Analytical approach to design wind turbine blades suitable for high power production based on operational conditions in Iraq

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Abstract. This study presents analytical approach to design wind turbine blades of high power production capable to work in actual operational conditions in Iraq. The study includes aerodynamics analysis related to wind features around the blades, stress analysis related to the weight of the blade and corresponding loads using SolidWorks software and finally selection the suitable material for manufacturing. Moreover, a survey has done to collect data of wind characteristics in Iraq. The effective parameters in the design were: wind speed, desired power and tower height. The design predicts many specifications in the design of blade for a rate power between (600-850 kW), where the diameter of rotary ranged from 48-57 m, length of blade ranged from 23-27 m and the thickness of the chord has not exceeded 0.12 m as maximum.

Keywords: Wind turbine, Renewable energy, Power, Mechanical design, Manufacturing

1. Introduction

Wind is a source of renewable and clean energy and it considers as an alternative energy to reduce the consumption of the fossil fuel. Wind energy can be harvested by a device called wind turbine which converts the rotational mechanical energy into electrical power with the aid of a generator. Wind farm is the area where many individual wind turbines are used to collect the energy and connect the produced power to the electrical network. Wind farms are either onshore (land grounded) or offshore (at the sea or close to it). The two common types of wind turbines are horizontal axis (HAWT) and vertical axis (VAWT). Horizontal axis wind turbine is the common type and has higher power than other type. Wind turbines are used for many applications such as water pumps and households in remote areas, or as a contribution to the domestic power supply. Typical wind turbines have a rate power between 10 kW - 5 MW [1]. Wind turbine market has many suppliers of wind turbines with wide range of designs, where the most famous brands are: Vestas, Siemens, Gamesa, GE, Goldwind, Enercon, Nordex, Senvion, United Power, Envision, Suzlon, Leitwind, Bonus, Delft and AAER. However, wind turbines can be classified according to the generated power to [1, 2]:

- Small-power wind turbines with production less than 20 kW, useful for remote homes and farms.
- Intermediate-power wind turbines with production between 20-200 kW, useful for small village power feeding or hybrid systems.
- High-power wind turbines with production more than 200 kW, useful for wind power plants.
2. Design Procedure

2.1. Wind characteristics in Iraq
In any analytical design, it is necessary to collect data related to wind characteristics (wind speed, direction and gust rate) in many locations in Iraq based on the measured values taken from several reliable references: Iraqi Meteorological Organization and Seismology (IMOS) [3], Weather Spark [4], Joint Research Center [5], RETScreen Application [6] and some individual resources [7-9]. These data represent average values for the last ten years. These references show that the most productive locations in Iraq are: Nasiriya, Kut, Kirkuk, Basrah, Haditha and Sinjar, depending on their wind characteristics. In general, the average wind speed is between (4-6 m/s) with a direction varies from northwest to north. These facts have taken into consideration during the design.

2.2. Desired power
The design of wind turbine requires understanding many dependent and independent parameters, like the wind speed, tower height, swept area and power generated. These parameters are quite conjugated to each other, as shown in figure 1.

![Figure 1. Typical horizontal axis wind turbine (HAWT).](image)

Wind profiles show that the wind energy could be harvested using HAWT turbine at a height no less than 30 m with three-blade arrangement [10-12]. Since weather data usually reports wind speeds at ground level, so it is seeking to calculate the wind speed at turbine hub elevation, where the wind speed increases with the height. It is noticed that the increasing of tower height up to 90 ft (about 27 m) increases the power by 75% [13]. This idea has cleared in figure 2.

![Figure 2. Effect of turbine height on produced power [13].](image)
However, a reliable wind speed can be calculated at the desired altitude (H) using the empirical seventh power law [14].

\[ V = V_0 \left( \frac{H}{H_o} \right)^{1/7} \]  

(1)

Where:
- \( V_0 \) is the velocity near ground level (m/s)
- \( H \) is the ground level (m)
- \( H_o \) is the hub level (m)

Since the wind speed at the selected locations is considered as a gentle according to Beaufort scale, hence a tower height of 60 m is suitable [13]. According to equation (1), the resultant wind speed at this height is between 8-12 m/s. By comparing these values with the produced power from power-wind speed curve, the expected power is between 650-1000 kW, as in figure 3.

![Power-wind speed curve](image)

**Figure 3.** Power-wind speed curve [15].

### 2.3. Dimensions of the blade

The area of the rotary blades besides the wind speed both are the main parameters in the calculation of harvested power, as following [10, 11]

\[ P = \frac{1}{2} \rho V^3 A \]  

(2)

Where:
- \( \rho \) is the air density (kg/m³)
- \( V \) is the wind speed (m/s)
- \( A \) is the effective area of air flow, also called as swept area (m²)

Since, the maximum theoretical power output of a wind turbine is 16/27 times the kinetic energy of the air passing through the effective area of the machine [16], so the maximum theoretical power output will be:

\[ P = \frac{8}{27} \rho V^3 A \]  

(3)

There are many aspects impacting the overall efficiency of wind power, such as the availability wind, volumetric contribution, gearbox losses as well as generator and converter losses. However, efficiency may decrease slightly over time, one of the main reasons being dust and insect carcasses on the blades which alters the aerodynamic profile and essentially reduces lift to drag ratio of the airfoil. Analysis of more than 3000 wind turbines older than ten years have shown that half of the turbines had decreased
by (1-2%) of power per year [17]. By incorporating the efficiency ($\eta$) into equation (3), the actual power output will be:

$$P = \frac{8}{27} \rho V^3 A \eta$$

(4)

The actual harvested energy might be less due: aerodynamic, mechanical, and electrical conversions. At each step, some energy is lost, and the final electric power is less than the total wind power by (70-80 %) [18]. Equation (4) is used to calculate: swept area ($A$), rotary diameter ($D$) and blade length ($L$). Recently, wind turbine blades have curved shape to generate maximum power from the wind, as shown in figure 4. Curved blade shape has many advantages, where the air moves over the curved top of the blade faster than it does under the flat side of the blade, which makes a lower pressure on top, thus higher aerodynamic lifting forces [19]. It is noticed that by slightly curving the turbine blades, they are able to capture (5-10%) more wind energy and operate efficiently in areas that have lower wind speeds. Modern rotor blades are twisted along their length by an angle of (10-15°) from root to tip to increase the angle of attack along the length, thus getting the best lift and easy rotating [20].

**Figure 4.** Typical shape of wind turbine blade.

Other dimensions of the blade, i.e. chord length and thickness (See figure 5), can be found based on: Betz limit and airfoil lift force. Blade cross-sectional shape varies into three categories according to both aerodynamic and stress analysis [21], as following:

- Root, where there is a transition between the circular base to the fusiform. This section carries the highest loads. Thick airfoil section is required to improve structural integrity.
- Mid span: it is aerodynamically significant area, where lift-drag ratio is higher. Therefore, using shorter airfoil section that tuning with structural considerations.
- Tip: it is aerodynamically critical area, where lift-drag ratio is maximized. Therefore, using slender airfoils and specially designed tip geometries to reduce noise and losses.

**Figure 5.** Shape variation along the wind turbine blade.
Since there are many procedures to calculate chord dimension, it is advised to initialize the design using a simple method based on a direct equation with tip speed ratios of \((6\text{-}8)\) [21-24]. The resultant values from this method can be improved by seeking a harmonic profile. However, in practice more advanced methods of optimization are often used. So, the chord length \((C)\) can be calculated from [21]:

\[
C = \frac{2\pi r}{n} \frac{8}{9C_L} \frac{U}{\lambda V} + C_0 \tag{5}
\]

Where:
- \(r\) is the radial position of a point on blade (m).
- \(n\) is the number of blades (3).
- \(V\) is the wind velocity (m/s).
- \(U\) is the design wind speed, i.e. minimum speed required to start full rotation (m/s).
- \(CL\) is the lift coefficient.
- \(C_0\) is the constant chord length at the root.
- \(\omega\) is the rotational speed in (rad/s).
- \(\lambda\) is the local tip speed ratio, which is given by:

\[
\lambda = \frac{\omega r}{V} \tag{6}
\]

Typical rotational speed of a wind turbine is between 5-20 rpm, while the generator machine may have a rotational speed between 750-3600 rpm due to gear action. Generally, wind turbine of med-high power has (8-16 rpm) rotational speed [25]. Experiments have shown that it is reasonable to achieve a lift coefficient \((CL)\) less or equal to 0.6 [26, 27].

Now, by substitution \((U = V)\) and simplifying equation (5), it yields;

\[
C = C_0 + \frac{\lambda^3 r}{\lambda} \tag{7}
\]

The ratio of airfoil thickness \((t)\) to chord length \((C)\) is variable along the blade length \((L)\) as following [28]:

\[
\begin{align*}
0.27 < t/C & \leq 0.33 & \text{root (} r \leq 1/3 \text{ L)} \\
0.21 < t/C & \leq 0.27 & \text{mid span (} 1/3 \text{ L} < r \leq 2/3 \text{ L)} \\
0.15 < t/C & \leq 0.21 & \text{tip (} 2/3 \text{ L} < r \leq \text{ L)}
\end{align*}
\]

2.4. Selection of material
The blades of wind turbine are commonly constructed from fiberglass composite (usually E-glass and epoxy resin). Typically, glass/epoxy composites used for wind blades contain more than 75% weight glass. This material has sufficient mechanical properties like: tensile strength, stiffness and hardness. This material has a density of 1800 kg/m\(^3\), tensile strength of 965 MPa and Young’s modulus of 39.3 MPa [29, 30].

2.5. Stress analysis
The mechanical design of wind turbine blade includes stress analysis related to aerodynamic features as well as the response of the body to the subjected forces and the material selected. In order to determine the loads, multiple airfoil sections should be tested. Therefore, the use of computer analysis software is recommended [21].

For turbine blades, the effective loads are [19]:

- Aerodynamic load: This load is generated by lift force which is depended on: wind velocity, blade velocity and angle of attack. The aerodynamic lift and drag are represented into useful thrust in the direction of rotation and reaction force.
Gravitational load: The gravitational force is defined as a mass multiplied by the gravity, where its direction is acting towards the earth which causes an alternating cyclic load. Generally, gravitational force is increased cubically with the increasing of rotary diameter.

Centrifugal load: It is a product of squared rotational velocity by the mass. It always acts radially outward.

For the present work, the stress analysis starts by finding the mass of the blade (m) from multiplying the volume of the blade by the density of the selected material. SolidWorks application is used to find the volume of the blade. Therefore, the gravitational load is:

\[ F_g = m \cdot g \]  \hspace{1cm} (9)

The centrifugal load is determined by:

\[ F_c = 0.5 \cdot m \cdot \omega^2 \cdot L \]  \hspace{1cm} (10)

Where (L) represents the effective length at the tested section.

For aerodynamic load calculation, the blade is considered as a simple cantilever beam with a uniform distributed load. The flapwise bending moment is a result of the aerodynamic force due to wind features which can be determined by calculating the thrust force. Bending moment can be calculated at any section along the blade using classical beam bending analysis [19], as in figure 6.

![Figure 6. Modeling of the blade as a beam with uniform distributed load [19].](image)

The momentum force (thrust force) is generated due to the velocity difference across the wind turbine and it can be determined by:

\[ F_a = \dot{m} \cdot (V_i - V_o) \]  \hspace{1cm} (11)

Where;

\( \dot{m} \) is the mass flow rate (kg.s)
\( V_i \) is wind speed at upstream (m/s)
\( V_o \) is wind speed at downstream (m/s)

The mean velocity measurements reveal that there is a velocity deficit about 2-3% close to the tip of the rotor in the upstream side. While in the near-wake side (downstream), the longitudinal velocity reductions become greater closer to the rotor plane (by 3-7%) and closer to the center of the rotor (by 10-20%) [31-34].
After calculating the affective loads, SolidWorks application is used to analysis the stresses applied to the blade, where: the aerodynamic load has modeled as a uniformly distributed load, the gravitational load has modeled as a transverse bending load and the centrifugal load has modeled as an outward axial load. Then, maximum stresses and failure regions on the blade could be obtained. Since the applied loads are not static, fatigue loading is assumed and endurance limit has been pointed. However, in blade design it is required to achieve efficient safety by implying suitable material with excessive strength [35].

3. Results and Discussions

The analytical approach, that used to design the blades, is based on both: mathematical relations and a simulating model by SolidWorks software. The design predicts diameter of rotary, length of blade, thickness, chord length. The study assumed a range of wind speed and power produced. Some specifications are based on empirical recommendations like: turbine efficiency and lift coefficient. The overall power-speed results, for the current design, show ranged values of output power between 600-850 kW, for estimated wind speed of 8-16 m/s at tower height, as shown in figure 7. The power generated decreases sharply below cut-in speed (where the low moment of wind affects the energy) and above cut-off speed (where the turbulence issue affects the energy). The overall power results indicated that rotary diameters ranged from 48-57 m, as shown in figure 8.

![Figure 7. Variation of output power with wind speed.](image1)

![Figure 8. Variation of output power with rotary diameter.](image2)
The whole parameters used in the design are shown in table 1. For 850 kW-turbine, the essential dimensions of each blade are shown in figure 9. Note that table 2 shows a detail of each suction in the blade. In general, the study has shown many reliable results, where it gives a range of specifications close to that approached in similar turbines, like Enercon 800 kW-wind turbine [36]. Failure stress analysis has occurred using a simulated model by SolidWorks application. Mesh generation of blade elements is shown in figure 10, and the applied loads are shown in figure 11. Shell mesh type (surfaces) was used with 754 elements, where the elements size was 544.169 mm. For the 850 kW-turbine, results based on steady wind conditions at (10 m/s) show that normal stresses during the operation are not exceeded 34 MPa, thus there is a safety factor of 6.4, while maximum stress is 218 MPa at the root of the blade. For high-speed conditions, failure is happened by a damage began in the region between mid-span and the tip of the blade, where some dislocations have occurred, as shown in figure 12. These results have matched many aspects stated by Thomas D. [30].

![Figure 9. Main dimensions of the blade for 850 kW-turbine.](image)

**Table 1. Specifications of the designed wind turbine.**

| It. | Specification                        |
|-----|--------------------------------------|
| 1   | Number of blades: 3                  |
| 2   | Tower height: 60 m                   |
| 3   | Wind speed: 8-16 m/s                 |
| 4   | Cut-off speed: 6 m/s (in), 18 m/s (out)|
| 5   | Output power: 600-850 kW             |
| 6   | Turbine efficiency: 70-80 %          |
| 7   | Swept area: 1800-2550 m²              |
| 8   | Diameter of rotary: 48-57 m          |
| 9   | Diameter of hub: 2-3 m                |
| 10  | Length of blade: 23-27 m             |
| 11  | Other dimensions of blade: See table 2.|
| 12  | Twist angle: 10-15°                  |
| 13  | Tip speed ratio: 6-8                 |
| 14  | Lift coefficient: 0.6                |
| 15  | Rotational speed: 6–20 rpm            |
| 16  | Direction of rotation from front: Clockwise |
| 17  | Material of blade: Fiberglass Density: 1800 kg/m³ |
| 18  | Tensile strength: 965 MPa Young’s modulus: 39.3 MPa |
| 19  | Weight of blade: 3.5-4.5 T            |
| 19  | Total weight of rotary (3 blades + hub): 12-15 T |
Table 2. Dimensions of each blade assigned for 850 kW-turbine.

| Distance far from the root, r (m) | Chord, C (m) | Thickness, t (m) |
|-----------------------------------|--------------|-----------------|
| 0                                 | 1.0          | 0.12            |
| 1.5                               | 1.0          | 0.12            |
| 3                                 | 1.4          | 0.10            |
| 6                                 | 2.2          | 0.08            |
| 9                                 | 3.0          | 0.06            |
| 12                                | 2.4          | 0.05            |
| 15                                | 1.8          | 0.04            |
| 18                                | 1.2          | 0.03            |
| 21                                | 0.8          | 0.02            |
| 24                                | 0.4          | 0.01            |
| 25.5                              | 0.2          | 0.01            |
| 27                                | 0.0          | 0.0             |

Figure 10. Mesh generation used in SolidWorks modeling for 850 kW-turbine.

Figure 11. Applied loads on the blade for 850 kW-turbine.
Figure 12. Failure stress analysis at high-speed conditions for 850 kW-turbine.

4. Conclusions
A suitable procedure is used to design wind turbine blades capable to work in actual conditions in Iraq. The approach used to design the blades depends on mathematical relations to determine wind aerodynamics and to find the dimensions of the blade. SolidWorks application is used to determine weight of the blade and the corresponding loads in order to check the reliability of the selected material to withstand the applied stresses. The study gives a range of valuable specifications required in the design of high power wind turbines workable between (600-850 kW) at actual wind speed rate. Where the diameter of rotary ranged from 48-57 m, length of blade ranged from 23-27 m and the thickness of the chord has not exceeded 0.12 m as maximum.

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