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DEVELOPMENT AND PERFORMANCE ANALYSIS OF PORTHOLE TYPE VERTICAL AXIS WIND TURBINE

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ABSTRACT:

The demand for electricity in the world is increasing and there is requirement of harnessing different kinds of renewable energies. Worldwide efforts have turned towards most reliable renewable energy source; wind power. In wind energy conversion systems, large research and development has observed in the area of The Horizontal Axis Wind Turbine (HAWT) than Vertical Axis Wind Turbine (VAWT). This paper describes the development and performance analysis of Porthole Type Vertical Axis Wind Turbine. The model of Porthole Type Vertical Axis Wind Turbine (PTVAWT) is fabricated and tested to predict the performance in terms of shaft speed, torque and power. The wind turbine model has radius of 500 mm and height of 850 mm. The analysis is carried out by varying control parameters such as wind speed and porthole angle. The effect of control parameters on the response parameters i.e. shaft speed, torque and power has been analyzed by conducting the various experiments. The response parameters are increases with increase in the wind speed and maximum values are obtained at wind speed of 21 m/s. The response parameters are increases up to 40° porthole angle and then decreases by increasing the porthole angle more than 40°.

KEY WORDS: Wind turbine, Porthole Type Vertical Axis Wind Turbine (PTVAWT), Shaft Speed, Torque, Power, Wind Speed, Porthole Angle.

INTRODUCTION:

Nowadays rapid depletion of fossil fuels, increasing energy costs and environmental issues have become vital issues due to excessive fossil fuel consumptions. Therefore, the renewable resources are becoming a more viable technology for electrical power generation to meet those challenges. Among different types of renewable resources, wind turbines are capable of producing higher power in a smaller place [6].

A wind turbine is a rotating machine which converts the kinetic energy in wind into mechanical energy. If the mechanical energy is used directly by machinery, such as a pump or grinding stones, the machine is usually called a windmill. If the mechanical energy is then converted to electricity, the machine is called a wind generator, Wind Power Unit (WPU), or Wind Energy Converter (WEC) [2]. The wind turbines are basically classified according to position of axis of shaft around which turbine rotates. The Horizontal Axis Wind Turbine (HAWT), in which the turbine shaft is in horizontal position and another turbine is Vertical Axis Wind Turbine (VAWT) which shaft is in vertical position. The Horizontal Axis Wind Turbine (HAWT) are mostly used in high power generation because of these turbines are aerodynamically efficient than Vertical Axis Wind Turbine (VAWT). Indeed it has been suggested that Vertical Axis Wind Turbine (VAWT) may be more appropriate than Horizontal Axis Wind Turbine (HAWT) at very large scale (10MW) due to the alternating gravitational loading on a HAWT blade becoming excessive.

This paper discusses the development and performance analysis of Porthole Type Vertical Axis Wind Turbine (PTVAWT). Performance Analysis of Porthole Type Vertical Axis Wind Turbine (PTVAWT) is carried out by using straight portholes along with variation in wind velocity and porthole angle.

WIND ENERGY BACKGROUND:

Wind energy is a fast-growing form of power generation around the world. This is in part due to concerns over global climate change and energy security while demand for electricity continues to grow. Electricity demand is projected to grow at an annual rate of 2.4 % globally. The new global total at the end of 2016 was 486.8 GW, representing cumulative market growth of more than 12 percent.

India is growing at a rapid pace. Today India is the 4th largest wind market globally, with total installations having crossed the 31GW mark at the end of March 2017. The industry is firmly on track to meet the short-term national target of 60GW by 2022 [4].

The global annual and cumulative installed capacity for last 16 years in the world is as shown in figure 1.

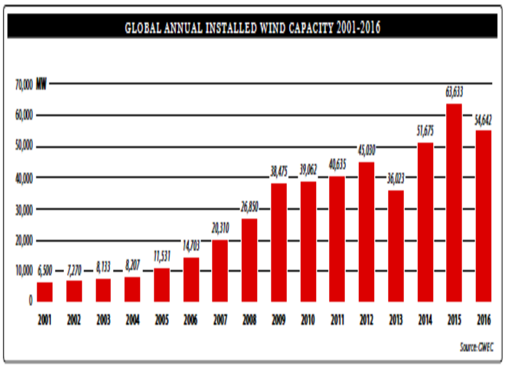
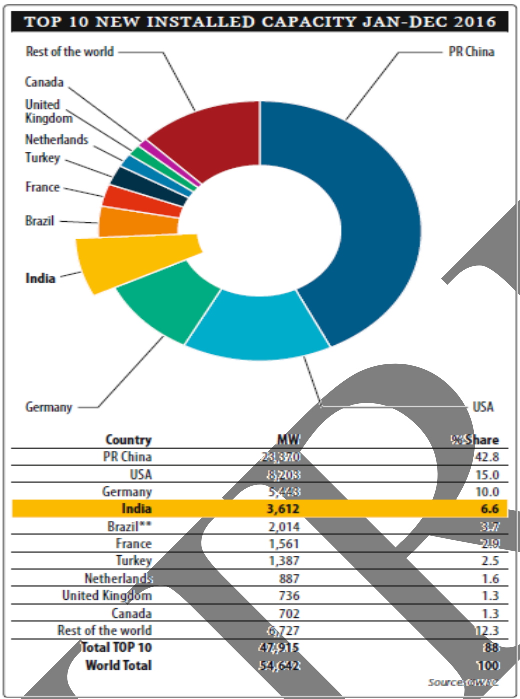


Figure 1: Global Annual Installed Wind Capacity

The share of India's installed wind power capacity in world wide installed wind power capacities along with regional distribution is presented in figure 2.



Country	MW	% Share
PR China	23,370	42.8
USA	8,203	15.0
Germany	5,443	10.0
India	3,612	6.6
Brazil**	2,014	3.7
France	1,561	2.9
Turkey	1,387	2.5
Netherlands	887	1.6
United Kingdom	736	1.3
Canada	702	1.3
Rest of the world	6,727	12.3
Total TOP 10	47,915	88
World Total	54,642	100

Figure 2: Share of India in world-wide installed wind power capacity

LITERATURE REVIEW:

For the performance improvement of a vertical axis wind turbine, aerodynamic analysis, control mechanism design of 1KW class model was carried out by In Seong Hwang, Seung Yong Minet.al. [2].Four straight blades of 1m span length were used and rotor radius was fixed to 1m. For this model, cycloidal blade system and individual active blade control system were applied respectively to improve its performance.

R.N. Sharma, U.K. Madawala [1] were analyzed a smart wind turbine concept with variable length blades & an innovative hybrid mechanical-electrical power conversion system. The variable length concept uses the idea of extending the turbine blades when wind speed fall below rated level, hence increasing the swept area and thus maintaining a relatively high power output.

A. S. Grinspan et. al. [5], were developed a Savonius wind turbine with conventional straight and curved rotor blades. The experiments were carried out with the rotor by varying the shape of blade i.e. aerofoil and twisted. In tested range of air velocity straight bladed rotor was less efficient than other rotors. The aerofoil and curved blades shown improved performance because of reduction in negative wetted area where as the twisted blade give the high torque and shaft speed because of reduction in negative wetted area.

A small vertical axis wind turbine with axial flux permanent magnet generator is designed and magnetic levitation method is used to increase the efficiency of the turbine, this work has done by Gulam Ahmad and Uzma Amin [6]. The article described the fabrication of the vertical axis wind turbine and three phase AC generator. The implementation of the magnetic levitation between rotating parts of turbine and generator which will be reduces the friction and increase the efficiency of turbine.

S. Jagdish Sai and T. Venkateshwara Rao [8] analyzed the Savonius baldes of concave and convex shape for the pressure regions using Computational Fluid Dynamics (CFD) and also analyzed the structural strength of the blades using Finite Element Analysis (FEA) softwares. They have developed the 3D model of two blade Savonius rotor using Solid Works software and analyzed using CFD and FEA. The results are found out that the concave region has high pressure and convex region have low pressure by CFD analysis.

H. Dumitrescu, A. Dumitrache et. al. [9] performs the experiments using the wind tunnel along with the flexible experimental model of VAWT with straight blades. The experiment was carried out by varying the blade pitch angle and number of blades. The results were obtained from experiment discussed about the pitch angle of blades of VAWT as; the blade pitch angle has a great influence on the self starting behavior of the vertical axis wind turbine i.e. higher values of the blade pitch angle are favorable for a low speed wind.

DESIGN OF PORTHOLE TYPE VERTICAL AXIS WIND TURBINE (PTVAWT):

One-dimensional theory considers a moving air stream passing through rectangular frame, force is applied on the frame and turbine shaft rotates about vertical axis. The power in moving air is [7],

$$KE_w = \frac{1}{2} \times m \times V_{wind}^2 \quad (1)$$

The mass of air in wind acting on the rotor is,

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$m = \rho \times A_{rotor} \times V_{wind}$ (2)

By putting the equation of mass of air acting on rotor in equation of kinetic energy supplied by moving air we can get the power in wind,

$P_w = \frac{1}{2} \times \rho \times A_{rotor} \times V_{wind}^3$ (3)

Where, KEw is kinetic energy, Vwind is velocity; m is mass, Pw is power, ρ is density of air in wind and Arotor is area of rotor of turbine. Now to derive the power generated by turbine, power coefficient is to be considered. The power coefficient is the ratio of power produced by the turbine rotor to the power available in wind given as below [7],

$$C_p = \frac{\text{Power produced by turbine rotor (P)}}{\text{Power available in the wind } (P_w)}$$

According to power coefficient equation the power produced by turbine rotor can be determine as below,

$P = C_p \times P_w$

$P = C_p \times \eta \times 0.5 \times \rho \times A_{rotor} \times V_{wind}^3$ (4)

By solving the equation (4) area of rotor can be determined. Where, η is overall efficiency of turbine will be taken as 50%. It is to be considering that the power output by Porthole Type Vertical Axis Wind Turbine (PTVAWT) is 15 kW.

Therefore area of the rotor can be calculated as

$$A_{rotor} = \frac{15}{0.25 \times 0.50 \times 0.5 \times 1.20 \times 9^3}$$

$A_{rotor} = 0.2743\ m^2$

FRAME OR BLADE DIMENSIONS:

A rotor = diameter of turbine × length (or height)

Assume the diameter as 925 mm therefore the length will be 300 mm

Diameter = 925 mm

Take the length (height) = 300mm

PORTHOLE DIMENSIONS: Attaching two portholes to each frame of radius 462.5mm. The frame is having diameter of 925mm.

Number of portholes to be fitted=2

Width of porthole =210mm

Height of porthole=290mm

Thickness of porthole=0.5mm

FORCE ACTING ON FRAME: The inertia forces caused by the angular velocity of the rotor are given by

$F = r_G \times \omega^2 \times m_{blade}$

Where

r_G = Distance from axis to the center of gravity = 0.4625 m

ω = Angular velocity of rotor (rad/s)

$$\omega = \frac{V_{wind}}{r} = \frac{9}{0.4625} = 19.480 \text{ rad/sec}$$

m_{blade} = mass of individual rotor blade (kg)

m_{blade} = (Volume of blade + Volume of portholes) × ρ

Volume of blade = 3×450×300×3 = 1215000mm^3

Volume of portholes = 6×290×210×0.5 = 182700mm^3

Total volume = Volume of blade + Volume of portholes

= 1215000+182700

= 1397700mm^3

= $1.3977 \times 10^{-3} m^3$

ρ= 7800 kg/m^3

Mass = 1.3977×10^{-3} × 7800 = 10.90kg,

$F = r_G \times \omega^2 \times m_{blade} = 0.4625 \times 19.48^2 \times 10.90$

F = 1913N

CHECK FOR DESIGN: For the first trial of Porthole Type Vertical Axis Wind Turbine (PTVAWT), the mild steel is taken as easily available in required form and at minimum cost.

Material = C40

Ultimate tensile strength, Sut = 540 N/mm2

Yield strength Syt = 340 N/mm2, Assume factor of safety = 2

FRAME OR BLADE: Due to wind force acting on the frame, there are chances of bending the frame. Therefore frame is to be checked for bending failure criteria.

Permissible bending stresses for given material

σ_b = Syt/FOS = 340/2 = 170 N/mm^2

Area of the frame subjected to the wind force,

F = 1913 N

Area = {(10×280×3) + (450×10×0.5)} = 10650 mm^2

$\sigma_{b(induced)}$ = F/A = 1913/10650 = 0.17 N/mm^2

Thus induced bending stresses are negligible and are very less than the permissible bending stresses. Therefore the frame design safe and dimension of the frame taken are right.

PORTHOLES: Due to wind force acting on the portholes, there are chances of bending of the portholes. Therefore the porthole is to be checked for bending failure criteria.

Permissible bending stresses for the given material

σ_b = Syt/FOS = 340/2 = 170 N/mm^2

Area of the frame subjected to wind force,

F=1913N

Area = 210 × 290 = 60900 mm2

$\sigma_{b(induced)}$ = F/A = 1913/60900 = 0.0314 N/mm^2

Thus, induced bending stresses are negligible and are very less than permissible bending stresses. Therefore, the porthole design is safe and the dimensions of the frame taken are correct.

DESIGN FOR SHAFT: The material for shaft is selected as C50. It is easily available and cost effective as compared with alloy steel.

PROPERTIES- Ultimate tensile strength, Sut = 720 N/mm^2

Yield strength Syt = 380 N/mm^2
Assume factor of safety = 2
The shock and fatigue factor (Kt and Kb)
Considering minor shocks, take Kt = 1 and Kb = 1.5
Determination of maximum shear stress as per ASME code
σ_{smax} = 0.3 × Syt or σ_{smax} = 0.18×Sut (whichever is minimum)
σ_{smax} = 0.3 × Syt = 0.3 × 380 = 114 N/mm^2
σ_{smax} = 0.18 × Sut = 0.18 × 720 = 129.6 N/mm^2
Therefore
σ_{smax} = 114 N/mm^2 (minimum value)

TORQUE ACTING ON THE SHAFT: The torque can be calculated by multiplication of the wind force acting on them and the distance from the shaft
T = Wind force × Distance from the shaft
T = 1913 × 225
T = 430425 N-mm

BENDING MOMENT OF THE SHAFT: The self weight of the frame is acting on the shaft in vertical condition and the wind force is acting radially inwards i.e. horizontally on the shaft. Therefore it is necessary to calculate the bending moment in vertical as well as horizontal condition and take the resultant of these two moments.
Mv = 10.90 × 9.81 × 225 = 24059.025 N-mm
Mh = 1913 × 150 = 286950 N-mm
Resultant bending moment,

$$MR = \sqrt{M_v^2 + M_h^2}$$
$$= \sqrt{24059.025^2 + 286950^2}$$
$$= 287956.83 \text{ N-mm}$$
$$T_{max} = \sqrt{(M_R \times K_b)^2 + (T \times K_t)^2}$$
$$T_{max} = \sqrt{(287956.83 \times 1.5)^2 + (430425 \times 1)^2}$$
$$T_{max} = 609781.718 \text{ N-mm}$$

The relation between Tmax, maximum permissible shear stresses and the diameter of the shaft is given by

$$T_{max} = \frac{\pi}{16} \times D^3 \times (1 - C^4) \times \sigma_{smax}$$

Where, C = d/D, Take d = 23 mm,

$$D^3 = \frac{16 \times T_{max}}{\pi \times \sigma_{smax} \times (1 - C^4)}$$
$$D^3 = \frac{16 \times 609781.718}{\pi \times 114 \times (1 - 0.92^4)}$$

Therefore D = 25 mm.

FINITE ELEMENT ANALYSIS OF SHAFT:

The Finite Element Analysis (FEA) is used to check the analytical design of shaft of a Porthole Type Vertical Axis Wind Turbine (PTVAWT). The 3D model of Porthole Type Vertical Axis Wind Turbine (PTVAWT) is done using the CATIA V5 software according to the dimensions occurred in analytical design as shown in figure 3.

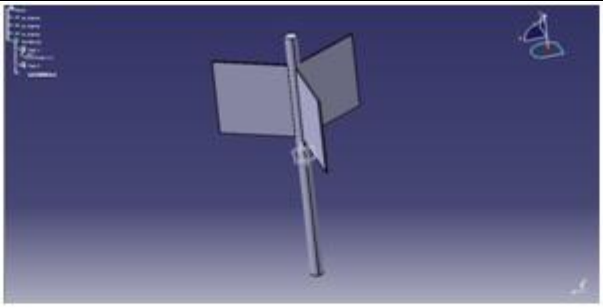

Figure 3 Model of PTVAWT

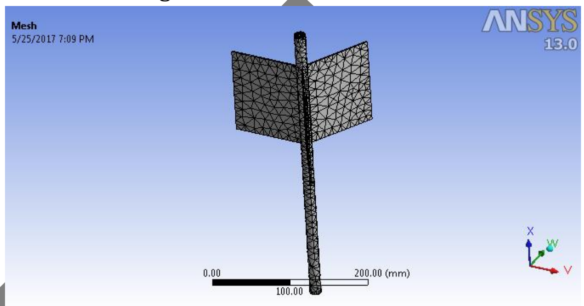

Figure 4 Meshing of PTVAWT

The descritization of the model as shown in figure 4 is done by meshing the number of elements to each. The quadrilateral-triangular meshing is used for the better results. In meshing of model minimum edge length of an element is 1.0030 mm considered. The total number of nodes and elements are obtained as 6875 and 3235 respectively.

The shaft of Porthole Type Vertical Axis Wind Turbine (PTVAWT) is subjected to the forces acting from wind pressure and weight of the rotor i.e. frames (blade) and portholes, so that the force is acting on the shaft is as shown in figure 5. The applied force on the shaft is 1913 N.

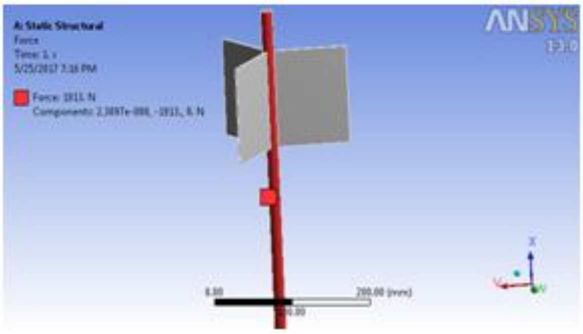

Figure 5 Force applied on shaft

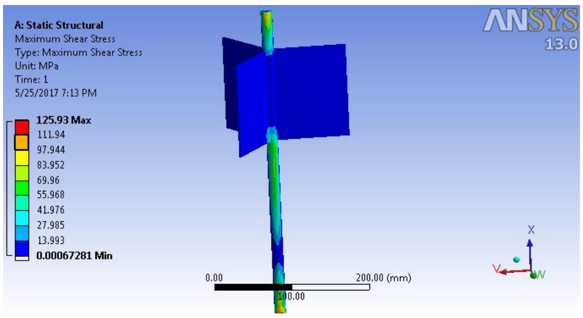

Figure 6 Maximum shear stress on shaft

Figure 6 shows the analysis of the shaft dimensions for an applied load for maximum shear stress. The maximum shear stress is obtained from Finite Element Analysis is 125.93 N/mm2 which is less than the maximum shear stress obtained from the ultimate strength of material as shaft in analytical method is 129.6 N/mm2. Hence, the dimensions of the shafts are safe for the maximum shear stress.

DEVELOPMENT OF PORTHOLE TYPE VERTICAL AXIS WIND TURBINE (PTVAWT):

The main components of Porthole Type Vertical Axis Wind Turbines are identified and fabricated as below,

ROTOR: The main function of rotor is to convert the wind energy in to rotary motion of shaft of turbine. The rotor includes following components,

FRAME (BLADE): The frame is fabricated to the shaft in which portholes are mounted. The wind exerts forces on the frame by changing its momentum.

PORTHOLES: Portholes are hinged component of rotor mounted on frame and can be adjusted in any angle.

SHAFT: The assembly of frame and porthole is mounted on shaft, when wind exerts force on frame shaft starts to rotate.

BEARING: It supports the shaft and reduces friction.

SUPPORTING STRUCTURE: It is fabricated to support the rotor of turbine along with bearings.

CONSTRUCTION AND WORKING OF PORTHOLE TYPE VERTICAL AXIS WIND TURBINE (PTVAWT):

The photograph is shown in figure 3 of Porthole Type Vertical Axis Wind Turbine (PTVAWT) consists of three blades with portholes. The portholes are mounted in a frame which is attached to the shaft. The diameter of the turbine is 925 mm and the height of the frame (blades) is 300mm. The three frames of radius 500 mm are fitted on the central shaft of 25mm diameter. Each frame has two straight portholes fitted in it with the help of hinges. There is deep groove ball bearing used to mount the shaft vertically in the supporting structure. The wind energy is used for rotation.

Figure 3: Photograph of Porthole Type Vertical Axis Wind Turbine (PTVAWT)

EXPERIMENTATION:

To study the performance of the Porthole Type Vertical Axis Wind Turbine (PTVAWT), first the different significant control parameters (input) are to be selected based on their effect on the performance i.e. response parameters (output).

CONTROL PARAMETERS (INPUT PARAMETER): There are two significant parameters affecting the performance of the Porthole type vertical axis turbine.

WIND SPEED: It is very important for the wind turbine to be able to describe the variation of wind speeds. Turbine designers need the information to optimize the design of their turbines, to minimize costs. Power is directly proportional to cube of wind speed.

PORTHOLE ANGLE: It is the angle made by Porthole with the frame or blade plane. This angle determines the amount of air passing through the blades at a given wind speed.

Response parameters (Output Parameters): As the wind passes over the rotor, it starts to rotate. There are three output parameters for the experimentation.

SHAFT SPEED: As the rotor starts to rotate due to wind force acting on it, the first parameter that can be measured is the speed of the shaft in rpm. It is required for calculation of power.

TORQUE: The shaft is rotating and then the torque will be there. This torque can be measured as an output parameter. The torque is also required for the calculation of mechanical power generated by the shaft. The torque measured is in N-mm.

Power: The ultimate outcome of any type of wind turbine is the power generated. The power can be calculated by using the formula,

$$P = \frac{2\pi NT}{60}$$

Where, P is power, N is shaft speed and T is torque acting on shaft.

In the initial stages of experimentation, it is not well understood how the control parameters influence the output parameters. At first stage readings are taken from 2 m/s to 25 m/s but it has been observed that up to 5 m/s there is no effect and after 21 m/s the Porthole Type Vertical Axis Wind Turbine (PTVAWT) get vibrations. So the shaft speed is taken from 5 m/s to 21 m/s. In second stage angle is varied from 0° to 70°, but it has been observed that up to 10° there is no effect and beyond 60° the Porthole Type Vertical Axis Wind Turbine (PTVAWT) is not effective. So we have considered angle from 10° to 60°.

RESULTS AND DISCUSSION:

After conducting the experiments, it is found that in the tested range of velocities PTVAWT work efficiently within the range of porthole angle of 10° to 40°. Also, it is observed that the shaft speed, torque and power increases with increase in wind velocity up to 40° of porthole angle.

RESULTS FOR SHAFT SPEED: From figure 4 it is observed that the shaft rpm increases with increase in wind speed from 5 m/s to 21 m/s. The result shows that the maximum turbine performance for the shaft speed (rpm) is obtained at wind speed of 21 m/s. As the Porthole angle increases from 10° up to 40°, the shaft rpm increases and further decreases with increase in Porthole angle up to 60°. The shaft speed for the Porthole Type Vertical Axis Wind Turbine (PTVAWT) is found better at 40° Porthole angle.

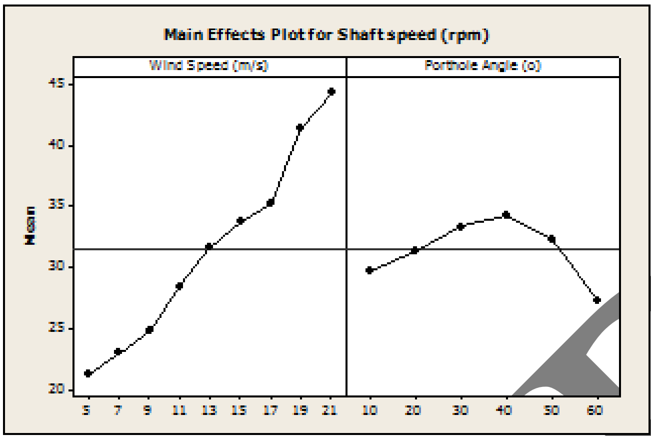

Figure 4 Main effects for shaft speed

Results for torque: From figure 5 it is observed that the torque increases with increase in wind speed from 5 m/s to 21 m/s. The result shows that the maximum turbine performance for the torque is obtained at wind speed of 21 m/s. As the Porthole angle increases from 10° up to 40°, the shaft rpm increases and further decreases with increase in Porthole angle up to 60°. The torque for the Porthole Type Vertical Axis Wind Turbine (PTVAWT) is found better at 40° Porthole angle.

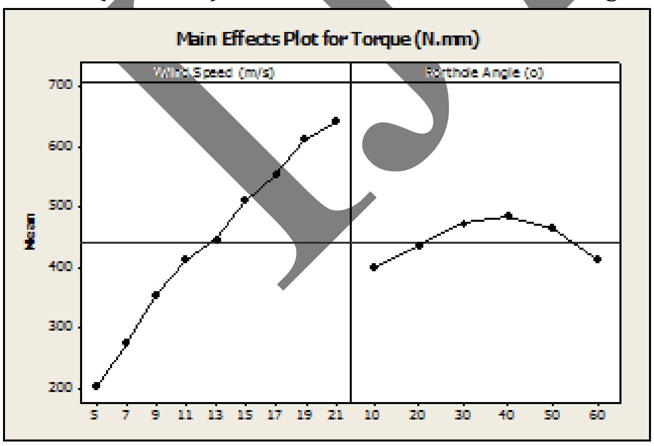

Figure 5: Main effects plot for torque

Results for power: From figure 6 it is observed that, the maximum turbine performance for the power (Watt) is obtained at wind speed of 21 m/s. As the Porthole angle increases from 10° up to 40°, the shaft rpm increases and further decreases with increase in Porthole angle up to 60°. The shaft power for the Porthole Type Vertical Axis Wind Turbine (PTVAWT) is found better at 40° Porthole angle.

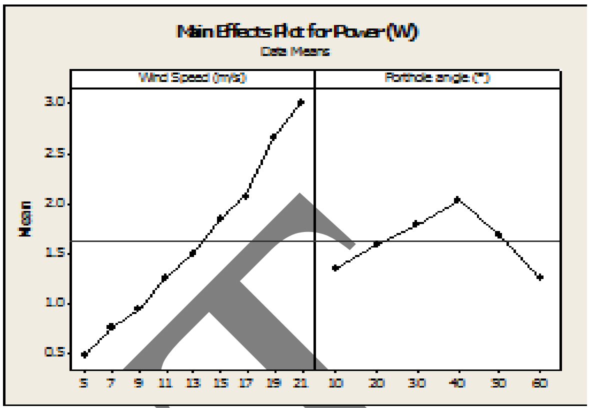

Figure 6: Main effects plot for power

CONCLUSION:

The Porthole type vertical axis wind turbine (PTVAWT) is designed and a model of the same is fabricated in the present study. The performance analysis of the Porthole Type Vertical Axis Wind Turbine (PTVAWT) is carried out and the major outcomes of the study are given below:

Shaft speed, torque and power increases with increase in wind speed and having maximum values at wind speed 21m/s within the tested ranges of wind velocities.

Shaft speed, torque and power increases with wind speed up to 40° Porthole opening angle from 10° Porthole angle and then decreases with further increase in Porthole opening angle.

From the above studies the newly developed Porthole Type Vertical Axis Wind Turbine (PTVAWT) is working efficiently at 40° Porthole opening angle.

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