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Review of Failed Transmission Line Towers during Full Scale Testing

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Abstract

Towers are the most important component of the overhead power transmission line system. When failure occurs, direct and indirect losses are very high; hence accurate prediction of tower failure becomes very important for the reliability and safety of the transmission system. One cannot accurately predict the behavior of tower after practical loading conditions, so testing of tower for various loading conditions before installing in field becomes very important. The present paper discusses the structural behavior of towers during full scale testing carried out at Central Power Research Institute, Bangalore, India. Although, the towers were safe for various loading conditions based on the design/analysis, during full scale testing, different types of premature failures were observed. Necessary modifications in towers have been carried out and these towers were retested successfully. The details of remedial measures / strengthening of members carried out during testing are brought out in this paper.

Keywords: Broken Wire Condition, Normal Condition, Redundant Members, Transmission Line Towers

1. Introduction

For transmitting electricity from power generation plant to substations, various types of structures like or Steel Lattice Towers, Steel Poles, Wooden Poles are used. In India, mainly Steel Lattice Towers are widely used for this purpose. These structures are the major part of the power grid. The cost of towers constitutes about quarter to half of the cost of transmission line[2]. So it becomes very important to design the towers very much cost efficient. In India, the structural design of a transmission line towers is most often governed by IS: 802-(Part-1)-2015 (Indian standard for design of transmission line towers) and Indian electricity rules. In this code there are provisions of designing main members like leg members, bracings, horizontal members and cross arm members. Structural design of the tower is mainly governed by wind loads acting on conductor/tower body, self-weight of conductor/tower and other loads due to line deviation, broken wire condition, erection and maintenance conditions, etc. Tower is modeled generally as a pin jointed space truss. In the model, legs, bracings and cross arm members are considered as primary members and other members as secondary members. Only primary members are considered in design, while the secondary members are provided to reduce slenderness ratio of main members i.e., to increase member capacity under compression. The slenderness ratio is a very important parameter for member design under compression. It is predefined in various design standards and codes of practices. The analysis of transmission line tower is the determination of axial forces (Tensile and Compressive) in various members. The design consists of providing members to withstand these axial forces and to satisfy slenderness ratios as per standards. Nowadays the transmission line towers are being designed with weight optimization technique. The factor of safety in the design of transmission line towers are not considered as high as other steel structures that are why in order to validate the economical design; full scale testing of these towers becomes essential.

The load carrying capacity of the tower, not only depends on the individual member capacity but, also on other aspects like joint detailing, uncertainties in framing eccentricities of members, force fitting of members, unequal force distribution in bolts and gusset plate connections, etc.

Rao and Knight[4], studied the different types of premature failures observed during full-scale testing of

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Transmission line towers at Tower Testing and Research Station, Structural Engineering Research Centre, Chennai. Failures that have been observed during testing were studied and reasons were discussed. Albermani and Kitipornchai, 2009, used the nonlinear methodology for structural failure analysis of towers and the approach was used for structural failure prediction.

Tower Testing Station, Central Power Research institute[7], Bangalore has the facility to test different types of transmission line structures like Square Base Towers, Triangular Base Towers, Rectangular Base Towers and Monopoles. During testing, the tower is loaded according to various loading conditions as per the design. Mainly Transverse, Vertical and Longitudinal loads are applied using calibrated Load Cells through electrically operated winches. The transmission line towers are tested for Normal Condition (Reliability), Broken Wire Condition (Security), and Erection and Maintenance (Safety) Conditions. While testing, the ultimate loads are applied in steps of 50%, 75%, 90%, 95% and 100%. The waiting period of 120 seconds for intermediate steps and 300 seconds for 100% loads are followed as per IS: 802-(Part-3)-1985[5], whereas no waiting period for intermediate steps and 60 second for 100% loads as per IEC-60652:2006.

2. Failure of Transmission Line Towers

Although while designing any transmission line structure whether it is a lattice structure, a pole or any other type of structure, all design parameters are carefully taken care, there may be the possibility of failure of the transmission line structure. Unlike other engineering structures the factor of safety in the design of transmission line towers are not considered. Only strength factor related to quality of materials is considered, i.e., 2 percent or 5 percent margin. The redundant members are not considered as the design members. They are provided to reduce the unsupported length of main members in order to increase the capacity of the member. These are designed only for 2.5% of the load in the main member. Many premature failures of test towers are caused by buckling of compression leg or bracing members, and maximum number of times the main reason of the buckling of main members is that the redundant member is not strong enough to resist the buckling. That is why improper design of redundant member may cause the failure of leg or main bracing members.

3. Present Study

At Tower Testing Station, Central Power Research Institute, Bangalore, India, full scale testing of more than 700 towers has been carried out since its inception covering 33kV to 800kV for domestic and foreign customers. In the present study, the premature failed towers during testing, either fully or partially has been studied. The Table 1 describes the summary of tested towers during the year 2014-15.

Table 1. Summary of tested towers

Tower Type	Total Numbers	No. of Failed Towers	%age of Failed Towers
33 kV	3	0	Nil
66 kV	4	1	25
115 kV	2	0	Nil
132 kV	16	1	6
161 kV	3	0	Nil
220 kV	12	4	33
230 kV	9	2	22
330 kV	3	1	33
400 kV	3	2	67

4. Description of Failed Towers

During full scale testing of Towers, many types of premature failures were observed. Some of the towers collapsed fully, while others undergone a minor failure. Strengthening of members, if required, was carried out without dismantling the tower. As per Table 1, out of a total 55 towers, 11 towers failed. The reasons and behavior of failure pattern of all these towers were not same. The reason behind premature failure was shearing of bolts or buckling of Leg members, buckling of Bracings and Cross arm members or buckling of redundant members etc. A summary of either fully or partially failed Transmission line towers are given below.

4.1 Tower Type

230kV Double circuit Suspension tower. Total height- 63.09 m. Weight- 108.89 KN.

Loading Conditions: Normal Condition, 90% of test loads. Maximum loads in Vertical, and Longitudinal directions- 15.20 KN, 32.20 KN & 32.20 KN respectively.

Description: While increasing to 90%, of Vertical and Transverse loads, the whole tower failed. Failure started from Leg member and subsequently the whole tower collapsed (Figure 1). It was decided to review the design of tested tower, and scheduled to test again after necessary modification.

Remedial Measures: Since the whole tower was collapsed, it was not possible to do any remedial measure. The tower was reanalyzed, modified and re-tested successfully.

4.2 Tower Type

220kV Double circuit Tension tower. Total Height- 50.57 m. Weight- 212.66 KN.

Loading Conditions: Normal Condition, 75% of test loads. Maximum loads in Vertical and Transverse Directions- 191.99 KN & 54.23 KN respectively.

Description: While increasing the loads from 75% to 90%, two Transverse bracing members and one Longitudinal bracing member buckled (Figure 2). Subsequently, Main leg got buckled below Ground wire level. The loads were released immediately.

Remedial Measures: The failed members were 80X80X6 MS Angle Section, after reanalyzing the tower, the existing member was replaced by 90X90X6 MS Angle Sections in the erected tower. Horizontal redundants of 45X45X5 MS size were also introduced on both transverse and longitudinal face to reduce the unsupported length of main member. After these remedial measures, the test was continued again and the tower was successfully tested.

Tower before test

Tower after failure

Figure 1. 230kV double circuit suspension tower.

Tower before test

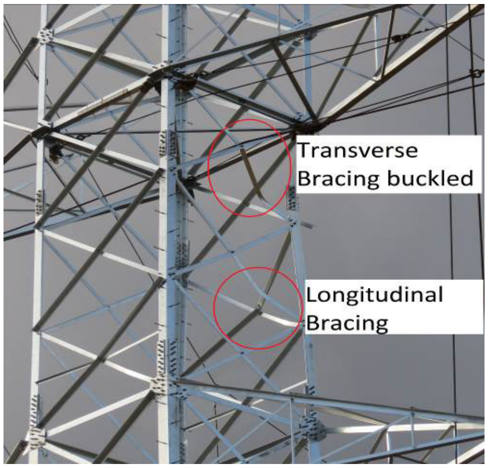


Figure showing Buckled bracing

Figure 2. 220kV double circuit Tension tower.

4.3 Tower Type

220kV Double circuit Tension tower. Total height- 51.07 m. Weight- 91.14 KN.

Loading Conditions: Normal Condition (Reliability Condition), 100% of test loads. Maximum loads in Vertical and Transverse Directions – 21.55 KN & 51.01 KN respectively.

Description: During waiting period after reaching 100%, of all loads, the tower failed. The failure occurred at compression leg members at the junction of first and second panel below waist level, (Figure 3). They started bowing outward. Subsequently the whole tower collapsed.

Remedial Measures: The tower was reanalyzed and after modification it was tested successfully.

4.4 Tower Type

220kV Double circuit Tension tower. Total Height- 39.6 m. Weight- 144.62 KN.

Loading Conditions: Broken Wire Condition (Security Condition), 100% of test loads. Maximum loads in Vertical, Transverse and Longitudinal directions- 41.67 KN, 65.19 KN & 88.25 KN respectively.

Description: During waiting period after 300 seconds, it was observed, that some bracing members of transverse and longitudinal face are slightly buckled, (Figure 4). The load was released immediately.

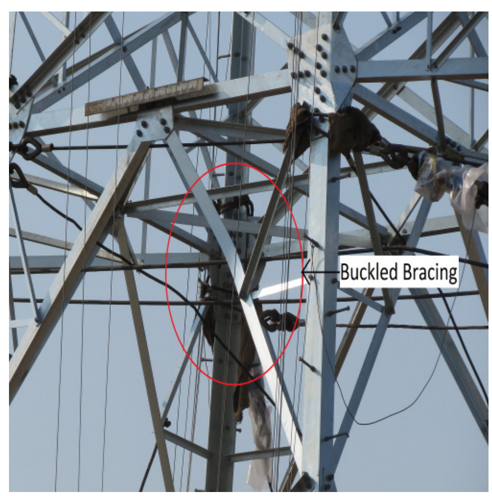
Remedial Measures: The buckled members were modified after reanalyzing the tower design. The existing member size L80X80X6 MS was replaced by L90X90X6 MS and L75X75X6 MS was replaced by L80X80X6 MS.

Tower before test

Failed Tower

Figure 3. 220kV double circuit Tension tower.

Tower before test



Failed Tower

Figure 4. 220kV double circuit tension tower.

The tower was tested again after these modifications the tower was successfully withstood the loads under the above loading condition.

4.5 Tower Type

66kV Multi circuit Tension tower. Total Height- 32.05 m. Weight- 122.11 KN.

Loading Conditions: Broken Wire Condition (Security Condition), 100% of test loads. Maximum loads in Vertical, Transverse and Longitudinal directions- 8.31 KN, 52.91 KN & 58.91 KN respectively.

Description: After completion of 240 seconds waiting period, it was observed that, redundant members of transverse side buckled (Figure 5). The loads were released immediately.

Remedial Measures: The buckled redundant members of existing size L45X30X4 were replaced by L45X45X4 and the test was continued again. The tower was successfully withstood all the loads under the specified loading condition.

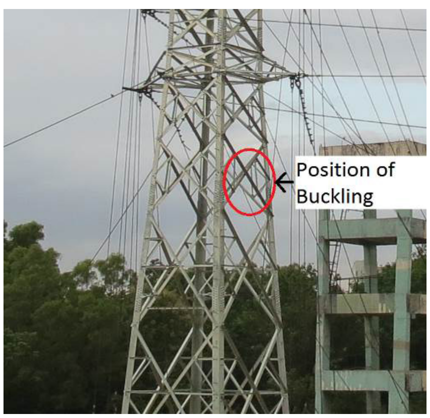
4.6 Tower Type

220kV Double circuit Tension tower. Total height- 55.54 m. Weight- 233.77 KN.

Loading Conditions: Broken Wire Condition (Security Condition), 75% of test loads. Maximum loads in Vertical, Transverse and Longitudinal directions- 15.01 KN, 120.81 KN & 70.36 KN respectively.

Description: While increasing all loads from 75% to 90%, one bolt sheared off at the joint of bracing and leg [Figure 6]. The loads were released immediately.

Remedial Measures: The bolt was replaced without any other modification in the tower. The testing was continued again and the tower was successfully –withstood all the loads under the above loading condition.



Tower before test

Figure showing position of Buckled redundant

Figure 5. 66kV multi circuit tension tower.

Tower before test

Figure showing location of Sheared bolt

Figure 6. 220kV double circuit tension tower.

4.7 Tower Type

230kV Double circuit Suspension tower. Total height- 67.30 m. Weight- 236.21 KN.

Loading Conditions: Normal Condition (Reliability Condition), 95% of test loads. Maximum loads in Vertical, Transverse and Longitudinal directions- 77.04 KN, 2.99 KN & 27.67 KN respectively.

Description: While increasing load from 95% to 100%, the tower failed. The failure started from leg member, which buckled below basic body and subsequently the whole tower collapsed, [Figure 7].

Remedial Measures: It was decided to reanalyze the tower design and after modification it was rescheduled for testing. The new tower was erected and retested successfully.

4.8 Tower Type

330kV Double circuit Tension tower. Total height- 44.03 m Weight- 136.45 KN.

Loading Conditions: Broken Wire Condition (Security Condition), 100% of test loads. Maximum loads in Vertical and Transverse directions- 59.21 KN & 40.08 KN respectively.

Description: Just after reaching 100% of all the loads, the tower failed. Failure started from Transverse bracing members and subsequently Leg members of Longitudinal side got buckled, [Figure 8]. All loads were released immediately.

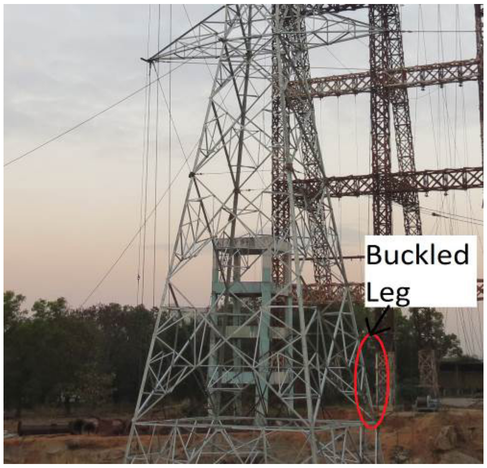
Remedial Measures: Leg member of size L100X100X7 HT angle section was replaced by L100X100X8 HT angle section and bracing member was replaced with same size but unsupported length of the member was reduced by introducing L45X45X5 MS Angle sections. The tower was tested again and successfully withstood the loads pertains to the above loading condition.

Tower before test

Fully collapsed tower

Figure 7. 230kV double circuit suspension tower.

Tower before test



Fully collapsed tower

Figure 8. 330kV double circuit tension tower.

4.9 Tower Type

400kV Double circuit Tension tower. Total height- 58.73 m. Weight- 454.12 KN.

Loading Conditions: Normal Condition (Reliability Condition), 95% of test loads. Maximum loads in Vertical and Transverse directions- 49.81 KN & 273.09 KN respectively.

Description: After reaching 95% of loads, during waiting period, one bolt of Leg member was sheared off [Figure 9]. The loads were released immediately.

Remedial Measures: The bolt was replaced by a new bolt of same grade and test was resumed. The tower successfully withstood the load pertains to the above loading condition.

4.10 Tower Type

132kV Double circuit Suspension tower. Total height- 25.15 m. Weight- 56.36 KN.

Loading Conditions: Normal Condition (Reliability Condition), 95% of test loads. Maximum loads in Vertical and Transverse directions- 6.25 KN & 27.03 KN respectively.

Description: While increasing the transverse load to 100%, three bolts sheared off at the joint connecting Transverse Bracing and Leg [Figure 10]. The test was stopped immediately.

Remedial Measures: The bolts were replaced with same grade bolts and the test was continued. The tower successfully withstood the load pertained to the above loading condition.

Tower before test

Figure showing the position of sheared bolt

Figure 9. 400kV double circuit tension tower.

Tower before test

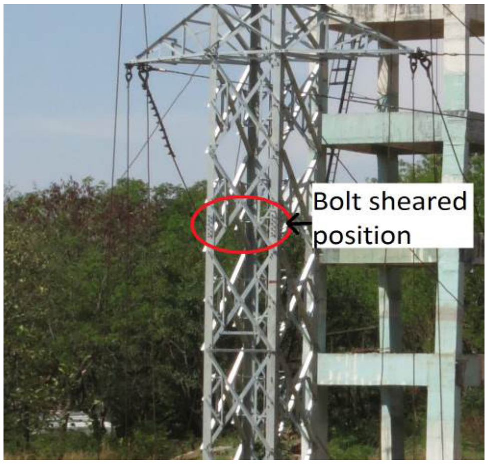


Figure showing the position of sheared bolt

Figure 10. 132kV double circuit suspension tower.

4.11 Tower Type

400kV Double circuit Tension type tower. Total height-45.45 m. Weight- 243.14 KN.

Loading Conditions: Broken Wire Condition (Security Condition), 100% of test loads. Maximum loads in Vertical, Transverse and Longitudinal directions- 12.41 KN, 38.08 KN & 76.18 KN respectively.

Description: During waiting period after reaching 100% of all the loads, some sound was heard from the tower [Figure 11]. On inspection, it was observed that one bolt was sheared off. The loading was stopped immediately.

Remedial Measures: The bolt was replaced with same Grade bolt and the test was started again. The tower successfully withstood the entire load after this modification.

The summary of types of failure, loadings Conditions and percentage of loading at which failure occurred is tabulated in Table 2.

Tower before test

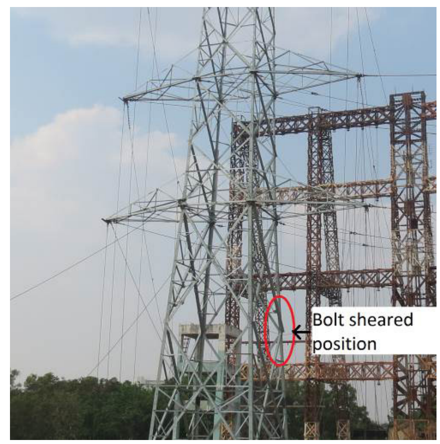


Figure showing the position of sheared bolt

Figure 11. 132kV double circuit tension tower.

5. Results and Discussion

Based on the failure patterns observed during full scale testing of towers listed in Table 2, there are many reasons of failure for a transmission line tower, so any particular reason cannot be generalized for all types of premature failure observed during testing. Following points summarize the conditions which are responsible to premature failure of a transmission line towers.

Table 2. Summary of failed towers

S. No.	Rating	Total Height (m)	Nature of Failure	Loading Condition	%age of Load
1	230 kV	63.09	Whole Tower Collapsed	Normal Condition (RC)	90%
2	220 kV	50.57	Bracing Buckled	Normal Condition (RC)	75%
3	220 kV	51.07	Whole Tower Collapsed	Normal Condition(RC)	100%
4	220 kV	39.60	Bracing Buckled	Broken Wire Condition (SC)	100%
5	66 kV	32.05	Redundant Buckled	Broken Wire Condition (SC)	100%
6	220 kV	55.54	Bolt Sheared	Broken Wire Condition (SC)	75%
7	230 kV	67.30	Whole Tower Collapsed	Normal Condition(RC)	95%
8	330 kV	44.03	Leg Buckled	Broken Wire Condition (SC)	100%
9	400 kV	58.73	Bolt Sheared	Normal Condition(RC)	95%
10	132 kV	25.15	Bolt Sheared	Normal Condition(RC)	95%
11	400 kV	45.45	Bolt Sheared	Broken Wire Condition (SC)	100%

From the Table 1, it is observed that the maximum percentage in number of failed towers is 400 kV towers. Three towers of 400 kV rating were tested, out of which only one tower passed in first instance. Two towers failed, one was at 90% of load and other was at waiting period after 100% of load. Since the failure was not major, only bolts were sheared off in both failed towers, it was not design deficiency. In one case the same Grade bolts were replaced and test was repeated and tested successfully. Similarly, it was also observed that the possibility of failure of transmission line towers increases with their rating. High voltage rating towers were more likely to fail during testing as compared to lower voltage rating.

Out of 11 failed towers, 6 towers failed in Normal Condition (Reliability Condition) and 5 in Broken Wire Condition (Security Condition). No towers were failed in Anti-cascading loading condition. Only three towers were fully collapsed and all these three were collapsed in Normal condition loading only. In Broken wire conditions the failures were not major.

It was observed that maximum towers were failed after reaching 90% of loading. Some towers failed after 100% of loading. They failed during waiting period of 300 seconds. These towers were easily withstood 100% of ultimate load without any visible sign of deformation in tower, but failed during waiting period.

While doing destruction test of many towers, it was observed, that maximum number of towers were collapsed within 110% of loads. These towers were most economically designed. It was also observed that some of the towers were able to withstand up to 125-130% of loads. These towers were over designed.

Four towers were failed because of the shearing failure of bolts. The bolt failure may be the result of improper detailing and fabrication error. When the loads are applied on any steel structure, the corresponding loads in various components are transferred through their joints. If the joint is not sufficient enough to take the load in that member, the structural behavior of tower will not be as expected.

The buckling of members was also observed in many towers during testing. The bulking of a member is the result of compression load in that member and the compression capacity of any steel member is directly proportional to the unsupported length of the member. In some cases, the force in the secondary members is more and they are not able to resist the buckling of main members.

6. Conclusion

Based on the above study, the following conclusions are drawn.

- The possibility of failure of higher voltage rating towers are more than that of lower rating towers.
- Many times bolts were responsible for tower failure. So it is desirable to provide a higher strength bolts than the designed strength.
- Normal condition (Reliability Condition) loading is critical loading. Three towers collapsed in Normal condition loading. So while designing, one should be very careful while calculating loads and analyzing the tower under normal condition loading.
- The factor of safety in the design of transmission line towers are considered smaller as compared to other steel structures in order to achieve economical design, that is why the design is very critical. This is the reason, maximum towers failed after 90% of loading. Since they are designed very critically, it becomes very important to fabricate the tower perfectly to meet all designed requirements. If there is any defect in fabrication, or assembling of tower, the possibility of failure may increase.
- The tower should be analyzed for calculated load to act on tower for longer duration. In general process of analysis of tower, the calculated load is applied on tower and sustainability of towers is checked. But in actual condition, the load may remain on tower for longer duration. As the stress in any member reaches its yield capacity, and remains for longer duration, the deformation starts in that member. This is the reason, some towers were able to withstand the design load up to 100%, but ultimately failed during waiting period.
- Buckling failure of main members can be minimized by proper designing of secondary members. Secondary members should be considered as design members in the structural design of towers.
- Plates, if provided at joints, should be strong enough to transfer load from bracing to leg. It was seen that sometimes plates were also bent when failure occurred during testing.

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