Optimal Design of Pole for Solar Wind Hybrid Energy System

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Abstract— *The work in this thesis represents how wind turbine pole is designed to give stability under extreme conditions. Different stability criteria are explained and analyzed for both numerically and analytically. For numerical analysis all work is performed on finite element package Ansys 14.0. The weather condition that effects the wind turbine pole is taken for Islamabad city. Small wind turbine pole that is used as hybrid solar system or as standalone is first modeled and then analyze in ansys whether it satisfied stability criterion including deflection, linear buckling and vibrational analysis. The stress analysis shows that the structure is withstand with the occurring forces. And finally modal analysis is done to find out the resonance of the model. After three analyses it was found that under extreme loading condition the design is safe.*

Keywords — Wind turbine, Pole, Vibration, Buckling, Stiffness, Rotor, Natural Frequency, Modal analysis

1. INTRODUCTION

Adequate supply of cheap energy is the basic necessity of today. Energy effects the economic as well as industrial growth of any country. With the passage of time, challenge to provide electricity has become a prominent issue. Energy disaster in Pakistan is one of the strong challenges the country is facing today. Shortage of power and gas has badly affected the economy and overall living in Pakistan. On the other hand, requirement of Information technology equipment is on increasing trend. One way to meet the energy requirement of that equipment is to produce more energy. Resources of fossil fuels are decreasing and becoming costlier day by day. This fast depletion has brought the world in the grip of energy crisis. Therefore, energy efficiency is the cheapest and quickest way to cope with that crisis.

Wind to produce energy is one of the utmost important methods of renewable energy. In fact, wind energy is the only renewable energy that is growing faster than expected. One important benefit of wind energy is that; it is practically economical way of producing energy.

Renewable energy is energy derived from resources usually as wind, sunlight, rain, waves or tides, and geothermal heat, which are naturally refilled. About 16% of consumption of energy in the world is from renewable, 10% form biomass, 3.4% from hydroelectricity. Hybrid energy methods also known as Hybrid renewable energy system (HRES) is the modern innovation in the era of technology. It consists of minimum two or more renewable energy resources used together to provide better system efficiency in addition to greater stability in energy supply.

This idea is piercing rapidly not merely at commercial level but also on domiciliary level. This novelty is becoming very common for fulfilling distant area energy needs due to the consequent rise in petroleum products prices and non-accessibility of grid energy in some regions. In Pakistan, about 64% of the total power created depends upon fossil fuels. Production of energy by fossil fuels is not only a cost proficient method of energy production, and with the reducing resources, the specialists have a big question ahead of them what then if these resources reduce sooner or later! Will the individual solar energy systems or wind energy systems be sufficient enough or efficient enough to sustain the nonstop supply of energy? There is a solitary answer to these questions which is a no, and yes we have answer too which is Hybrid energy. Advantages and disadvantages are;

- The use of resources HRES are renewable therefore they are in plenty thus is long lasting.
- There is no contamination of environment or waste from the system.
- Tidal, wind and solar resources produce energy that is generously available.
- It involves a very low maintenance
- It is economical resource of energy such as hybrid is made among sustainable and renewable energies.

- Hybrid Renewable Energy is not only clean but safe source of energy.[1]
- The energy sources which possess their separate system so they need suitable place to assemble them without creating them a hurdle at home or in any industry.
- Hybrid renewable technology is reliant on the region, capacity environment and. It is impossible to use same sort of renewable technology in all places.
- Some regions are hot some are cold and are merely suitable for precise energy systems. So, it is favored to confer fossil fuel energy system through either solar, wind or water renewable energies.[2]

Researches have been introduced renewable energies firstly for wind power and formerly for solar power. Efficiency of solar power exchange systems is 18%, whereas that of wind power is 55%. These efficiencies can be increased by 50% with the help of beam tracking, beam concentrating and wind direction adaptive motion approaches.

Solar panels having the medium to transform solar power into the electrical power and wind turbine transform wind power into electrical power. It works under a microcontroller to use the solar and wind power. Electric generator in the turbine transforms the mechanical energy into the electric energy.
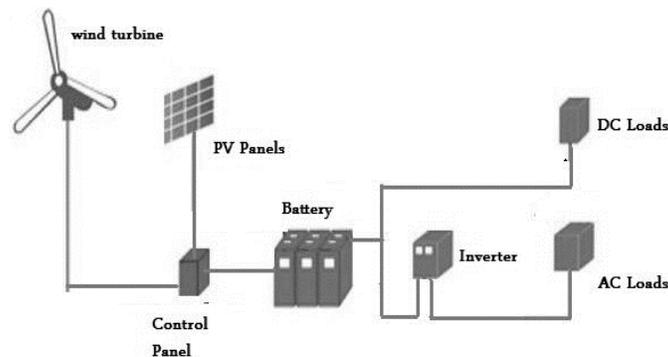
Figure: 1. How Solar Wind Hybrid Energy System Works [3]

Extracting energy from wind, wind turbine is one of the maximum effective means of transforming kinetic energy of wind power into mechanical energy. Energy Providers are spending their assets on research and expansion of wind turbines. Now a days wind turbines are installed in many countries.[4]

However, over the past decade damage of many wind turbine tower arising from the structural failure. Most of these failures are result of powerful winds striking and wind effect vibrations. In addition to buckling loads and high stresses are others causes of failures.

Design of wind turbine tower proposed as thin-walled cylinder typed structure possess breadth as compared to diameter is very low. So as to lessen the load of tower, the erect dimensions of the tower as compared to straight are large. This lean characteristic of wind turbine pole makes it very delicate to wind loading. Wind turbine support structure is designed in different many configurations. Commonly, Wind turbine towers are designed as tapper tabular pole as they show more stability compared to the wind loads, also saving of the material.[5]

2. METHODOLOGIES

Indeed, there are no straightforward criteria for measuring the above arrangement of goals. Then again, it ought to be perceived that the accomplishment of tower structural design is judged by the degree to which the wind turbine fundamental fuctions is accomplished. The different optimization methodologies measured. Each methodology fluctuated, however, in choosing a condition to be optimized.

Minimization of the tower's mass

A less mass structural design is of vital significance for effective and financial operation of a wind turbine. The lessening in structural weight is favorable from the creation and expense perspectives.

Maximization of the tower's stiffness

The principle tower structure must have a sufficient stiffness level. Amplification of the stiffness is crucial to improve the general structural stability and minimize the prospect of fatigue failure. For a cantilevered tower, stiffness can sensibly be measured by the extent of a horizontal force connected at the free end and creating a most extreme deflection of unity.

Maximization of the tower's stiffness to mass ratio

Boosting of the stiffness to-mass proportion which is straightforwardly identified with the physical substances of the design is a superior and clearer plan model than expansion of the s stiffness alone or minimization of the structural mass alone.

Minimization of vibrations

Minimization of the general vibration level is a standout amongst the most practical answers for an effective wind turbine plan. It encourages other critical design objectives, for example, long fatigue life, high strength and little noise level. Decrease of vibration can be accomplished by isolating the natural frequencies of the structure from the exiting frequencies to large vast amplitudes brought on by resonance.

Maximization of the system natural frequency

The phenomenon of resonance needs to be avoided to safeguard against the failures due to large amplitude responses, stresses and strains. The frequency of excitation cannot be changed as it is directly related to the operational requirements of wind turbine rotor. Hence the only way of avoid resonance is to control the natural frequency of the system.

Another option for decreasing vibrations is the immediate expansion of the system natural frequencies. Higher natural frequencies are great for decreasing both of the steady-state and transient reactions of the tower.

Different research studies were done in the past on these optimization techniques it was found that the maximization of tower natural frequency yields the most favorable results.[6]

Basic Design Assumptions

The fundamental structural model of the pole is spoken to by a proportionate long, slim cantilever shaft constructed from portions (modules) having distinctive however uniform cross- sectional properties. The pole is cantilevered to the ground, and is conveying a concentrated mass at its free end approximating the inertia properties of the nacelle/rotor unit. This mass is thought to be rigidly affixed to the pole top.

- Material of structure is linearly elastic, isotropic and homogeneous. The pole has a thin walled circuitous cross-section.
- The Euler-Bernoulli beam theory is utilized for anticipating deflections. Secondary effects, for example, axial and shear deformations, and rotating inertia are omitted.
- Disseminated aerodynamic loads are limited to profile drag forces. A two-dimensional (2D) consistent flow model is considered.
- Nonstructural mass won't be optimized in the design process. Its dispersion along the pole stature will be taken equivalent to some division of the structural mass dissemination.
- Structural analysis is kept just to the instance of flapping movement (i.e. bending normally to the plane of rotor circle).

Under any load fusion (counting any load safety measures), the material of the load bearing structural components of the pole ought to stay in the linear elastic region of its stress-strain graph i.e. no plastic deformation has happened.

Depiction of pole the structure

We have considered tubular tower in our study right all through as most of the wind pole used for solar wind hybrid energy system that is installed either on ground or roof top are tabular type for small wind turbine systems. We have model wind turbine pole for 5kw. It is planned as tapered tubular pole with expanding breadth towards the base. The thickness stays consistent all through the stature of pole.

The measurements of 5kw pole are at base the external diameter is 495mm and at the top the inward diameter is 179mm. the thickness of the pole is steady all through and it is 6mm. The stature of the pole is 12m.[3].

Table-1 The dimensions of pole

Dimensions	5kw Pole
Outside diameter at base	0.495m
Inside diameter at the base	0.489 m
External diameter at the top	0.185m
Internal diameter at the top	0.179m
Thickness	0.006m
Height	12m

Material assumed in wind turbine pole

ASTM 572 is most usually utilized material as a part of wind turbine poles. ASTM A572 Grade 50 is viewed as a "workhorse" grade and is generally utilized as a part of numerous applications. ASTM 572 is a high strength, low alloy steel that thinks that its best application where there is requirement for more strength per unit of weight. Less of this material is expected to satisfy given quality prerequisites than is vital with customary carbon steels. Furthermore, ASTM A572 is noted for its expanded resistance to barometrical consumption i.e. atmospheric corrosion. Especially Grade 50 contains more alloying components than plain carbon steel and accordingly is fairly harder to shape. Grade 50 is harder to cold work, yet can be effectively bent or molded yet needed more force than plain carbon steel.

It is ordinarily utilized as a part of basic applications, overwhelming development hardware, building structures, substantial obligation anchoring frameworks, truck frames, poles, liners, conveyors, boom sections, structural steel shapes, and applications that oblige high strength per weight proportion.[7]
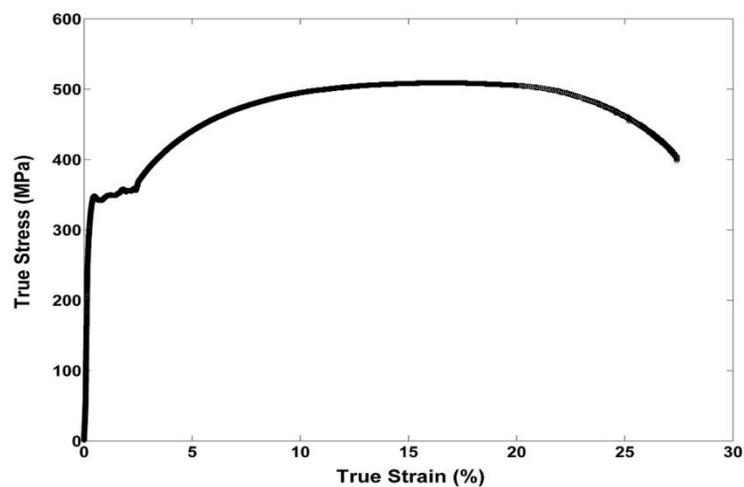
Figure-2 Stress-strain curve for ASTM 572[7]

Table-2 Material properties for ASTM 572[7]

Material	Composition	Thickness (mm)	Elastic Modulus (Gpa)
ASTM 572	0.18C, 1.2Mn, 0.44P, 0.05Si	25	200

Yield Stress(Mpa)	Percentage Elongation (Gauge length=)
350	25

Figure-3 Monthly average wind variation at Islamabad [8]

3 POLE DESIGN

Height of the pole

The stature of the pole is a site-subordinate parameter in light of the fact that it is up to the wind characteristics of the site. The design optimization for the slightest expense could support tall pole in low wind ranges and shorter poles in high wind regions. In any case, if there are obstructions, for example, trees or tall protests that may make the twist more turbulent, taller pole will be needed. Moreover, tall towers may keep the turbine from the impact of wind shear if the site has continuous wind shear event.

POLE DESIGN REQUIREMMENTS

The tower design is based primarily on types of load acting on the pole. These loads include[9]:

- **Dead Load:** loads acting from the rotor, nacelle and additional equipment at the top of the pole.

- **Lateral Load:** loads acting on the tower due to wind. This include wind shear which is may be uniform or linearly acting along the height of the pole or it may be varying by a cubic polynomial function.

To counter these loads the pole must have adequate:

i) **Axial Strength:** the critical load capacity of the tower in the axial direction must be greater than the applied axial loads by a factor of safety.

ii) **Flexural Strength:** the flexural strength of the pole must be greater than the bending strength i.e. it can sustain moment generated by the wind force. Also it can sustain local buckling moment taking into account the slenderness of the pole.

Certain limitations are also applied on the tower cross-sectional dimensions and on pole top deflection and rotation. A satisfactory tower design must meet all the above design requirements.

Wind Load calculation

Wind load along the pole is applied at extreme wind conditions which is obtained at the hub height of 12m at extreme wind condition in Islamabad i.e 60 m/sec [10]. It is converted into pressure according to the following equation

$$P = 1/2 \rho V^2 C_d \quad (1)$$

Where
P = Total Pressure of the wind
ρ = Air Density=1.23 kg/m^3
V= 60 m/sec
C_d= Drag Coefficient=3
So the pressure at extreme wind condition is
P=1/2 $\times$ 1.23 $\times$ (60)^2 $\times$ 3
Which is 6642 Pa and assumed to act uniformly along the height of tower.

Maximum pole Top Deflection

Since we have assumed that the wind turbine pole behaves as a cantilever beam, the pole top deflection is determined by applying uniform lateral load along the height of the pole. So, the maximum deflection δ at the free end is obtained by [11]

$$\delta_{max} = \frac{Fl^3}{3EI} \quad (2)$$

The obtained δ must be less than 1% of the total height of the pole [11]That is δ< 0.01

Where
F= Force acting uniformly along the height of tower
F= 6642 $\times$ 0.185 $\times$ 12
F=14475N
E= Modulus of Elasticity 200 GPa
I=Second moment of area of pole= $\Pi \times R^3 \times t$ [11]
Where
R= Mean diameter of pole
R= (.495+.185)/2
R=0.34m
t_Thickness of pole=0.006m
So,
I=3.1416$\times$ (0.34)^3 $\times$ 0.006=7.41$\times$ 10^{-4} m^4
So,

$$\delta_{max} = \frac{14475 \times 12^3}{3 \times 200 \times 10^9 \times 7.4 \times 10^{-4}}$$

$$\delta_{max} = 0.0563m$$

$$\delta_{max} = 56.3mm$$

So, maximum deflection is still under 1 % of total height of pole. So deflection criteria are satisfied.

7 Rotor frequency and the blade passing frequency

The frequency, in Hertz (Hz), of a specific turbine is gotten by dividing the turbine angular speed in rotations per minute (rpm) by sixty [12]

$$f_{rotor} = \frac{angular\ speed\ of\ turbine}{60} \quad (3)$$

$$f_{rotor} = \frac{240}{60} \quad (4)$$

Which is equal to 6 Hertz (Hz)

The blade passing frequency is determined by multiplying rotor frequency to the number of blades.

N_{bp}= number of blades $\times$ f_{rotor} (5)

As the rotor has 3 blades. So blade passing frequency is 18 Hertz (Hz)

We assumed the soft-soft pole structure, so our natural frequency of 5 kW tower must be less than rotor frequency and blade passing frequency.

4 Analysis and Simulation
Firstly, I modeled the required pole in Creo 2.0 and then analyzed it on the ANSYS 14.0 for further detailed. Following static and dynamic analysis are performed.
  a) Static structural analysis (static)
  b) Buckling analysis (static)
  c) Modal analysis (dynamic)

Static structural analysis
3-D modeling of wind turbine pole is done in Creo 2.0. this assembly is done by creating two segment which are separated along the vertical axis. First step to perform the analysis in Ansys 14.0 is to change .asm file of geometry to. IGES format. This. IGES format is then imported to Ansys workbench 14.0 for further analysis.
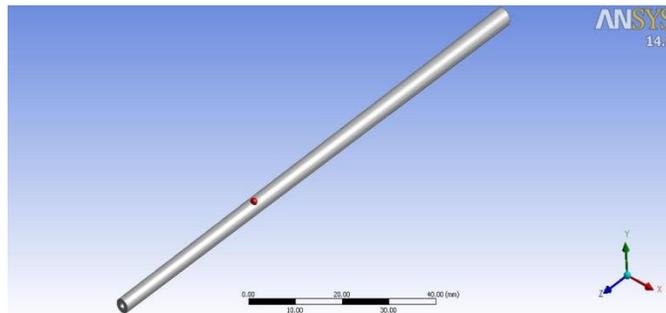
Figure: 4 Model of turbine pole imported in Ansys 14.0

Material and Material Properties**:**
Selected material for the pole of the wind turbine is structural steel. This material is linear isotropic and ASTM 572. Properties of the selected material can be find out in Ansys 14.0 "Engineering Data" section. Properties of the selected material are modulus of elasticity is E=200GPa and Poisson ratio is 0.3. Element type selected is Solid186.

SOLID186 Element Description
SOLID186 20 node 3-D solid element of superior order, which is a square displacement in behavior. Element defines 20 nodes with three degrees of freedom per node: translations in the nodal x, y and z the directions. Element supports, hyper elasticity, large stress, stiffening, plasticity, creep, and large refraction abilities distortion. It is able to simulate the mixed arrangement of nearly incompressible elasto plastic distortion of the material and entirely incompressible hyper elastic materials.
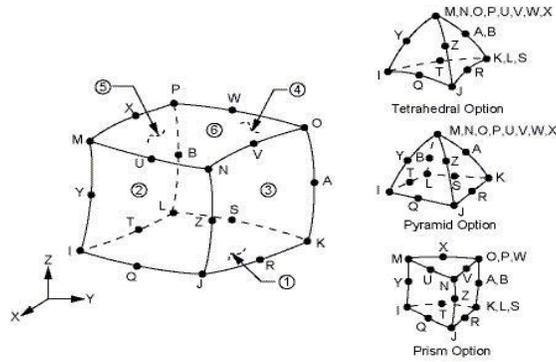
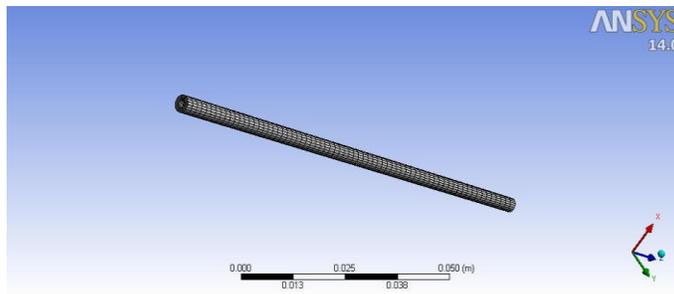**Figure: 5 SOLID186 Homogenous Structural Solid Geometry**
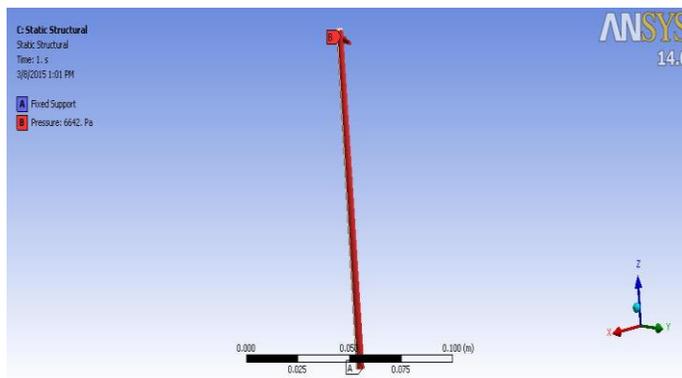

Figure: 6 Mesh of the wind Turbine pole

Figure: 7 Boundary of the wind Turbine pole

5 Static structure analysis Results
In static structure analysis of pole of wind turbine von mises stresses, total deformation and maximum principal stresses are find out under the uniform load along the height of pole.

Equivalent von mises stresses on the Pole:
The height of the tower is 12 m and at that height we analyze the extreme condition of wind in Islamabad which is 60 m/s and this wind speed is then converted into the pressure with the help of following equation.

$$P = \frac{1}{2}\rho V^2 C_d \quad (6)$$

And the pressure we find out from this equation is 6642 Pa and this pressure is acting along the height of the pole uniformly. The maximum stress on the pole which is 28.3 Mpa is on the bottom side and pressure is acting along the pole and minimum stresses are at the top side of the pole which is 2202 pa. and we use the stainless steel as a material for this pole and yield point of the stainless steel is 245 Mpa by using the material safety factor which is 1.5 then we have stress safe limit is 165 Mpa. For this pole design the maximum stress is 28.3 Mpa which is very under the safe limit of material safety. And our tower is safe with the safety factor of 5.83.
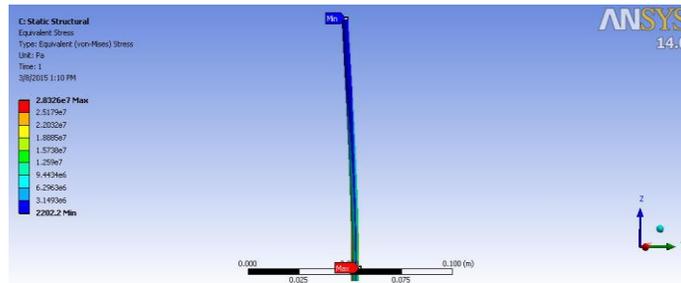
Figure: 8 Equivalent stress
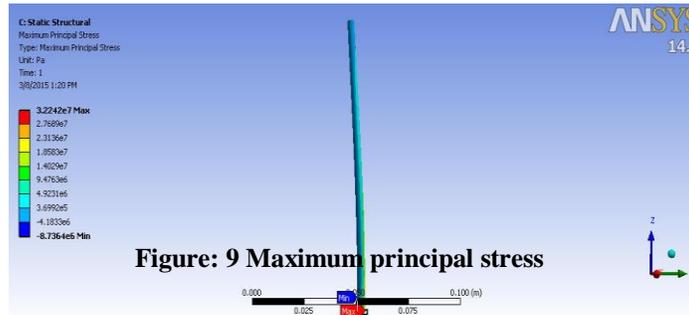
Figure: 9 Maximum principal stress

Total Deformation on Pole

The maximum and minimum deformation on the tower is 0.0203 mm and 0 mm from top and bottom side of the pole respectively. As pressure is acting on the tower all along uniformly which acts like a fixed beam with some deflection at the top of the pole.
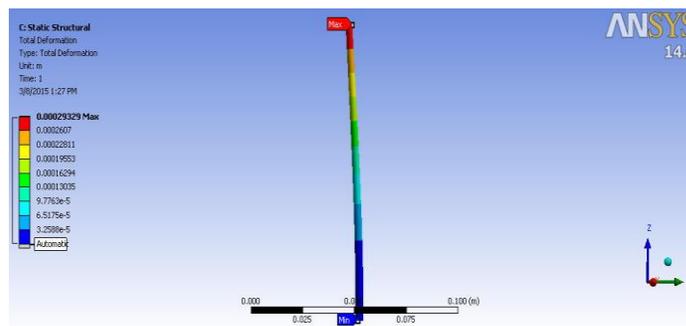
Figure:10 Total deformation

6 Buckling Analysis

Under the static load on wind turbine pole load multiplier values are obtained in buckling analysis. Other loads like wind load and gravity are neglected.

The compressive load is applied at the top of the tower as a collective load of rotor or nacelle and generator. In our case we applied 3000 N force at the top of the pole as compressive load.[13]
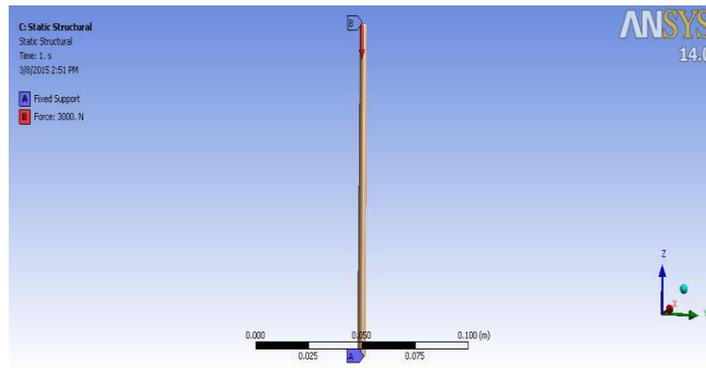

Figure : 11 Bucking analysis load condition

Linear Buckling Analysis Results**:**

For 5Kw tower, the maximum deflection for linear buckling modes are 1.14m with load multiplier of 0.10293 . these values are well in the safe zone. Linear buckling analysis result are shown bellow.
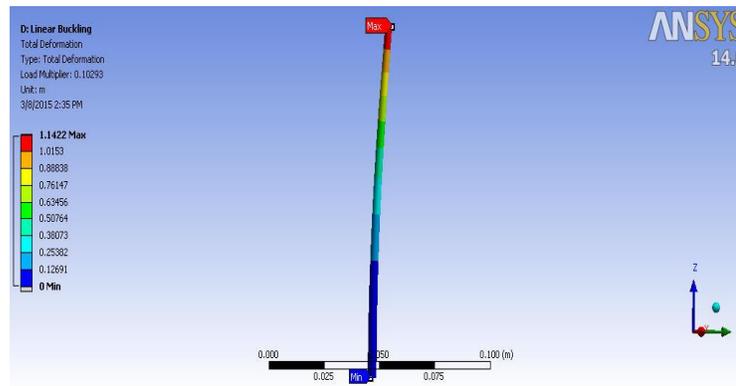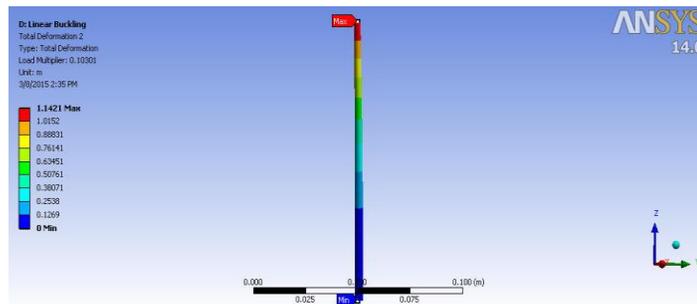

Figure: 12 Linear buckling mode 1

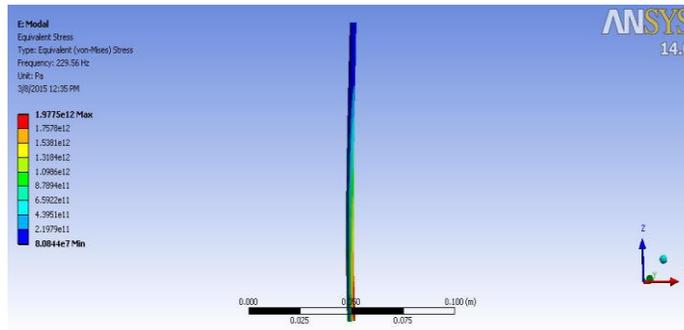**Figure: 13 Linear buckling mode 2**

Figure: 14 Linear buckling mode 3

7 Modal analysis of wind turbine pole

Modal analysis is an important analysis to see the dynamic behavior of the wind turbine pole. Modal analysis is analyzed in terms of two frequencies that are natural frequency and existing frequency of the blades and rotor. Natural frequency of the pole is very important to find out to check the resonance of the system. Generally, natural frequency of the pole should be isolated from the operating frequency of the pole when the load applied of wind turbine. These separations of frequency prevent the system from resonance. The isolation between these two frequencies that are natural frequency and operating frequency should be more than 5%.

Mode Shape 1

For modal analysis shape1, the natural frequency is 229.62Hz while the operating frequency of the wind turbine pole is 18 Hz for 3 blades turbine. Range of both frequencies (natural and operating is isolated more than 5% so there is no tendency of resonance in the system. For modal shape1 equivalent stress and maximum deformation are shown in the following figure.
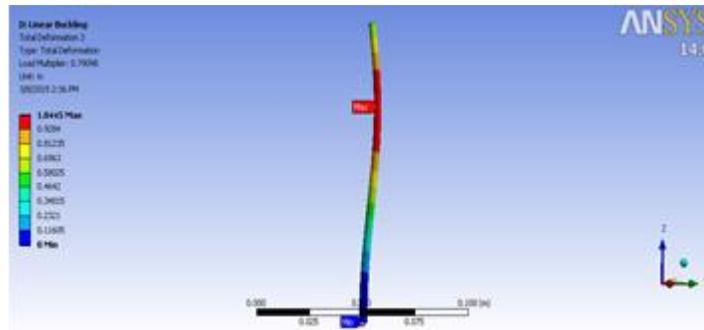

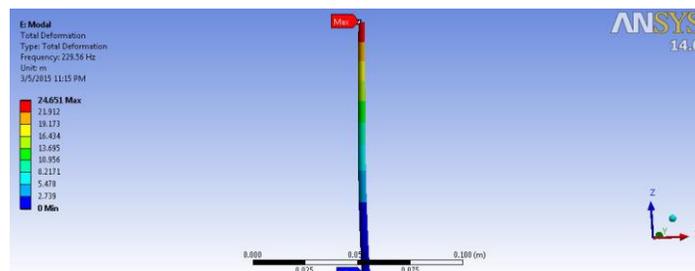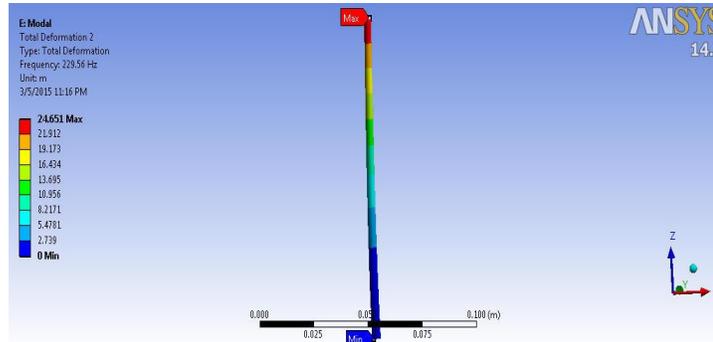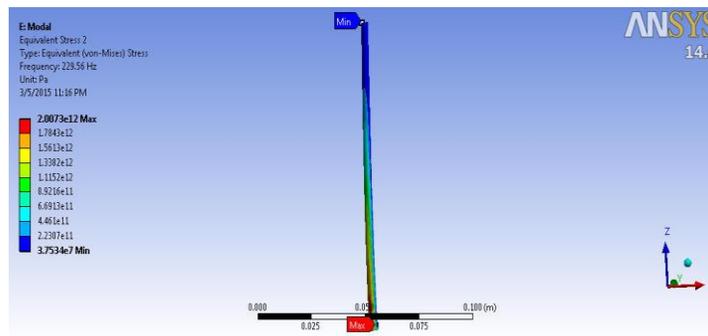**Figure: 15 Total Deformation in mode shape 1**

Figure: 16 Von-mises stress mode shape 1

Mode Shape 2

For modal analysis shape2, the natural frequency is 229.62Hz while the operating frequency of the wind turbine pole is 18 Hz for 3 blades turbine (equation no 3.5). Range of both frequencies (natural and operating) is isolated more than 5% so there is no tendency of resonance in the system. For modal shape2 equivalent stress and maximum deformation are shown in the following figure.

Figure: 17 Total Deformation in mode shape 2

Figure: 18 Von-mises stress mode shape 2

Mode Shape 3

For modal analysis shape3, the natural frequency is 1263.4Hz while the operating frequency of the wind tower is 18 Hz for 3 blades turbine. Range of both frequencies (natural and operating) is isolated more than 5% so there is no tendency of reso nance in the system. For modal shape3 equivalent stress and maximum deformation are shown in the following figure.
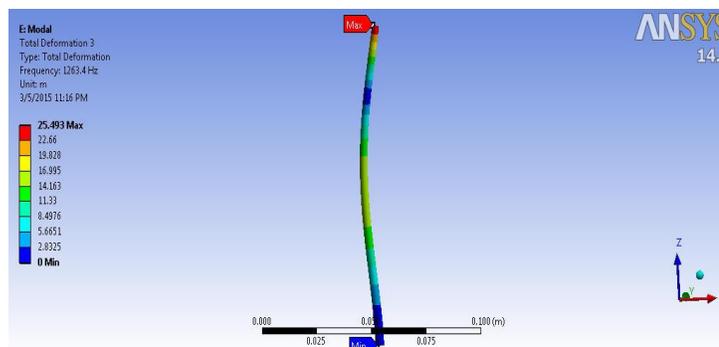

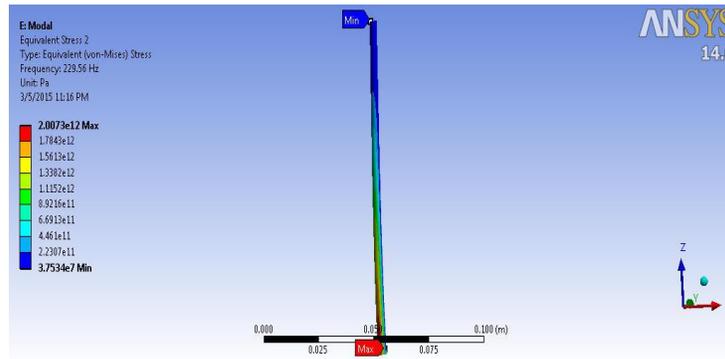**Figure: 19 Total Deformation in mode shape 3**

Figure: 20 Von-mises stress mode shape 2

From all three modal shapes it is concluded that our pole design is safe.

8 CONCLUSION

Different type of three analyses on Ansys software to predict the stability of 5-KW small wind turbine pole which can be used in wind turbine system either in standalone or combines with solar wind hybrid energy system.

First we perform the static structure analysis by considering the extreme wind condition on the wind turbine pole which stands as cantilever beam. The wind pressure is applied normal throughout the height of pole. After analysis on Ansys we see that total deformation is very low which is under the safe zone of material of pole. Also the maximum stress on the pole which is 28.3 Mpa is on the bottom side and pressure is acting along the pole and minimum stresses are at the top side of the pole which is 2202 pa. and we use the stainless steel as a material for this pole and yield point of the stainless steel is 245 Mpa by using the material safety factor which is 1.5 then we have stress safe limit is 165 Mpa. So our design is safe. After static analysis, linear buckling analysis is done on the geometry the load multiplier result come out just 0.0102 which means that the critical load is well above the applied load. Finally, we have done the dynamic modal analysis on the pole in which min. natural frequency is 229 Hz and maximum is 1263 Hz, as our operating frequency is 18 Hz.so natural frequency is well above the operating frequency, so there is no chance of resonance. Analytically, we have already calculated the maximum deflection which is already satisfy the deflection criteria. From all three analysis of tower the total deflection, deformation and natural frequency are in safe zone. So finally our design is safe.

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