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EVALUATION OF OVERHEAD TRANSMISSION TOWER SUBJECTED TO PREDOMINANTLY WIND LOADING

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A B S T R A C T

Malaysia has increasing demand on power with 17,788 MW maximum demand in 2016. Through the National Grid operated and owned by Tenaga Nasional Berhad, the electricity distributed to the consumer with more than 22,400 km transmission network length. Overhead transmission tower become a major energy infrastructure to the Nation. Collapse of any overhead transmission tower would caused disruption in power supply affecting huge area, danger to maintenance workers as well as the public and economic. This paper presents the result of wind analysis from 30 years monthly wind data for three different area at Pahang State, Malaysia. This study is aimed to determine the stability of overhead transmission tower (OTT) subjected to predominantly wind loading. Using the wind data, a 275 kV overhead transmission tower is modelled and analyzed with linear static analysis method in different load cases. A CFD simulation result is also presented in this paper to determine the wind behavior when it flown through a lattice steel OTT. It is found that the maximum wind velocity from the 30 years wind data of 29.5% and even increased as per MS 1533 : 200 of 33.5 m/s is not caused failure of the 275 kV OTT. Once the wind load is increased to 95 m/s based on 2D CFD simulation the internal compression force in the main leg of the tower have exceeded its compression capacity by 56.67% and will induce failure.

1. Introduction

Nowadays, transmission line is an important lifeline project as it can carry electric power, and its safety affects the national economy and people's life. The main supporting unit of transmission line is overhead transmission tower (OTT). The OTT have to carry the heavy transmission conductor at a sufficient safe height from ground. In addition to that, all towers have to sustain from all kinds of natural calamities. The OTT design is become an important engineering tasks where three basic engineering concepts, civil, mechanical and electrical engineering are equally applicable. The highest ever demand for electricity in Peninsular Malaysia was recorded at 17,788 megawatts (MW), in April 2016 (Tenaga National Berhad, 2016). However in the annual report 2016, it is stated that the peak reading of 17,788 megawatts recorded was a 37.82% increase compared to demand on January 2016 (12,906 MW) due to the El-Nino phenomenon. In other study, it was stated that in 2030 the world will consume energy from electricity two-third more than present demand (Bendjebbas, Abdellah-ElHadj, & Abbas, 2016).

Regards to the demand of the electric power, collapse of any overhead transmission tower would cause disruption in power supply affecting huge area, danger to maintenance workers as well as the public and economic. There were cases of collapse of OTT recorded in Malaysia. On 13 January 2005, a power

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blackout on Northern Peninsular Malaysia occurred when a transmission line near Serendah, Selangor, had broken down. In response to this, the Central Area Reinforcement (CAR) project was approved to ensure security of power supply to the Klang Valley. In addition, On 22 April 2008 Sabah had the worst power outage since the commissioning of the east west power grid. Suspected vandals were believed to have removed steel pieces of a 132 kV overhead transmission tower led to its collapse, triggering a major power blackout. An emergency temporary tower was built immediately but it also collapsed during construction killing a TNB personnel. While on 1 May 2008, another tower collapsed due to missing structural members of the tower that were suspected of being stolen.

Failure of transmission tower due to extensive wind loading was recorded in China. There were studies discussed about the common factor that lead to the tower collapsed and have concluded that it was due to strong wind. Three cases reported on transmission tower failure within 6 years in China. In 2007, strong wind in Liaoning Province of China causes many transmission towers damaged poorly. Meanwhile, in 2010, five transmission towers collapsed due to the strong wind and rain in Guangdong Province of China. During 2013, natural disaster typhoon Fitow in Zhejiang Province of China affected the area and collapse of the tower also charged to power interruption (Tian, Yu, Ma, & Wang, 2014). This shows that the structure stability contribute to the stability of the power transmission and distribution.

In Malaysia percentage of supply interruption caused by storm is 0.42% that was 293 cases (Energy Commision Malaysua, 2015). Thus, this paper is aimed to determine the stability of overhead transmission tower (OTT) subjected to predominantly wind loading.

2. Problem Statement

The collapse of overhead transmission tower has occurred in recent years. It can be seen from failure cases that the collapse of the transmission tower often leads to huge losses. Although the transmission towers were designed by code provisions, some of them might be failed during testing due to various reasons such as incorrect design assumptions, defects in materials, fabrication errors, and force fit during erection, and variations in the strength of the bolt (Prasad Rao, Samuel Knight, Mohan, & Lakshmanan, 2012). Therefore, it is very important to study the failure mode and design of the transmission tower. Based on the ASCE/SEI 48-11, any design stresses for transmission tower shall be based on ultimate strength methods using factored design loads (ASCE, 2012). However, earlier research discussed about the wind load as the main control load case of transmission towers. Transmission tower is one of the most wind-sensitive structures. Wind loads are very important for the structural design of transmission towers. Hence, the parameter values and the calculation methods for the wind loads are basis of the structural design of transmission towers.

3. Objectives

1. To study the wind velocity and its direction in 3 different area of State of Pahang, Malaysia.
2. To evaluate stability of overhead transmission tower (OTT) subject to wind load.

4. Methodology

4.1 Wind Loading Analysis

4.1.1 Data Collection

For this study, the information is collected and gathered from Malaysia Meteorological Department (MMD) for 30 years wind data. Three locations have been selected which are Kuantan, Muadzam Shah and Temerloh.

4.1.2 Wind Loading Analysis

This part is divided into two which are wind velocity and wind direction study followed by wind loading analysis. These two data taken in a 30 years period. The assigned data is then transferred to the software Autodesk Robot Structure Analysis Professional 2017 (ARSA) for generating wind loading analysis.

4.2 Evaluation of the model

There are 11 different sections of steel members used in 275 kV overhead transmission tower. The structural member of 275 kV transmission tower is varies from 100x100x8 to 65x65x6 of equal angle standard sections. The 3D model of the OTT is generated in the ARSA software. Figure1 shows the model. The main load cases are divided into four condition which are Normal Condition (NC), Ground Wire Broken (GWB), Middle Conductor Broken (MCB) and Top Conductor Broken (TCB). The loading tree for each condition are presented in Figure 2 to Figure 5 respectively. These loading containing factor of safety (FOS) of 2.0 – 2.5 for normal condition and FOS of 1.25 – 1.50 for broken wire condition. Three different directions of load assigned to the structure of the tower which are vertical, transverse and longitudinal. 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 OTT (Usman &

Megat Asyraf, 2011). In this study, the 3D model of the tower is analyzed using linear static analysis method. The members are assumed to be imposed axially.

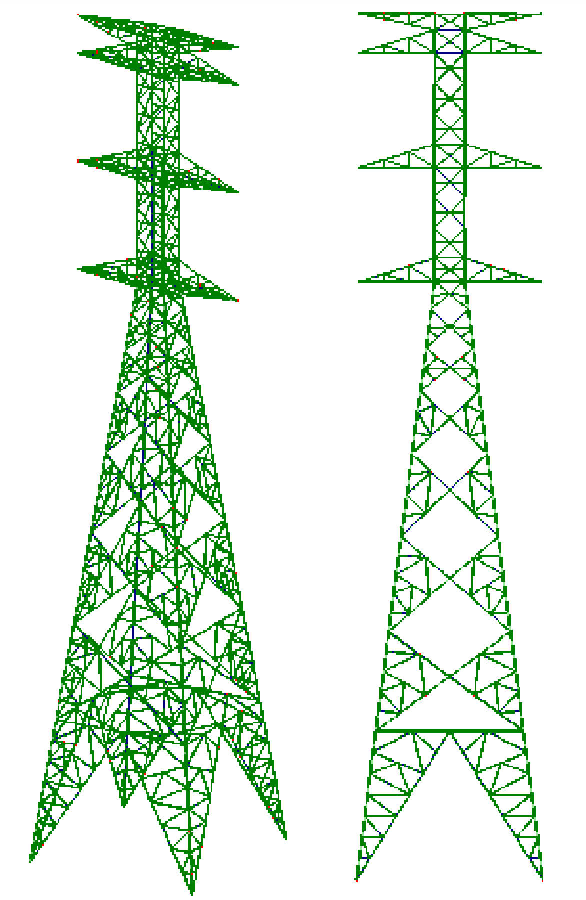

Figure 1: The 3D model of 275 kV OTT

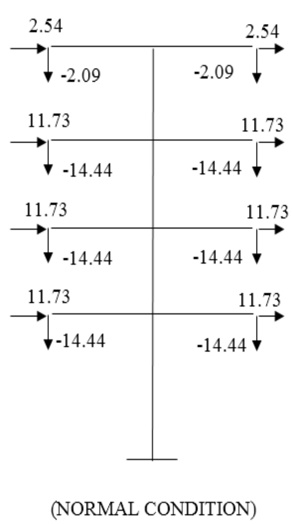

Figure 2: Normal Condition

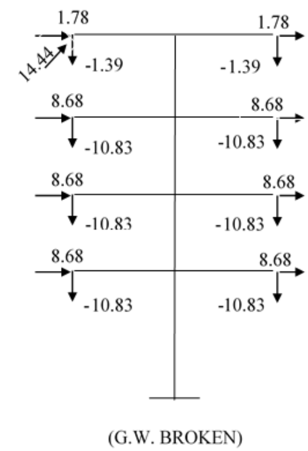

Figure 3: Ground Wire Broken

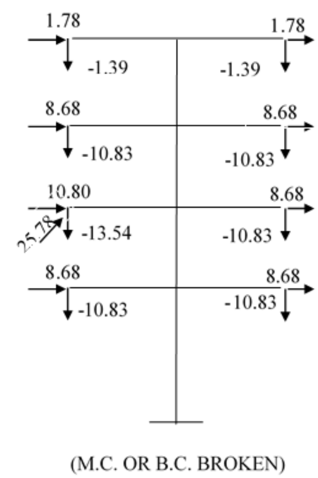

Figure 4: Middle Wire Broken

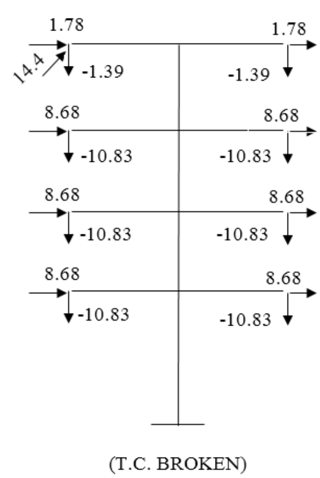

Figure 5: Top Conductor Broken

According to standard tower design used by Tenaga Nasional Berhad Transmission Division (TNBT), those loadings are derived from these calculations as in Table 1 to Table 4.

Table 1: Normal Condition (Conductor 'Zebra')

Item	Description of loads	Calculation	Force (N)
1	Wind on insulator string	1 × 0.5 × 3.28 × 0.254 × 430	179
2	Wind on conductor	2 × 365 × 0.02862 × 430	8984
3	Transverse load due to tension in conductor	2 × 2 × 3754 × sin 1 × 9.81	2571
4	Weight of insulator string	1 × 1690	1690
5	Weight of conductor (downward vertical load)	2 × 600 × 1.635 × 9.81	19247
6	Minimum vertical load		6502

Table 2: Normal Condition (Earthwire 'Skunk')

Item	Description of loads	Calculation	Force (N)
1	Wind on earth wire	1 × 365 × 0.01295 ×430	2033
2	Transverse load due to tension in earth wire	2 × 1472 × sin 1 ×9.81	504
3	Weight of earth wire fittings	1 × 100	100
4	Weight of earth wire (downward vertical load)	600 × 0.473 × 9.81	2784
5	Minimum vertical load		796

Table 3: Broken Wire Condition (Conductor 'Zebra')

Item	Description of loads	Calculation	Force (N)
1	Wind on insulator string	1 × 0.5 × 3.28 × 0.254 × 430	179
2	Wind on conductor	2 × 275 × 0.02862 × 430	6769
3	Transverse load due to tension in conductor	(2 × sin 1 × 3754 × sin 1 × 2638) × 9.81	1736
4	Longitudinal load due to tension in conductor	0.7 × 3754 × 9.81	25779
5	Weight of insulator string	1 × 1690	1690
6	Weight of conductor (downward vertical load)	2 × 450 × 1.635 × 9.81	14435
7	Minimum vertical load		5299

Table 4: Broken Wire Condition (Earthwire 'Skunk')

Item	Description of loads	Calculation	Force (N)
1	Wind on earth wire	275 × 0.01295 ×430	1531
2	Transverse load due to tension in earth wire	1472 × sin 1 × 9.81	252
3	Longitudinal load due to tension in earth wire	1472 × cos 1 × 9.81	14438
4	Weight of earth wire fittings	1 × 100	100
5	Weight of earth wire (downward vertical load)	450 × 0.473 × 9.81	2088
6	Minimum vertical load		796

4.3 CFD Simulation

The Computational Fluid Dynamic simulation in this paper is conducted by using Autodesk Flow Design (AFD) in Autodesk Inventor Professional 2017. The AFD software is a tools to virtually model a condition inside wind tunnel for investigating behavior of wind to the structure of transmission tower. 2D simulation is chosen for rapid investigation. The software is also very geometric tolerance and able to accept complex geometry easily in various 3D model format. The 3D model of 275 kV overhead transmission tower generated in Autodesk Advance Steel 2017 and convert into solid model before placed in the Autodesk Inventor Professional 2017's assembly file. Connections on the transmission tower is not placed in the model.

The angle of attack, α for the simulation is 45°. It is based on study that 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 (Tian et al., 2014). The virtual wind tunnel is oriented to 45°.

5. Result and Discussion

5.1 Wind Analysis

Wind rose is part of wind analysis. Wind rose shows the pattern of the wind direction. There are two axis which are circular axis and x-axis. Circular axis is the direction of the wind in 360° while x-axis is the percentage of direction occur for the time interval to the direction. During the analysis, there are 24 intervals in every 15° of direction. The win rose diagram for Kuantan is shown in Figure 6. Figure 7 and Figure 8 show the wind rose diagram for Muadzam and Temerloh respectively.

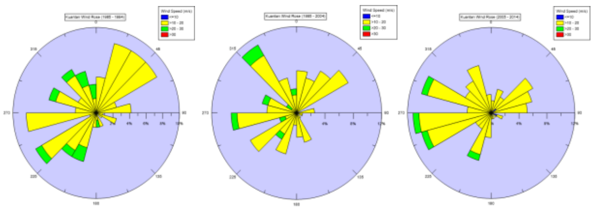

Figure 6: Wind rose diagram for Kuantan

In Figure 6, for the first 10 years monthly data, it shows that the wind direction is come from North East with the 8% percentage of the wind occurred toward the direction and wind speed ranges from 10 – 20 m/s. the other 20 years monthly interval data, the wind direction is occurring from North West direction and West direction with the wind speed ranges from 20 – 30 m/s. The percentage of wind occurred towards the direction is almost 12%. Based on this direction the wind angle of attack of 45^{o} is set for the wind simulation.

In Figure 7, for the first 10 years interval shows the direction of the wind is come from South West with the speed of 20 – 30 m/s and 19% percentage of the wind occur towards South West direction. While the next 20 years interval shows that the wind direction is coming from North East and North direction. The percentage of the wind occur towards the direction are 17% and 15% with the speed ranges from 20 – 30 m/s and 10 – 20 m/s. while Figure 8 shows that the wind direction for 30 years monthly data is coming from East direction. With the speed ranges from 10 – 20 m/s and the percentage of wind occur towards East direction ranges from 10 – 14%. From the analysis, it shows that the wind direction is dominantly coming from West direction.

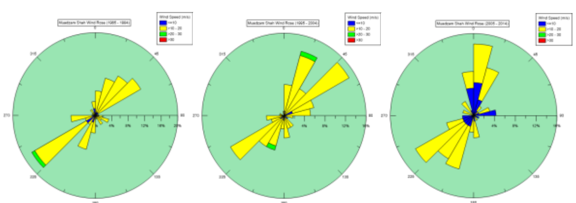

Figure 7: Wind rose diagram for Muadzam Shah

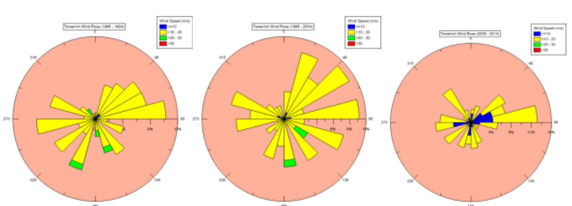

Figure 8: Wind rose diagram for Temerloh

Figure 9 shows the wind velocity for the three locations. It is shown that the highest velocity of wind was not occurred during monsoon season and the highest velocity was recorded in Kuantan area with 29 m/s of wind velocity. The mean value of wind velocity is between 12 m/s – 18 m/s or within range of 6 – 7 Beaufort number (ASCE, 2006). It is half of the maximum wind velocity set in MS 1533 : 2002.

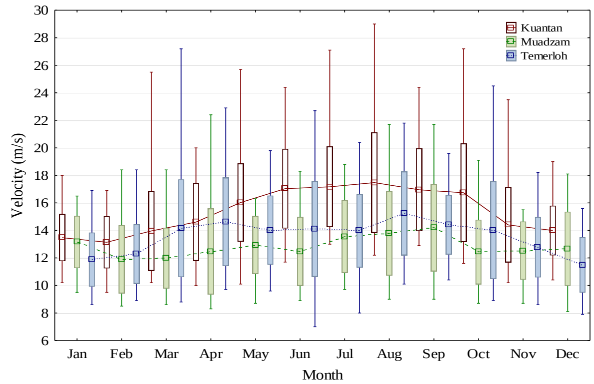

Figure 9: Boxplot diagram of wind velocity

5.2 Stability Evaluation

5.2.1 Load Combination

In general, a transmission tower consist of two separate structural systems, structural support system and wire system (ASCE, 2006). There are 4 main loading conditions applied to the tower as in Figure 2 to Figure 5. The wind load from wind simulation of 33.5 m/s generated in the ARSA is added to the main loading conditions. The wind velocity is taken based on clause 3.2 of MS 1533 : 2002 9 which is the 50 years return period, V_{50} (Department of Standards Malaysia, 2002) and (ASCE, 2006). The wind loads from 8 different angles of attack (i.e. X+. X+Y+, Y+, X-Y+, X-, X-Y-, Y- and X-Y-) are applied in the analysis to determine the worst-case situation. Total load combination with different angle of attack is 32 combination of load cases. The applied factor of safety (FOS) in the analysis is 2.0 for SL type OTT. Result of the static linear analysis is given in Table 5.

Table 5: Maximum internal force.

	Fx (kN)
Compression	507.48
Bar	5
Case	16 (C)
Tension	-360.60
Bar	211
Case	16 (C)

It is determined that the maximum internal force of 507.48 kN on member number 5 (i.e. leg of the transmission tower) is derived from load combination 16 (Dead Load + Normal Condition + Wind Load) where the angle of attack is in X+Y+ direction as in Figure 10.

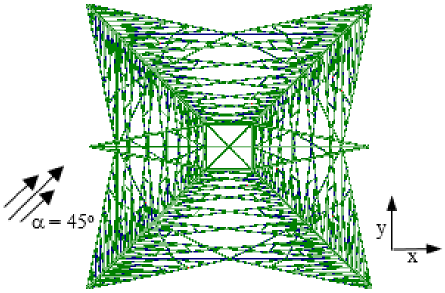

Figure 10: The angle of attack, α = 45°

5.2.2 Compression Capacity

The compression capacity, fa is calculated referring clause 3.6 and clause 3.7 of ASCE 10-97 (ASCE, 1997). It is started by comparing value of w/t agains $(w/t)_{lim}$.

$$\left(\frac{w}{t}\right) = 9.5 \text{ where } w = B - 3t$$

$$\left(\frac{w}{t}\right)_{lim} = \frac{80\varphi}{\sqrt{Fy}}$$

$$\left(\frac{w}{t}\right)_{lim} = \frac{80(2.62)}{\sqrt{335}} = 11.12 \therefore \left(\frac{w}{t}\right) < \left(\frac{w}{t}\right)_{lim}$$

Then, $C_c = \pi\sqrt{\frac{2E}{Fy}} = \pi\sqrt{\frac{2(205\times10^6)}{355}} = 179.19$

Value of f_a for equal angle **100×100×8** section:

Check $\frac{KL}{r_v}$ agains C_c

$$\frac{KL}{r_v} = \frac{1\times1.31}{0.0197} = 57.36 \leq C_c$$

$$F_a = \left[1 - \frac{1}{2}\left(\frac{KL/r_v}{C_c}\right)^2\right]F_y = \left[1 - \frac{1}{2}\left(\frac{57.36}{179.19}\right)^2\right] \times 355$$

F_a =336.81 N/mm^2

The compression capacity, $f_a = F_a \times A_s$

f_a = 526.43 kN

It is determined that the tower model has adequate compression capacity subject to the combination wind load. The factor of safety (FOS) as per above mentioned is already applied in the ARSA software for calculation generating the internal forces value.

5.2.3 CFD Simulation

The CFD simulation is conducted in 2D simulation where the 2D plane is located at the main body close to arm of the tower. It is shown that there is influx of wind velocity ranged from 0 m/s in dark blue to 95 m/s in red color. Normally, the influx is caused by gust wind. The gust wind eiatance in high wind speed conditions is important for load estimation on large structures in exposed locations. This is because the atmospheric wind is turbulent over a large range of scales and wind gusts of the scale of a wind turbine become important for load calculation and wind turbine control (Bardal & Saetran, 2016). Figure 11 shows the development of wind turbulence for the wind velocity of 33.5 m/s.

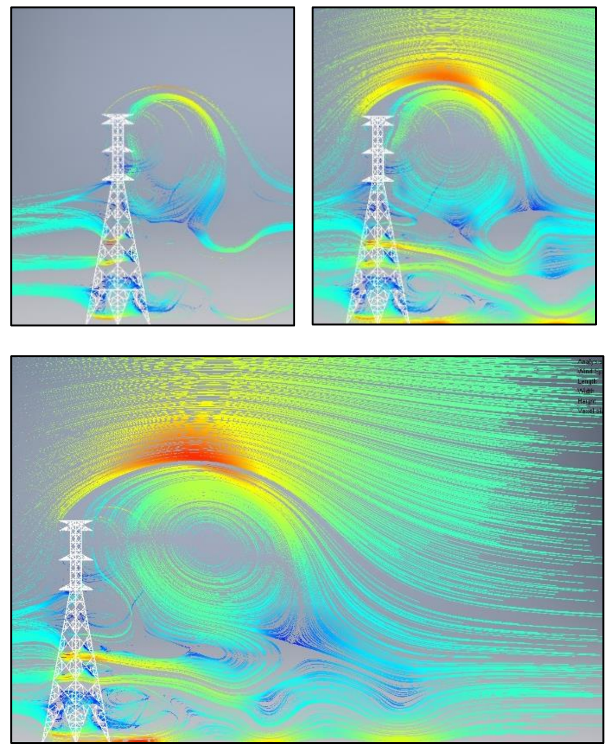

Figure 11: The CFD of wind simulation.

Re-analysis of the transmission tower model have been conducted for possible wind velocity of 95 m/s. The wind velocity generates maximum +ve and -ve member pressure of 5.55 kPa. It is found that the internal forces of 800.07 kN at the leg member of the tower has exceeded its compression capacity. The internal force is 57.65% higher than internal force derived from wind velocity of 33.5 m/s. There is possible potential of failure of the transmission tower regards to this influx of wind velocity. Further investigation and wind simulation in 3D CFD simulation are required to determine detail behavior of the OTT subject to wind loading.

6. Conclusions

In this paper, discussion on wind velocity and wind direction for 3 different areas in Pahang State, Malaysia have been presented. Linear static analysis is evolved to determine possible failure of the 275 kV type SL OTT subject to 33.5 m/s wind velocity. It is found that if influx wind velocity of 95 m/s based on 2D CFD simulation is considered the main leg of the OTT imposed to internal force that exceed its compression capacity. Further detail investigation and analysis are required.

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