Chapter 5

Overhead lines

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5.1 Introduction

The purpose of this chapter is to provide an overview of the design, manufacture, construction, testing and maintenance of the various components which go to make up overhead transmission (visit http://www.cigre.sc22.org) and distribution lines. The transmission of electrical energy is carried out over long distances at voltages of 66 kV and above, whereas distribution is carried out over short distances at voltages of between 11 and 66 kV using the same technology.

In the early days of electricity transmission, the methods already established by telegraph authorities, using telephone wires fixed to wood pole supports, were adopted by the electricity supply authorities. This involved the fixing of bare, uninsulated conductors to small porcelain insulators (Figure 5.1*a*) screwed on to metal spindles which were mounted on to metallic or wooden crossarms supported by wooden poles; see Figure 5.1*b*.

As transmission/distribution distances increased, it became necessary to increase the system voltages. Consequently, the pin-type insulators were increased in size to provide longer creepage paths to earth; conductor sizes were also increased to allow higher current carrying capacities (ampacities). This resulted in increased vertical loads due to the conductor mass and increased transverse wind loads due to the increased conductor projected area. Insulator spindle diameters were of necessity increased to cater for the greater mechanical loads, and similarly single wood poles were replaced by 'A' and 'H' pole construction, i.e. two poles side by side at 1 or 1.5 m centres and braced together to cater for the higher transverse loads. The simple pin-type insulator designs progressively reached their limit of mechanical strengths under side or transverse loads.

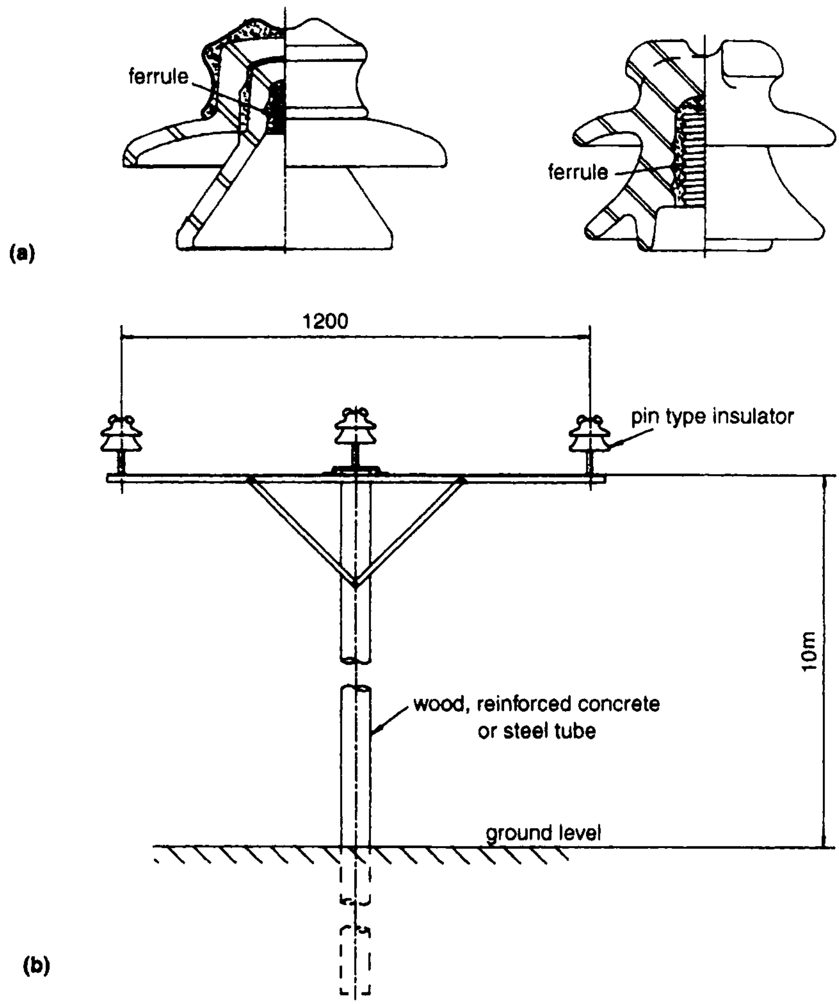

Figure 5.1 **(a)** *Section drawing of toughened glass (left) and porcelain pin-type insulators*
(b) *Overhead line construction (11 kV)*

To overcome the problems of the limited mechanical strength of pin-type insulators, the cap and pin insulator was developed; see Figure 5.2 With this design, the tensile forces applied to the insulator are axial, and it is not required to support side loads, therefore higher conductor loading can be achieved. Short suspension strings of one or two insulators for 11 kV up to six insulator units for 66 kV etc. were used, thus allowing increased conductor diameters and longer spans.

The strength of the wood poles tended to limit any further increases in

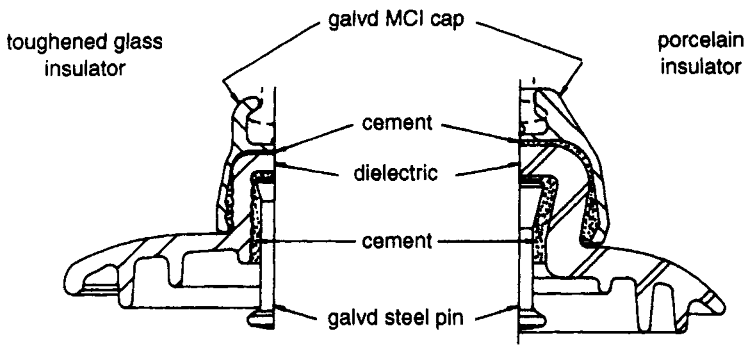

Figure 5.2 Section drawing of cap and pin insulators

span lengths, and progressively small towers of lattice steel construction were introduced as supports. As voltages increased from 66 to 132 kV, the lattice steel tower became the accepted method of support. Over the years, as voltages have further increased through 275–420–500–765–1100 kV, the most frequently adopted method of support remains the lattice steel tower.

As a substitute for wood poles, concrete poles of pre-stressed concrete of rectangular cross-section – and more recently spun concrete poles – are used with voltages up to about 132 kV.

In recent years, wood pole lines have been developed for 66 to 132 kV using a 'trident' form of construction where either line-post or post-type insulators are employed. This type of construction is lightweight and easy to transport and erect. It is increasingly used in areas of high amenity value where the low height construction allows the line to blend with the background. A number of authorities employ the trident form of construction to provide short lengths of quickly erected lines to bypass faults or substation bays during modifications to substations. A typical 'trident' structure is shown in Figure 5.3.

5.2 Towers and supports

5.2.1 General

The tower or supporting structure is required to carry the overhead line conductors and earth conductors, each of which will be subjected to a variety of forces. These range from normal still air load, extreme wind loads, ice loads in some parts of the world, and any additional loads during erection and maintenance of the conductors or insulator sets. The tower must be capable of safely withstanding all the various forces applied to it and at the same time the electrical clearances between the

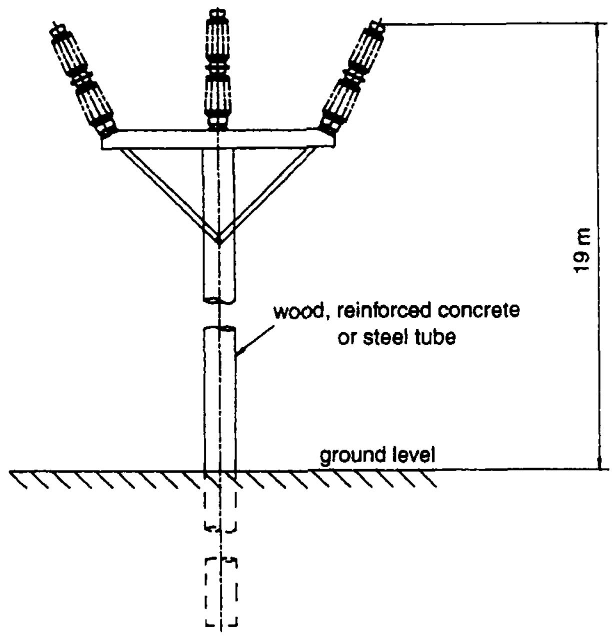

Figure 5.3 Trident overhead line construction (132 kV)

live conductors and the earthed metal must be maintained under all loading conditions.

The tower may be designed to cater for a single 3-phase circuit, double 3-phase circuits, multiple voltage circuits and, with direct current transmission, either a monopolar (with earth return) or bipolar construction.

5.2.2 Self-supporting single circuit towers

Single circuit (SC) towers are generally of one of three forms: horizontal, delta or triangular conductor configuration. Some typical towers are shown in Figure 5.4.

Towers equipped with horizontal configuration conductors require a lower tower height than an equivalent vertical configuration tower but, because of the clearance requirements between phases, they require a wider strip of ground. If the region in which the line is to be constructed has a high lightning level (isoceraunic level) it is usually necessary to install two overhead earth wires to provide proper shielding of the line conductors. Horizontal configuration results in the capacitance between conductors and earth being approximately the same for each phase, but the capacitance and inductance between phases is not equal. To overcome the problem of asymmetry, towers may be constructed with conductors deployed in delta formation and with this arrangement the

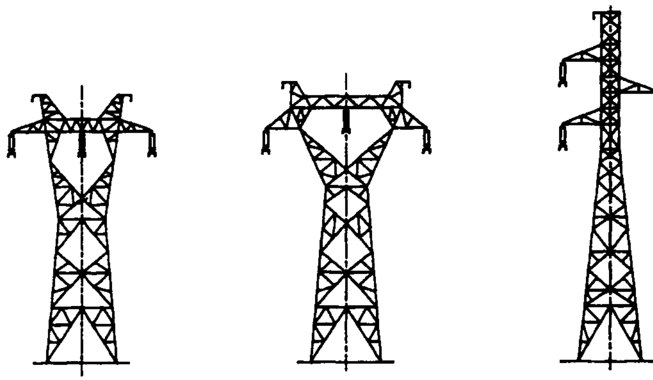

Figure 5.4 *Single circuit steel towers (left to right: horizontal, delta, triangular formations; twin, twin, single earthwire, respectively)*

inductance and capacitance between conductors is virtually the same for each phase.

5.2.3 Self-supporting double circuit towers

A line comprising double circuit (DC) towers can be constructed at a lower capital cost than two parallel SC lines. Double circuit lines are generally 7 to 10% cheaper than the equivalent two SC lines depending on the voltage and conductor sizes. A double circuit line will occupy less land than the equivalent two SC lines. However, the most frequently adopted design of double circuit tower with vertical configuration conductor arrangements is of necessity higher than the equivalent SC tower.

There may be a case for using SC lines when heights must be restricted, perhaps near to an airport or on the grounds of amenity. Generally, two SC lines can assist in this situation but specially designed double circuit lines can also be employed. A typical 'low height' double circuit tower for 400 kV is shown in Figure 5.5.

Probably the main disadvantage of double circuit lines is the possibility of a double circuit fault arising from a lightning strike, accidental damage resulting from a vehicle or aircraft colliding with a tower, or possibly due to abnormal weather conditions, for example a tornado or very severe icing. Deliberate damage to towers, perhaps by means of an explosive charge or by the removal of bolts critical to the tower strength, is increasingly occurring in many parts of the world and this type of damage will cause more disruption with double circuit towers than with SC towers. If a reliable interconnection is required then two SC lines spaced as far apart as possible reduces the likelihood of a total interruption of supply due to many of the reasons listed above.

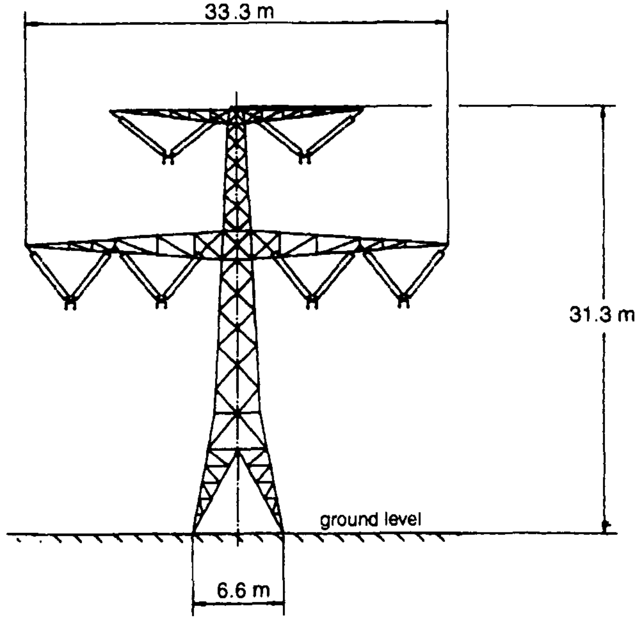

Figure 5.5 Double circuit low height tower

5.2.4 Guyed towers

In addition to self-supporting towers, structures which rely on guy wires to provide longitudinal and transverse support are employed; see Figure 5.6. The use of guyed towers will result in a saving of about 5% of erected cost over the equivalent self-supporting towers at 500 kV system voltages. The saving is largely achieved because of the reduced weight of tower steel.

Guyed towers can only be employed on relatively flat ground because, on sloping ground, one pair of guy wires can become prohibitively long. In addition, relatively level ground is required if a mobile crane with a 40–50 m jib is to be employed safely for tower erection.

In regions which are densely populated or intensively farmed, the total area of land required by guyed towers makes them less attractive than a self-supporting tower.

5.2.5 Tower design

5.2.5.1 General

Tower design involves a number of distinct stages:

(a) derivation of loads to be resisted and clearances to be accommodated by the tower

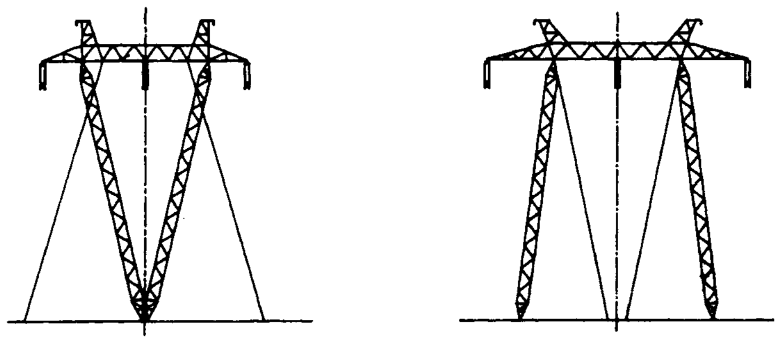

Figure 5.6 Guyed steel towers

(b) selection of tower shape resulting from (a)
(c) derivation of member loads
(d) design of members.

Stages (c) and (d) will also affect the choice of tower shape and will be repeated by a designer to provide the optimum design.

The various tower types described in the previous section can all be analysed by similar methods. It is not the intention of these notes to provide a complete guide to tower design, and the following sections relate mainly to the checking of contractors' designs. However, the basis behind each stage is described so that towers requiring special characteristics can be properly checked.

At each conductor attachment point on the tower, the loads are defined in three axes X, Y, Z, more commonly known as transverse, longitudinal and vertical, respectively. The derivation of each of these is discussed below. An IEC document [1] covering transmission line design is available.

5.2.5.2 Transverse loads

These comprise those wind-induced loads acting on the conductor and insulators, together with the transverse component of conductor tension, resulting from a deviation in the line for angle towers.

(a) Wind loads

The wind load on a conductor (T_w) may be derived by the formula:

$$T_w = P_c\,(d\,n\,S_w) + A_i P_c$$

where

P_c = the design wind pressure for cylindrical surfaces
d = the conductor diameter
n = the number of conductors in the bundle (note: no allowance is made for the shielding effect of one conductor on another)
S_w = the effective wind span
A_i = the projected area of the insulator sets.

The wind span is defined as half the sum of the two spans adjacent to the tower and is based on a percentage increase over the chosen economic basic (or standard) span, to allow for errors in plotting and profiling. The increase is usually in the region of 10% over the basic span. To arrive at the effective wind span, the length projected normal to the direction of the wind is taken. This is the true situation for a suspension (straight line) tower, for example tower no. 2 of Figure 5.7. For angle towers, however, due to the many possible permutations of deviation and wind direction

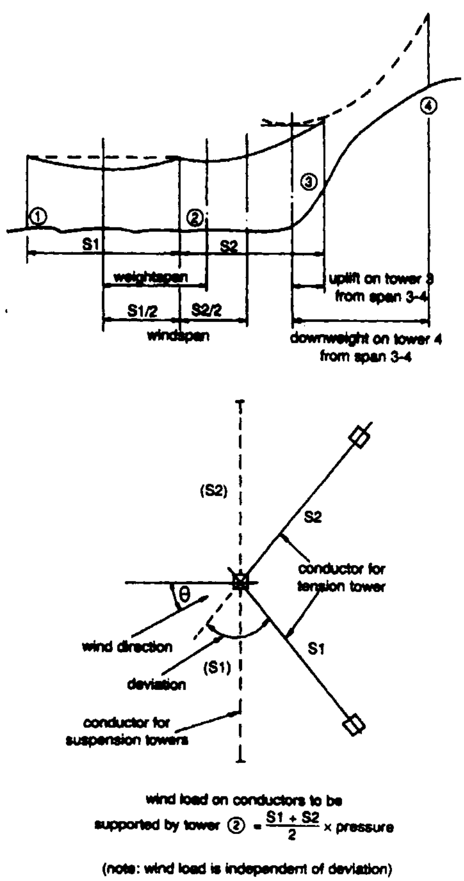

Figure 5.7 Wind and weight spans

on spans S_1 and S_2, it is usual to assume the conductors to be in a straight line for the calculation of S_w.

The effective wind span for all tower types may therefore be written as:

$$S_w = \frac{S_1 + S_2}{2} \cos \theta$$

where θ = the line deviation angle and

$$\frac{S_1 + S_2}{2} = \text{basic span} \times 1.1$$

(b) Deviation loads

For angle towers (and small angle suspension towers) a proportion of the transverse load at a conductor attachment point is due to the tension of the conductors. This load is known as the deviation load (T_d) and is calculated by:

$$T_d = Tn \sin \frac{\theta}{2}$$

where T is the maximum horizontal tower design tension of the conductors which is dependent on the wind pressure and n = the number of sub-conductors. The loads T_d and T_w are therefore considered to act simultaneously on the tower.

5.2.5.3 Longitudinal loads

These are the loads which result from the conductor tension. Suspension towers are not subjected to these design loads except in exceptional cases where a conductor is broken. The incidence of broken conductors is sufficiently infrequent to allow the longitudinal conductor load for the design of suspension towers to be reduced by some factor from the maximum tension so as not to unduly penalise the line in economic terms because of unnecessary longitudinal suspension tower strength. Tension towers, on the other hand, which experience the full conductor tension at all times, require an enhanced longitudinal design load to provide the necessary security and capability to resist the associated dynamic loads developed during conductor failure.

5.2.5.4 Vertical loads

These are the loads resulting from the deadweight of conductors, insulators and fittings. The length of conductor to be considered is termed the weight span, the definition being the horizontal distance between the lowest point of the conductors on the two spans adjacent to the tower (see tower no. 2 of Figure 5.7). The vertical load is therefore:

$$V = (S_{wt}\, n\, w) + W_f$$

where

S_{wt} = weight span. The design weight span is taken as the basic span increased by a profile factor, usually 2, to allow for undulating terrain, together with an additional factor to allow for errors in plotting and setting out
n = number of subconductors
w = the total mass of conductor inclusive of grease, an allowance for spacers and, if necessary, ice,
W_f = the weight of insulators and fittings.

When the lowest point of the conductors in a span approaches the tower position itself, the effective vertical weight due to the conductors reduces in proportion. Should the 'apparent' lowest point move past the tower and into the next span the tower will experience uplift from the former span.

Tower designs must be checked for vertical conditions other than that for maximum weight because minimum weight and uplift conditions are critical for the leg and foundation designs in tension and uplift, respectively. For suspension towers it is usual to consider in the design a minimum vertical condition of zero. This is necessary, although the actual *in situ* weight span is restricted to a positive value which may be, for example, 45% of the conductor weight in the adjacent spans. This positive load is maintained to ensure that the insulator strings, which are designed to cater for tensile loads only, are not subjected to compressive loads. Tension towers may experience any variation of vertical load from the maximum permitted by the specification through zero to uplift.

The design uplift loads may be defined as either:

(a) $T \tan \varphi$, where φ is the incoming angle of the conductor above the horizontal and is dependent on the type of terrain

or

(b) some number, for example 'one' or 'two', of uplift or negative weight spans. It is recommended that this be based on the value obtained from (a).

5.2.5.5 *Tower wind loads*

Traditionally, tower wind loads have been derived by multiplying the design wind pressure (for flat surfaces) and the projected area of tower members of one face increased by a shielding factor (usually 1.5) to allow for the members on the back face of the tower. For especially large towers, often required for river crossings, the shielding factor should be increased.

The transverse and longitudinal wind loads on towers are derived from:

$$T_t = P_f A_t \cos \theta f$$

$$T_l = P_f A_l \cos (90 - \theta) f$$

where

T_t and T_l	=	transverse and longitudinal tower wind loads
P_f	=	design wind pressure for flat surfaces
A_t and A_l	=	net area of tower members in one face
f	=	shielding factor.

5.2.5.6 Tower self-weight

These loads are applied at various positions down the tower and shared equally between all four legs. For iced conditions, it will be necessary to consider the weight of members when covered with a stipulated thickness of ice.

5.2.5.7 Loading cases

Each type of tower must be designed to withstand the loads imposed by the conductors and/or ancillaries whether under normal or unbalanced (broken wire) conditions together with the loads imposed on and by the tower itself (wind and self-weight). Each type of tower may be utilised on the line within clearly defined limits, for example a specification may define normal load, unbalanced load, broken wire load and maintenance load.

5.2.5.8 Tower clearances

The second stage of tower design is to determine or check the tower shape. As mentioned previously, the function of the tower is to support and maintain all the necessary clearances required for the earth and phase conductors. It is this latter requirement which determines to a major degree the shape of the tower. The main parameters are:

- ground clearance (minimum distance between phase conductors and normal flat ground)
- sag of conductors (maximum conductor temperature, still air, standard span)
- insulator set length (suspension towers only)
- specified vertical or horizontal spacing between phase conductors

- specified height of earth conductor above upper phase conductor
- minimum groundwire shielding angle.

These parameters enable the conductors to be located in space (see Figure 5.8), and all that remains necessary before the initial shape can be determined is to allocate those areas around the conductors in which the earthed steel may not encroach. This is accomplished by the drawing of wire clearance diagrams which take into account the methods of transferring the live conductors through or past the towers whilst maintaining electrical clearance.

5.2.5.9 Methods of analysis

Traditionally, lattice towers have been designed by static methods employing force diagrams (Maxwell) or hand calculations (Method of Sections). More recently, the computer and finite element space truss programs have allowed elastic techniques to be employed. For the purpose of analysis by both techniques, it is assumed that the transmission towers are pin-jointed structures with axially loaded members.

In the past all types of towers, whether of conventional construction (vertical configuration) or waisted (horizontal formation with central window), were designed employing the static method of analysis. The proof of an adequate design is demonstrated by means of type tests (see Section 5.2.5.12) where any differences between predicted and actual failing loads will become apparent.

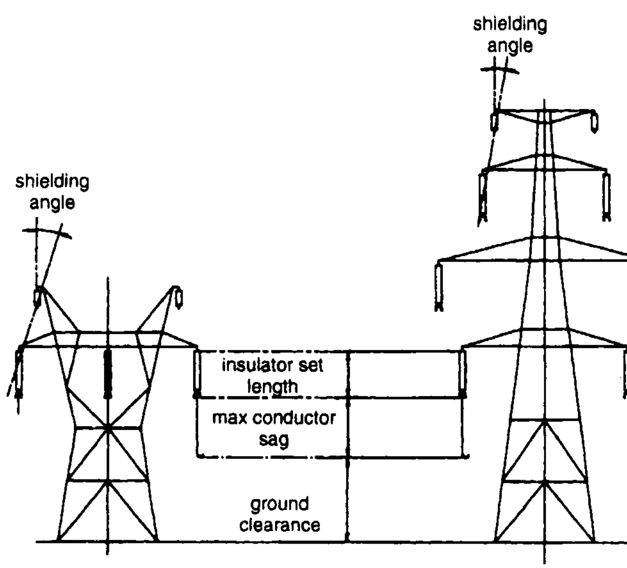

Figure 5.8 Parameters defining minimum tower shape: SC horizontal (left) and DC (right)

5.2.5.10 Tower weight

There are a number of methods for deriving tower weights for preliminary studies, the most common of which involves the use of the Ryle formula. This was developed originally to cover 132 kV towers designed with typical United Kingdom loading but its use may be extended to cover all tower types by sensible adjustment of the factor K in the following relationship:

$$W = KH\sqrt{M}$$

where

- M is the maximum ultimate overturning moment due to all loads (including wind) in tonne-metres
- H is the total tower height in metres
- W is the tower weight in tonnes
- K is the Ryle factor (approx. 0.014).

The factor K is influenced by a number of parameters, some of which are outlined below:

(a) *tower material*, whether mild steel only or mild and high yield steel (the tower containing HY steel will be lighter)
(b) *tower type*, whether suspension, tension or terminal. The heavier the tower, due to the increased complexity of joints and connections, the greater the proportion of bolts and plates to the tower members
(c) *tower formation*, whether 'waisted' or 'conventional'. 'Waisted' towers are lighter than 'conventional' towers and, due to their reduced height and overturning moment, require an increased K factor
(d) *range of steel sections available*. The wider the range of sections available the lighter the tower can be designed
(e) *the presence of any restrictions* that have been imposed on the tower so that the design shape deviates from its optimum (i.e. restricted base width).

5.2.5.11 Tower materials

The vast majority of overhead line (OHL) towers throughout the world are constructed from galvanised, hot rolled, mild and/or high tensile steel angle sections. This material is convenient to fabricate by means of numerically controlled presses which crop the bars to length, then punch the many holes required for the various joints. After forming, the steel is galvanised and, when assembled as a tower, should have relatively few pockets and depressions to hold water which could allow corrosion to set up.

Mild steel (MS) with yield strengths of up to about 250 N/mm^2 is readily available throughout the world and is a very suitable material to provide a reliable tower. High tensile (HT) steel with yield strengths of up to about 400 N/mm^2 is now used in conjunction with MS. A tower fabricated with HT steel requires a lower tonnage than a MS only tower. However, suitable HT steel is not produced in all parts of the world at the present time.

Steels with yield strengths in excess of about 400 N/mm^2 should not normally be used in tower construction particularly in those parts of the tower in which vibration, possibly as a result of wind action on the conductors or the tower members themselves, is likely to arise. Cases of fatigue failure of tower members fabricated from very high tensile steel have been reported on a number of occasions although generally in regions where low temperatures (– 10 to – 20 °C) prevail.

To minimise the mass of towers, particularly for areas with difficult access problems, e.g. in swampy ground or in mountainous regions, towers fabricated from aluminium alloy have been employed.

A number of utilities, particularly in the USA and Japan, employ towers fabricated from galvanised steel tube of circular or hexagonal tapering cross-sections. These tubes, usually from 0.5 to 1 m in diameter, are used as a single support. Cross-arms are also formed from similar tubular sections. It has been said that a structure formed from steel tube is aesthetically more pleasing than a lattice steel tower. A tubular steel tower certainly takes up a smaller area of land and it is possible to construct a line in a heavily populated area in which it would not be possible to construct a lattice steel tower line with its comparatively wide base.

Towers for use up to 500 kV constructed from laminated timber bonded with resins under heat and pressure are used in parts of the USA. It is believed that the capital cost of this material is greater than for the equivalent lattice steel towers. An advantage of timber structures is that the timber itself can be considered to provide part of the insulation when calculating the basic impulse level (BIL) of the insulation. This form of construction is often adopted on aesthetic grounds.

5.2.5.12 Tower testing

Generally each contractor will have his or her own methods of analysis, member design and method of detailing of members. The purpose of tower testing is to check that the selected method of analysis (and inherent assumptions) is correct and to ensure that the methods of detailing the connections etc. correctly reflect these assumptions. Testing is normally carried out to IEC 60652[2].

Each tower test station usually has its own particular methods of recording and applying the loads. Sometimes it may not be possible to apply the loads exactly in accordance, with the design assumptions due to the physical constraints of the test station. In this situation, the test programme should be altered and checked to ensure that the loads as applied provide the correct design component loads.

5.3 Conductors

5.3.1 Conductor types

The first transmission lines utilised stranded copper conductors largely because of the good electrical conducting properties (volume resistivity at 20 °C, 0.0177 ohm mm²/m) and resistance to corrosion of the material.

Pure copper has a relatively low ultimate breaking strength of about 250 MN/m², and the maximum working tension of conductor manufactured from annealed copper must be limited so that the stress in the conductor does not exceed about 125 MN/m². Copper can be 'work-hardened', resulting in a material with an improved breaking load of about 420 MN/m² at the expense of a slight increase in resistivity. The increase in breaking strength allows higher working loads and longer span lengths. Alloys of copper, particularly cadmium copper, provide a material with a breaking strength of about 630 MN/m² but again an increase in resistivity to 0.0217 ohm mm²/m results. Copper and cadmium copper are expensive and as a result these have largely been replaced by aluminum as a conductor material.

Aluminium has a higher resistivity than copper, being 0.0282 ohm mm²/m. However, if the resitivity is expressed as mass resistivity at 20 °C in ohm g/m, because of the lower density of aluminium, copper is seen to have a value of 0.1532 and aluminum 0.076 ohm g/m. Because aluminium has a low breaking strength of only 165 MN/m², in order to provide a conductor with an acceptable breaking strength, it is necessary to combine the good conducting properties of aluminium with a material with high mechanical strength. This is done by 'laying-up' a centre core of galvanised steel wire with surrounding strands of aluminium, i.e. aluminium conductor, steel reinforced (ACSR). The steel core wires of ACSR conductors are protected from corrosion by a zinc (galvanising) layer and frequently in addition, a special grease coating. IEC Publication 61089 [3] describes manufacturing and testing requirements for ACSR and for all aluminium conductors, aluminium alloy stranded conductor and aluminium alloy conductors, steel reinforced.

Various alloys of aluminium can be produced and formed into conductors and some of these alloys, often containing silicon or magnesium, have virtually twice the breaking or ultimate tensile strength (UTS) of pure aluminium. The gain in UTS is offset to some degree, however, by the increased resistivity which many aluminium alloys exhibit. In recent years, big improvements have been made with aluminium alloys and stronger alloys with reduced electrical resistance have resulted. A big advantage of aluminium alloy over pure aluminium is that alloys are in general more resistant to the corrosive effects of saline or industrial chemical attack. All aluminium alloy conductors. (AAAC) are being used in greater quantity and will gradually replace ACSR conductors.

Other methods of increasing the effective breaking strength of both copper and aluminium are employed. Copper or aluminium clad steel are used. This material is formed by 'drawing' an ingot of steel which is surrounded by a concentric layer of aluminium or copper, the ratio of the thickness of the coating to the diameter of the steel core in the ingot being the same as the ratio of thickness of the coating to the diameter of the core material of the finished strand. In 'drawing' the material through a series of dies to produce the required strand diameter, the steel core is 'work-hardened', which increases the strength of the steel. The core wire of clad steel is therefore usually of a higher UTS than the core wire of normal ACSR. The aluminium clad steel core wire can then be used as the load-bearing portion of a conductor with two, three or more layers of standard strands of aluminium wires.

One of the advantages of clad steel is that the material of the conducting strands and the material cladding the core is the same and therefore the possibility of interstrand electrolytic corrosion, due to the dissimilar metals, i.e. zinc/aluminium in an ACSR conductor, is avoided. Clad steel conductors therefore are not normally required to be provided with greased cores which is usually necessary with ACSR conductors. In addition, there is a slight reduction in resistance since the aluminium of the cladding has a lower resistivity than zinc.

There are various other types of conductor produced for particular situations. ACSR conductors can be produced as 'smooth bodied' conductor. To achieve the 'smooth body' the final layer of strands is made up of wedge shaped segments. Smooth body conductors are used to reduce the possibility of wind induced conductor vibration which might otherwise occur particularly with long river crossing spans.

A number of producers manufacture a 'self-damping' conductor. This is a conductor which is laid-up with an annular air space between the inner aluminium layer and generally the final two layers of aluminium strands. The system of damping is said to operate because if conductor vibration occurs the double layers of conductor strands move relative to the inner conductor and absorb and 'damp' the vibrational energy.

A further type of conductor which is perhaps worthy of note, although little used, is of 'expanded body' construction. This type of conductor is built around spacers to produce a conductor of larger diameter than the normally laid-up conductor with no increase in cross-sectional area. The intention of this conductor is to provide an increased diameter and hence reduced surface electrical stress at working voltage, resulting in improved radio-interference performance and reduced corona loss.

Experimental sections of gapped conductor are now in service. This conductor literally has a coaxial gap between the inner steel strands and the outer aluminium alloy strands. The advantage of this conductor is that it can be operated at higher temperatures than normal conductors. The conductor also has the virtue that it can be operated, under emergency conditions, at considerably higher temperatures than traditional conductor types.

Mention must also be made of a conductor into which optical fibre strands are laid, usually within a protective tube at the centre of the conductor, surrounded by conventional wire strands. The optical fibre is used for the transmission of communication and control information.

Summarising, the conductors most frequently employed at present are either ACSR or aluminium alloy as these provide the most economical type of construction, aluminium being cheaper than copper, and the reduced sag resulting from the higher tensile loadings available from the steel content or high strength aluminium alloy, allows tower heights and hence costs to be minimised.

5.3.2 Clamps and joints

Clamps and joints are very critical components of overhead lines. Joints and dead-ends must be capable of supporting the full line conductor tension, with any current up to full line current (and occasionally fault current) and at any temperature, from minimum ambient to the maximum conductor operating temperature, traditionally 75 K or 85 K. AAAC is frequently operated at greater than 85 K. To cater for emergency conditions conductors are now being operated, for short periods of time at greater than 85 K. See Section 5.3.6. Clamps and joints must also provide a radio noise performance at least equal to that of the line conductor.

For an ACSR conductor, the joint is made in two parts, a galvanised or stainless steel inner cylindrical sleeve, surrounded by an outer cylindrical aluminium sleeve. Figure 5.9 shows a cross-section of a midspan joint. The inner and outer sleeves are compressed by means of a hydraulic, motor-driven press. The dies of the press are interchangeable and are selected for the particular diameter of sleeve which is being compressed.

In preparation for fitting the sleeve, the aluminium conductor strands must be cut away to expose the correct length of steel core wire. The steel strands must not be damaged when the aluminium strands are cut. Most manufacturers require the steel and aluminium to be coated with grease compounds before compression. These compounds generally have corrosion inhibiting properties and may contain lithium based soaps. Some manufacturers require the compounds to be loaded with small abrasive particles which increase the friction developed between strands and the joint body.

A vital detail which must be carefully controlled during fixing of two-part joints is that the outer sleeve must be correctly centred over the inner sleeve. This feature can be controlled by means of the simple jig shown in Figure 5.9. Small dome-headed aluminium plugs are driven into the two locating holes after compression.

During type testing [4], samples must be subjected to a heating cycle current test amounting to at least 1000 cycles of heating due to full load current followed by cooling to room temperature with zero current. During the test, the conductor must be supported under a tensile load applied between clamp and conductors of 20% of the conductor breaking load. After the application of 1000 heating and cooling cycles the clamps and joints are cut open for examination. There must be no indication of burning, fusing or local heating of the fittings or conductor.

Conductor dead-end clamps are manufactured using similar designs to midspan joints and in the past were normally of the 'compression' type. Latterly, wedge-type clamps are being used more frequently but generally only on AAAC conductors. This is because the compression derived from the wedging action of the clamp can only be applied to the complete conductor. It is not easy to apply a wedge clamping system to the steel load-bearing strands of an ACSR conductor.

It is good line maintenance practice to examine the operational performance of midspan joints and dead-end clamps. This is done by means of infra-red or heat sensitive cameras either from ground level or, more

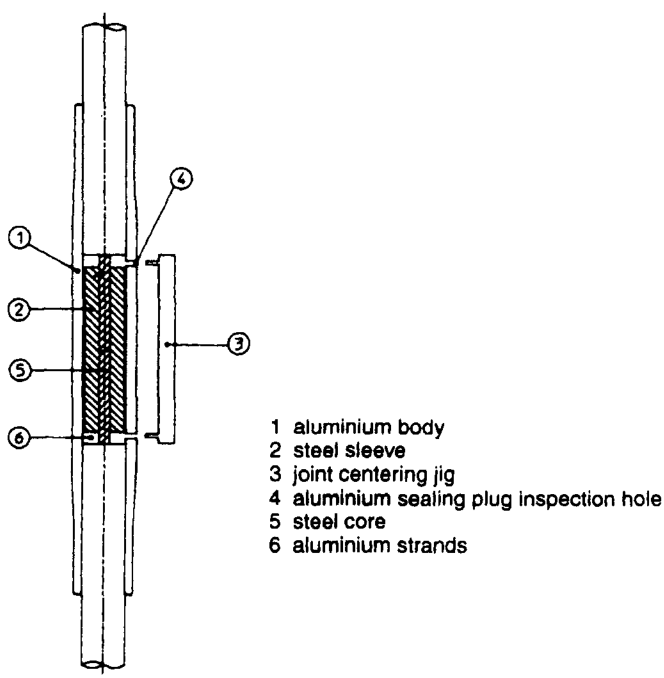

Figure 5.9 Midspan joint for ACSR conductor

frequently, by means of a camera fitted into a helicopter. The helicopter allows the camera operator to film each joint and clamp and, by means of simultaneous voice recording, the current being carried by the line whilst each joint is examined can be superimposed on the record. After the flight, the condition of each joint can be monitored in comfort on the ground.

Badly fitted clamps or those of poor design will become heated. Therefore, any clamp showing signs of heating must be replaced soon after being located. Heating of the clamp is caused by poor contact, which results in high resistance. This becomes progressively more severe until total burn-out occurs, resulting in the dropping of the line conductor.

5.3.3 Equilibrium of the suspended wire

When a wire or conductor is supported at equal height at its extremities the wire will sag in the centre and assume the form of a catenary. The curve of the catenary can be expressed as

$$y = c \cosh \frac{x}{c}$$

For convenience the origin of the curve is chosen so that:

c $= T/W$
L = span length
S = true conductor length C to B
D = sag
T = tension at C
W = mass per unit length
c = distance between C and origin.

Figure 5.10 shows the catenary under consideration:

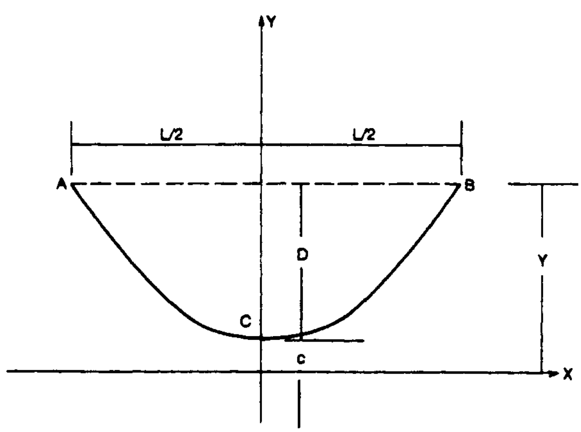

Figure 5.10 Diagram of catenary showing location of parameters

The method of calculating the true conductor length S from A to B is given in Appendix 5.1 together with the derivation of an equation for determining the sag of a conductor in a span. The 'change of state equation' which enables the conductor tension to be calculated for a range of conductor temperatures is given in Appendix 5.2.

The method of calculating conductor sag and tension in steeply sloping ground situations is covered in detail in [5].

5.3.4 Conductor creep

When a conductor is strung in a 'section' of line ('section' being the name for the length of line between any two angle or section towers) the conductors in each span will form catenaries and the tension throughout the section will be virtually constant provided the conductors are supported on suspension insulator sets which are free to swing. The average or equivalent span throughout a section is calculated using the equation:

$$\text{equivalent span} = \sqrt{\frac{L_1^3 + L_2^3 + L_3^3 + L_n^3}{L_1 + L_2 + L_3 + L_n}}$$

where the span lengths, L_1, L_2, L_n etc. are the horizontal distance in metres between the centre of each tower.

When a new ACSR conductor is tensioned for the first time the conductor is found to change in length in a nonelastic manner. That is, the conductor increases in length due to the applied tension and does not return to its original length when the tension is reduced to zero. This increase in length is termed 'creep'. The amount of creep which a conductor exhibits is a function of the proportion of aluminium to steel, the number and diameter of strands and the degree of tightness with which the strands are 'laid-up' during manufacture.

Manufacturers are required to measure and state the creep of the conductor. This information is required because, when the sag of a conductor is calculated to establish the ground clearance for a particular tower height, any slight increase in conductor length will generally result in a significant increase in sag. Typically, with a 500 m span of 'dove' conductor at a tension of 10 kN, a 200 mm increase in true length of the conductor will result in an increase in sag of 1 m.

The value of creep can be expressed as an increase in length for a particular tension. A more convenient method is based on the sag and tension curves which a contractor produces as an aid to establishing correct conductor tensions during stringing. The sag and tension curves are a series of curves of conductor sag against tension for a range of all likely ambient temperatures for the region in which the line will be constructed. If the temperature of a conductor is increased, the true length increases, reducing the tension and increasing the sag. A convenient method of indicating the creep factor is to relate the change in conductor length due to creep to the increase in temperature which would cause the same increase in length.

The contractor is required to provide 'initial' and 'final' sag and tension charts. The 'initial' chart showing the sag and tension of the newly strung conductor and the 'final' sag and tension chart showing the sag and tensions which will prevail after about one year in service and for the remainder of a conductor's service life. The amount of creep is high during the first few hours after tension is applied and gradually diminishes with time during the service life of the conductor.

Typically the allowance for the increase in sag which will result from the inelastic extension, due to creep, is equivalent to the increase in sag which would result from raising the conductor temperature by approximately 22 degrees C.

5.3.5 Wind and ice loads on conductor

The effect of wind pressure on transmission line conductors is to increase the conductor tension. The resultant of the transverse wind load and the vertical load due to conductor mass (combined with ice load if appropriate) is applied to the change of state equation (see Appendix 5.2) in order to arrive at the conductor tension under these particular conditions. It is necessary to consider various combinations of transverse and vertical loads when arriving at the final design parameters for both conductors and towers.

The design wind pressure is derived from meteorological records of wind gust velocities. A number of years' records are necessary to provide statistically meaningful information. An approximate empirical formula which relates wind velocity to pressure (p) on cylindrical bodies is:

$$p = \frac{1}{2}\rho C G V^2$$

where:

- ρ is the air density which is equal to 1.225 kg/m^3 at 15 °C and at normal atmospheric pressure
- C is the drag coefficient, typically equal to 1 for most conductors
- G is the gust response factor which varies with terrain roughness, span length and mean height above ground and typically is between 1.5 and 2.0
- V is the design wind velocity in m/s.

If ice loading has to be considered in the design, it is usual to consider that this is of a uniform radial thickness with a density of 900 kg/m^3. It is unusual to find a combination of maximum wind and maximum ice loading and various combinations of the two loadings are used in transmission line design. The selection of the combination of loads is heavily dependent on the designer's experience.

Ice loading has in recent years become a major problem. Considerable disruption to the high voltage network was experienced in the USA and Canada in the 1997/1998 winter due to heavy formations of ice on both line conductors and the towers. Interesting situations arose where, in some cases, lines running parallel and built to differing design specifications gave different performances. Some lines withstood the severe icing whilst adjacent lines suffered collapse. The early findings are reported in the Insulator News and Market Report (INMR) publications.

Since it appears that more severe weather is being experienced worldwide it is vital that extreme care is exercised in establishing, and probably amending, line criteria. This care is of considerable importance if reliable systems are to be achieved.

5.3.6 Ampacity

When electrical energy is carried by a conductor, the conductor gains heat due to I^2R heating and, if the conductor is exposed to the sun, heat is also gained due to solar radiation. The conductor loses heat by convection and radiation.

In order to calculate the current rating of a conductor, a heat balance equation is employed where the heat gained by the conductor is equal to heat lost by the conductor. This empirical equation can be expressed by:

$$I^2R + \alpha s'd = H_c + E_s\,[(\theta + t + 273)^4 - (t + 273)^4]\,\Pi d \quad \text{W/cm}$$

A typical conductor ampacity calculation is included in Appendix 5.3. A more rigorous method of conductor ampacity calculation is given in [6]. The method shows the allowance which is to be given not only for solar and joule heating but also due to heating developed by magnetic effects.

In recent years utility companies have recognised that the maximum line current ratings traditionally adopted, usually based on the simplistic heat balance equation, give rise to very conservative transfer power capacity. Roger Urwin of the National Grid Company plc [7] analyses the very significant increases in line rating which the NGC has achieved between the 1950s and the present day. In the 1950s the maximum continuous winter rating for double current 400 kV twin 400 mm ACSR conductor lines was 1320 MVA at 400 kV. Progressively, by reconductoring with 599 mm AAAC and with increased conductor working temperature, the winter rating was increased to 1900 MVA. The introduction of a probabilistic approach to line rating calculations, which allows for conductors to be operated at elevated temperatures for short periods of time, gave post-fault winter-time ratings of 2000 MVA. By changing the conductor type to a 570 mm AAAC a further increase to 2180 MVA has been possible.

Finally, by using information supplied by the UK meteorological office, relating to wind velocity and air temperature, the NGC has been able, using a dedicated computer, to calculate the ratings which all lines will have the following day.

The details extracted from Roger Urwin's paper and given above give an indication as to how it has been possible to very significantly increase line transfer capacity. Savings in operational costs will obviously accrue and, if short time ratings are adopted, it is possible to maintain system stability during relatively short periods to allow vital maintenance to be safely undertaken.

5.4 Dampers and spacer dampers

5.4.1 Introduction

Transmission line conductors frequently vibrate, generally because of the action of wind blowing over the conductors. In this section, the causes of vibration and methods of minimising vibration levels are discussed.

5.4.2 Single conductors

Single conductors exhibit two separate forms of vibration. The first, of small amplitude and high frequency, is known as aeolian vibration. The frequency of aeolian vibration is usually in the range of 5 to 100 Hz and with an amplitude of 0.5 to 2 conductor diameters. The wave motion is largely in the vertical plane. The second type of oscillation is called galloping and this type of violent oscillation is most often, but not always, associated with ice-covered conductors.

Aeolian vibration is generally caused by wind blowing 'normal' or up to an angle of about 75 ° to the conductor axis with a velocity of 2 km/h (0.55 m/s) to 32 km/h (8.8 m/s). When wind blows past a conductor at a velocity greater than the critical velocity, vortices begin to form on the leeward side of the conductor. The conductor, because of the helical form of the outer strands, will be subjected to either 'lift' or 'depression' and the direction of the force will depend on the 'yaw' angle of the wind and on the lay of the conductor. Figure 5.11 depicts the lift and drag forces developed by the action of wind on a single conductor.

Aeolian vibration was first noted in the 1920s and it was at about that time that the Stockbridge damper was developed to counteract the effects of this type of vibration. The vibration is developed because of the synchronous shedding of vortices along a length of conductor. This results in alternating lift forces which occur at some natural frequency

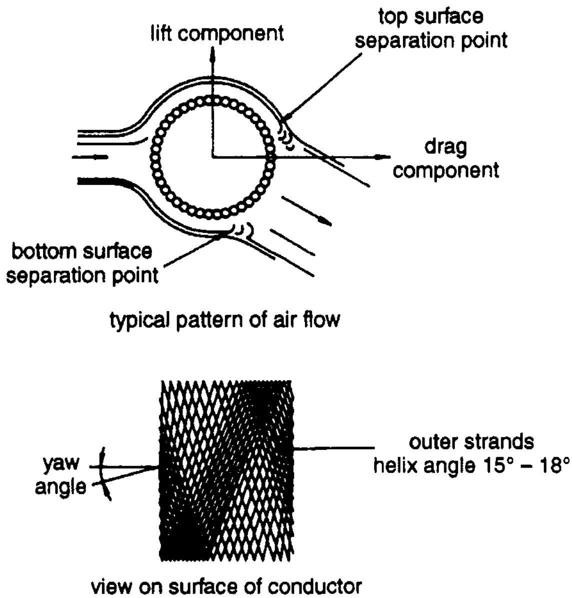

Figure 5.11 Aerodynamic lift developed with stranded conductor

which is proportional to the wind velocity and inversely proportional to the conductor diameter. If the conductor is assumed to have negligible stiffness a conductor will have a natural oscillation frequency of:

$$f = \frac{1}{2L}\sqrt{\frac{T}{m}}$$

where

f = frequency (Hz)
L = length between node points (m)
T = tension (N)
m = mass (kg/m).

If uncontrolled, aeolian vibration can give rise to fatigue damage to conductor strands adjacent to clamps. The damage may occur to the strands beneath the outer layer and may not become visible until severe damage has been incurred.

The Stockbridge damper provides assistance in controlling aeolian vibration. The damper comprises a clamp which is securely fixed to the conductor. A messenger wire of high tensile steel is fixed to the clamp and arranged to be parallel to the conductor. Galvanised iron weights are fitted to each end of the messenger wire and arranged to hang below the conductor. The dampers are fixed at points where antinodes form during conductor vibration in order to absorb the maximum amount of vibrational energy. This energy is dissipated as heat in the messenger wires of the dampers. An equation to establish the fixing position of dampers with respect to the suspension clamp is as follows:

$$D = \frac{0.0152}{V}\sqrt{\frac{Td^2}{W}}$$

where

D = distance, Stockbridge clamp to conductor clamp centres (m)
V = critical wind velocity (m/s)
T = conductor tension (kg)
d = conductor diameter (mm)
W = conductor mass/metre (kg/m).

The design of the Stockbridge damper means that each type of damper will have its own natural vibration frequency. The frequency will depend on the mass of the damper weights and the stiffness of the messenger cable. The result is that a damper will absorb vibrational energy in a relatively limited range of frequencies. One method of improving the performance of Stockbridge dampers is to provide weights of two different masses. The result is to produce a 'flatter', less peaky vibration response curve which will enable a wider range of vibrational frequencies to be absorbed.

A further method of minimising the possibility of aeolian vibration occurring is to string the conductor with a relatively low tension. With ACSR, it is found that if the conductor tension at everyday temperature is kept to less than 20% of the conductor breaking tension then the likelihood of vibration is significantly reduced.

More detailed international studies into conductor vibration performance have been undertaken recently [8]. The CIGRE Task Force who undertook the study quantify some features of conductor vibration which have been noted in service.

It was well known, qualitively, that troublesome vibration was more likely to occur in open Pampas and Desert Regions. The new paper gives 'turbulence intensity factors' for various terrains, which can be applied at the line design stage.

The paper recommends a more precise method of achieving low levels of vibration than the simple consideration of 'line tension at everyday temperature'. The new approach is based on the ratio of H/W where:

'H' is the horizontal tensile load derived at the average temperature of the coldest month in the region where the line will be built
'W' is the conductor mass per metre.

At present the Task Force recommends values of H/W in the range of 1000 m for flat open ground up to a value of 1425 m for 'built up' areas with trees and residential suburbs.

The second mode of conductor vibration, namely galloping, most frequently occurs with ice coated conductors. The conductor is usually found to be coated with ice with a crescent formation which results in a marked change in the aerodynamic properties of the normally circular conductor. Usually, the conductor movement is in the vertical plane and amplitudes of 1 or more metres can occur. In severe cases, interphase flashovers can result due to the transient reduction in phase clearances. Cases of conductors of different phases clashing are not unknown. Generally wind speeds no greater than 45 km/h are required to induce galloping.

There are a number of recorded cases of conductor galloping which had apparently been induced by short duration wind gusts. In general, gust-induced galloping occurs in very long, usually river crossing, spans. Gust-induced galloping can be largely controlled by the use of segmental, smooth-bodied conductors, the smooth conductor surface providing an improved aerodynamic performance over that achieved with a conventionally stranded conductor.

Cases have been recorded where galloping has been induced as a result of corona discharges on the conductor. In these cases the conductor has been of relatively small diameter and the system voltage such as to provide a surface stress of greater than 23 kV_{RMS}/cm. This stress is significantly higher than the stresses at which most normal overhead lines are operated. Accordingly, we do not consider corona induced galloping further.

Fortunately, the occurrence of severe galloping is very rare and generally only affects a limited number of isolated spans and then only in particular geographical locations with particular wind conditions. One method of controlling this type of oscillation is to use interphase ties. These are composite insulators capable of withstanding the full phase to phase voltage, with a creepage path and dry arcing distance of at least $\sqrt{3}$ times the requirements for line to earth voltages. The rod insulators are clamped between the conductor of each phase usually in a delta formation to position the conductors of each phase and eliminate clashing.

5.4.3 Bundled conductors

Twin, triple and quadruple bundled conductors are subject to wind induced aeolian vibration and galloping and, when fitted with spacers, also to sub-span oscillation. Multi-conductor bundles are more prone to vibration than single conductors because any vortices formed by the 'up wind' conductor will affect the 'down wind' conductor. For example, with twin conductors the leading conductor may initially lift causing the leeward conductor to be depressed and then the leading conductor can 'stall' and drop. The action can easily set up a natural rocking action of the conductor.

When first employed some years ago, twin conductors were fitted with Stockbridge dampers to control aeolian vibration. These dampers do control vibration but only at the end of the spans. Vibration of the conductors frequently occurs between the spacers because the Stockbridge dampers fitted to the end of the spans cannot provide any damping action beyond the first spacer. This type of vibration is termed sub-span oscillation. The sub-span vibration generally has a vibrational frequency in the range 0.5 to 2 Hz with amplitudes of up to 2 or 3 times the conductor diameter. The result of much research work was the development of the Spacer damper. Some of the early Spacer dampers employed messenger wires as energy absorbing devices as employed in Stockbridge dampers. Later devices have largely utilised elastomers, loaded in shear or compression, as energy absorbers. Many of the early designs of elastomer spacer provided energy absorption by allowing the arms to swing through a small arc at right angles to the conductor axes. Since sub-conductor oscillation tends to take place in the vertical plane these simple types of spacer damper provide relatively limited amounts of vibration energy absorption. More recent spacer dampers have energy absorption capacity in both the vertical and horizontal planes.

Correctly designed Spacer dampers will provide protection against aeolian vibration, thus dispensing with the requirements for Stockbridge dampers. They will also provide protection against sub-span oscillation.

5.5 Foundations

5.5.1 General

The foundation is the name given to the system which transfers to the ground the various steady state (dead) and variable (live) loads developed by the tower and conductors. Foundations may be variously subjected to compressive or bearing forces, uplift and shear forces, either singly or as a result of any combination of two or three of the forces.

Usually, the limiting design load with transmission line foundations is the uplift load. In this respect, there is a major difference between the design of foundations for transmission lines compared to the design of foundations for most normal civil engineering structures. Accordingly, the amount of literature describing design techniques for overhead line foundations is relatively small compared to the literature available for more traditional civil engineering foundation design practice.

The selected foundation design for a particular tower must provide an economical, reliable support for the life of the line. The foundation must be compatible with the soil and must not lose strength with age. With the progressive increase in transmission system voltages there has been a related increase in foundation sizes and it is worth noting that with a typical quad conductor 500 kV line, single leg uplift and ultimate compression loads of 70 or 80 tonnes are usual for suspension towers. With tension towers, ultimate loads of 200 or 300 tonnes are often developed. In ground of poor load-bearing capacity the dimensions of foundations become considerable.

In the past, it was often acceptable to 'over-design' foundations to allow for uncertainties in the soil characteristics. With the large sizes of foundations for EHV and UHV transmission it is obvious that significant economies can be made in producing foundation designs to exactly match the soil conditions.

Increasingly, transmission lines are routed through areas of poor ground conditions, often for reasons of amenity. This results in the need for the use of special, generally larger, foundations. The logistical problems of installing large foundations, often in difficult ground conditions, must be taken into account when considering foundation design.

5.5.2 Types of ground

The ground in which the foundations are installed can vary from igneous, sedimentary or metamorphic rock, noncohesive soils, sand or gravel to cohesive soil, usually clays. Equally, soils with a high organic content, for example peat, can also prevail. Composite soils will also be found, and examples of these are sandy gravels and silty sand or sandy peat.

Fundamental to the proper design of foundations is an accurate series of soil tests to determine the range of soil types for which the foundation designs will be required. It is good practice to carry out soil tests at a rate of 1 in 5 tower sites. This is generally sufficient to enable an accurate forecast of the range of soil types to be established. It should be pointed out, however, that with large towers having 15 or 20 m square bases, occasionally each of the four legs of a tower may be founded in four different types of ground.

5.5.3 Types of foundation

There are seven basic types of tower foundations:

(i) steel grillage
(ii) concrete spread footing
(iii) concrete auger or caisson
(iv) pile foundation
(v) rock foundation
(vi) raft foundation
(vii) novel foundations.

5.5.4 Foundation calculations

There are a number of methods of calculation of foundation uplift and bearing capacity. In his paper [9] M.J. Vanner gives some relatively sophisticated methods of foundation uplift design. For the purposes of this chapter, however, we will confine ourselves to a simple approach which must be treated with care. Nevertheless, the methods indicated will give reasonably accurate results for the relatively shallow foundations which are normally employed with transmission line towers. A shallow foundation is usually defined as one in which the breadth of the pad is greater than the setting depth.

It is usual to calculate the uplift capacity of a foundation as being equal to the mass of soil contained in the frustum developed between the base of the foundation pad and the soil surface. The angle of the face of the frustum to the vertical is usually designated Φ and will vary from 35 ° to 40 ° in rock, to 25 ° in good homogeneous hard clay to zero in saturated noncohesive ground. The soil density will vary from just over 2000 kg/m^3 for homogeneous rock to about 1600 kg/m^3 for soil with normal moisture content to about 800 or 900 kg/m^3 in the case of ground subjected to water uplift. Methods of calculation of uplift capacity are shown on Figures 5.17 and 5.18 which are presented in Appendix 5.4.

5.6 Insulator design

5.6.1 General

As indicated in Section 5.1, it is usual to employ 'pin-type' insulators for distribution voltages up to 30 or 40 kV. Above this voltage and up to about 132kV system voltage 'line post' insulators may be used or, more usually, from 40kV to the highest transmission system voltages the 'cap and pin' insulator is used.

In Germany and in parts of the world influenced by German design practice, the 'long rod' insulator is sometimes used. In recent years, other designs of insulator have been developed, notably rigid insulators utilising a central load-bearing core formed from glass fibre bonded to form a rod, and having plastic sheds. This type of unit is often referred to as a 'composite insulator'.

5.6.2 Pin-type insulators

The pin-type insulator is so called because in use it is screwed onto a galvanised forged steel 'pin' which is mounted vertically on a metal or wooden crossarm.

For low voltage systems, 6.6 to 11 kV, it is usual to have a one-piece