limits the transient overshoot in the circuit formed by test object,L,RdandC.Itsvaluehasadecidedeffectontheperformanceofthedivider.Inorderto evaluate thevoltagetransformationof thedivider,thelowvoltage armvoltageV_2resultingfrom a square wave impulse V_1on the hv side must be investigated. The voltage V_2follows curve 2in Fig. 4.15 (a) in case of a periodic damping and curve 2in Fig. 4.15 (b) in case of sub-critical damping. The total area between curves 1 and 2 taking into consideration the polarity is described as the response time.

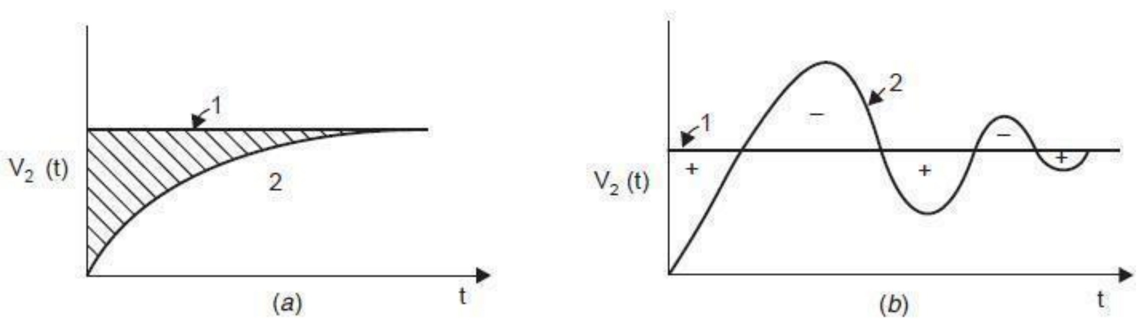


Figure:4.15theresponse ofresistancevoltage divider

With subcritical damping, even though the response time is smaller, the damping should not be Very small. This is because an undesirable resonance may occur for a certain frequency within the passing frequency band of the divider. A compromise must therefore be realized betweentheshortrisetimeandtherapidstabilizationofthemeasuringsystem.AccordingtoIEC publication No. 60 a maximum overshoot of 3% is allowed for the full impulse wave, 5% for an impulse wave chopped on the front at times shorter than 1 micro sec. In order to fulfill these requirements, the response time of the divider must not exceed 0.2 micro sec. for full impulse waves 1.2/50 or 1.2/5 or impulse waves chopped on the tail. If the impulse wave is chopped on the front at time shorter than 1 micro sec the response time must be not greater than 5% of the time to chopping.

KlydonographorSurge Recorder

Since lightning surges are infrequent and random in nature, it is necessary to install a large number of recording devices to obtain a reasonable amount of data regarding these surges produced on transmission lines and other equipments. Some fairly simple devices have been developed for this purpose.

Klydonograph is one such device which makes use of the patterns known as Lichtenberg Figure which are produced on a photographic film by surface corona discharges. The Klydonograph (Fig. 4.16) consists of a rounded electrode resting upon the emulsion side of a photographic film or plate which is kept on the smooth surface of an insulating material plate backed by a plate electrode. The minimum critical voltage to produce a Figure is about 2 kV and the maximum Voltage that can be recorded is about 20 kV, as at higher voltages spark over's occurs which spoils the film. The device can be used with a potential divider to measure higher voltages and with a resistance shunt to measure impulse current. There are characteristic differences between the Figure for positive and negative voltages. However, for either polarity the radius of the Figure (if it is symmetrical) or the maximum distance from the centre of the Figure to its outside edge (if it is unsymmetrical) is a function only of the applied voltage. The oscillatoryvoltagesproducesuperimposedeffectsforeachpartofthewave.Thusitispossibleto know whether the wave is unidirectional or oscillatory. Since the size of the Figure for positive polarity is larger, it is preferable to use positive polarity Figure. This is particularly desirable in case of measurement of surges on transmission lines or other such equipment which are ordinarily operating on a.c. voltage and the alternating voltage gives a black band along the centre of the film caused by superposition of positive and negative Figure produced on each half cycle.

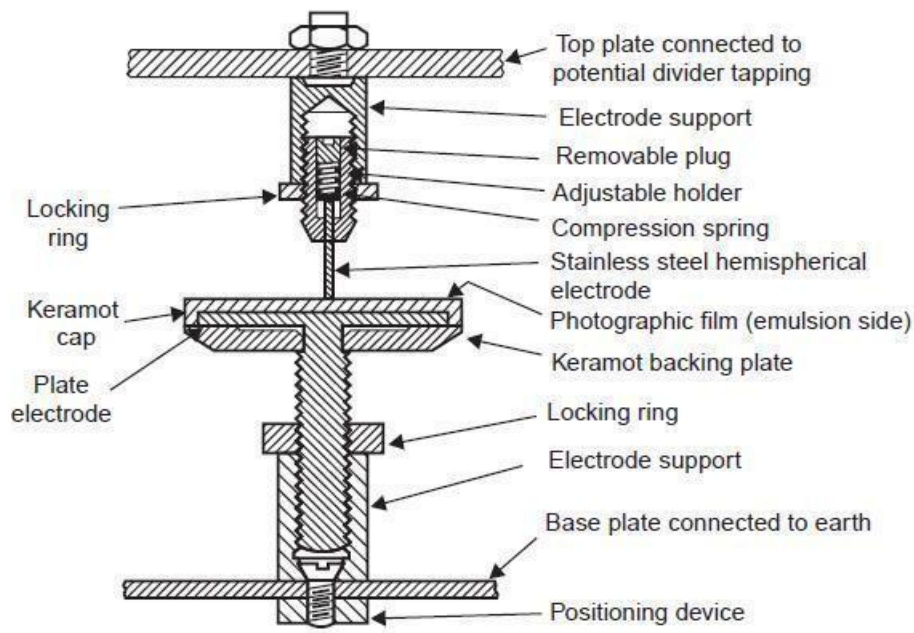


Figure:4.16 Klydonograph

For each surge voltage it is possible to obtain both positive and negative polarity Figure by connecting pairs of electrodes in parallel, one pair with a high voltage point and an earthed plate and the other pair with a high voltage plate and an earthed point.

Klydonographbeinga simpleand inexpensivedevice, alargenumberof elementscan be used.

UNIT-V HIGHVOLTAGETESTINGOFELECTRICALPOWERAPPARATUS

INTRODUCTION

Man has been power hungry since time-immemorial. In modern times the world has seen phenomenalincreaseindemandforenergy,ofwhichanimportantcomponentisthatofelectrical energy. The production of electrical energy in big plants under the most economic condition makes it necessary that more and more energy be transported over longer and longer distances.Therefore,transmissionatextrahighvoltagesandtheerectionofsystemswhichmayextend over whole continents has become the most urgent problems to be solved in the near future. The very fast development of systems is followed by studies of equipment and the service conditions they have to fulfill. These conditions will also determine the values for testing at alternating, impulseandd.c.voltagesunderspecificconditions.Aswegoforhigherandhigheroperating voltages (say above 1000 kV) certain problems are associated with the testing techniques. Some of these are:

- Dimensionof high voltagetest laboratories.
- Characteristicsofequipmentforsuchlaboratories.
- Somespecialaspectsofthetesttechniquesatextrahigh voltages.

Thedimensionsoflaboratoriesfortestequipmentsof750kVandabovearefixedbythe following main considerations:

- Figures(values)oftestvoltagesunderdifferentconditions.
- Sizesof thetestof equipments in a.c.,d.c. and impulse voltages.

Distances between the objects under high voltage during the test period and the earthed surroundings such as floors, walls and roofs of the buildings. The problems associated with the characteristics of the equipments used for testing are summarized here. In alternating voltage system, a careful choice of the characteristics of the testing transformer is essential. It is known that the flash over voltage of the insulator in air or in any insulating fluid depends upon the capacitance of the supply system. This is due to the fact that a voltage drop may not maintain preliminary discharges or breakdown. It is, therefore, suggested that a capacitance of at least 1000 Pf must be connected across the insulator to obtain the correct flash over or puncture voltageandalsounderbreakdowncondition(avirtualshortcircuit)thesupplysystemshouldbe abletosupplyatleast1ampforclean and5ampforpollutedinsulatorsatthetestvoltage.There are some difficult problems with impulse testing equipments also especially when testing large power transformers or large reactors or large cables operating at very high voltages. The equivalent capacitance of the impulse generator is usually about 40 nano farads independent of the operating voltage which gives a stored energy of about 1/2 × 40 10–9 × 36 × 109 = 720 KJ for 6 MV generators which is required for testing equipments operating at 150 kV. It is not at all difficult to pile up a large number of capacitances to charge them in parallel and then dischargein series to obtain a desired impulse wave.

But the difficulty exists in reducing the internal reactance of the circuit so that a shortwave front with minimum oscillation can be obtained. For example for a 4 MV circuit the inductance of the circuit is about 140 μH and it is impossible to test an equipment with a capacitance of 5000 pF with a front time of 1.2 μ sec. and less than 5% overshoot on the wave front. Cascaded rectifiers are used for high voltage d.c. testing. A careful consideration is necessary when test on polluted insulation is to be performed which requires currents of 50 to 200 mA but extremely predischarge streamer of 0.5 to 1 amp during milliseconds occur. The generator must have an internal reactance in order to maintain the test voltage without too high a voltage drop.

TestingOfOverheadLineInsulators

Various types of overhead line insulators are (i) Pin type (ii) Post type (iii) String insulator unit(iv) Suspension insulator string (v) Tension insulator.

Arrangement of Insulators for Test String insulator unit should be hung by a suspension eye from an earthed metal cross arm. The test voltage is applied between the cross arm and the conductor hung vertically down from the metal part on the lower side of the insulator unit.

Suspension string with all its accessories as in service should be hung from an earthed metal Cross arm. The length of the cross arm should be at least 1.5 times the length of the string being tested and should beat least equal to 0.9 m on eithersideoftheaxis ofthestring. Noother earthed object should be nearer to the insulator string then 0.9 m or 1.5 times the length of the string whichever is greater. A conductor of actual size to be used in service or of diameter not less than1 cm and length 1.5timesthelength ofthestring is secured in thesuspension clamp and should lie in a horizontal plane.

The test voltage is applied between the conductor and the cross arm and connection from the impulse generator is made with a length of wire to one end of the conductor. For higher operating voltages where the length of the string is large, it is advisable to sacrifice the length of the conductor as stipulated above. Instead, it is desirable to bend the ends of the conductor overin a large radius. For tension insulators the arrangement is more or less same as in suspension insulator except that it should be held in an approximately horizontal position under a suitable tension (about 1000 Kg.).For testing pin insulators or line post insulators, these should be mountedontheinsulatorpinorlinepostshankwithwhichtheyaretobeusedinservice. Thepin orthe shankshould befixed ina verticalpositiontoa horizontalearthedmetalcross arm situated 0.9 m abovethe floor ofthelaboratory.

A conductor of 1 cm diameter is to be laid horizontally in the top groove of the insulator and secured by at least one turn of tie-wire, not less than 0.3 cm diameter in the tie-wire groove. The length of the wire Should be at least 1.5 times the length of the insulator and should over hang the insulator at least 0.9 mon either side in a direction at right angles to the cross arm. The test voltage is applied to one end of the conductor. High voltage testing of electrical equipment requirestwotypesoftests:(i)Typetests,and(ii)Routinetest.Typetestsinvolvesqualitytesting of equipment at the design and development level i.e. samples of the product are taken and are tested when a new product is being developed and designed or an old product is tobe redesigned and developed whereas the routine tests are meant to check the quality of the individual test piece. This is carried out to ensure quality and reliability of individual test Objects.

High voltage tests include (i) Power frequency tests and (ii) Impulse tests. These tests are carried out on all insulators.

(i) 50%dryimpulseflashovertest

The test is carried out on a clean insulator mounted as in a normal working condition. An impulse voltage of 1/50 μ sec. wave shape and of an amplitude which can cause 50% flash over of the insulator, is applied, i.e. of the impulses applied 50% of the impulses should cause flash over.Thepolarityoftheimpulseisthenreversedandprocedurerepeated.Theremustbeatleast 20 applications of the impulse in each case and the insulator must not be damaged. The magnitude of the impulse voltage should not be less than that specified in standardspecifications.

(ii) Impulsewithstand test

The insulator is subjected to standard impulse of 1/50 μ sec. wave of specified value under dry conditions with both positive and negative polarities. If five consecutive applications do not cause any flash over or puncture, the insulator is deemed to have passed the impulse withstand test. If out of five, two applications cause flash over, the insulator is deemed to have filed the test.

(iii) Dryflashoveranddry oneminutetest

Power frequency voltage is applied to the insulator and the voltage increased to the specified value and maintained for one minute. The voltage is then increased gradually untilflash overoccurs.Theinsulatoris thenflashed overat least fourmoretimes,thevoltageis raised gradually to reach flash over in about 10 seconds. The mean of at least five consecutive flash over voltages must not be less than the value specified in specifications.

(iv) Wetflash overand oneminuteraintest

If the test is carried out under artificial rain, it is called wet flash over test. The insulatoris subjected to spray of water of following characteristics:

Precipitationrate3± 10%mm/min.Direction 45°tothevertical

Conductivity of water 100 micro Siemens ± 10%Temperature of water ambient +15°C

Theinsulatorwith50%oftheone-min.raintestvoltageappliedtoit,isthensprayedfor twoMinutes,thevoltagerosetotheoneminutetestvoltageinapproximately10sec.and maintained therefore one minute. The voltage is then increased gradually till flash over occurs and the insulator is then flashed at least four more times, the time taken to reach flash over voltage being in each case about10 sec. The flash over voltage must not be less than the value specified in specifications.

(v) Temperaturecycletest

The insulator is immersed in a hot water bath whose temperature is 70° higher than normal water bath for T minutes. It is then taken out and immediately immersed in normal water bath for T minutes. After T minutes the insulator is again immersed in hot water bath for T minutes. The cycle is repeated three times and it is expected that the insulator should withstand the test without damage to the insulator or glaze. Here T = (15 + W/1.36) where W is the weight of the insulator in Kg's.

(vi) Electro-mechanical test

The test is carried out only on suspension or tension type of insulator. The insulator is Subjected to a 2½ times the specified maximum working tension maintained for one minute. Also, simultaneously 75% of the dry flash over voltage is applied. The insulator shouldwithstand this test without any damage.

(vii) Mechanicaltest

This is a bending test applicable to pin type and line-post insulators. The insulator is subjected to a load three times the specified maximum breaking load for one minute. There should be no damage to the insulator and in case of post insulator the permanent set must be less than 1%. However, in case of post insulator, the load is then raised to three times and there should not be any damage to the insulator and its pin.

(viii) Porositytest

The insulator is broken and immersed in a 0.5% alcohol solution of fuchsine under a pressure of 13800 kN/m2 for 24 hours. The broken insulator is taken out and further broken. It should not show any sign of impregnation.

(ix) Puncturetest

An impulse over voltage is applied between the pin and the lead foil bound over the top and side grooves in case of pin type and post insulator and between the metal fittings in case of suspension type insulators. The voltage is 1/50 µ sec. wave with amplitude twice the 50% impulse flash overvoltage and negative polarity. Twenty such applications are applied. The procedure is repeated for 2.5, 3, and 3.5 times the 50% impulse flash over voltage and continued till the insulator is punctured. The insulator must not puncture if the voltage applied is equal to the one specified in the specification.

(x) Mechanicalroutinetest

The string in insulator is suspended vertically or horizontally and a tensile load 20% in Excess of the maximum specified working load is applied for one minute and no damage tothe string should occur.

TestingOf Cables

Highvoltagepowercableshaveprovedquiteusefulespeciallyincaseof HVd.c.transmission.Undergrounddistributionusingcablesnotonlyaddstotheaestheticlooksofa metropolitan city but it provides better environments and more reliable supply to the consumers. PreparationofCableSampleThecablesamplehastobecarefullypreparedforperforming varioustestsespeciallyelectricaltests.Thisisessentialtoavoidanyexcessiveleakageorend flash over‘s which otherwise may occur during testing and hence may give wrong informationregardingthe qualityof cables.The lengthof thesample cable variesbetween50cmsto10m. The terminations are usually made by shielding the ends of the cable with stress shields so as to relieve the ends from excessive high electrical stresses. A cable is subjected to following tests:

(i) Bending tests

It is to be noted that a voltage test should be made before and after a bending test. The cable is bent round a cylinder of specified diameter to make one complete turn. It is then unwound and rewound in the opposite direction. The cycle is to be repeated three times.

(ii) Loadingcycle test

A test loop, consisting of cable and its accessories is subjected to 20 load cycles with a Minimum conductor temperature 5°C in excess of the design value and the cable is energized to1.5 times the working voltage. The cable should not show any sign of damage.

(iii) Thermalstabilitytest

Aftertestasat(ii),thecableisenergizedwithavoltage1.5timestheworkingvoltagefor a cable of 132 kV rating (the multiplying factor decreases with increases in operating voltage) and the loading current is so adjusted that the temperature of the core of the cable is 5°C higher than its specified permissible temperature. The current should be maintained at this value for six hours.

(iv) Dielectricthermalresistancetest

The ratio of the temperature difference between the core and sheath of the cable and theHeatflowfromthecablegivesthethermalresistanceofthesampleofthecable.Itshould be within the limits specified in the specifications.

(v) Lifeexpectancytest

In order to estimate life of a cable, an accelerated life test is carried out by subjecting the Cable to a voltage stress higher than the normal working stress. It has been observed that the relation between the expected life of the cable in hours and the voltage stress is given by gKn t=whereKisaconstantwhichdependsonmaterialandnisthelifeindexdependingagainonthe material.

(vi) Dielectricpowerfactortest

High Voltage Schering Bridge is used to perform dielectric power factor test on the cable Sample. The power factor is measured for different values of voltages e.g. 0.5, 1.0, 1.5 and 2.0 times the rated operating voltages. The maximum value of power factor at normal working voltage does not exceed a specified value (usually 0.01) at a series of temperatures ranging from 15°C to 65°C. The difference in the power factor between rated voltage and 1.5 times the rated voltage and the rated voltage and twice the rated voltage does not exceed a specified value. Sometimes the source is not able to supply charging current required by the test cable, a suitable choke in series with the test cable help sin tiding over the situation.

(vii) Powerfrequencywithstandvoltagetest

Cables are tested for power frequency a.c. and d.c. voltages. During manufacture the entire cable is passed through a higher voltage test and the rated voltage to check the continuity ofthecable.As aroutinetestthecableissubjectedtoavoltage2.5 timestheworkingvoltagefor 10 min without damaging the insulation of the cable. HV d.c. of 1.8 times the rated d.c. voltage of negative polarity for30 min. is applied and the cable is said to have withstood the test if no insulation failure takes place.

(viii) Impulsewithstandvoltagetest

The test cable is subjected to 10 positive and 10 negative impulse voltage of magnitudeas specified in specification, the cable should withstand 5 applications without any damage. Usually, after the impulse test, the power frequency dielectric power factor test is carried out to ensure that no failure occurred during the impulse test.

(ix) Partialdischargetest

Partial discharge measurement of cables is very important as it gives an indication of expected life of the cable and it gives location of fault, if any, in the cable. When a cable is subjectedtohighvoltageandifthereisavoidinthecable,thevoidbreaks downandadischarge takes place. As a result, there is a sudden dip in voltage in the form of an impulse. This impulse travels along the cable. The duration between the normal pulse and the discharge pulse is measured on the oscilloscope and this distance gives the location of the void from the test end of the cable. However, the shape of the pulse gives the nature and intensity of the discharge. In order to scan the entire length of the cable against voids or other imperfections, it is passed through a tube of insulating material filled with distilled water. Four electrodes, two at the end and two in the middle of the tube are arranged. The middle electrodes are located at a stipulated distance and these are energized with high voltage. The two end electrodes and cable conductor are grounded. As the cable is passed between the middle electrodes, if a discharge is seen on the oscilloscope, a defect in this part of the cable is stipulated and hence this part of the cable is removed from the rest of the cable.

Testingof Bushings

Bushings arean integral component of high voltage machines. A bushing is used to bring high voltage conductors through the grounded tank or body of the electrical equipment without excessive potential gradients between the conductor and the edge of the hole in the body. The bushing extends into the surface of the oil at one end and the other end is carried above the tank to a height sufficient to prevent breakdown due to surface leakage.

Followingtests arecarriedout on bushings:

(i) PowerFactorTest

The bushing is installedas in service or immersed in oil.The high voltage terminal of the bushing is connected to high voltage terminal of the Schering Bridge and the tank or earthportion of the bushing is connected to the detector of the bridge. The capacitance and p.f. of the bushing is measured at different voltages as specified in the relevant specification and the capacitance and p.f. should be within the range specified.

(ii) ImpulseWithstandTest

The bushing is subjected to impulse waves of either polarity or magnitude as specified in the standard specification. Five consecutive full waves of standard wave form (1/50 μ sec.) are applied and if two of them cause flash over, the bushing is said to be defective. If only one flash

(iii) ChoppedWaveandSwitching SurgeTest

Chopped wave and switching surge of appropriate duration tests are carried out on high voltage bushings. The procedure is identical to the one given in (ii) above.

(iv) PartialDischargeTest

In order to determine whether there is deterioration or not of the insulation used in the bushing, this test is carried out. The shape of thedischarge is an indication of nature and severity of the defect in the bushing. This is considered to be a routine test for High voltage bushings.

(v) Visible DischargeTest atPowerFrequency

The test is carried out to artain whether the given bushing will give rise to ratio interference or not during operation. The test is carried out in a dark room. The voltage as specified is applied to the bushing (IS 2099). No dischargeother than that from the grading rings or arcing horns should be visible.

(vi) PowerFrequencyFlashOverorPuncture Test

(Under Oil): The bushing is either immersed fully in oil or is installed as in service condition. This test is carried out to artain that the internal breakdown strength of the bushing is 15% more than the power frequency momentary dry withstand test value.

TestingOfpowercapacitor

power capacitor are one of part of the modern power system. These are used to control the voltage profile of the system. Following tests are carried out on shunt power capacitors (IS 2834):

(i) RoutineTests

Routine tests are carried out on all capacitors at the manufacturer‘s premises. During testing, the capacitors should not breakdown or behave abnormally or show any visible deterioration.

(ii) Testfor Output

Ammeter and Voltmeter can be used to measure the kVAr and capacitance of the capacitor. The kVAr calculated should not differ by more than –5 to+10% of the specified value for capacitor units and 0 to10% for capacitors banks. The a.c. supply used for testing capacitor should have frequency between 40 Hz to 60 Hz, preferably as near as possible to the rated frequency and the harmonics should be minimum.

(iii) Testbetween Terminals

Everycapacitor is subjected tooneof thefollowingtwo tests for10secs:

(iii) D.C.test; the testvoltagebeing V_t= 4.3 V_0

(iv) A.C.test V_t =2.15 V_0,

where V_0 is the rms value of the voltage between terminals which in the test connection gives the same dielectric stress in the capacitor element as the rated voltage V_n gives in normal service.

(iv) TestbetweenLineTerminalsandContainer(Forcapacitor units)

An a.c. voltage of value specified in column 2 of Table 5.1 is applied between the terminals (short-circuited) of the capacitor unit and its container and is maintained for one minute, no damage to the capacitor should be observed. Figures with single star represent values correspondingtoreducedinsulationlevel(Effectivelygroundedsystem)andwithdoublestarfull insulation level (non-effectively grounded system).

Table5.1Power frequencyandimpulse testvoltages(Betweenterminalsandthe container)

System voltage Kv(rms)	PowerFrequency Test Voltage Kv(rms)	ImpulseTest voltage Kv(peak)
12	28	75
24	50	125
36	70	170
72.5	140	325
145	230*	550*
245	275**	650**

(v) IR Test:

The insulation resistance of the test capacitor is measured with the help of a megger. The megger is connected between one terminal of the capacitor and the container. The test voltage shall be d.c. voltage not less than 500 volts and the acceptable value of IR is more than 50 megohms.

(vi) Testfor efficiencyofDischargeDevice:

In order to provide safety to personnel who would be working on the capacitors, it is desirable to connect very high resistance across the terminals of the capacitor so that they get discharged in about afewseconds afterthesupply is switched off. Theresidual capacitorvoltage after the supply voltage is switched off should reduce to 50 volts in less than one minute of the capacitorisratedupto650voltsand5minutesifthecapacitorisratedforvoltagemorethan650 volts. A d.c. voltage 2 × rms rated voltage of the capacitor is applied across the parallel combination of R and C where C is the capacitance of the capacitor under test and R is the high resistance connected across the capacitor. The supply is switched off and the fall in voltage across the capacitor as a function of time is recorded. If C is in microfarads and R in ohms, the time to discharge to 50 volts can be calculated from the formula $t = 2.3 \times 10^{-6} CR (\log_{10} V - 1.7)$ secs Where V is the rated rms voltage of the capacitor in volts.

TypeTests

The type tests are carried out only once by the manufacturer to prove that the design of capacitor complies with the design requirements:

(i) DielectricLossAngleTest(p.f.test):

High voltage Schering Bridge is used to measure dielectric power factor. The voltage applied is the rated voltage and at temperatures 27°C ± 2°C. The value of the loss angle tan δ shouldnotbemorethan10%thevalueagreed tobetweenthemanufacturerandthepurchaserand it should not exceed 0.0035for mineral oil impregnates and 0.005 for chlorinated impregnates.

(ii) TestforCapacitorLoss:

The capacitor loss includes the dielectric loss of the capacitor and the V2/R loss in the discharge resistance which is permanently connected. The dielectric loss can be evaluated from the loss angle as obtained in the previous test and V2/R loss can also be calculated. The total

powerlossshouldnotbemorethan10%ofthevalueagreedtobetweenthemanufacturerand consumer.

(iii) Stability Test:

The capacitor is placed in an enclosure whose temperature is maintained at ±2°C above the maximum working temperature for 48 hours. The loss angle is measured after 16 hours, 24 hours and 48 hours using High voltage Schering Bridge at rated frequency and at voltage 1.2 times the rated voltage. If the respective values of loss angle are tan $\delta 1$, tan $\delta 2$ and tan $\delta 3$, these values should satisfy the following relations (anyone of them):

(a)tan $\delta 1$+tan $\delta 2 \leq$ 2tan $\delta 2$ <2.1 tan $\delta 1$or(b)tan $\delta 1 \geq$ tan $\delta 2 \geq$ tan $\delta 3$

(iv) Impulsevoltagetest betweenterminaland container:

The capacitor is subjected to impulse voltage of 1/50 μ sec. Wave and magnitude as stipulated in column 3 of Table 5.1. Five impulses of either polarity should be applied between theterminals(joinedtogether)andthecontainer. Itshouldwithstandthisvoltagewithoutcausing any flash over.

TESTINGOFPOWER TRANSFORMERS

Transformer is one of the most expensive and important equipment in power system. If it is not suitably designed its failure may cause a lengthy and costly outage. Therefore, it is very important to be cautious while designing its insulation, so that it can withstand transient over voltage both due to switching and lightning. The high voltage testing of transformers is, therefore, very important and would be discussed here. Other tests like temperature rise, short circuit, open circuit etc. are not considered here. However, these can be found in the relevant standard specification. Partial Discharge Test The test is carried out on the windings of the transformer to assess the magnitude of discharges. The transformer is connected as a test specimen similar to any other equipment as discussed in and the discharge measurements are made. The location and severity of fault is artained using the travelling wave theory technique as explained. The measurements are to be made at all the terminals of the transformer and it is estimated that if the apparent measured charge exceeds 104picocoulombs, the discharge magnitude is considered to be severe and the transformer insulation should be so designed that the discharge measurement should be much below the value of 104 Pico-coulombs.

ImpulseTesting of Transformer

The impulse level of a transformer is determined by the breakdown voltage of its minor insulation (Insulation between turn and between windings), breakdown voltage of its major insulation (insulation between windings and tank) and the flash over voltage of its bushings or a combination of these. The impulse characteristics of internal insulation in a transformer differ from flash over in air in two main respects. Firstly the impulse ratio ofthe transformer insulation is higher (varies from 2.1 to 2.2) than that of bushing (1.5 for bushings, insulators etc.).Secondly, the impulse breakdown of transformer insulation in practically constant and is independent of time of application of impulse voltage.

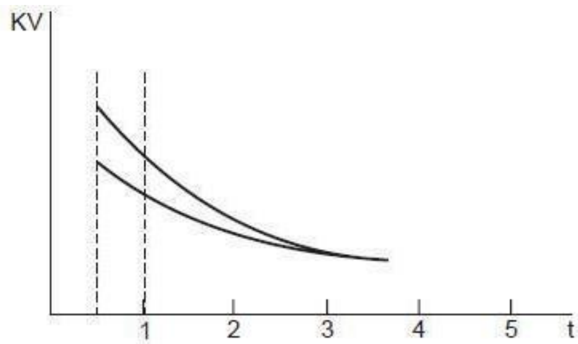


Figure:5.1Volttime curveoftypical majorinsulationin transformer

Fig.5.1 shows that after three micro seconds the flash over voltage is substantially constant. The voltage stress between the turns of the same winding and between different windings of the transformer depends upon the steepness of the surge wave front. The voltage stress may further get aggravated by the piling up action of the wave if the length of the surge wave is large. In fact, due to high steepness of the surgewaves, the first few turns of the winding areoverstressed and that is why the modern practice is to provide extra insulation tothe first few turns of the winding. Fig. 5.2 shows the equivalent circuit of a transformer winding for impulse voltage.

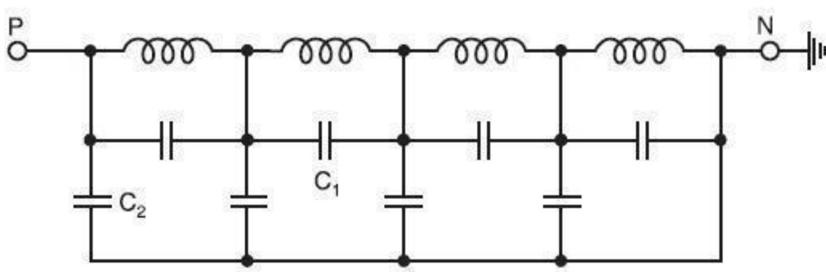


Figure:5.2Equivalentcircuitofatransformerforimpulsevoltage

Here C_1 represents inter-turn capacitance and C_2 capacitance between winding and the ground (tank). In order that the minor insulation will be able to withstand the impulse voltage,the winding is subjected to chopped impulse wave of higher peak voltage than the full wave.This chopped wave is produced by flash over of a rod gap or bushing in parallel with the transformer insulation. The chopping time is usually 3 to 6 micro seconds. While impulsevoltage is applied between one phase and ground, high voltages would be induced in the secondary of the transformer. To avoid this, the secondary windings are short-circuited and finally connected to ground. The short circuiting, however, decreases the impedance of the transformer and hence poses problem in adjusting the wave front and wave tail timings of wave. Also, the minimum value of the impulse capacitance required is given by

$$C_0 = \frac{P \times 10^8}{Z \times V^2} \mu F$$

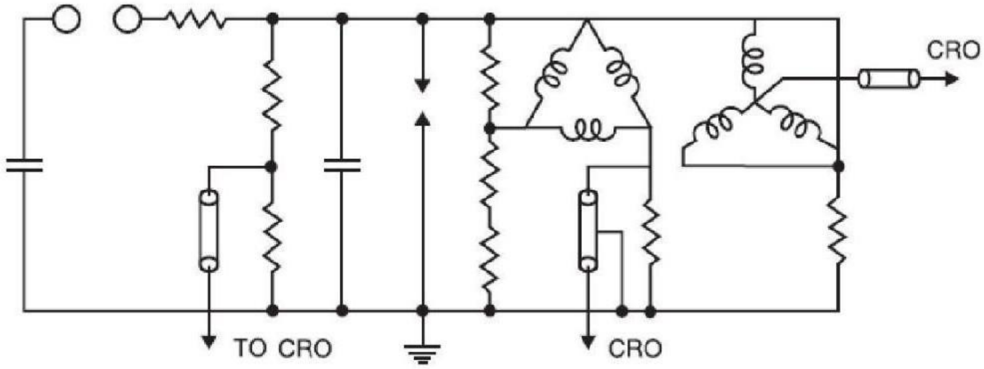


Figure:5.3Arrangementfor impulsetestingoftransformer

Where P = rated MVA of the transformer Z = per cent impedance of transformer. V = rated voltage of transformer. Fig. 5.3 shows the arrangement of the transformer for impulse testing. CRO forms an integral part of the transformer impulse testing circuit. It is required to record to wave forms of the applied voltage and current through the winding under test.

Impulsetestingconsistsofthefollowingsteps:

(iv) ApplicationofimpulseofmagnitudeNo75%oftheBasicImpulseLevel(BIL)of the transformer under test.

(v) Onefull waveof 100%of BIL.

(vi) Twochopped waveof115%of BIL.

(vii) Onefullwave of100% BILand

(viii) Onefull wave of 75%ofBIL.

During impulse testing the fault can be located by general observation like noise in the tank or smoke or bubble in the breather. If there is a fault, it appears on the Oscilloscope as a partial of complete collapse of the applied voltage. Study of the wave form of the neutral current also indicated the type of fault. If an arc occurs between the turns or form turn to the ground, a train of high frequency pulses are seen on the oscilloscope and wave shape of impulse changes.If it is a partial discharge only, high frequency oscillations are observed but no change in wave shape occurs. The bushing forms an important and integral part of transformer insulation. Therefore, its impulse flash over must be carefully investigated. The impulse strength of the transformer winding is same for either polarity of wave whereas the flash over voltage for bushing is different for different polarity. The manufacturer, however, while specifying the impulse strength of the transformer takes into consideration the overall impulse characteristic of the transformer.

TestingOfCircuitBreakers

Equipments when designed to certain specification and is fabricated needs testing for its performance. The general design is tried and the results of such tests conducted on one selected breaker and are thus applicable to all others of identical construction. These tests are called the type tests. These tests are classified as follows:

(i)Shortcircuittests:

- Making capacity test.
- Breakingcapacitytest.
- Shorttimecurrenttest.
- Operating duty test

2. Dielectrictests:

Powerfrequencytest:

- Oneminutedrywithstandtest. •

Oneminute wet withstand test.

- Impulsevoltagedrywithstand test.

3. Thermaltest.

4. Mechanicaltest

Once a particular design is found satisfactory, a large number of similar C.Bs. are manufactured for marketing. Every piece of C.B is then tested before putting into service. These tests are known as routine tests. With these tests it is possible to find out if incorrect assembly or inferior quality material has been used for proven design equipment. These tests are classified as

(i)operationtests(ii)millvoltdroptests,(iii)powerfrequencyvoltagetestsat manufacturer‘s premises, and (iv) power frequency voltage tests after erection on site.

We will discuss first the type tests. In that also we will discuss the short circuit tests after the other three tests. Dielectric Tests The general dielectric characteristics of any circuit breaker or switchgear unit depend upon the basic design i.e. clearances, bushing materials, etc. upon correctness and accuracy in assembly and upon the quality of materials used. For a C.B. these factors are checked from the viewpoint of their ability to withstand over voltages at the normal service voltage and abnormal voltages during lightning or other phenomenon.

The test voltage is applied for a period of one minute between (i) phases with the breaker closed, (ii) Phases and earth with C.B. open, and (iii) across the terminals with breaker open. With this the breaker must not flash over or puncture.

These tests are normally made on indoor switchgear. For such C.Bs the impulse tests generally are unnecessary because it is not exposed to impulse voltage of a very high order. The high frequency switching surges do occurbut the effect of these in cablesystems used forindoor switchgear are found to be safely withstood by the switchgear if it has withstood the normal frequency test. Since the outdoor switchgear is electrically exposed, they will be subjected to over voltages caused by lightning. The effect of these voltages is much more serious than the power frequency voltages in service. Therefore, this class of switchgear is subjected in addition to power frequency tests, the impulse voltage tests. The test voltage should be a standard 1/50 μsec wave, the peak value of which is specified according to the rated voltage of the breaker. A higher impulse voltage is specified for non-effectively grounded system than those for solidly grounded system. The test voltages are applied between (i) each pole and earth in turn with the breaker closed and remaining phases earthed, and (ii) between all terminals on one side of the breaker and all the other terminals earthed, with the breaker open. The specified voltages are withstanding values i.e. the breaker should not flash over for 10 applications of the wave. Normally this test is carried out with waves of both the polarities. The wet dielectric test is used for outdoor switchgear. In this, the external insulation is sprayed for two minutes while the rated servicevoltageis applied,thetestovervoltageisthenmaintained for30secondsduring whichno flash over should occur. The effect of rain on external insulation is partly beneficial, insofar as the surface is thereby cleaned, but is also harmful if the rain contains impurities.

ThermalTests

These tests are made to check the thermal behavior of the breakers. In this test the rated current through all three phases of the switchgear is passed continuously for a period longenough to achieve steady state conditions. Temperature readings are obtained by means of thermocouples whose hot junctions are placed in appropriate positions. The temperature rise above ambient, of conductors, must normally not exceed 40°C when the rated normal current is less than 800 amps and 50°C if it is 800amps and above.

An additional requirement in the type test is the measurement of the contact resistances between the isolating contacts and between the moving and fixed contacts. These points are generally the main sources of excessive heat generation. The voltage drop across the breakerpole is measured for different values of d.c current which is a measure of the resistance ofcurrent carrying parts and hence that of contacts.

MechanicalTests

A C.B. must open and close at the correct speed and perform such operations without mechanical failure. The breaker mechanism is, therefore, subjected to a mechanical endurance typetestinvolvingrepeatedopeningandclosingofthebreaker.B.S.116:1952requires500such operationswithoutfailureand withnoadjustment ofthe mechanism.Somemanufacture feel that as many as 20,000operations may be reached before any useful information regarding the possible causes of failure maybe obtained. A resulting change in the material or dimensions of a particular component may considerably improve the life and efficiency of the mechanism.

ShortCircuitTests

Thesetestsarecarried outinshort circuittestingstations toprovethe ratingsoftheC.Bs. Beforediscussingthe testsit isproper todiscussabout theshort circuittesting stations. Therearetwotypesoftestingstations;(i)fieldtype,and (ii)laboratorytype. In caseoffieldtype stations the power required for testing is directly taken from a large power system. The breaker tobetestedisconnectedtothesystem.Whereasthismethodoftestingiseconomicalforhigh voltage C.Bs. it suffers from the following drawbacks:

- The tests cannot be repeatedly carried out for research and development as it disturbs the whole network.
- Thepoweravailabledependsuponthelocationofthetestingstations,loading conditions, Installed capacity, etc.
- Test conditions like the desired recovery voltage, the RRRV etc. cannot be achieved conveniently. In case of laboratory testing the power required for testing is provided by specially designed generators.

Thismethodhas thefollowing advantages:

1. Testconditionssuchascurrent,voltage,powerfactor,restrictingvoltagescanbecontrolled accurately.
2. Severalindirecttestingmethodscanbeused.
3. Testscanbe repeatedandhenceresearchanddevelopmentoverthedesignispossible.

Thelimitationsofthismethodarethecostandthelimitedpoweravailabilityfortestingthe breakers.

ShortCircuitTest Plants

The essential components of a typical test plant are represented in Fig. 5.4. The short-circuit power is supplied by specially designed short-circuit generators driven by induction motors. The magnitude of voltage can be varied by adjusting excitation of the generator or the transformer ratio. A plant master breaker is available to interrupt the test short circuit current if the test breaker should fail. Initiation of the short circuit may be by the master breaker, but is always done by a making switch which is specially designed for closing on very heavy currentsbut never called upon to break currents. The generator winding may be arranged for either star or delta connection according to the voltage required; by further dividing the winding into two sections which may be connected in series or parallel, a choice off our voltages is available. In addition to this the use of resistors and reactors in series gives a wide range of current and power factors. The generator, transformer and reactors are housed together, usuallyin the building accommodating the test cells.

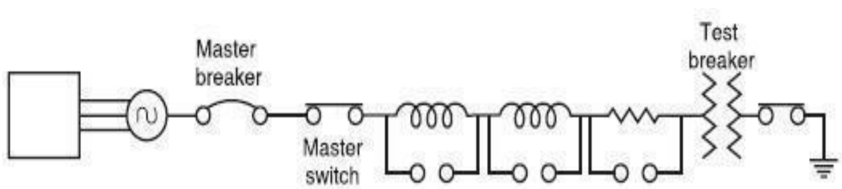


Figure:5.4Schematicdiagramof atypicaltestplant

Generator

Theshortcircuitgeneratorisdifferentindesignfromtheconventionalpowerstation.The capacity of these generators may be of the order of 2000 MVA and very rigid bracing of the conductors and coil ends is necessary in view of the high electromagnetic forces possible. The limiting factor for the maximum output current is the electromagnetic force. Since the operation of the generator is intermittent, this need not be very efficient. The reduction of ventilation enables the main flux to be increased and permits the inclusion of extra coil end supports. The machine reactance is reduced to a minimum.

Immediatelybeforetheactualclosingofthemakingswitchthegeneratordrivingmotoris switched out and the short circuit energy is taken from the kinetic energy of the generator set. This is done to avoid any disturbance to the system during short circuit. However, in this case it is necessary to compensate for the decrement in generator voltage corresponding to the diminishing generator speed during the test. This is achieved by adjusting the generator field excitation to increase at a suitable rate during the short circuit period. The resistors are used to control the p.f of the current and to control the rate of decay of d.c component of current. There are a number of coils per phase and by combinations of series and parallel connections desired value of resistance and/or reactance can be obtained. These are used for breaking line charging currents and for controlling the rate of re-striking voltage.

ShortCircuit Transformers

The leakage reactance of the transformer is low so as to withstand repeated short circuits. Since they are in use intermittently, they do not pose any cooling problem. For voltage higher than the generated voltages, usually banks of single phase transformers are employed. In the shortcircuitstation atBhopaltherearethreesinglephaseunitseachof11kV/76kV.Thenormal rating is 30 MVA but their short circuit capacity is 475 MVA. Master C.Bs.

These breakers are provided as backup which will operate, should the breaker under test fail to operate. This breaker is normally air blast type and the capacity is more than the breaker under test. After every test, it isolates the test breaker from the supply and can handle the full short circuit of the test circuit.

MakeSwitch

The make switch is closed after other switches are closed. The closing of the switch is fast, sure and without chatter. In order to avoid bouncing and hence welding of contacts, a high air pressure is maintained in the chamber. The closing speed is high so that the contacts are fully closed before the short circuit current reaches its peak value.

TestProcedure

Before the test is performed all the components are adjusted to suitable values so as to obtain desired values of voltage, current, rate of rise of restricting voltage, p.f. etc. Themeasuring circuits are connected and oscillograph loops are calibrated. During the test several operations are performed in a sequence in a short time of the order of0.2 sec. This is done with the help of adrum switch with several pairs of contacts which is rotated with a motor. This drum whenrotatedclosesandopensseveralcontrolcircuitsaccordingtoacertainsequence.Inoneof the breaking capacity tests the following sequence was observed:

- Afterrunningthemotortoaspeedthesupplyisswitchedoff. Impulse
- excitation is switched on.
- Master C.B. is closed.
- Oscillographisswitchedon.
- Make switch is closed.
- C.B. under test is opened.
- Master C.B. is opened.
- Excitercircuitisswitchedoff.

ThecircuitfordirecttestisshowninFig. 5.5

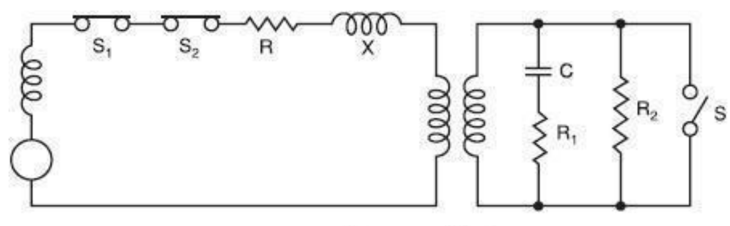


Figure:5.5Circuitfordirecttesting

Here XG = generator reactance, S1 and S2 are master and make switches respectively. R and X are the resistance and reactance for limiting the current and control of p.f., T is the transformer, C, R1 andR2 is the circuit for adjusting the restricting voltage. For testing, breaking capacity of the breaker under test, master and breaker under test are closed first. Short circuit is applied by closing the making switch. The breaker under test is opened at the desired moment and breaking current is determined from the oscillograph as explained earlier. For making capacity test the master and the make switches are closed first and short circuit is applied by closing the breaker under test. The making current is determined from the oscillograph as explained earlier. For short-time current test, the current is passed through the breaker for ashort-time say1 second and the oscillograph is taken as shown in Fig. 5.6.From the oscillogram the equivalent r.m.s value of short-time current is obtained as follows:

Thetimeinterval 0to Tis dividedinto10 equalparts markedas 0,1,2 ...,9 and10. Let

ther.m.svalueofcurrentsattheseinstantsbeI0,I1,I2...I9andI10(asymmetricalvalues). From these values, the r.m.s value of short-time current is calculated using Simpson formula.

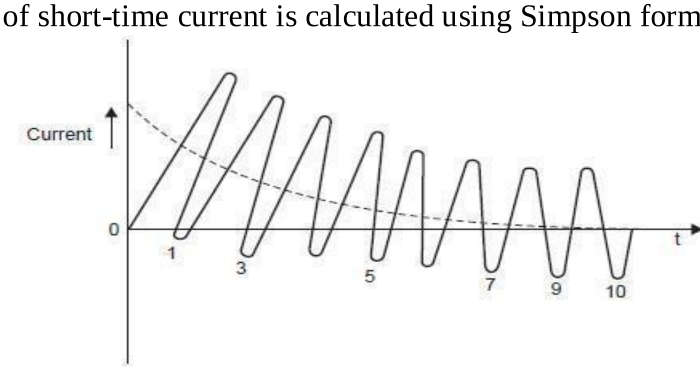


Figure5.6Determinationofshort-timecurrent

$$I = \sqrt{\frac{1}{3}[K_0^2 + 4(I_1^2 + I_2^2 + I_3^2 + \cdots. + I_9^2) + 2(I_2^2 + I_4^2 + \cdots + I_{10}^2)}$$

Operatingdutytestsareperformedaccordingtostandardspecificationunlessthedutyis marked on the rating plate of the breaker. The tests according to specifications are:

(i) B—3′—B—3′—Bat10%ofratedsymmetricalbreakingcapacity;
(ii) B—3′—B—3′—Bat30%ofratedsymmetricalbreakingcapacity;
(iii) B—3′—B—3′—Bat60%ofratedsymmetricalbreakingcapacity;
(iv) B—3′—MB—3′—MBatnotlessthan100%ofratedsymmetricalbreakingcapacityand

notlessthan100%ofratedmakingcapacity.Testduty(iv)maybeperformedastwoseparate duties as follows:

(a) M—3′—M(Make test);
(b) B—3′—B—3′—B(Break test)
(c) B—3′—B—3′—Batnotlessthan100%rated asymmetricalbreakingcapacity.

Here B and M represent breaking and making operations respectively. MB denotes the making operation followed by breaking operation without any international time-lag.3′ denotes the time in minutes between successive operations of an operating duty.

TestingIsolators

Coupler digital isolators are tested in production to guarantee that both the isolation and data transmission conform to the data sheet specifications. This is done with a two-pass test performed on 100% of our products: a High Voltage test followed by a parametric test. This differs from most non-isolated ICs which are subjected only to parametric testing.

TheHigh Voltagetest

It has two elements: guaranteeing the Isolation Rating and ensuring the integrity of the isolation barrier. ―Isolation Rating‖ is the voltage (60 Hz rms) that can safely be applied across the inputs and outputs of a device for one minute. This rating is certified by regulatory agencies such as UL; typical isolation ratings guaranteed on iCoupler devices are 2.5 kV rms and 5 kV rms. A one minute test in production would be cost-prohibitive, so UL, for example, allows the test to be reduced to one second provided the test voltage is 120% of the specified isolation rating; for a 2.5 kV rms isolation rating, the production test is performed at 3 kV rms for one second, while a 6 kV rms test is performed to guarantee a 5 kV rms isolation rating. During this test, we check for leakage that indicates that barrier has broken down, but leakage current can also be caused by capacitance across the isolation barrier. Most isolators rated at 2.5 kV rmshave a leakage current less than 5 µA which is proportional to the voltage across the isolation barrier. This requires that we set test limits to account for these two main components of leakage current during high voltage testing fig shown in 5.6(a).

The second element of High Voltage testing checks the integrity of the isolation barrier using amethod knownas Partial Discharge. This test detects defects, such as cavitiesorvoids, in the insulation. Applying a high voltage induces breakdown in voids or cavities in the device and will transfercharge across thevoid. Therepeatedtransferofcharge can makethevoid larger and eventually causes the insulation to fail. Charge transfer is measured in pico-Coulombs and a maximum limit of 5 pC at 1050 V peak. is accepted per the applicable VDE standards. The 1050 V peak test voltage is calculated from as 1.875 times the maximum working voltage rating (e.g., 560 V peak times 1.875 to a meet 1 minute rating. After High Voltage testing the part is then subjected to parametric testing performance (e.g., supply current, input signal current, propagation delay, Pulse Width Distortion, Data Rate, Supply voltage range, etc.). Allparameters that have Min/Max limits on the data sheet are tested 100 % in production.

surge arresters

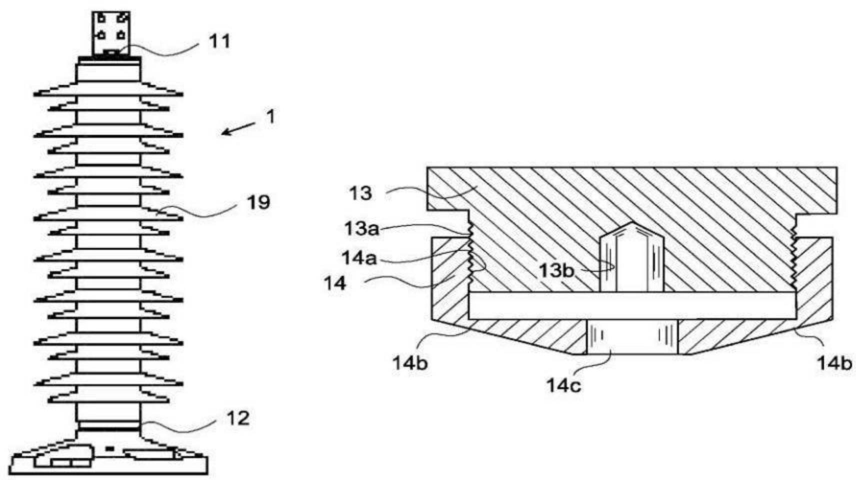


Figure:5.6(a)surge arresters

A surge arrester is a protective equipment installed between communication equipment and coaxial cable connector or between two communication equipment‘s to protect communication equipment from damage caused by transient state voltage formed by lightning induction. It adopts quarter-wave technology, is designed according to VSW theory and frequency spectrum of lightning wave. It has features of quick reaction, big current passing capacity, wide frequency band, low VSWR, low insertion loss, easy installation and free maintenance. It can be used to meet protection requirements of various communication equipment‘s and lightning sensitivity.

Anelectricalapplianceusedtoprotectelectronicequipmentagainstlightningovervoltage transients. It is usually connected to wires (power phase line, signal line, zero line) and ground between being protective devices in parallel, when the lightning over-voltage the value of the required actions voltage, arrester immediate to limit over-voltage amplitude lead to protection equipment and systems, enabling the system to work properly.

- Low-voltagesurgearresterApplyinLow-voltagedistributionsystem,exchangeof electrical appliances protector, low-voltage distribution transformer windings
- DistributionarresterApplyin3KV,6KV,10KVACpowerdistributionsystemtoprotect distribution transformers, cables and power station equipment
- Thestationtypeofcommonvalvearrester Usedtoprotectthe3~220KVtransformer station equipment and communication system
- MagneticblowvalvestationarresterUseto35~500KVprotect communicationsystems, transformers and other equipment
- ProtectionofrotatingmachineusingmagneticblowvalvearresterUsedtoprotecttheAC generator and motor insulation
- LineMagneticblowvalvearresterUsedtoprotect330KVandabovecommunication system circuit equipment insulation
- DCorblowingvalve-typearresterUsetoprotecttheDCsystem‘sinsulationofelectrical equipment
- Neutral protection arrester Apply in motor or the transformer‘s neutral protection
- Fiber-tubearresterApplyinthepowerstation‘swiresandtheweaknessesprotectionin the insulated.
- Plug-inSignalArresterUsedtotwisted-pairtransmissionlineinordertoprotect communications and computer systems
- High-frequencyfeederarresterUsedtoprotectthemicrowave,mobilebasestations satellite receiver, etc.
- Receptacle-type surge arrester Use to Protect the terminal Electronic equipment
- SignalArresterApplyinMODEM,DDNline,fax,phone,processcontrolsignalcircuit etc.
- Network arrester Apply in servers, workstations, interfaces etc.
- CoaxialcablelightningarresterUsedtothecoaxialcableinordertoprotectthewireless transmission and receiving system

TANDELTA MEASUREMENT

Incaseoftimevaryingelectricfields,thecurrentdensityJcusing Ampereslawisgiven by

$$J_c = \sigma E + \frac{\partial D}{\partial t} = \sigma E + \varepsilon \frac{\partial E}{\partial t}$$

Therefore,

$$J_c = \sigma E + j\,\omega\,\varepsilon\,E$$
$$= (\sigma + j\,\omega\,\varepsilon)E$$

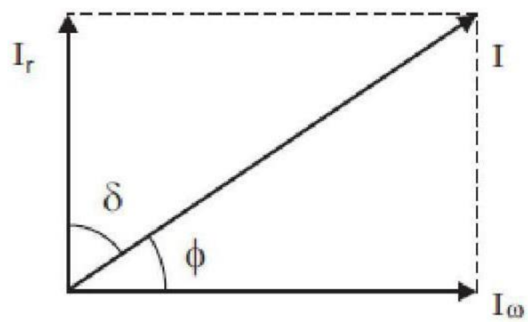


Figure:5.7Phasor diagramforarealdielectricmaterial

Ingeneral,inadditionto conductionlosses,ionizationandpolarizationlossesalsooccur and, therefore, the dielectricconstant ε = ε0 εrisno longerareal quantity ratherit isa complex quantity. By definition, the dissipation factor tan δ is the ratio of real component of current Iω to the reactive component *Ir* (Fig.5.7). Here δ is the angle between the reactive component of currentandthetotalcurrentflowingthroughthedielectricatfundamentalfrequency.Whenδis very small tan δ = δ when δ is expressed in radians and tan δ = sin δ = sin (90 – φ) = cos φ *i.e.,* tan δ then equals the power factor of the dielectricmaterial.As mentioned earlier, the dielectric loss consists of three components corresponding to the three loss means for each of these an individual dissipation factor can be given such that mechanism

$$\tan\delta = \tan\delta_c + \tan\delta_p + \tan\delta_i$$

Ifonlyconductionlossesoccurthen

$$\tan\delta = \frac{\sigma}{\omega\varepsilon_0\,\varepsilon_r}$$

where

$$\varepsilon_r^* = \frac{(\varepsilon' - j\,\varepsilon'')}{\varepsilon_0} = \varepsilon'_r - j\,\varepsilon''_r$$

εr^* is called thecomplex relative permittivity orcomplex dielectric constant, ε' and $\varepsilon r'$ are called the permittivity and relative permittivity and ε'' and $\varepsilon r''$ are called the loss factor and relative loss factor respectively.T he loss tangent the product of the angular frequency and ε'' is equivalent to the dielectric conductivity ζ'' *i.e.*, $\zeta'' = \omega\varepsilon''$. The dielectric conductivity takes into account all the three power dissipative processes including the one which is frequency dependent. Fig. 5.8showstwoequivalentcircuitsrepresentingtheelectricalbehaviorofinsulatingmaterialsunder a.c.voltages,losseshave beensimulatedbyresistances

Theloss tangent

$$\tan \delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\varepsilon_r''}{\varepsilon_r'}$$

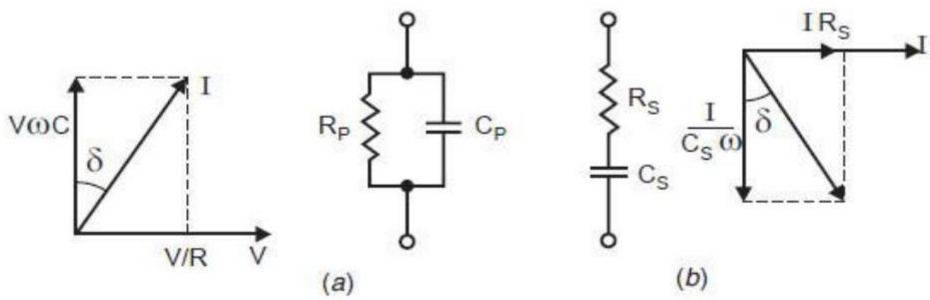


Figure:5.8Equivalentcircuitsforaninsulatingmaterial

Normally the angle between V and the total current in a pure capacitor is 90°. Due to losses, thisangle is less than 90°. Therefore, δ is the angle by which the voltage and charging current fall short ofthe 90° displacement.
Fortheparallelcircuitthedissipationfactorisgivenby

$$\tan \delta = \frac{1}{\omega C_p R_p}$$

andfortheseries circuit

$$\tan \delta = \omega\, C_s R_s$$

For a fixed frequency, both the equivalents hold good and one can be obtained from the other. However, the frequency dependence is just the opposite in the two cases and this showsthe limitedvalidity of these equivalent circuits.The information obtained from the measurement oftanδandcomplexpermittivityisanindicationofthequalityof theinsulatingmaterial.

- Iftanδvariesandchangesabruptlywiththeapplicationofhighvoltage,itshows inceptionof internal partial discharge.

The effect to frequency on the dielectric properties can be studied and the band of frequencies where dispersion occurs i.e., where that permittivity reduces with rise in frequency can be obtained.

PARTIALDISCHARGEMEASUREMENTS

Whatisa_partialdischarge'?LetususethedefinitiongivenintheInternationalStandard of the IEC (International Electro technical Commission) related to partial discharge measurements, Partial discharge (PD) is a localized electrical discharge that only partiallybridges the insulation between conductors and which may or may not occur adjacent to a conductor.This definition is supplemented by threenotes, from which only notes1 and2 shall be cited.

NOTE 1 – Partial discharges are in general a consequence of local electrical stress concentrations in the insulation or on the surface of the insulation. Generally such discharges appear aspulsesofdurationofmuchlessthan1µs.Morecontinuousformsmay,however,occur, as for example the socalledpulse-less discharges in gaseous dielectrics. This kind of discharge will normally not be detected by the measurement methods described in this standard.

NOTE 2 – _Corona' is a form of partial discharge that occurs in gaseous media around conductors which are remote from solid or liquid insulation.' Corona' should not be used as a general term for all forms of PD.No further explanations are necessary to define this kind of phenomena: PDsare thus localized electrical discharges within any insulation system as applied in electrical apparatus, components or systems. In general PDs are restricted to a part of the dielectric materials used, and thus only partially bridging the electrodes between which the voltage is applied. The insulation may consist of solid, liquid or gaseous materials, or any combination of these. The term' partial discharge' includes a wide group of discharge phenomena:

(i)internal dischargesoccurringin voidsor cavitieswithinsolid orliquid dielectrics;

(ii) surfacedischargesappearingattheboundaryofdifferentinsulationmaterials;

(iii)corona discharges occurring in gaseous dielectrics in the presence of inhomogeneous fields;

(iv)Continuousimpactofdischargesinsoliddielectricsformingdischargechannels(treeing).

The significance of partial discharges on the life of insulation has long been recognized. Every discharge event causes a deterioration of the material by the energy impact of high energy electrons or accelerated ions, causing chemical transformations of many types. As will be shown later, the number of discharge events during a chosen time interval is strongly dependent on the kind of voltage applied and will be largest for a.c. voltages. It is also obvious that the actual deterioration is dependent upon the material used. Corona discharges in air will have noinfluenceonthelifeexpectancyofanoverheadline;butPDswithinathermoplasticdielectric, e.g.PE,maycausebreakdownwithinafew days.

It is still the aim of many investigations tolerate partial discharge to the lifetime of specifiedmaterials.Such aquantitativelydefinedrelationshipis,however,difficulttoensure.PD measurements have nevertheless gained great importance during the last four decades and large number publications are concerned either with the measuring techniques involved or with the deterioration effects of the insulation. The detection and measurement of discharges is based on the exchange of energy taking place during the discharge. These exchanges are manifested as:

(i) electricalpulsecurrents (withsome exceptions,i.e. sometypes ofglow discharges);

(ii) Dielectriclosses;

(iii) e.m.radiation(light);

(iv) Sound(noise);increased gaspressure;

(v) Chemicalreactions.

Therefore, discharge detection and measuring techniques may be based on theobservation of any of the above phenomena. The oldest and simplest method relies on listening tothe acoustic noise from the discharge, the _hissing test‘. The sensitivity is, however, often low and difficulties arise in distinguishing between discharges and extraneous noise sources, particularly when tests are carried out on factory premises. It is also well known that the energy released by PD will increase the dissipation factor; a measurement of tan υ in dependency of voltage applied displays an _ionization knee‘, a bending of the otherwise straight dependency. This knee, however, is blurred and not pronounced, even with an appreciable amount of PD, as the additional losses generated in very localized sections can be very small in comparison to the volume losses resulting from polarization processes.

The use of optical techniques is limited to discharges within transparent media and thus not applicable in most cases. Only modern acoustical detection methods utilizing ultrasonic transducers can successfully be used to localize the discharges. These very specialized methods arenottreatedhere. The most frequentlyused and successfuldetectionmethodsarethe electrical ones, to which the new IEC Standard is also related. These methods aim to separate the impulse currents linked with partial discharges from another phenomena. The adequate application of different PD detectors which became now quite well defined and standardized presupposes fundamental knowledge about the electrical phenomena within the test samples and the test circuits.Thusanattemptismadetointroducethereadertothebasicsofthesetechniqueswithout full treatment, which would-be too extensive. Not treated here, however, are non-electrical methods for PD detection.

Thebasic PDtestcircuit

Electrical PD detection methods are based on the appearance of a _PD (current or voltage) pulse' at the terminals of a test object, which may be either a simple dielectric test specimen for fundamental investigations or even a largeh.v. apparatus which has to undergo aPD test. For the evaluation of the fundamental quantities related to a PD pulse we simulate the test object, as usual, by the simple capacitor arrangement as shown in Fig.5.9(a), comprisingsolid orfluid dielectric materials between the two electrodes or terminals A and B, and a gas- filled cavity. The electric field distribution within this test object is here simulated by some partial capacitances, which is possible as long as no space charges disturb this distribution. discharge current which cannot be measured, would have a shape as governed by the gas discharge process and would in general be similar to a Dirac function, i.e. this discharge current is generally a very short pulse in the nanosecond range. Let us now assume that the sample was charged to the voltage Va but the terminals A, B are no longer connected to a voltage source.

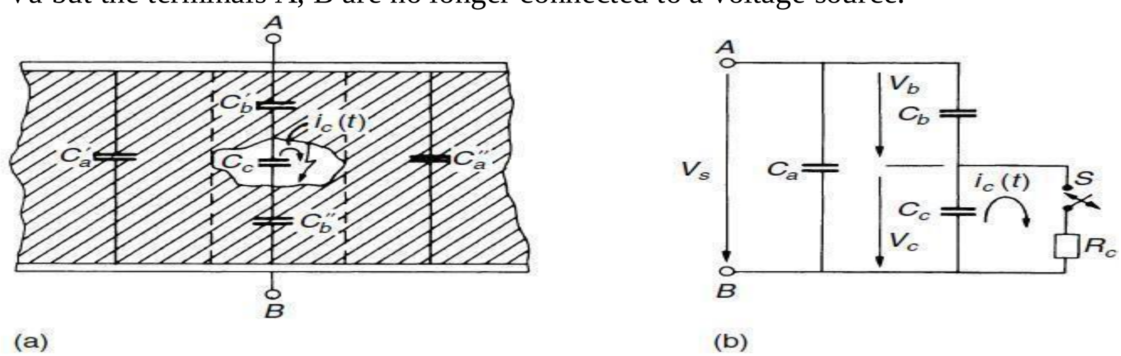


Figure:5.9SimulationofaPDtestobject.(a)Schemeofaninsulation system comprising a cavity. (b) Equivalent circuit

If the switch Sis closed and Cc becomes completely discharged, the current i releases charge υqc D Ccυ Vc from Cc, a charge which is lost in the whole system asassumed for simulation. By comparing the charges within the system before and after this discharge, we receive the voltage drop across the terminal υVa as This voltage drop contains no information about the charge υqc, but it is proportional to Cbυ Vc, a magnitude vaguely related to thischarge, as Cbwill increase with the geometric dimensions of the cavity. Va is clearly a quantity which could be measured.

It is a negative voltage step with a rise time depending upon the duration of ic. The magnitude of the voltage step, however, is quite small, although υVc is in a range of some102to 103 V; but the ratio Cb/Ca will always be very small and unknown according to eqn. Thus a direct detection of this voltage step by measurement of the whole input voltage would be a tedious task. The detection circuits are therefore based upon another quantity, which can immediately be derived from a nearly complete circuit shown in Fig. 5.10.

$$\delta V_a = \frac{C_b}{C_a + C_b}\delta V_c$$

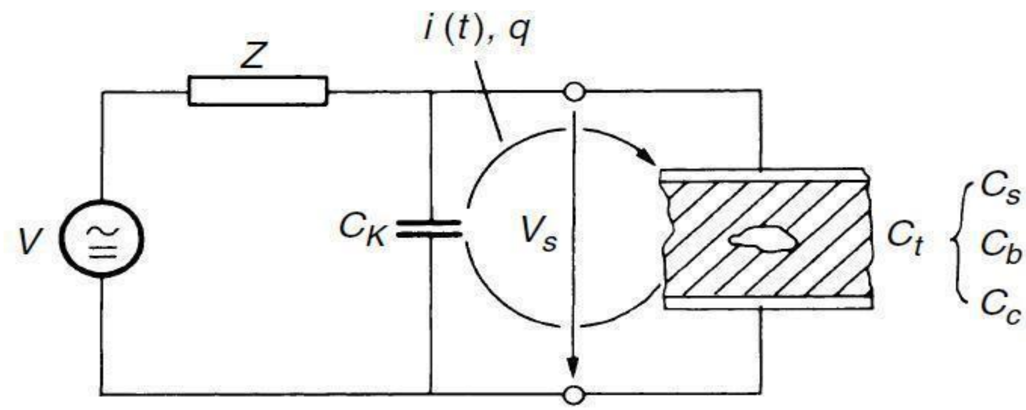


Figure:5.10ThePDtestobject Ctwithina PDtest circuit

The test object, Fig. 5.9 (a), is now connected to a voltage source V, in general an a.c. power supply. An impedance Z, comprising either only the natural impedance of the lead between voltage source and the parallel arrangement of CK and enlarged by a PD-freeinductance or filter, may disconnect the ‗coupling capacitor' CK and the test specimen Ct from the voltage source during the short duration PD phenomena only. Then CK is a storage capacitoror quite a stable voltage source during the short period of the partial discharge. It releases a charging current or the actual ‗PD current pulse' i between CK and Ct and tries to cancel the voltage drop υVa across υVa is completely compensated and the charge transfer provided by the current pulse i is given by

$$q = \int i(t) = (C_a + C_b)\delta V_a$$

Witheqnthischarge becomes

$$q = C_b \delta V_c$$

and is the so-called apparent charge of a PD pulse, which is the most fundamental quantity of all PD measurements. The word ‗apparent' was introduced because this chargeagain is not equal to the amount of charge locally involved at the site of the discharge or cavity Cc. This PD quantity is much more realistic than Va in eqn as the capacitance Ca of the test object, which is its main part of Ct, has no influence on it. And even the amount of charge as locally involved during a discharge process is of minor interest, as only the number and magnitude of their dipole moments and their interaction with the electrodes or terminals determine the magnitude of the PD current pulse. The condition CK ×Ca_.DCt is, however, not always applicable in practice, as either Ct is quite large, or the loading of an a.c. power supply becomes high and the cost of building such a large capacitor, which must be free of anyPD, is not economical.

For a finite value of CK the charge q or the current is reduced, as the voltage across CK will also drop during the charge transfer. Designating this voltage drop by υVŁa, we may compute this value by assuming that the same charge Cb, Vc has to be transferred in the circuits of Figs 5.9(b) and 5.10 . Therefore The relationship qm/q indicates the difficulties arising in PD measurements for test objects of large capacitance values Ct. Although CK and Ct may be known, the ability to detect small values of q will decrease as all instruments capable of integrating the currents i will have a lower limit for quantifying.

Equation therefore sets limits for the recording of _pi co coulombs' in large test objects. During actual measurements, however, a calibration procedure is needed during which artificial apparent charge q of well-known magnitude is injected to the test object, critical note is made with reference to the definition of the apparent charge q as given in the new IEC Standard 60270.31 The original text of this definition is: apparent charge q of a PD pulse is that unipolar. charge which, if injected within a very short time between the terminals of the test object in a specifiedtestcircuit,wouldgivethesamereadingonthemeasuringinstrumentasthe PDcurrent pulse itself. The apparent charge is usually expressed inpicocoulombs.

Thisdefinitionendswith:

NOTE – The apparent charge is not equal to the amount of charge locallyinvolved at the site of the discharge and which cannot be measured directly. This definition is an indication of the difficulties in understanding the physical phenomena related to a PD event. As one of the authors of this book has been chairman of the International Working Group responsible for setting up this new standard, he is familiar with these difficulties and can confirm that the definition is clearly a compromise which could be accepted by the international members of the relevant Technical Committee of IEC. The definition is correct. It relates to a calibration procedure of a PD test and measuring circuit, as already mentioned above. The _NOTE', however, is still supporting the basically wrong assumption that a certain amount or number of charges at the site of the discharge should be measured. As already mentioned: it is not the number of charges producing the PD currents, but the number of induced dipole moments which produce a sudden increase in the capacitance of the test object.

PDcurrents

Before discussing the fundamentals of the measurement of the apparent charge some remarks concerning the PD currents i will be helpful, as much of the research work has been and is still devoted to these currents, which are difficult to measure with high accuracy. The difficulties arise for several reasons. If V is an a.c. voltage, the main contribution of the currents flowing within the branches CK and Ct of Fig. 5.10 are displacement currents C dV/dt, and both are nearly in phase. The PD pulse currents i with crest values in the range of sometimes smaller than 104 A, are not only small in amplitude, but also of very short duration. If no stray capacitancein parallel to CKwerepresent, Iwould bethesamein both branches, but ofopposite polarity. For accurate measurements, a shunt resistor with matched coaxial cable may be introducedinthecircuitasshowninFig.5.11.ThevoltageacrosstheCRO(ortransientrecorder) input .Only if the capacitance of the test object is small, which is a special case, will the voltages referring to the PD currents i be clearly distinguished from the displacement currents i

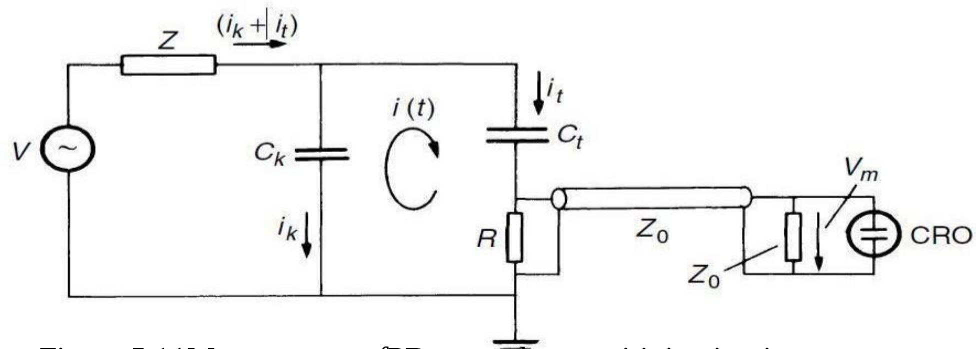


Figure:5.11MeasurementofPDcurrentlowsensitivitycircuit

Improvements are possible by inserting an amplifier (e.g. active voltage probe) of very high bandwidth at the input end of the signal cable. In this way the signal cable is electrically disconnected from R. High values of R,however, will introduce measuring errors, which are explained with Fig. 5.12.A capacitance C of some 10 pF, which accounts for the lead between Ctand earth as well as for the input capacitance of the amplifier or other stray capacitances, will shunt the resistance R and thus bypass or delay the very high-frequency components of the current i. Thus, ifi is a veryshort current pulse,its shapeand crest valueareheavily distorted, as C will act as an integrator. Furthermore, with R within the discharge circuit, the current pulsewill be lengthened, as the charge transfer even with C D 0 will be delayed by a time constant RCtCK/Ct C CK. Both effects are influencing the shape of the original current pulse, and thusthe measurement of i is a tedious task and is only made for research purposes.

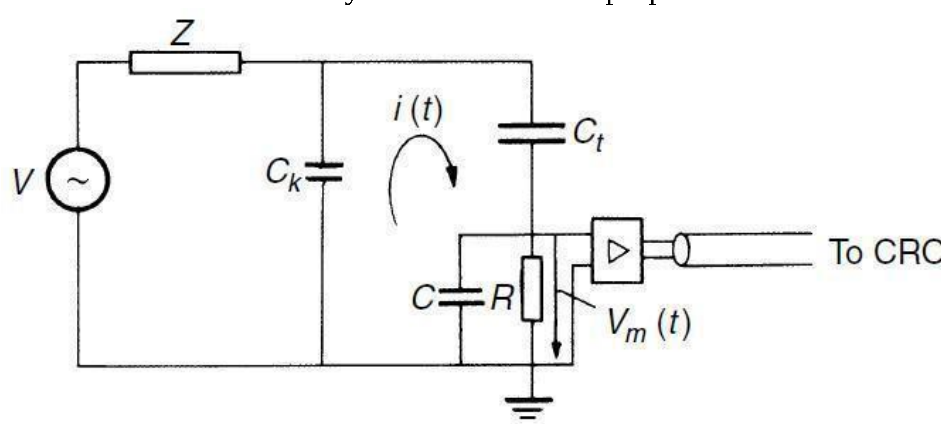


Figure:5.12MeasurementofPDcurrents–highsensitivitycircuit

All measured data on current shapes published in many papers are suffering from this effect. One may, however, summarize the results by the following statements. Partial discharge currents originated in voids within solids or liquids are very short current pulses of less than a few nanoseconds duration. This can be understood, as the gas discharge process within a very limited space is developed in a very short time and is terminated by the limited space for movementofthechargecarriers.Dischargeswithinahomogeneousdielectricmaterial,i.e. agas, produce PD currents with a very short rise time5nsec and a longer tail. Whereas the fast current rise is produced by the fast avalanche processes the decay of the current can be attributed to the drift velocity of attached electrons and positive ions within the dielectric. Discharge pulses in atmospheric air provide in general current pulses of less than about 100 nsec duration.

Longer current pulses have only been measured for partial discharges in fluids or solid materials without pronounced voids, if a number of consecutive discharges take place within a short time. In most of these cases the total duration of Iis less than about 1 μsec, with only some exceptions e.g. the usual bursts of discharges in insulating fluids. All these statements refer totest circuits with very low inductance and proper damping effects within the loop CK Ct. The current I however, may oscillate, as oscillations are readily excited by the sudden voltage drop across Ct. Test objects with inherent inductivity or internal resonant circuits,e.g. transformer or reactor/generator windings, will always cause oscillatory current pulses. Such distortions of the PD currents, however, do not change the transferred charge magnitudes, as no discharge resistor is in parallel to CKor Ct. To quantify the‘ individual apparent charge magnitudes‘ qi for the repeatedly occurring PDpulses which may have quite specific statistical distributions, a measuring system must be integrated into the test circuit which fulfils specific requirements. Already at this point it shall be mentioned that under practical environment conditions quite different kinds of disturbances (background noise)are present, which will be summarized in a later section. Most PD measuring systems applied are integrated into the test circuit inaccordance with schemes shown in Figs 5.13 (a) and (b), which are taken from the new IEC Standard31 which replaces the former one as issued in 1981.Within these ‗straight detection circuits‘, the coupling device ‗CD‘ with its input impedance Zmi forms the input end of the measuring system. As indicated in Fig. 7.20(a), this device may also be placed at the high- voltageterminal side, whichmaybenecessaryif thetest object has oneterminal earthed. Optical links are then used to connect the CD with an instrument instead ofa connecting cable ‗CC‘.

Some essential requirements and explanations with referenceto thesefigures as indicated by the standard are cited here: the coupling capacitor Ck shall be of low inductance design and should exhibit a sufficiently low level of partial discharges at the specified test voltage to allow the measurement of the specified partial discharge magnitude.

A higher level of partial discharges can be tolerated if the measuring system is capable of separating the discharges from the test object and the coupling capacitor and measuring them separately;thehigh-voltagesupplyshallhavesufficientlylowlevelofbackgroundnoisetoallow the specified partial discharge magnitude to be measured at the specified test voltage; high- voltage connections shall have sufficiently low level of background noise to allow the specified partial discharge magnitude to be measured at the specified test voltage; an impedance or a filter may be introduced at high voltage to reduce background noise from the power supply.

The main difference between these two types of PD detection circuits is related to theway the measuring system is inserted into the circuit. InFig.5.13 (a), the CD is at groundpotential and in series to the coupling capacitors as it is usually done in praxis. In Fig. 5.14(b), CD is in series with the test object Ca.

Here the stray capacitances of all elements of the high-voltage side to ground potential willincreasethevalueof Ckprovidingasomewhathighersensitivityforthiscircuitaccordingto eqn . Thedisadvantageis thepossibility ofdamageto thePDmeasuring system, if thetest object fails. The new IEC Standard defines and quantifies the measuring system characteristics. The most essential ones will again be cited and further explained below:

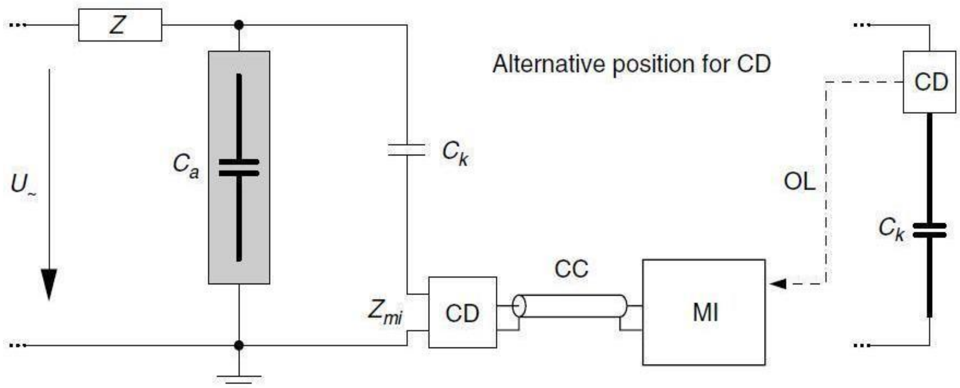
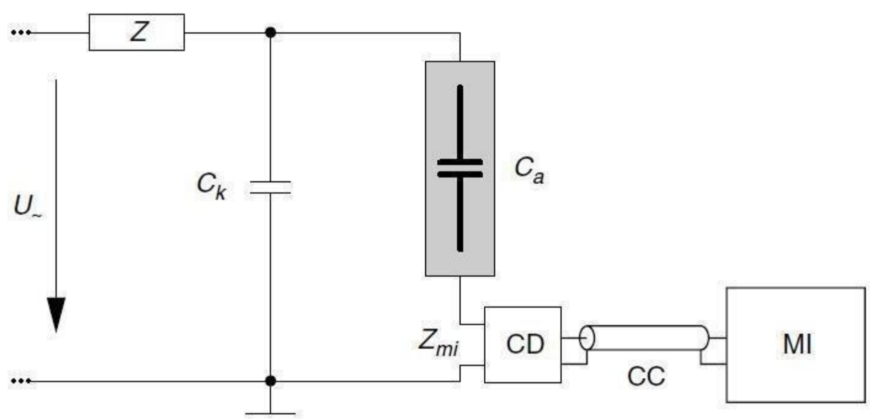


Figure:5.13(a)CouplingdeviceCDinserieswiththecouplingcapacitor



(b) Coupling device CD in series with the test object

Figure:5.14Basicpartialdischargetestcircuits–'straightdetection'

The transfer impedance Zis the ratio of the output voltage amplitude to a constant input current amplitude, as a function of frequency f, when the input is sinusoidal. This definition is due to the fact that any kind of output signal of a measuring instrument (MI) as used for monitoring PD signals is controlled by a voltage, whereas the input at the CD is a current. The lower and upper limit frequencies f1 and f2 are the frequencies at which the transfer impedanceZ has fallen by 6 dB from the peak passbandvalue.Midband frequency fm and bandwidth of: for all kinds of measuring systems, the midland frequency is defined by:

$$f_m = \frac{f_1 + f_2}{2}$$

andthebandwidthby:

$$\Delta f = f_2 - f_1;$$

Thesuperpositionerroriscausedbytheoverlappingoftransientoutputpulseresponseswhen the time interval between input current pulses is less than the duration of a single output response pulse. Superposition errors may be additive or subtractive depending on the pulse repetition rate n of the input pulses. In practical circuits both types will occur due to the random nature of the pulse repetition rate. This rate _n‘ is defined as the ratio between the total number ofPD pulses recorded in a selected time interval and the duration of the time interval.

The pulse resolution time Tr is the shortest time interval between two consecutive input pulses of very short duration, of same shape, polarity and charge magnitude for which the peak value of the resulting response will change by not more than 10 per cent of that for a singlepulse. The pulse resolution time is in general inversely proportional to the bandwidth of the measuring system. It is an indication of the measuring system‘s ability to resolve successive PD events. The integration error is the error in apparent charge measurement which occurs when the upper frequency limit of the PD current pulse amplitudespectrumis lower than (i) the upper cut- off frequency of a wideband measuring system or (ii) the mid-band frequency of a narrow-band measuring system. The last definition of an _integration error‘ will need some additional explanation. PD measuring systems quantifying apparent charge magnitudes are band-pass systems, which predominantly are able to suppress the high-power frequency displacement currents including higher harmonics. The lower frequency limit of the band-pass f1 and the kind of _roll-off‘ of the bandpasscontrol this ability. Adequate integration can thus only be made if the‘ pass-band‘ or the flat part of the filter is still within the constant part of the amplitude frequency spectrum of the PD pulse to be measured. Figure 5.14,

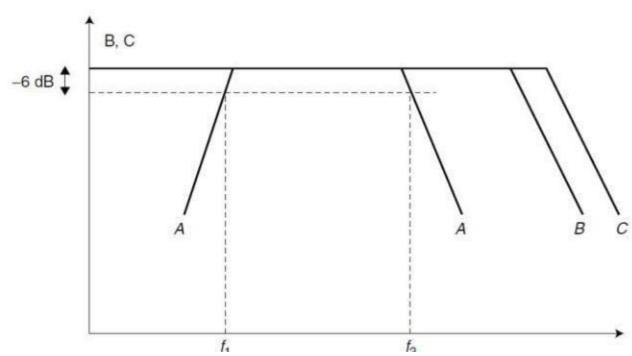


Figure:5.15Correctrelationshipbetweenamplitudeandfrequencytominimize integration errors for a wide-band

- system A band-pass of the measuring system
- B amplitude frequency spectrum of the PD pulse
- Camplitudefrequencyspectrumofcalibrationpulse f1
- lower limit frequency
- f2upperlimitfrequency

Againtakenfromthenewstandard,providesatleastformalinformationaboutcorrect relationships. More fundamental information may be found within some specific literature.

RADIOINTERFERENCEDUETOHIGHVOLTAGEINSULATOR STRINGSourcesofcoronaonlineconductorsandhardware

The local electric breakdown of air or the corona is quite common on the high voltage powertransmissionlinehardware.Theoperating stressisideallylowerthanthecoronainception levels, however, due to some manufacturing defects, damages caused during the transportation and installation, deposition of contaminants like dust particles or water droplets etc. the local field can get significantly intensified. As a result, the corona can occur on line conductors, nuts and bolts of the hardware, arcing horns, guard rings, suspension clamps, etc. Also, since the conductors and tie-wires with the tops of the insulator; and the pins with the entire surface of the thread in the pin holes, do not make perfect electrical contacts, corona may occur in the intervening air gaps.

ThegenerationmechanismofRadionoise

Radio noise in High Voltage transmission line is associated with the pulsating modes of corona discharges developing at the line conductor and hardware, sparking resulting from poor electrical contact and scintillations on the contaminated insulator surfaces. The current pulse associated with individual corona discharges typically possess a rise time measurable in 10s of ns,whichisfollowedbyaslowtailmeasuredin100sofns.Aseveraldischargesareproducedin every half cycle of the power frequency voltage and there could be several sites producingcorona and the noise generated has considerably wide frequency spectrum. The RI level is highin the broadcast frequency range (0.5-1.6MHz) and then decreases gradually at higher frequencies. Detailed studies of corona current characteristics have shown that positive corona is the main source of radio noise from transmission line.

Consequenceofradionoise:

The Radio Interference (RI) from electric power transmission line hardware, if not controlled, poses serious electromagnetic interference to system in the vicinity Also, in future, if the transmission lines are to be employed for general communications, it becomes imperative to limit the corona generated electromagnetic noise .With regard to the transmission lines, the sources of RI are both line conductors and the line hardware including the insulator strings . The present work mainly concerns with the insulator string along with the associated line hardware.

The existing standards have two tests pertaining to RI and corona. First one involves measurement of conducted RIthrough suitablecircuit configuration and a radio noisemeter. The second one involves identification of onset a visual corona, which is relatively subjective.

Associatedstandard:

Hence, governing standards have prefixed upper limits for radio interference levels from different components of high voltage transmission lines. For convenience, the laboratory testing for the RI levels are carried out through the measurement of the conducted radio interference levels.

Problem identification

The RI measurement does not really locate the coronating point, as well as, the modes of corona. At the same time experience shows that it is rather difficult to locate the coronating points by mere inspection. The associated geometry involves both highly localized field intensificationpoints,aswellas,relativelyextendedmoderatefieldintensificationpoints.Thisin turn leads to both point corona and a diffuse corona to start with, which later transform into Details of experimental investigationsExperimental arrangement commonly used test circuits for measuring radio interference are those recommended by IEC and NEMA. For the present work the IEC circuit shown in Figure 1 is employed.

The main components of the circuit are high voltage source (50 Hz, 150 kV, 300 kVA transformer with primary voltage of 230/440 V and with a rated continuous current of 2A), low pass filter which can be tuned to the required frequency, high voltage bus end terminations, coupling capacitor (0.00161 realised by two units of 0.00322 F of GE make connected in series), measuring impedance radio noise meter type SMV 11, VEB Messelektronik Berlin make is used for the measurements. The input voltage to the transformer is 400 V two phase ac. The testing arrangement is so designed to be simpler for operation and all the necessary precautions have been incorporated for proper safety and protection with essential tripping arrangements. The test object consisted of 9-disc insulators(132kV system) and the test voltage was 85kV

RadioInterference Measurements

The International Standard specifies the procedure for a radio interference (RI) test carried out in a laboratory on clean and dry insulators at a frequency of 0,5 MHz or 1 MHz or, alternatively, atotherfrequenciesbetween0.5MHzand 2MHz.Thefrequenciesof0.5or1Mhz are preferred because, usually the level of radio noise at this part of the spectrum and also because 1 MHz lies between the low and medium frequency radio broadcast bands. As per the standard , the measuring apparatus, as per the specification of CISPR 16-1, has been currently used for the RI characteristics of insulators.

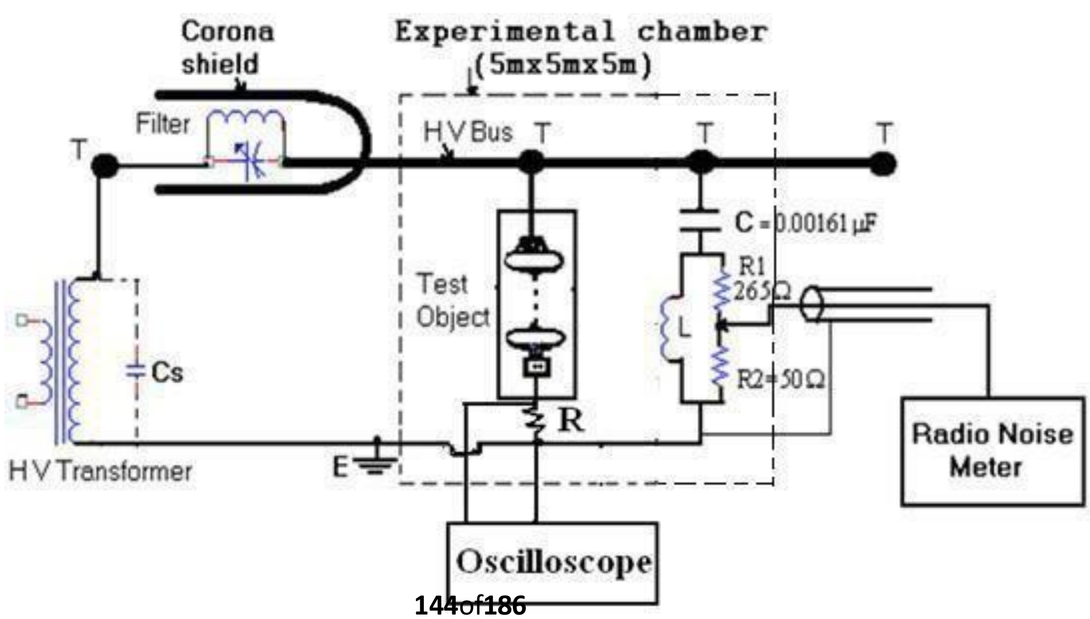


Figure:5.15.RIVmeasuringcircuitasperIECaugmentedwithground end current measurement

The voltage is gradually applied in steps, to reach a value of 90 kV (15% above phase voltage), held for at least five minutes, to allow RIV phenomenon to stabilize. Then, voltage is reducedslowlyinsteps.Theradionoisegeneratedbytheinsulatorstringisobserved. Threesuch cycles are repeated, and RIV in dB (above 1 mV) at different voltages is recorded for four insulator strings. The experiments were repeated at least five times to check for repeatability.

CurrentMeasurements

The corona current in principle is measurable at two ends of the string i.e. from high voltage end and from ground end. Of course, for very accurate measurements, optical link between measuring system and the oscilloscope would be essential. At present, due to the non-availability of such a system at our laboratory, conventional method is only employed. The current is indirectly sensed by measuring the voltage across a 50 Ω resistor connected at the ground end. It applies to both the ground end lead of insulator string, as well as, the input to RIV.meter as indicated in the figure. However, for safety purpose, in the ground end lead of insulator string a high resistance 5 kΩ is also inserted. However, before proceeding further on measurement, the following needs to be discussed.

The corona current pulses are known to have short front durations measured in 10s of ns. As a consequence, their propagation characteristics would be more like waves on antenna rather than classical circuit domain pulses and further, their propagation is not governed by the applied voltages. A very similar situation prevails with the measurement of partial discharge pulses in high voltage power apparatus and cables. Therefore, the quantity measured at any given point on the circuit need not be and will not be the actual corona current pulse generated at the source. Nevertheless, owing to the linearity of the system for such pulses, measured current should be directly related to the corona pulse at the generation point.

Amongst the two possible current measurement points, the investigation is started with measuring the current at the input to RIV meter. The reasons for the same are as follows. Firstly, the reference value as per prevailing standards, the RIV measurement as per the prescribedcircuit is the testing method and therefore, the current coupled through the RIV coupling capacitor governs the test result. Therefore, it would be prudent first to consider this current and study whether intended identification of coronating source could be carriedout. Secondly, as mentioned before, the corona pulse will propagate on ground lead in an antenna mode and hence several reflections and attenuation can be expected in the path of the ground lead which has several bends and runs along supporting steel frame. It will therefore be quite involved to correlate the signal strength at the RIV input. Considering these, first the input to the RIV meter itself is considered for its characteristics.

INTERNATIONALANDINDIANSTANDARDSDCTESTINGTESTVOLTAGE

Fordifferenttransmissionvoltages,thetestvoltagesrequiredaregiveninthefollowing

Tables:

Table5.2

Testvoltagesfora.cequipments

Systemvoltage Kv(rms)	Power Frequency TestVoltage Kv(rms)	ImpulseTest voltage Kv(peak)	Switchingstage withstand voltage
400	520	1425	875
525	670	1800	1100
765	960	2300	1350
1100	1416	2800	1800
1500	1920	3500	2200

Table5.3

Testvoltagesford.cequipments

Normalvoltage	D.CWithstand Voltage	ImpulseTestvoltage Kv	Switchingstage withstand voltage Kv
±400	800	1350	1000
±600	1200	1900	1500
±800	1600	2300	1500

Table5.4

Testvoltagesrequiredfordifferentd.c.systemvoltages

Normalvoltage	D.CVoltagekv	ImpulseTest voltageKv	Switchingstage withstandvoltageKv
±400	800	1750	1300
±600	1200	2500	2000

±800	1600	3000	2600

Table5.5

Approximatedimensionsof thetesting equipmentand theequipment tobetested

Normalvoltage (rms)	ACtransformer height(m)	Impulsegenerator height(m)	Dimensionoftest object
400	10	6	7×2×11
765	15	8	11×2×17
1100	18	12	17×2×24
1500	22	15	28×2×28

Table 5.6

InternationalandIndianstandards

Location	Dimension	Power frequency	ImpulseTest voltageKv	Switching surgevoltage
		Voltagekv		Mv
Australia BharatHeavy Elect, Bhopal, India	67×35×35	1.5	8.0	–
CESI-Milan, Italy	150×75×55	1.5 2.3	3.6 4.8 (200KJ)	2.0 3.0
Collegeof Engineering Guindy, madras	25×15×15	0.3	1.2	–
Collegeof Engineering Jabalpur(MP)	33×26×30	0.5	1.4 (16KJ)	–
CollegeOf Engineering	20×12×8	0.5	1.4 (16KJ)	–

Kakinda,AP				
ElectricityDC France	65×65×45	2.5	7.2 (1010KJ)	6.0
Hydro-Quebec Montreal,	82×68×50	2.5	6.4 (400KJ)	6.0
Canada IndianInstt.of Technology	37.5×25×19	1.05	3.0 (50KJ)	1.6
Bangalore IndianInstt.of Technology	28×10×9.7	0.80	1.5 (36KJ)	--
Madras	115×80×60	3.0	8.0	--
Russia Technical	32×25×21	1.2	3.2	--

InsulationCoordination

Insulation Coordination is defined by the values of test voltages which the insulation of equipment under test must be able to withstand. In the earlier days of electric power, insulation levels commonly used were established on the basis of experience gained by utilities. As laboratory techniques improved, so that different laboratories were in closer agreement on test results, an international joint committee, the Nema-Nela Committee on InsulationCoordination, was formed and was charged with the task of establishing insulation strength of all classes of equipment and to establish levels for various voltage classification. In 1941 a detailed document18 was published giving basic insulation levels for all equipment inoperation at that time. The presented tests included standard impulse voltages and one-minute power frequency tests.

In today‘s systems for voltages up to 245 kV the tests are still limited to lightning impulses and one-minute power frequency tests, see section 5.3.Above 300 kV, in addition to lightning impulse and the one-minute power frequency tests, tests include the use of switching impulsevoltages.Tables5.2and5.3listthestandardizedtestvoltagesfor245kVandabove ½300 kV respectively, suggested by IEC for testing equipment. These tables are based on a 1992 draft of the IEC document on insulation coordination.

Table5.7Standard insulationlevelsforRange II(Um >245kV)(From IECdocument 28

CO58, 1992,InsulationcoordinationPart 1:definitions,principlesandrules)

Highest	Longitudinal	Standard	Phaseto phase	Standard

Voltagefor equipmentU_m KV (rmsValue)	**Insulation (+)KV PeakValue**	**lighting withstand voltagephase toearthvalue (PeakValue)**	**(ratiotophase toearthpeak value)**	**lighting withstand voltage (PeakValue)**
300	750	750	1.50	850 950
362	750	850	1.50	950 1050
420	850	850	1.50	950 1050
	850	950	1.50	1050 1175
	850	850	1.60	1050 1175
525	950	950	1.50	1175 1300
	950	1050	1.50	1300 1425
	950	950	1.70	1425 1425
	950	1050	1.60	1550 1800
	950	1175	1.50	1675 1800
	950	1300	1.70	1800 1425
765	1175	1425	1.60	1675 1800
	1175	1550	1.70	1800

	1175	1425	1.60	1950 1950 2100

Statisticalapproachtoinsulationcoordination

In the early days insulation levels for lightning surges were determined by evaluatingthe 50 per cent flashover values (BIL) for all insulations and providing a sufficiently high withstand level that all insulations would withstand. For those values a volt–time characteristic was constructed. Similarly the protection levels provided by protective devices were determined. The upper curve represents the common BIL for all insulations present, while the lower represents the protective voltage level provided by the protective devices. The difference between the two curves provides the safety margin for the insulation system. Thus the Protection ratio=Max. Voltage it permits/Max.

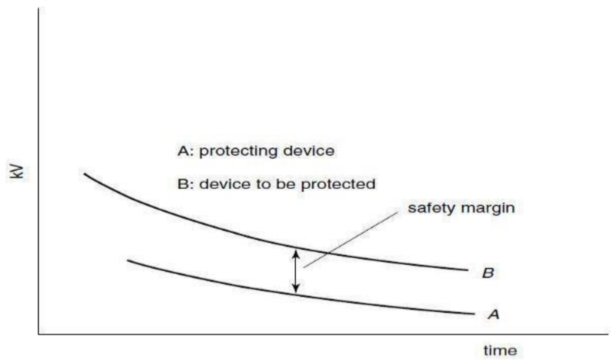


Figure:5.16CoordinationofBILsandprotectionlevels(classicalapproach)

This approach is difficult to apply at e.h.v. and u.h.v. levels, particularly for external insulations. Present-day practices of insulation coordination rely on a statistical approach which relates directly the electrical stress and the electrical strength. This approach requires knowledge of the distribution of both the anticipated stresses and the electrical strengths. The statistical nature of over voltages, in particular switching over voltages, makes it necessary to compute a large number of over voltages in order to determine with some degree of confidence the statistical over voltages on a system. The e.h.v. and u.h.v. systems employ a number of non-linear elements, but with today's availability of digital computers the distribution of overvoltages can be calculated. A more practical approach to determine the required probability distributions of a system's over voltages employs a comprehensive systems simulator, the older types using analogue units, while the newer.

Employrealtimedigitalsimulators(RTDS).Forthepurposeofcoordinatingtheelectrical stresses with electrical strengths it is convenient to represent the overvoltage distribution in the form of probability density function (Gaussian distribution curve as shown in Figure) and the insulation breakdown probability by the cumulative distribution function. The knowledge of these distributions enables us to determine the _risk of failure‘. If Va is the average value of overvoltage, Vk is the kth value of over voltage, the probability of occurrence of overvoltage is p0Vk du, where as the probability of breakdown is PbVkor the probability that the gap willbreak down at an overvoltage Vk is PbVkp0Vk du. For the total voltage range we obtain for the total probability of failure or _risk of failure‘.

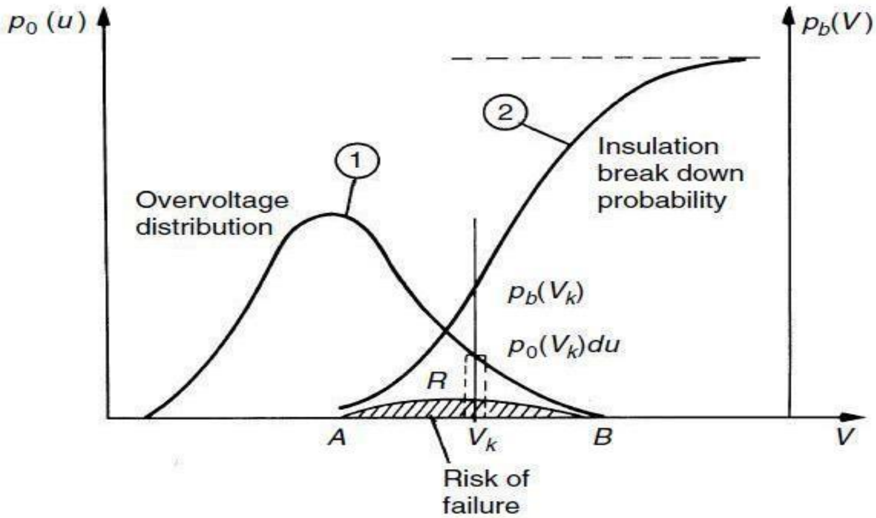


Figure:5.17Method ofdescribingtheriskoffailure.

1. overvoltagedistribution–Gaussianfunction.2.Insulationbreakdownprobability–cumulative distribution)

$$R = \int_0^\infty Pb(Vk)P0(Vk)du$$

Theriskoffailurewillthusbegivenbytheshadedareaunderthecurve R. In engineering practice it would become uneconomical to use the complete distribution functions for the occurrence of overvoltage and for the withstand of insulation and a compromise solution is accepted as shown in Figs 5.18 (a) and (b) for guidance. Curve (a) represents probability of occurrence of over voltages of such amplitude Vsthat only 2 per cent (shaded area) has a chance to cause breakdown. VS are known as the _statistical overvoltage‘. In Fig. 5.18(b) the voltage Vw is so low that in 90 per cent of applied impulses, breakdown does not occur and such voltage is known as the _statistical withstand voltage‘ Vw.

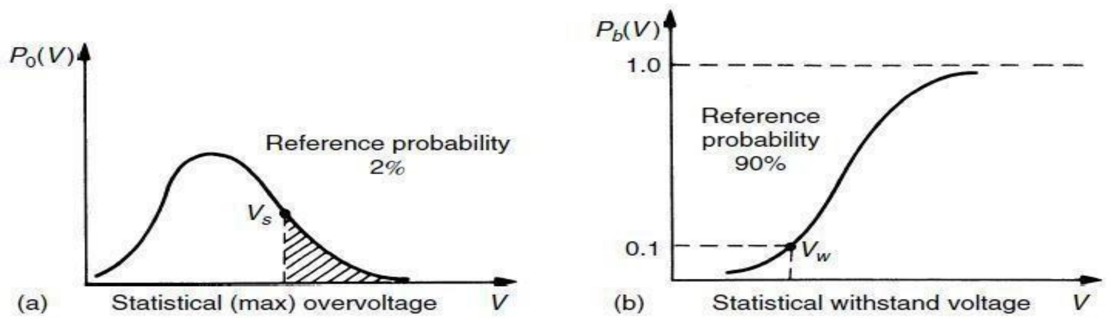


Figure:5.18Referenceprobabilities forovervoltageand forinsulationwithstand strength

In addition to the parameters statistical overvoltage _VS‘ and the statistical withstand voltage _VW‘ we may introduce the concept of statistical safety factor 4. This parameter becomes readily understood by inspecting Figs 5.19(a) to (c) in which the functions Pb V and p0Vk are plotted for three different cases of insulation strength but keeping the distribution of overvoltage occurrence the same. The density function p0Vkis the same in (a) to (c) and the cumulative function giving the yet undetermined withstand voltage is gradually shifted along the V-axis towards high values of V.

$$\frac{Vw}{Vs} = \gamma$$

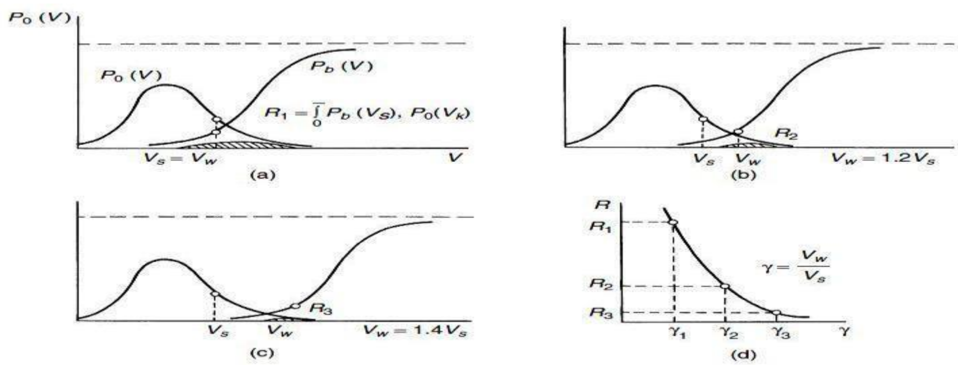


Figure:5.19Thestatistical safetyfactor and itsrelationto theriskoffailure

Thiscorrespondstoincreasingtheinsulationstrengthbyeitherusingthickerinsulationor material of higher insulation strength. As a result of the relative shift of the two curves [PbV and p0Vk] the ratio of the values Vw/Vs will vary. This ratio is known as the statistical safety factor.

CorrelationbetweenInsulationandProtection Levels

The_protectionlevel‘providedby(say)arresters isestablishedin asimilarmannertothe insulation level‘; the basic difference is that the insulation of protective devices (arresters) must not withstand the applied voltage. The concept of correlation between insulation and protection levels can be readily understood by considering a simple example of an insulator string being protected by a spark gap, the spark gap (of lower breakdown strength)protecting the insulator string. Let us assume that both gaps are subjected to the same overvoltage represented by the probability density function p0V,Fig. 5.20. The statistical electrical withstand strength of the insulator string is given by a curve identical to Fig. 5.19 The probability of breakdown of this insulation remains in the area R which gives _risk of failure‘. Since the string is protected by a spark gap of withstand probability.

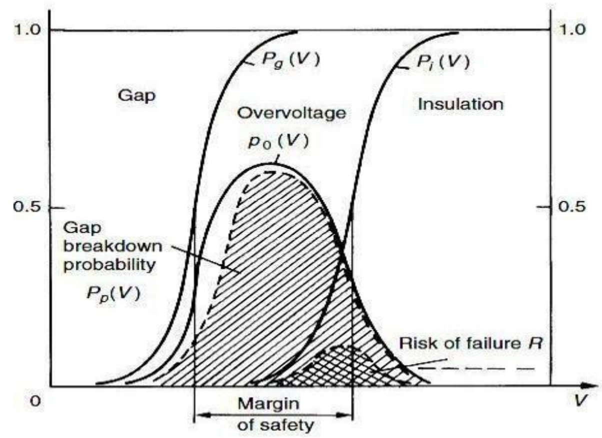


Figure:5.20Distributionfunctionsofbreakdown voltagesforprotectivegapandprotected insulationbothsubjectedtoan overvoltagep0 V

PgV, the probability that the gap will operate (its risk of failure) is obtained from integratingtheproductPgVp0VdV. InFig.5.11thisprobabilityisdenoted(qualitatively)byPPV. As is seen the probability is much higher than the probability of insulation damage or failure R. In the same figure is shown the traditional margin of safety corresponding to the voltage.