MECHANICAL CONSIDERATIONS IN LINE PERFORMANCE

1.7.1 Types of Vibrations and Oscillations

In this section a brief description will be given of the enormous importance which designers place on the problems created by vibrations and oscillations of the very heavy conductor arrangement required for e.h.v. transmission lines. As the number of sub-conductors used in a bundle increases, these vibrations and countermeasures and spacings of sub-conductors will also affect the electrical design, particularly the surface voltage gradient. The mechanical designer will recommend the tower dimensions, phase spacings, conductor height, sub-conductor spacings, etc. from which the electrical designer has to commence his calculations of resistance, inductance, capacitance, electrostatic field, corona effects, and all other performance characteristics. Thus, the two go hand in hand.

The sub-conductors in a bundle are separated by spacers of suitable type, which bring their own problems such as fatigue to themselves and to the outer strands of the conductor during vibrations. The design of spacers will not be described here but manufacturers' catalogues should be consulted for a variety of spacers available. These spacers are provided at intervals ranging from 60 to 75 metres between each span which is in the neighbourhood of 300 metres for e.h.v. lines. Thus, there may be two end spans and two or three sub spans in the middle. The spacers prevent conductors from rubbing or colliding with each other in wind and ice storms, if any. However, under less severe wind conditions the bundle spacer can damage itself or cause damage to the conductor under certain critical vibration conditions.

Electrically speaking, since the charges on the sub-conductors are of the same polarity, there exists electrostatic repulsion among them. On the other hand, since they carry currents in the same direction, there is electromagnetic attraction. This force is especially severe during short-circuit currents so that the spacer has a force exerted on it during normal or abnormal electrical operation.

Three types of vibration are recognized as being important for e.h.v. conductors, their degree of severity depending on many factors, chief among which are: (*a*) conductor tension, (*b*)span length, (*c*) conductor size, (*d*) type of conductor, (*e*) terrain of line, (*f*) direction of prevailing winds, (*g*) type of supporting clamp of conductor-insulator assemblies from the tower, (*h*) tower type, (*i*) height of tower, (*j*) type of spacers and dampers, and (*k*) the vegetation in the vicinity of line. In general, the most severe vibration conditions are created by winds without turbulence so that hills, buildings, and trees help in reducing the severity.

The types of vibration are: (1) Aeolian Vibration,
(2) Galloping, and
(3) Wake-Induced Oscillations.

The first two are present for both single-and multi-conductor bundles, while the wake-induced oscillation is confined to a bundle only. Standard forms of bundle conductors have sub-conductors ranging from 2.54 to 5 cm diameters with bundle spacing of 40 to 50 cm between adjacent conductors. For e.h.v. transmission, the number ranges from 2 to 8 sub-conductors for transmission voltages from 400 kV to 1200 kV, and up to 12 or even 18 for higher voltages which are not yet commercially in operation. We will briefly describe the mechanism causing these types of vibrations and the problems created by them.

1.6.2 Aeolian Vibration

When a conductor is under tension and a comparatively steady wind blows across it, small vortices are formed on the leeward side called Karman Vortices (which were first observed on aircraft wings). These vortices detach themselves and when they do alternately from the top and bottom they cause a minute vertical force on the conductor. The frequency of the forces is given by the accepted formula

$$F = 2.065\, v/d, \text{ Hz} \quad \text{...(1.5)}$$

where v = component of wind velocity normal to the conductor in km/ hour, and d = diameter of conductor in centimetres. [The constant factor of equation (1.5) becomes 3.26 when v is in mph and d in inches.]

The resulting oscillation or vibrational forces cause fatigue of conductor and supporting structure and are known as aeolian vibrations. The frequency of detachment of the Karman vortices might correspond to one of the natural mechanical frequencies of the span, which if not damped properly, can build up and destroy individual strands of the conductor at points of restraint such as at supports or at bundle spacers. They also give rise to wave effects in which the vibration travels along the conductor suffering reflection at discontinuities at points of different mechanical characteristics. Thus, there is associated with them a mechanical impedance.

Dampers are designed on this property and provide suitable points of negative reflection to reduce the wave amplitudes. Aeolian vibrations are not observed at wind velocities in excess of 25 km/hour. They occur principally in terrains which do not disturb the wind so that turbulence helps to reduce aeolian vibrations. In a bundle of 2 conductors, the amplitude of vibration is less than for a single conductor due to some cancellation effect through the bundle spacer. This occurs when the conductors are not located in a vertical plane which is normally the case in practice. The conductors are located in nearly a horizontal plane. But with more than 2 conductors in a bundle, conductors are located in both planes. Dampers such as the Stockbridge type or other types help to damp the vibrations in the subspans connected to them, namely the end sub-spans, but there are usually two or three sub-spans in the middle of the span which are not protected by these dampers provided only at the towers.

Flexible spacers are generally provided which may or may not be designed to offer damping. In cases where they are purposely designed to damp the sub-span oscillations, they are known as spacer-dampers. Since the aeolian vibration depends upon the power imparted by the wind to the conductor, measurements under controlled conditions in the laboratory are carried out in wind tunnels.The frequency of vibration is usually limited to 20 Hz and the amplitudes less than 2.5 cm.

1.6.3 Galloping

Galloping of a conductor is a very high amplitude, low-frequency type of conductor motion and occurs mainly in areas of relatively flat terrain under freezing rain and icing of conductors. Theflat terrain provides winds that are uniform and of a low turbulence. When a conductor is iced, it presents an unsymmetrical cross-section with the windward side having less ice accumulation than the leeward side of the conductor. When the wind blows across such a surface, there is an aerodynamic lift as well as a drag force due to the direct pressure of the wind. the two forces give rise to torsional modes of oscillation and they combine to oscillate the conductor with very large amplitudes sufficient to cause contact of two adjacent phases, which may be 10 to 15 metres apart in the rest position. Galloping is induced by winds ranging from 15 to 50 km/hour, which may normally be higher than that required for aeolian vibrations but there could be an overlap.

The conductor oscillates at frequencies between 0.1 and 1 Hz. Galloping is controlled by using "detuning pendulums" which take the form of weights applied at different locations on the span. Galloping may not be a problem in a hot country like India where temperatures are normally above freezing in winter. But in hilly tracts in the North, the temperatures may dip to below the freezing point. When the ice loosens from the conductor, it brings another oscillatory motion called Whipping but is not present like galloping during only winds.

1.7.4 Wake-Induced Oscillation

The wake-induced oscillation is peculiar to a bundle conductor, and similar to aeolian vibration and galloping occurring principally in flat terrain with winds of steady velocity and low turbulence. The frequency of the oscillation does not exceed 3 Hz but may be of sufficient amplitude to cause clashing of adjacent sub-conductors, which are separated by about 50 cm. Wind speeds for causing wake-induced oscillation must be normally in the range 25 to 65 km/hour. As compared to this, aeolian vibration occurs at wind speeds less than 25 km/hour, has frequencies less than 20 Hz and amplitudes less than 2.5 cm. Galloping occurs at wind speeds between 15 and 50 km/hour, has a low frequency of less than 1 Hz, but amplitudes exceeding 10 meters. Fatigue failure to spacers is one of the chief causes for damage to insulators and conductors. Wake-induced oscillation, also called "flutter instability", is caused when one conductor on the windward side aerodynamically shields the leeward conductor.

To cause this type of oscillation, the leeward conductor must be positioned at rest towards the limits of the wake or wind shadow of the windward conductor. The oscillation occurs when the bundle tilts 5 to 15° with respect to a flat ground surface. Therefore, a gently sloping ground with this angle can create conditions favourable to wake-induced oscillations. The conductor spacing to diameter ratio in the bundle is also critical. If the spacing B is less than $15d$, d being the conductor diameter, a tendency to oscillate is created while for $B/d > 15$ the bundle is found to be more stable. As mentioned earlier, the electrical design, such as calculating the surface voltage gradient on the conductors, will depend upon these mechanical considerations.

1.7.5 Dampers and Spacers

When the wind energy imparted to the conductor achieves a balance with the energy dissipated by the vibrating conductor, steady amplitudes for the oscillations occur. A damping device helps to achieve this balance at smaller amplitudes of aeolian vibrations than an undamped conductor. A simpler form of damper is called the Armour Rod, which is a set of wires twisted around the line conductor at the insulator supporting conductor and hardware, and extending for about 5 metres on either side. This is used for small conductors to provide a change in mechanical impedance. But for heavier conductors, weights must be used, such as the Stockbridge, which range from 5 kg for conductors of 2.5 cm diameter to 14 kg for 4.5 cm. Because of the steel strands inside them ACSR conductors have better built-in property against oscillations than ACAR conductors.

1.8 RESISTANCE OF CONDUCTORS

Conductors used for e.h.v. transmission lines are always stranded. Most common conductors use a steel core for reinforcement of the strength of aluminium, but recently high tensile strength aluminium is being increasingly used, replacing the steel. The former is known as ACSR (Aluminium Conductor Steel Reinforced) and the latter ACAR (Aluminium Conductor Alloy Reinforced). A recent development is the AAAC (All Aluminium Alloy Conductor) which consists of alloys of Al, Mg, Si. This has 10 to 15% less loss than ACSR.

When a steel core is used, because of its high permeability and inductance, power-frequency current flows only in the aluminium strands. In ACAR and AAAC conductors, the cross-section is better utilized.Fig. 1.1 shows an example of a stranded conductor.

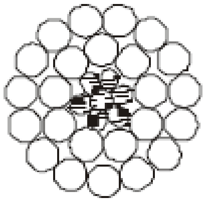

Fig 1.1 Cross-section of typical ACSR conductor.

If n_s = number of strands of aluminium, d_s = diameter of each strand in metre and ρa =specific resistance of Al, ohm-m, at temperature *t*, the resistance of the stranded conductor per

km is

$$R = \rho_a 1.05 \times 10_3/(2 /4\pi d_s n_s) = 1337\rho_a d_{s2} n_s, \text{ ohms } ...(1.6)$$

The factor 1.05 accounts for the twist or lay whereby the strand length is increased by 5%

1.9 PROPERTIES OF BUNDLED CONDUCTORS

Bundled conductors are exclusively used for e.h.v. transmission lines. Only one line in the world, that of the Bonneville Power Administration in the U.S.A., has used a special expanded ACSR conductor of 2.5 inch diameter for their 525 kV line. Fig. 1.2 shows examples of conductor configurations used for each phase of ac lines or each pole of a dc line.

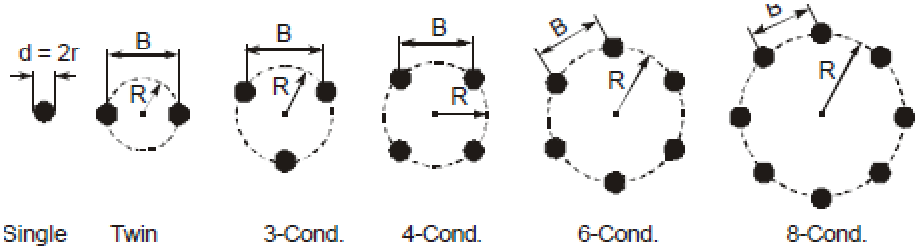

Fig. 1.2 Conductor configurations used for bundles in e.h.v. lines.

As of now a maximum of 18 sub-conductors have been tried on experimental lines but for commercial lines the largest number is 8 for 1150-1200 kV lines.

1.10 INDUCTANCE OF E.H.V. LINE CONFIGURATIONS

Fig. 1.3 shows several examples of line configuration used in various parts of the world. They range from single-circuit (S/C) 400 kV lines to proposed 1200 kV lines. Double-circuit (D/C) lines are not very common, but will come into practice to save land for the line corridor. As pointed out in chapter 2, one 750 kV circuit can transmit as much power as 4-400 kV circuits and in those countries where technology for 400 kV level exists there is a tendency to favour the four-circuit 400 kV line instead of using the higher voltage level.

This will save on import of equipment from other countries and utilize the know-how of one's own country. This is a National Policy and will not be discussed further.

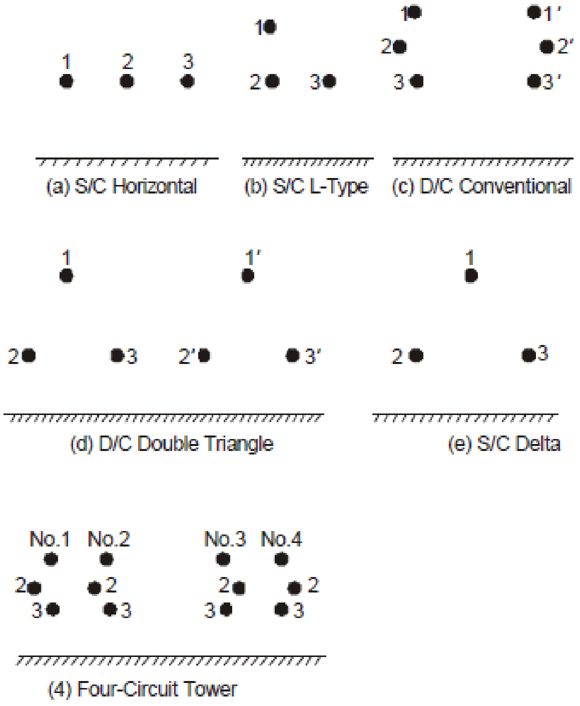

Fig. 1.3 E.h.v. line configurations used.

1.10.1 Inductance of Two Conductors

We shall very quickly consider the method of handling the calculation of inductance of two conductors each of external radius *r* and separated by a distance *D* which forms the basis for the calculation of the matrix of inductance of multi-conductor configurations.

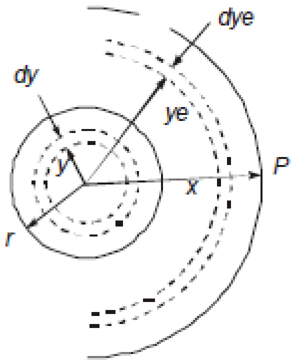

Fig. 1.4 Round conductor with internal and external flux linkages.

Figure 1.4 shows a round conductor carrying a current *I*. We first investigate the flux linkage experienced by it due, up to a distance *x*, to its own current, and then extend it to two conductors. The conductor for the present is assumed round and solid, and the current is also assumed to be uniformly distributed with a constant value for current density $J = I/\mathrm{p}r_2$. There are two components to the flux linkage: (1) flux internal to the conductor up to *r*; and (2) flux external to the conductor from *r* up to *x*.

Inductance Due to Internal Flux

At a radius *y* inside the conductor, Ampere's circuital law gives *H.dl*= current enclosed. With a uniform current density *J*, the current enclosed up to radius *y* is $I_y = y_2 I/r_2$. This gives,

$$H_y . 2\pi y = I y^2/r^2 \text{ or, } H_y = \frac{I}{2\pi r^2} \cdot y$$

Now, the energy stored in a magnetic field per unit volume is

$$w_y = \frac{1}{2}\mu_0 \mu_r H_y^2 = \frac{I^2 \mu_0 \mu_r}{8\pi^2 r^4} y^2, \text{ Joules/m}^3$$

Consider an annular volume at *y*, thickness *dy*, and one metre length of conductor. Its volume is ($2\pi y$.dy.1) and the energy stored is

$$dW = 2\pi\, y.w_y.dy = \frac{I^2\mu_0\mu_r}{4\pi r^4} y^3.dy$$

Consequently, the total energy stored up to radius *r* in the conductor can be calculated. But this is equal to , where = *Li* = inductance of the conductor per metre due to the internal flux linkage.

Therefore,

$$\frac{1}{2}L_i I^2 = \int_0^r dW = \frac{I^2\mu_0\mu_r}{4\pi r^4}\int_0^r y^3.dy = \frac{\mu_0\mu_r}{16\pi} I^2$$

Consequently, $L_i = \mu_0\mu_r/8\pi$, Henry/metre

For a non-magnetic material, $\mu_r = 1$. With $\mu_0 = 4\pi\times 10^{-7}$ H/m, we obtain the interesting result that irrespective of the size of the conductor, the inductance due to internal flux linkage is

$$L_i = 0.05\ \mu\ \text{Henry/metre for } \mu_r = 1$$

The effect of non-uniform current distribution at high frequencies is handled in a manner similar to the resistance. Due to skin effect, the internal flux linkage decreases with frequency, contrary to the behaviour of resistance. The equation for the inductive reactance is

$$X_i(f) = R_0.(X/2).\ \frac{\text{Ber}(X).\text{B}'\text{er}(X) + \text{Bei}(X).\text{B}'\text{ei}(X)}{[\text{B}'\text{er}(X)]^2 + [\text{B}'\text{ei}(X)]^2}$$

where *Xi(f)* = reactance due to internal flux linkage at any frequency *f*, *R*0 = dc resistance of conductor per mile in ohms, and $X = 0.0636\, f/R_0$. [If *Rm* = resistance per metre, then $X = 1.59 \times 10^{-3} f/Rm$.]

1.11 SEQUENCE INDUCTANCES AND CAPACITANCES

The use of Symmetrical Components for analysing 3-phase problems has made it possible to solve very extensive network problems. It depends upon obtaining mutually-independent quantities from the original phase quantities that have mutual interaction. Following this concept, we will now resolve the inductances, capacitances, charges, potentials etc., into independent quantities by a general method. This procedure will be used for many types of excitations other than power-frequency later on. The basis for such transformations is to impress suitable driving functions and obtain the resulting responses.

1.12 RESISTANCE AND INDUCTANCE OF GROUND RETURN

Under balanced operating conditions of a transmission line, ground-return currents do not flow. However, many situations occur in practice when ground currents have important effect on system performance. Some of these are:

(*a*) Flow of current during short circuits involving ground. These are confined to single line to ground and double line to ground faults. During three phase to ground faults the system is still balanced;
(*b*) Switching operations and lightning phenomena;
(*c*) Propagation of waves on conductors;
(*d*) Radio Noise studies.

The ground-return resistance increases with frequency of the current while the inductance decreases with frequency paralleling that of the resistance and inductance of a conductor. In all cases involving ground, the soil is inhomogeneous and stratified in several layers with different values of electrical conductivity. In this section, the famous formulas of J.R. Carson (B.S.T.J. 1926) will be given for calculation of ground resistance and inductance at any frequency in a homogeneous single-layer soil. The problem was first applied to telephone transmission but we will restrict its use to apply to e.h.v. transmission lines.