A Study on Vertical Axis Wind Turbine for Effective Harnessing of Wind Energy in Satara Region

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Abstract—With continuously increasing energy crisis occurring in the world it will be a prime important to investigate alternative methods of generating power other than fossil fuels i.e. conventional sources. Wind energy from non-conventional energy sources is one of the biggest sources of energy available all around us, it means unlike solar energy cannot be harness during night. Vertical axis wind turbines (VAWT) offer similar efficiencies as compared with the Horizontal axis wind turbines (HAWT) and in fact have several distinct advantages. One advantage is that unlike their HAWT counterparts, they can be placed independently of wind direction. This makes them perfect for locations where the wind direction changes continuously. In India there are various geographically advantageous places where wind energy can be harness very effectively because of useful environmental conditions for wind power generation. Satara is one of such places in Maharashtra situated in Sahyadri Hills, where wind velocity is adequate for the generation of energy. Thousands of horizontal axis wind mills are installed by various national and multinational organizations for generation of electricity. But due to the direction changing nature of the wind sometimes it is ineffective to use horizontal axis wind mills. This study is an attempt to study effectiveness of implementing Vertical axis wind mills in this region. In this paper study of various research papers published by many of the researchers nationally and internationally is done.

Key words: Renewable Energy, VAWT, Satara, Aerodynamic Analysis, Wind Energy Potential

I. INTRODUCTION

Renewable Energy Sources are those energy sources which are not destroyed when their energy is harnessed. Human use of renewable energy requires technologies that harness natural phenomena, such as sunlight, wind, waves, water flow, and biological processes such as anaerobic digestion, biological hydrogen production and geothermal heat. Amongst the above mentioned sources of energy there has been a lot of development in the technology for harnessing energy from the wind. Wind energy is not a constant source of energy. It varies continuously and gives energy in sudden bursts. About 50% of the entire energy is given out in just 15% of the operating time. Wind strengths vary and thus cannot guarantee continuous power. The difference between windmill and wind turbine is explained below:

- Windmill: If the mechanical energy is used directly by machinery, such as a pump or grinding stones, the machine is usually called a windmill.
- Wind Turbine: If the mechanical energy is then converted to electricity, the machine is called a wind generator or turbine.

There are two main types of wind turbines. The two general categories for wind turbines include vertical axis or horizontal axis wind turbines. The turbines are classified upon how the shaft of the generator is mounted. The horizontal axis wind turbine HAWT was invented before the vertical axis wind turbine (VAWT)

A. Horizontal Axis Wind Turbines (HAWT)

Horizontal-axis wind turbines typically have two or three blades. These wind turbines are operated “upwind” with the blades facing into the wind. The HAWT has three blades that rotate on a horizontal axis as shown in Fig 1. Almost all commercial wind turbines are horizontal axis machines with rotors using 2 or 3 airfoil blades. The rotor blades are fixed to a hub attached to a main shaft, which turns a generator normally with transmission through a gearbox. [3]

B. Vertical Axis Wind Turbines (VAWT)

Vertical-axis wind turbines (VAWTs) are a type of wind turbine where the main rotor shaft is set vertically. Changes in wind direction have fewer negative effects on this type of turbine because it does not need to be positioned into the wind direction. VAWTs turbines are categorized as Darrieus and Savonius turbine, according to the principle used to capture the wind flow as shown in Fig. 2. Savonius turbines are one of the simplest turbines; aerodynamically they are drag-type devices consisting of two or three scoops. [3]

In general, VAWT is driven by two types of forces of wind, drag and lift force. Savonius rotor is the simplest kind of VAWTs is a drag-type configuration and a bit complex type is Darrieus rotor which is lift-type configuration.

Types of Vertical axis wind turbines are explained below:
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Fig. 2: Vertical Axis Wind Turbines (VAWT)

1) Savonius Rotor:
The operation of Savonius rotor depends on the difference of drag force when the wind strikes the concave and convex part of the semi-spherical blades. The flow energy utilization of Savonius rotor is lower than that of Darrieus rotor. Hence this type of turbine is generally not used for high-power applications and usually used for wind velocimetry applications. The greatest advantage of a Savonius rotor is its ability to self-start in contrast to other ‘Lift type’. VAWTs recently, some generators with high torque at low rotational speed, suitable for small-scale wind turbines, have been developed, suggesting that Savonius rotors may yet be used to generate electric power.

Fig. 3: Savonius Rotor

2) Darrieus Rotor:
The energy is taken from the wind by a component of the lift force working in the direction of rotation. Lift force is perpendicular to the resultant of two velocity component of wind velocity and relative velocity of airfoil to the shaft. These types of turbines have highest values of efficiency among VAWTs and the tip speed ratio can be much higher resulting in a much higher rpm. But generally suffer from problems of low starting torque and poor building integration.

Fig. 4: Darrieus Rotor

C. Combined Savonius and Darrieus Rotor:
Since the Darrieus rotor is not self-starting; a blended design with Savonius blade can make the hybrid which can make it starting and more efficient than any of the single rotor.

D. Giromill:
In these turbines the “egg beater” blades of the common Darrieus are replaced with straight vertical blade sections attached to the central tower with horizontal supports. These turbines usually have 2 or 3 vertical airfoils. The Giro mill blade design is much simpler to build, but results in a more massive structure than the traditional arrangement and requires stronger blades. In these turbines the generator is located at the bottom of the tower and so it can be heavier and bigger than a common generator of a HAWT and the tower can have a lighter structure. While it is cheaper and easier to build than a standard Darrieus turbine, the Giro mill is less efficient and requires motors to start. However these turbines work well in turbulent wind conditions and represent a good option in those areas where a HAWT is unsuitable.

Fig. 5: Spiral & Airofoil shaped Giromill

E. Cyclo Turbine:
A variant of the Giro mill is the Cyclo turbine, which uses a vane to mechanically orient the pitch of the blades for the maximum efficiency. In the Cyclo turbines the blades are mounted so they can rotate around their vertical axis. This allows the blades to be pitched so that they always have some angle of attack relative to the wind. The main advantage of this design is that the torque generated remains almost constant over a wide angle and so the Cyclo turbines with 3 or 4 blades have a fairly constant torque. Over this range of angles the torque is near the maximum possible and so the system can generated more power. Compared with the other Darrieus wind turbines, this kind of VAWT shows the advantage of a self-starting: in low wind conditions, the blades are pitched flat against the wind direction and they generated the drag forces that let the turbine start turning. As the rotational speed increases, the blades are pitched so that the wind flows across the airfoils generating the lift forces and accelerating the turbine. The blade pitching mechanism is complex and usually heavy, and the Cyclo turbines need some wind direction sensors to pitch the blades properly.

1) Why Vertical Axis Wind Turbine?
There are several reasons why we would choose a vertical axis wind turbine over a horizontal axis wind turbine. The main advantages of the vertical axis wind turbine over horizontal axis wind turbine are given below. [1]
VAWT can operate at low speed and start creating electricity and it can be built at location where tall building or structures are located. They are mounted near the roof which makes it easy for maintenance. It produces low noise during operation therefore suitable for living condition and hence recommended for home application.

VAWT rotates about a vertical axis and are always facing the wind therefore does not need to turned into the wind direction.

Safer operation and Spins at slower speed than horizontal turbines, decreasing the risk of injuring birds, simpler installation and maintenance. Besides the traditional installation site, it can be mounted directly on a rooftop, highways, in parking areas etc.

VAWT is inherently simple, less expensive to built and more aesthetically pleasant.

II. POTENTIAL OF WIND ENERGY IN INDIA

A. Energy Status in India

Recent Study In September 2013 by India Expo Center, Greater Noida shows that 87.7 % of the total energy used in India is non-renewable energy. The remaining 12.3% energy is shared by renewable energy. [2] The details of share % utilization of energy in India are given in table below:

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Type of energy sources</th>
<th>Utilization of energy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Renewable Energy</td>
<td>12.3</td>
</tr>
<tr>
<td>2</td>
<td>Non-Renewable Energy</td>
<td>87.7</td>
</tr>
</tbody>
</table>

Table 1: Utilization of Energy sources in India

Electrical energy generation from renewable sources is increased in India with the share of 7.8% in year 2008 to 12.3% in year 2013. India has about 28.1 GW of installed renewable energy capacity as of 31 March 2013. [2] The % break-up installed capacity from various types of renewable sources is given in Table below:

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Type of Renewable Energy</th>
<th>Installed Capacity(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wind Energy</td>
<td>67.9</td>
</tr>
<tr>
<td>2</td>
<td>Hydraulic Energy</td>
<td>12.9</td>
</tr>
<tr>
<td>3</td>
<td>Biomass</td>
<td>12.8</td>
</tr>
<tr>
<td>4</td>
<td>Solar Energy</td>
<td>6.0</td>
</tr>
<tr>
<td>5</td>
<td>Others</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 2: Installed Capacity of Renewable Energy

It is clear from the above table that, awareness regarding use of wind energy is increasing day by day. Installed wind capacity in India makes us 5th largest wind energy producer after China, US, Germany and Spain. Lawrence Berkeley National Laboratory study estimates India’s wind energy potential is between 2,000 GW and 3,000 GW [2].

State wise wind energy status is given in the Table below:

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>State</th>
<th>Potential (MW)</th>
<th>Installed (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Andhra Pradesh</td>
<td>5394</td>
<td>203.840</td>
</tr>
<tr>
<td>2</td>
<td>Gujarat</td>
<td>10609</td>
<td>2176.765</td>
</tr>
<tr>
<td>3</td>
<td>Karnataka</td>
<td>8591</td>
<td>1763.920</td>
</tr>
<tr>
<td>4</td>
<td>Kerala</td>
<td>790</td>
<td>35.950</td>
</tr>
<tr>
<td>5</td>
<td>Madhya Pradesh</td>
<td>920</td>
<td>214.040</td>
</tr>
<tr>
<td>6</td>
<td>Maharashtra</td>
<td>5439</td>
<td>2304.355</td>
</tr>
<tr>
<td>7</td>
<td>Rajasthan</td>
<td>5005</td>
<td>1528.395</td>
</tr>
<tr>
<td>8</td>
<td>Tamil Nadu</td>
<td>5374</td>
<td>5867.165</td>
</tr>
<tr>
<td>9</td>
<td>Others</td>
<td>7008</td>
<td>3.050</td>
</tr>
</tbody>
</table>

Total 49130 14097.480

Table 3: State wise wind energy potential and installed capacity (MW)

Satara Region having maximum number of potential sites for wind energy generation in Maharashtra.

<table>
<thead>
<tr>
<th>Sr . No</th>
<th>Station in Satara District</th>
<th>Height (m)</th>
<th>Elevation (m/s)</th>
<th>Mean Annual Wind Speed (m/s)</th>
<th>Mean Annual Wind Power Density (W/m2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Amberi</td>
<td>25</td>
<td>980</td>
<td>6.39</td>
<td>237</td>
</tr>
<tr>
<td>2</td>
<td>Chalkewadi</td>
<td>20</td>
<td>1185</td>
<td>5.61</td>
<td>206</td>
</tr>
<tr>
<td>3</td>
<td>Jagmin</td>
<td>120</td>
<td>1185</td>
<td>7.42</td>
<td>410</td>
</tr>
<tr>
<td>4</td>
<td>Mandhardeo</td>
<td>25</td>
<td>1286</td>
<td>5.64</td>
<td>153</td>
</tr>
<tr>
<td>5</td>
<td>Matrewadi*</td>
<td>25</td>
<td>898</td>
<td>5.67</td>
<td>211</td>
</tr>
<tr>
<td>6</td>
<td>Palsi</td>
<td>25</td>
<td>970</td>
<td>5.24</td>
<td>137</td>
</tr>
<tr>
<td>7</td>
<td>Panchgan i</td>
<td>20</td>
<td>1318</td>
<td>5.11</td>
<td>133</td>
</tr>
<tr>
<td>8</td>
<td>Thoseghar* (Ref.Stn.)</td>
<td>20</td>
<td>1140</td>
<td>6.03</td>
<td>229</td>
</tr>
<tr>
<td>9</td>
<td>Vankusawad e - II</td>
<td>50</td>
<td>1100</td>
<td>5.68</td>
<td>188</td>
</tr>
<tr>
<td>10</td>
<td>Vankusawad e* - I</td>
<td>25</td>
<td>1100</td>
<td>5.89</td>
<td>231</td>
</tr>
</tbody>
</table>

Table 4: Wind power generation stations in Satara District

(Source: C-WET)
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III. AERODYNAMIC ANALYSIS

In this section, the rotor design parameters are described as well as the model used to calculate its aerodynamic performance. The model limitations are exposed and the computer algorithm and its validation are presented.

A. Wind Turbine Design Parameters:

The wind turbine parameters considered in the design process are:

- Swept area
- Power and power coefficient
- Tip speed ratio
- Blade chord
- Number of blades
- Solidity
- Initial angle of attack

1) Swept area

The swept area is the section of air that encloses the turbine in its movement, the shape of the swept area depends on the rotor configuration, this way the swept area of an HAWT is circular shaped while for a straight-bladed vertical axis wind turbine the swept area has a rectangular shape and is calculated using:

\[ S = 2RL \]

Where,

- \( S \) is the swept area [m²], \( R \) is the rotor radius [m], and \( L \) is the blade length [m].

The swept area limits the volume of air passing by the turbine. The rotor converts the energy contained in the wind in rotational movement so as bigger the area, bigger power output in the same wind conditions.

2) Power and Power Coefficient

The power available from wind for a vertical axis wind turbine can be found from the following formula:

\[ P_w = \frac{1}{2} \rho S V_o \]

Where,

- \( V_o \) is the velocity of the wind [m/s] and \( \rho \) is the air density [kg/m³], the reference density used its standard sea level value (1.225 kg/m³ at 15°C).

Note that available power is dependent on the cube of the airspeed.

The power the turbine takes from wind is calculated using the power coefficient:

\[ C_p = \frac{\text{Captures Mechanical Power by blades}}{\text{Available power in wind}} \]

Cp value represents the part of the total available power that is actually taken from wind, which can be understood as its efficiency.

There is a theoretical limit in the efficiency of a wind turbine determined by the deceleration the wind suffers when going across the turbine. For VAWT, the limit is 16/25 (64%). These limits come from the actuator disk momentum theory which assumes steady, inviscid and without swirl flow. Making an analysis of data from market small VAWT the value of maximum power coefficient has been found to be usually ranging between 0.15 and 0.22.

This power coefficient only considers the mechanical energy converted directly from wind energy; it does not consider the mechanical-into-electrical energy conversion, which involves other parameters like the generator efficiency.

3) Tip Speed Ratio

The power coefficient is strongly dependent on tip speed ratio, defined as the ratio between the tangential speed at blade tip and the actual wind speed.

\[ \text{TSR} = \frac{\text{Tangential speed at the blade tip}}{\text{Actual wind speed}} = \frac{R \omega}{V_o} \]

Where,

\( \omega \) is the angular speed [rad/s], \( R \) the rotor radius [m] and \( V_o \) the ambient wind speed [m/s]. Each rotor design has an optimal tip speed ratio at which the maximum power extraction is achieved. This optimal TSR presents a variation depending on ambient wind speed.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Consideration</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Centrifugal stress</td>
<td>Decrease</td>
<td>Increase</td>
</tr>
<tr>
<td>2</td>
<td>Area of solidity</td>
<td>Increases</td>
<td>Decreases</td>
</tr>
<tr>
<td>3</td>
<td>Efficiency</td>
<td>Decreases</td>
<td>Increases</td>
</tr>
<tr>
<td>4</td>
<td>Torque</td>
<td>Increases</td>
<td>decreases</td>
</tr>
</tbody>
</table>

Table 5: Tip speed design considerations

4) Blade chord

The chord is the length between leading edge and trailing edge of the blade profile. The blade thickness and shape is determined by the airfoil used, in this case it will be a NACA airfoil, where the blade curvature and maximum thickness are defined as percentage of the chord.

5) Number of blades

The number of blades has a direct effect in the smoothness of rotor operation as they can compensate cycled aerodynamic loads. For easiness of building, four and three blades have been contemplated. The calculations used to evaluate the power coefficient of the turbine do not consider the wake turbulence effects of the blade, which affect the performance of adjacent blades.

6) Solidity

The solidity \( \sigma \) is defined as the ratio between the total blade area and the projected turbine area. It is an important non dimensional parameter which affects self-starting capabilities and for straight bladed VAWTs is calculated with:

\[ \sigma = \frac{N c}{R} \]

Where, \( N \) is the number of blades, \( c \) is the blade chord, \( L \) is the blade length and \( S \) is the swept area, it is considered that each blade sweeps the area twice.

This formula is not applicable for HAWT as they have different shape of swept area.

Solidity determines when the assumptions of the momentum models are applicable, and only when using high \( \sigma \geq 0.4 \) a self starting turbine is achieved

7) Initial angle of attack

The initial angle of attack is the angle the blade has regarding its trajectory, considering negative the angle that locates the blade’s leading edge inside the circumference described by the blade path.

8) Mounting system

The most common method for a mounting structure for wind turbines is a monopole design. This consists of some sort of base, usually concrete, with a steel structured pole that extends to the owners desired height. As the progression of turbines has grown there has been desire for roof mounted systems. These roof mounted systems have not had the amount of research as the traditional monopole design. As the growth of roof mounted turbines rises there is an urge to
design out the flaws that has been shadowing previous roof mounted systems.

IV. CONCLUSION

There are number of sources for generation of power but in the recent years wind energy shown its potential as the clean source of energy and contributing to the high energy demands of the world. Vertical axis wind turbine is the best option for the areas with high population density. They can be easily mounted on roof top of tall buildings because of its stable design and low noise producing characteristics. VAWT suitable for areas with extreme weather conditions like mountains, hilltops, ridgelines and passes. The main reason behind searching possibility for installation of VAWT is it does not need to be pointed towards the wind in order to be effective.

A three-bladed design is more efficient than a four-bladed rotor; a low solidity wind turbine may present self-starting problems as rotor efficiency is poor at low tip speed ratios. In most of the cases, airfoils showed better results than regular circular shaped turbines. The performance at higher tip speed ratio, depend on lift to drag ratio; the higher is the lift to drag ratio, for any tip speed ratio or blade number the performance is higher.

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