CHAPTER 1

INTRODUCTION

1.1 ROLE OF POWER TRANSMISSION AND IMPORTANCE OF TRANSMISSION LINE STRUCTURES

Electric power today plays an increasingly important role in the life of the community and the development of various sectors of economy. Developing countries like India therefore give a high priority to power development programmes. In fact, the economy has become increasingly dependent on electricity as a basic input.

Soon after Independence (1947), the economic importance of electricity was recognised and legislation was enacted for the creation of the requisite organisational base - Central Electricity Authority at the National level and Electricity Boards at the State level - for implementing a planned development programme framed under the successive plans beginning with the First Five-Year Plan which was launched in 1950-51.

While in absolute terms the level of electrical energy consumption in India is far below the levels obtaining in the developed countries, the per capita consumption has increased from 14.6 kWh in 1950 to 154 kWh in 1983-84. The installed generating capacity and the transmission and distribution networks to carry power from the generating stations to the load centres and from thereon to the ultimate consumers have increased manifold.

As in other countries, the growth of transmission networks in India is dependent on the historic growth of electrical energy consumption and the future growth expected for the next few decades. As loads grow and individual systems
FIG. 1.1. GROWTH OF TRANSMISSION NETWORK IN INDIA
and interconnections between systems develop, the transmission capability must correspond to the system capability.

Overhead transmission lines provide the means of connecting the generating capacities to the load centres as well as interconnecting the continuous power systems, and the cost and reliability of power supply are considerably influenced by them.

The transmission voltage has increased from 110 kV around 1945 to 400 kV in 1978. The growth of the transmission networks at different voltages over the period from 1950 to 1984-85 together with the anticipated increase upto 1989-90 (end of the Seventh Plan Period) is shown in Fig.1.1.

It is significant that the higher voltage lines at 220 kV and 400 kV with higher transmission capability have experienced a much higher rate of growth. This trend is expected to continue for some years in view of the large pithead thermal stations and nuclear stations likely to come up in the various regions of the country to serve the regional needs rather than the individual area needs.

The structures of overhead transmission lines, comprising essentially the supports and foundations, have the role of keeping the conductors at the necessary distance from one another and from the earth, with the specified factors of safety, and from the point of power transmission, are unproductive. The cost per kilometre of line related to the cross-section (in \( \text{mm}^2 \)) of all line conductors may therefore be taken as a criterion for the economy of the line.

The 'unproductive' costs are much higher than the 'productive' costs per \( \text{km/mm}^2 \) of aluminium cross-section and the towers and foundations constitute the major components of the 'unproductive' costs about 35-45\% of the total cost of the line.
This underlines the importance of effecting all possible economies in towers and foundations from the design stage through erection.

The anticipated growth during the Seventh Plan period is about 10,000 circuit-km per year. This corresponds to an annual expenditure of approximately Rs.2,500 million (1986 price level) on transmission line supports.

With the anticipated growth of transmission network of about 10,000 circuit-km per year in the Seventh Plan and increase in exports, it is expected that a production capacity of 200,000 tonnes per annum would be required, pointing to the need for increasing the tower fabricating capacity during the Seventh Plan period as the small fabricators and the captive units of some State Electricity Boards together have an installed capacity of about 51,300 tonnes per annum.

Thus, the transmission programme in the country is likely to be accelerated in future and the need for effecting all possible economies through improved designs on the one hand and implementing the transmission projects on schedule on the other, need hardly be emphasised.

1.2 VARIOUS TYPES OF TOWERS AND TOWER CONFIGURATIONS

1.2.1 Types of towers

In many countries various types of towers for transmission lines are used. They are

- Single pole or H type using timber
- Reinforced, composite or prestressed concrete pole or frame type
- Steel pole guyed or truss type
- Aluminum pole guyed or truss type
- Truss type towers with light gauge cold formed tubes and sections.
The selection depends on the availability of materials, cost of materials, feasibility of erection and functional importance of tower.

Towers are classified generally in current practice as guyed and self-supporting types. The guyed towers may be pole guyed, V frame guyed, two leg cross braced and guyed. The self supporting towers may be narrow based or wide based. For high voltage single circuits B or corset type (horizontal configurations) and for double circuits barrel type (vertical configurations) towers are used efficiently. Guyed towers are light in weight but required more space than self supporting towers. Self supporting towers are heavier but occupy less ground space. The weight of self supporting towers is reduced by introducing tubes or cold formed sections or aluminium sections instead of steel angle sections that are normally used in practice.

Based on line deviation, towers are classified as tangent towers, small angle towers, medium angle towers, large angle and dead end towers. Anchor towers are also used for end support.

Based on circuits they are classified as single circuit, double circuit, multiple circuit and parallel towers.

Special towers are used for river-crossing, railway or highway crossing, or allied situations, telecommunication line etc. According to the tower base, they are called rectangular, square or triangular base towers.

1.2.2 Tower configuration

The tower configuration is dictated by the number of circuits and clearances required for the transmission line and the clearances required for the ground or other obstructions. Within these limits, various tower configurations can be developed and the designer should investigate these to select the most economical one.
The selection of an optimum outline and system of bracing patterns contributes to a great extent, in developing an economical design of power transmission line towers. For a particular tower configuration selected, the outline decided shall satisfy both electrical and structural requirements, consistent with economy.

The tower configurations of a transmission tower line depend on the following factors:

- length of insulator assembly
- minimum clearance from conductors to both tower steel and personnel doing hot-line maintenance work
- mid span clearance under dynamic conductor behaviour and lightning protection of the line
- geometric mean distance between conductors and between conductor and tower
- location of ground wire or wires with respect to the outermost conductor
- the minimum clearance of the lowest conductor above ground level.

The various constituents of an outline diagram are:

- tower height considered from ground level
- length of cross arms
- tower widths at base and top hamper
- bracing patterns adopted

The various constituents are described below briefly.

1. Square and rectangular bases: Square based towers are commonly used. The more recent developments in the structural configurations are triangular and rectangular. The customary practice is the use of the square cross-section with all the faces of the tower identical. Examination of the various loading conditions, for which the tower is designed, will reveal that the tower need have no longitudinal strength under the normal operating conditions. Its longitudinal strength is required only during the wire stringing operations
and under the assumptions of brokenwire conditions. It is
apparent from these loading conditions that the tower need not
be as strong in the longitudinal direction as in the transverse
direction. Considerable investigations had proved that a
rectangular cross section will be the most economical configura-
tion and is being adopted in some countries.

(ii) Triangular base: Some of the advantages offered by this
type are smaller overall dimensions requiring minimum right-of-
way, significant reduction in cost etc.

The maximum width of tower for any angle of viewing is
equal to the side of the equilateral triangle, whereas for a
square base tower, the maximum width when viewed diagonally is
41.4% more than the side of the square base. Because of the
reduction in the number of faces from four to three, there is a
reduction in the number of foundations, bolts and gusset plates.
A saving of 15% steel is estimated by the use of a three legged
tower when compared to a square based tower.

The structure is isostatic with all the attendant
advantages. The only disadvantage felt earlier was the
requirement of special 60° sections for leg members. However,
by a proper orientation of the usual 90° angles, the
difficulties earlier experienced in the fabrication of such
3 legged towers had been avoided, while retaining the full
benefit of their lesser weight.

(iii) Tower height: The factors governing the height of a tower are:

. minimum permissible ground clearance
. maximum sag
. vertical spacing between conductors
. vertical clearance between the groundwire and top
conductors.
(iv) Minimum permissible ground clearance: On safety considerations, power conductors, along the route of the transmission line, should maintain requisite clearances to ground in open country, National Highways, rivers, railway tracks, tele-communication lines, other power lines, etc. as laid down in the Indian Electricity Rules, or standards or codes of practice in vogue.

(v) Spacing of conductors: Considerable differences are found in the conductor spacings adopted in different countries and in different transmission systems in the same country.

The spacing of conductors is determined by considerations that are partly electrical and partly mechanical. The material and diameter of the conductors should also be taken into account when deciding upon the spacing, because a smaller conductor, especially if made of aluminium, having a small weight in relation to the area presented to a cross wind, will swing out of the vertical plane farther than a conductor of a larger cross section. Usually conductors will swing synchronously (in phase) in wind, but with long spans and small wires, there is always the possibility of the conductors swinging non-synchronously, and the size of the conductor and the maximum sag at the centre of the span are factors which should be taken into account in determining the distance apart at which they should be strung. A horizontal separation equal to between one and one-and-a-half times the sag at the temperature corresponding to the season of the highest wind velocities should be sufficient to prevent wires swinging within sparking distance of each other. The vertical spacing may be from three quarters to two-thirds of the horizontal spacings.

With suspension insulators, the swing of the insulator string has to be considered and clearances to the structure are to be determined accordingly. The clearances so determined generally give a spacing for the conductors at the supports greater than the required mid-span separation. This clearance
should then be checked to see if it is sufficient for the required midspan separation.

(iii) Vertical clearance between groundwire and top conductor:
This is governed by the angle of shielding (that is, the angle which the line joining the groundwire and the outermost conductor makes with the vertical) required for the interruption of direct lightning strokes at the ground and the minimum midspan clearances between the groundwire and the top power conductor, the shield angle varies from about $25^\circ$ to $30^\circ$ depending on the configuration of conductors and the number of groundwires (one or two) provided.

(iv) Determination of tower width at the base: The base width at the concrete level is the distance between the centre of gravity at one corner leg and the centre of gravity of the adjacent corner leg. There is a particular base width which gives the minimum total cost of the tower and foundations.

Ryle(1) has given the following formula for a preliminary determination of the economic base width.

$$B = 0.42 \sqrt{M_0} \tag{1.1}$$

The ratio of base width to total tower height for most towers is generally about $1/5$ to $1/10$ from large-angle towers to tangent towers.

Recently the following equations have been suggested, based on the best fit straight line relationship between the base width $B$ and $\sqrt{M_0}$

$$B = 0.0782 \, \sqrt{M_0} + 1.0 \tag{1.2}$$
$$B = 0.0691 \, \sqrt{M_0} + 0.7 \tag{1.3}$$

Equations 1.2 and 1.3 are for suspension and angle towers respectively.
It should be noted that Ryle's formula is intended for use along with actual external loads acting on the tower whereas the formulas in eq.1.2 and eq.1.3 take into account a factor of safety of 2.0 and is applicable for construction and design practices in India.

Narrow-base towers are commonly used in Western Europe, especially Germany, mainly on way leave considerations. British and American practices generally favour the wide-base type of design, for which the total cost of tower and foundations is a minimum. In the USA a continuous, wide strip of land called the 'right of way' has usually to be acquired along the line route. In Great Britain the payments made for individual tower way-leaves are generally reasonably small and not greatly affected by tower-base dimensions. Therefore, it has been possible to adopt a truly economical base width in both the United States and Great Britain.

A wide taper in the tower base reduces the foundation loading and costs but increases the cost of the tower and site. The minimum cost in respect of a tower width, is greater in the case of bad soil than good soil. A considerable saving in foundation cost results from the use of towers with only three legs, the tower being of triangular section throughout its height. This form of construction entails tubular legs or special angle sections. The three-footing anchorage has further advantages, e.g., greater accessibility of the soil underneath the tower when the land is cultivated.

(viii) Determination of tower width at top hamper: The width at top hamper is the width of the tower at the level of the tower cross-arm in the case of barrel type of towers (in double circuit towers it may be at the middle cross-arm level) and at the waist line in the case of towers with horizontal configuration of conductors.
The following considerations are taken into account in finding the width of the tower at the top bend line:

(i) Horizontal spacing between conductors based on the midspan clearance between the power conductor under the severest wind and of galloping conditions, and the electrical clearance of the line conductor to tower steel work.

(ii) The slope of the legs should be such as to enable the corner members intersect as near the C.G. of the loads as possible. Then braces will be least loaded. Three cases are possible depending upon the relative position of the C.G. of the loads and intersection of the tower legs. In case (i) the entire shear is taken up by the legs and the bracings do not carry any stress. In case (ii) a condition in which the resultant of all loads is below the intersection of tower legs. The shear, here, is shared between legs and bracings, which is a desirable requirement for an economical tower design. In the last case, the legs have to withstand greater forces than in cases (i) and (ii) because the legs intersect below the C.G. of the loads acting on the tower. This outline is uneconomical.

The top hamper width is generally found to be about $1/3$ of the base width for tangent and light angle towers and about $1/3.5$ of the base width for medium and heavy angle towers. For horizontal configurations, the width at the waist line is, however, found to vary from $1/1.5$ to $1/2.5$ of the base width.

(ix) Bracing patterns: Irrespective of the type of bracing, all diagonal members of the bracing should be designed for tension and compression. The usual systems of bracing adopted for transmission line towers are as follows:
According to the various systems mentioned above suitable configurations are selected.

1.3 TOWER FOUNDATIONS

The tower foundations form 10 to 30% of the overall cost of towers depending on the type of foundations, loading on towers and the type of soil. The type of foundation adopted varies from location to location even for the same type of transmission tower. Experience shows that collapse of towers, is often initiated by foundation failures. To design a safe and economical foundation, knowledge of soil behaviour, structural behaviour of the foundation and a realistic estimate of loads acting on the tower are necessary.

The types of foundations generally adopted for transmission line towers are shown in Figure 1.2 and described below.

- Straight drilled shaft
- Bellied drilled shaft
- Pad and stem footing without undercut
- Pad and stem footing with undercut
- Pad screw anchor type
- Under-reamed pile type
- Grillage
- Rock anchors

(i) Straight drilled shaft: This is constructed by augering a cylindrical hole and filling it with reinforced concrete. The diameter varies from 0.5 to 2 m and shaft depth from 3 to 15 m. The skin friction between ground and shaft is an important factor in resisting uplift in such foundations. This type is
1. STRAIGHT DRILLED SHAFT
2. BELLED DRILLED SHAFT
3. PAD AND STEM FOOTING
4. PAD AND STEM FOOTING WITH UNDER CUT
5. SCREW ANCHOR FOOTING
6. GRILLAGE
7. UNDER - REAMED PILES
8. ROCK ANCHOR

FIG. 1.2. TYPES OF TOWER FOUNDATION
extensively used for tower foundations in the USA and is likely to gain acceptance for wide use in India.

(11) Bailed drilled shaft: In this case, a bell shaped pit is excavated below the drilled shaft hole by means of some mechanical equipment and very little disturbance of the adjacent soil takes place so that the uplift loads are resisted by the undisturbed material. This avoids the use of forms except for the portion above ground level. This type of foundation has been found to develop an uplift load of 2 to 3 times that of an identical footing without undercut.

(iii) Pad and stem type without undercut: These footings are generally provided for non-cohesive soils such as uncemented sand or gravel, which will not stand on vertical excavation lines and are therefore not undercut on the pad. The practice usually followed in India at present is to provide pad type footings without undercut.

(iv) Pad and stem type with undercut: These footings are adopted in firm cohesive soils which stand up on vertical excavation lines and are undercut on the pad. The excavation does not require the use of any mechanical equipment. Experience with pad type footing with undercut has shown that this type of footing develops resistance to uplift to the extent of 2 to 3 times that of the footing without undercut.

(v) Pad screw anchor type: The screw anchor footing is a hybrid design not yet in widespread use. It combines the advantage of pad as well as anchor type. It is generally used in situations where large uplift forces are to be resisted and the soil bearing capacity is low.

(vi) Under-reamed pile type: Drilled shaft of more than 3 m length with one or more under reams is used successfully in medium dense cohesive soils. This is more economical than any other type in such soils. Generally a group of piles are used for each tower
leg. The group capacity is assessed both by the block capacity and individual pile capacity. The individual capacity is controlled either by the plug failure or cone failure.

(vii) **Grillage foundation**: Earth grillage has found wide application in the U.S.A., Canada and some continental countries. The chief objection to earth grillage appears to be that steel may be easily attacked by corrosive constituents of the soil and that the periodical excavation necessary for purposes of maintenance would loosen the soil and consequently lessen the anchorage until the earth consolidates again. However, the Canadian experience shows that, when the grillage is employed in medium dry sand, clay or sandy clay soils, no special precautions are necessary for protecting the buried steel work apart from using galvanised steel for all the subterranean members and generally limiting the minimum thickness of steel to above 6 mm. In isolated cases where excess moisture exists or chemically active soil is encountered, the tower footing members are coated with some form of asphalt or completely encased in concrete. In India, the Tata Hydro Electric Co. have used grillage foundations with satisfactory results. The steel is treated with one coat of bituminous paint and a top coat of asphalt given every year at ground level and 0.6 m below ground level.

(viii) **Rock anchors**: Rock anchors are suitable in the areas with rock out-crop. Based on the amount of uplift, the anchor may be a single bar or a group of bars welded to the tower leg. Where solid rock is encountered the vertical bars below the stub angle which form the cage for the footing may be drilled and grouted into the rock.

Within the fixed anchor length the applied load may be mobilised from the top and downwards or from the base upwards, depending on the method of attachment of the tendon to the grout column. The former is known as tension anchor and the
latter, compression anchor. Tension anchors are common in India. Compression anchors are gradually coming into usage.

1.4 NEED FOR OPTIMIZING TOWERS AND TOWER FOUNDATIONS

For a long time towers were analysed in design offices by treating each face of a square lattice tower as a plane truss. With simplifying assumptions these redundant plane trusses were designed as determinate systems using graphical methods.

In view of the large number of identical towers required to support the power lines and since invariably steel, a scarce costly and valuable material is used for the fabrication of these towers, a small saving in weight and hence in the cost of one tower, will result in an enormous saving in the total cost of the project. Hence it has become evident that a rational design procedure is essential for the design of Power Transmission Line Towers.

The aim of optimisation in tower design is to minimise the overall cost. This is achieved by considering the following as design variables.

- cross sectional area of members
- geometry of the towers
- material of the tower
- shape and type of members.

The cross sectional area and geometry can be optimised using mathematical programming techniques. Similarly the effect of changing material and/or shape of member on the overall weight of the tower should also be investigated.
The cost of transmission line towers is 35 to 45% of their total cost and the cost of tower foundation is 5 to 15% of the cost of a transmission line. It is believed that about 5 to 10% in tower cost and 20 to 40% in the cost of foundation could be saved through the use of optimization procedures or better design methods.

Thus there is need to evolve efficient analytical methods involving optimization techniques and effect economy using new materials and techniques.

1.5 FEASIBILITY

Since computer facility is available, the finite element method has become the major numerical analysis tool in structural engineering. It seemed straightforward to pose the design problem as a mathematical programming formulation. One would optimise the weight or cost of the structure under stress, displacement, frequency, instability, and failure constraints. Design variables included cross-sectional area, geometrical and even topology variables and the structure would invariably be subjected to multiple independent loading conditions. However, it turned out that the available computer time and minimisation algorithm restrict optimal solution to a limit.

Further it is known that although structural optimisation can be expressed in a certain mathematical formulation, it can only produce the preliminary design information. Selection of a method from an economical, simple and practical viewpoint is important. Optimum solution is modified properly in accordance with factors not included in the mathematical formulation. Transmission line tower design involves innumerable parameters. A few of them are specified on the electrical engineering considerations.
The foundation of the tower is influenced considerably by different soil conditions available at various sites when compared with the work done on tower optimisation. Very little has been written about how to design tower foundations that can cope with the unique loading conditions encountered by transmission towers. Test results available are very few and they are not fully correlated. It is because of the nature and state of soil condition and it is further variable from one tower location to another even if the superstructure is the same. The current design practice is mainly by judgement derived from experience rather than analysis. Recently more work is done in the area of soil-structure interaction; the tower industry is still struggling for the proper application. It is possible to postulate an engineering approach using acceptable principles of structural engineering and soil mechanics. Once a suitable design method of soil-structure interaction is selected for the analysis, the application of optimisation technique to bring out a most suitable and economical foundation is feasible.

1.6 SCOPE OF THE INVESTIGATION

The main aim of this thesis is to generate a procedure for obtaining overall economy in towers and tower foundations while ensuring reliable structural performance. To realise this, the investigation is carried out in three stages as listed below:

Stage I

1. Tower analysis is made using SAP IV and member design is carried out using fully stressed design conforming to IS:802(Part I)-1977 Code of practice for use of structural steel in overhead transmission line towers (loads and permissible stresses for towers). The following materials have been used:

(i) hot rolled steel angles
(ii) steel tubes.
The investigation in this stage brings out the demerits of the conventional method of design using the force diagram in comparison with the design based on computer analysis.

2. Normally towers are made of steel to the geometry as shown in Figure 1.3.a. In this investigation the economy that can be achieved by employing two new composite designs is examined. In these new designs, the bottom one third of the tower is replaced

(i) partly by RCC (Figure 1.3.b)  
(ii) fully by RCC (Figure 1.3.c)

and the analysis is carried out using SAP IV. For the design of RCC elements, the limit state method as per IS:1456-1978 Code of practice for plain and reinforced concrete is adopted.

Stage II

A small saving in the weight of a single tower will lead to considerable saving in the total cost of the project when we consider the total number of towers employed. Two different optimization techniques are employed for reducing the tower weight.

1. Fully stressed design: Analysis and design of a space truss of a given configuration by the use of fully stressed design concept is performed to determine the reduction in weight.

2. Development of optimum design using complete procedure:

In this technique the configuration of the space truss and the member properties are treated as variables. Two separate procedures have been developed for barrel and corset type towers. The member design is based on discrete sizing. The design conforms to IS:802(Part I)-1977.
FIG. 1-3. TOWERS USING STEEL AND CONCRETE

- **(a)** STEEL TOWER
- **(b)** R.C.C. COLUMN-STEEL COMPOSITE TOWER
- **(c)** R.C.C. FRAME-STEEL COMPOSITE TOWER

Steel Frame with Steel Bracings

Concrete Frame

2160 cm

3360 cm

1200 cm
Stage III

A detailed literature survey of the current design practices of tower foundations is made. Based on the available literature, a rational design method for tower foundation subjected primarily to uplift load, using soil-structure interaction principles, is proposed. The design of foundations for most towers are governed by uplift forces rather than compression. For large uplift forces belled/undreamed piles are made use of. This part of study includes a full scale experimental investigation on undreamed piles subjected to uplift forces. A mathematical model has been developed to predict the uplift capacity. The experimental results for the uplift capacity are then compared with those predicted by existing methods as well as the proposed model. This comparison has shown that the present model is an improvement over the existing methods.