PRESENTATION OF WIND TURBINE MODEL AND SIMULATION

Automation in Regenerativen Energiesystemen

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in Dynamics of Renewable Based Power Systems

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Presentation Overview

Drive Train and Equation

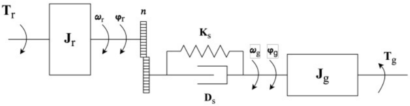

Figure: Drive Train Schematics

For the rotor:

$$\dot{\omega}_r = \frac{-k_s\left(n_g\theta_r - \theta_g\right) + d_s\left(n_g\omega_r - \omega_g\right) + T_r}{J_r}. \tag{1}$$

For the generator:

$$\dot{\omega}_g = \frac{k_s\left(n_g\theta_r - \theta_g\right) - d_s\left(n_g\omega_r - \omega_g\right) - T_g}{J_g}. \tag{2}$$

Additionally, the relationships for $\Delta\dot{\theta}_s$ and $\Delta\theta_s$ are:

$$\Delta\theta_s = n_g\theta_r - \theta_g. \tag{3}$$

$$\Delta\dot{\theta}_s = n_g\dot{\omega}_r - \dot{\omega}_g, \tag{4}$$

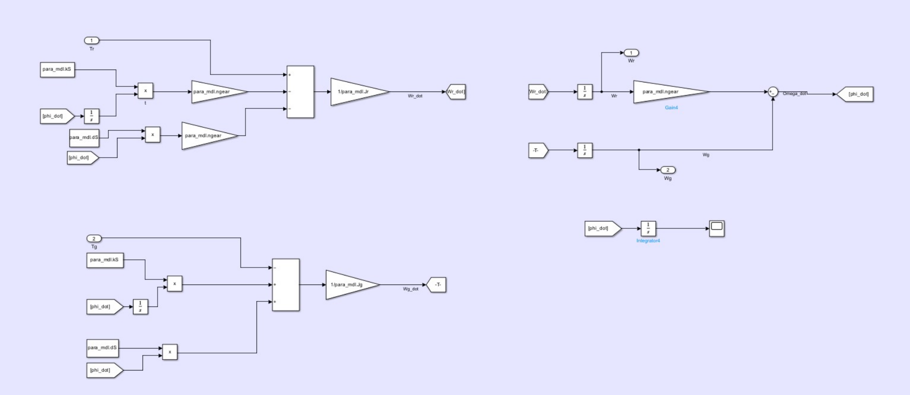

Figure: Drive Train Simulation

Aerodynamics Equations and Simulations

The equations for rotor torque (T_r) and thrust force (F_T) are given by:

$$T_r = \frac{1}{2}\rho\pi R^3 V_\infty^2 C_Q(\lambda, \beta), \tag{5}$$

$$F_T = \frac{1}{2}\rho\pi R^2 V_\infty^2 C_T(\lambda, \beta), \tag{6}$$

where:

- ρ is the air density,
- R is the rotor radius,
- V_∞ is the freestream velocity,
- $C_Q(\lambda, \beta)$ is the torque coefficient as a function of tip-speed ratio λ and pitch angle β,
- $C_T(\lambda, \beta)$ is the thrust coefficient as a function of λ and β.

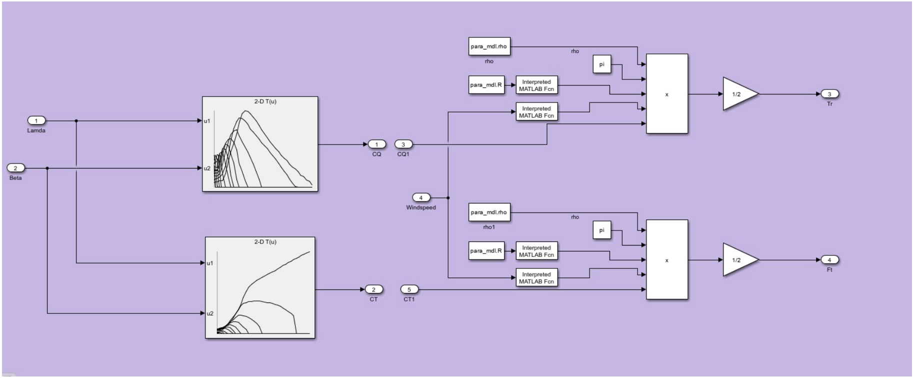

Figure: Aerodynamics Modeling

Tower and Blade Displacement

Mechanical structure dynamics of the turbine tower and blades

The equations for the tower and blade are as follows:

For the Tower:

$$F_T = S^2 y_T M_T + S y_T d_T + y_T K_T, \tag{7}$$

$$S^2 y_T M_T = F_T - S y_T d_T - y_T K_T, \tag{8}$$

$$\ddot{y}_T = \frac{1}{M_T}\big(F_T - d_T \dot{y}_T - y_T K_T\big), \tag{9}$$

where:

- y_T is the displacement of the tower,
- M_T is the effective of Nacelle-Tower Motion
- d_T is the damping coefficient of the tower,
- K_T is the stiffness of the tower,
- F_T is the force acting on the tower.

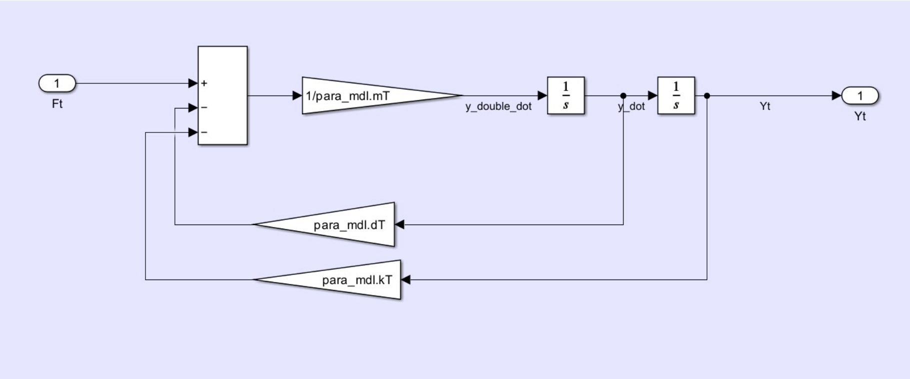

Figure: Tower Displacement

For the Blade:

$$F_T = S^2 y_B N M_B + S y_B d_B + y_B K_B, \tag{10}$$

$$S^2 y_B N M_B = F_T - S y_B d_B - y_B K_B, \tag{11}$$

$$\ddot{y}_B = \frac{1}{N M_B}\left(F_T - d_B \dot{y}_B - y_B K_B\right), \tag{12}$$

where:

- y_B is the displacement of the blade,
- M_B is the effective mass of the blade,
- d_B is the damping coefficient of the blade,
- K_B is the stiffness of the blade,
- F_T is the force acting on the blade.
- N is the numbers of Blade.

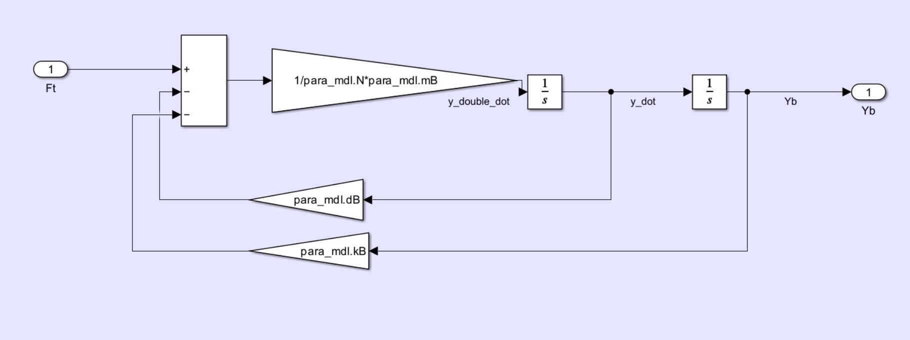

Figure: Blade Displacement

Control Implementation considering different regions

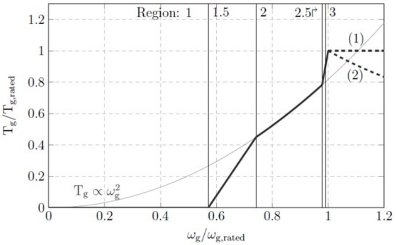

Figure: Graphical representation of Wind Turbine Region

Three key aspects will be analyzed:

1. **Power Optimization**: This applies when the wind speed is below the rated speed ($v < v_{\text{rated}}$).
2. **Power Limitation**: This ensures that the power remains at the rated level when the wind speed exceeds the rated speed ($v > v_{\text{rated}}$).
3. **Load Mitigation**: This focuses on maintaining structural efficiency.

For power optimization in Region 2, $P_g \approx P_r$, we get:

$$T_g \omega_g = \frac{1}{2}\rho\pi R^3 v^2 \frac{c_P}{\lambda}\omega_r. \tag{13}$$

Using $\omega_g = n_g \omega_r$ and the extension with $\frac{\omega_r^2}{\omega_r^2}\frac{R^2}{R^2}$, we obtain:

$$T_g n_g \omega_r = \frac{1}{2}\rho\pi R^5 \frac{v^2}{\omega_r^2 R^2}\frac{c_P}{\lambda}\omega_r^3. \tag{14}$$

Here, $\frac{v^2}{\omega_r^2 R^2}$ simplifies to $\frac{1}{\lambda^2}$, leading to:

$$T_g n_g \omega_r = \frac{1}{2}\rho\pi R^5 \frac{1}{\lambda^2}\frac{c_P}{\lambda}\omega_r^3. \tag{15}$$

Finally, by substituting $\omega_r = \frac{\omega_g}{n_g}$ and $\lambda = \lambda_{\text{opt}}$, we obtain:

$$T_g = f(\omega_g) = \frac{1}{2}\rho\pi R^5 \frac{c_{P,\max}}{n_g^3 \lambda_{\text{opt}}^3}\omega_g^2 = k_{\text{opt}}\omega_g^2, \tag{16}$$

where:

$$k_{\text{opt}} = \frac{1}{2}\rho\pi R^5 \frac{c_{P,\max}}{n_g^3 \lambda_{\text{opt}}^3}. \tag{17}$$

Tg Implementations

The general equation:

$$y = mx + b$$

$$0 = \frac{0.45}{0.15} \cdot 0.6 + b$$

Solving for b:

$$b = -1.8$$

Where:

$$y = \frac{T_g}{T_{g,\text{rat}}} \quad \text{and} \quad x = \frac{\omega_r}{\omega_{\text{rat}}}$$

```
switch region
    case 1
        Tg = 0; % Region 1
    case 1.5
        Tg = (3*(wg/wg_rated) - 1.8)*Tg_max; % Region 1.5
    case 2
        Tg = k_Opt * wg^2; % Region 2
    case 2.5
        Tg = (5.5*(wg/wg_rated) - 4.61)*Tg_max; % Region 2.5
    otherwise
        Tg = 0; % Default value for other regions
end
end
```

Control of region 3

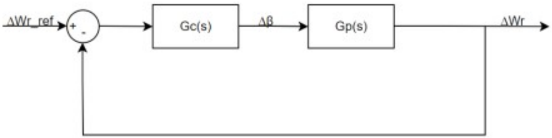

Figure: control scheme

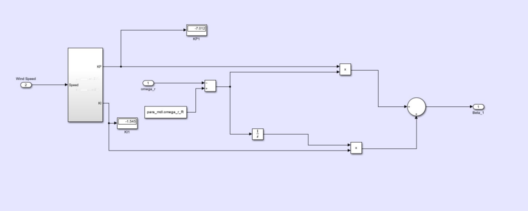

Figure: PI control implemented on simulink

Actualization of KP and KI

1. Plant Transfer Function ($G_p(s)$):

$$G_p(s) = \frac{\frac{K\beta}{J}}{s - \frac{K\omega_r}{J}}$$

2. Controller Transfer Function ($G_c(s)$):

$$G_c(s) = K_p\left(s + \frac{K_i}{K_p}\right)$$

—

Transfer Functions:
With $a = \frac{K_p}{K_i}$, the transfer functions are:
1. Open-loop ($G_o(s)$):

$$G_o(s) = \frac{K_p \cdot b}{s}$$

2. Closed-loop ($G_{cl}(s)$):

$$G_{cl}(s) = \frac{K_p \cdot b}{s + K_p \cdot b}$$

$$K_p \cdot b_i = \frac{1}{\tau_{ref}}$$

$$K_p = \frac{1}{\tau_{ref} \cdot b}$$

$$K_i = \frac{a_i}{\tau_{ref} \cdot b_i}$$

```
% Compute control parameters
tau_ref = 0.1;
a = -k_omega / J;
b = k_beta / J;
k_P = 1 ./ (b .* tau_ref);
k_I = a ./ (b .* tau_ref);
```

Figure: implementation of Kp and Ki on matlab script

```
switch prev_region
    case 1 % Region_1
        if wg > wg_R1_max
            turbineRegion = 1.5; % Region_1.5
        else
            turbineRegion = 1; % Region_1
        end
    case 2 % Region_1.5
        if wg > wg_R1_5_max
            turbineRegion = 2; % Region_2
        elseif wg <= wg_R1_max
            turbineRegion = 1; % Region_1
        else
            turbineRegion = 1.5; % Region_1.5
        end
    case 3 % Region_2
        if wg > wg_R2_max && Tg > Tg_max
            turbineRegion = 2.5; % Region_2.5
        elseif wg <= wg_R1_5_max
            turbineRegion = 1.5; % Region_1.5
        else
            turbineRegion = 2; % Region_2
        end
    case 4 % Region_2.5
        if wg > wg_R2_5_max && Tg > Tg_max
            turbineRegion = 3; % Region_3
        elseif wg <= (wg_R2_max - dwg)
            turbineRegion = 2; % Region_2
        else
            turbineRegion = 2.5; % Region_2.5
        end
    case 5 % Region_3
        if wg <= wg_R2_5_max || Tg <= Tg_max
            turbineRegion = 2.5; % Region_2.5
        else
            turbineRegion = 3; % Region_3
        end
end
```

Figure: Decision Algorithms

Selected Project Results

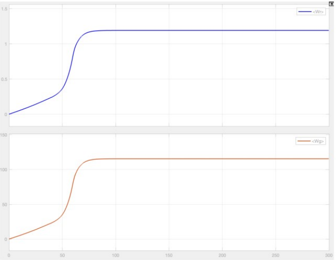

Figure: W_r and W_g at 10 m/s wind speed

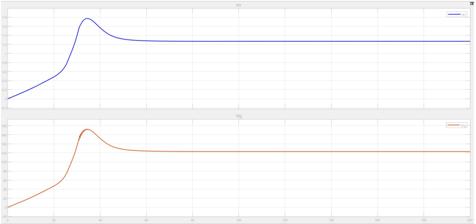

Figure: W_r and W_g at 20 m/s wind speed

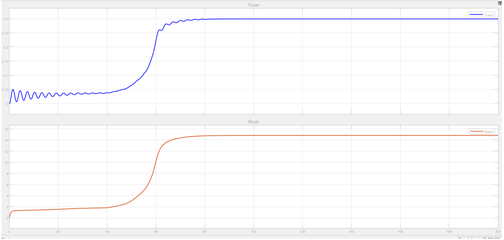

Figure: Tower and Blade Displacement

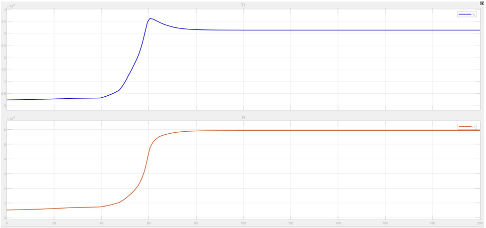

Figure: Results of rotor torque and thrust force scope

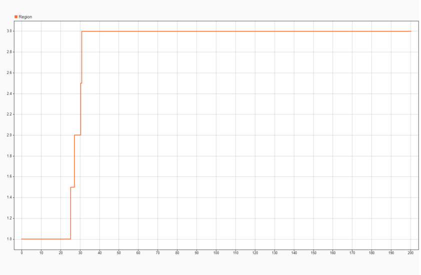

Figure: The Operating Regions

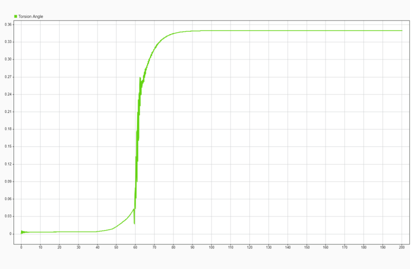

Figure: Torsion Angle

Operating Regions and Pitch angles

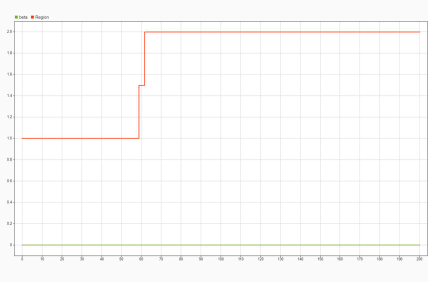

Figure: Plot of pitch for wind speed of 10 m/s.

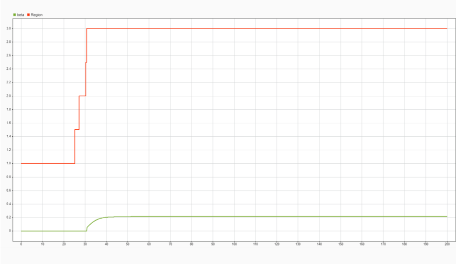

Figure: Plot of pitch for wind speed of 20 m/s.

Conclusion

- This presentation covered key aspects of wind turbine modeling and simulation, focusing on **mechanical structure dynamics, aerodynamics, tower and blade motion, and control strategies**.
- Simulations provide insights into **efficiency, power regulation, and load management**, highlighting how different factors affect turbine performance.
- Proper control implementation ensures **optimal energy extraction, structural stability, and longevity of turbine components**.
- Future advancements in **control techniques, materials and aerodynamics** will further improve turbine performance and efficiency.
- Wind energy remains a key player in the transition to renewable energy. Continuous improvements in modeling and simulation will lead to more **efficient, reliable and sustainable** wind power solutions.