Chapter 6

Field Testing of Full-Scale VAWT Model

The wind turbine model has been finalised after carrying out several simulations and wind tunnel test. The performance parameters like starting speed and coefficient of power are satisfactory in wind tunnel testing. The analysis of performance of wind turbine on the field plays a vital role for to understand the difficulties of the full-scale model. The field testing involves development of full-scale turbine model and measurement of performance parameters.

This chapter is organized in three sub parts. The first segment explains the details of design of different parts of wind turbine. The second segment of this chapter explains the experimentation of vertical axis wind turbine, describing in detail about the data acquisition system, software related to the acquisition system and the sensors used. Chapter concludes with estimation of power generation of the turbine.
6.1 Design of Vertical Axis Wind Turbine

Proper design of wind turbine is essential in terms of material and structure so that it must withstand the uncertainty in loads. The configuration and orientation of the turbine is finalised after simulating different turbine configuration discussed in previous chapter. This segment describes calculation of power, torque, design of shaft, selection of belt and pulley, selection of bearings.

6.1.1 Power Available in Wind

The power available in wind is calculated as:

\[ P = \frac{1}{2} \rho A V^3 \]  \hspace{1cm} (6.1)

Density of air \( \rho = 1.29 \text{ kg/m}^3 \)

The rotor diameter of the turbine = 0.9 m

The wind velocity is taken maximum. Wind velocity assumed = 6 m/sec

The power available in wind is

\[ P = 125 \text{ W} \]

The maximum rotor speed available at the wind speed 36 m/s is

\[ V = r \omega \]  \hspace{1cm} (6.2)

\[ \omega = 72 \text{ rps} \]
The angular velocity is also given as

\[ \omega = 2\pi n \]  \hspace{1cm} (6.3)

\[ n = 11.46 \text{ rps} \]

### 6.1.2 Calculation of Torque Transmitted

The mechanical power is given as

\[ P = \frac{2\pi nT}{60} \]  \hspace{1cm} (6.4)

\[ T = 5.98 \text{ N-m} \]

### 6.1.3 Weight of Turbine

1. Weight of turbine plate

\[ w_{\text{plate}} = \rho V_{\text{Plate}} gN. \]  \hspace{1cm} (6.5)

\[ W_{\text{plate}} = 3w_{\text{plate}} \]  \hspace{1cm} (6.6)

2. Weight of Blades:

Blades are made of sheet having thickness of 2 mm. The blades profile is made from a sheet having 300 mm length and 300 mm height. The weight of the blade is:
\[ w_{\text{blade}} = \rho V_{\text{blade}} gN \]  
\[ \text{(6.7)} \]

Total weight of six blades

\[ W_{\text{blade}} = 6w_{\text{blade}} \]  
\[ \text{(6.8)} \]

3. Weight of Flaps:

Weight of one flap

\[ w_{\text{flap}} = \rho V_{\text{flap}} gN \]  
\[ \text{(6.9)} \]

Total weight of nine flaps

\[ W_{\text{flap}} = 9w_{\text{flap}} \]  
\[ \text{(6.10)} \]

Total weight acting on the shaft is calculated as follows:

\[ W_{\text{shaft}} = W_{\text{plate}} + W_{\text{blade}} + W_{\text{flap}} \]  
\[ \text{(6.11)} \]

\[ W_{\text{shaft}} = 118 \text{ Kg} \]

### 6.1.4 Belt and Pulley Selection

For 100 W and 200 rpm speed the V belt section is B type. For B type section, the minimum pitch diameter for driver pulley is \( D = 200 \text{ mm} \). The diameter of the driven pulley is

Centre distance between the pulley is \( C = 2D = 400 \text{ mm} \).

Length of belt is given as
\[ L = 2C + \pi \left( \frac{D + d}{2} \right) + \frac{(D - d)^2}{4C} \]  

(6.12)

\[ L = 1206 \text{ mm} \]

From the manufacturers catalogue for B type section of V belt, the pitch length of the belt and inside length of the belt is

\[ L_i = L - 43 = 1163.5 \text{ mm}. \]

From the manufacturers catalogue dimensions of V belt for B type section is

Width = 17 mm

Height = 11 mm.

The angle of wrap \( \alpha_s \) is given as follows,

\[ \alpha_s = 180 \left[ 2\sin^{-1} \left( \frac{D - d}{2C} \right) \right] \]  

(6.13)

\[ \alpha_s = 2.72 \text{ radian} \]

The width of the base of the belt is calculated as 8.9 mm and the area of cross section is 142.45 \( \text{mm}^2 \).

The mass of the belt is calculated as 0.138 kg/m.

The peripheral velocity is

\[ v = \frac{\pi dn}{60 \times 10^3} \]  

(6.14)

\[ v = 0.523 \text{ m/s} \]

The maximum Power equation is

\[ \frac{P_1 - mv^2}{P_2 - mv^2} = e^{\frac{t_o}{1000.59}} \]  

(6.15)
Where \( f = \text{coefficient of friction} = 0.2 \)
\[ \theta = \text{belt angle} = 20^\circ \]
\[ P_1 = \text{Belt tension in tight side (N)} \]
\[ P_2 = \text{Belt tension in loose side (N)} \]

Assuming that,
\[ P_1 = 3P_2 \]
\[ P_1 = 0.6 \text{ N and} \]
\[ P_2 = 0.2 \text{N} \]

### 6.1.5 Design of Shaft

1. Material Selection
   (a) The material selected for shaft is 50C4
   (b) Ultimate tensile strength of 50C4 = 700 \( N/mm^2 \)
   (c) Yield strength of 50C4 = 460 \( N/mm^2 \)
   (d) Density of material = 7800 \( Kg/m^3 \)

2. Calculation of Shear stress

   \[ \tau_{max} = 0.30S_{yt} = 0.30(460) = 138 \text{ N/mm}^2 \quad (6.16) \]

   \[ \tau_{max} = 0.18S_{ut} = 0.18(700) = 126 \text{ N/mm}^2 \quad (6.17) \]

\( S_{yt} \) - yield strength of the material in tension \( N/mm^2 \)

\( S_{sy} \) - yield strength of the material in tension \( N/mm^2 \)
3. Estimation of diameter of shaft

The shaft supporting the plates, blades and flaps is subjected to a combined load of bending and torsional moments. $M_b$ is bending moment subjected to bending stress $\sigma_b$, $M_t$ is the twisting moment subjected to shear stress $\tau$.

The shaft supporting flaps, blades and plates is subjected to a combined loading of bending and torsional moments. The shaft material is ductile, thus principle shear stress theory of failure is used to determine the shaft diameter.

The shaft is subjected to bending moment $M_b$ due to $\sigma_b$ and torsional moment $M_T$ due to $\tau$.

According to ASME code, the bending and torsional moments are multiplied by $K_b$ and $K_t$ respectively, to account for shock and fatigue in operating condition. The values of $K_b$ and $K_t$ is 3.0 for load suddenly applied condition.

$$\tau_{max} = \frac{16}{\pi} \sqrt{(K_b M_b)^2 + (K_t T)^2} \quad (6.18)$$

The minimum diameter of the shaft for designed load is estimated is 4.35mm.

The shaft diameter selected for the shaft is 10 mm.

From manufacturers catalogue for 10 mm diameter the bearing selected is 61800.
6.2 Experimental Setup

The multistorey vertical axis wind turbine having three stories is installed in a farm field at Jamgaon, Ahmednagar. The wind turbine system has belt pulley arrangement for enhancement of speed and power transmission to the generator shaft. For measurement of power generated by wind turbine and vibration various parameters of wind are measured and monitored by setting up a system. The parameters are current, voltage and rotor speed and wind velocity. The interface to pc is done using a micro controller which is used as a data acquisition system.

6.2.1 Data Acquisition System

Fig. 6.1 shows the data acquisition system setup. It consists of sensors and microcontroller. The measurement of current, voltage, speed and rpm is done by sensors. The sensor sends the information to microcontroller. The information of microcontroller is converted to digital form and can be stored in memory card.

Figure 6.1: Architecture of data acquisition system
1. Data Acquisition System Fig 6.2 shows the Mega 2560 is a micro controller board based on the ATmega 2560. Table 6.1 shows Specification of Micro controller ATmega 2560.

<table>
<thead>
<tr>
<th>Parts</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Voltage</td>
<td>5V</td>
</tr>
<tr>
<td>Input Voltage</td>
<td>7-12V</td>
</tr>
<tr>
<td>Digital I/O Pins</td>
<td>54</td>
</tr>
<tr>
<td>Analog Input Pins</td>
<td>16</td>
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<tr>
<td>DC Current per I/O Pin</td>
<td>20 mA</td>
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<tr>
<td>DC Current for 3.3V Pin</td>
<td>50 mA</td>
</tr>
<tr>
<td>Flash Memory</td>
<td>256 KB</td>
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<tr>
<td>SRAM</td>
<td>8 KB</td>
</tr>
<tr>
<td>EEPROM</td>
<td>4 KB</td>
</tr>
<tr>
<td>Clock Speed</td>
<td>16 MHz</td>
</tr>
<tr>
<td>Length</td>
<td>101.52 mm</td>
</tr>
<tr>
<td>Width</td>
<td>53.3 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>37 g</td>
</tr>
</tbody>
</table>

Table 6.1: Specification of Micro controller ATmega 2560

2. Power pins

(a) Vin: Through this pin input voltage is supplied to the acquisition system when external power source is used.

(b) 5V: This pin provides regulated 5V output from the regulator. The input power source can be DC power.

(c) 3V3: It consists of ground pin and IOERF. IOERF provides the voltage reference to micro controller. The capacity of this pin is about 50mA.

3. Input and Output
There are 54 digital pins on the Mega board which is used as input and output pin. These pins operate at 20mA and 5 volts. In addition, some pins have specialized functions:

(a) Serial: Pins 0 and 1 are also connected to the corresponding pins of the ATmega 16U2 USB-to-TTL Serial chip.

(b) External Interrupts: These pins are used to initiate an interrupt on a low level, a rising or falling edge, or a change in level.

(c) PWM: 2 to 13 and 44 to 46. Provide 8-bit PWM output with the analog Write() function.

(d) SPI: These pins support SPI communication. The pins are segregated on ICSP header which makes it compatible with Aurdino.

(e) LED: The rise in voltage is signaled by lighting of LED. The LED is connected to pin 13.
4. Software

The board is coded with Aurdino software. The ATmega 2560 on the board is coupled with bootloader which make it capable to upload new code with using external hardware code. ATmega 16U2/8U2 available in Aurdino repository can be loaded using DFU bootloader. The software is enable to reset the board without need of physical reset button. But this provision is associated with certain drawbacks.

The Mega 2560 board contains a trace that can be cut to disable the auto-reset. The pads on either side of the trace can be soldered together to re-enable it. It’s labeled ”RESET-EN”. You may also be able to disable the auto-reset by connecting a 110 ohm resistor from 5V to the reset line;

5. Sensors
(a) Accelerometer Fig. 6.3 shows ADXL 335 accelerometer. The accelerometer measures static and dynamic acceleration due to motion or shock. The bandwidth can be adjusted by using capacitors at the output pins. The size of accelerometer is compact made up of plastic lead frame. The accelerometer has 3 axis with signal conditioned voltage output.

![Accelerometer Image](image)

Figure 6.3: Accelerometer

(b) Current sensor Fig. 6.4 The sensor consists of a copper conduction path which generates a magnetic field. The BiCMOS Hall IC converts the magnetic field into proportional voltage. BiCMOS Hall IC provides precise voltage. When the current increases the output of the device has a positive slope. The internal resistance of this conductive path is 1.2 m\(\text{-ohm}\) typical, providing low power loss. The ACS 712 is mounted on SOIC package made up of lead frame.
(c) B25 Voltage sensor

Fig. 6.5 shows a Voltage sensor. OLED module is constructed with 128×64 dot matrix, each of which can light. It can display Chinese / English character, pattern. OLED screens are more competitive, which has a number of advantages such as high brightness, self-emission, high contrast ratio, slim / thin outline, wide viewing angle, wide temperature range, and low power consumption (0.08W for full light, 0.06W for full Chinese character display). Supports Continuous Horizontal Scrolling.

<table>
<thead>
<tr>
<th>Parts</th>
<th>Specification</th>
<th>Household</th>
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<tr>
<td>Operating Voltage</td>
<td>3.5V</td>
<td></td>
</tr>
<tr>
<td>Driver IC</td>
<td>7-1SSD1306</td>
<td></td>
</tr>
<tr>
<td>Communicate Mode</td>
<td>I2C</td>
<td></td>
</tr>
<tr>
<td>Viewing Angle</td>
<td>less than 160°</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.2: Specification of B25 Voltage Sensor
6.2.2 Generator

The generator used is rated as 100 Watt/200 rpm/24 volt/3A. Fig 6.6 shows the detail drawing of generator. The generator used has a stator and rotor. Magnet is mounted on the rotor while the stator is wound with required number of poles. The windings of motor are coupled to control circuit. The function of control circuit is to energize the winding at proper time. The rotor magnet gets aligned with the electromagnet of stator winding.
Figure 6.6: Generator drawing
6.3 Result and Discussion

The full scale multi storey vertical axis wind turbine is designed and manufactured having rotor diameter 0.9 m and rotor height 0.9 m. The turbine model is having three stories of which first and third story are placed orthogonal to the middle storey. The turbine is installed at farm field. The testing of the turbine is done for performance parameters like self starting speed and coefficient of power.

6.3.1 Minimum Wind Speed For Self-Starting

The full scale turbine model has been fabricated using blade having 68-613 NACA aerofoil. The blade is having cambered aerofoil which is having better self starting capability as compared to symmetrical aerofoils. The turbine parts were designed after understanding the fundamental physics of self-starting of vertical axis wind turbine. Full scale multistory vertical axis wind turbine has been tested for self starting speed. It has been observed that turbine initially self starts at wind speed of 2-3 m/s and the rotor speed accelerates with further increase in wind speed. The turbine has steady rotation above 5 m/s wind velocity. The turbine rotor speed ranges from 20 rpm to 70 rpm. It is observed that the turbine self starting is independent of wind direction as the flaps and the blades of each storey are arranged in such a way that they assist the motion of turbine.

6.3.2 Coefficient of power

Fig. 6.7 shows the plot $C_p$ Vs TSR. The data presented here is for wind velocity range of 5-7 m/s. The turbine rotates at wind speed of 4 m/s. The plot indicates
that \( C_p \) is very low for a vertical axis wind turbine operating at tip speed ratios below 0.28. The correspondingly low shaft power is insufficient to overcome friction of the generator. At tip speed ratios above 0.28, the vertical axis wind turbine is able to extract power from the wind to accelerate itself up to the desired operating angular velocity. The \( C_p \) value increases from 6% to 12%.

![Figure 6.7: \( C_p \) vs Tip Speed Ratio](image)

For higher tip speed ratio above 0.35 the power in the wind continues to increase and the value of \( C_p \) increases noticeably. The value of \( C_p \) increases from 16% to 25%. It is seen that as the wind speed increases the coefficient of power also increases. The maximum value of \( C_p \) could not be noted as the the stall point will be for higher tip speed ratios.

### 6.3.3 Vibration Analysis

Fig 6.8 and Fig 6.9 shows the plot of Acceleration vs Time. This value of acceleration was recorded for time cycle of 1000 milliseconds. From Fig 6.8 shows the plot which has been recorded when the wind turbine starts moving. It is observed that, their are vibrations in X and Y direction through the time domain. These
vibration are due to starting of the wind turbine. When the turbine starts there is very little noise in one parts of its rotation. The high spike seen in X and Y direction are due to the noise. Fig. 6.9 shows when the turbine is moving at speed of 30-50 rpm. It is observed that the vibration in X and Y direction has been reduced considerably. The vibrations in Z direction is not significant at the start and also when the turbine gains speed.

Figure 6.8: Acceleration vs Time
6.4 Summary

After lot of experimentation mentioned in previous chapters the model for full scale is finalised. The full scale model of three storey configuration is fabricated and tested in farm field. The performance testing of wind turbine has been done for self starting speed, coefficient of power and vibration. The self starting speed of turbine is 4–5.5 m/s. The maximum coefficient of power measured in range of wind speed 5–7 m/s is 29%.