WIND TURBINE CONTROL BASICS

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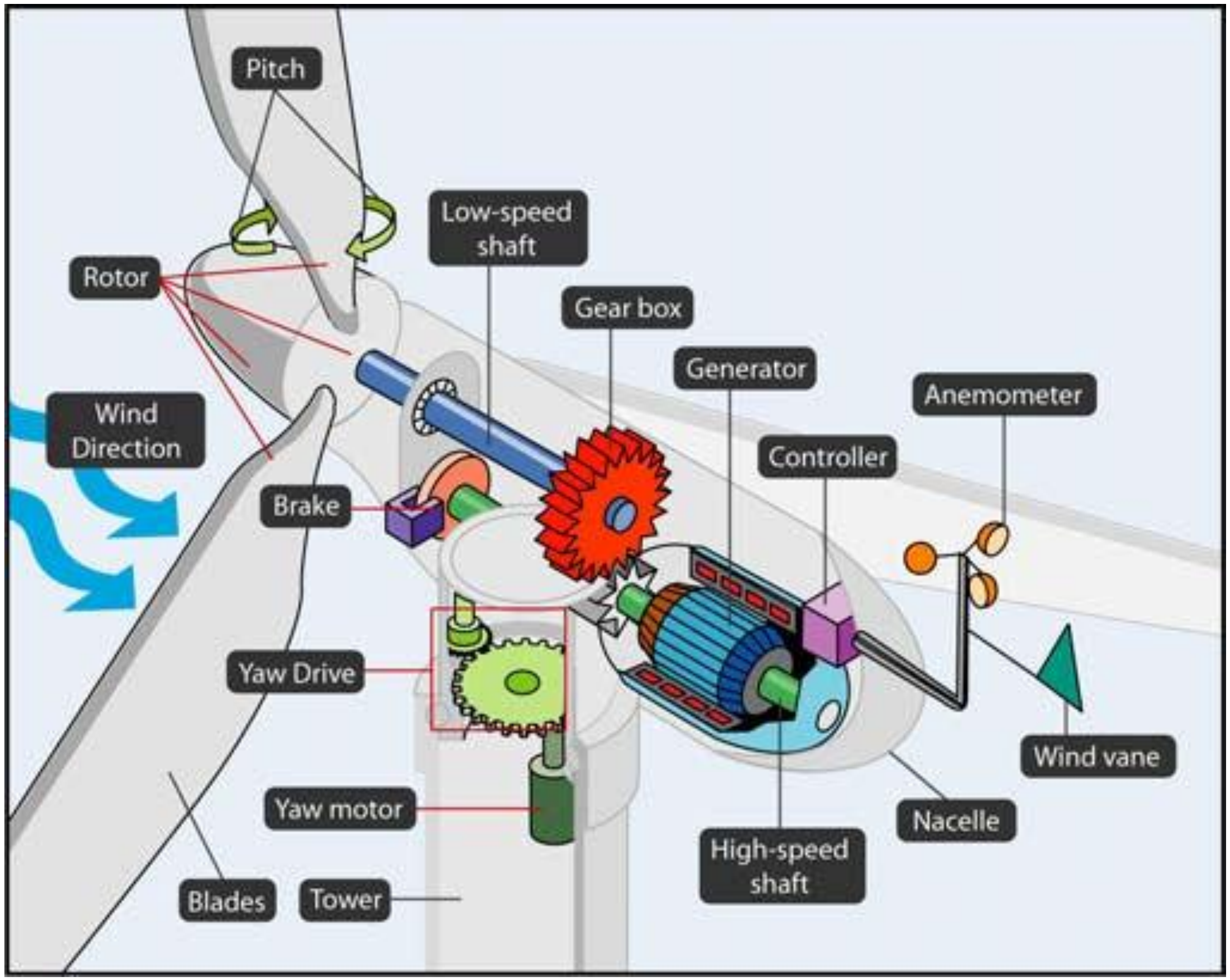
Wind Turbine Components



Wind Turbine Classification

Variable-pitch vs Fixed-pitch

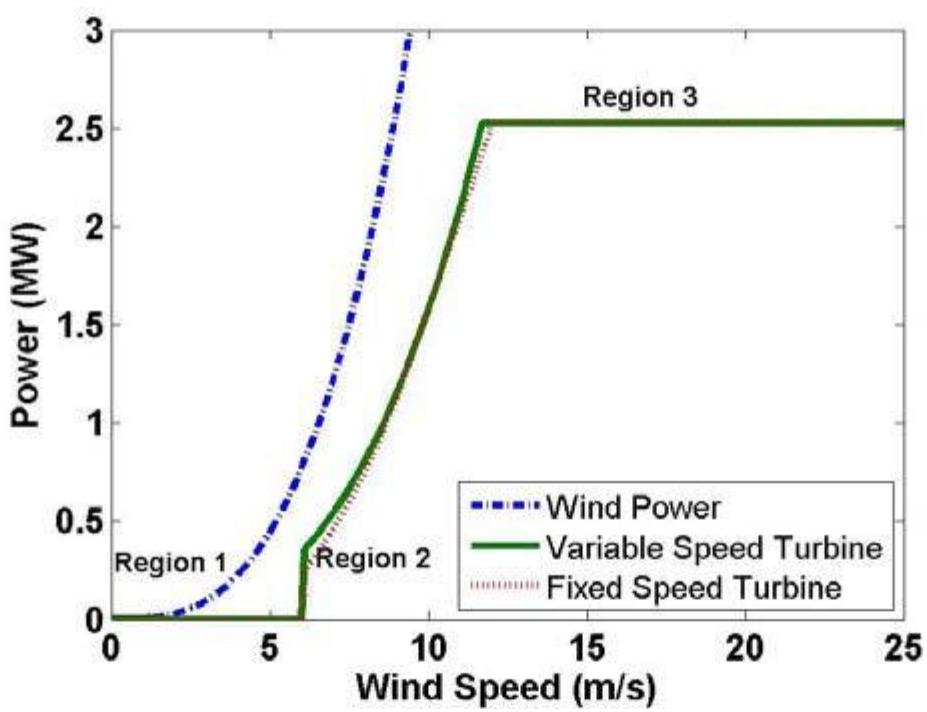
- Fixed-pitch turbines are less expensive initially, but they they lack the ability to control loads and change the aerodynamic torque
- Variable-pitch turbines allow all or part of their blades to rotate along their longitudinal axis

Wind Turbine Classification

Variable-speed vs Fixed-speed

- Variable-speed wind turbines
  - advantage: they tend to operate closer to their maximum aerodynamic efficiency
  - disadvantage: require electrical power processing so that the generated electricity can be fed into the electrical grid at the proper frequency, costly
  - as generator and power electronics technologies improve, costs are reduced and variable-speed WT have become more popular

Wind Power Curve



$$C_p = \frac{P}{P_{wind}}$$

"power coefficient"
or
"aerodynamic efficiency"

$$P_{wind} = \frac{1}{2}\rho A v^3$$

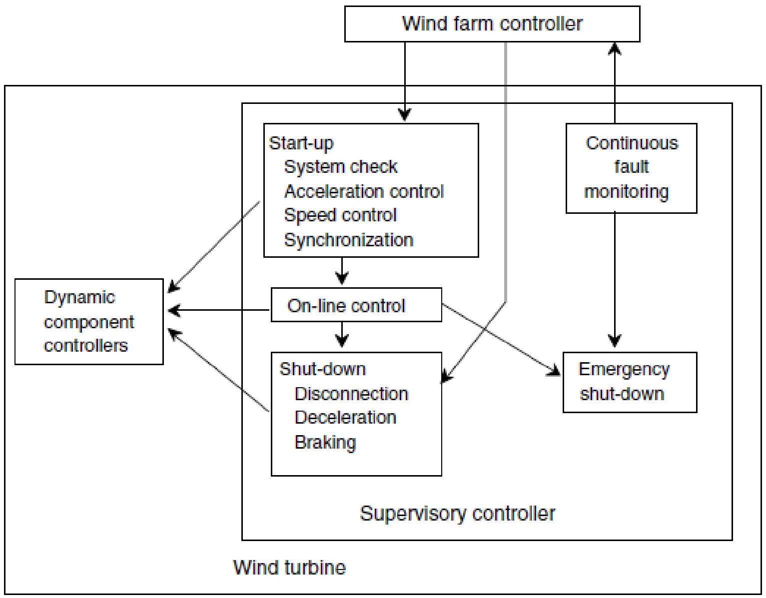
Why Do We Need to Control Wind Turbines?

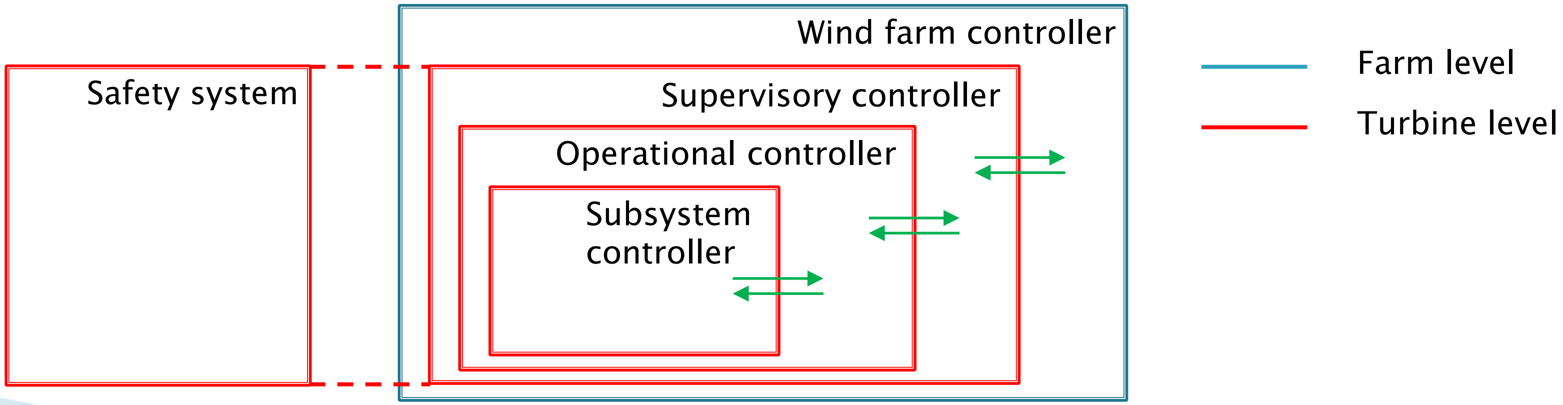
- Controllers can help to achieve;
  - Decrease the **cost** of wind energy
    - by **increasing the efficiency** and thus the energy capture
    - by **reducing structural loading** and increasing the lifetimes of the components and turbine structures
  - Ensure **safety**

"Maximize annual energy capture from the wind while minimizing turbine loads"

Levels of Control in a Utility-Scale Wind Turbine

- Wind farm control
- Supervisory control
- Operational control
- Subsystem control
- Safety system (fail-safe mechanism)





Levels of Control in a Utility-Scale Wind Turbine

- Wind farm control
  - Control of numerous wind turbines in a farm
  - Initiates and shuts down turbine operation
  - Coordinates the operation of numerous turbines
  - Communicates with the supervisory controller of each wind turbine

Levels of Control in a Utility-Scale Wind Turbine

- Supervisory control
  - Reacts to medium and long term environmental and operating conditions, long time between controller actions
  - Functions are;
    - Switching between turbine operating conditions (e.g. power production, low wind shut down)
    - Determines when the turbine starts and stops in response to changes in wind speed
    - Monitors the health conditions of the wind turbine
    - Provides control inputs to the operational controller (e.g. desired tip speed ratio, rpm)

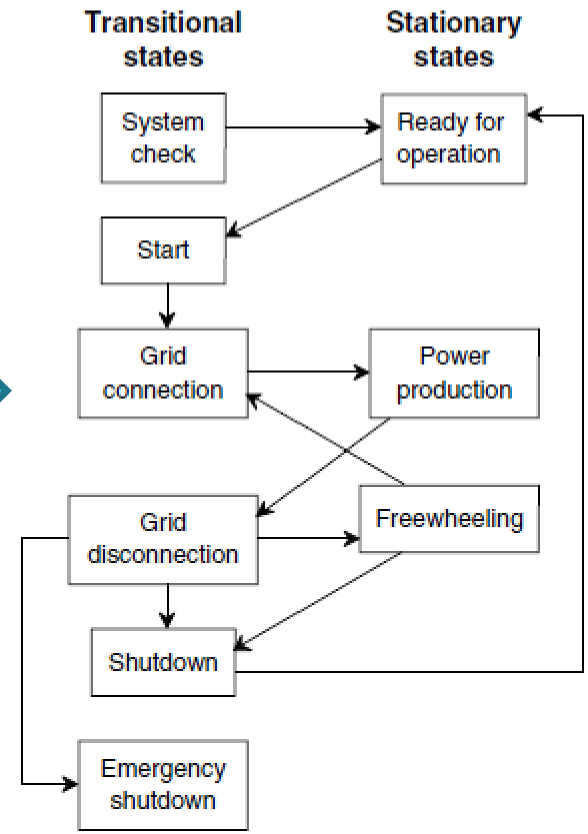


Figure 8.8 Typical turbine operating states

Levels of Control in a Utility-Scale Wind Turbine

- Operational control
  - Determines how the turbine achieves its control objectives. It includes
    - control of generator torque in order to regulate the rotational speed of a variable speed turbine
    - control of blade pitch in order to regulate the power output of the turbine to the rated level in **above-rated wind speeds**
    - control of yaw motors in order to minimize the yaw tracking error

Levels of Control in a Utility-Scale Wind Turbine

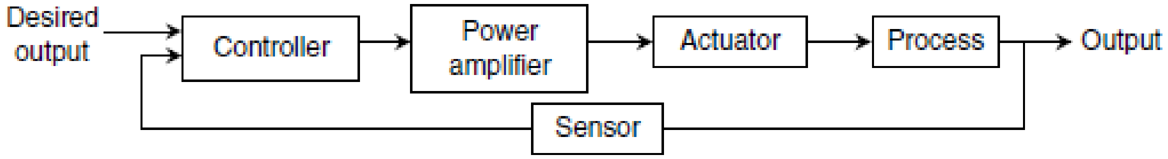
- Subsystem control
  - causes the generator, power electronics, yaw drive, pitch drive and other actuators perform as desired
- Safety system
  - bring the turbine to a safe condition (applying brakes) in the event of a serious or potentially serious problem
  - if the supervisory control fails, the safety system takes over
  - should be independent from the main control system as far as possible

Sensors & Actuators

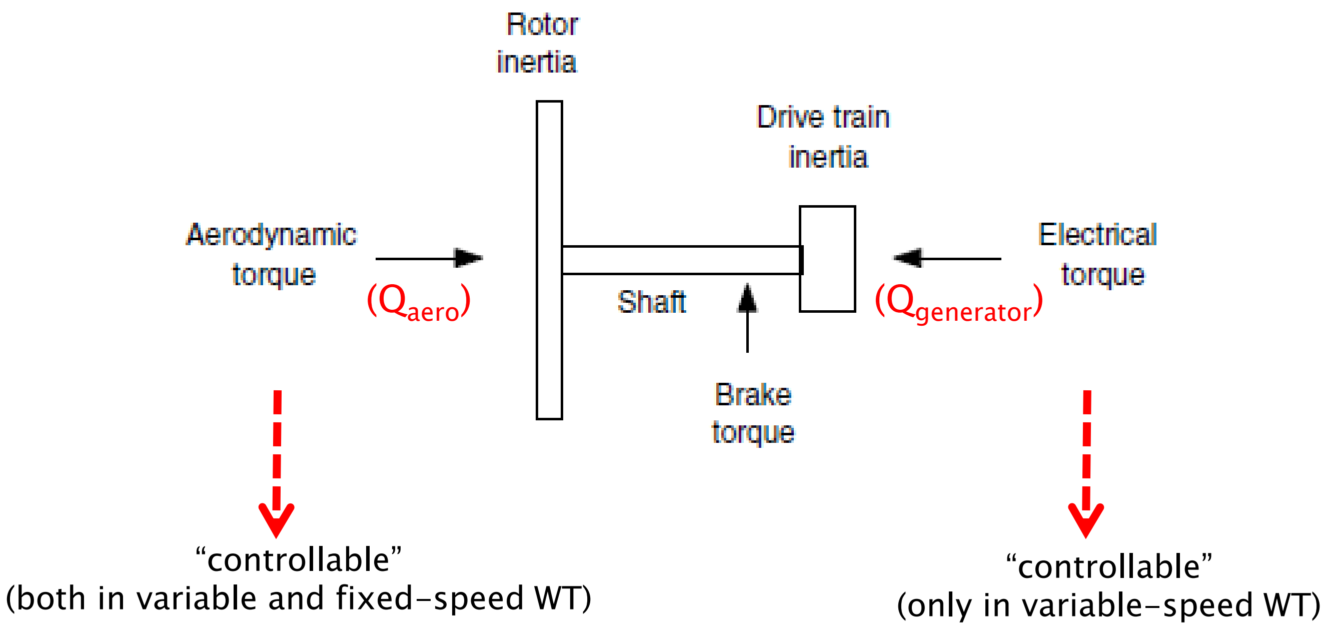
- Sensors
  - Rotor speed measurement sensor (Operational Control)
  - Anemometer (Supervisory Control)
  - Power measurement devices
  - Strain gauges on the tower and blades
  - Accelerometers
  - Position encoders on the drive shaft and blade pitch actuation systems
  - Torque transducers

- Actuators
  - Yaw Motor ($<$1deg/s)
  - Generator (very fast)
  - Blade pitch motor

    (18 deg/s→600kW, 8 deg/s→5MW)



Basic Wind Turbine Model



the rotational speed of the wind turbine is determined by the net torque:

$$J\dot{\omega} = Q_{aero} - Q_{generator}$$

Based on the net torque, the turbine either <u>accelerates</u> or <u>decelerates</u>

Basic Wind Turbine Model

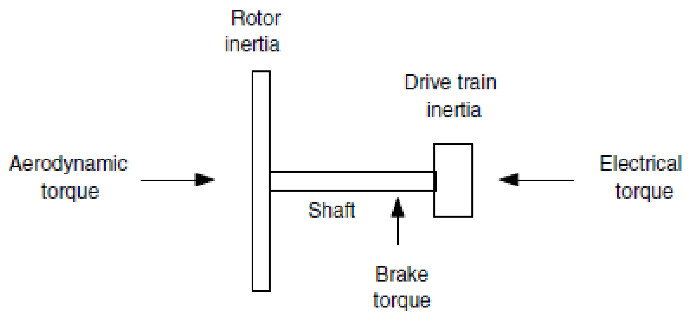
- Aerodynamic torque depends on;
  - Rotor tip speed ratio
    - controllable (variable-speed WT)

$$\lambda = \frac{\omega R}{v}$$

  - Blade geometry
    - controllable (pitch-regulated turbines)
  - Wind speed
    - uncontrollable
  - Yaw error
    - controllable (yaw control)
  - Rotor drag
    - controllable (auxiliary drag devices)

Basic Wind Turbine Model

- Generator ('electrical' or 'load') torque;
  - Function of aerodynamic torque and system dynamics (fixed-speed WT)
    - System dynamics are fixed by design (not controllable)
    - Aerodynamic torque (controllable)



Most of the modern utility-scale wind turbines today are of this type

  - Independently controlled (variable-speed, pitch-regulated WT)

Wind Turbine Control Strategies

Below rated region

Above rated region

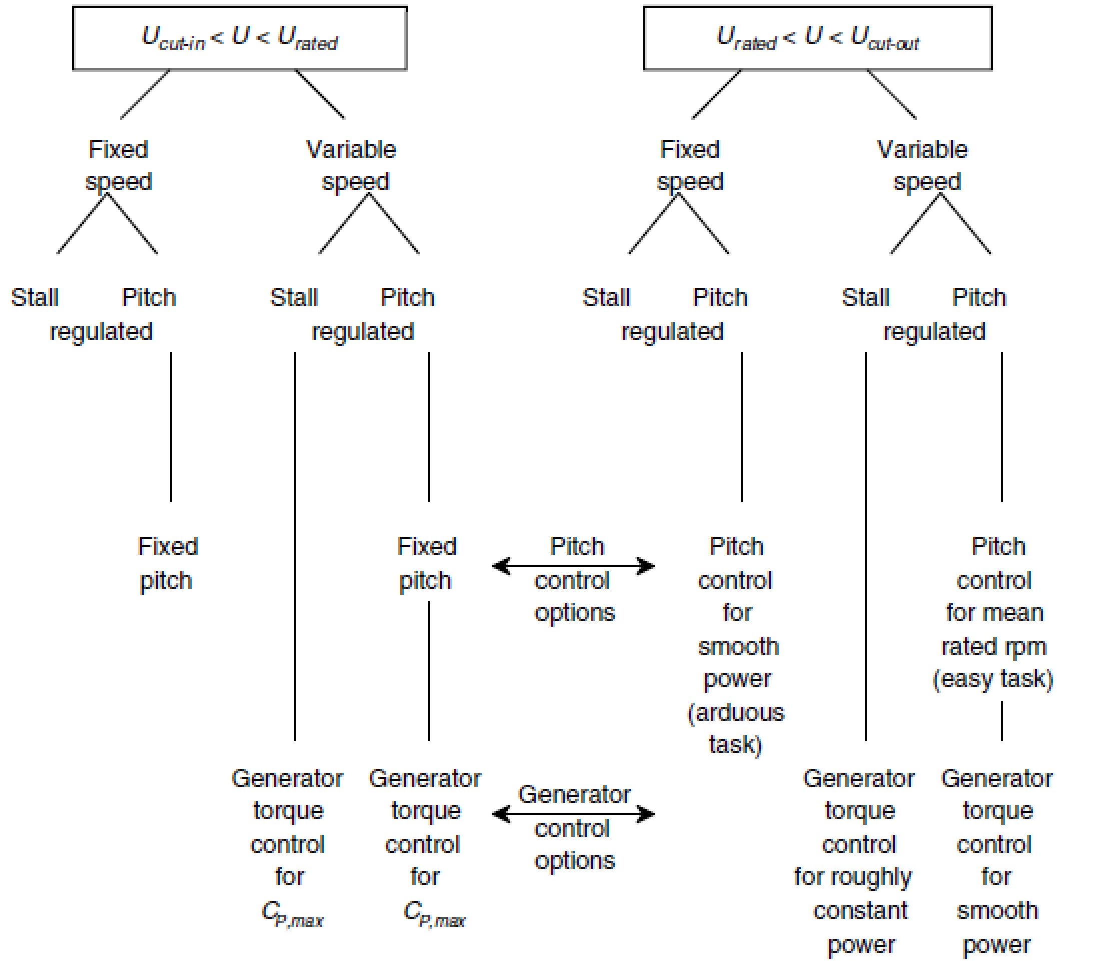
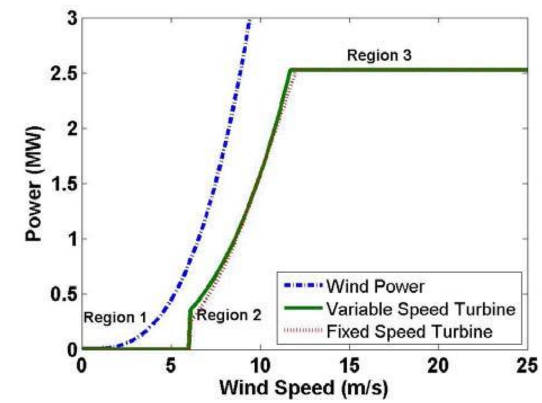
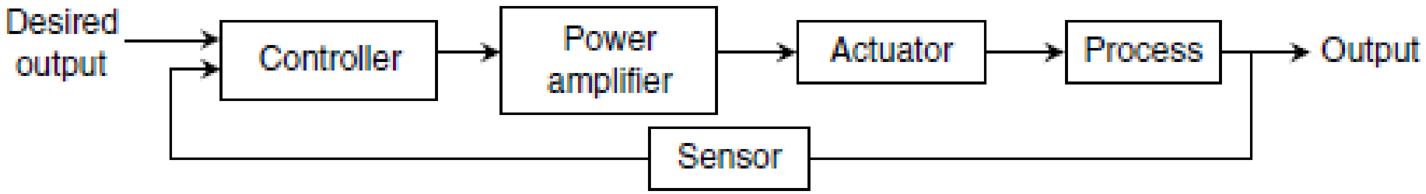


Figure 8.6 Overview of typical control strategies; U, mean wind velocity; U_{cut-in}, $U_{cut-out}$, U_{rated}, cut-in, cut-out, and rated wind speed, respectively

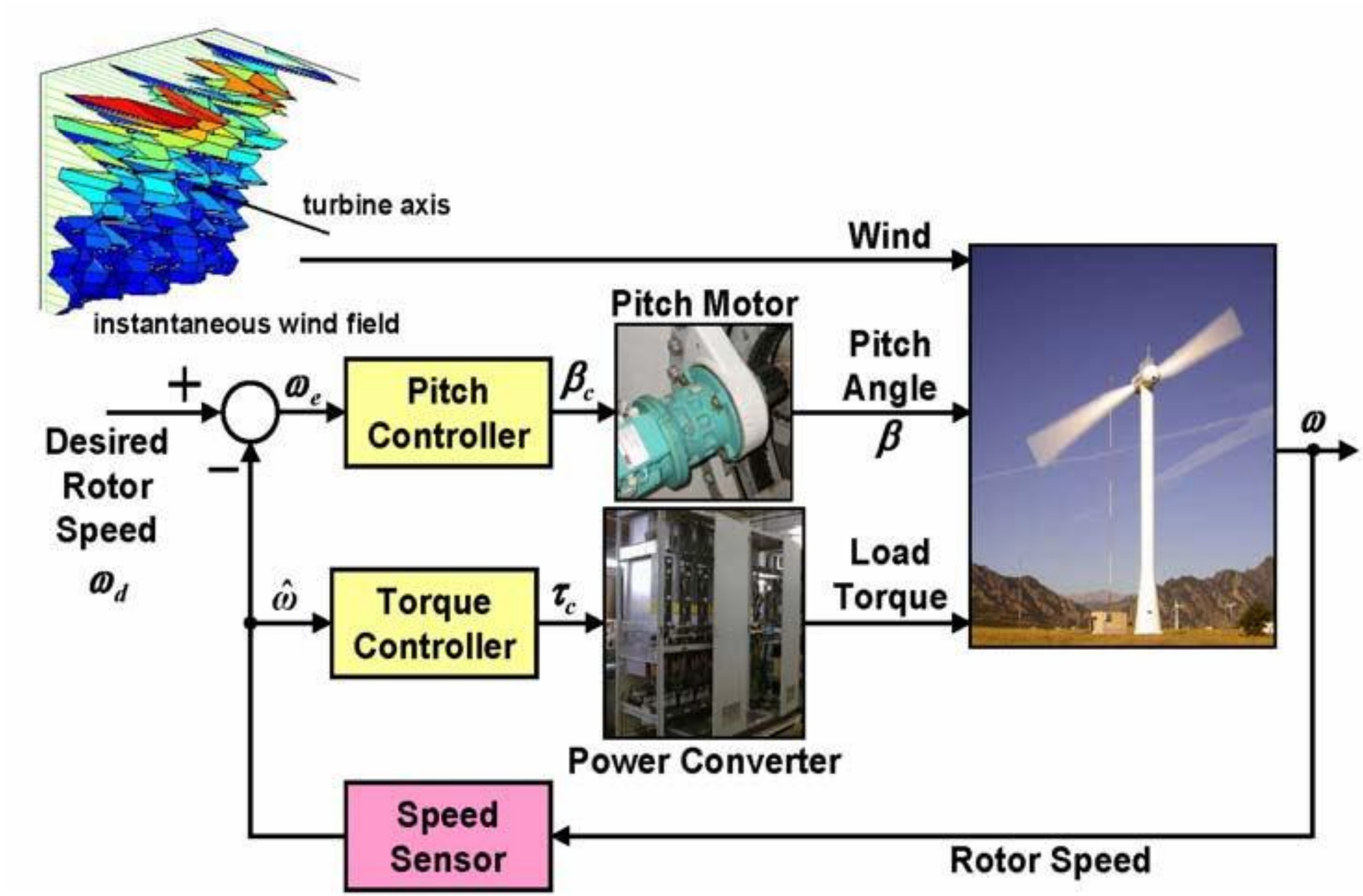


“we will focus on operational control of a variable-speed, pitch-regulated wind turbine”

Any closed-loop system block diagram looks like this:



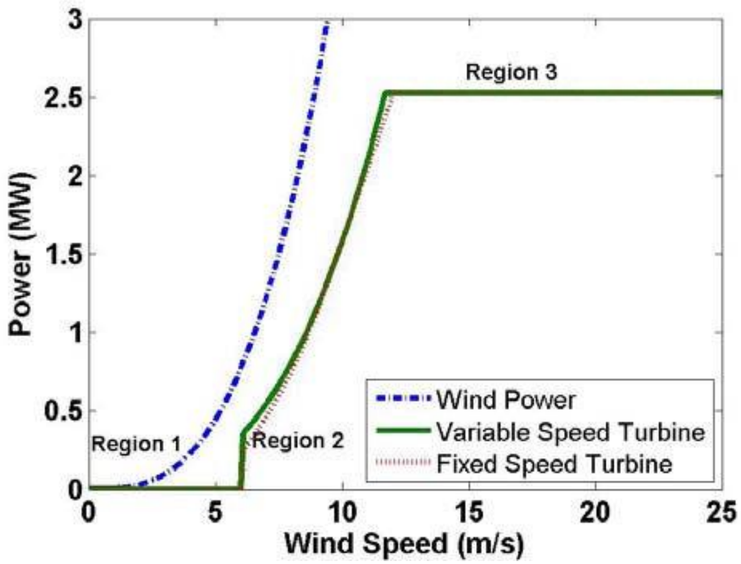
Wind Turbine Control Block Diagram



Control Objective in Region 2

- Region 2 control objective is to <u>maximize Cp</u>

$$\lambda = \frac{\omega R}{v}$$ "tip speed ratio"



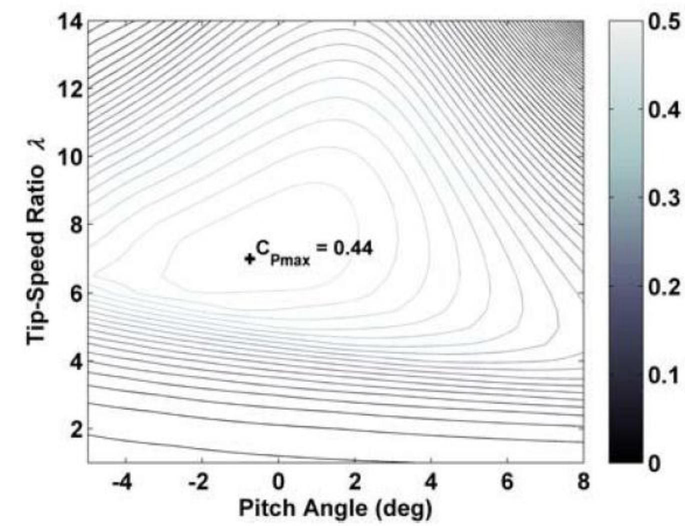


Fig. 12. C_p surface for CART3. The peak power coefficient $C_{p_{max}} = 0.4438$ for CART3 occurs at a tip-speed ratio $\lambda_* = 7.0$ and a blade pitch angle $\beta_* = -0.75$ deg.

$$C_p(\lambda, \beta) \qquad C_{p_{\max}}(\lambda_*, \beta_*)$$

Control Policy in Region 2

- In Region 2, pitch angle is kept constant. In order to achieve the maximum aerodynamic efficiency ($C_{p_{max}}$), **tip-speed-ratio should also be kept constant.**

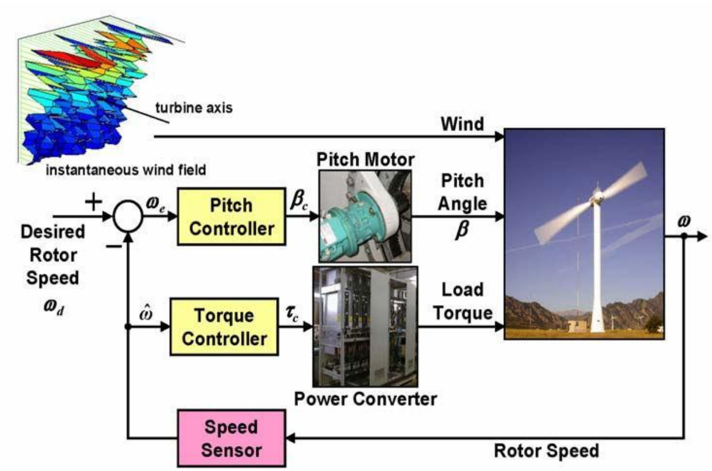
$$\lambda = \frac{\omega R}{v}$$

- Therefore, we need to control rotational speed (ω) of the turbine

"use generator torque control in below rated region"

Torque Control

- Torque control is applied in Region 2 (below rated region) to maximize Cp
- Turbine rotational speed is controlled to keep the tip-speed-ratio at maximum efficiency (C_p) point (blade pitch angle is kept constant)



$$\tau_c = K\hat{\omega}^2$$ "control law"

$$K = \frac{1}{2}\rho\pi R^5 \frac{C_{p_{max}}}{\lambda_*^3}$$

Verification of control law;

$$\dot{\omega} = \frac{1}{J}\left(\tau_{aero} - \tau_c\right)$$

$$\dot{\omega} = \frac{1}{2J}\rho\pi R^5\omega^2\left(\frac{C_p}{\lambda^3} - \frac{C_{p_{max}}}{\lambda_*^3}\right)$$

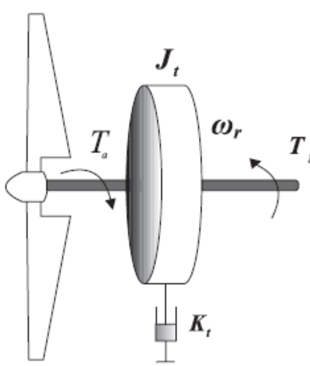


Fig. 3. One-mass model of a wind turbine.

Torque Control

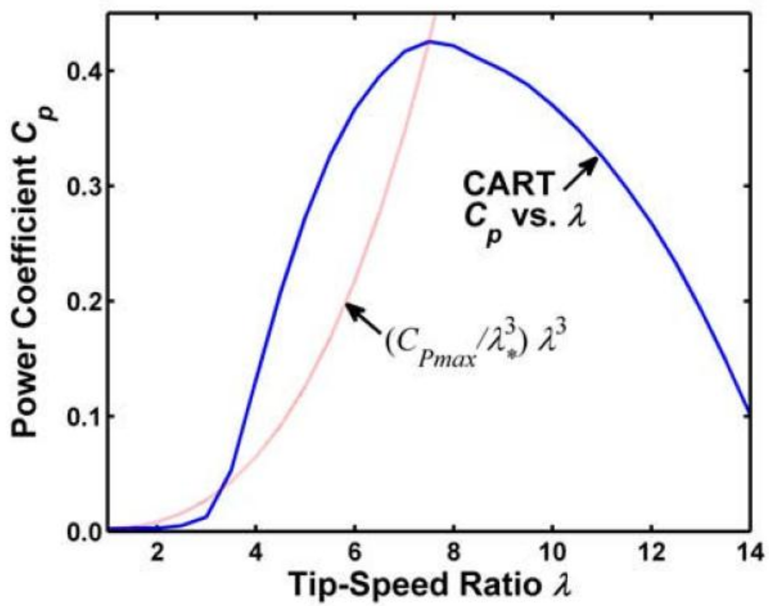


Fig. 13. C_p versus λ curve for the CART3 when the blade pitch angle β = -0.75 deg. The turbine accelerates toward the optimal tip-speed ratio λ_* when the red curve (representing (8)) is less than the blue curve ("CART C_p vs. λ"), and decelerates when the opposite is true.

$$\dot{\omega} < 0 \quad \text{when} \quad C_p < \frac{C_{pmax}}{\lambda_*^3}\lambda^3$$
$$\dot{\omega} > 0 \quad \text{when} \quad C_p > \frac{C_{pmax}}{\lambda_*^3}\lambda^3$$

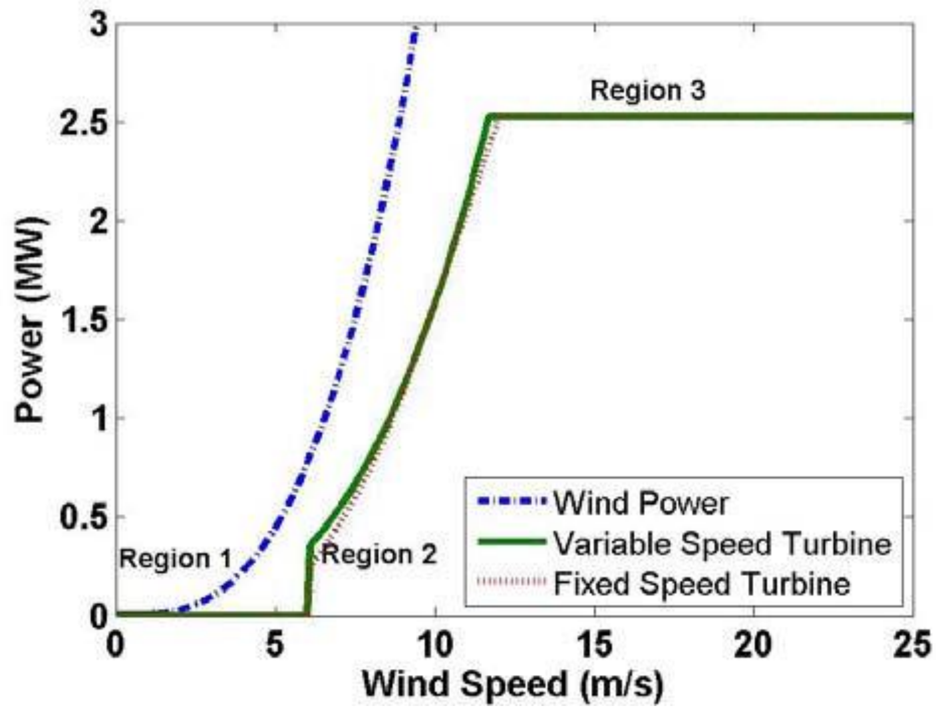
- The turbine accelerates to obtain maximum Cp when the rotor speed is too slow and vice versa

Control Objective in Region 3

- Region 3 control objective is to <u>limit the turbine power</u> so that safe mechanical and electrical loads are not exceeded

$$P = \tau_{aero}\omega$$

"power–torque relationship"



Control Policy in Region 3

- In Region 3, power limitation can be achieved by pitching the blades (–to feather or –to stall) or by yawing the turbine out of the wind

- We want to **keep rotational speed constant** (at rated speed) and limit the aerodynamic torque, and thus operate the turbine at its rated power

"use aerodynamic torque control in above rated region"

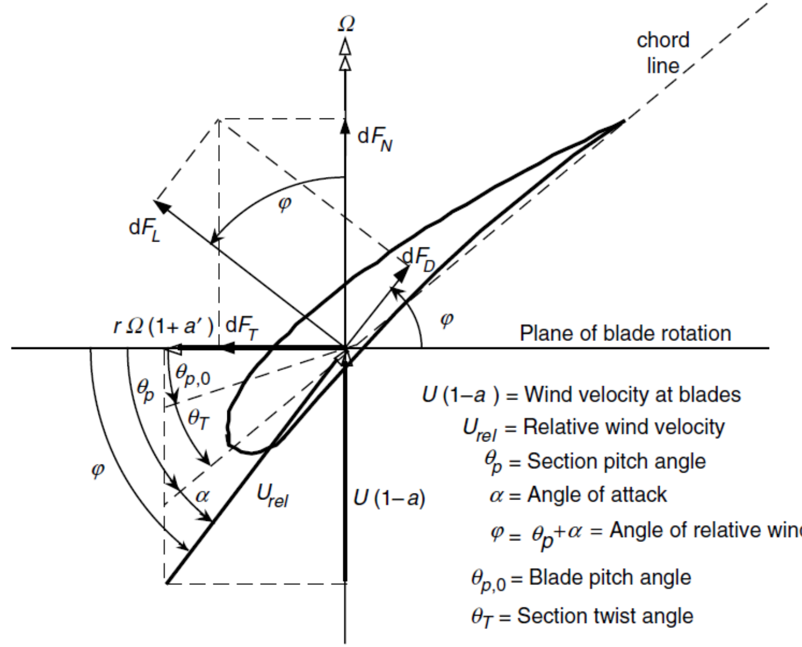
Pitch Control

- Pitch control is applied in Region 3 (above rated region) to <u>limit the turbine power</u>
- In order to limit the aerodynamic torque, either reduce the angle of attack (pitching to feather) or increase the angle of attack (pitching to stall)

$$\mathrm{d}Q = B\tfrac{1}{2}\rho U_{rel}^2(C_l \sin\varphi - C_d \cos\varphi)cr\,\mathrm{d}r$$

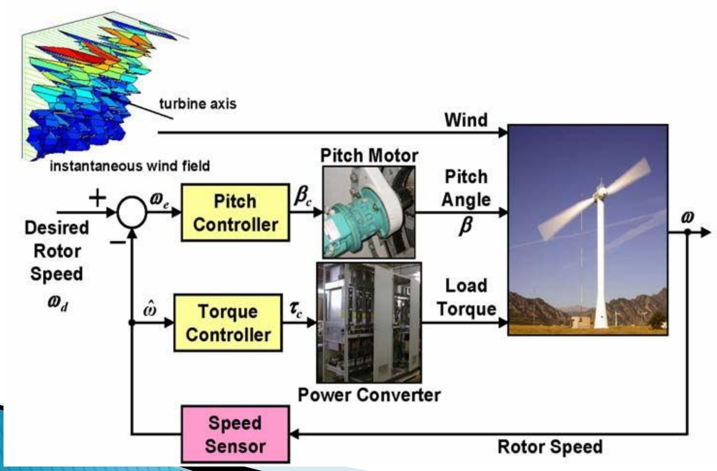
$$\mathrm{d}F_N = B\tfrac{1}{2}\rho U_{rel}^2(C_l \cos\varphi + C_d \sin\varphi)c\mathrm{d}r$$

"torque and thrust equations derived from BEM theory"



Pitch Control

- In pitch control, blade pitch angle is controlled to limit the aerodynamic torque (keep the rotational speed constant)
- Classical proportional-integral-derivative (PID) control is applied to rotor speed error
- Aim of the controller is to reduce the rotor speed error such that the turbine rotor speed matches the desired rotor speed (rated rotor speed)



$$\beta_c(t) = K_P \omega_e(t) + K_I \int_0^t \omega_e(\tau) d\tau + K_D \frac{d\omega_e(t)}{dt}$$

$$\omega_e = \omega_d - \hat{\omega}$$ "rotor speed error"

"Pitch control based on collective PID control"

Power Limitation in Fixed-Pitch Turbines

- Fixed-pitch turbines limit the power by entering the aerodynamic stall regime above rated wind speed (not a controlled process, or can be called as passive control)

Sample results

- Time < 450s (below rated)
  - Pitch angle at its nominal value
  - Generator speed below rated rpm
  - Torque control is applied
- Time > 450s (above rated)
  - Generator speed reaches rated rpm
  - Torque control signal is saturated
  - Pitch control is applied

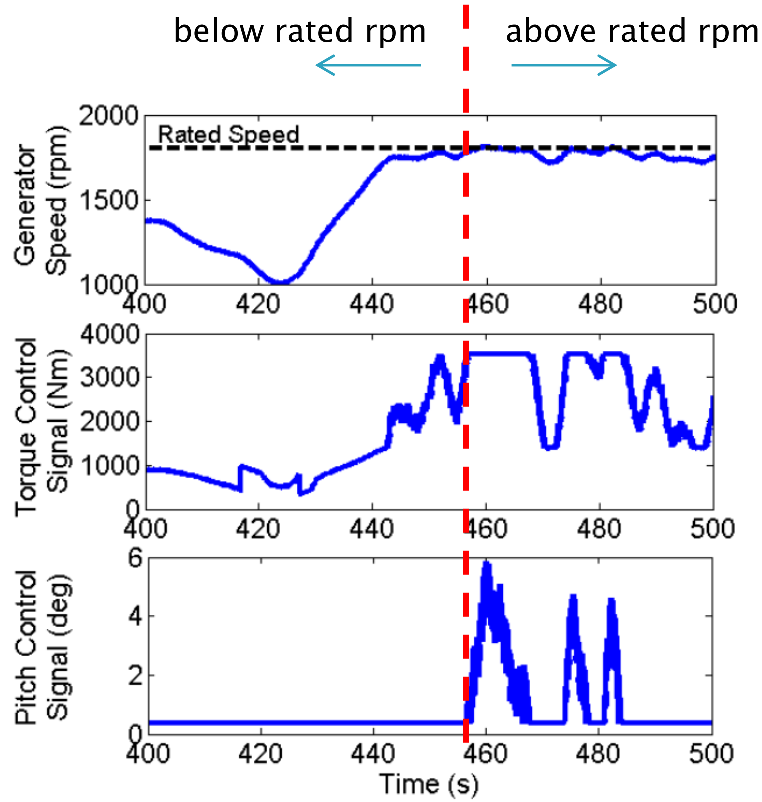


Fig. 14. Experimental generator speed and torque and pitch control signals for the CART2 in normal operation. The rated speed for CART2 is 1800 rpm; when this rated value is reached, the torque control signal is saturated at its maximum value and pitch control is used to limit turbine power.

Issues in Wind Turbine Control

- Individual blade pitch control
- Transition regime between Region 2 and 3
- Turbine shut down (especially in case of failure)
- Adaptive control techniques to compensate for unknown or time-varying parameters
- Feedforward control to improve disturbance rejection performance
- Modeling and control of wind farms
- Stability, controllability and observability issues of offshore wind turbines (floating)

References

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  - (Sections 8.1 and 8.2)