CHAPTER 2

MEDIUM VOLTAGE POWER LINE DESIGN AND
CONSTRUCTION

2.1 Selection of Line Route and Profile Survey

Medium voltage (33 kV) power line design and construction in Sri Lanka is done by Projects and Heavy Maintenance branches of four Distribution Regions (Distribution Licensees) of Ceylon Electricity Board. Distribution planning branches of four distribution licensees decide new power line requirement and the features of decided lines. Starting grid substations and ending switching gantry points are identified for planned medium voltage backbone lines.

After selection of start and end points of the line, next step is to identify and mark the line route on 1:50,000 maps. In this stage, main consideration is given to select paddy fields for the line route as much as possible in accordance with availability, and to avoid highly populated areas, sanctuaries, reserved forests, schools, religious premises and places of historical importance. The next consideration is for avoiding marshy lands where access is difficult and which incur high foundation costs. Considering above facts the possible line route is marked roughly on 1:50,000 map from grid substation to the proposed gantry.

Next step is to conduct field visits to confirm the route marked on the map. During field visits, the places are identified where some marks on the map have been developed or differed. To encounter with these changes found in the field, previous line route selected should be adjusted shifting existing angle points or introducing new angle points. Finally a feasible preliminary line route is selected and next step is to start the preliminary survey along the selected line route.

Preliminary survey of the line route is carried out by licensed surveyors. Surveyor produces a preliminary drawing of the plan view and profile view through selected line route in 1:2000 horizontal scales. Details and information included in the preliminary drawings are [7],
• The visual nature of the ground within 60m band of 30m to each side of the center line.

• All buildings and high obstructions (with their height) within 60m band of 30m to each side of the center line.

• Voltage, height of lower, upper conductor and earth wire of all power lines within the 60m band of 30m to each side of the center line.

• Details of all telecommunication lines within 60m band of 30m to each side of the center line.

• Details of all roads, pathways, rivers, canals and drains (with their widths) within 60m band of 30m to each side of the center line.

• Angle of deviation of the line including sketch of tie measurement to re-establish any missing pegs in future.

• Valuable trees and Plants.

Detailed profile survey is carried out after studying the preliminary profile survey and deciding the required modifications. The profile drawing is prepared with horizontal scale of 1:2000 and a vertical scale of 1:200. Following details and information should be included in the detailed profile drawing [7].

• The visual nature of the ground with special reference to paddy fields, marshy soft ground or instability, paths and seismic disturbance.

• All buildings or high obstructions within 20m band of 10m to each side of the center line.

• At each angle position a ‘tie-in’ sketch.

• All changes of levels of 300 mm or more along the route centerline and along the offset lines. All features such as hedges, fences, ditches, roads, railways, rivers, canals, buildings, telegraph, power and pipelines should be included.
- Following details at the crossings of power lines:
  - Voltage and type of construction
  - Ground levels at point of crossing and support structures
  - Height of the top Conductor/Earth wire and lowest Conductor at point of crossing and support structures
  - Distance from crossing point to support structures along route of line to be crossed and the angle of crossing

- Along the bottom of the profile sheet a route map plan view showing all relevant details, within a distance of 10m each side of the route centerline should be drawn, to the same scale as the horizontal scale of the profile.

### 2.2. Selection of Line Supports

Broad based lattice steel structures are used as the common support type for medium voltage backbone lines. “Tower” and “Mast” are the two steel structures designs adopted now in the sector. In a basic Tower type structure, the height to lowest conductor attachment point is 14 m. Mast type steel structures are smaller in size and lower in height compared to Tower type structures. It has only 10m to lowest conductor attachment point. Applications of two support types are determined with terrain features along the line route.

**Lines in urban and mountainous areas**

The double circuit steel support type “Tower” are used with “Aluminum Conductor Steel Re-inforced (ACSR 30/2.79, 7/2.79) Lynx” conductor and 7/3.25 Galvanized Steel Earth Wire, in 33 kV lines in urban and mountainous areas.

Towers are self supporting, broad based lattice steel structures, which are categories in accordance with their ranges of bearable horizontal angles. Categorization of 33kV Towers is stated in Table 2.1. In support notation, the support type (whether Tower or Mast) is denoted by its first letter. Middle letter represent number of circuits which can attach to the support and last letter represent angle type. A drawing of basic Tower type structure is attached as Appendix 1.
Table 2.1: Types of Tower steel structures

<table>
<thead>
<tr>
<th>Tower type symbol</th>
<th>Description</th>
<th>Horizontal Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDL</td>
<td>Suspension (line) tower</td>
<td>0°</td>
</tr>
<tr>
<td>TDM</td>
<td>Medium angle section tower</td>
<td>0° - 30°</td>
</tr>
<tr>
<td>TDH</td>
<td>Heavy angle section tower</td>
<td>30° - 60°</td>
</tr>
<tr>
<td>TDT</td>
<td>Terminal tower</td>
<td>0° - 45° entry on line side</td>
</tr>
</tbody>
</table>

Body extensions of 3m and 6m and leg extensions of -2m, -1m, 0m, +1m, +2m and +3m are available for use in sites where required. Basic span for tower lines is 300m.

Lines in non-urban low country areas

The double circuit steel support type “Mast” is used with ACSR Lynx conductor and 7/3.25Galvanized Steel Earth Wire, for 33 kV lines in non-urban and low country area. Types of 33 kV double circuit Masts are stated in Table 2.2.

Table 2.2: Types of Mast steel structures

<table>
<thead>
<tr>
<th>Mast type symbol</th>
<th>Description</th>
<th>Horizontal Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDL</td>
<td>Suspension (line) mast</td>
<td>0°</td>
</tr>
<tr>
<td>MDM</td>
<td>Light angle section mast</td>
<td>0° - 30°</td>
</tr>
<tr>
<td>MDH</td>
<td>Heavy angle section mast</td>
<td>30° - 60°</td>
</tr>
<tr>
<td>MDT</td>
<td>Terminal mast</td>
<td>0° - 45° entry on line side</td>
</tr>
</tbody>
</table>

Body extensions are available from +1m to +6m in 1m intervals for MDL and in case of MDM, MDH and MDT, +3m and +6m body extensions are available. Basic span for the mast lines is 200m.

Summary of the support types with their approximate height to bottom conductor attachment point is appended in Table 2.3. The integer which is appeared after “+” mark of support symbol represents available body extension height (e.g. TDM+3 represent double circuit medium angle tower three meter body extension). A drawing of basic Mast type structure is attached as Appendix 2.
2.3. Sag-Tension Calculation

If conductor is sagged with a given tensile force between A and B which represents the attachments of the conductor at the support as indicated by Figure 2.1, sagging curve will be formed due to force balance between conductor dead loads and tensile forces. This sagging curve is known as the catenary curve. Vertical distance of the conductor at any point of conductor to the line connecting A and B attachment points is called “Conductor Sag” at particular point.

Conductor catenary curve equation is:

\[ y = \frac{TH}{w} \left[ \cosh \left( \frac{wx}{TH} \right) - 1 \right] \]  
(2.1)[8]

Where, \( w \) = conductor unit weight and \( TH \) = Horizontal tension of conductor.

Approximated Formula

\[ y = \frac{w x^2}{2TH} \]  
(2.2)[8]

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Table 2.3: Medium voltage line support types and heights

<table>
<thead>
<tr>
<th>Support Type</th>
<th>Height to bottom conductor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower</td>
<td></td>
</tr>
<tr>
<td>TDL+0, TDM+0, TDH+0, TDT+0</td>
<td>14 m</td>
</tr>
<tr>
<td>TDL+3, TDM+3, TDH+3, TDT+3</td>
<td>17 m</td>
</tr>
<tr>
<td>TDL+6, TDM+6, TDH+6, TDT+6</td>
<td>20 m</td>
</tr>
<tr>
<td>Mast</td>
<td></td>
</tr>
<tr>
<td>MDL+0, MDM+0, MDH+0, MDT+0</td>
<td>10 m</td>
</tr>
<tr>
<td>MDL+3, MDM+3, MDH+3, MDT+3</td>
<td>13 m</td>
</tr>
<tr>
<td>MDL+6, MDM+6, MDH+6, MDT+6</td>
<td>16 m</td>
</tr>
</tbody>
</table>
When span is L the maximum sag,

\[
D = \frac{wL^2}{2T_H} \quad (2.3)
\]

**Conductor Basic Span**

The basic span of a line or a set of structures is the span for which maximum sag has been calculated to determine the height of standard structures. A conductor correctly tensioned between two standard height structures, a basic span apart on flat ground will have the minimum design ground clearance. For the two support types Tower and Mast has different basic spans since those supports are with different basic heights [6].

**Equivalent Span**

Sags and tension of a line section (between two tension supports) are calculated on the “Constant Tension” and “Equivalent Span” principle. The theory is that any applied tension will be constant and uniform throughout the section and this constant tension will produce finite sag on equivalent span. Mathematical expression for determining the equivalent span for a section made up of five spans with lengths, a, b, c, d and e could be expressed as indicated in Equation (2.4).

\[
Equivalent \ Span = \sqrt{\frac{a^3+b^3+c^3+d^3+e^3}{a+b+c+d+e}} \quad (2.4) [9]
\]

**Wind Span**

The term wind span represents half the sum of adjacent horizontal span lengths supported on any one support. To maintain the loads within support strength limitations, wind span limits have been defined for each support type. The span for broken wire conditions will be applied only for one phase conductor or earth wire considered broken. The loading for intact wires will be based upon normal working loads [9].
Weight Span

The term weight span represents the equivalent length of the weight of conductor supported at any one support at minimum temperature at still air [9].

Wind span and weight span limits related to tower and mast supports are stated in Table 2.4.

<table>
<thead>
<tr>
<th>Tower Type</th>
<th>Description</th>
<th>Wind Span(m)</th>
<th>Weight Span(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mast Double Circuit</td>
<td>MDL Suspension Tower 0°</td>
<td>&lt; 240</td>
<td>&lt; 400</td>
</tr>
<tr>
<td></td>
<td>MDM Light angle section tower 0°-30°</td>
<td>&lt; 240</td>
<td>&lt; 600</td>
</tr>
<tr>
<td></td>
<td>MDH Heavy angle tower 30°-60°</td>
<td>&lt; 240</td>
<td>&lt; 600</td>
</tr>
<tr>
<td></td>
<td>MDT Terminal tower 0°-45° entry on line side</td>
<td>&lt; 240</td>
<td>&lt; 600</td>
</tr>
<tr>
<td>Tower Double Circuit</td>
<td>TDL Suspension Tower 0°</td>
<td>&lt; 360</td>
<td>&lt; 600</td>
</tr>
<tr>
<td></td>
<td>TDM Light angle section tower 0°-30°</td>
<td>&lt; 360</td>
<td>-600 to 1200</td>
</tr>
<tr>
<td></td>
<td>TDH Heavy angle tower 30°-60°</td>
<td>&lt; 360</td>
<td>-600 to 1200</td>
</tr>
<tr>
<td></td>
<td>TDT Terminal tower 0°-45° entry on line side</td>
<td>&lt; 360</td>
<td>-600 to 1200</td>
</tr>
</tbody>
</table>

Source: CEB MV Overhead Line Design and Construction Tender Document

2.4. Conductor State Change Equation

A conductor stringed between two supports is undergone number of changes with the change of weather and climate conditions such as temperature, wind and ice. From above mentioned conditions, ice is not considered for power lines in Sri Lanka. Following tension conditions should be satisfied by the conductor for conductor to be within tensile strength limits [9],

- Tension of the conductor at the highest tension conditions (minimum temperature with wind) should keep a safety factor of 2.5 with the Ultimate Tensile Strength (UTS).
- At everyday conditions at no wind the safety factor should be 4.5.
- At highest temperature at no wind condition the tension should be such that the ground clearance should not be violated.
Starting with one condition, calculating sag and tension at the other condition is the procedure in sag-tension calculation of power lines. A tower line conductor is usually subjected to following external forces:

- A horizontal force due to wind pressure.
- A vertical force due to dead weight of conductor.

If \( w \) is the weight of conductor per meter length and \( p \) is the horizontal force due to wind pressure acting on the conductor per meter length, the resultant force \( q \) on conductor per meter length is,

\[
q = \sqrt{(w^2 + p^2)} \tag{2.5}
\]

Proportion of \( q \) to unit conductor weight \( p \) is called the wind factor and it is shown as \( Q \) where,

\[
Q = \frac{\sqrt{(w^2+p^2)}}{w} \tag{2.6}
\]

If temperature or loading conditions varies in a span, the conductor length will be expanded or contracted, resulting again in a variation of the conductor tensile force. This changing of tensile force changes conductor sag curve as shown in Figure 2.2. These changes could be calculated by “Conductor State Change Equation”; Equation (2.7).

\[
f_2^2 \left\{ f_2 - \left( f_1 - \frac{a^2 \delta^2 Q_2^2 E}{24 f_2^2} - a \ell E \right) \right\} = \frac{a^2 \delta^2 Q_2^2 E}{24} \tag{2.7}[8]
\]
Where,

\[ A = \text{Cross section area of the conductor} \]
\[ f_1 = \frac{H_1}{A} ; \quad H_1 = \text{Horizontal tension at state 1 of the conductor} \]
\[ f_2 = \frac{H_2}{A} ; \quad H_2 = \text{Horizontal tension at state 2 of the conductor} \]
\[ a = \text{Span length AB} \]
\[ \delta = \frac{w}{A} ; \quad w = \text{unit weight of the conductor} \]
\[ Q_1 = \text{Wind factor at state 1} \]
\[ Q_2 = \text{Wind factor at state 2} \]
\[ \alpha = \text{Coefficient of linear expansion of the conductor} \]
\[ t = t_2 - t_1 ; \quad t_1 = \text{Temperature at state 1}, \ t_2 = \text{Temperature at state 2} \]
\[ E = \text{Modulus of elasticity of the conductor} \]

2.5. Medium Voltage line design conventional procedure

In conventional method of medium voltage line design, the design engineers do designs on hard profile drawings or Auto-CADD profile drawings, which are provided by the surveyor. Under mentioned steps are followed by the design engineer in the design process of medium voltage overhead power lines in conventional method. Following abbreviations have been used in the explanation [7].

MWT - Maximum working tension of the line (i.e. at minimum temperature, 7°C, with wind)
EDT  - Every day temperature (i.e. at 32°C and no wind condition)
MOT  - Maximum operating temperature (i.e. at 75°C without wind)
UTS  - Ultimate tensile strength of the conductor

Step 1: Find the equivalent span of the tension section.

Step 2:

- Apply MWT as initial condition (i.e. \( T_1 = \frac{UTS}{2.5} \)) and find the horizontal tension \( T_2 \) of the conductor at EDT (at 32°C) for the particular equivalent span value.
For obtained $T_2$ check the EDT condition (i. e. $T_2 < \text{UTS/4.5}$) for the equivalent span.

If EDT condition is not satisfied redo the calculation taking EDT (i. e. $T_1 = \text{UTS/4.5}$) as the initial condition and find $T_2$ at minimum temperature ($7 \, ^\circ\text{C}$) with wind condition.

**Step 3:** Apply MWT (output of step 1) as initial condition and find $T_2$ at MOT (i. e. $75 \, ^\circ\text{C}$) for the equivalent span.

**Step 4:**

- Find Sag ($d$) at MOT using maximum sag equation,
  \[ d = \frac{wa^2}{8T_2} \]

- Find coordinates for the catenary curves applying tension ($T_2$) at MOT for equivalent span using,
  \[ y = \frac{wx^2}{2T_2} \]

**Step 5:** Plot the catenary curve of the conductor at $75 \, ^\circ\text{C}$ with no wind for all equivalent spans.

**Step 7:**

- Project the hot curve (catenary at $75 \, ^\circ\text{C}$) for ground clearance value (6.1 m for medium voltage 33 kV).

- Including these two curves prepare the sag template for equivalent span. Drawn curves should be carved as plastic sag templates for designing on hard profile drawings. If the design is being done on Auto-CADD profile drawings, the design engineer has to draw catenary curves as Auto-CADD drawings. Sag templates should be in the scale same as scale of profile drawing.
Equivalent spans which sag templates are prepared is 100m, 200m, 300m and 400m. According to the parameters of selected section of the line, equivalent span is differed and selection of the sag template for particular line section is done as shown in Table 2.5.

Table 2.5: Selection of sag templates [7]

<table>
<thead>
<tr>
<th>Range of equivalent span (m)</th>
<th>Sag Template (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>76-175</td>
<td>100</td>
</tr>
<tr>
<td>176-275</td>
<td>200</td>
</tr>
<tr>
<td>276-375</td>
<td>300</td>
</tr>
<tr>
<td>376-475</td>
<td>400</td>
</tr>
</tbody>
</table>

Step 8:

After preparing sag templates, the design engineer starts tower spotting on profile drawings. Drawing of a sample sag template is shown in Figure 2.4. Tower spotting process is carried out section wise along the line route by placing designed sag template on hard profile drawing. After, location and height of starting tower of a span is decided, the selected sag template for equivalent span placed on the profile drawing as shown in Figure 2.3, to decide next tower location and height. Angle
points along the selected route are fixed points for tower locations. Only heights of angle towers are to be decided at tower spotting stage.

In Figure 2.3, sagging template has been placed in a position to determine the location and height of Tower 2, assuming that Tower 1 is fixed at location 1. The sagging curve starts at the conductor attachment point of Tower 1. Sagging template is adjusted such that its horizontal edge is placed parallel to the horizontal line of longitudinal profile.

After preparing preliminary tower spotting, wind and weight spans need to be checked in detail for each tower placed. If these conditions are not complied with tower heights; tower types or the tower spotting at all need to be corrected accordingly.
2.6. Design by PLS-CADD power line design software (Manual Spotting)

PLS-CADD software is available for easily carried out the explained design steps. Design procedure has become simplified and less time consuming with PLS-CADD software. The files and parameters we have to input to the PLS-CADD program is,

- Profile survey data: X, Y, Z, H co-ordinates of profile survey points with feature code as a comma-delimited Microsoft Excel work sheet.
- Feature code file (definition of available feature types)
- Design criteria file (definition of safety factors, wind and weight span limits, weather conditions, etc.)
- Conductor file (definition of conductor parameters)
- Structure files (definitions of structure parameters of each structure type)

Then, profile view and plan view of terrain is developed by the software as shown in Figure 2.5.

![Figure 2.5: Profile terrain; profile view and plan view](image)

PLS-CADD software does not have inbuilt procedure for automatic tower spotting. The procedure is available as extra cost optional facility. Therefore, in basic PLS-CADD software interface, the Design Engineer has to spot structures manually along the developed profile view. If any design constraint is violated (eg: wind or weight...
span limits, required clearances, etc.), the Design Engineer has to correct it by shifting structure locations or changing the tower heights manually. By this way the final design of the line by PLS-CADD software is also achieved by the trial and error method.

2.7. Importance of Medium Voltage Power line cost optimization

Figure 2.6 and Figure 2.7 shows two manually spotted designs of a section of 33 kV Lynx double circuit tower line from Polonnaruwa Grid Substation to 33 kV Gantry at Jayanthipura. In the figures, two possible design configurations have been shown for the same line section in manual spotting. Section length is 1958 m and section starting and end towers are medium angle towers.

![Figure 2.6: Design solution 1 for a line section of MV line](image)

In first solution, the design was done placing five suspension towers in between two medium angle towers with different body extensions. In second solution, six suspension towers were placed without body extensions. Comparison of two
solutions is shown in Table 2.6 with their estimated construction costs. The total construction cost of each tower type which is used for cost calculation, is shown in Table 2.7. The comparison shows that, solution 2 incurred 4.8% higher cost than the solution 1.

Table 2.6: Cost comparison of two design solutions

<table>
<thead>
<tr>
<th>Solution No.</th>
<th>Tower Configuration</th>
<th>Total Cost (LKR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TDM+0, TDL+3, TDL+0, TDL+3, TDL+0, TDL+6, TDM+0</td>
<td>7,502,096.00</td>
</tr>
<tr>
<td>2</td>
<td>TDM+0, TDL+0, TDL+0, TDL+0, TDL+0, TDL+0, TDL+0, TDM+0</td>
<td>7,899,932.00</td>
</tr>
<tr>
<td></td>
<td>Cost difference</td>
<td>357,836.00</td>
</tr>
</tbody>
</table>

Table 2.7: Total cost of tower steel parts, erection and foundation

<table>
<thead>
<tr>
<th>Tower type</th>
<th>Tower Cost + Erection and Foundation Cost (Good Soil) (LKR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDL</td>
<td>TDL+0 815,518, TDL+3 939,990, TDL+6 1,024,250, TDL+0 1,483,412, TDL+0 1,656,245, TDL+0 1,804,382</td>
</tr>
<tr>
<td>TDM</td>
<td>TDM+0 1,483,412, TDM+3 1,656,245, TDM+6 1,804,382</td>
</tr>
<tr>
<td>TDH</td>
<td>TDH+0 1,568,573, TDH+3 1,797,392, TDH+6 1,933,763</td>
</tr>
<tr>
<td>TDT</td>
<td>TDT+0 1,477,373, TDT+3 1,977,648, TDT+6 2,142,983</td>
</tr>
</tbody>
</table>

Source: CEB stock values-2012

Each section of line has many design solutions which incur different investments from each other. The design engineer is hardly in a position to manually identify and evaluate all the solutions available for a line section. Therefore, application of automatic design methodology with cost optimization is highly valuable for reduction of investment at initial stage.