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Research paper

Analysis and Optimization of 275 kV Transmission Tower by Using Linear Static Analysis and P-Delta Analysis.

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Abstract

The increasing global population was demanded for more consumption of electricity. In Malaysia, it was reported that 17,790 megawatts (MW) was consumed in October 2017 due to high demand. The peak reading recorded is 0.011% increase compared to demand on April 2016 (17,788 MW). Following this, more transmission tower lines need to be developed to generate more electricity. Land acquisition is the main issue for constructing the new transmission tower because it requires a large area to set it up. The idea of optimization on the existing transmission tower helps in reducing cost for constructing the new structure. The aim of this study is to develop an optimal design of the transmission tower. A 275 kV transmission tower model is used in this study for analyzing and optimizing by using linear static and p-delta analysis. This optimization method is done by reducing tower members as well as increasing size of member's element. A design calculation for modification and arrangement of the transmission tower members is referred to manual guidelines of EN1993-3-1 and ASCE 10-97. Two alternatives are being prepared to produce an optimal design and result shows that a reduction percentage in term of reduced number of bar members can be saved up to 34 %.

Keywords: *electricity demand; linear static; optimization; p-delta; transmission tower.*

1. Introduction

The power industry is moving toward the use of high-voltage transmission tower to meet the demand for greater transmission capacity. This results in taller, more slender transmission towers that are subjected to heavier loads and undergo larger displacements [1]. The transmission towers are usually designed to resist many types of loading condition. However, many worldwide failures of power transmission towers can be attributed to various extreme loading condition such as broken lines, strong wind or ice loadings. These power transmission tower failures can interrupt the power supply, causing a severe impact on economy and society. A better understanding of the structural response is necessary to improve the performance of power transmission towers [2]. 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 [3].

The design optimization of steel lattice towers has always been a difficult task due to a large number of design variables, in which size, layout and sometimes topology design variables should often be considered simultaneously in order to minimize the weights of the structures. Therefore, it has drawn attention of numerous researchers for a long time [4]. By doing the configuration of tower bracing, the tower can form the lightest design. After all, latticed steel structures shall be designed with geometric configurations based on electrical, economic, and safety requirements according to the American Society of Civil Engineers 10 - England 1997 [5].

2. Study of Optimization

Optimization is done to get an optimum design of the transmission tower. There is a study in [6] shows that an optimization method performed on the layout and sizing of a truss transmission tower. The performance of optimizing is based on the algorithm that then been improved with first order sensitivity analysis. After that, a developed algorithm has also been tested in sizing and layout optimization problems with remarkable results. The method used is Simulated Annealing (SA) and the efficiency the optimization of real transmission structures is proved as shown in a real application example. Four constraints are considered which are cross-sectional area slenderness, element slenderness, tensile stress and compression stress. The obtained solutions are 40% better than actual designs.

A study done by Cenk in [4] demonstrated a practical application of structural optimization in industry practice. An optimization tools is developed by integrated annealing algorithm with PLS-Tower software so it can optimize transmission tower for minimum weight according to ASCE 10-97 design specification using both size and layout design variables. The result for the optimized design weights of the towers also been compared with the conventional result of design process which showed weight reduction in the range of 10–26% compared to the industry practice.

In [7], a study on structural optimization of transmission tower is performed. A 400kV double circuit tower is modeled using angle and tubular sections in STAAD.Pro V8i software. The models is then been analyzed for wind load by using linear static and p-delta analysis in order to study the importance of p-delta analysis for transmission tower. The comparative study is presented in this study with respective to cost as well as displacement for both sections. The result shown that the displacement values increased when tower is analyzed for p-delta as compared to static analysis. There is a saving in weight of steel up to 20.9% when tubular section is compared with angular section.

Rodrigues in his study presented a general methodology for the size, shape and topology optimization of transmission towers. The redundant members in the structural model is not necessary. The optimization was conducted through the Firefly Algorithm (FA) and the Backtracking Search Algorithm (BSA). The result shown that the proposed scheme is able to reduce up to 6.4% of the weight, when compared to a classical size optimization procedure on original structures [8].

3. Methods

This part explained methods used in this study. In this part, transmission tower background and structural analysis are presented.

3.1. Structural Model Geometry and Description

For an actual 275 kV of transmission tower, this part covers transmission tower dimension, member of sections, segments, shapes of tower and table of quantities.

An actual tower of 275 kV 24SL type is used in this study. The tower is 37 m in height with 15 m body extension and type of connection for each member is bolted connection. Figure 1 shows the dimension of the transmission tower and the extension. The 3D model of the transmission tower is generated in the Autodesk Robot Structural Analysis (ARSA) software. A number of nodes and bar members of the tower structure are 568 and 1162 respectively

The structural member of 275 kV transmission tower is varies from 100×100×8 to 45×45×5 of equal angle standard sections. Table 1 presents type of sections used on the structure model and its location. The transmission tower is divided into six (6) segments for grouping of transmission tower members. Figure 2 shows the group member classification of transmission tower which consists of main leg, leg bracing, main body, body bracing, main arm and arm bracing. The classification of transmission tower members is needed in order to observe the difference of bar numbers in each group between alternatives before getting an optimum design.

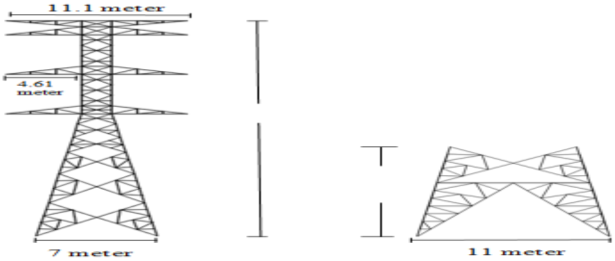


Fig. 1: Dimension of the transmission tower.

Table 1: List of sections and its location for the transmission tower

Section	Location
L 45x45x5	Arm Bracing, Body Bracing
L 50x50x5	Leg Bracing, Body Bracing
L 50x50x6	Main Arm
L 60x60x5	Leg Bracing, Main leg, Body Bracing
L 60x60x6	Main Arm
L 65x65x5	Leg Bracing
L 65x65x6	Main Body
L 70x70x5	Leg Bracing
L 75x75x6	Main Arm
L 90x90x7	Main Body
L 100x100x8	Main Leg

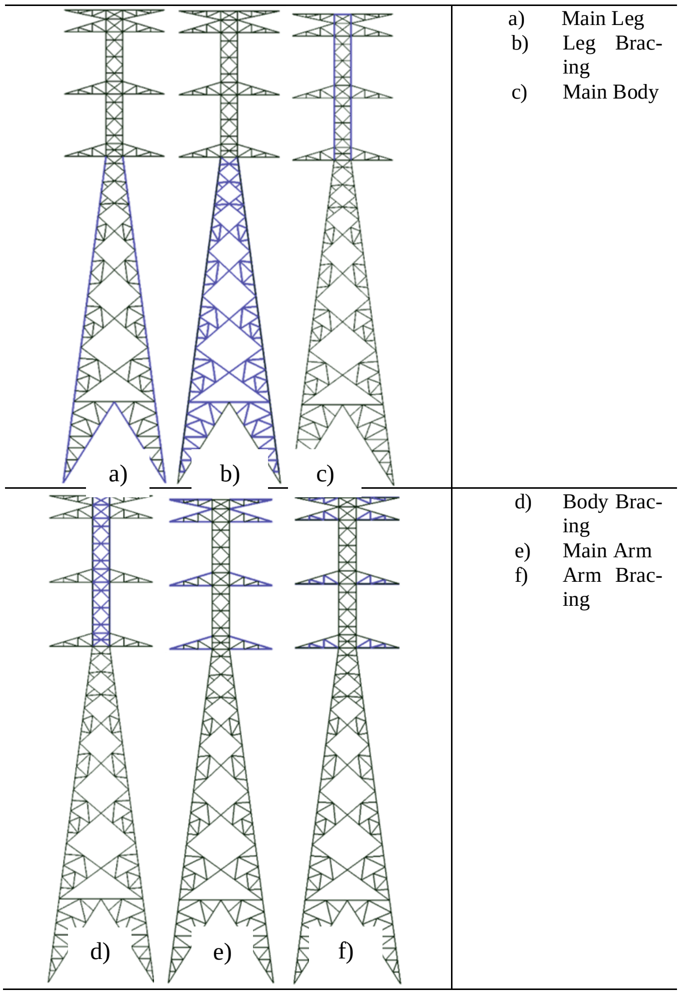


Fig. 2: A member classification of the transmission tower.

All members are divided into 11 sections where each sections carries its own weight and length. Each restrained members are assume as a single member. This assumption aims to observe the pattern in details on how internal force being distributed to the members. Table 2 shows the quantity properties for number of member, length and weight of each section. The leg support for this tower model is a fixed support where it does not allow movement in x and y direction as well as rotation movement. The factors of safety (FOS) used in this study are 2.0 for normal condition and FOS of 1.25 for broken wire condition.

Right selection of material for tower structure is important to ensure its strength and reliability. It should conform to a standard specification and to have a required minimum strength level. It is important that the structure to have a good mechanical property due to high external loading [9].

Table 2: Quantity properties of transmission tower

No.	Sections	Number	Length (m)	Total Weight (kg)
1	L 45x45x5	144	233	793
2	L 50x50x5	226	365	1387
3	L 50x50x6	47	77	346
4	L 60x60x5	286	498	2292
5	L 60x60x6	12	18	103
6	L 65x65x5	196	409	2798
7	L 65x65x6	22	35	241
8	L 70x70x5	72	121	794
9	L 75x75x6	37	58	401
10	L 90x90x7	28	33	320
11	L 100x100x8	120	147	1807
	Total	1190	1998	11272

3.2. Structural Analysis

3.2.1. Linear Static and P-Delta Analysis

There are two (2) analysis involved which are linear static analysis and p-delta analysis for transmission tower structure. Linear static analysis forms the basis of calculations in structural design of overhead power lines [10]. While, p-delta effect occurs due to the large deflections of the loading points that cause further bending in the legs thus reducing the ultimate load-bearing capacity of tower [11]. Assumptions are considered in this study where the tower structure is assumed as beam and truss. For truss system, there are releases applied in order to control the rotation and translation on the model. Assumption in the transmission tower design is important as of any improper assumption can lead to the failure of the transmission tower.

3.2.2. Loading Cases

In this study, four (4) loading conditions are considered which are normal condition (NC), ground wire broken (GWB), top conductor broken (TCB) and middle conductor broken (MCB) as shown in Figure 3. For the loads that are being assigned to the structure of the tower, generally there are three (3) loads which are transverse load, longitudinal load and vertical loads. The longitudinal loads act parallel to the line and the transverse load is perpendicular to the line. For the vertical load, it is basically from the self-weight of the transmission tower. The ASCE 74 mentioned that load on transmission tower are the forces that applied on the wires and on the structure. The load applied on the wires are then transfer to the structure and the loads should include relevant load factors [12]. There are two types of load carried by transmission tower that have been categorized by European Standard, EN50341-1 which are permanent load and wind load. Permanent load consists of self-weight of support, insulator set and conductor resulting from the adjacent spans. While for wind load, terrain factor is the main consideration while doing the calculation in the code [13]. Wind loading is one of the important type of loadings that need to be considered for transmission structures design. Several industry documents exist and they have relatively similar approaches for wind loading analysis [14]. In this study a value of 33.5 m/s is applied as the maximum wind velocity for the transmission tower according to MS 1553: 2002.

The wind load constitutes an important and major component of the total loading on towers and so a basic understanding of the computation of wind pressure is useful [15]. For wind loading in this study involves eight (8) of different directions (i.e. X+. X+Y+, Y+, X-Y+, X-, X-Y-, Y- and X-Y-). Wind load in several directions were considered in order to determine its related maximum magnitudes. This is done in determining the critical wind direction experienced by the structure during operation [9]. The study in [16] stated that the maximum wind velocity is coming from 45° direction. It can be supported by Tian in his study where the collapse of transmission tower occurs easily at 45° angle of attack compared to the other two angles of attack (i.e. $\alpha = 0°$ and $\alpha = 90°$) with the same wind velocity. Wind loading by its nature is a dynamic force, which give an effect on a structure as a whole and start vibrating at its natural frequency thus inducing dynamic bending. This causes shear and bending stresses at all points, depending on the mass and acceleration of that point [17].

4. Result and Discussion

Three models have been studied to observe the difference patterns in term of weight, ratio, internal force, member sections and displacement. The transmission tower member is categorized according to its group as mentioned in Fig. 2 earlier. Fig. 4 presents model of transmission tower while, Fig. 5 shows a number of members for Original, Alternative 1 and Alternative 2 where each carries the value of 1173, 1046 and 770 number of bars. The removing process of bar members is mainly focus on redundant members and remain the main members. This is because any changes made on the main member need a detail and careful step as it might disturbs the stabilization of the transmission tower. From the models, it can be seen that by removing members can help to simplify the connection of the tower like the study in [1]. It stated that by identifying the redundant members that can be eliminated from the connection without significantly affecting the structural behavior.

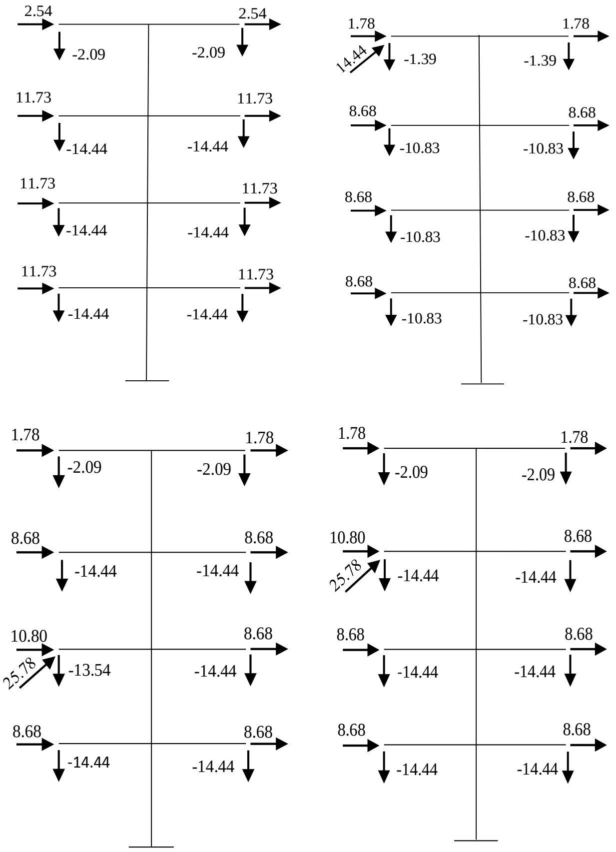
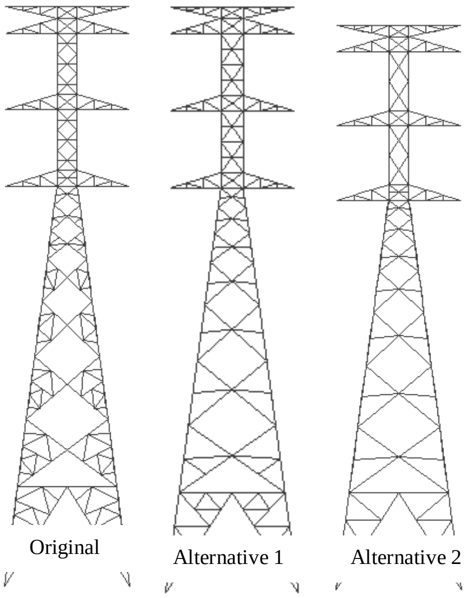


Fig. 3: Loading cases of 275 kV transmission tower.


Original

Alternative 1

Alternative 2

Fig. 4: Models of transmission tower.

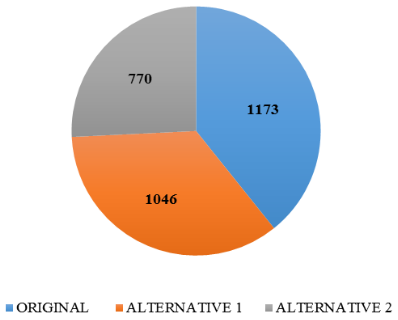


Fig. 5: Number of members for all tower models.

Fig. 6 shows the displacement values for all structure models. Alternative 2 shows increasing up to 47 % and Alternative 1 is 3.83 % less compared to the Alternative 1. This is because of the rigidity issue of the transmission tower where the tower lack of horizontal bracing that can interrupted the displacement value. More models need to be developed by adding more horizontal bracing on the body of tower in order to study the pattern of displacement. All structures undergo displacements when subjected to loads, but the importance of the displacements varies according to the relation between the size of the structure and the magnitude and direction of the loads and the size of the displacements [18]. A study by [19] declares that under the same general conditions, a member removal at an upper level will induce larger vertical displacement than a member removal at ground level.

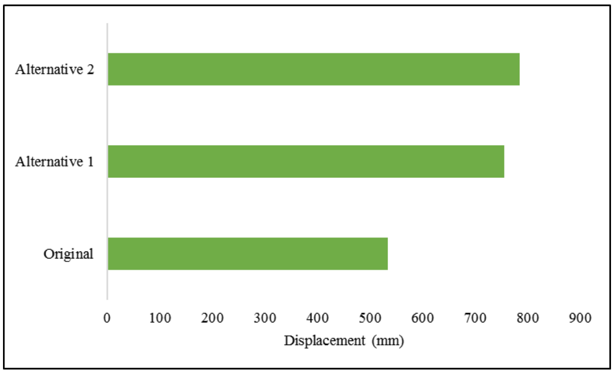


Fig. 6: Displacement value for all structure models.

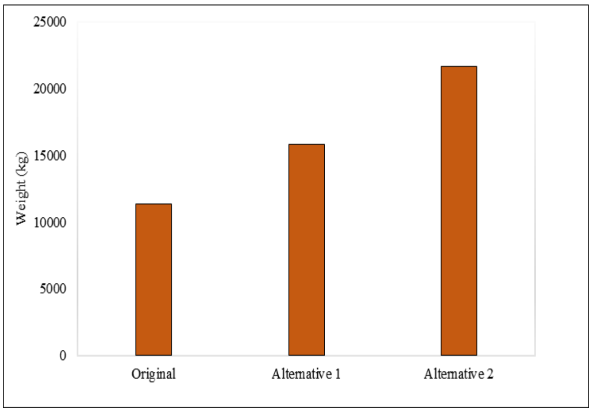


Fig. 7: Weight (kg) for all structure models.

For Alternative 1, the maximum internal force is increase up to 21 %. While for Alternative 2, the maximum internal force increase up to 36 %. Fig. 7 presents the weight for both Alternative 1 and 2 where it increases up to 40 % and 90 % due to the usage of the bigger section size that contributes to the increasing of the weight. The bigger section size is used in order to control the value of design compression ratio. The lowest value of section size devotes to a shorter length of steel.

The stability of the transmission tower can be measured by comparing the ratio of internal force and compression capacity *(fa)* where this ratio indicated the allowable loading that can subject to the tower instability. The tower structure of 275 kV is analyzed to get the result of internal force as well as the displacement mode. Compression capacity (fa) is needed in order to know the maximum allowable ratio that can contributed to the buckling failure. By removing the members with least design resistance ratio, the reduced percentage is decrease to 10%. The concept of ratio can be supported by the study in [20], an impact factors and capacity-to-demand ratios are calculated for various failure scenarios and for different elevation levels of removal. Thus, the obtained ratios are used to appraise the critical areas of the structure.

Table 3: Maximum internal force for original tower model.

Methods	**Maximum Internal Force (kN)**
Linear Static Analysis	418.55
P-Delta Analysis	495.21

Table 3 shows the maximum internal force by using both linear static and p-delta method analysis of an original model. There is a minimal difference between linear static analysis and p-delta analysis. Thus, in fact the tower model reveals that the effect of p-delta analysis significantly influence the axial, moment and displacement of the structural component [21].

5. Conclusion

Transmission towers are prone to progressive collapse. In this paper, optimization was done by applying the method of bar removing and increasing size of member. Thus, by reducing almost 34 % of bar members, this paper presents the effect of its structural weight, displacement, internal force and design compression ratio.

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