Previous Page

insulator shed in which the porcelain is loaded largely in compression. A typical pin-type insulator is shown in Figure 5.1*a*. The sketches show that the top of the porcelain body is formed into a groove into which the conductor is bound by means of wire or fixed with the aid of special clips. Toughened glass pin-type insulators require a metal cap; this holds together the 'diced' pieces of glass which result if the glass becomes shattered.

For increased working voltages, the number of 'sheds' of the insulator unit are increased, additional sheds being jointed together by means of portland cement/sand mortars.

For system voltages above about 33kV, pin-type insulators become quite large and unwieldy devices. For 33 kV systems a creepage distance of about 650 mm will be required for reasonably clean areas. Accordingly, above about 33kV cap and pin insulators or line post insulators are usually employed. A typical so called 'trident' wood pole 132 kV line is shown in Figure 5.3. using line post insulators. An upper limit for systems insulated with the line post units is about 150kV with present day practice.

5.6.3 Cap and pin insulators

The name 'cap and pin' insulator is given because the insulators are fitted with a 'bell' shaped galvanised, malleable cast iron or forged steel cap and galvanised forged steel pin. The dielectric material can be of toughened glass or porcelain. With both porcelain and glass the shed is formed to produce a smooth upper surface and generally a ribbed lower surface to maximise the creepage path. Typical cross-sections of cap and pin insulators are shown in Figure 5.2.

The load bearing section of the dielectric must be carefully dimensioned to ensure that the material is correctly stressed electrically and mechanically. This is because both toughened glass and porcelain are brittle materials with comparatively limited tensile strengths. The load-bearing portion of the dielectric is designed to ensure that any tensile load applied between the cap and the pin is transferred from the load bearing cone of the pin to the re-entrant bell mouth of the cap, through the cement so that the dielectric is loaded largely in compression, the compressive strength of porcelain and toughened glass being about 10 times the tensile strength.

In the event of the dielectric being destroyed, perhaps due to rifle fire, resulting in the skirt being completely broken away, the mechanical security of the broken insulator is assured by the design of the metal fittings.

Generally, a correctly designed cap and pin insulator will, in clean nonpolluted areas, provide a satisfactory service life of at least 25 years. It is worth noting that there are many cap and pin insulator units which are still in service after 50 years in nonpolluted areas. In regions with high levels of marine or industrial/chemical pollution, however, the galvanised coating of the metal fittings is often quickly degraded and, if the pollution is severe, the 'tell-tale' sign of rust can become visible after five or six years in service. There are instances where insulator pins have been so severely attacked by corrosion that the original pin diameter of 16 mm has reduced to 7 mm, resulting in a severe loss of mechanical strength.

In recent years, this type of attack has been largely eliminated by means of zinc collars alloyed to the galvanizing coating of the insulator pin. The collar is arranged to intercept any leakage currents which pass over the insulator surface and terminate at the pin near to the cement surface. By this means it is possible to protect the 'pin' from the corrosive effects of leakage currents for 10 or 12 years even in severely polluted areas.

5.6.4 Dielectric materials

5.6.4.1 Porcelain

The material used to manufacture electrical porcelain is usually a combination of ball clay, china clay, quartz, alumina and various flux materials, for example feldspar. The constituents are crushed and mixed together with water to form a suspension. The clay suspension, known as slip, is then pumped to a de-watering press where the water content is reduced to about 20% by volume, resulting in the formation of a plastic clay cake. The air is then removed by means of a vacuum process in a pug mill from which the clay is extruded in a plastic state. The soft clay body can then be pressed or turned to form the insulator shape; this is then dried to enable the shaped body to be handled without distortion.

The clay form is then dipped into a glaze (a suspension in water of metallic earth elements and clays), and subsequently fired in a gas or oil fired kiln where the temperature is slowly raised to about 1200 °C and then carefully cooled to room temperature. During firing, the clay materials are converted to form a glassy matrix with a dielectric strength of about 200kV/cm with a dielectric constant of approximately 5. The porcelain matrix has a coefficient of thermal expansion of about 4×10^{-1} K^{-1} and a volume resistivity at 20 °C of 10^{12} ohm.

After firing, metal fittings are fixed by means of a cement mortar. When the cement mortar is cured, the insulator is subjected to a routine mechanical test load of 40 or 50% of the guaranteed minimum failing load (MFL) for 10s. Finally, the complete insulator is subjected to a flashover test for 5 min at a voltage equal to the dry flashover voltage of the insulator.

5.6.4.2 Toughened glass

Glass insulators are most usually made from soda-lime-silica glass. The crushed raw material being melted in a furnace called a 'tank' in which the temperature of the raw material is raised to about 1250 °C. The molten glass slowly flows through the tank and is fed in 'tear' shaped blobs of constant weight into steel moulds where the viscous glass is moulded to shape. If at this stage in the manufacturing process the glass is allowed to cool slowly an annealed glass will form. This type of glass, like window glass, can easily be cracked. However, if the hot, shaped insulator shed is cooled rapidly by blowing cold compressed air onto the surface of the glass, the material becomes toughened.

This process arises because the outer surface of the glass chills and becomes solid but the inside of the glass remains molten and cools more slowly. The result is that the outer layer of the glass goes into compression and the inner layer goes into tension. The toughening process provides a mechanically strong material with a dielectric strength of some 1350 kV/cm, a dielectric constant of 7.0, resistivity at 20 °C of 10^{12} ohm and a coefficient of expansion of 8.5×10^{-6} K^{-1} similar to that of the ferrous fitting which is approximately 11.5×10^{-6} K^{-1}.

Assembly with metal end fittings uses similar methods to those employed with porcelain insulators, although high alumina cement is usually employed for the assembly. Toughened glass, however, has a unique property which is that if the shed is in one piece the disc must be electrically sound. There is no need therefore to carry out routine electrical tests on toughened glass insulators; only routine mechanical tests are required.

The unique feature of toughened glass is used to advantage in service since, if the glass shed of an insulator can be 'seen', the electrical properties of the disc are good. Toughened glass insulators can therefore be examined from a distance and seen to be electrically sound. Toughened glass insulators are more resistant to the melting effects of high power fault currents than porcelain insulators. Generally, for equivalent mechanical ratings, toughened glass units are lighter than porcelain. However, toughened glass insulators are much more susceptible to surface damage resulting from the effects of leakage currents which develop in service in polluted conditions. Damage by leakage currents results in melting of the glass surface and the formation of small molten channels of glass which, when these become sufficiently deep, cause the glass to shatter.

Test methods for toughened glass and porcelain insulators are defined in IEC60383-1 [10].

Traditionally the dielectric strength of insulators has been checked by the Puncture Oil Test. A more representative test has recently been introduced. This test uses steep fronted impulse voltage waves, similar in form to the waves the insulator may experience during a lightning storm. The tests for toughened glass and porcelain insulators are described in [11].

5.6.5 Long rod insulators

Long rod insulators are generally manufactured from high alumina porcelain, but some are marketed which are formed from boro-silicate annealed glass. A recent survey showed that 86% of all insulators covered by the survey were of the cap and pin type and 14% were of the porcelain long rod type.

With long rod insulators the tensile service load is supported entirely by the core of the porcelain. Because of the brittle nature of the porcelain, considerable effort is spent on quality control during the manufacture of long rods. The quality control procedures employ ultrasonic crack detection equipment, both before and after routine mechanical tests during which the units are loaded to about 80% of their guaranteed minimum failing load. By means of the stringent quality control, faults are largely eliminated from these insulators. However, when accidental damage is sustained by long rod insulators the results, due to the brittle cracking of the core, are usually catastrophic.

5.6.6 Composite insulators

Composite insulators have been under development for more than 40 years and are being introduced into line service in increasing quantities, notably in the USA at transmission voltages. In the UK, although some composite units have been fitted to transmission lines, the majority of recently installed composite insulators have fitted to distribution lines at 11 and 33 kV. Increasing amounts of service experience with composite insulators, some of which have been in service for more than 16 years, are being gained.

As stated earlier the composite insulator is based on a load bearing resin bonded glass fibre core fitted into cylindrical metal, aluminium alloy or galvanised steel end fittings. Typically, a 50 mm diameter core will have a minimum failing load of about 500kN. To protect the core from attack by leakage currents and to provide an extended creepage path, the cores are surrounded by weather sheds. These may be cast as one piece onto the core or as separate weather sheds which, after bonding, are effectively vulcanised to form a homogeneous insulating unit.

It is in the study of weather shed materials that most development effort has been concentrated. Early insulators utilised polysulphide rubber. Later, ethylene propylene dimethyl monomer (EPDM) and other monomers and polymers were used. Most of these suffered serious damage by attack from the ultraviolet content of sunlight. The attack caused the surface to lose the shiny finish produced during manufacture and become rough, which allowed pollution materials to build up. The rough surface results in the increase in the magnitude of leakage currents and when sufficient energy is available in the leakage current, the surface melts. The early materials were generally organic compounds and rapidly the surface became carbonised as a result of the leakage currents.

Considerable improvements have been made recently by the use of silicone rubber compounds. These compounds, when formed into weather sheds, are hydrophobic. As a result they cause any rain-water to form into discrete droplets so that continuous wetted areas do not form. Accordingly, leakage currents are kept to low levels and good pollution performances are achieved with silicone rubber, certainly for the first 8 to 10 years of service life. It is found that the particles of pollution deposited on the weather shed also become impregnated with silicone exuded by the silicone compound. Hence the pollution itself becomes hydrophobic together with the surface of the weather shed. The hydrophobicity can be lost by the action of intense surface discharge activity. When the discharge activity stops, the surface and pollution particles recover their hydrophobic properties over a period of about 24 h. It is for this reason that prudent line designers would specify creepage path lengths equivalent to those used presently for the toughened glass or porcelain insulation. By this action, the level of discharge activity under heavy rain and pollution conditions is minimised.

Composite insulators are lighter in weight than the equivalent glass or porcelain insulators. At present, however, it is necessary to estimate the likely strength reduction which will occur with composite insulators in service using the methods described in [12, 13] since service life experience is limited to about 16 years.

In service care must be given to protecting the end fittings of composite insulators from the melting effects of power arc currents. If an arc is allowed to root on the end fitting of a composite unit, adjacent to the polymeric coating, the heat of the arc is likely to cause sufficient damage to allow water ingress. This will result in failure of the unit and the unit should be replaced. Accordingly all composite insulators should be fitted with carefully designed arc protection devices.

5.6.7 *Insulator sets*

5.6.7.1 *General description*

The line conductor is supported from the tower by means of an insulator set, the name given to the string of insulators, associated clamps, fittings and frequently arcing horns or grading rings. The number of insulator units in the string is determined by the clearance requirements demanded by the lightning flashover performance and, with systems above about 220 kV, the required switching impulse performance requirements. The numbers and types of insulator are also fixed by the creepage path requirements necessary to cater for the likely pollution levels. Finally, the mechanical strength of the insulator set is established by the everyday load and overload which the conductors will apply to the insulator set.

Insulator sets are of two basic types. The first, nominated a suspension set, is so called because the insulator set is suspended from the tower cross arm and the conductor is suspended from the clamp at the lower end of the set. The simple suspension set is free to swing from the cross arm transversely or longitudinally to the line route. The second basic type of insulator is called the tension set since the full line conductor tension is supported axially by this set.

Methods of testing insulator sets are described in [14].

The shape of the insulator unit selected depends largely on the type of pollution to which the line will be exposed. With normal relatively low levels of pollution requiring Class I creepage nominated in BS 137, i.e. 20 mm/kV of system highest voltage, the normal or plane-shedded insulator is employed. This type of insulator has comparatively small ribs on the under surface. Further recommendations for creepage path requirements are given in [15].

If the line is to be constructed in an area where significant amounts of salt spray or heavy fog are likely to occur then an anti-fog insulator is usually selected. This type of insulator has deep 'anti-fog' ribs to enhance the creepage path.

In desert situations, an open profile or aerodynamic insulator is often employed. This type of insulator is basically a flat disc, generally with no ribs on the underside. To achieve the appropriate amount of creepage the diameter of these units is greater than that of standard insulators. The open profile insulator operates successfully in the desert because the wind, which usually supports dust and salts (frequently sodium chloride), passes by the insulator with little disturbance. In dusty situations, eddies would form around the ribs of conventional insulators and the change in velocity of the air stream would cause the deposition of polluting particles onto the insulator ribs. The rate of disposition can be quite high and this can result in the insulator becoming heavily polluted, which results in the increased probability of flashover.

5.6.7.2 The effects of lightning

When lightning strikes an overhead line, the voltage at the struck point rapidly rises, and surges in the form of travelling waves progress rapidly along the conductor away from the struck point to a region where the clearance to earth is sufficiently low to allow the air between conductor and earth to become totally ionised allowing a flashover to develop. Usually, the location with minimum clearance is at an insulator set. To ensure that a preferential path between conductor and earth exists, arc horns are fitted to the insulator sets. The arc gaps are arranged to be to the side of suspension sets and above tension sets. The length of the arc gap is less than the dry arcing distance of the insulator string. Thus, when as a result of a lightning induced surge an arc gap becomes ionised, a sparkover to earth will result. The spark will be fed by the power frequency energy of the line and the result will be a power frequency arc which will 'run' safely between the arc-horn tips away from the insulator units until the line protection trips.

The energy of a power-follow-through arc is considerable and it is necessary to design the arc-horns and associated metalwork to have sufficient cross-sectional area to withstand the heating effects of the arc.

5.6.7.3 The effects of switching surges

During switching operations surges can be generated, and in spite of special arrangements for suppression, surges of 1.7 times the system voltage can occur. The surges can cause flashover, and the preferred paths for these will be across arc gaps. Power-follow-through arcs will generally develop and arc gaps are therefore required to provide the same protection as is afforded to the insulator set during lightning impulse flashovers. Tests to determine the effect of power arcs on insulator sets are described in [16].

5.6.7.4 Voltage distribution across an insulator string

In service, the transmission voltage shared across each unit of an insulator string is not uniform. Unless special precautions are taken, up to 15% of the line voltage will be developed across the line-end insulator and the voltage across each of the remainder of the insulators will progressively decrease towards the earth end of the string. The voltage is shared in relationship to the self-capacitance of each insulator unit and the stay capacitance of each insulator to earth.

The voltage sharing can however be significantly improved by specially designing the arc-horns to serve the purpose of voltage grading rings. With well-designed grading rings the line-end unit may be found to support only 8 or 9% of the phase voltage, resulting in significant improvements in the RIV performance of the insulator set.

5.7 Electrical discharges

5.7.1 Radio interference

Transmission lines sometimes produce radio interference often heard as the crackling, buzzing noise on a car radio when a car passes beneath a power distribution or transmission line. Radio interference (RI) is essentially a random radio signal radiated from some source. Depending on the relative strengths of the broadcast signal and the interfering noise, the signal to noise ratio (SNR) – or perhaps more accurately defined as the 'protection ratio' – varies from being a minor annoyance to a level which results in the total blotting out of a radio station. RI can have serious consequences if essential services involving air or marine radio navigation equipment are affected. Equally, power line carrier (PLC) equipment which generally operates at frequencies of 50 kHz to a few 100 kHz must not be affected by RI.

The main source of RI radiated by overhead lines are corona discharges formed on the conductor, hardware or insulators. Corona discharges form when the electric field intensity exceeds the breakdown strength of air and localised ionisation of the air occurs. There are a number of factors which affect the voltage at which corona forms, including the air density, the air humidity, the amount of photo-ionisation and to a limited degree the material of the electrode.

Corona will form when an electrode is charged to a sufficiently high voltage from a power frequency voltage source. The mechanism of corona production is different for each half-cycle of voltage. The negative half-cycle tends to produce short duration pulses of current up to perhaps 1 mA in magnitude lasting for about 0.03 μs. The radio noise generated by a negatively charged electrode tends to be of a low level compared to the noise generated by a positively charged electrode.

With an electrode charged with a low positive voltage, but which is sufficiently high to cause the formation of corona, a low level of steady corona forms giving very little radio noise. When the voltage is raised the radio interference voltage (RIV) becomes much greater and is usually about 100 times as high as the noise produced during the negative half-cycle. Positive current pulses have a much longer duration than the negative pulses, positive pulses lasting up to 0.5μs. This corona produces a frequency spectrum shown in Figure 5.12.

The value of E, the surface gradient at which corona forms on a cylindrical conductor is determined from the relationship established by Peek:

$$E = 30\,\rho m\left[1 + \frac{0.0301}{\sqrt{r}}\right]$$

where ρ = air density
m = roughness or stranding factor
r = radius of the conductor (cm)
E = surface gradient (kVpk/cm).

Air density can be seen to affect the corona starting voltage. The higher the density, the higher the corona starting voltage in the range of normal atmospheric pressures which we consider.

Water vapour is electro-negative, that is, it will absorb free electrons

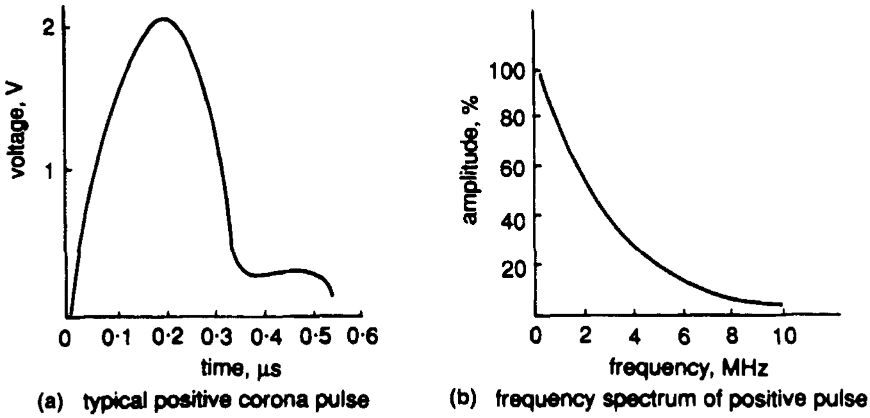

Figure 5.12 Details of positive corona pulse **(a)** *and* **(b)**

and thus tends to inhibit the formation of corona pulses. Therefore, a high humidity atmosphere tends to provide an improved RIV performance for insulator sets. However, when water condenses to form droplets, or when drops resulting from rain attach to the conductor, corona forms on these water drops because the surface voltage gradient is increased by the water droplet and RIV is generated and power loss due to corona increases.

Although corona is the main source of RIV generated by an overhead line, RIV can often be generated by small sparks developing across very small gaps. These gaps may be caused by poor electrical contacts between, for example, metal fittings of an insulator as shown in Figure 5.13.

This type of breakdown generates very high frequency noise in the region 10 to 200 or 300 MHz. Contact-generated radio noise is much more prevalent in dry weather because during rainfall the small spark gaps caused by the poor contacts are 'shorted out' by the conducting electrolytes formed from the rain-water and dissolved salts.

Contact gap generated noise can usually be avoided by ensuring that there is sufficient mechanical load on the insulator sets to break down the insulating oxides or carbonates which form at the contact surfaces of the metallic ball and socket fittings. It is also possible to eliminate the noise source by coating the contact surface with conducting grease which inhibits the formation of sparks across the otherwise poor contact area.

The insulators of an insulator set can also give rise to radio interference. Generally, the noise produced by cap and pin insulators is caused because the surface voltage gradient exceeds the breakdown strength of the air surrounding the insulator. Proper design of the insulator can improve the RIV performance of the insulator by careful improvement in the shape of the electrodes (the caps and pins) and careful quality control

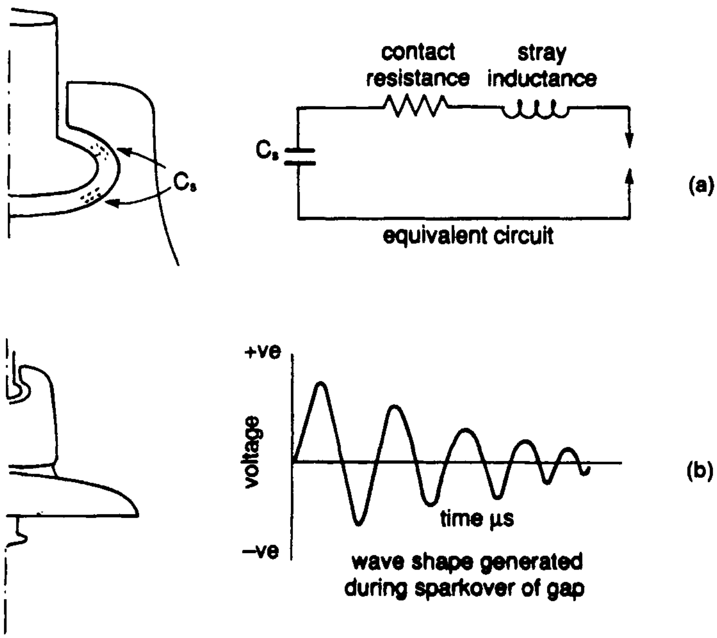

Figure 5.13 *Source of 'contact' generated RIV* **(a)** *and wave shape of the RIV* **(b)**

of the level and surface finish of the cement used to fix the metal parts to the dielectric weather shed.

The surface resistance of an insulator has a very significant effect on the RIV generated by an insulator. Glass adsorbs moisture from the atmosphere and adsorbed moisture collected in the surface molecules of the insulator may well improve the RIV performance of an insulator by tending to improve the voltage grading around the insulator. It is therefore essential before commencing any RIV tests to allow an insulator to stabilise to the humidity of the atmosphere in which the test will be carried out. A period of about 24 h should be allowed for proper stabilisation. In addition, during testing the insulator units should not be exposed to the humidity of the exhaled breath of the test operator.

We have briefly considered how corona discharges and small sparks cause radio noise. We should therefore examine how the levels of radio noise are measured. RI is heard as a buzzing crackle or click in a radio loudspeaker. At low distribution voltages, and even up to system voltages of 66 kV, with normal conductor sizes, the conductor operating stress is very low, about 6 or 7 kV RMS cm^{-1}. As a result, corona and RIV does not occur. The only sources of RIV at these low voltages are the insulators, bindings and stirrups or extraneous debris, for example short pieces of wire which might be thrown onto the conductor.

As 132 kV was replaced by 275 kV in the 1950s, people began to consider more seriously the problem of RIV, although in the United Kingdom at that time only a corona test was specified for 275 kV insulator tests. Nevertheless, the corona discharge was recognised as a potential source of power loss as well as being likely to give rise to difficulties with the operation of PLC and production of RI.

A typical RIV measuring circuit is shown in Figure 5.14.

The RIV measuring circuits and equipment currently used to determine the RIV performance of line hardware and insulator sets are defined by a number of National and International standards [17–20].

As radio and TV signal wavelengths have been progressively reduced and with the much more frequent use of frequency modulated (FM) signals and digital systems, problems caused by RIV are tending to lessen. In addition, the signal strength measured at the receiver resulting from the more general use of local radio stations is generally higher. Radio interference, in spite of increases in system voltages, is therefore becoming less of a problem. Nevertheless, any corona generated by the line represents a power loss and because energy costs continue to rise, the corona loss must be kept to economically low levels. Consideration must also be given to avoiding annoyance to the public by the audible noise generated by corona.

During the design of an overhead transmission line, the acceptable RIV level which can be generated by the line is established taking into account the signal strengths of the local radio transmission signals and the density of population living near to the proposed line route. A typical calculation of the RIV level likely to be generated by a 500 kV transmission line is included as Appendix 5.5.

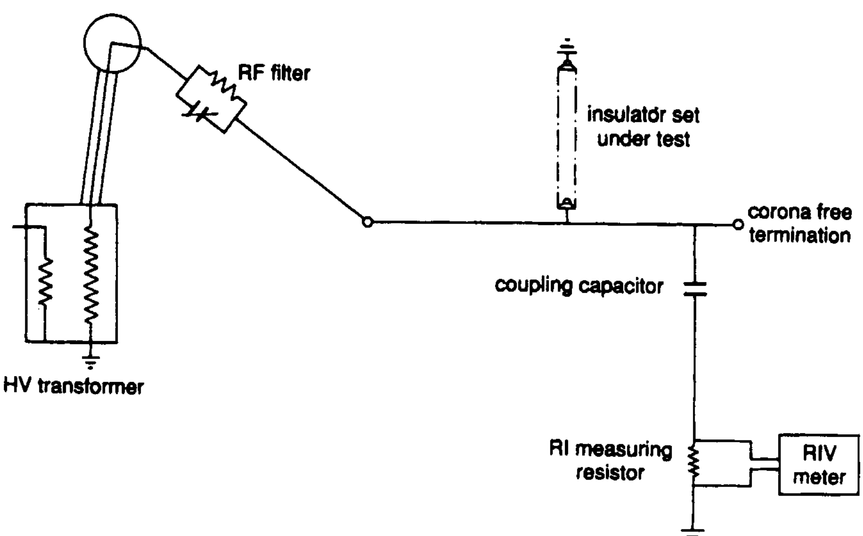

Figure 5.14 RIV measuring circuit

5.7.2 Corona loss

Consideration is also given to the likely corona loss from a transmission line during the design of the line. Generally, if the line is designed to have a good RIV performance, the corona loss from the line will be relatively low in dry weather. Under rainfall or in the period following rain when water droplets are still present on the conductors, losses of some tens of MW occur with 500 kV systems due to corona. A typical calculation of corona loss from a transmission line is given in Appendix 5.6 employing the method established by V.V. Burgsdorf [21].

5.8 Line construction

5.8.1 General

At the inception of an overhead line project, as part of the feasibility study, the location of the load centres both present and projected, together with present and future generation sources, will be established. The required transfer capacity of the line will then be known and the type of construction fixed. The economic study of the line design will have established the optimum span length and tower heights to provide proper ground clearance from the line conductor to satisfy the local ground clearance requirements. In most parts of the world the electricity supply authority or utility will have a schedule of mandatory ground clearances for the range of transmission voltage in use.

5.8.2 Route selection

Initially, the available maps covering the line route are obtained and a straight line between the line terminals drawn on the overall planning map. A convenient scale for use for a line 200 km or more in length is 1:250 000. The major topographical features of the regions crossed by the route should then be considered; for example, areas with major access problems or regions with known areas of bad or poor quality ground should not be crossed if excessive foundation prices are to be avoided. Areas of outstanding natural beauty should also be considered. It may be necessary to avoid crossing areas with particular types of vegetation.

Other features crossed by the route must be considered, for example airports, major highways, pipelines, the lines of sight between microwave aerials and river crossings. The proximity of sea coasts or major isolated sources of industrial pollution must also be considered.

It will be necessary at this stage of the route selection to discuss the proposed route with town and country planners and other major planning authorities, for example highway planners, post and telephone, civil and military aviation authorities to ensure that the line would not cause obstruction or require to be re-routed as other developments take place along the route.

Bearing in mind the various points mentioned above, a preliminary line route can be established and transferred to 1:50 000 scale maps if these are available. If the maps are reasonably up to date it may be possible to establish the route with sufficient accuracy to hand over to the overhead line contractor at the start of the contract. However, in many parts of the world where line of sight access is limited, perhaps because of dense vegetation or where towns and villages are developing rapidly, it is sometimes useful after the proposed route has been marked on the 1 : 50 000 scale maps to carry out an aerial photographic exercise. A photomosaic strip map, about 1 km wide, of the proposed line route is produced. Careful examination of the photomosaics will allow existing maps to be updated with the minimum of disturbance to the local landowners.

A complete aerial survey of the line route can also be made, locating angle points and other features of special interest by means of satellite signals and Global Positioning Systems (GPS) to produce the necessary accuracy, particularly in areas of dense vegetation. The aerial survey is followed by a ground survey which allows close inspection of soil and geology of the area crossed.

5.8.3 Basic span

The economic span was referred to in Section 5.2.5.2. It is determined by calculating the effect the span length has on the installed cost of the line. If a short span is selected then short towers can be employed and foundation loads are minimised. There are, however, more towers per km and more insulator sets and hardware. If a long span is considered then increased tower lengths will be necessary to provide proper ground clearance to cater for the increased conductor sag. The number of insulator sets per km will be reduced but the working load of the insulator sets will be increased and may become critical. Further, conductor working tension at everyday temperature must be limited to about 20% of conductor failing load to avoid problems with vibration.

The economic span can therefore be established by calculation by allocating costs to the various components. The optimum span established is sometimes referred to as the basic span. The length of the basic span fixes the distance between suspension tower centres in level ground to provide the correct clearance to ground. Because lines are frequently constructed in undulating ground it is necessary to cater for uneven ground. Similarly, it may be necessary to site towers in particular locations to avoid rivers or roads etc. Accordingly, for reasons of economy, it becomes necessary to provide towers with a range of increased heights.

Usually, this is done by providing extended heights in steps of 3 m. In addition, for areas where short spans will be used, towers with 'minus' heights are provided. Further consideration should be given to towers to be constructed on sloping sites and towers with a range of individual leg extensions are designed.

5.8.4 Line route profile

Having established the range of tower heights to provide the correct ground clearance for the various ground levels and span lengths it is next necessary to establish a convenient method of drawing a profile or cross-section of the line. In Section 5.3.4 we stated that the conductors in a section will be strung at virtually the same tension throughout the section. The towers throughout a section will usually be located at irregular intervals. It is found convenient to use a template cut from transparent plastic material to the shape of the conductor catenary at maximum operating temperature and with allowance for creep. This sag template, on which the heights of standard and minus and plus height towers are inscribed, can then be overlaid on the profile drawing of the ground surface. The profile of the centreline of the route is prepared by the survey team. The sag template can then be positioned on the profile to provide the correct ground clearance in each span, and the tower heights can also be marked on the profile. In ground subject to side slopes, profiles left and right of centre line should also be marked so that ground clearances are achieved; this is especially necessary for horizontal configuration towers. It should be noted that for accuracy of plotting it is usually necessary to provide three sag templates, the first for the basic span, one for spans 10% less than the basic span and the third for spans 10% greater in length than the basic span.

During the survey, a record will be taken of the types of ground crossed, and this information will be backed-up by soil investigations. Foundation designs will be based on the prevailing soil conditions. In preparation for construction, the range of types of foundation are tested by installing sample foundations in the various types of ground along the route. The test foundations are usually stressed in uplift to progressively higher loads relaxing the uplift load to zero after each increment. By this means, it is possible to demonstrate that the foundation will withstand the ultimate load applied by the tower and that any movement of the foundation is 'elastic' and that plastic movement does not occur.

The foregoing preparation of profiles can be seen to be a time-consuming labour-intensive operation. For a number of years now, overhead line construction companies have adopted computer profiling programmes designed to operate interactively and thus optimise the location and types of tower in all line sections. The programmes print out a continuous profile drawing using the digitised levels and chainage down-loaded from the survey team's computerised records.

5.9 European standards and their impact

Many European countries have in the past produced their own national standards for insulators and fittings required for overhead line construction. In the early days there were considerable differences, particularly in dimensions – and in some instances test procedures – between these various standards.

In the early 1950s, under the auspices of the International Electrotechnical Commission (IEC), considerable international standardisation was achieved in details of dimensions and testing of insulators. The IEC, with its central office in Switzerland, has always been fully supported by European manufacturers and utilities. As the IEC Standards for dimensions and testing procedures of insulators have been agreed and published, European countries have generally adopted the text of these documents and translated them into their own language as the national standard. Thus, there is already a very large degree of consensus regarding the requirements for overhead line insulators.

In a few countries, notably Germany and Austria, there are additional standards in the DIN or VDE series which provide for standardisation in areas not covered by IEC Publications, e.g. caps for long rod insulators. These still employ the standardised IEC couplings.

In direct contrast to some areas of standardisation, there has been little attention given to European standards drawn up by the Comité Européen de Normalisation Electro Technique (CENELEC) for overhead line insulators, or indeed for insulators generally. The requirement for European Norms has now been recognised. In principle the existing IEC Standards will be adopted without amendment as the basis for European Standards. In a very few instances special national conditions will need to be recognised as deviations from a completely unified practice throughout Europe. An example of this does occur on overhead line construction where one of the couplings for 28 mm diameter pins was introduced in the UK many years before IEC 120 was extended to include this size. For excellent technical reasons the UK Standard differs from the IEC Standard, and will therefore have to be included in the European Standard as a special national condition.

In future, there will be very close co-operation between IEC and the European authority CENELEC so that new or revised standards will be submitted to dual voting procedures. With a long history of co-operation between the UK and its European partners, and on a worldwide basis, it is not envisaged that there will be any significant problems in reaching agreement on common IEC and CENELEC, European Standards, at least so far as insulators and their testing are concerned.

The situation on overhead line fittings in relation to European Standards is potentially more complex than for insulators. In the absence of any IEC Standards, other than those for coupling dimensions, each country has produced its own range of standard designs and testing procedures. Although the design requirements are in many cases identical, the details between one country – or manufacturer – and another often differ. In the UK BS3288: Parts 1 and 2, covering fittings, have been applicable to testing and design for many years.

At the present time, both IEC and CENELEC have Technical Committees and Working Groups responsible for preparing overhead line standards. It is hoped that the documents dealing with fittings will be identical, but achievement of this aim may involve considerable compromise by the various countries involved to reach agreement. The UK is actively participating in both organisations in order to protect its own interests where possible and to achieve a smooth transition from individual national standards to a common European Standard.

5.10 References

1 IEC 60826 1991–06 'Transmission line design'
2 IEC 60652 1979–01 'Loading tests on overhead line towers'
3 IEC 61089 1991–06 'Round wire concentric lay overhead electrical conductors
4 BS 3288 'Insulators and conductor fittings for overhead lines: Part 1–1997: Performance and general requirements; Part 2–1990 Specification for a range of fittings'
5 BRADBURY, J., KUSKA, G.F. and TARR, D.J.: 'Sag and tension calculations in mountainous terrain', *IEE Proc. C*, 1992, **129**, (5)
6 'The thermal behaviour of overhead line conductors,' *Electra*, October 1992, **144**(CIGRE Working Group 22.12)
7 URWIN, R.J.: 'Engineering challenges in a competitive electricity market.' ISH99, IEE High Voltage Engineering Symposium, 22–27 August 1999, paper 5.366 SO
8 'Safe design tension with respect to aeolian vibrations. Part 1: Single unprotected conductors', *Electra*, October 1999, **186**
9 VANNER, M.J.: 'Foundation uplift resistance: the effects of foundation type and seasonal changes in ground conditions', *IEE Proc. C*, 1982, **129**, (6)
10 IEC 60383 'Insulators and conductor fittings for overhead lines. Part 1 1993–04 Ceramic or glass insulator units for AC systems'
11 IEC 61211 1994–06 'Puncture testing'
12 IEC DRAFT DOC 36 (Secretariat) 65 'Tests on composite insulators for overhead lines with voltages greater than 1000V'

13 C 29-11 1989 'Tests on composite insulators for overhead lines with voltages greater than 1000V'
14 IEC 60383 'Insulators and conductor fittings for overhead lines. Part 2 1993–04 Tests on insulator strings'
15 IEC 60815 1986–05 'Guide for the selection of insulators'
16 IEC Document in preparation. 'The effects of power arcs on insulator sets'
17 CISPR 16 'Specification for RIV measuring equipment'. Part 1 1998–01; Part 2 1996–11
18 IEC 60437 1997–09 'Radio interference tests on high-voltage insulators'
19 BS 5049 1987 'Methods for measuring RIV'. Part 1-1994; Part 2-1994 + Amend 1; Part 3-1994 + Amend 1&2
20 BS 5049 'Code of practice for noise abatement from overhead power lines'. Part 1-1994; Part 3-1994
21 BURGSDORF *et al.*: CIGRE 413 (1960) 'Corona investigations on extra high voltage lines'

Appendix 5.1: Conductor sag and tension calculations

Referring to the diagram in Section 5.3 the true length of the conductor from C to B may be calculated from:

$$\frac{S}{2} = C \sinh \frac{L}{2c}$$

Hence the complete conductor length S from A to B is obtained by substituting

$$\text{for } c = \frac{T}{W}$$

$$S = \frac{2T}{w} \sinh \frac{WL}{2T}$$

and the conductor sag is:

$$D = Y - C$$

$$\text{but } D = \left(\cosh \frac{LW}{2T} - 1\right)$$

and cosh x can be expanded:

$$\cosh x = 1 + \frac{x^2}{2!} + \frac{x^2}{4!} + \ldots$$

The equation for sag, D, can also be expanded as follows:

$$D = \frac{T}{W} 1 + \frac{LW^2}{2T} \cdot \frac{1}{2!} + \frac{LW^4}{2T} \cdot \frac{1}{4!} + \ldots - 1$$

$$D = \frac{WL^2}{8T} + \frac{W^3L^4}{384T^3} + \ldots$$

Typically, a 400 m span and a tension of 2500 kg with a conductor of mass 1.74 kg/m will have a sag of:

$$D = \frac{1.74 \times 400^2}{8 \times 2500} + \frac{1.74^3 \times 400^4}{384 \times 2500^3} = 13.942 \text{ m}$$

The second term of the calculation is only 0.15% of the first term and, therefore, to a first approximation it is usual to ignore it. Accordingly, the equation:

$$D = \frac{WL^2}{8T}$$

is used to calculate sags and tensions for level spans when the sag is less than about 10% of the span. This equation describes the shape of a parabola.

For use in the case of supports on sloping ground, i.e. with supports at A and B in the following diagram, the parabolic equation for sag and tension is adapted as follows:

$$X = \frac{L_2^2 W - 2TL}{2L_2 W}$$

where, as shown in Figure 5.15. X is the distance from the lower support B.

It should be noted that the parabola follows the same curve from A to B as for a parabola with level supports fixed at A and C. The above equation is sufficiently accurate for determining sags and tensions of slack spans from the terminal towers to the substation gantry.

In mountainous regions, however, where there are steep sided slopes, often resulting in uplift being applied to cross-arms, a more rigorous analysis is required [5].

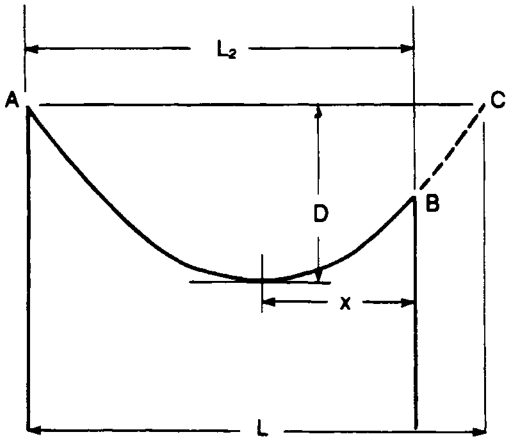

Figure 5.15 Parabola for line conductor supported at unequal heights.

Appendix 5.2: Change of state equation

An equation for the change in conductor tension with temperature change is:

$$T_2^3 + T_2^2\left[\frac{EAW_1^2 L^2}{24\,T_1^2} + EA\alpha\,(t_2 - t_1) - T_1\right] = \frac{EAW_2^2 L^2}{24}$$

where

T_1 = initial conductor tension at t_1 (kg)
T_2 = final conductor tension at t_2 (kg)
E = modulus of elasticity (H bar)
A = conductor area (mm^2)
W_1 = initial conductor mass (kg/m)
W_2 = final conductor mass (kg/m)
L = span (m)
α = coefficient of linear expansion (°C^{-1})
t_1 = initial temperature (°C)
t_2 = new temperature (°C).

Example: We wish to calculate the conductor tension at 75 °C and know the tension at 25 °C (ambient temperature) that is at 20% nominal breaking load.

Using a 'canary' ACSR conductor:

$E = 6960$ kg/mm^2, $A = 515.2$ mm^2, $W = 1.726$ kg/m, $T_1 = 2826$ kg,

$\alpha = 23 \times 10^{-6}\,°C^{-1}$, $L = 400$ m, $t_1 = 25$ °C, $t_2 = 75$ °C, and substituting in the formula with zero wind:

$$T_2^3 + T_2^2\left[\frac{6960 \times 515.2 \times 1.726^2 \times 400^2}{24 \times 2826^2} + 6960 \times 23 \times 10^{-6} \times 515.2.\,(75 - 20) - 2826\right]$$

$$= \left(\frac{6960 \times 515.2 \times 1.726^2 \times 400^2}{24}\right)$$

$$T_2^3 + 10627T_2^2 = 7.1216 \times 10^{10}$$

$$\text{Hence, } T_{75} = 2378 \text{ kg}$$

If we consider wind loading acting on the conductor then the calculation is carried out as shown below:

$$T_2^3 + T_2^2\left[\frac{EAW_1^2\,L^2}{24\,T_1^2} + EA\alpha\,(t_2 - t_1) - T_1\right] = \frac{EAW_2^2\,L^2}{24}$$

in which W_2 = conductor resultant weight with wind (kg/m)

$$W_2 = \sqrt{W_1^2 + F^2}$$

where

F = wind force = $0.0047 \times V^2 \times d$ (kg/m)
V = wind speed (km/h)
d = overall diameter (m).

Appendix 5.3: Ampacity of OHL conductor

To calculate the ampacity of overhead line conductor based on its thermal rating:

1. A simple method for calculation of current rating on a thermal basis is as follows:

$$I^2R + \alpha' S' d = H_c + \varepsilon s\,[(\theta + t + 273)^4 - (t + 273)^4]\,\Pi d$$

where

I = current rating (A)
R = AC resistance (Ω cm^{-1}) at operating temperature and current; see 2
α' = solar absorption coefficient (1.0 for aged conductor and 0.6 for new conductor)

S' = intensity of solar radiation (Wcm^{-2})
d = overall diameter of conductor (cm)
H_c = convection loss (Wcm^{-1})
ε = emissivity of conductor (1.0 for aged conductor and 0.3 for new conductor)
s = Stefans's constant = 5.7×10^{-12} (Wcm^{-2})
t = ambient temperature (°C)
θ = conductor temperature rise above ambient (°C).

2. Calculation of AC resistance is made using the following equation which relates conductor resistance at any given temperature:

$$\frac{R't_2}{R't_1} = \frac{M + t_2}{M + t_1}$$

in which

t_1 = temperature of conductor
t_2 = new temperature of conductor
$R't_1$ = DC resistance at t_1
$R't_2$ = DC resistance at t_2
M = constant for type of conductor material = 228.1 for ACSR.

To calculate the AC resistance of a conductor knowing the DC resistance, the following relationship for skin effect is used:

$$R_{t2} = K \times R'_{t2}$$

where R_{t2} = AC resistance at t_2.

The value of K may be read from Figure 5.16. The derivation of the values of K is based on the method described by V.T. Morgan (*IEE Proceedings*, 1965, **112**, pp: 325–334):

$$X = 0.050133 \sqrt{\frac{\mu f}{R'_{t_2}}}$$

where

R'_{t2} = DC resistance at t_2 (Ω/km)
f = power supply frequency (Hz)
μ = permeability = 1 for nonmagnetic materials.

3. Calculation of convection loss (H_c). The experimental evidence on which values of H_c are based is found in Electrical Research Association (ERA) reports. The values of H_c are significantly different for stranded as compared with smooth conductors but substantially independent of the number of strands from 3 to 37.

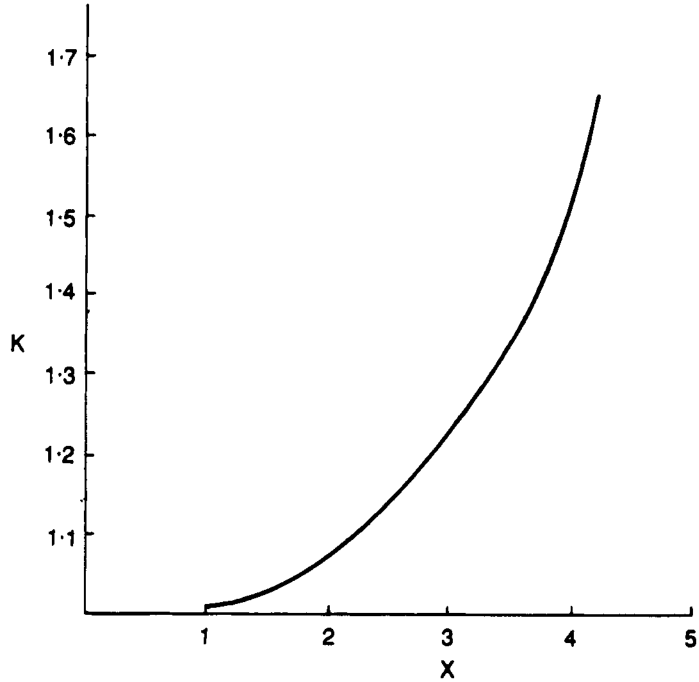

Figure 5.16 Curve of relationship of K and X.

The values of H_c for the various types of conductor and wind conditions are derived from:

natural convection (no wind):

$$H_c = (12.8 \times 10^{-4} d)^{0.699}\,\theta^{1.233}$$

for stranded conductor

$$H_c = (19.5 \times 10^{-4} d)^{0.561}\,\theta^{1.187}$$

for smooth conductor.

forced convection (with wind):

$$H_c = 13.8 \times 10^{-4}\,(V \times d)^{0.448}\,\theta$$

for stranded conductor

$$H_c = 15.95 \times 10^{-4}\,(V \times d)^{0.462}\,\theta$$

for smooth conductor

and V = wind velocity (cms^{-1}).

4. Example of calculation of thermal rating, based on ACSR conductor code name 'Canary';

α' = 1.0 for aged conductor
S' = 0.135 (Wcm^{-2}) for the island of Java
d = 2.95 cm
ε = 1.0
s = 5.7×10^{-12} (Wcm^{-2})
θ = 50 °C
t = 25 °C
V = 50 cms^{-1}
R'_{t1} = 0.06351 Ω/km at t_1 = 20 °C
t_2 = 75 °C

$$\frac{R'_{75}}{0.06351} = \frac{228.1 + 75}{228.1 + 20}$$

$\therefore R'_{75} = 0.07759$ Ω per km at 75 °C

and AC resistance is derived from

$$X = 0.050133\sqrt{\frac{1 \times 50}{0.07759}} = 1.27264$$

and from the curve, $X = 1.27264 \equiv$ K of 1.01.

$R'_{75} = 1.01 \times 0.07759 \therefore R_{75} = 0.0783659\ \Omega km^{-1}$

using the values of R, V given below:

$R = 0.0783659 \times 10^{-5}\ \Omega cm^{-1}$
$V = 50\ cms^{-1}$

$$H_c = 13.8 \times 10^{-4}\,(50 \times 2.95)^{0.448} \times 50$$

$$\therefore H_c = 0.64635$$

and substituting the values in the heat balance equation:

$$I^2R + \alpha'S'd = H_c + 1.0 \times 5.7 \times 10^{-12}\,[(50 + 25 + 273)^4 - (25 + 273)^4]\,\Pi \times 2.95$$

$$I^2R + \alpha'S'd = H_c + 0.35816$$

$$\therefore I = 879\text{ A}$$

Appendix 5.4: Foundation calculations

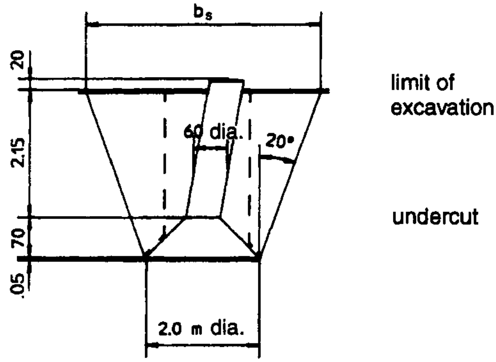

Figure 5.17 Undercut pyramid foundation

Concrete volume

$0.3^2 . \pi . 0.2$	$= 0.056 \text{ m}^3$
$0.3^2 . \pi . 2.15$	$= 0.607 \text{ m}^3$
$\dfrac{0.7^2 . \pi .}{3} (1.0^2 + 0.3^2 + 1.0 \times 0.3)$	$= 1.018 \text{ m}^3$
$1.0^2 . \pi . 0.05$	$= 0.157 \text{ m}^3$
	$= 1.838 \text{ m}^3$

Concrete weight

$1.838 . 2240 = 4117$ kg $\quad = 4.117$ t

Earth volume

$b_s = 2.\ 2.85 \times \tan 20° + 2.0 = 4.07 \text{ m}^3$

$\dfrac{2.85 . \pi}{3} (2.035^2 + 1.0^2 + 2.035 \times 1.0)$	$= 21.40 \text{ m}^3$
$-(0.607 + 1.018)$	$= -1.625 \text{ m}^3$
	$= 19.775 \text{ m}^3$

Earth weight

$19.775 \times 1600 \quad = 31.640$ t

Total weight resisting uplift	$= 31.640$ t
	$+ \ 4.117$ t
	35.757 t

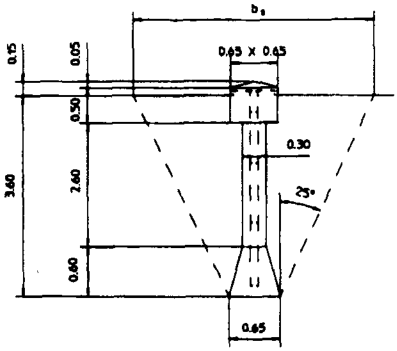

Figure 5.18 Concrete auger foundation

Volume of concrete		
$\pi \times 0.6\ (0.65^2 + 0.3^2 + 0.65 \times 0.3)/12$	=	0.111
$\pi \times 0.3^2 \times 2.60/4$	=	0.183
$0.65^2 \times 0.5$	=	0.211
$0.65^2 \times 0.05/3$	=	0.007
	=	0.512 m^3
Volume of frustum		
$b_s = 2 \times 3.6 \tan 25 + 0.65$	=	4.007
volume $=3.6\ \pi\ (3.632^2 + 0.65^2) + 3.632 \times 0.65/12$	=	15.05 m^3
Weight of concrete 0.512×2240 kg/m^3	=	1146 kg
Weight of ground 15.05×1600 kg/m^3	=	24086 kg
Total uplift capacity	=	25232 kg

Appendix 5.5: Calculation of RIV generated by a typical transmission line

Calculation of surface voltage gradient using the following equation:

$$E = \frac{V}{\sqrt{3}} \cdot \frac{\beta}{r \ln\left(\dfrac{a}{Re} \cdot \dfrac{2h}{\sqrt{4h^2 + a^2}}\right)}$$

in which

$$\beta = \frac{1 + (n-1)\dfrac{r}{R}}{n}$$

$$r_e = R\,n\sqrt{\frac{n.r}{R}}$$

$$R = \frac{S}{2.\sin\dfrac{\pi}{n}}$$

where

E = conductor surface voltage gradient (kV/cm^{-1})
V = rated voltage (kV)
β = factor for multiple conductor (= 1 for tube)
r = radius of conductor (cm)
R = outside radius of bundle (cm)
r_e = equivalent radius of bundle conductor (cm)
s = distance between component conductor centres (cm)
a = phase spacing (cm)
h = height of conductor above ground (cm)
n = number of component conductors in bundle.

The stress on a quadruple bundle of conductors codenamed 'Dove' set at 45 cm centres:

'DOVE' dia = 2.355 cm
r = 1.1775 cm
a = 12.0 m = 1200 cm
h = 1530 cm
s = 45.0 cm
V = 500 kV

(i)

$$R = \frac{45.0}{2\sin\dfrac{\pi}{4}} = 31.8 \text{ cm}$$

(ii)

$$\beta = \frac{1 + (4-1)\dfrac{1.1775}{31.8}}{4} = 0.2777$$

(iii)

$$r_e = 31.8 \times 4\sqrt{\frac{4 \times 1.1775}{31.8}} = 19.72 \text{ cm}$$

$$E = \frac{500}{\sqrt{3}} \cdot \frac{0.2777}{1.1775 \ln\left(\dfrac{1200}{19.72} \cdot \dfrac{2 \times 1530}{\sqrt{4 \times 1530^2 + 1200^2}}\right)}$$

$$\therefore\ E = 17.79 \text{ kV/cm}$$

We then calculate the mean stress for the conductor bundle under consideration:

$$\text{mean stress} = 17.79 \times \frac{1}{1 + 2.12 \times \dfrac{2.355}{45.0}} = 16.01 \text{ kV/cm}$$

RI at 60 m from line at 500kV using the comparison formula:

$$E - E_0 = 3.9\,(g - g_0) + 40 \log_{10}\frac{d}{d_0} + 10 \log_{10}\frac{n}{n_0}$$

Use E_0 = the noise generated by the 'Apple Grove' 750 kV overhead line, reported in IEEE paper no. 69, TP 688 PNR,

where

E, E_0 = RI noise level dB > 1 μV/m
g, g_0 = mean voltage gradient 1 > μV/cm
d, d_0 = conductor diameter
n, n_0 = number of conductors in bundle.

$$E - 36 = 3.9\,(16.01 - 15.62) + 40 \log_{10}\frac{23.55}{35.1} + 10 \log_{10}\frac{4}{4}$$

$$= 30.58 \text{ dB} > 1\ \mu\text{V/m at 60 m, say 31 dB}$$

Ratio of noise at 60 m from the line to noise at 20 m from the line is established from the relationship:

$$30 \log_{10}\frac{60}{20} = 14.31 \text{ dB} > 1\ \mu\text{V/m}$$

Therefore the noise level at 20 m from the line will be:

$$31 + 14.3 = \underline{45.3} \text{ dB} > 1\ \mu\text{V/m}$$

Appendix 5.6 Calculation of corona loss dissipated by a typical transmission line

Using the method developed by V.V. Burgsdorf *et al.* [21].

<u>Transmission line parameters</u>

Conductor radius	1.288 cm
Number of conductors in bundle	4
Bundle centres	45.0 cm
Conductor configuration	horizontal
Phase spacing	12 m
System voltage	500 kV_{RMS} = 707 kV_{pk}
Line altitude	500 m

Average duration of weather types:

(a) fair weather	7300 h
(b) wet weather	1460 h

1. Calculate E_0 from:

$$E_0 = 30.3 \times m\left(1 + \frac{0.3}{\sqrt{r}}\right)$$

where m = surface factor = 0.82 for stranded conductor and unity for polished cylindrical surfaces and r = conductor radius (cm)

$$E_0 = 30.3 \times 0.82\left(1 + \frac{0.3}{\sqrt{1.288}}\right)$$

$$\therefore\ E_0 = 31.41 \text{ kV}$$

2. Determine value of E_{pk} using Maxwell's coefficients:

$$E_{pk} = \frac{1.66 \times 707}{52.9} = 22.18 \text{ kV}_{pk}\text{/cm}$$

3. Determine E_{AV} centre phase from:

$$E_{AV} = E_{pk} \times \frac{1}{= \left(1 + \frac{2.12\,d}{A}\right)}$$

where

E_{pk} = maximum conductor surface stress per phase (kV/cm)
d = subconductor diameter (cm)
A = bundle spacing (cm)

$$E_{AV} = 22.18 \times \frac{1}{\left(1 + \left[2.12 \times \frac{2.576}{45}\right]\right)}$$

$$= \underline{19.77}\ \text{kV}_{pk}/\text{cm}$$

4. Determine E_{AV} outerphase:

$$E_{AV} = 0.943 \times 19.77$$

$$= \underline{18.64}\ \text{kV}_{pk}/\text{cm}$$

5. Correction due to air density at 500 m
Correction factor = 0.96

E_{AV} (corrected) centre phase = 19.77/0.96 = 20.59 kV_{pk}/cm

and

E_{AV} (corrected) outer phases = 18.64/0.96 = 19.41 kV_{pk}/cm

6. Determine values of E_{AV}/E_0

for centre phase = 20.59/31.41 = 0.655
for outer phases = 19.41/31.41 = 0.617

7. Determine from Burgsdorf's curves the values of

$$\frac{Pk}{n^2 r^2}$$

for fair weather and wet weather:

	centre phase	outer phases
fair weather	0.026	0.019
wet weather	0.545	0.36

8. Calculate average annual line losses from:

$$P_k = \frac{n^2 r^2}{8760} \Sigma fi \frac{E_{AV}}{E_0} Ti$$

where

P_k = average annual phase losses due to corona (kW/km)
n = number of conductors/bundle
r = subconductor radius (cm).

Dry weather loss, power loss, centre phase

$$4^2 \times 1.288^2 \times 0.026 \quad = \quad 0.6901 \text{ kW/km}$$

power loss, outer phases

$$2 \times 4^2 \times 1.288^2 \times 0.0199 \quad = \quad \underline{1.00863}$$

Total power loss $\quad 1.6987$ kW/km

Wet weather loss, centre phase

$$4^2 \times 1.288^2 \times 0.545 \quad = \quad 14.465 \text{ kW/km}$$

outer phases

$$2 \times 4^2 \times 1.288^2 \times 0.36 \quad = \quad \underline{19.11}$$

Total wet weather loss $\quad 33.576$ kW/km

with, say, 1000 h rain per annum and 7760 h fair weather

$$\begin{aligned} \text{annual loss} &= 7760 \times 1.6987 &&= 13\,181 \\ &+ 1000 \times 33.57 &&= \underline{33576} \\ & &&= 46757.9 \text{ kWh/km} \end{aligned}$$