CHAPTER 6

DESIGN OF WIND TURBINE PLANT USING THE DEVELOPED CONCEPTS

Design of wind turbine plant consists of four major categories (Eggleston 1987)

i. Design and fabrication of blades
ii. Design of gear box and other mechanical accessories and its fabrication
iii. Design of control circuit elements
iv. Design and erection of tower

As described in chapter 1, NACA 4412 profile was used to generate the basic aerofoil shape of the wind turbine. This profile has excellent flow characteristics and offer best power coefficient. In order to account for blade twist angle, Pattern of the blade was fabricated by slicing the blade into sixty pieces. Since the fabrication process commences before arriving to the conclusion about the alternative materials for the blade, the blades were fabricated using conventional blade material, E-glass Epoxy resin composite laminate (Poore, SAND Report 1999). Field survey was carried out in the proposed site to identify the optimum height of installation. Average wind velocity necessary for generating 5 kW power is 3.5 m/sec. This was obtained at an elevation of 25 m. Corresponding speed of rotation of blade at this condition was identified as 36 rpm. But the rated speed of the alternator for power generation is 1500 rpm. Hence a two stage gear box was designed and
fabricated. The first stage of the gear box is of planetary type the second stage consists of two stage helical gear box. The control elements for the efficient operation of turbine were properly designed for the specified power rating and formed. Finally a tower was erected to mount the nacelle of the turbine at an elevation of 25 m. Before commissioning the tower, it was designed using STAAD.Pro software. Each elements of the tower was checked for the induced stresses and their relative displacement with respect to its adjacent member. Strain gauges were located at the hub section of the blade to estimate the maximum induced stresses (Working stresses) under different working condition. Failure envelope was drawn using the proposed Modified criterion. It was ensured that the working stresses are within safe operating condition.

6.1 DESIGN OF BLADES FOR 5 kW WIND TURBINE

The power equation for the wind turbine blade is expressed as

\[ P = C_p \left( \frac{1}{2} \rho AV^3 \right) \]  

(6.1)

Using the calculated value of rotor swept area (m²), the blade length is calculated as 2.44 m for the designed power of 5 kW and power coefficient for NACA 4412 section of 0.3541. Tip speed ratio (TSR) is one of the important variable in wind turbine terminology, which is defined as the ratio between speed of the rotor tip to free wind speed. Mathematically,

\[ TSR = \frac{V_{tip}}{V} \]  

(6.2)

The ratio of the projected area of the rotor to the swept area of the rotor is known as solidity. In order to minimize the inertia of the rotor, in general, the blades are manufactured with low solidity. The designed blade is having a solidity of 0.1, i.e., the blades occupies only 10% of the rotor swept area.
Solidity = \frac{BC}{\pi D} \quad (6.3)

B is number of blades, C is Chord length at \frac{2}{3} of blade length = 511 mm;

Ratio \frac{c}{c_1} for NACA 4412 profile is 2.53; Hence root chord length, c = 676.82 mm; Tip chord length, c_1 = 338.40 mm.

6.1.1 Model Generation

The created aerofoil is exported to SolidWorks 2001 Plus version and this represents the root chord length of the blade and is shown in Figure 6.1. The tip section is then created and is then rotated to have the appropriate blade twist angle as shown in Figure 6.2. Surfaces are generated using lofted protrusion option along the length of the blade. Circular root section is created in different planes and then the final solid model of the blade is shown in Figure 6.3.

Figure 6.1 Imported NACA 4412 aerofoil section
Figure 6.2 Twisted tip with blade root

Figure 6.3 Solid model of the blade
6.1.2 Pattern Making

It is well known fact that the wind turbine blades were cast when it came for production process. In order to make the mold of the blade, the first necessity is the pattern preparation. Since the blade is twisted along its length, varying thickness from leading edge to trailing edge and varying size from root section to tip section, it was not easy to prepare the pattern with accurate profile dimension and twist. Hence, it was decided to prepare the pattern using Malaysian sal wood. For this purpose, the blade profile was divided into 60 pieces as shown in Figure 6.4. After making 60 pieces, they were joined together with a central pipe along the maximum thickness line by making holes in each profile. In order to prepare the pattern with best accuracy, the following dimensions were noted in the sectional view of the profile.

i. Distance of upper and lower camber from the chord line (Figure 6.5).

ii. Distance of maximum thickness center from the leading edge and the chord (Figure 6.6).

With the dimensions thus obtained, the profiles were drawn on the wooden pieces. At first chord is drawn on the wooden piece and then upper camber and lower camber lines were drawn on the wooden profile with reference to the position of chord line. The same procedure is repeated for all 60 pieces with their corresponding chord length. Then a drill of 10 mm diameter is made at maximum thickness of the profile and a central pipe is allowed to join all the pieces together as shown in Figure 6.7. After creating the pattern, dies are fabricated as two parts die. Following the conventional procedure of applying fiber and resin material in alternative manner, the wind turbine blade was fabricated. Thus fabricated blade is shown in Figure 6.8.
Figure 6.4  60 Piece division of aerofoil section

Figure 6.5  Camber distance measurement from chord line
Figure 6.6 Location of maximum thickness center from the leading edge

Figure 6.7 Positioning of pieces as per twist
6.1.3 Blade Flange

The blades are connected to the hub which is a part of nacelle. In order to facilitate this connection, a flange manufactured in MS plate is fitted inside the blade using fasteners as shown in Figure 6.9.
The flange which is assembled with wind turbine blade is subjected to:

i. Tensile stress due to centrifugal force of blade

ii. Bending stress due to lift force.

iii. Centrifugal force in the blade, \( F_c = \frac{mV_{tip}^2}{R} \)

Here, \( m \) is the measured mass of the blade = 36.5 kg; \( R \) is the length of the blade = 2.44 m. For a three rotor wind turbines, tip speed ratio (TSR) is 6. Using (6.2), \( V_{tip} = 90 \) m/sec, when free stream wind velocity is 15 m/sec. Hence the flange is subjected to a centrifugal force of 121.17 kN. This force is resisted by fifteen numbers of studs around the flange circumference. These studs are of C45 steel whose allowable tensile stress \( [\sigma_t] \leq 160 \) N/mm\(^2\). Using \( F_c \leq n \frac{\pi}{4} d_i^2 [\sigma_t] \), it was found that the design was safe for the environment.

6.2 DESIGN OF GEAR BOX

The blades were designed to run at 36 rpm whereas the rated speed of the generator is 1500 rpm. Hence the speed ratio of this unit is around 42. This much amount of increase in speed was achieved by employing a multi stage gear box in which the first stage is of planetary gears and the second stage is of helical gears. The input speed obtained from the main shaft is fed to the arm of the planetary train. The planetary gear train is having a gear ratio of 3.77. Hence the speed of the sun gear which is connected to the output shaft of the planetary gear train runs with 136 rpm. This output shaft is in turn connected to a compound helical gear train whose speed ratio is 11.2; hence the speed of the output shaft from this compound gear train is about 1520 rpm. The schematic of gear box is shown in Figure 6.10. Design of gear
box includes design of gears, shafts, bearings, keys and selection of suitable materials for these accessories. The designed parameters for these accessories are shown in Table 6.1.

![Diagram of gear box]

**Figure 6.10 Layout of gear box**

This gear box contains four shafts, two each in low speed side and high speed side. These shafts are labeled by A, B, C and D respectively. These shafts were fabricated using low carbon steel. These are designed considering the effect of twisting moment, bending and axial thrust and the designed shaft was also checked for torsional twist also. Diameters of these shafts from low speed side to high speed side are 400 mm, 320 mm, 200 mm and 180 mm respectively.
Table 6.1 Design parameters (in mm) of gears

<table>
<thead>
<tr>
<th>Parameters</th>
<th>G1</th>
<th>G2</th>
<th>G3</th>
<th>G4</th>
<th>S</th>
<th>P</th>
<th>R</th>
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<td>18</td>
<td>74</td>
<td>21</td>
<td>16</td>
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<td>62</td>
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<td>6.0</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Tooth thickness</td>
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<td>4.71</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>0.7</td>
<td>1.2</td>
<td></td>
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6.3 DESIGN OF CONTROL CIRCUIT

In latest wind turbines, the blades rotate with constant speed with the help of pitching effect. Pitching is the process of rotating all the three blades equally depending upon the directional changes in wind direction and wind velocity in order to keep the blade speed as constant. In order to effect this pitching operation, additional installation of motor mounted in the hollow portion of the blade and necessary control elements with appropriate microprocessor controlled feedback mechanism. Considering the cost factor, the installed plant does not incorporate the pitching mechanism. In stead a mechanically operated pitch mechanism was installed in its place. But the response time is high; hence, the speed of the blade can not be maintained constantly. Under this circumstance, it is not possible to use induction generators which were warranted for constant speed operation. Hence an Alternator was used for this purpose (Mohan et al 1989).
The control circuits involved in this work can be broadly divided into three types namely

i. Starting Circuit
ii. Braking Circuit
iii. Interlocking or Switch over Circuit

### 6.3.1 Starting Circuit

The initial torque required by the blade to start rotate is directly proportional to the Inertia of the blades and indirectly proportional to the wind velocity. The average wind velocity at the proposed site where the wind turbine plant was installed is only 3.5 m/sec, which was lower than the required average. Hence it is very essential to incorporate a starting circuit. The starting motor circuit was designed to perform its function only when the wind velocity is more than 3.5 m/sec. A calibrated anemometer (ANME) is employed for this purpose. It was found that, when the wind velocity reaches 3.5 m/sec, the anemometer rotates with 160 rpm and is coupled (C) with a trigger motor (M). At this operation, the trigger generates a voltage that will be compared with the preset value in the comparator (CMP) and in turn it generates a signal which actuates a relay switch (R). The relay, which was normally open contact, will close after receiving the signal from the comparator.
Figure 6.11 Starting circuit
Figure 6.12 Braking circuit
Figure 6.13 Loading circuit
Once the switch was closed, power from the battery/grid is given to starting motor (SM). The starting motor is in turn rotates the generator shaft through a clutch assembly (CL). The clutches engage when it receive power. At this condition, the brake shoes (BS) were released from the coupling (C) and the system was free to rotate. A timing circuit was also connected to this stating circuit to disconnect the clutch and the starting motor from the supply after few seconds, i.e. after the blades attained their initial momentum. The starting circuit used for the installed wind turbine is shown in Figure 6.11.

6.3.2 Braking Circuit

A.C. Solenoid brake was employed as a key element of braking circuit. The rated speed of the alternator was 1500 rpm at which it will generate 230 V. Under the operating condition the rated speed should be in the range of 1500±10%. In order to have it under safe condition, the braking circuit was designed by keeping 1600 rpm as key parameter. A small motor (M) is coupled with the alternator (GEN) through a belt drive. When the speed of the alternator reaches 1600 rpm, the motor generates a voltage and was compared with a preset voltage in the comparator (CMP). If the speed is beyond 1600 rpm, the comparator generates a signal which will actuate a relay (R). The relay which is normally closed contact opens when the relay was activated. This will in turn disconnect the supply to the solenoid of the brake. It will make the brake shoes (BS) to apply the pressure over the coupling (C) and causes the braking effect. Hence the operating speed of the alternator was maintained as constant for safer operation of the alternator. The employed braking circuit is shown in Figure 6.12.

6.3.3 Interlocking or Switch Over or Loading Circuits

During normal operating condition, power required by the load will be supplied by the generator. During the starting time the plant, the flow will
be in reverse direction. In order to ensure that the power flow happens in only one direction at a time, this interlocking or switch over circuit was employed. A comparator (CMP) compares the voltage from the generator (GEN) with the reference set voltage. The comparator receives two inputs; one from the generator and another from grid, which acts as a reference voltage. Since the comparator operates on DC source, a thyristor (T)-rectifier (RECT) circuit was employed to convert AC to DC and vice versa. The output voltage from the generator fed to the comparator and was compared with the reference value. If it does not match with the reference value, then the current flows directly from the grid to the load. On the other hand, if the reference voltage and the output voltage are the same, the comparator energizes two relay coils (R) which further close two normally open switches. Now the current will from grid to load through rectifier, battery and inverter (INV) from the normally open switch. Hence, the rectified current will be stored in a battery. The stored D.C current can be inverted to A.C by means of an inverter and was connected to load through the second normally open switch, when power was not generated from wind. Figure 6.13 shows a typical load circuit.

6.4 ANALYSIS OF STRUCTURE

STAAD.Pro is general purpose structural analysis and design software with extensive model generation and post processing facilities. Structure for the proposed 5 kW wind turbine was modeled and analysed using this environment. Since the power capacity of the turbine is low, a simple, reliable lattice structure was selected for the mentioned application. STAAD employs either one of SPACE, PLANE, TRUSS or FLOOR structure as its basic element for structure generation. Among them SPACE is an optimum element for three dimensional framed structure and was selected for this application. Number of links in a chain can be computed using,
\[ m = 2j - 3 \] Here, \( j \) is number of joints (Madsen et al 1986). Hence number of links in a chain was computed as 5 and was of three different types.

i. Horizontal bracing of ISA 40 \( \times 40 \times 6 \)

ii. Vertical bracing of ISA 50 \( \times 50 \times 6 \)

iii. Cross bracing of ISA 35 \( \times 35 \times 6 \)

The structure was modeled for a height of 25 m as shown in Figure 6.14. The nodes at the foundation end are arrested by specifying the type of support as pinned. Various types of loads as detailed in section 1.6 and 2.4.1 were applied on the structure as shown in Figure 6.15. After specifying that the members were of ANSI steel, the model was analysed statically. In the post processing module, it can be ensured that the relative nodal displacement among the members in a chain is zero. A typical nodal displacement plot is shown in Figure 6.16. Induced stresses in various members due to the effect of single kind of load and load combination can be computed and is shown in Figure 6.17. Maximum induced stress in the tower member was estimated as 27.82 MPa, whereas the allowable yield stress for the tower material is in the order of 360 MPa. Hence the factor of safety for the structure would be 12.94 which are very much in safe condition. The erected tower is shown in Figure 6.18.
Figure 6.14 Three dimensional view of tower

Figure 6.15 Loads applied on the tower
Figure 6.16  Nodal displacements in various members of the tower

Figure 6.17  Stress plot from STAAD of the tower
6.5 FAILURE ENVELOPE GENERATION USING PROPOSED CRITERIA

The strength properties of the E Glass fiber Epoxy resin composite laminate used for the fabrication of wind turbine blade was determined using the procedure explained in section 2.7. Using the strength properties in FPCL coding, demonstrated in section 3.9, failure envelope was generated. As explained in section 3.4, failure index equation in \( \sigma_{yy} - \tau_{xy} \) can be expressed as

\[
FI = A \left( \frac{\sigma_{22}}{S_T} \right)^2 + B \left( \frac{\sigma_{22} \tau_{12}}{S_T S_L} \right) + C \left( \frac{\tau_{12}}{S_L} \right)^2
\]

(6.4)

The action plane coefficients A, B and C are:

\[
A = (\eta_T \cos^2 \theta - \sin \theta \cos \theta)^2 + \eta_L^2 \cos^4 \theta \quad ; \quad B = 2\eta_T \cos^3 \theta \quad \text{and} \quad C = \cos^2 \theta .
\]
Figure 6.19 shows the failure envelope using the proposed modified criteria for the installed wind turbine with working stresses for different operating conditions viz. 5 m/sec, 10 m/sec and 15 m/sec.

The failure index equation in \( (\sigma_{xx} - \tau_{xy}) \) can be expressed as

\[
FI = A_1 \left( \frac{\sigma_{11}}{S_L} \right)^2 + B_1 \left( \frac{\sigma_{11} \tau_{12}}{S_L} \right) + C_1 \left( \frac{\tau_{12}}{S_L} \right)^2 \tag{6.5}
\]

Here the action plane coefficients \( A_1, B_1 \) and \( C_1 \) are:

\[
A_1 = \left( 1 + 2 \eta_T^2 \right) \sin^4 \theta; \quad B_1 = 2 \eta_T \sin^3 \theta; \quad \text{and} \quad C_1 = \sin^2 \theta.
\]

Using the failure index equations (6.4) and (6.5) failure envelope in \( (\sigma_{xx} - \sigma_{yy}) \) field can be drawn as shown in Figure 6.20. In both cases it was found that the criteria predict safe working condition.

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**Figure 6.19**  Failure envelope generation using modified criteria for wind turbine blade material in \( (\sigma_{yy} - \tau_{xy}) \) field
Figure 6.20  Failure envelope generation using modified criteria for wind turbine blade material in \((\sigma_{xx} - \sigma_{yy})\) field

6.6   FUTURE TREND

In the last few years the trend has moved from installations with single or small groups of wind turbines, to large wind farms with a capacity of hundreds of MW. The increasing and concentrated penetration of wind energy makes the power system more and more dependent on and inevitable to wind energy production. Future wind farms must be able to replace the present power stations, and thus to act as active controllable elements in the power system. In other words, wind farms must develop power plant characteristics. Another consequence of the increased size of future wind farms is that large wind farms will be connected directly to the transmission level. Until now, wind turbines and wind farms have been connected to the distribution system, typically on 10/20 kV grid or on 50/60 kV grid. Consequently, main focus has been on the influence of wind farms on the power quality in the distribution system. An important requirement made by the system responsible is that in future, wind farm owners must provide models that can simulate the dynamic
interaction between a given wind farm and a power system during transient grid fault events. Such developed models will enable both wind farm investors and technical staff at the respective utility grid to undertake the necessary preliminary studies before connecting wind farms to the grid. Simulation of the wind farm interaction with the grid may thus provide quite valuable information and may even lower the overall grid connection costs. In addition, these models can be used to study control strategies for wind farms. Large research projects have been initiated to analyze different control strategies of large wind farms. There are many control topologies, and they all have their particular advantages and disadvantages. One option is a decentralized control structure with an internal AC grid connected to the main grid, where each wind turbine has its own control system with its own frequency converter. Such a system has the advantage of ensuring that each wind turbine can work optimally with respect to its local wind conditions. Another option is a centralized control structure where the wind farm is connected to the grid via an HVDC connection. Here, the internal behaviour of wind turbines is separated from the grid behaviour, thus enabling the wind farm to become sufficiently robust to withstand possible failures on the grid. Another way to control wind farms is the combination of wind farms and energy storage systems, which makes it possible to buffer some of the energy.

### 6.7 Scope for Future Research and Development

In view of the rapidly increasing use of high modulus and high strength fiber reinforced composite materials in aero space structures, damage tolerance and reliability of composite materials and structures have been of significant concern. Non polymeric composites like Metal matrix composites (MMC) and Ceramic matrix composites (CMC) finds their role in these applications. The mechanical behaviour of these composites is different from that of polymeric based composites. Future research is directed towards the
predictive capabilities of Modified criteria for failure prediction of these composites.

The capabilities of Interface crack which cause the delamination may also be analyzed based on the concepts of fracture mechanics. The fracture characteristic variables such as Stress Intensity factor, Energy release rate, CTOD and J Integral can be evaluated. Efforts can also be made to interpret the failure equation in terms of fracture characteristic variables.

The blade model can be fabricated using suggested alternative materials and the working stresses can be plotted under different operating conditions.