Analysis of Transmission Towers with Different Configurations

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ABSTRACT

Transmission line towers constitute about 28 to 42 percent of the cost of the transmission line. The increasing demand for electrical energy can be met more economically by developing different light-weight configurations of transmission line towers.

In this report, an attempt has been made to make the transmission line more cost effective by changing the geometry (shape) and behavior (type) of transmission line structure. This objective is met by choosing a 220 kV single circuit transmission line carrying square base self-supporting towers. With a view to optimize the existing geometry, one of these suspension towers is replaced by a triangular base self-supporting tower. Then, the structural behavior of existing tower is looked upon by developing a square base guyed mast. Using STAAD, analysis of each of these three towers has been carried out as a three-dimensional structure. Then, the tower members are designed as angle sections. For optimizing any member section, the entire wind load computations have to be repeated, simultaneously for the analysis and design. Then, all these three towers are compared and analyzed.

KEYWORDS: Transmission towers, Geometry of tower, Self-supporting tower, Configuration of tower.

INTRODUCTION

In design of tower for weight optimization, below mentioned basic parameters are constrained on the basis for electrical requirements:

- Base width.
- Height of the tower.
- Outline of the tower.

Keeping in mind the above restrictions, an attempt has been made to make the transmission line more cost effective by optimizing the geometry (shape) and behavior (type) of transmission line structure. A 220 kV single circuit transmission line with suspension towers is selected. For optimizing the geometry, square base self-supporting type is replaced by a triangular base self-supporting tower. Further, the structural behavior (type) of tower is looked upon by developing a square base guyed mast.

The following work has been done:

- The sag tension calculation for conductor and ground wire using parabolic equation.
- Towers are configured with keeping in mind all the electrical and structural constrains.
- Loading format including reliability, security and safety pattern is evaluated. Now, all the towers are modeled using STAAD.
- The wind loading is calculated on the longitudinal face of the towers.
- Then, the towers are analyzed as a three-dimensional structure using STAAD.
- Finally, tower members are designed as angle sections.

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Transmission Line Components

The following parameters for transmission line and its components are assumed from I.S. 802: Part 1: Sec: 1:1995, I.S. 5613: Part 2: Sec: 1:1989.

- Transmission Line Voltage: 220 kV (A. / C.)
- Right of Way (recommended): 35, 000 mm
- Angle of Line Deviation: 0 to 2 degrees
- Terrain Type Considered: Plain
- Terrain Category: 2 (Normal cross country lines with very few obstacles)
- Return Period: 50 yrs
- Wind Zone: 4
- Basic Wind Speed: 47 m/s
- Basic Wind Pressure: 71.45 kg/sqm
- Tower Type: Self-Supporting Tower, Suspension Type Tower, Tower Type "A"
- Tower Geometry: Square Base Tower
- No. of Circuits: Single Circuit
- Tower Configuration: Vertical Conductor Configuration
- Tower Shape: Barrel Shaped
- Bracing Pattern: Warren Type (Double Web System), Portal System (K Type)
- Cross Arm: Pointed
- Body Extension: Not Considered
- Steel Used: Mild Steel (IS-2062)
- Slope of Tower Leg: 40 to 90 (Permissible)
- Conductor Material: ACSR, (Aluminium Conductor Steel Reinforced)
- Conductor Configuration: Zebra
- Maximum Temperature: 75°C (ACSR)
- Number of Ground Wires: Single
- Peak Type: Triangular
- G.W. Type: Earth wire – 7 / 3.66
- Shielding Angle: 300
- Maximum Temperature: 53°C (7 / 3.66)
- Insulator Type: I String
- Number of Insulator Discs: 14
- Size of Insulator Disc: 255 * 145 mm (Skirt Diameter)
- Length of Insulator String: 2,340 mm
- Minimum Ground Clearance: 7,000 mm
- Sag Error Considered: 160 mm
- Creep Effect: Not Considered
- Mid Span Clearance: 8,500 mm
- Minimum Height above G.L.: 28,555 mm
- Width at Hamper Level: 1,500 mm (Square Tower)
- Width at Base: 4,500 mm (Square Tower)
- Phase to Phase Clearance: Vertical Spacing between Conductors (Minimum): 5,200 mm.

Horizontal Spacing between Conductors (Minimum): 8,500 mm

- Lightning Impulse Level (Air Clearance): 1700 mm
- Minimum Phase to Earth (Air Clearance): 1970 mm
- Phase to Ground Metal Clearance:
  -Swing Angle:
  0° - 2130 mm
  15° - 1980 mm
  30° - 1830 mm
  45° - 1675 mm
- Tower Weight (Minimum): 2,570 kg
- Base Width (C.L.) / Height above G.L. = 1: 6.3
- Minimum Thickness of Member:
  - Leg Member, G.W. Peak and Lower Member of C.A.: 5 mm
  - Others: 4 mm
- Permissible Weight Span:
  • Normal Condition:
  Maximum: 525 mm
  Minimum: 200 mm
  • Broken Wire Condition:
  Maximum: 315 mm
  Minimum: 100 mm
- Normal Span: 320 mm to 380 mm
- Design Span: 350 mm
- Wind Span = Normal Span: 350 mm
- Weight Span: 1.5 X 350 mm
- Concrete Level to Ground Level: 225 mm

Sag Tension for Conductor and Ground Wire

Indian standard codes of practice for use of structural steel in over-head transmission line towers have prescribed following conditions for the sag tension calculations for the conductor and the ground wire:

- Maximum temperature (75°C for ASCR and 53°C for ground wire) with design wind pressure (0% and 36%).
- Every day temperature (32°C) and design wind pressure (100%, 75% and 0%).
- Minimum temperature (0°C) with design wind pressure (0% and 36%).

IS 802: part 1:sec 1: 1995 states that conductor/ ground wire tension at every day temperature and without external load should not exceed 25 % (up to 220 kV) for conductors and 20% for ground wires of their ultimate tensile strength. Sag tensions are calculated by using the parabolic equations as discussed in the I.S. 5613: Part 2: Sec: 1: 1989 for both the conductor and ground wire. We have considered the sag of ground wire as 90% the sag of the conductor at 0°C and 100% wind condition**.**

Parabolic Equation

$$F_2^2.\left(F_2-(K-\alpha.t.E)\right)=\frac{L^2.\partial^2.q_2^2.E}{24}$$

$$\text{Take } K = F1-\frac{L^2.\partial^2.q_0^2.E}{24.F_1^2}$$

Table 1. Sag tension for conductor (ASCR)

Temperature variation C		**0**		**32**		**75**
Wind variation %	0	0. 36	0	0.75	1.0	0
Tension= F x A (kg)	4060	4879	3322	5763	6804	2687
Sag $\frac{wL^2}{8T}$ (m)	6.114	5.088	7.471	4.307	3.648	9.239

Table 2. Sag tension for ground wire

Temperature variation C		**0**		**32**		**53**
Wind variation %	0	0. 36	0	0.75	1.0	0
Tension= F x A (kg)	1520	2001	1327	2629	3127	1226
Sag $\frac{wL^2}{8T}$ (m)	5.874	4.462	6.725	3.395	2.855	7.284

Configuration of Towers

Configurations of all three towers are done by first fixing the outline of all the towers as per the Indian standard requirements.

- The base width of triangular tower is restricted as (4/3) X base width of square tower and guyed mast as simply 1000 mm.
- The width at the hamper level for both the square tower and the triangular tower is reduced to (1/3) of the base width, but the width of the guyed mast is kept constant throughout the height of the tower.
- The members for all the towers are so chosen that the effective length is kept between 1200 mm and 1500 mm.
- The bracing angle for all the towers is kept between 400 and 500.
- The minimum factor of safety is kept as 1.1 for the design of angle members.

The square and triangular towers are having their legs inclined till hamper level (for tower body), while guyed mast is having straight legs. All the towers are having straight legs above the hamper level (cage). Final height of each of the towers is taken as the maximum of both conditions; that is 29900 mm. Thus, all the towers are having the same height. Horizontal grounded metal clearance for all the towers is the same, except for the minor change in the slope of tower leg. Horizontal clearance between the phases is maximum for the triangular tower and the least for guyed mast. This is because of their width at the hamper level.

Table 3. Configuration of tower

	Square tower	Triangular tower	Guyed mast
Base width	4500 mm	6000 mm	1000 mm
Hamper width (L.C.A.)	1500 mm	2000 mm	1000 mm
Hamper width (U.C.A.)	1500 mm	2000 mm	1000 mm
Height till L.C. A. Level	18900 mm	18900 mm	18900 mm
Height till U.C. A. Level	24100 mm	24100 mm	24100 mm
Total Tower Height	**(from G.L.)**		
Minimum	28555 mm	28555 mm	28555 mm
Peak clearance	29100 mm	29600 mm	28700 mm
Mid-span clearance	29900 mm	29900 mm	29900 mm
Horizontal Gr. Metal Clear.	3600 mm	3600 mm	3600 mm
Horizontal Spacing between	Cross Arm Tip		
Minimum	8500 mm	8500 mm	8500 mm
Actual	8700 mm	9200 mm	8200 mm

Wind Loads on Towers

Wind loads on all the towers are calculated separately by developing excel programs by following Indian Standards. For finding the drag coefficients for the members of triangular tower, the solidity ratio is derived from Table 30 –IS-875 (part 3)-1987 in the similar fashion as prescribed in the IS- 826 (part-1/sec 1)-1995.

Design Wind Pressure

To calculate design wind pressure on conductor, ground wire, insulator and panels:

$$\mathbf{P_d = 0.6 \times V_d^2}$$

where,

P_d = design wind pressure in N/m^2

V_d = design wind speed in m/s

To calculate design wind pressure

$$\mathbf{V_d = V_R \times K_1 \times K_2}$$

V_R = 10min wind speed (or) reduced wind speed

$$\mathbf{V_R = V_b/k_0}$$

V_b = basic wind speed

K_0 =1.375 [conversion factor]

K_1 = risk coefficient

K_2 = terrain roughness coefficient.

Wind Loads on Conductor/Ground Wire

To calculate wind loads on conductor and ground wire

$$\mathbf{F_{wc} = P_d \times C_{dc} \times L \times d \times G_c}$$

F_{wc} = wind load on conductor

P_d = design wind pressure

C_{dc} = drag coefficient for ground wire=1.2

drag coefficient for conductor = 1.0

L = wind span

d = diameter of conductor/ground wire

G_c = gust response.

Wind Load on Insulator

To calculate wind load on insulator

$$\mathbf{F_w = P_d \times C_{di} \times A_I \times G_I}$$

where,

A_I = 50% area of insulator projected parallel to the longitudinal axis of string

G_I = gust response factor for insulator

C_{di} = drag coefficient, to be taken as 1.2.

Wind Load on Panels

To calculate wind load on panels

$$\mathbf{F_w = P_d \times C_{dt} \times A_e \times G_T}$$

C_{dt} = drag coefficient for panel considered against which the wind is blowing

A_e = effective area of the panel

G_T = gust response factor for towers.

Table 4. Wind loading on towers

Height (m) / Wind (kg) (from G.L.)	Square Tower	Triangular Tower	Guyed Mast
0	292	306	129
8.91	-	-	279
10.5	475	-	-
12.14	-	461	-
18.9	243	210	195
20.2	118	111	101
24.1	127	119	108
25.4	107	101	89
29.1	122	118	103
Total	**5571**	**5353**	**3708**
No. of exposed members	**180**	**195**	**174**

The square tower is facing the maximum total wind load followed by the triangular tower and then the guyed mast. This implies that the member sectional area exposed to wind is maximum in the square tower. The maximum number of tower members exposed to the wind is in the triangular tower followed by the square tower and then the guyed mast. This might be because of the fact that the loading is the same (other than wind), thus the triangular tower is handling same forces (almost) by three legs so the member sections have increased. The lowest panel of triangular tower is having the highest wind load followed by the square tower and then the guyed mast. This might be because of the fact that the panel height of the triangular tower is comparatively higher as the number of panels is reduced in the trunk of the tower.

Analysis of Towers

All the three towers are modelled and analyzed in STAAD Pro2004.

Following results were obtained.

Square tower is found to have the maximum node deflection throughout the tower height, followed by the triangular tower and then the guyed mast. Guyed mast is having the least deflection at the lower cross arm level as those are the connection points of the guy ropes. Triangular tower is having the maximum forces in the legs members. The probable reason behind this can be the reduced number of legs. Guyed mast is having the least forces for the leg members. This is because of the guy ropes which themselves transfer the load to the ground. Guyed mast is having the maximum forces for the lower cross arm members.

Design of Towers

The tower is designed and summed as:

Triangular tower is having the heaviest member section for the legs. As the forces (other than wind) are

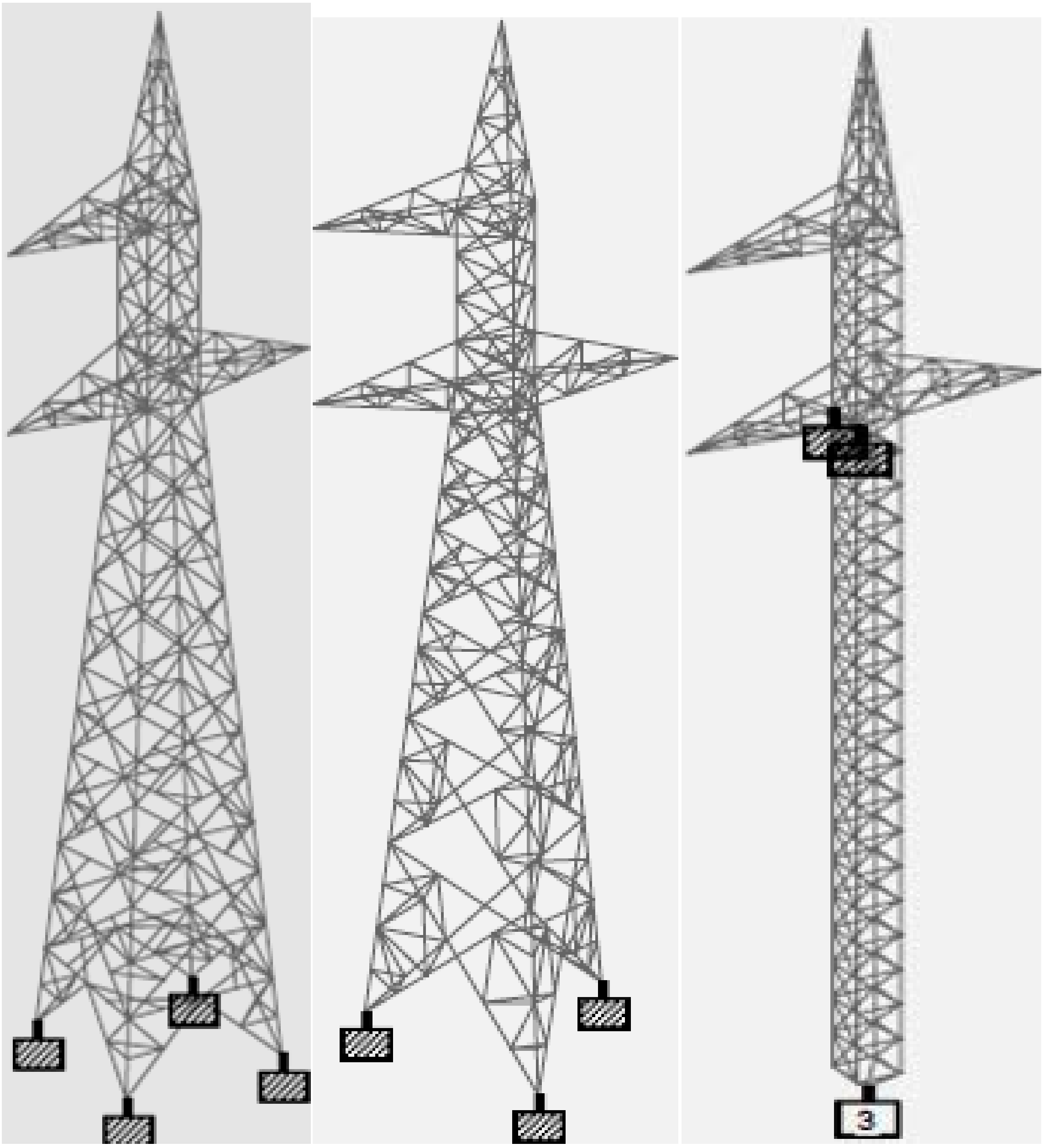


Figure 1: Square tower, triangular tower and guyed mast

almost the same, the probable reason behind this can be the reduced number of legs. Also, the reduced number of panels can be one of the probable reasons, because of which the base panel height has increased; thus increasing the forces in the leg sections and thus making the member sections comparatively heavy. Guyed mast is having the least member sections with the maximum factor of safety. This might be because of the guy ropes which themselves transfer the load to the ground. The lower cross arm members for the triangular tower are having different lengths. This could be because of the asymmetrical geometry of the tower. Square tower is having the maximum factor of safety for the upper cross arm members. This behavior might be because of the minimum length of the members. Upper cross arm member sections are found to be the same for all the towers. This may be because these members are designed as the tension members and steel already has good margin of safety in tension.

Table 5. Maximum force in the leg member

	Guyed Mast		Triangular Tower		Square Tower	
Panel no.	Compressive kg	Tensile kg	Compressive kg	Tensile kg	Compressive kg	Tensile kg
0	3981	1160	-	-	-	-
1	2492	977	31175	28247	22945	20716
2	2662	1292	28469	25907	22033	20028
3	2839	1610	24726	22324	20560	18698
4	3013	1927	21430	19256	18306	16723
5	3188	2244	18355	16182	16536	15028
6	3362	2560	13826	11874	14242	12936
7	3535	2876	-	-	12892	11542
8	3708	3191	-	-	10604	9490
9	3884	3503	-	-	-	-
10	4608	3308	-	-	-	-
11	5334	3055	-	-	-	-
12	6063	2799	-	-	-	-
13	6792	2674	-	-	-	-
14	7522	3924	-	-	-	-
15	8255	4172	-	-	-	-
16	8990	4916	-	-	-	-
17	9736	5655	-	-	-	-
18	10463	6381	-	-	-	-
19	11302	7148	-	-	-	-
20	8498	12350	9999	8343	7950	5454
21	9013	1178	-	-	-	-
22	7853	8864	7455	6799	6755	6231
23	6556	7116	6206	4982	5509	4979
24	6638	5412	6835	4606	5090	3348
25	4008	3359	4660	2684	3322	2628
26	5256	4955	4610	3537	3553	3459

Table 6. Maximum force in cross arm

	Guyed Mast		Triangular Tower		Square Tower	
Panel no.	Compressive kg	Tensile kg	Compressive kg	Tensile kg	Compressive kg	Tensile kg
Lower member						
Lower	6268	4307	4969	3645	4651	2912
Upper	6767	4478	5463	2312	5111	2675
Upper member						
Lower	1320	4801	1037	5418	669	4410
Upper	631	4064	825	5729	276	4150

Table 7. Maximum force in cross arm

Height (m)	Square Tower (mm)	Triangular Tower (mm)	Guyed Mast (mm)
0	0	0	0
18.9	85	71	8
20.2	98	90	14.5
24.1	142	129	60
25.4	157	142	76
29.9	216	192	144

Table 8. Design of leg members

	Guyed mast			Triangular tower			Square tower		
Panel no.	Angle section	Effective length (cm)	FOS	Angle section	Effective length (cm)	FOS	Angle section	Effective length (cm)	FOS
0	65X65X05	87	3.4	100X100X8	129	1.1	90X90X8	110	1.3
1	65X65X05	99	5.1	100X100X8	127	1.2	90X90X8	155	1.2
2	65X65X05	99	5.1	90X90X8	107	1.3	90X90X8	140	1.4
3	65X65X05	99	4.5	90X90X8	130	1.4	90X90X6	125	1.2
4	65X65X05	99	4.3	90X90X6	110	1.3	90X90X6	135	1.3
5	65X65X05	99	4.1	75X75X6	105	1.3	75X75X06	110	1.3
6	65X65X05	99	3.8	-	-	-	75X75X06	95	1.5
7	65X65X05	99	3.6	-	-	-	75X75X06	160	1.3
8	65X65X05	99	3.5	-	-	-	-	-	-
9	65X65X05	99	3.3	-	-	-	-	-	-
10	65X65X05	99	2.8	-	-	-	-	-	-
11	65X65X05	99	2.4	-	-	-	-	-	-
12	65X65X05	99	2.1	-	-	-	-	-	-
13	65X65X05	99	1.9	-	-	-	-	-	-
14	65X65X05	99	1.7	-	-	-	-	-	-
15	65X65X05	99	1.6	-	-	-	-	-	-
16	65X65X05	99	1.4	-	-	-	-	-	-
17	65X65X05	99	1.3	-	-	-	-	-	-
18	65X65X05	99	6.3	-	-	-	-	-	-
19	65X65X05	99	1.1	-	-	-	-	-	-
20	65X65X05	130	1.3	75X75X06	130	1.7	65X65X05	130	1.3
21	65X65X05	97	1.4	-	-	-	-	-	-
22	65X65X05	98	1.6	65X65X05	130	1.4	65X65X05	137	1.6
23	65X65X05	98	2.0	65X65X05	130	1.7	65X65X05	127	2.0
24	65X65X05	98	2.0	65X65X05	130	1.5	65X65X05	127	2.1
25	65X65X05	131	2.6	65X65X05	133	2.2	65X65X05	132	3.2
26	65X65X05	151	1.7	65X65X05	153	1.9	65X65X05	152	2.5

RESULTS AND DISCUSSION

As all the towers are designed with enough factor of safety, the self weight of different towers obtained is as follows:

Square Tower 2775 kg

Triangular Tower 2519 kg

Guyed Mast 1666 kg.

Triangular tower is compared with the square tower in the following aspects:

1. The self weight for the triangular tower is found to be 9.23% less than that of the square tower. Hence, the triangular tower is more economical than the square tower (self-supporting tower).

Table 9. Design of cross arms

Guyed mast				Triangular tower			Square tower		
Panel no.	Angle section	Effective length (cm)	FOS	Angle section	Effective length (cm)	FOS	Angle section	Effective length (cm)	FOS
Lower members									
Lower	75X75X6	136	2.4	75X75X6	164	2.6	75X75X6	123	3.4
				65X65X5	120	4.7			
Upper	75X75X6	136	2.2	75X75X6	164	2.4	75X75X6	123	3.1
				65X65X5	124	4.3			
Upper members									
Lower	50X50X4	143	1.4	50X50X4	143	1.2	50X50X4	130	1.5
Upper	50X50X4	154	1.4	50X50X4	128	1.2	50X50X4	146	1.6

2. The triangular tower is found to have the lesser amount of node deflection throughout the height of the tower as compared with the square tower. This implies that the triangular tower is behaving more rigidly than the square tower.
3. The square tower is facing the maximum total wind load followed by the triangular tower and then the guyed mast. This implies that the member sectional area exposed to wind is maximum in the square tower.
4. The lowest panel of triangular tower is having the highest wind load followed by the square tower and then the guyed mast. This might be because of the fact that the panel height of the triangular tower is comparatively higher as the number of panels is reduced in the trunk of the tower.
5. The triangular tower is found to have little higher amount of axial forces in the leg members in comparison with the square tower. This might be because the forces are being transferred by three legs instead of four.

Guyed mast is coming all the way more economical than the triangular tower and the square tower. Even the self weight of the tower, wind loading on the tower, axial forces in the members (except the lower cross arm members) and the node deflection all are coming comparatively lesser. The above noted weight of guyed mast is excluding the self weight of guy ropes. The different structural behavior of the guyed mast and its requirements need to be checked before its use. The value of land is one of the major factors to be taken into consideration in case of guyed mast. The saving in the cost of transmission line by using guyed mast can be nullified by the premium value of land.

CONCLUSIONS

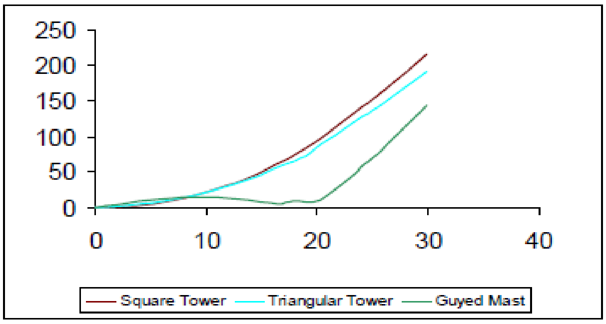
Least weight of the tower implies greatest economy in the transmission line cost. Following conclusions can be made:

- Configuration of towers has revealed that all the three towers are having the same height but different base widths.
- Reliability, security and safety conditions have been kept the same for all the three towers. Wind loading is calculated for each tower leading to the following results:

  Square Tower 5571 kg
  Triangular Tower 5353 kg
  Guyed Mast 3708 kg

Analysis of Towers as a 3-D space structure with STAADPRO 2004 is showing maximum axial compressive force in leg member of the lowest panel (panel one).

- Deflection of tower



Note: * Height – "m" (X-Axis) and Deflection – "mm" (Y-Axis)

Figure 2: Deflection of tower

Maximum Force (kg)

Square Tower	22945
Triangular Tower	31175
Guyed Mast	11302

- Design has been done with conserving every kg of steel possible. The economic design of towers has led to the following conclusion:

Square Tower	2775 kg
Triangular Tower	2519 kg
Guyed Mast	1666 kg

Thus, using triangular base self-supporting tower will bring a saving of **9.23%** in the weight of structural steel, and using square base guyed mast will lead to a saving of **39.96%** in the structural steel (excluding guy ropes), which is directly the cost saving in each tower or the structural optimization of the transmission line.

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