# Wind Power Curve Modeling

**BBP1009 - WIND GENERATION**

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# Contents

# 1 Introduction

Wind turbines play a pivotal role in renewable energy production by harnessing the kinetic energy of wind to generate electricity. The power output of a wind turbine is intricately linked to wind conditions. This text aims to explore the wind factors affecting power generation, the dynamics behind these factors, and strategies for optimizing wind power generation.

One of the primary factors affecting wind turbine power output is wind speed. The relationship between wind speed and power output follows a power curve, where power increases exponentially with wind speed until reaching a saturation point, beyond which power stabilizes (1). Hence, stronger winds result in higher power output, up to a certain limit.

In addition to wind speed, air density also plays a crucial role in power generation. Air density varies with altitude, temperature, and humidity, affecting the amount of air mass available for capture by wind turbine rotors (2). Under conditions of higher air density, such as in colder climates and lower altitudes, power output tends to be greater.

Wind direction is another important factor to consider. Wind turbines are designed to operate most efficiently when exposed to winds from a certain direction. Changes in wind direction can significantly affect the efficiency of wind power generation, necessitating strategies for turbine positioning and orientation to maximize power output (3).

Apart from the mentioned factors, turbulence and wind speed gradients can also influence power output. Turbulence, caused by obstacles like trees and buildings, can affect the efficiency of wind turbine rotors, thereby reducing power output. Wind speed gradients, resulting from differences in terrain topography, can also influence the distribution of power output across a wind farm.

To optimize wind power generation, various strategies are employed. These include careful site selection for wind farms, considering local wind patterns, and minimizing the impact of obstacles that may cause turbulence. Additionally, the use of advanced technologies such as active yaw control systems and more efficient aerodynamic rotors can further enhance the efficiency of wind power generation.

In summary, wind power generation is closely linked to wind conditions, including speed, direction, air density, turbulence, and wind speed gradients. Understanding these factors and implementing strategies to optimize wind power generation is essential for maximizing the contribution of this renewable energy source to sustainable electricity supply.

# 2 Modeling

For the output power ($P_{wt}$) of the wind generator, the definition of the following equation is considered (4):

$$P_{wt} = \frac{\rho}{2} \cdot A_{wt} \cdot C_p\left(\lambda, \beta\right) \cdot {V_w}^3 \tag{1}$$

where $\rho$ is the air density, $A_{wt}$ is the area swept by the generator blades, $C_p$ is the power coefficient, and $W_w$ is the wind speed.

The power coefficient ($C_p$) is defined as (4):

$$C_p\left(\lambda, \beta\right) = c_1 \left(\frac{c_2}{\lambda_i} - c_3 \cdot \beta - c_4 \cdot \beta^{c_5} - c_6\right) \exp\left(\frac{-c_7}{\lambda_i}\right) \tag{2}$$

where $c_n$ are the parameters used for modeling the approximation of power curves obtained empirically (4), and:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + c_8 \cdot \beta} - \frac{c_9}{\beta^3 + 1} \tag{3}$$

Furthermore, the Tip Speed Ratio is (5):

$$\lambda = \frac{R \cdot \omega_m}{V_w} \tag{4}$$

where $R$ is the radius of the blades (in meters), $\omega_m$ is the angular velocity of the blades (in radians per second), and $V_w$ is the wind speed.

To obtain the power curves, the coefficients for the variable-speed wind turbine in Figure 1 were considered.

| | $c_1$ | $c_2$ | $c_3$ | $c_4$ | $c_5$ | $c_6$ | $c_7$ | $c_8$ | $c_9$ |
|---|---|---|---|---|---|---|---|---|---|
| Heier (1998) | 0.5 | 116 | 0.4 | 0 | — | 5 | 21 | 0.08 | 0.035 |
| Constant-speed wind turbine | 0.44 | 125 | 0 | 0 | 0 | 6.94 | 16.5 | 0 | −0.002 |
| Variable-speed wind turbine | 0.73 | 151 | 0.58 | 0.002 | 2.14 | 13.2 | 18.4 | −0.02 | −0.003 |

Figure 1: Approximation of power curves (4).

Substituting the coefficients from Figure 1 into Equation 2 and considering $\beta = 0$, $R = 3.79m$, $\rho = 1.225\ kg/m^3$ and $V_w = [7, 8, 9, 10, 11, 12]\ m/s$, results in the curves shown in Figure 2 below, which represent the output power of the wind generator for different wind speed values.

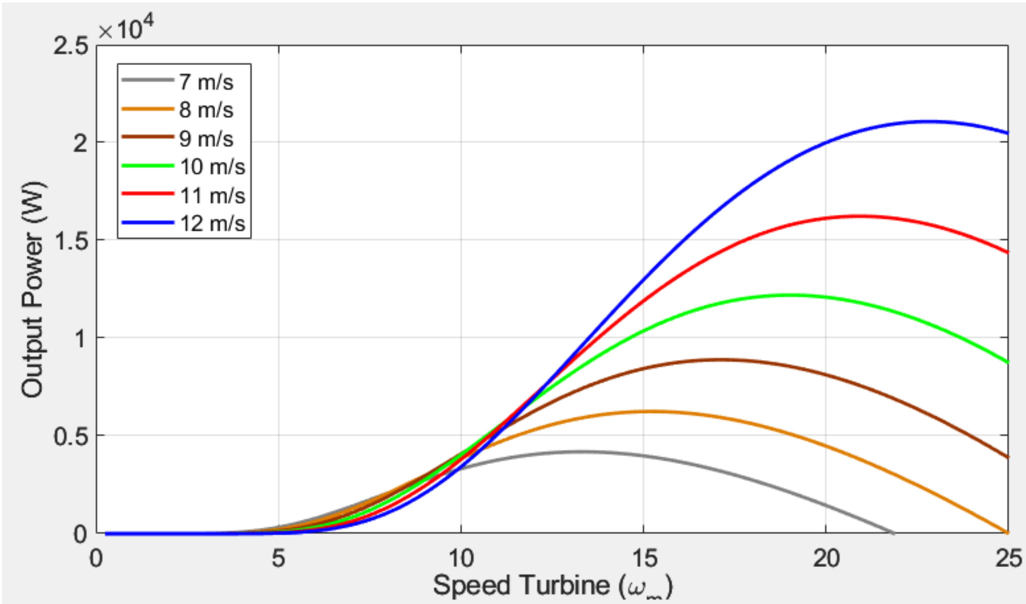


Figure 2: Turbine Power Characteristics (Pitch angle $\beta = 0$ deg).

# 3 MATLAB Code

The code below describes in detail how to reproduce the curves in Figure 2.

```

% Clearing workspace variables
clearvars;

% Defining the parameters of the power coefficient
c1 = 0.73;
c2 = 151;
c3 = 0.58;
c4 = 0.002;
c5 = 2.14;
c6 = 13.2;
c7 = 18.4;
c8 = -0.02;
c9 = -0.003;

% Defining other variables
Beta = 0;
omega_m = linspace(0,25,100);
```

```
radius = 3.79;
area = pi*radius^2;
air_density = 1.225;
wind_speed = [7,8,9,10,11,12];

% Calculating the values of lambda
Lambda = zeros(6,100);

for m = 1:length(wind_speed)
    Lambda(m,:) = radius*omega_m/wind_speed(m);
end

% Calculating the power coefficient curves
L = zeros(6,100);
Cp = zeros(6,100);

for k = 1:length(wind_speed)
    L(k,:) =  (1./(Lambda(k,:)+c8*Beta)) - (c9/(Beta^3 + 1));
    Cp(k,:) = c1*(c2*L(k,:) - c3*Beta - c4*Beta^c5 - c6).*exp(-c7*L(k,:));
end

% Calculating the power curves
Pm = zeros(6,100);

for i = 1:length(wind_speed)
    Pm(i,:) = Cp(i,:)*0.5*area*air_density*(wind_speed(i))^3;
end

% % Plotting the curves
plot(omega_m,Pm.','b-')
ylim([-0.1 25e3])
grid;
xlabel('Speed Turbine (\omega_{m})')
ylabel('Output Power (W)')
legend('7 m/s', '8 m/s', '9 m/s', '10 m/s', '11 m/s', '12 m/s')
hold off
```

# References

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[4] T. Ackermann, *Wind Power in Power Systems*. John Wiley & Sons, 2005.

[5] D. D. V. Mota *et al.*, "Optimization of power generation using the tip speed ratio method in a wecs equipped with pmsg," in *2023 IEEE 8th Southern Power Electronics Conference and 17th Brazilian Power Electronics Conference (SPEC/COBEP)*, pp. 1–6, 2023.