WIND TURBINE GENERATOR DESIGN

BY

OLAOMI

Institute of Technology
Electrical Engineering Dept
Ilorin, Kwara State

ABSTRACT

Wind is one of the existing energy renewables. Wind machines have potential for individual homes, isolated villages, farms, and connection to the national grid. Today wind power can be harnessed to provide some or all of the power for many useful tasks such as pumping of water and generating electricity. Different applications require different wind system geometries (including design materials, and implementation). Pumping of water needs much torgue produced by a rotor with high blade surface area operating at a low speed. Generation of electricity, however, needs just the opposite low torque with low blade surface area that spins very fast. This type of machine for generation of electricity is called wind dynamo or turbine. The designed capacity of the wind turbine under consideration is 100Kw or 125 KVA at a power factor of 0.8 at a wind speed of 36 km/hour. The span of the rotor is about 20m having 2 blades. The blades are to be made of aluminium alloy. The height of the machine will be determined by the topographical feature of the site of installation.

INTRODUCTION

Wind energy is ready to be utilized now in many practical applications. It has long being considered as a clean and renewable domestic source of energy and has been widely used for mechanical power and battery charging. In recent years, environmental concerns, rapid depletion, and escalating costs of fossil fuels have brought the need for alternative and renewable energy sources into the limelight.

Wind may be traced ultimately to the effect of the sun on the earth, including the lower portions of the atmosphere. The sun provides the heat required to warm the air above the earth, i.e. wind is acutally solar energy. When air is in motion, it is called wind. The motion is produced by differences of atmospheric pressure, which are mostly attributable to differences in temperature. Solar energy, in it broadest sense, includes almost every form of energy alternative. As this solar radiant energy from the sun arrives at the earth, about 43 percent is reflected back into space by the atmosphere, about 17 percent is absorbed in the lower portions of the atmosphere, and the remaining 40 percent reaches the surface of the earth where much of it is reradiated into space. Two percent of all the solar energy reaching the earth is converted to wind energy.

The radiation from the earth is in long wave, relative to the short wave radiation from the sun, since it emanates from earth which is cooler. Long wave radiation, being readily absorbed by the water vapour in the air is primarily responsible for the warmth of atmosphere near the earth's surface.

RESEARCH

A Betz of Institute of Gottigen, in his studies of windmill published in 1927 showed that the power absorbed from the wind by a wind turine is

$$M(V_1 - V_2)V$$

where

V_1 = wind speed at a distance upwind

V_2 = wind speed at a distance down the wind

V = wind speed actually passing through the rotor

M = Mass of air passing through the rotor.

He also showed that the maximum fraction of power that could be extracted by an ideal aeromotor was 16/27 or 0.593.

A Parker in his article of 1949 titled 'world energy resources and their utilization' declared that annual energy available in the winds over the earth's surface amounts to $13x10^{12}$ KVh although it is only possible to envisage the utilization of a fraction of the enormous total.

History of Wind Dynamic Construction

Before the turn of the century, Denmark was perhaps the first country to use an appreciable number of dynamos or wind turbines to produce electricity up to 100 KW per wind dynamo. In the Soviet Union, an experimental machine rated at 100 KW in a 38 -Km/h wind was built in Crimean Russia in 1931. Smaller machines were used in Soviet agricultural communities. Other countries of world also made appreciable efforts in exploiting wind power to generate electricity.

The largest and most impressive wind power harnessing was that of the Granpa's Knob wind dynamo sited near putland vermont. This was a result of enthusiastic promotion by Parmer C. Putnam and it was built by the S. Mergan Smith Company of York, Pennsylvania, which was a firm interested in developing a new product. It fed 1.25KW into the commercial power grid of the central Vermont Services Company. From the Company's first interest in 1939, it took two years to complete the engineering design, build the machine, and start feeding power into the commerical grid. Some parts were procured early, in the race with wartime scarcity, and when the design was completed, it was found that a part supporting the blades was not strong enough. It could not be replaced but it was decided, despite the risk of breakage, to complete the project. In 45 when the planned testing period was almost finished, the machine broke, throwing a blade, and the project was abandoned.

The most significant wind system with cogeneration capabilities was built by students and faculty at the Tvind school on the Jutland penisula, Denmark, in a wind speed of 53 Km/h, sparning a diameter of about 53.30m. The 2-MW wind turbine generator was made of fiberglass with 3 blades each weighing 5 tons. The two blades of the putnam WTG were made of stainless steel each, weighing about 8 tons. 1.500KW were used by the school and the remaining 500KW were converted to synchronized ac by the synchronous inverter after being rectified.

Wind Energy Resources

The wind can be a fickle servant. It may not be available when you need it and you can be overwhelmed by its abundance when you don't need it. To harness the wind you must become familiar with its moods and be able to select a site suitable for a wind machine - a site where strong, steady breezes blow most of the year. After choosing a favourable site, you need to know how much wind energy is actually available and when it blows hardest. Good wind system design begins with a realistic assessment of energy needs and available wind resources statistical data compiled for many years at airports and weather stations can give you a general grasp of average wind behaviour, but there is no substitute for setting out to the site and measuring the wind resource directly.

Types of Machines

There are four genetic types of wind machines which are (1) the savonious (2) Darrieus rotor (3) multibladed farm windmills, (4) high speed propeller-type. These are the types most often encountered in design discussions and in the field.

Each of these types has evolved to serve specific needs or conditions. Savonius rotors and farm windmills are slow-turning with high-starting torque - which suits them well to mechanical tasks such as lifting water. The Darrieus and propellor type rotors spin much faster and have little or no starting torque at all. Their higher rpm make them well-suited for driving electric generators.

Wind Machine Design

Wind machine design is a process of trial and retrial. The design process consists of two major tasks: aerodynamic design and structure design. Since the load is an electrical generator, low starting torque but high rpm will be required. Aerodynamic design means sorting out airflow, airfoil selection, blade twist, torque and performance coefficient. The sophistication required is determined by two things: size of wind machine, and tip speed ratio. Structural design is simply concerned with the ability of machine to withstand static loads and the forces on the structural member (blade, powershaft, tower) without bending or breaking from fatigue.

A wind machine that supplies power to the utility grid will be large and expensive. A very detailed understanding of this machine's response to gusts or its match with the load is very crucial to the final success of such a system.

WIND ENERGY CONVERSION

Wind To Electricity

The machine used for converting wind energy to electricity is called a wind energy coversion system (WECS) or wind turbine generator (WTG). This machine must efficiently capture the wind energy and convert it to usable electrical energy. The capture function is usually accomplished by means of rotating blades attached either to a hub (horizontal axis wind turbines, HAWT or torque type (straight or curved blades vertical axis wind turbine, VAWT, or egg-beater type). The amount of wind useful to WECS is limited to the swept area of rotor which the wind passes through. The kinetic energy captured is proportional to the circular area of the rotor.

After the rotor has captured the kinetic wind energy and turned it into rotating mechanical power, a drive train speeds up the rotation and transmits the torque to the generator to convert the mechanical energy to eletrical energy. The drive train usually includes a gear box or speed increaser, rigid and flexible couplings, diagnostic sensors, emergency brakes, and other features for environmental protection and safety. The generator is usually either synchronous or induction for ac electricity or a dc generator for indirect ac electricity. Everything is interrelated by sophisticated controls which also integrate the WECS hardware with the wind (usually by means of anenometer) and the user load of utility grid. If the WECS generates dc, an inverter has to bring it to ac.

The Power in the Wind and how to find it

The power in the wind is computed using the concept of kinetics. The kinetic energy of any moving particle is equal to one half of its mass times the square of its speed or $\frac{1}{2}$ MV^2. The volume of air passing in unit time through an area A, with speed V, is AV, and its mass M is equal to its volume times its density, or M = AV. Therefore kinetic energy = $\frac{1}{2}PAV^3$ per unit time.

where

ρ = density

A = area swept by the turbine blades

$$\frac{\pi}{4} D^2$$

V = wind speed in km per hour

Power in kilowatts =

$$\frac{1}{2} \rho KAV^3$$

where

K = a constant

and the power density of the wind ($P_d = P/A$) is given by $P_d = \frac{1}{2}PV^3$

Wind System Performance

An estimate of mean power output, P_m, may be computed using the equation.

$$P_m = \int P(V)f(V)dv \qquad (1)$$

where

P(V) is the power output at the blade centre with wind speed V

f(V) is the wind speed probability description function corresponding to blade centre elevation.

The wind turbine will begin to produce power at the cut-in wind speed V_3. The power increases monotonically from zero at V_o to the maximum or rated power (P_o) at the rated wind power speed (V_o). Above the rated wind speed, the power remains constant until the machine's cut-out wind speed, V_c, is reached. The machine's blades are feathered or designed to stall at wind speeds above the cut-out value to prevent damage to the machine. Therefore, the integral becomes

$$P_m = \int_{V_o}^{V_o} P(V)f(V)dv \qquad (2)$$

Performance Co-efficient

The rotor or aerodynamic, power coefficient C_{oe} is the fraction of the power contained in a stream of wind flowing

perpendicular to the rotor disk which is transformed to power at the rotor shaft. The rotor power coefficient depends upon the tip speed ratio, TSR, and blade pitch angle, B. The tip speed ratio is

$$TSR = RW/V \quad (3)$$

where

R is the rotor radius
W is the rotor angular speed
V is the wind speed

The plade pitch angle is defined as the angle between the chord of the blade (at the 0.75R station if the blade has pitch and plane of the cone of rotation of the rator. The rotor power coefficient is defined by the equations

$$C_{rp}\ (\beta,\lambda) = P_r(V)/P_w(V) \quad (4)$$

and

$$P_w(V) = \frac{1}{2}\rho AV^3 \quad (5)$$

where

$P_r(V)$ is the power at the rotor shaft

for the wind speed V

P_w is the power of the wind which flows

at normal to the swept area.

For the case of a variable rpm machine which adjusts ß and TSR to maintain C_p constant at the maximum value (Cpmax) the power swept out may be expressed as

$$P_r(V) = C_{pm} P_w(V) \quad (6)$$

The system power coefficient (C_p) is the fraction of the power contained in the wind which is transfered to electrical power, P(V)

$$C_p(V) = P(V)/P_w(V) \quad (7)$$

Equations 5,6 and 7 may be used to express equation 2 as

$$P_m = \frac{1}{2}\rho A\int_{V_o}^{V_c} C_p(V)V^3 f(V)dV \quad (8)$$

Capacity Factor

Capacity or plant factor C_f is defined as the ratio of the mean power, Pm, to the rated power. The rated power may be expressed in terms of the system performance coefficient (C_{mp}) and the rated wind speed

$$P_r = C_{mp}(\tfrac{1}{2})\rho AV_r \quad (9)$$

The capacity factor may be obtained by dividing equation 8 by equation 9

$$C_f = \frac{P_m}{P_r} = \int_{V_o}^{V_c} \frac{C_p(V)}{C_{pr}} \frac{(V)^3}{V_o^3} f(V)dV$$

The amount of electrical energy produced during a period of duration to, may be calculated using the equation

$$E_{to} = t_o P_m = tOC_f P_r \quad (11)$$

then

$$C_f = E_{to}/t_o P_r$$

The capacity factor therefore provides a measure of energy efficiency of a machine in terms of its rated power. The annual specific output equals the equivalent number of hours per year during which the machine operates at its rated output. The annual capacity factor therefore equals the annual specific output divided by 8760, the number of hours in a year. Today, annual energy outputs (E_A) or capacity factors are usually employed to describe the performance of wind turbine generators.

The density of air, ρ, varies with altitude and with atmospheric conditions. During the year the air density may vary due to pressure and temperature changes by 10-15 per cent. A Betz of Institute of Gottingen showed that the maximum factor of wind power that could be extracted by an ideal aerogenerator was 16/27 or 0.593. If this fraction is applied, the formula for maximum power theoretically obtainable is $0.593KAV^3$ where K = ½. The table below shows the variation of power obtainable from the wind with the variation in wind speed and rotor size.

Wind Speed (KM/h)	Power in Kilowatts from Circular Areas				
	Diameter 3.8m	Diameter 7.6m	Diameter 15.24m	Diameter 30.48m	Diameter 60.96
16.10	0.38	1.50	6.00	24.00	97.00
32.20	3.08	12.30	49.00	196.00	784.00
48.30	10.40	41.60	166.40	606.00	2664.00
64.40	24.60	98.40	393.60	1574.00	6296.00
80.50	48.20	192.80	771.20	3085.00	12,340.00
96.60	83.20	332.80	1331.20	5325.00	21,300.00

Table 1: **Wind Power Table**

Because of aerodynamic imperfections in any practical machine and of mechanical and electrical losses, the power extracted is less than that calculated in practice, the multiplying factor may not be greater than about 0.4 (instead of 0.593) and may be less.

Design of Wind Turbine Generator Procedure: Power

Formula Derivation

The wind turbine generator (WTG) envisaged here is to have a generating capcity of 125 KVA or 100 KW at a power factor of 0.8. The retardition of the wind passing through a rotor blade occurs in two stages: one before and one after its passage through the rotor. Thus

V_1 = wind speed at a considerable distance upwind

V = wind speed actually passing through a rotor

V_2 = wind speed at considerable distance downwind from the rotor.

If M is the mass of the air passing through the rotor in a unit time, the rate of change of momentum is $M(V_1 - V_2)$ which is equal to the resulting thrust. The power absorbed is, therefore, $M(V_1 - V_2)V$.

And again the rate of change of kinetic energy in the wind is

$\frac{1}{2}M(V_1^2 - V_2^2)$

These two expressions are obviously equal so that

$$M(V_1 - V_2) = \frac{1}{2}M(V_1^2 - V_2^2)$$

from which

$$V = \frac{V_1 + V_2}{2}$$

Thus the retardation of the wind V_1-V before the rotor is equal to the retardation $V - V_2$ behind it. The power extracted from the wind by the rotor is

$$P = \rho AV(V_1 - V_2)V$$

$$= \rho AV^2(V_1 - V_2)$$

where

ρ = air density

A = area swept by the rotor blades

ρAV = M i.e mass of air passing through the blades per unit time.

$$P = \rho A \frac{(V_1+V_2)^2}{2}(V_1 - V_2)$$

$$\frac{1}{2}\rho AV_1^3[(1+\alpha)(1-\alpha^2)]$$

By differentiating P with respect to we have

$$\frac{d_p}{d_\alpha} = \frac{d}{d_\alpha}\left[\frac{\rho AV_1^3}{4}(1+\alpha-\alpha^2-\alpha^3)\right]$$

$$= 0$$

If the negative value is discarded because it is extraneous.

$$i.e\ \frac{d_p}{d_a} = 1-2a-3a^2=0$$

$$where\ a = \frac{1}{3}\ or\ -1$$

Then

$$\frac{V_2}{V_1} = a = \frac{1}{3}$$

Thus P is maximum when = 1/3, i.e. when the final velocity V_2 is one-third of the upwind velocity V_1, therefore the maximum power which can be extracted from the wind is

$$AV_1^3,\ 8/27$$

as compared with

$$AV_1^{3/2}$$

in the wind originally

i.e. an ideal wind rotor could extract

$$\frac{AV_1^3, \frac{8}{27}}{AV_1^{\frac{3}{2}}} = \frac{16}{27}$$

or 59.3 percent of the power in the wind.

That this power is maximum is demonstrated by the second derivative of P i.e

$$\frac{d^2P}{da^2} = \frac{d^2}{da^2}(1-2a-3a^2)$$

$$= -2-6a$$

and substituting for a = 1/3

$$\frac{d^2P}{da^2} = 2-6a = -4$$

which shows that the power P is maximum

when V_2/V_1 = 1/3

According to A Betz of Gottingen, the power from the rotor is

$$P = 0.593\ KAV^3$$

where 0.593 is the power coefficient

If P is in kilowatts, then A is in square metres

V is in Kilometres per hour. K is a constant and has a numerical value of 137×10^7. The area swept by the rotor wings is

$$A = \frac{\pi}{4} D^2$$

where D is the diameter of the rotor in m

Because of losses in the mechanical bearings and the alternator, the power coefficient in practice is about 51%.

Therefore $P = 0.51\ [137 \times 10^7, \pi/4D^2V^3]$

The VTG under consideration here is a 2 - blade propellor, horizontal axis type whose power output is about 100 kilowatts (KW) i.e. P = 100KW. If the rated wind speed of the machine is 36 Km/hr with an annual mean wind speed of 33 Km/hr at the site of construction. Hence

$$100 = 0.51\ (137 \times 10^7, x/4\ D^2, 36^3$$

i.e. D = 19.8m and R = 9.9m

Rayleigh Distribution

The Rayleigh distribution gives an approximate estimate of number of hours this rated wing speed will be available at a particular site. Rayleigh distribution takes the follwoing form.

$$Hours = 8760, \frac{x}{2}\frac{V}{v}\ e^{-k}$$

where V = rated windspeed

V = annual mean windspeed

$$K = \frac{x}{4}\frac{V^2}{\overline{V^2}}\ or\ K = \frac{V^2}{V^2}\frac{\pi}{4}$$

For the problem at hand, rated wind-speed = 36Km/hr = V, annual mean windspeed 33Km/hr = V and hence the total number of hours the wind is expected to blow, at the rated windspeed V is 179 hours.

Matching the Generator to the Rotor

The tip ratio (TSR) is the speed of the rotor tip (as it races) around its circular path) divided by the windspeed i.e.

$$TSR = \frac{\text{Blade tip speed}}{\text{windspeed}}$$

$$TSR = \frac{2\pi RN}{V}$$

where

N = revolutions of rotor per second

R = radius at which TSR is being calculated

For high speed electric generating WTG, the best number of blades for the rotor is two and TSR of about 11.5, V = 10 m/s. From equation

$$\pi = \frac{TSR.V}{2\pi R} = \frac{1.5x10.0}{2\pi \times 9.8} \text{ rps}$$

$$\frac{11.5 \times 10.0 \times 60}{2\pi \times 9.8} = 112 \text{ rpm}$$

For direct coupling of the rotor to a synchronous or induction generator, an electrical machine of 54 poles will be required. The type of machine is usually costly and too bulky to be hoisted to a height. An alternative is to employ a machine of 4 poles 1500 rpm. A gearbox with a transmission ratio of 13:4:1 will be needed. This two will be big in size and expensive. A machine of 10 poles, 600 rpm will fit a gearbox of ratio 5.4:1.

Generator Selection

In medium and large size WTG system for ac supply, there are three main alternatives

(a) an induction generator

(b) synchronous alternator

(c) a dc generator used with a converter

A fourth possibility is an ac commutator generator which can give a constant frequency output while running at a variable speed.

There is not much difference between the costs of the induction and the synchronous machines. The induction machine may be preferred to the synchronous generator mainly because of its greater stability, robustness and the ease with which it can be made automatic in operation as the generating plant will need to be when it is in one of many wind power stations located in remote districts. An induction generator will rather give less energy from a given wind regime and has also the disadvantage of requiring power factor correction for the magnetizing current which it takes from the network.

The synchronous generator has a very substantial data base for network operation large and small. The main advantage is versatile control of power factor by variation of exitation current and automatic voltage regulation is simple. On the other hand there are justifiable doubts about the electrical stability of a synchronous generator when subjected to a rapidly - varying driving torque which will occur in a qutsy wind. The output of the machine selected should be 3 phase, 125KVA, 240V, and 415V phase and line voltages respectively. The stator windings should be star connected with the neutral wire earthed. The power factor will be expected to be adjusted to 0.8.

Blade Size

The ratio of the blade area to the frontal area of the rotor or the swept area of the rotor is a term referred to as solidity. The graph below shows rotor solidity as a function of tip speed ratio (TSR). This graph may be used to estimate the blade size.

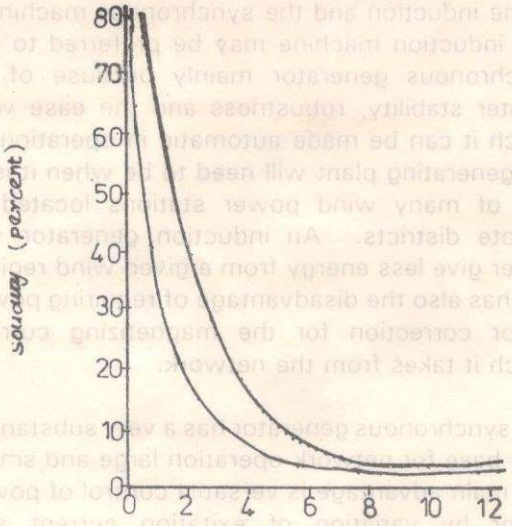


Figure 1: Rotor Solidity as a Function of TSR

Blade Number Versus Tip Speed Ratio

TSR	Number of Blades
1	6-20
2	4-12
3	3-8
4	3-5
5-8	2-4
5-15	1-2

Table 2: Blade Number Vs TSR

From the graph it can be seen that the solidity at TSR = 11.5 is about 2.5 percent or 0.025 of the frontal area. For the system under consideration, the frontal area = $\frac{1}{2}\pi D^2 = \frac{1}{4}\pi \times 19.8^2 = 307.91\ N^2$. Area of the two blades = 0.025 x 307.91 = 7.70m^2. The blade is designed to taper from "a" m to "ka" from the hub to the tip as shown in Fig. 2 so that the blade is trapezoidal and hence $\frac{1}{2}(a + \frac{1}{2}a)\ 9.9 = 3.85$ i.e. a = 0.52m and ka = 0.26m.

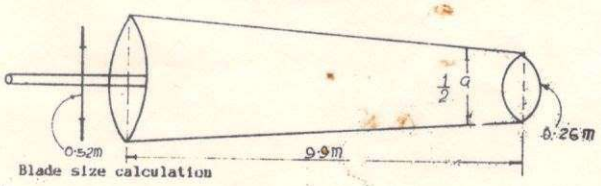


Figure 2: Blade Size Circulation

Blade Material

The material used for the blades must be strong and yet light and must not be subjected to serious deterioration or corrosion in bade climatic conditions. Wood is used for the solid blades of small rotor. For this medium type of machine of 100KW, galvanised aluminium alloy will be suitable. The thickness of the sheet is 1/16 inch or 1587.5 x 10^{-6}m. The volume of each blade is 3.85 x 1587 x 10^{-6} = 6111.875 x 10^{-6}m^3. The density of aluminium = 2643 Kg/m^3. Hence the mass of a single blade = 2643 x 6111.875 x 10^{-6} = 16.15 kg. The mass of the two blades will be 32.30kg.

Powershaft Torque

Powershaft torque can be used to calculate blade bending in its thrust direction. Torque is not really a force but more precisely the result of a force applied at a certain radius from the centre of rotation. The powershaft torque in Newton-metres on the wind machine can be calculated from the formula

$$Torque = 1.78509\ \frac{DP}{V(TSR)} = \frac{P}{w}$$

where

D = rotor diameter in metres

P = the power in watts generated by the rotor

V = the rated windspeed in Km/hr

V = the angular velocity in rad/s

Therefore the torque on the two blades will be

$$Torque\ (T) = 1.78509\ \frac{19.8 \times 10^5}{36 \times 11.5}$$

$$= 8537.387\ Km$$

The following equations are also true for all powershaft designs

$$\frac{T}{J} = \frac{\gamma}{R} = \frac{2\gamma}{d} = \frac{G\theta}{L}$$

where

J = polar 2nd moment of area (m^4)
T = torque
L = 20d (shaft length)

Θ = 1° or 0.0195 radian
d = shaft diameter in metres
G = modulus of rigidity (80×10^9 II/m^2)
Y = shear stress in II/m^2 and
r = shaft radius in metres

$$Hence \ \frac{2}{d} = \frac{80 \times 10^9 \times 0.0175}{20d}$$

$$i.e. \ \gamma = \frac{80 \times 10^9 \times 0.0175}{40}$$

$$= 34.9 \times 10^6 \ \pi/m^2$$

$$= 34.9\pi/mm^2$$

This is the permissible shear stress for mild steel under the conditions stipulated thus: the above calculation is based on the rule of shaft design which states that the angle of twist shall not exceed 1 degree on a length of 20 times the diameter of the shaft.

From the above equations

$$\frac{I}{J} = \frac{2}{d}$$

$$Let \ J = \frac{\chi}{32} d^4 \ (for \ solid \ shaft)$$

$$i.e. \ \frac{32T}{\pi d^4} = \frac{2}{d}$$

$$i.e. \ d^3 = \frac{16T}{\pi\gamma} = \frac{16 \times 8537{,}387}{\pi \times 34.9 \times 10^6}$$

i.e d = 107.6mm

Thus the powershaft diameter will be about 107.6mm

The length of the powershaft - 20d = 107.6 x 20 = 2.152m

Centrifugal Force

The centrifugal force pulling a blade away from the rotor hub is given by the formula:

$$Centrifugal \ force = \frac{116554.4 \times 10^{-6} \ \pi(SR,V)^2}{RC}$$

where

M = mass of the blade in Kg

SR = speed ratio at the blade centre of gravity

V = wind-speed in Km/h

RC = distance in metres from centre of rotation to the blade centre of gravity.

To calculate RC, the centroid of the blade should be worked out as shown below.

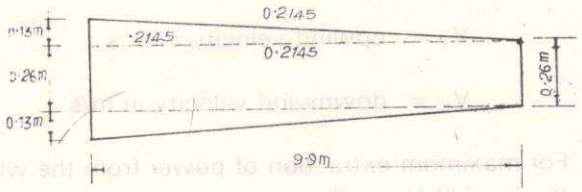


Figure 3: Determination of the Blade Centroid

Taking moments about the base

0.6435 x 3.3 x 2 + 0.26 x 9.9 x 99 x 0.5 = 0.5 (0.26 + 0.52) 9.9

i.e. = 16.9884/3.861 = 4.4m

If the spar length from the hub to the pitch is 0.1m, then

RC = 4.4 + 0.1 = 4.5m

The speed ratio (RS) at RC = 4.5 is given by

$$SR = 4.5 \times \frac{11.5}{10} = 5.175$$

Hence the centrifugal force when V = 36Km/h and M = 16.15kg is given by

$$\text{Centrifugal force} = \frac{11655.44 \times 10^{-6} \times 16.15\ (5.175 \times 30)}{4.5}$$

$$= 14518\pi = 14.518\ K\pi$$

This centrifugal force gives the information needed to select the blade attachment bolts.

Cut - in Velocity

Thrust of the wind on the blade and moving parts to set them on the motion is given by The Bernoli equation:

$$F = A \triangle P = \frac{1}{2}\rho A(V_1^2 - V_2^2)$$

where

F = thrust in newtons

A = area of the blade disc in m^2

P = density of air in kg/m^3 (1.23 kg/m^3)

V_1 = upwind velocity in m/s

V_2 = downwind velocity in m/s

For maximum extraction of power from the wind $V_2 = 1/3\ V_1$ so that

$$F = \frac{1}{2}\rho A(V_1^2 - V_1^{\frac{2}{9}}) = \frac{4}{9}\rho A V_1^2 \pi$$

The mass of the two blades has been found to be 32.30kg. The mass of the power-shaft and the two blade spars must be considered in order to calculate the effective mass of the moving parts. The volume of the powershaft = $0.1076^2 \times /4 \times 2.15$. The density of steel = 7849 kg/m^3. The mass of the powershaft = $0.1076^2\ \pi/4 \times 0.25 \times 2.15 + \pi \times 7849.8$ = 153.4 kg.

The blade spars, like the powershaft, are made of mild steel whose diameter is 50% of the powershaft diameter i.e. 50% of 107.6mm = 53.75mm and its length, 100mm. Hence the mass of the blade spar = $0.05775^2 \times 0.25 \times \pi \times o.1 \times 7849.8$ = 1.78. The mass of the 2 spars will be = 3.56 kg.

The normal friction coefficient between lubricated metal bearings and the gears that will be employed is 0.1 so that the total effective mass to be overone by the wind thrust is 153.4 + 3.56 + 32.30 + 189.26 x 0.1 = 208.186 kg.

To set the turbine, in motion, an imertia of 208.189 + 9.81 Newtons must be over-come and hence the thrust must be equal to the inertial force

$$\text{i.e. } \frac{4}{9}\rho AV^2 = 208.186 \propto 9.81$$

$$V^2 = \frac{208.186 \propto 9.81 \propto 9}{4x1.23x19.8^2 x0.25\pi} = 12.133$$

i.e. V = 3.48 m/s = 9.67 km/h

That is the cut-in speed is 9.67 km/h and the machine will start to produce electricity at this speed.

Furling Windspeed

The furling or cut-out or shut-down windspeed is the speed at which the turbine must be shut down to prevent damage to the machine. Empirically this speed occurs when the centrifugal force on the machine is about 4 times the centrifugal force at the rated wind-speed i.e. when the rated windspeed is doubled or when the TSR is doubled. The cut-out speed in this ease is 72 km/hr or 20 m/s.

Rotor Shape Design

The rotor is divided into several sections from A to 1. The speed ratio of the blade at each section is calculated by multiplying the design TSR by the fraction of the total distance from the hub to the section. Thus the speed ratio at point A, $SR_A = 11.5 \times 10/10 = 11.5$; $SR_s = 11.5 \times 0.9 = 10.35$ etc. The result is as shown below in Table 3.

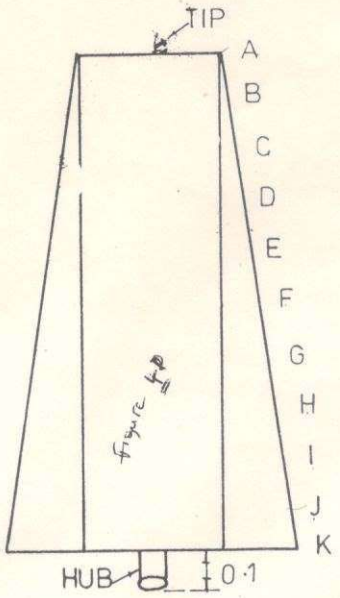


Figure 4: Calculation of Speed Ratios

Table 3: Speed Ratio at the indicated section in Fig. 4.

Section	Speed Ratio	Section	Speed Ratio
SR_A	11.50	SR_G	4.60
SR_B	10.35	SR_H	3.45
SR_C	9.20	SR_I	2.30
SR_D	8.05	SR_J	1.15
SR_E	6.90	SR_K	0.575
SR_F	5.75		

The wind angle Θ corresponding to each speed ratio is read from the graph in Fig. 5 and the result is tabulated in Table 5.

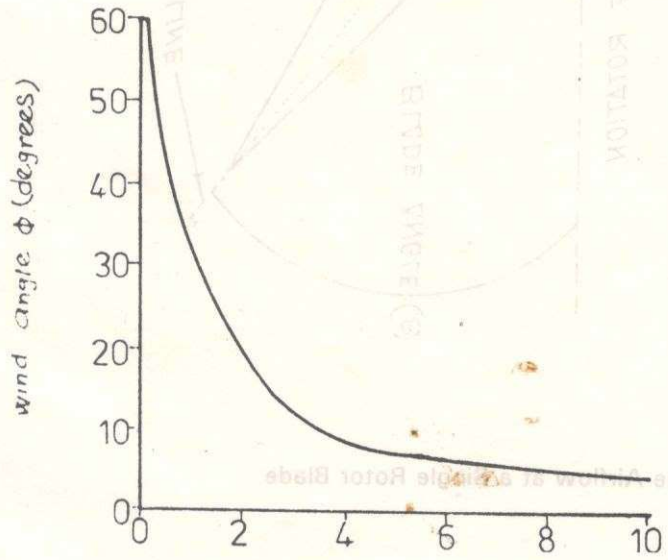


Figure 5: Wind Angle Vs. Speed Ratio

Table 4: Wind angle for each speed ratio

Speed ratio SR	Wind angle 0 (degrees	Speed ratio SR	Wind angle 0 (degrees)
50	2.50	2.30	16.00
..35	3.50	1.15	26.10
9.20	4.10	0.575	35.00
8.05	4.90		
6.90	5.10		
5.75	6.50		
4.60	8.50		
3.45	10.50		

Figure 6 shows the shape parameter versus the speed ratio. From this graph the value of shape parameter SP, for each station is read off and tabulated in Table 5.

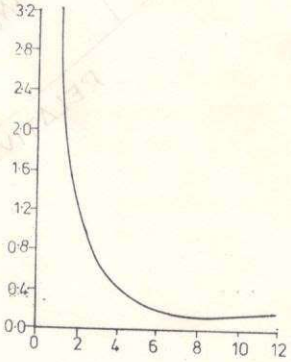


Figure 6: Shape Parameter Vs. SR

Table 5: Shape parameter at each speed ratio

SP_A	=	0.12	SR_G	=	0.21
SP_B	=	0.13	SR_H	=	0.45
SP_C	=	0.16	SR_I	=	1.0
SP_D	=	0.17			
SP_E	=	0.18	SR_J	=	1.60
SP_F	=	0.19			

The Lift and Drag Forces

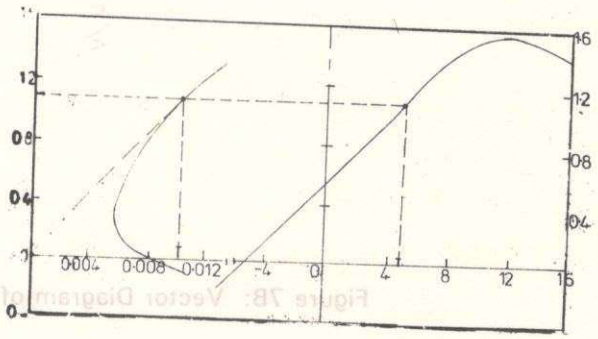


Figure 7A: Lift and Drag Coefficient Plots

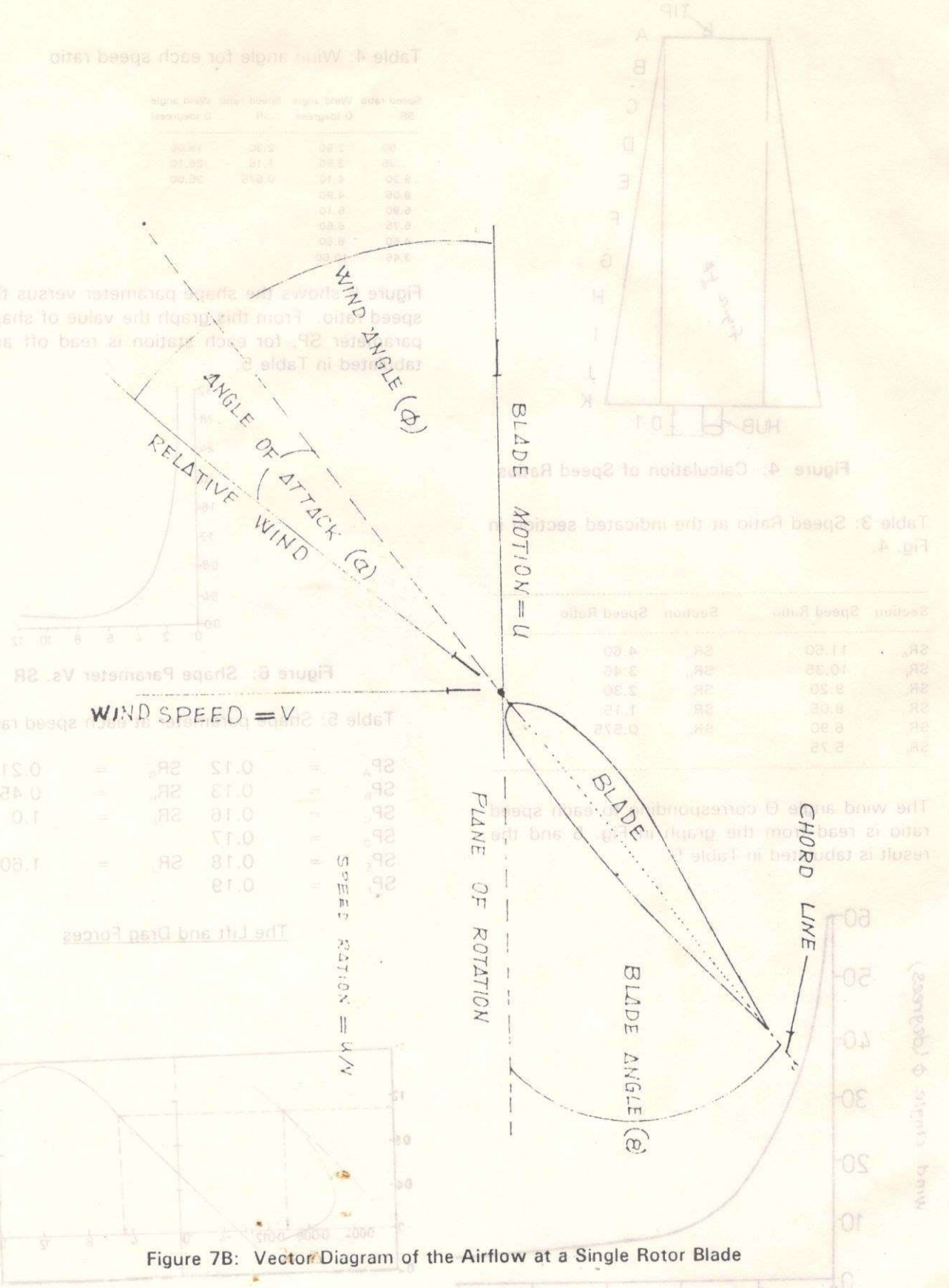


Figure 7B: Vector Diagram of the Airflow at a Single Rotor Blade

Lift is the force produced on the blade in a direction perpendicular to the relative wind speed approaching the blade i.e. $V_r = ((2\pi RN)^2 + (V)^2)^{\frac{1}{2}}$. The lift force tugs the blade along its rotary path. The aerodynamic lift force can be calculated from the formula:

$$\text{Lift force} = \frac{1}{2}\rho V_o^2 \, A \, oC_L$$

where

P = the air density in kg/m^3

V_a = the speed of relative wind

A_b = the surface area of the blade

C_L = the lift coefficient of the blade

The drag force on the other hand occurs in a direction parallel to the relative wind. It acts to retard the forward motion of the blade. Its value is calculated by replacing the lift coefficient in the above equation by the blade drag coefficient C_o. The ratio of the lift to drag force should lie between 50 and 100. The curves in figure 7A show the drag coefficient C_o varies with the lift coefficient C_l. If L/D is 100 then, the chord length is calculated using the formula and the chord lengths are as shown in Table 7.

$$C = \frac{R \times SP}{C_L \times \pi}$$

where

R = radius of each station
C_L = lift coefficient
SP = shape parameter
N = number of blades

Table 6: The chord lengths

C_A	=	0.545	C_F	=	0.682
C_D	=	0.573	C_G	=	0.691
C_C	=	0.582	C_H	=	0.709
C_O	=	0.601	C_I	=	0.277
C_E	=	0.668	C_J	=	0.772

The average chord length is given by

(0.545 + 0.582 + 0.573 + 0.601 + 0.668 + 0.682 + 0.691 + 0.709 + 0.727 + 0.772)/10 = 0.655m

The blade span or total radius plus the hub length is 10m, and so the aspect ratio is AR = 10.00/0.655 = 15.27.

The angle of attack can be empiricaly corrected for optimum L/D. The correction is started with angle of attack a_o where the lift curve crosses with x-axis. Then the corrected angle is given by the formula

$$a_c = a_o + \frac{C_L}{0.11}\left(1 + \frac{3}{AR}\right)$$

where

C_L = the lift coefficient at optimum L/D

AR = blade aspect ratio.

From above $C_L = 1.01$, AR = 15.27 and from the graph in figure 7A $a_o = -5_o$ approximately.

Thus

$$a_c = -5 + \frac{1.10}{0.11}\left(1 + \frac{3}{15.27}\right)$$

$$= 7°$$

With this corrected angle of attack, ac, the blade angle Θ is calculated from $\Theta = \Theta - a_c$

where the wind angle Θ is taken from table 4 and a_c = 7° and so

O_A	=	2.5-7	=	-4.5°
O_E	=	3.5-7	=	-3.5°
O_C	=	4.1-7	=	-2.9°
O_J	=	26.1-7	=	19.1°
O_K	=	35.0-7	=	28°

The pitch or the inclination can now be constructed to follow the angles above as is shown in Figure 7B. In practice most machines in the medium size range (up to 20m diameter) use fixed pitch blades for simplicity, reliability, and cheapness. Variable speed opertion when network coupled can be achieved with a variable ratio transmission, special generator type or rectifier/synchronous inverter type.

Figure 8: The assembly of the components of a typical propellor - type wind generator

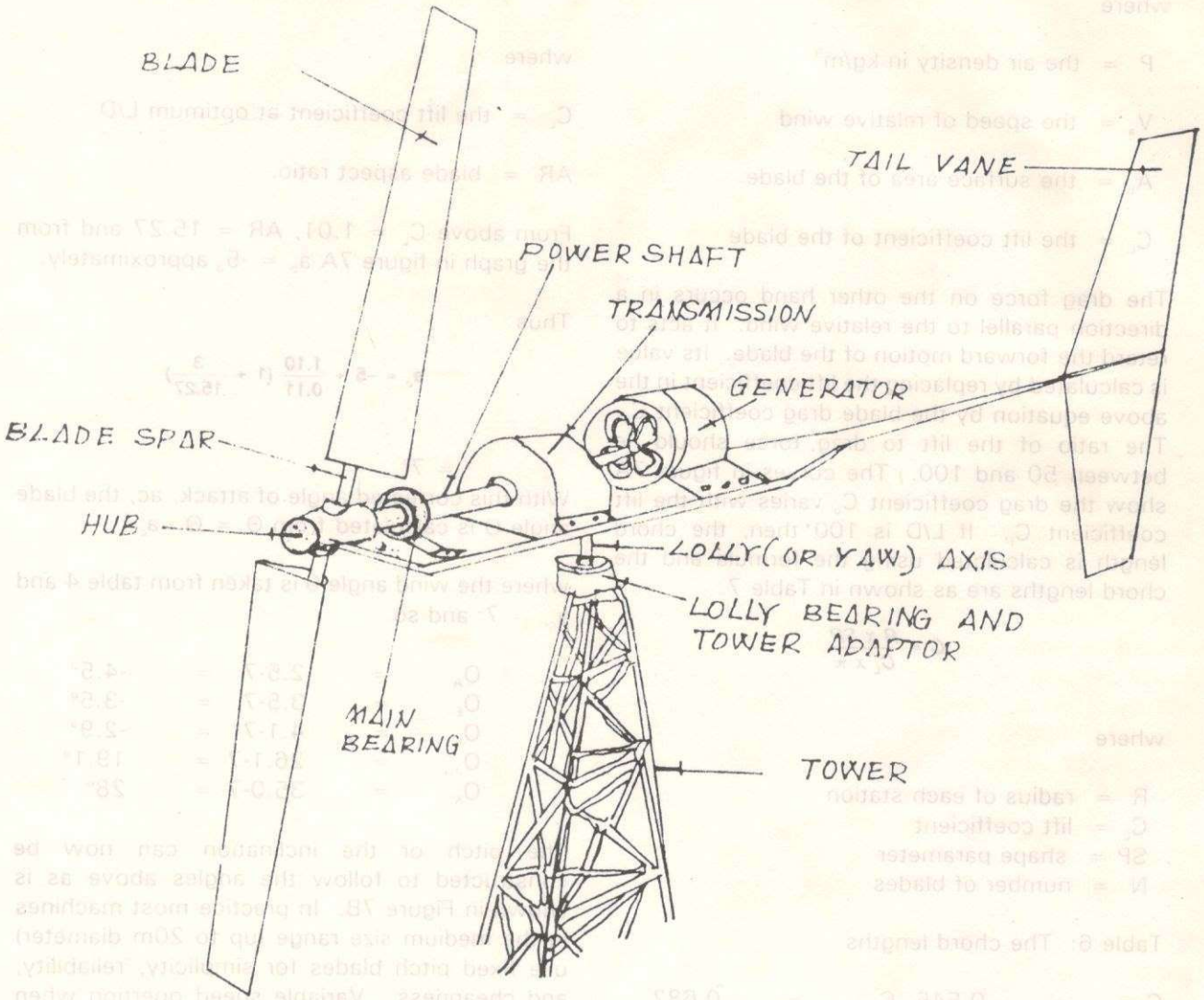


Figure 8: The feature of a wind Turbine Generator

CONCLUSION

Availability of a consistent and strong wind regime dictates the selection of site for the installation of viable wind energy conversion system. Various sites should be evaluated by monitoring the wind speed for a reasonable period of time to ascertain the presence and the behaviour of the wind. It is after ascertaining the suitability of the site that installation work can start. Paul N. Vosburgh enumerates the following commercial capplication capabilities for a wind energy conversation system:

It must:

1. produce quality electricity in reasonable quantities;
2. operate in a safe and reliable manner
3. operate without causing the utility system interference problems were applicable;
4. survive for 20-30 years without excessive operating and maintenance costs;
5. be installable at a total cost low enough to be widely affordable.

It is recommended that the Federal Government should be encouraged to finance the feasibility study of wind regime in Nigeria as a renewable energy resource. No individual can carry out the feasibility study without financial aid. It is good that the government should help in developing the technology of wind turbines especially for generation of electricity and pumping of water for irrigation in the rural areas. Moreover, wind machines can be exported to Asian nations.

It is after the feasibility study has been successfully carried out that the following can be estimated.

1. Construction cost per KW
2. Energy output per KWh
3. Specific output in KWh per annum per kilowatt

5.6 Technical Information

Power Rating: 100 KW at 36 km/h

Expected Annual Energy output: 17,900 KWh (tentative)

Generator:

Type: Brushless alternator

Speed: 0-600 rpm

Frequency: 50-Hz

Voltage: 415 volts AC

Rotor Blades:

Number of Blades: 2

Blade Length 9.9m

Rotor Diameter 20m

Blade Material: Aluminium Alloy

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