# Solidity Study and its Effects on the Performance of A Small Scale Horizontal Axis Wind Turbine

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***Abstract: The solidity is one of the most important factor which greatly affects the performance of the horizontal axis wind turbine (HAWT). The study was carried out for a small horizontal axis wind turbine (HAWT), model setup was placed on the roof of the building at Energy Centre, MANIT Bhopal. In this study, numerical calculations were carried out on a small model of the HAWT with different solidities to investigate its effects on power coefficient $C_P$, rotor shaft torque $T_{sh}$, power extracted by the wind turbine $P_T$ and the rotor speed $N_r$ of the wind turbine. The solidity study of small HAWT model was carried out for 2 to 6 number of blades. It was found that increasing the number of blades, increase the solidity, this led to increase the power coefficient, rotor shaft torque, and power extracted by the wind turbine. The numerical result shows that the solidity for two blades is minimum and for this the power coefficient, rotor shaft torque and power extracted by the wind turbine is minimum while the rotor speed is maximum. The solidity for six blades is maximum and for this power coefficient, rotor shaft torque and power extracted by the wind turbine is maximum while the rotor speed is minimum.***

***Keywords: Solidity, Horizontal Axis Wind Turbine, Blades, rotor shaft torque, and power extracted by the wind turbine.***

## 1. INTRODUCTION

With the raise of energy shortage and environment pollution, the increase and use of renewable energy become more significant. The wind energy as a class of renewable energy is forthcoming to the surrounding environment and has huge amount of resource. Windmills have been used for numerous centuries for pumping water and milling grain. In current years there has been a stimulation of attention in wind energy and attempts are in progress all over the world to initiate lucrative wind energy conversion systems for this renewable and environmentally benign energy source. In developing countries, wind power can play a major role for water supply and irrigation and electrical generation. This concise gives a general overview of the resource and of the technology of extracting energy from the wind. Therefore, people have paid more and more attentions on the researches on wind energy technologies, especially on improving the performance of the wind turbine which is the principal equipment for power generation. The efficiency of any wind energy conversion system is described in terms of its power coefficient, Cp [1]. Design parameter choice is critical for optimizing wind turbine performance. For any fixed diameter there are various parameters influencing energy production: rotor rotation velocity, blade number, airfoil chord distribution and longitudinal blade twist. [2].Although the horizontal axis wind turbine is popular for large scale power generation now, the vertical axis wind turbine as another important kind of wind turbine is a good choice for small scale power generation [3, 4]. Small wind turbines have largely adopted the three bladed, low solidity design philosophy of large utility-scale wind turbines. Increasing the number of blades has been shown theoretically to increase the aerodynamic efficiency of a wind turbine. An increase in aerodynamic efficiency could have the potential to decrease the overall cost of energy from a small wind-energy conversion system (WECS) [5]. The major factors involved in deciding the number of blades includes the effect on power coefficient, the design TSR (tip-speed ratio), the means of yawing rate to reduce the gyroscopic fatigue[6]. Solidity greatly affects the performance of the horizontal axis wind turbine (HAWT) such as power coefficient, rotor shaft torque and power extracted by the wind turbine.

## 2. METHODS FOLLOWED

A small scale horizontal axis wind turbine model setup was placed on the top of the building at Energy Centre, MANIT Bhopal. A multi-bladed prototype turbine rotor has been designed which a modified design of hub to enable variable blade capabilities for 2,3,4,5 and 6 blade configurations and the weight of hub have been reduced many time than of other hub material. In this paper the data are as number of rotor blades, solidity, power coefficient, rotor shaft torque and power extracted by the wind turbine by the experiment for this model.

### *Rotor swept area*

The rotor swept area depends upon the chord of rotor blade and it can be increase by increasing the chord of blades. The rotor swept area greatly affects the size and performance of horizontal axis wind turbine.

Rotor swept area, $A = \pi R^2$ (1)

Where, R =radius of rotor (length of blade)

### *Solidity*

Solidity is usually defined as the percentage of the circumference of the rotor which contains material rather than air. High-solidity machines carry a lot of material and have coarse blade angles.

Solidity, $\sigma = \frac{N \times A}{\pi R^2}$ (2)

Where N is blade number, C is blade chord (m), R is wind turbine radius (m).

It is clear that solidity can be altered by changing either the turbine radius to blade chord ratio or by changing the number of blades. Here, we prefer to alter the solidity by changing the number of turbine blades. The radius of the model of HAWT considered for calculation in this study was 0.61meter. A centre hub with the radius of 0.13meter was also included in radius of the rotor set. The solidity, blade chord and number were decided respectively shown in Tab. 1

**Table 1. PARAMETERS OF THE MODEL**

| Number of blades | Blade chord (m) | Solidity |
|---|---|---|
| 2 | 0.48 | 9.69% |
| 3 | 0.48 | 14.54% |
| 4 | 0.48 | 19.39% |
| 5 | 0.48 | 24.23% |
| 6 | 0.48 | 29.08% |

***Wind power***

The power available in wind, is equal to the kinetic energy associated with the mass of moving air. Although the power available is proportional to the cube of wind speed, the power output has a lower order dependence on wind speed. This is because the overall efficiency of the windmill changes with wind speed.

Wind power, $P_0 = \frac{1}{2} \rho A V_0^3$ (3)

where, ρ= Air density, A= Rotor swept area, V= Speed of free wind.

***Tip Speed Ratio***

The **tip speed ratio** is defined as the ratio of the speed of the extremities of a windmill rotor to the speed of the free wind. It is a measure of the 'gearing ratio' of the rotor. Drag devices always have tip-speed ratios less than one and hence turn slowly, whereas lift devices can have high tip-speed ratios and hence turn quickly relative to the wind [7].

Tip speed ratio, $\lambda = \frac{\text{Blade tip speed}}{\text{Wind speed}} = \frac{R\Omega}{V_0}$ (4)

$\Omega$ = rotational speed in radians /sec, R = Rotor Radius, V = Wind “Free Stream” Velocity

The proportion of the power in the wind that the rotor can extract is termed the coefficient of performance (or power coefficient or efficiency; symbol Cp) and its variation as a function of tip speed ratio is commonly used to characterise different types of rotor.

***Rotor shaft torque***

The ***interference factor***, $a$ is defined as the fractional wind speed decrease at the wind turbine. For maximum output of turbine, $a = \frac{1}{3}$

The speed of rotor, $\omega = \frac{2\pi n_s}{60}$

where, ω= Rotor speed in radian/sec, $n_s$ = Rotor speed in rpm

The proportion of the power in the wind that the rotor can extract is termed the ***coefficient of performance*** (or power coefficient or efficiency; symbol Cp) and its variation as a function of tip speed ratio is commonly used to characterise different types of rotor [8].

Mechanical torque developed [9].

$$T_M = \frac{P_0}{V_0} R \qquad (5)$$

Maximum torque coefficient, $C_{T\max} = \frac{C_{P\max}}{\lambda}$ (6) ($Cpmax$ =0593)

The maximum torque produced at the shaft, $T_{sh} = T_M \times C_{T\max}$ (7)

Power extracted by the wind turbine is-

$$P_0 = \omega \times T_{sh} \qquad (8)$$

## 3. RESULTS AND DISCUSSION

### *A. Effect of number of blades on solidity*

It is shown in the graph that as the number of blades on the rotor increases, the rotor blade material increased and solidity of wind turbine increased proportionally. The higher rotor solidities require a lower angular velocity to obtain the maximum amount of power produced for a certain wind speed. Moreover, a slight reduction in rotor efficiency with the increase of rotor solidity can be observed [8].

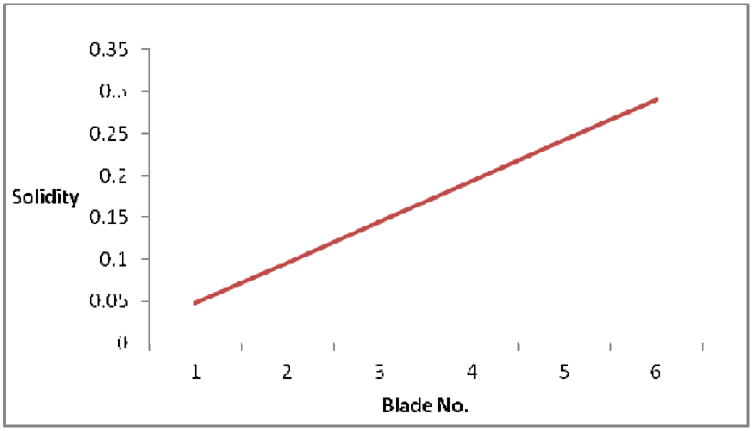


**Fig. 1 Graph between the solidity and number of blades.**

***B. Effect of solidity on the rotor speed***

The present work investigates the influence of the solidity of wind turbine on the rotor speed. This shows that as the solidity of wind turbine increases, the rotor speed get reduced. The rotor speed for this model is highest for two blade and for the solidity of 9.60%. The turbines with high solidity have the advantage of enabling the rotor to start rotating easily because more rotor area interacts with the wind initially [10].

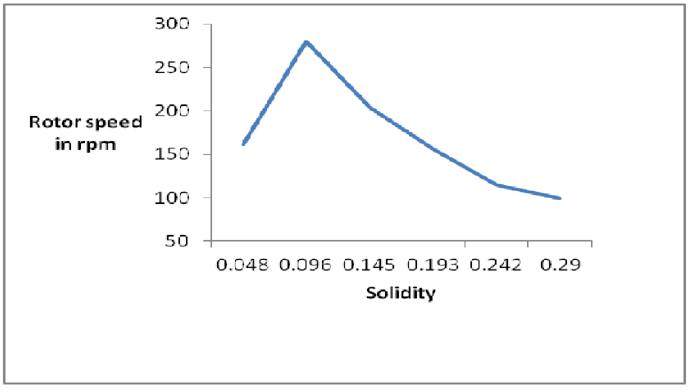


**Fig. 2 Graph between the solidity and rotor speed**

***E. Effect of solidity on the rotor shaft torque***

The following graph shows the effect of solidity on the rotor shaft torque. As the solidity of turbine increases the rotor shaft torque also increases. This is because the more area of rotor strikes with wind. By increasing the turbine solidity; it increases the static torque coefficient. High solidity HAWT turbine has a self-starting capability, because it has higher static torque coefficient than the low solidity turbines[11].

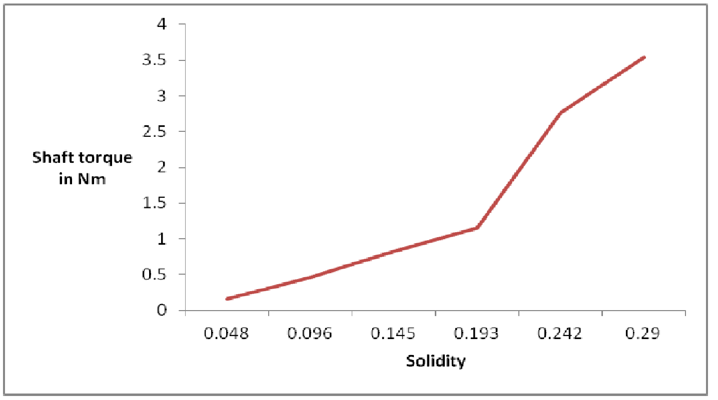


**Fig.3 Graph between the solidity and rotor shaft torque.**

***D. Effect of solidity on power extracted by the wind turbine***

The following graph shows that as the solidity of the wind turbine increases, the power extracted by the wind turbine also increases. The power extracted by the wind turbine is maximum for the solidity of 29% for this model. The peak power appears to be augmented with increasing the solidity till $\sigma = 0.25$; then, the peak seems to be decreased with further increasing the solidity from $\sigma = 0.25$ to $\sigma = 0.5$. Moreover, the blade speed range, in which the power can be generated, is considerably reduced with increasing the solidity [12].

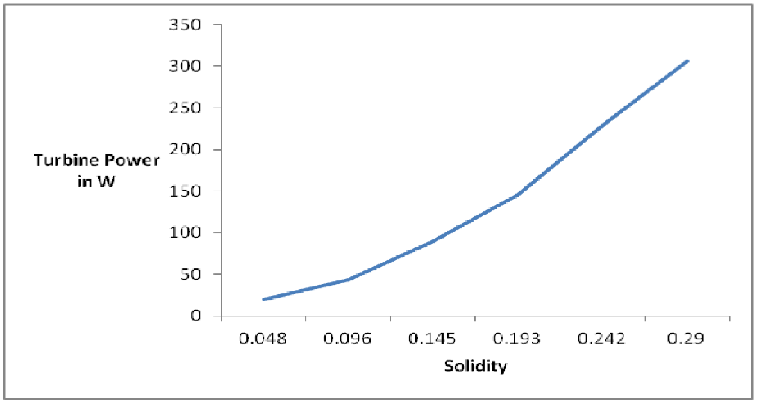


**Fig.4 Graph between the solidity and power extracted by the wind turbine**

***D. Effect of solidity on power coefficient***

This is shown in the graph that as the solidity of wind turbine increases, the power coefficient of turbine also increases.The study shows that the greatest power coefficients result from increased blade number and greater rotor solidity, both of which contribute to the added torque that improves cut-in wind speed. Consequently there is a maximum value of Cp of 59.3% (known as the Betz limit), although in practice real wind rotors have maximum Cp values in the range of 25%-45%.[7]. The theoretical results predict a 30% increase in $C_p$ going from a 3 bladed rotor to 12, at equal solidities of 0.27. Even at σ = 0.14, an increase from 3 to 6 blades provides 10% greater $C_p$ [10].

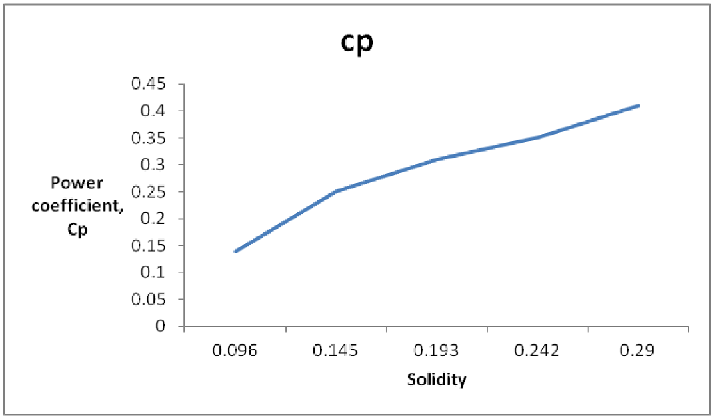


**Fig.4 Graph between the solidity and power coefficient.**

## 4. CONCLUSIONS

By changing blade numbers and solidity, the relationship between solidity, blade number, and power coefficient, rotor speed, shaft torque and power extracted by turbine was explored numerically for 2 to 6 number of blades. Rotor speed varied moderately with changes in blade number and solidity. The power coefficient, Cp varied strongly with solidity and blade number. All of the studies shows that an increase in blade number and solidity increased power coefficient, rotor shaft torque and power extracted by turbine while the rotor speed get decreased with increase in solidity. This is also clear from the study that when solidity is low, torque is low and rotor speed is high. When solidity is high, torque is high and rotor speed is low. For reasons of rotor speed, rotor shaft torque and power extracted by the turbine, the three blade horizontal axis wind turbine design is most suitable. The number of the blades of a turbine has great impact on its performance. Thus the three blade rotor is the most important and most visible part of the wind turbine.

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