Wind Turbine Blade Efficiency and Power Calculation with Electrical Analogy

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Abstract- Wind turbines work by converting the kinetic energy in the wind first into rotational kinetic energy in the turbine and then electrical energy that can be supplied. The energy available for conversion mainly depends on the wind speed and the swept area of the turbine. A 1kW @ 11m/s, 1 meter diameter wind turbine designed with the support of software. The wind turbine blades power and efficiency has been measured at different tip-speed-ratios as well as calculated using software tool. The wind turbine blades power and efficiency has been measured at different tip-speed-ratios and a maximum efficiency of 30% at a TSR of 11.6 was recorded, verifying the blade calculator's accuracy. This paper is an insight into the design aspects of a wind turbine, like turbine blade design, wind power and output power calculation.

Index Terms- wind turbine, betz limit, tip speed ratio (TSR), blade efficiency

I. INTRODUCTION

Power production from a wind turbine is a function of wind speed. The relationship between wind speed and power is defined by a power curve, which is unique to each turbine model and, in some cases, unique to site-specific settings. In general, most wind turbines begin to produce power at wind speeds of about 4 m/s (9 mph), achieve rated power at approximately 13 m/s (29 mph), and stop power production at 25 m/s (56 mph). Variability in the wind resource results in the turbine operating at continually changing power levels. At good wind energy sites, this variability results in the turbine operating at approximately 35% of its total possible capacity when averaged over a year.

The amount of electricity produced from a wind turbine depends on three factors:

1) Wind speed : The power available from the wind is a function of the cube of the wind speed. Therefore if the wind blows at twice the speed, its energy content will increase eight-fold. Turbines at a site where the wind speed averages 8 m/s produce around 75-100% more electricity than those where the average wind speed is 6 m/s.

2) Wind turbine availability : This is the capability to operate when the wind is blowing, i.e. when the wind turbine is not undergoing maintenance. This is typically 98% or above for modern European machines.

3) The way wind turbines are arranged : Wind farms are laid out so that one turbine does not take the wind away from another. However other factors such as environmental considerations, visibility and grid connection requirements often take precedence over the optimum wind capture layout.

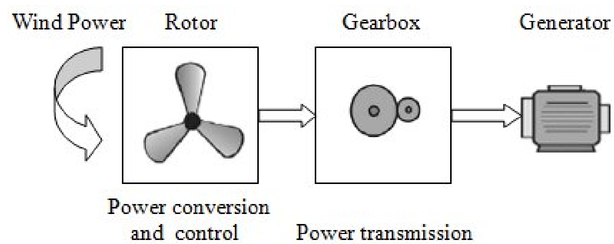


Figure 1: Mechanical components of wind turbine.

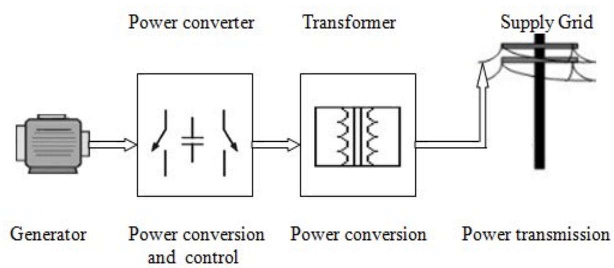


Figure 2 : Electrical components of wind turbine.

Usually, WTBs are designed to operate for a period of 20 years. But, no final statement can be made yet concerning the actual life expectancy of modern WTBs as, until now, no operational experience of such period is available.

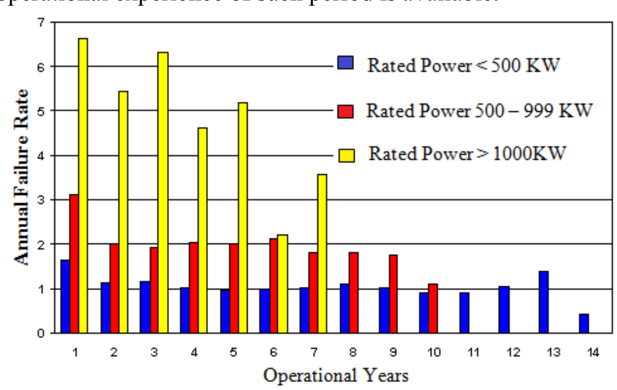


Figure 3 : Frequency of 'failure rate' with increasing operational age

Changes in reliability with increasing operational age can, however, provide indications of the expected lifetime and the amount of upkeep required. Reliability can be expressed by the number of failures per unit of time, i. e. 'Failure Rate'. In the following, the failure rates of WTBs depending on their operational age will be depicted (Fig. 3).

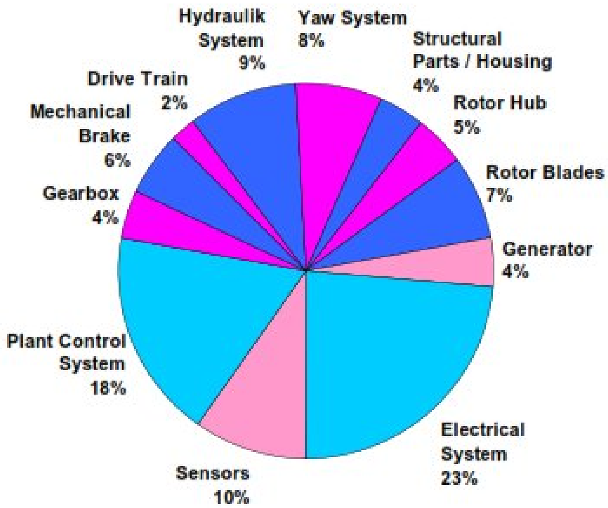
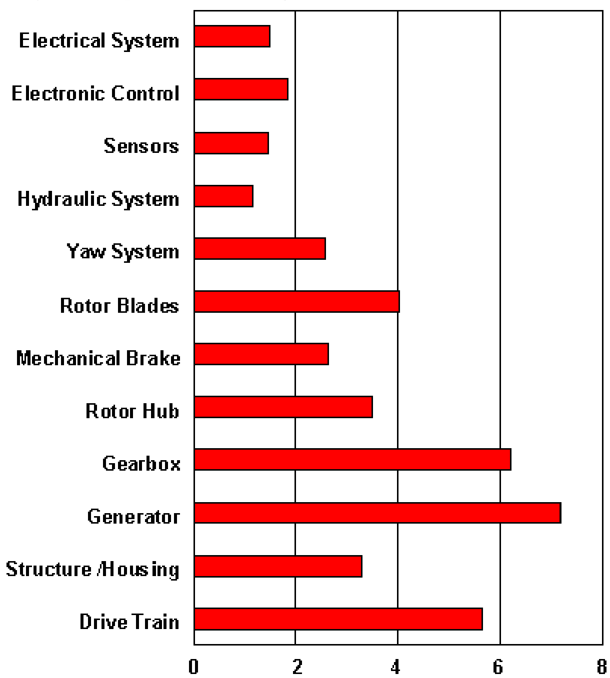


Figure 4: Share of the main components of total number of failures

It is clear that the failure rates of the WTs now installed, have almost continually declined in the first operational years. This is true for the older turbines under 500 kW and for the 500/600 kW class. However, the group of mega-watt WTs show a significantly higher failure rate, which also declines by increasing age. But, including now more and more mega-watt. WTB models of the newest generation, the failure rate in the first year of operation is being reduced.



Down time per failure [days]

Figure 5: Down time of wind turbine system components

Wind turbines achieve an excellent technical availability of about 98% on average, although they have to face a high number of malfunctions.

II. IMPROVING SYSTEM LIABILITY

A. Identify Critical Components

Within any complex system, certain components will stand out as high-risk items, either because they are 'weak points' that are demonstrated to be failure prone, are absolutely essential to turbine operation, or are expensive and time-consuming to diagnose and repair. Identifying the critical components allows the O&M staff to direct their monitoring, training, inventory, and logistics efforts on areas that will provide the most benefit.

Although to some extent the critical components depend on the manufacturer, configuration, and operating environment, certain candidates for attention (gearboxes, generators, and power converters, for example) are well known throughout the industry. Minor components, though perhaps less costly to replace or repair, may be elevated to a critical status if their frequency of failure is high.

B. Characterize Failure Modes

Understanding the failure mode allows the maintenance staff to focus monitoring efforts and potentially delay or prevent catastrophic failures. A generator short may be difficult to predict, but gearbox bearing or gear wear may be detected early with scrupulous lubricant monitoring and/or "condition" monitoring, and the progression of damage possibly mitigated with more frequent oil changes or better filtering. An understanding of the way in which a failure progresses is essential to ensuring that staff avoid consequential damage due to unanticipated breakage.

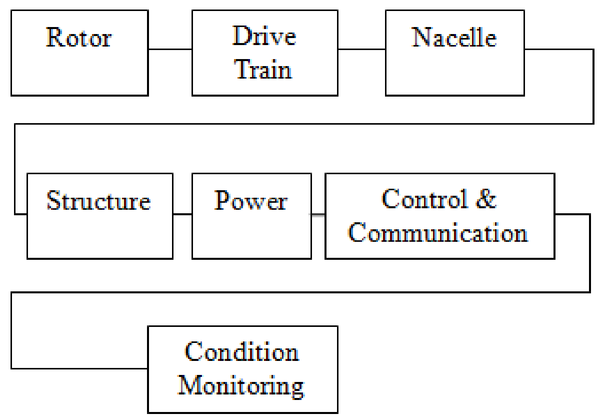


Figure 6: Reliability block diagram of wind turbine

C. Determine the Root Cause

Although the wind plant operator may be primarily interested in replacing a failed component and getting their machine back on-line, a failure always represents an opportunity for improvement. Most wind turbine manufacturers include failure analysis as an essential part of their continuous quality improvement process. Evaluating the root cause of a major component failure is essential to determining if the failure is due to manufacturing quality, product misapplication, design error, or inappropriate design assumptions. This information, in turn, assists the manufacturer in determining if the problem is an isolated instance or a systemic problem that is likely to result in serial failures. In the latter case, retrofits or redesigns will be required and a field replacement plan will be developed.

It can be assumed that these good availability figures can only be achieved by a high number of service teams who respond to turbine failures within short time. In order to further improve the reliability of WTBs, the designers have to better the electric and electronic components. This is particularly true and absolutely necessary in the case of new and large turbines.

III. TURBINE BLADE DESIGN

Tip Seep Ratio(TSR) : Select a value for the Tip Speed Ratio (TSR) which is defined as : TIP SPEED RATIO (TSR) = (tip speed of_lade)/(wind speed). The tip speed ratio is a very important factor in the different formulas of blade design. Generally can be said, that slow running multi bladed wind turbine rotors operate with tip speed ratios like 1-4, while fast runners use 5-7 as tip speed ratios.

The task is now to fit the known generator capacity and revolutions to the wind speed and to the swept rotor area. Two formulas are needed:
Power (W) = 0.6 x Cp x N x A x V^3, Revolutions (rpm) = V x TSR x 60 / (6.28 x R), Cp = Rotor efficiency, N = Efficiency of driven machinery, A = Swept rotor area (m^2), V = Wind speed (m/s) TSR = Tip Speed Ratio , R = Radius of rotor , Rotor efficiency can go as high as Cp = 0.48, but Cp = 0.4 is often used in this type of calculations.

This concept works without transmission. If a transmission with efficiency of 0.95 was to be included this means that
N = 0.95 x 0.7 ,
Tip speed ratio "TSR" = 7"
Wind speed "V" = 8.6 m/s
Rotor efficiency "Cp" = 0.4
Generator efficiency "N" = 0.7
Swept rotor area "A" = 2.11 M2
Radius of rotor = 0.82 m
Revolutions = 701 rpm
Power output = 226 W.

The width of the blade is also called the blade chord. A good formula for computing this is: Blade Chord (m) = 5.6 x R^2 / (i x Cl x r x TSR^2), R = Radius at tip, r = radius at point of computation, i = number of blades, Cl = Lift coefficient, TSR = Tip Speed Ratio.

IV. CALCULATION OF WIND POWER

There are many complicated calculations and equations involved in understanding and constructing wind turbine generators however the layman need not worry about most of these and should instead ensure they remember the following vital information:
1) The power output of a wind generator is proportional to the area swept by the rotor - i.e. double the *swept area* and the power output will also double.
2) The power output of a wind generator is proportional to the cube of the wind speed.

Kinetic Energy = 0.5 x Mass x Velocity^2, where the mass is measured in kg, the velocity in m/s, and the energy is given in joules. Air has a known density (around 1.23 kg/m^3 at sea level), so the mass of air hitting our wind turbine. (which sweeps a known area) each second is given by the following equation: Mass/sec (kg/s) = Velocity (m/s) x Area (m^2) x Density (kg/m^3). Therefore, the power (i.e. energy per second) in the wind hitting a wind turbine with a certain swept area is given by simply inserting the mass per second calculation into the standard kinetic energy equation given above resulting in the following vital equation: Power = 0.5 x Swept Area x Air Density x Velocity^3, where Power is given in Watts (i.e. joules/second), the Swept area in square metres, the Air density in kilograms per cubic metre, and the Velocity in metres per second.

The equation for wind power(P) is given by P= 0.5 x ρ x A x C_p x V^3 x Ng x Nb where, ρ = Air density in kg/m^3, A = Rotor swept area (m^2).
Cp = Coefficient of performance
V = wind velocity (m/s)
Ng = generator efficiency
Nb = gear box bearing efficiency.

The world's largest wind turbine generator has a rotor blade diameter of 126 metres and so the rotors sweep an area of PI x $(\text{diameter}/2)^2$ = 12470 m^2! As this is an offshore wind turbine, we know it is situated at sea-level and so we know the air density is 1.23 kg/m^3. The turbine is rated at 5MW in 30mph (14m/s) winds, and so putting in the known values will give, Wind Power = 0.5 x 12,470 x 1.23 x (14 x 14 x 14), which gives us a wind power of around 21,000,000 Watts. Why is the power of the wind (21MW) so much larger than the rated power of the turbine generator (5MW)? Because of the Betz Limit, and inefficiencies in the system. The Betz law means that wind turbines can never be better than 59.3% efficient. The law can be simply explained by considering that if all of the energy coming from wind movement into the turbine were converted into useful energy then the wind speed afterwards would be zero. But, if the wind stopped moving at the exit of the turbine, then no more fresh wind could get in - it would be blocked. In order to keep the wind moving through the turbine, to keep getting energy, there has to be some wind movement on the outside with energy left in it. There must be a 'sweet spot' somewhere and there is, the Betz limit at 59.3%.

V. WIND TURBINE BLADE CALCULATION AND POWER CALCULATION

Power, rotational speed and torque of the wind turbine can be calculated using the free software *Blade Calculator*.

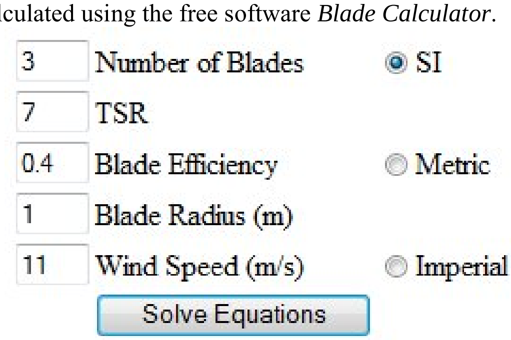


Table 1 : Output obtained for the given parameters

Power	1.02 KW
Rotational speed	77 rad/sec
Torque	13.25 Nm

The program display three power. The first power is the power available in the wind for given wind speed and radius. The second power is the Betz Power. This is the maximum power can be extracted from the wind if there were no losses or inefficiencies in the system. Please note that it is very difficult to get the Betz power from any turbine. The last power which is labeled as Real Power is the power you can get from the turbine with the efficiency displayed in the screen. This kind turbines will have 0 efficiency for wind speeds above 25 m/s, meaning that turbine reached it is cut of speed and turned of to prevent damage to turbine.

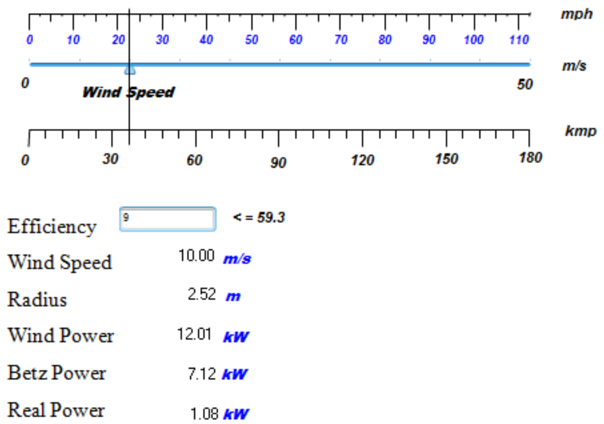


Figure 7 : Result obtained for a wind speed of 10m/s and turbine efficiency 9%.

VI. CALCULATION OF GENERATOR EFFICIENCY

The following conditions/status are assumed.

1. The 3 phases are isolated, and connected as 3 single phase outputs.
2. Each output is rectified to DC using asingle phase bridge rectifier.

At 666rpm, generator voltage Vs = 65 Volts.
Rs = Resistance of each phase of the generator (5.6 Ohms), Voltage across R_s = 65 - 48 = V_s = 17 Volts, V = IR and therefore V/R = I, Current into battery = 17/5.6 = 3 amps per phase, P = VI. Power into battery = 48 x 3 = 144 watts per phase *(432 watts for all 3 phases)*, P = V^2/R, Power Lost is = 17^2/5.6 = 51.6 per phase, Efficiency of generator = 144/(144+51.6) = 73.6% (Theoretical)

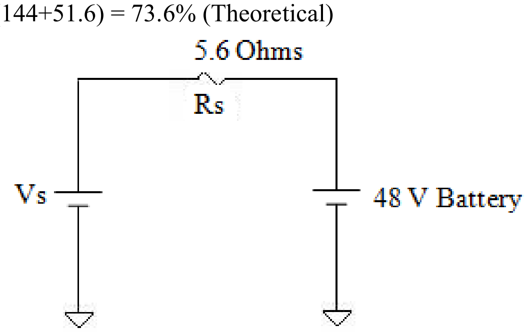


Figure 8 : One phase representation of generator

VII. MEASURED RESULTS

R_s is the resistance of the generator windings plus the power cable; 5.75 ohms and R_l is the resistance of the load; 6.6, 10, 15, 21.5 an 25 ohms.

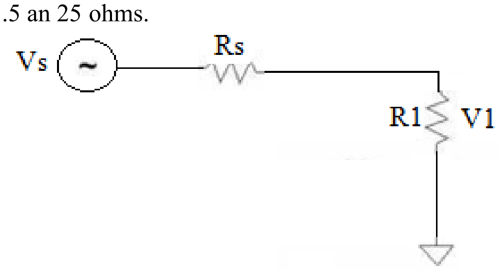


Figure 9 : Electrical analogy of wind turbine

Table 2 : Specification and result for 1kw generator

Parameter	Unit	Value
Rated power	W	1000
Rated speed	rpm	300
Rated frequency	Hz	40
Rated EMF (per coil)	V	33.6
Number of phases	-	3
Number of pole pairs	-	8
Number of armature coils	-	12
Generator diameter	mm	462
Generator length	mm	55

Table 3 : Rotational speed of turbine for different wind speed(rpm)

Wind Speed	25 ohms	21.5 ohms	15 ohms	10 ohms	6 ohms
30km/h	820	766	809	-	-
40km/h	1302	1363	851	645	-
50km/h	1753	1676	1489	1291	1105
60km/h	-	2365	2098	1744	1607

Table 4 : Power in Watts

Wind Speed	25 ohms	21.5 ohms	15 ohms	10 ohms	6 ohms
30km/h	208	205	300	-	-
40km/h	524	649	332	252	-
50km/h	950	981	1017	1008	940
60km/h	-	1953	2019	1837	1990

Table 5 : Blade efficiency of turbine

Wind Speed	25 ohms	21.5 ohms	15 ohms	10 ohms	6 ohms
30km/h	0.23	0.23	-	-	-
40km/h	0.24	0.30	0.15	-	-
50km/h	0.22	0.23	0.24	0.24	-
60km/h	-	0.27	0.27	0.25	0.27

Table 6 : Tip speed (km/hour)

Wind Speed	25 ohms	21.5 ohms	15 ohms	10 ohms	6 ohms
30km/h	278	260	275	-	-
40km/h	441	463	289	218	-
50km/h	595	569	506	438	375
60km/h	-	803	712	592	546

Table 7 : Tip speed ratio

Wind Speed	25 ohms	21.5 ohms	15 ohms	10 ohms	6 ohms
30km/h	9.2	8.7	9.2	-	-
40km/h	11.0	11.6	7.2	5.5	-
50km/h	11.9	11.4	10.1	8.8	7.5
60km/h	-	16.1	14.2	11.8	10.9

Power generated by the blades was calculated by dividing by the efficiency of the generator. Once the blades have been

characterized, a new generator will be designed. Powers generated by the blades are calculated by the following:
Voltage across the resistor load was measured V_l,
$V_s = V_l \times [(R_s + R_l) / R_l]$. Power produced by blades, and lost in generator, power cable and resistor load is given by;
$P = V^2/R$
$P = V_s^2 / (R_s+R_l)$

VIII. CONCLUSION AND FUTURE SCOPE

A 1kW @ 11m/s, 1 meter diameter wind turbine designed with the support of software. The wind turbine blades power and efficiency has been measured at different tip-speed-ratios as well as calculated using software tool. The wind turbine blades power and efficiency has been measured at different tip-speed-ratios and a maximum efficiency of 30% at a TSR of 11.6 was recorded, verifying the blade calculator’s accuracy. The environmental factors like wind direction, corrosion, water vapour intrusion, thermal expansion, mechanical load, summer-winter climate change, ageing and component derating which degrades the performance can be considered for estimating a more practical and accurate design.

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