1 Wind Turbine Control

- The control system on a wind turbine is designed to:
  1. seek the highest efficiency of operation that maximizes the coefficient of power, C_p,
  2. ensure safe operation under all wind conditions.
- Wind turbine control systems are typically divided into three functional elements:
  1. the control of groups of wind turbines in a wind farm,
  2. the supervising control of each individual wind turbine, and
  3. separate dedicated dynamic controllers for different wind turbine sub-systems.

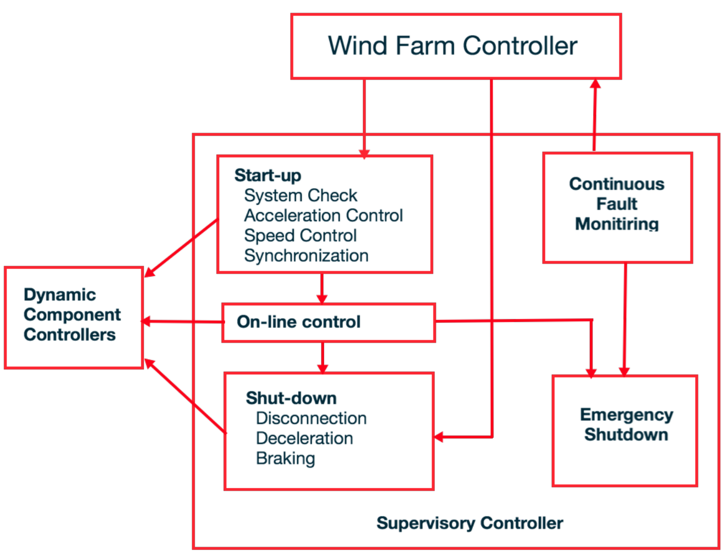

Figure 1: Schematic of the wind turbine functional control elements.

- The wind farm controller's function is "power management".
  - It can initiate and shut down turbine operation as well as coordinate the operation of numerous wind turbines in response to environmental and operating conditions.
- The wind turbine supervisory controller manages the individual turbine operation.
  - Including power production, low-wind shutdown, high-wind shutdown, high load limits, and orderly start-up and shutdown
  - Also provides control input to the dynamic controllers for r.p.m. control to maintain an optimum tip-speed-ratio, and blade pitch control.

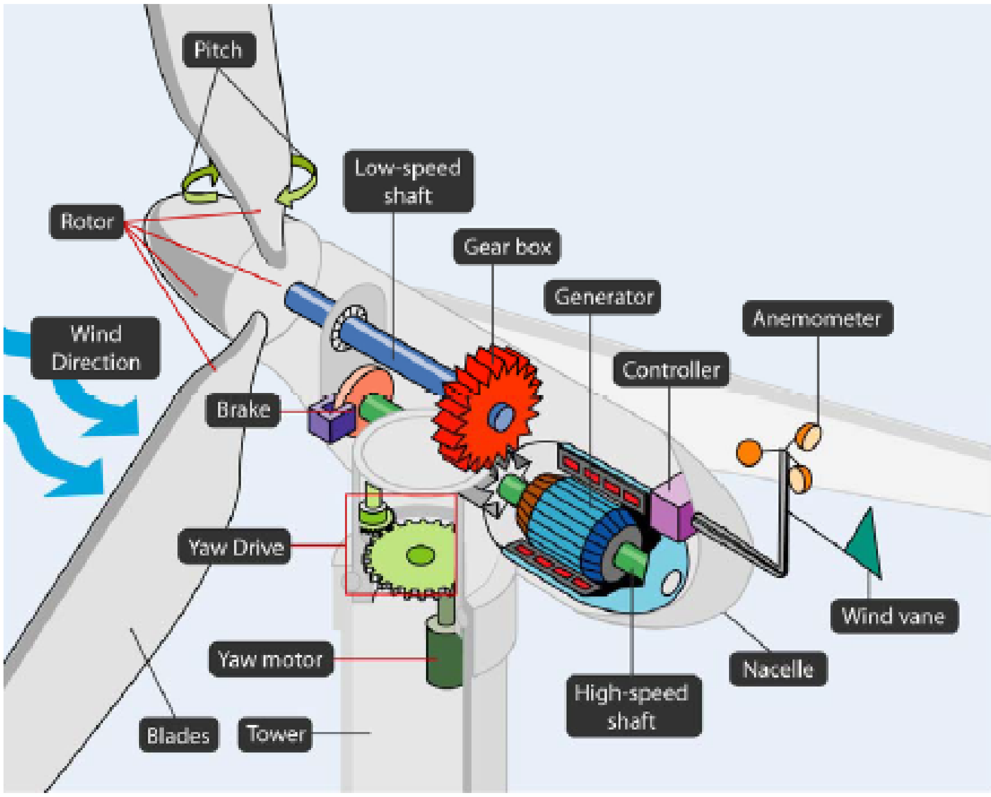

Figure 2: Section view of typical components of a wind turbine that are involved in its monitoring and control.

- Generally, there exists an **optimum** tip-speed-ratio, λ that maximized C_p.
  - The exact λ depends on the individual wind turbine design $(6 \leq \lambda \leq 8)$

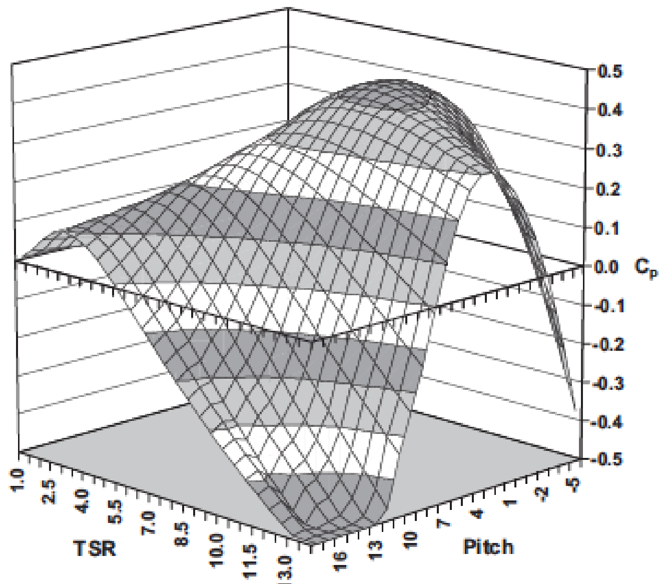

Figure 3: Example of the relation between the rotor tip-speed ratio and rotor pitch angle on the coefficient of power for a 600kW two-bladed horizontal wind turbine.

- The sensitivity of C_p to λ motivates closed-loop control focusing on the the rotation frequency

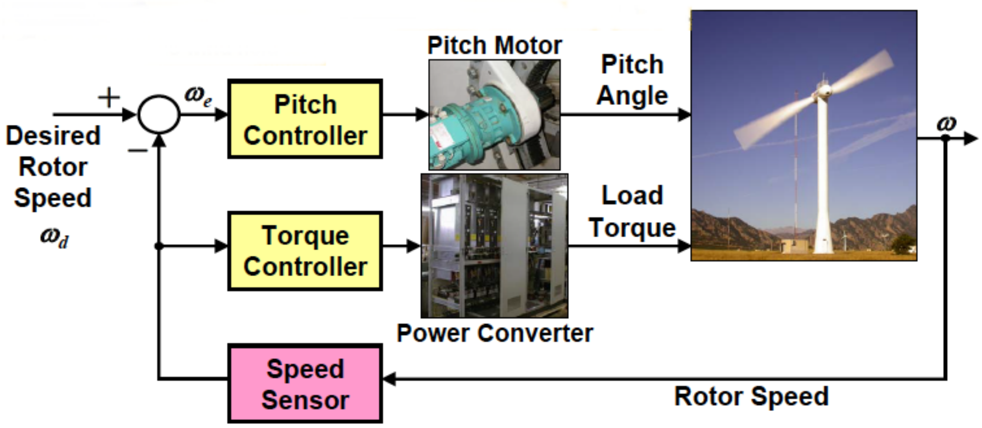

Figure 4: Schematic of a wind turbine closed-loop control system.

1.1 Aerodynamic Torque Control

- One of the approaches to control λ is through control of the rotor aerodynamic torque.
  - This ultimately comes by controlling the rotor L/D.
- For L/D control, there are two approaches:
  1. stall-regulated rotor designs
  2. pitch regulated rotor designs
- **Stall-regulated** rotors are designed with section shapes and mean angles of attack to cause the rotor to stall at higher wind speeds, beginning at rated power wind speeds. *(More detail on this later)*
- **Pitch-regulated** rotors reduce the aerodynamic torque by reducing the pitch and thereby the local angle of attack of the rotor sections.
  - The lower angles of attack reduce the section lift coefficients and thereby the aerodynamic torque on the rotor.
  - The pitch control initiates when the wind velocity is sufficient to generate the turbine rated power level.
  - It continues to reduce the pitch to seek to maintain an optimum λ while also maintaining a constant rated power up to the cut-out wind speed.

1.2 Electrical Torque Control

- Another approach to control λ is through electrical torque control.
- Synchronous generators are most commonly used in large wind turbines
- Synchronous machines are commonly used as generators especially for large power systems, such as turbine generators and hydroelectric generators in the grid power supply.
- The reactive power generated by a synchronous machine can be adjusted by controlling the magnitude of the rotor field current unloaded synchronous machines are also often installed in power systems solely for power factor correction, or for control of reactive kV-A flow.
- For a general case of a synchronous machine with P poles, the relationship between the electrical and mechanical angular velocities, ω and ω_m is

$$\omega = \frac{P}{2}\omega_m. \tag{1}$$

- In terms of physical frequency, f(Hz) and n (r.p.m),

$$n = \frac{120f}{P}. \tag{2}$$

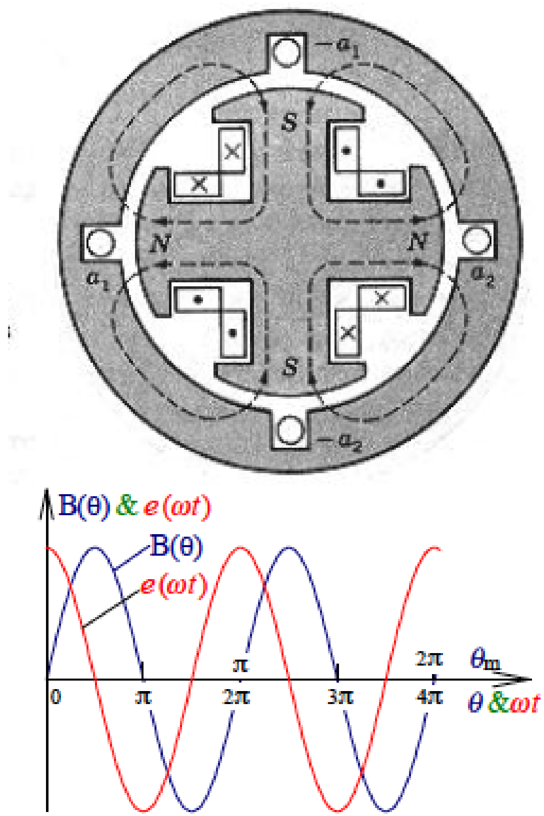

Figure 5: Schematic drawing of a 4-pole synchronous machine along with the sinusoidal waveform of the induced electromotive force (emf) which has units of volts, that is produced by the rotation of the rotor.

- Most wind turbine generators have 4 poles.
- To produce the 60 Hz. frequency that is the U.S. power standard, the rotor would need to spin at 1800 r.p.m!

- For a fixed r.p.m. wind turbine, a gear box would be designed so that at the optimum tip-speed ratio, the generator rotor would spin at the r.p.m. that would produce 60 Hz.
  - This approach is quite restrictive
- An alternate approach is converting the AC power to DC power, after which it is converted back to AC power with the U.S. standard 60 Hz frequency.

2 Wind Turbine Operation Strategy

- Four strategic objectives to wind turbine operation:
  1. to maximize energy production while keeping operation within speed and load constraints,
  2. to prevent extreme loads and to minimize fatigue damage that can occur as a result of repeated bending caused by weight on the rotors and unsteady aerodynamics loads,
  3. to provide acceptable power quality at the point of connection to the power grid, and
  4. to provide safe operation.
- The control approach depends on the wind turbine design:
  1. For ($U_{cut-in} < U_\infty < U_{rated}$) the object is to maximize power production.
  2. For ($U_{rated} < U_\infty < U_{cut-out}$) the object is to limit power to the rated value.
- Two approaches to accomplish this:
  1. Fixed Speed Designs
  2. Variable Speed Designs

2.1 Fixed Speed Designs

- Fixed speed designs fall under two categories:
  1. Stall Regulated
  2. Active Pitch Regulated
- With **Stall Regulated Fixed Speed Control**, the rotor blades are at a fixed pitch angle and are designed to stall at U_{rated} to passively regulate the generated power.
  - They are designed to operate near the optimum tip-speed ratio below U_{rated}.
  - As the wind speed increases, the effective angle of attack of the rotor sections, α, increases, e.g.:

$$\alpha = \phi - [\theta_T + \theta_{cp}] \tag{3}$$

– Now ϕ is given by

$$\phi = \tan^{-1}\left[\frac{1-a}{1+a'}\frac{U_\infty}{\Omega r}\right] \;=\; \tan^{-1}\left[\frac{1-a}{(1+a')\lambda_r}\right] \tag{4}$$

– For fixed θ_T and θ_{cp}, α, is only a function of ϕ.

– For a constant, $\lambda = \lambda_{optimum}$, and near optimum power coefficient, $a \simeq 1/3$ and $a' \simeq 0$,

$$\alpha \simeq \phi \;\sim\; \tan^{-1}(U_\infty) \tag{5}$$

- Therefore there is a direct link between the effective angle of attack and the free-stream wind speed.
- When $\alpha \geq \alpha_{stall}$, L/D will decrease resulting in a decrease in the aerodynamic torque and generated power
- This is the fundamental mechanism of **passive stall regulated fixed speed control**.

- With **Active Pitch Regulated Fixed Speed Control**, the blade pitch is changed to provide power smoothing in high wind conditions.
  - For $U_\infty < U_{rated}$, the blade pitch is kept fixed.
  - This is the chosen approach to limit the pitch mechanism wear.
  - At $U_\infty = U_{rated}$, the blade pitch is dynamically varied to seek to hold a constant power level.
  - At $U_\infty \geq U_{cut-out}$, the blade is pitched to a position that minimized the rotor aerodynamic torque.
  - Mechanical or electrical/reactive breaking is sometimes used to further prevent rotor rotation above $U_{cut-out}$.

2.2 Variable Speed Designs

- Variable speed designs utilize electrical torque control to seek to optimize $\lambda_{optimum}$.
- This is applied to both **stall regulated** and **active pitch regulated** appoaches.
- With **Stall Regulated Variable Speed Control**
  - For $U_\infty < U_{rated}$, variable speed control is used to maintain the optimum tip-speed ratio, seeking to maximize C_p.
  - For $U_\infty = U_{rated}$, Ω is decreased and the rotor blades are allowed to stall.

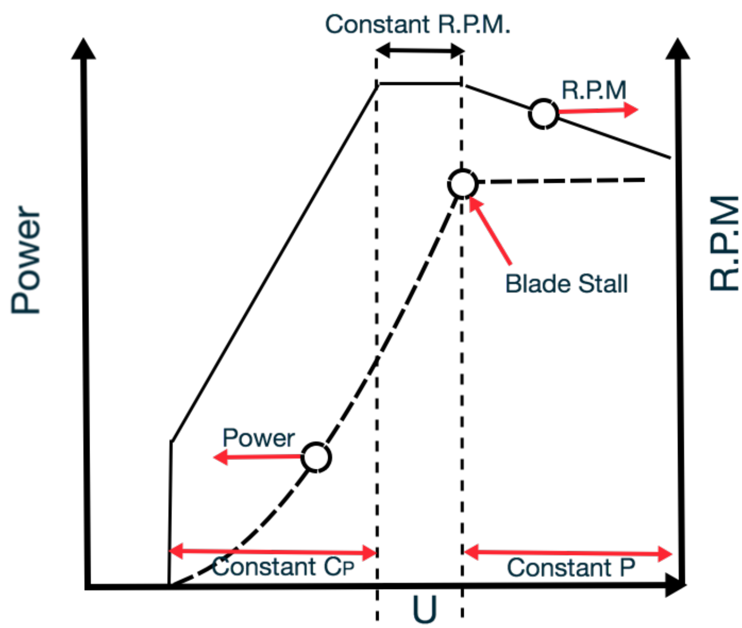

Figure 6: Power curve for a stall regulated wind turbine with variable speed design.

- With **Active Pitch Regulated Variable Speed Control**
  - For $U_\infty < U_{rated}$, the blade pitch is fixed, and variable speed control is used to maintain the optimum tip-speed ratio, seeking to maximize C_p.
  - For $U_\infty = U_{rated}$, the generator torque is used to maintain constant power, pitch control is used to regulate the rotor r.p.m., seeking to maintain the optimum tip-speed ratio.

- Consider a control scheme for **Variable Speed Adaptive Torque Control**
- Object to maximize energy capture between $U_{cut-in} \leq U_\infty \leq U_{rated}$ using variable speed, torque control
- It can be shown that the rotor inertial, $\dot{\Omega}$ is

$$\dot{\Omega} = \frac{1}{2J}\rho A R^3 \Omega^2 \left[\frac{C_p}{\lambda^3} - \frac{C_{p_{max}}}{\lambda^3_{opt}}\right]. \tag{6}$$

where J is the inertial of the rotor.

- If $C_{p_{max}}$ is known apriori, then
  1. if $\lambda > \lambda_{opt}$ then $\dot{\Omega} < 0$ and the rotor needs to decelerate towards $\lambda = \lambda_{opt}$
  2. if $\lambda < \lambda_{opt}$ then $\dot{\Omega} > 0$ and the rotor needs to accelerate towards $\lambda = \lambda_{opt}$.
- Therefore $C_p = (C_{p_{max}}/\lambda^3_{opt})\lambda^3$ is the control trajectory.

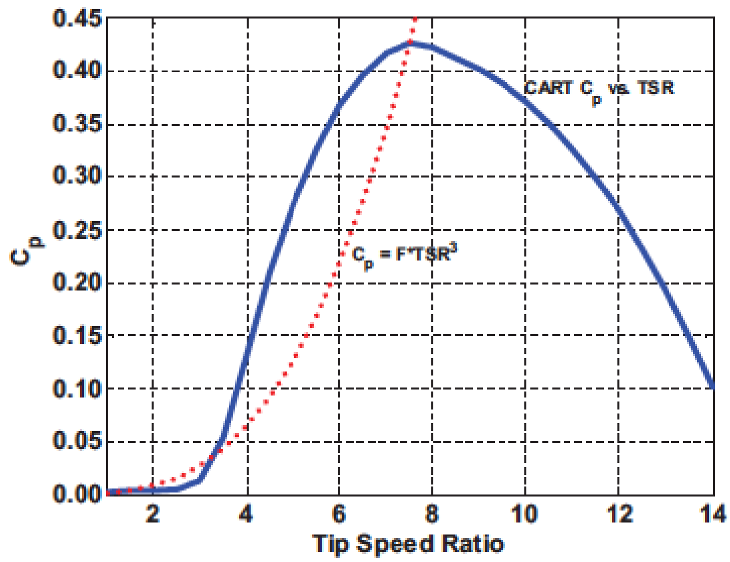

Figure 7: Example of control trajectory to seek the optimum tip-speed ratio for the wind turbine performance shown in Figure 3 with $\beta = -1°$.

3 Axial Induction Control

- Standard control of wind turbines has focused on changing the pitch of the rotor and control of the rotor RPM in order to maintain an λ.
- Standard practice is to have a fixed pitch angle for Region II wind speeds
- The fixed pitch in Region II wind speeds is intended to maximize the average efficiency from U_{cut-in} to U_{rated}
- However, with a rigid rotor, the optimum (Betz) efficiency is generally only approached at a single wind speed, and As a result, performance falls short of optimum.

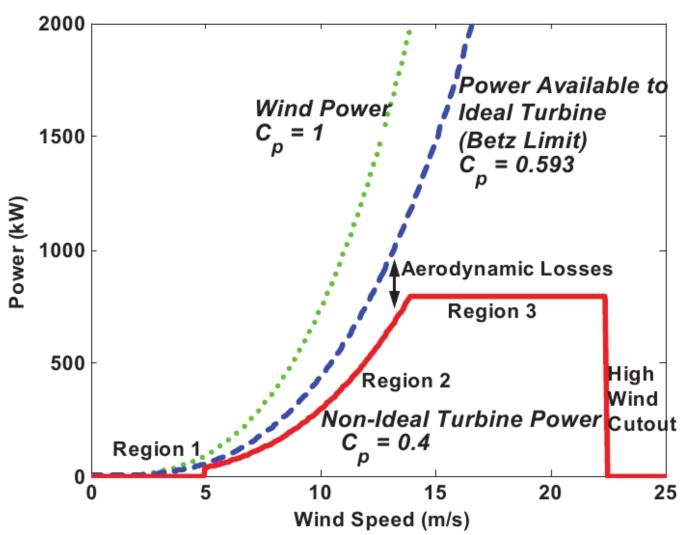

Figure 8: Generic power curve for a wind turbine illustrating optimum (Betz) and actual performance in Region II.

- Following the BEM analysis, the differential torque produced by radial segment of the rotor at radius, r, is

$$dQ = 4\pi\rho U_\infty(\Omega r)a'(1-a)r^2dr - \frac{1}{2}\rho W^2 NcC_d\cos(\phi_r)rdr. \quad (7)$$

- The second term in Equation 7 represents the aerodynamic drag.
- As long as $\alpha < \alpha_{stall}$, we can neglect the drag, therefore

$$dQ = 4\pi\rho U_\infty(\Omega r)a'(1-a)r^2dr. \quad (8)$$

- Substituting for a' in terms of a

$$dQ = 4\pi\rho U_\infty^2 \frac{a(1-a)^2r^2}{\lambda}dr. \quad (9)$$

- Assuming constant wind conditions (ρ and V_∞) and constant λ,

$$dQ = C_1 a(1-a)^2r^2dr. \quad (10)$$

or

$$Q \propto a(1-a)^2. \quad (11)$$

- In terms of the aerodynamic power,

$$P_{aero} = Q\Omega \ = \ P_{aero} \propto a(1-a)^2 \ \propto \ A. \quad (12)$$

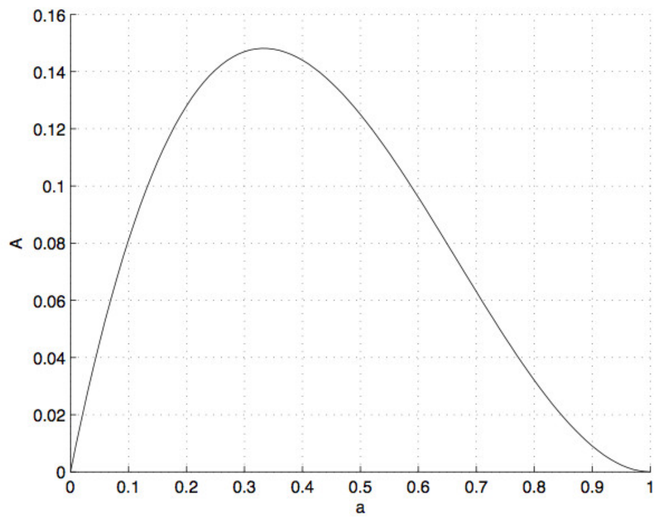

Figure 9: Plot of $A = a(1-a)^2$ versus a showing that the maximum occurs at $a = 1/3$.

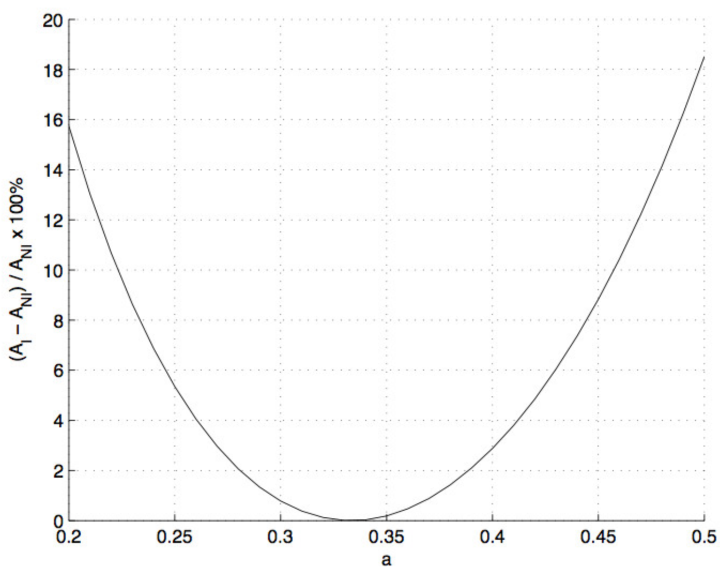

Figure 10: Plot of percent improvement obtained by optimizing the axial induction factor.

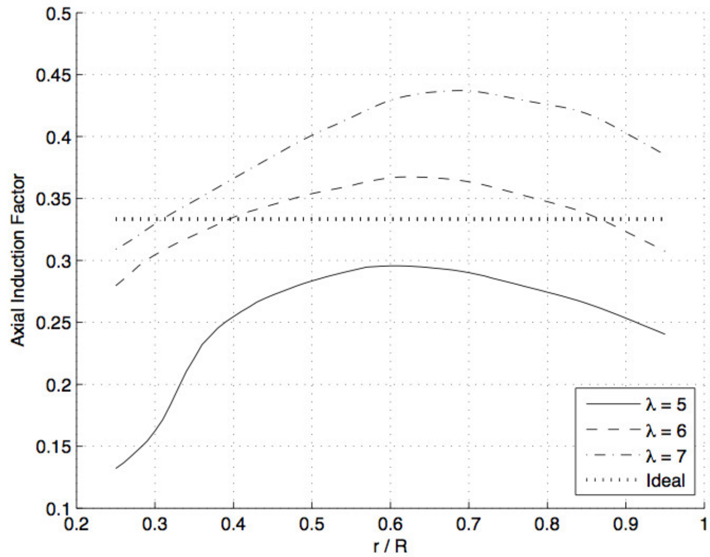

Figure 11: Plot of the rotor radial distribution of the axial induction factor for three tip speed ratios of an existing current-generation wind turbine.

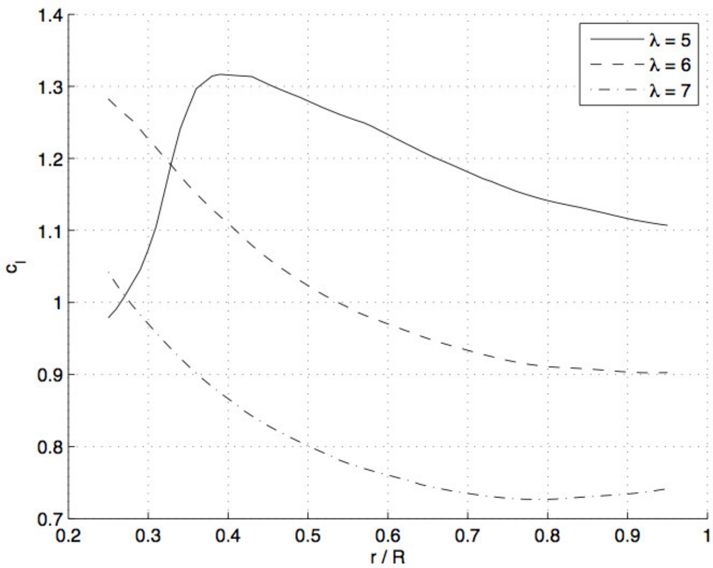

Figure 12: Plot of the rotor radial distribution of the lift coefficient for three tip speed ratios of an existing current-generation wind turbine.

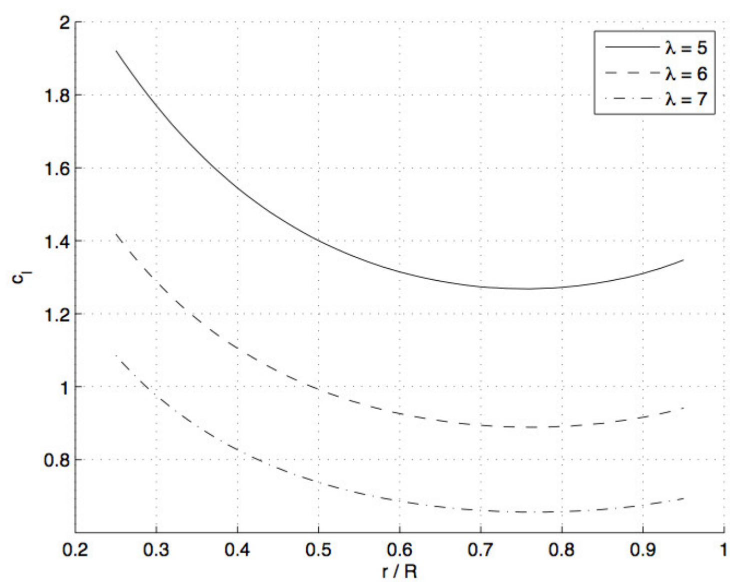

Figure 13: Plot of the rotor radial distribution of the lift coefficient that for which the axial induction factor is the ideal 1/3 for three tip speed ratios of an existing current-generation wind turbine.

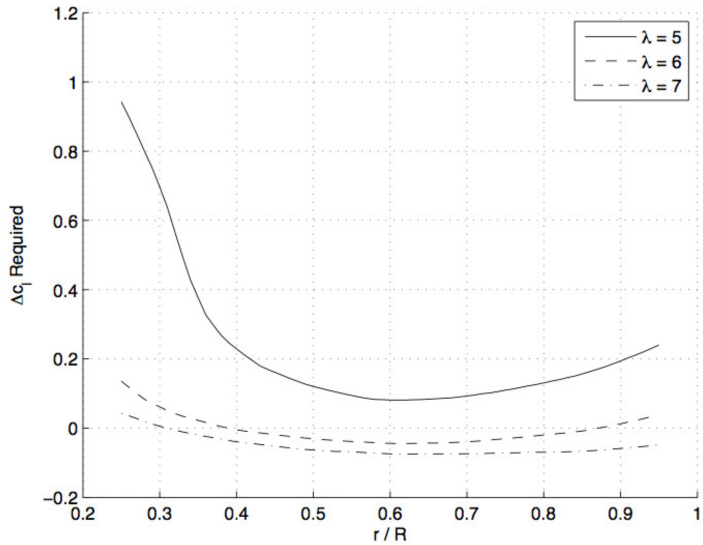

Figure 14: Plot of the rotor radial distribution of the change needed in the lift coefficient to achieve the ideal 1/3 axial induction factor for three tip speed ratios of an existing current-generation wind turbine.

- **Example:** A wind farm rated at 100 MW (approximately 65 1.5 MW wind turbines) and operating with a reasonable 35% capacity factor can produce about 307 GWh of energy in a given year.
  - If the cost of energy is \$0.04 per kWh, each GWh is worth about \$40,000
  - Therefore a 1% loss of energy on this wind farm is equivalent to a loss of \$123,000 per year.
  - A 4% improvement in the power would result in approximately \$500K profit for the wind farm.

Lift Control

- Lift control techniques that have been developed for general airfoils can be applied to wind turbine rotors. These include
  1. plane trailing edge flaps
  2. split trailing edge flaps
  3. Gurney flaps
  4. trailing edge blowing
  5. plasma actuators

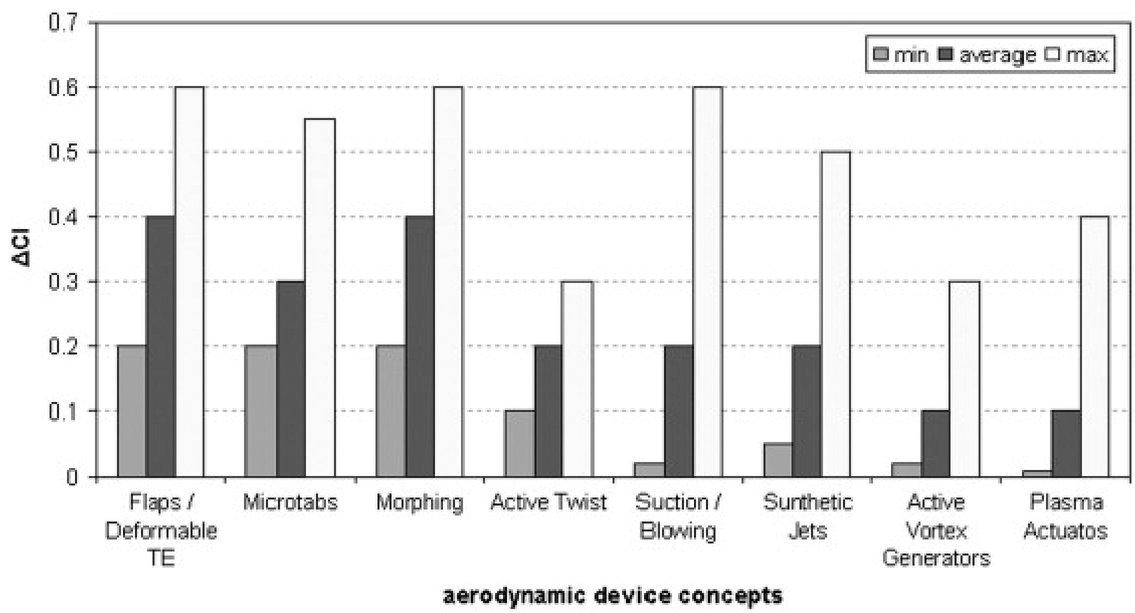

Figure 15: Comparison of the performance of different active lift control approaches.

- **Plane and split trailing edge flaps** have the same effect as changing the camber of an airfoil.

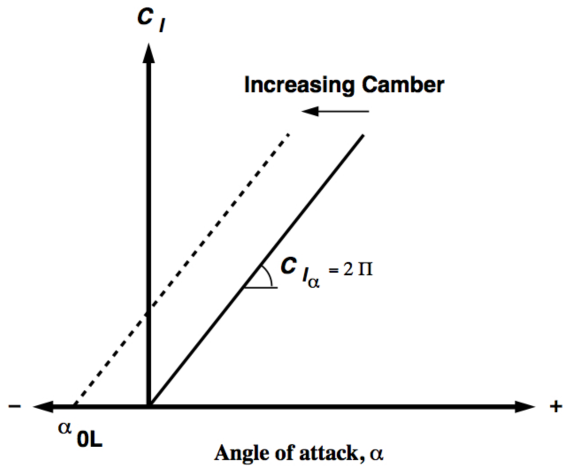

Figure 16: Lift as a function of angle of attack (left) and drag polar (right) for a zero camber airfoil (solid curve) and with a plane trailing edge flap with downward deflection (dashed curve).

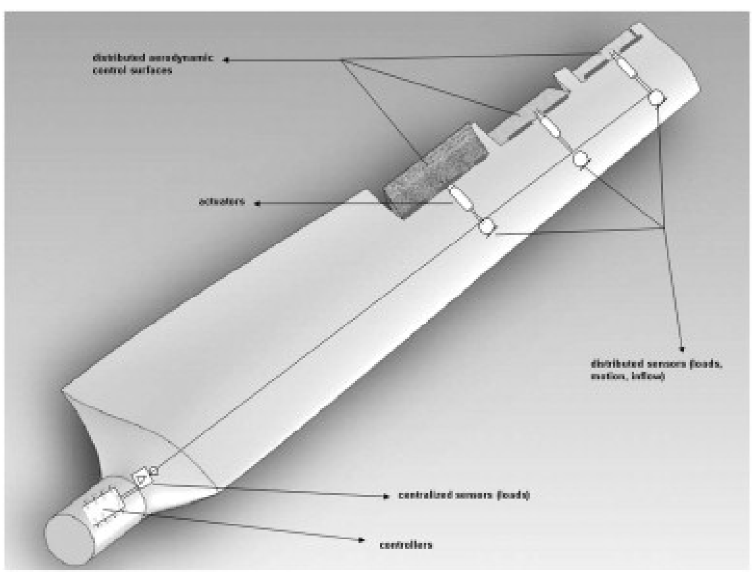

Figure 17: Illustration of spanwise segmented flaps.

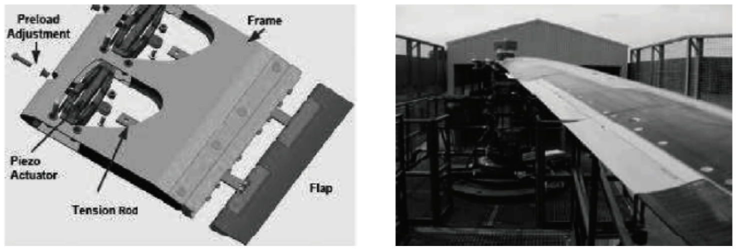

Figure 18: Illustration of spanwise segmented piezo-actuator controlled flaps.

- A variation on a split flap is a **Gurney flap**.
- A Gurney flap on the lower (pressure) surface will produce positive lift
- A Gurney flap on the upper (suction) surface will produce negative lift
- The general rule of thumb for Gurney flaps is that their height should range between 1% to 1.5% of the airfoil chord length, and that their position should be from 0% to 10% of the chord length from the trailing edge of the airfoil.
- The largest effect occurs when the Gurney flap is placed at the exact trailing edge.

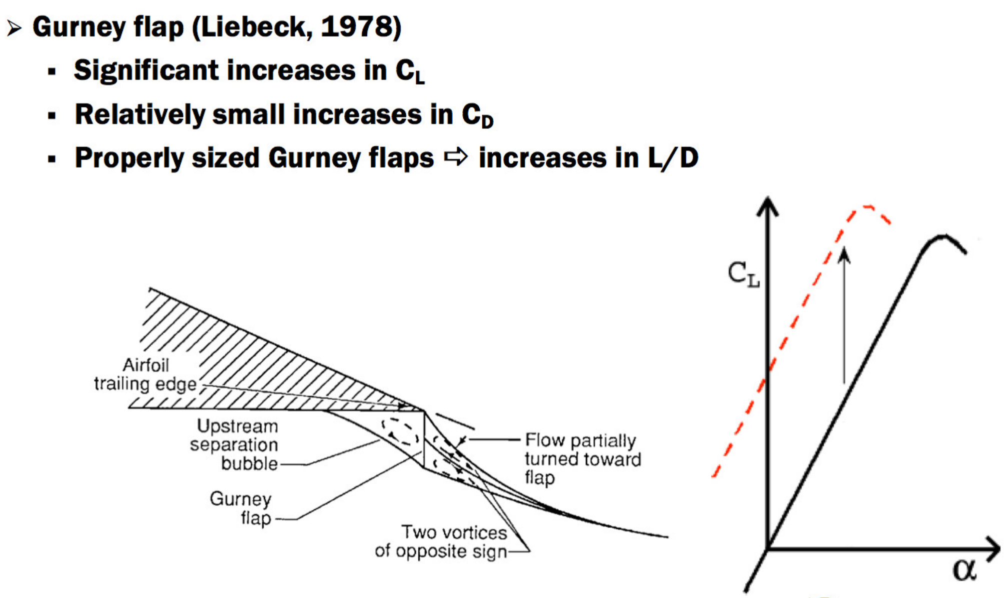

Figure 19: Illustration of a Gurney flap for lift control.

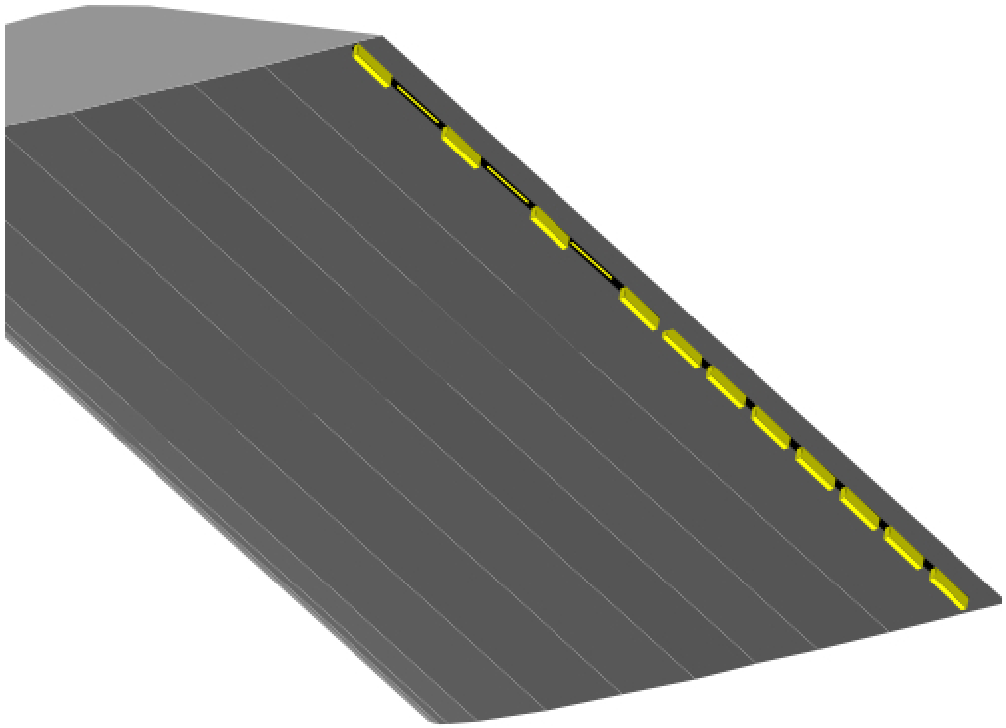

Figure 20: Illustration of multiple spanwise Gurney flaps for spanwise varying lift control. (From VanDam

- Variable geometry section shapes

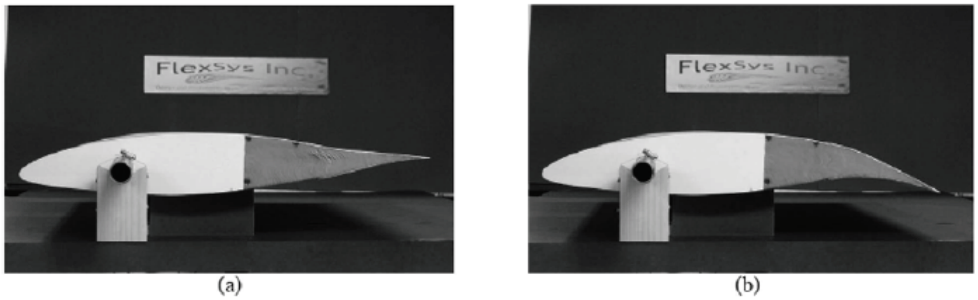

Figure 21: Flexsys flexible airfoil.

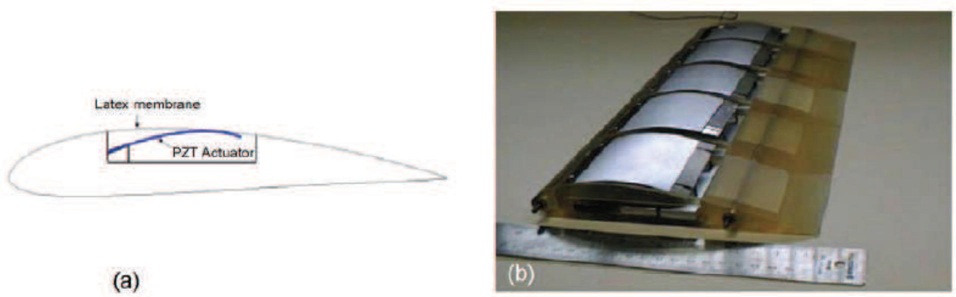

Figure 22: Flexsys flexible airfoil.

- Circulation control

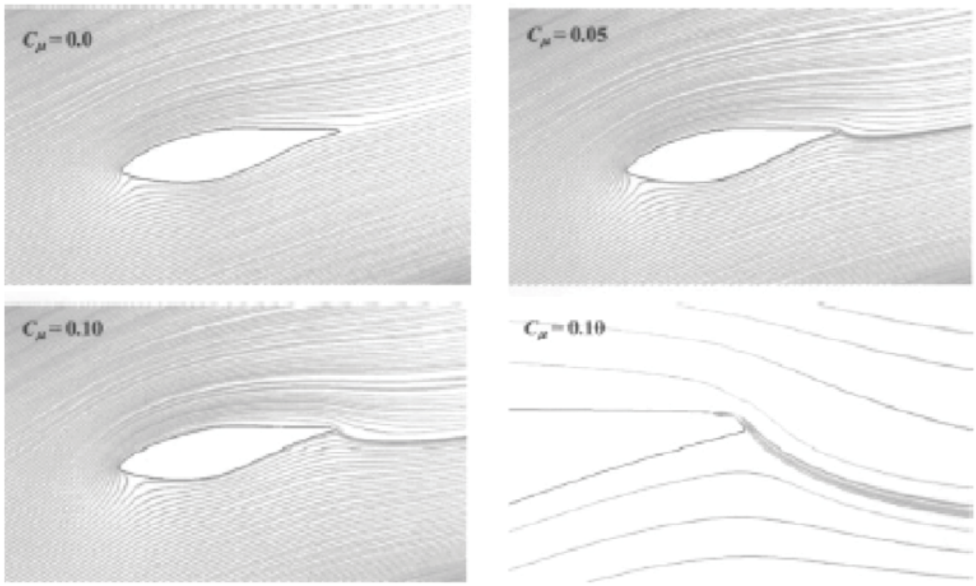

Figure 23: Circulation control airfoil.

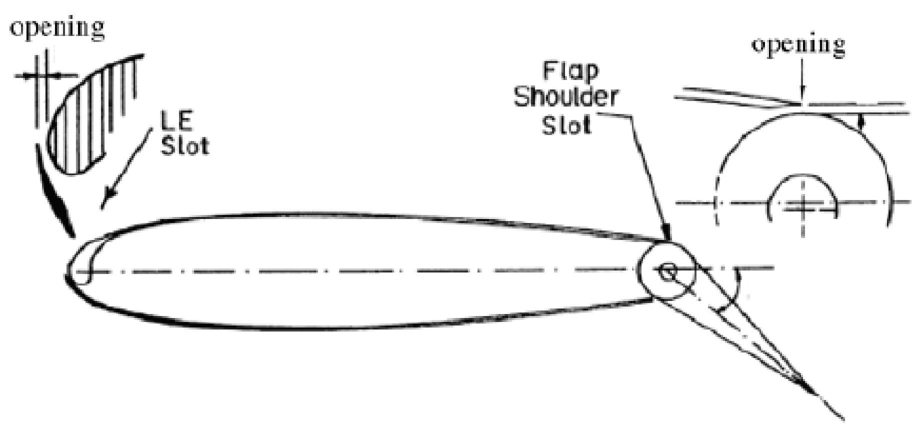

Figure 24: Leading and trailing-edge blowing airfoil.

- Plasma actuators

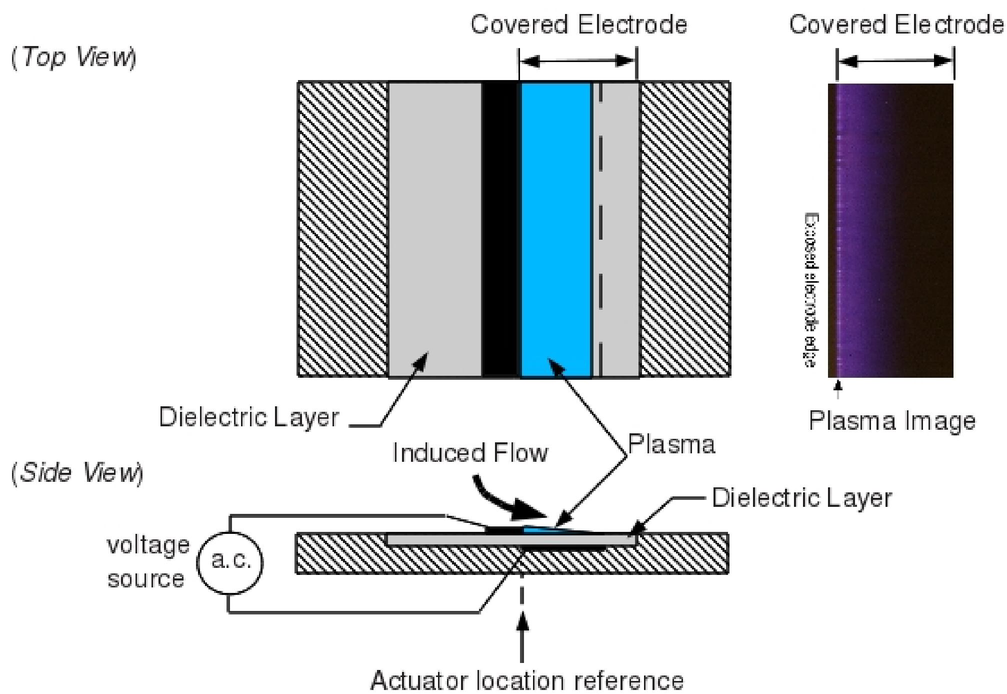

Figure 25: Plasma actuator schematic.

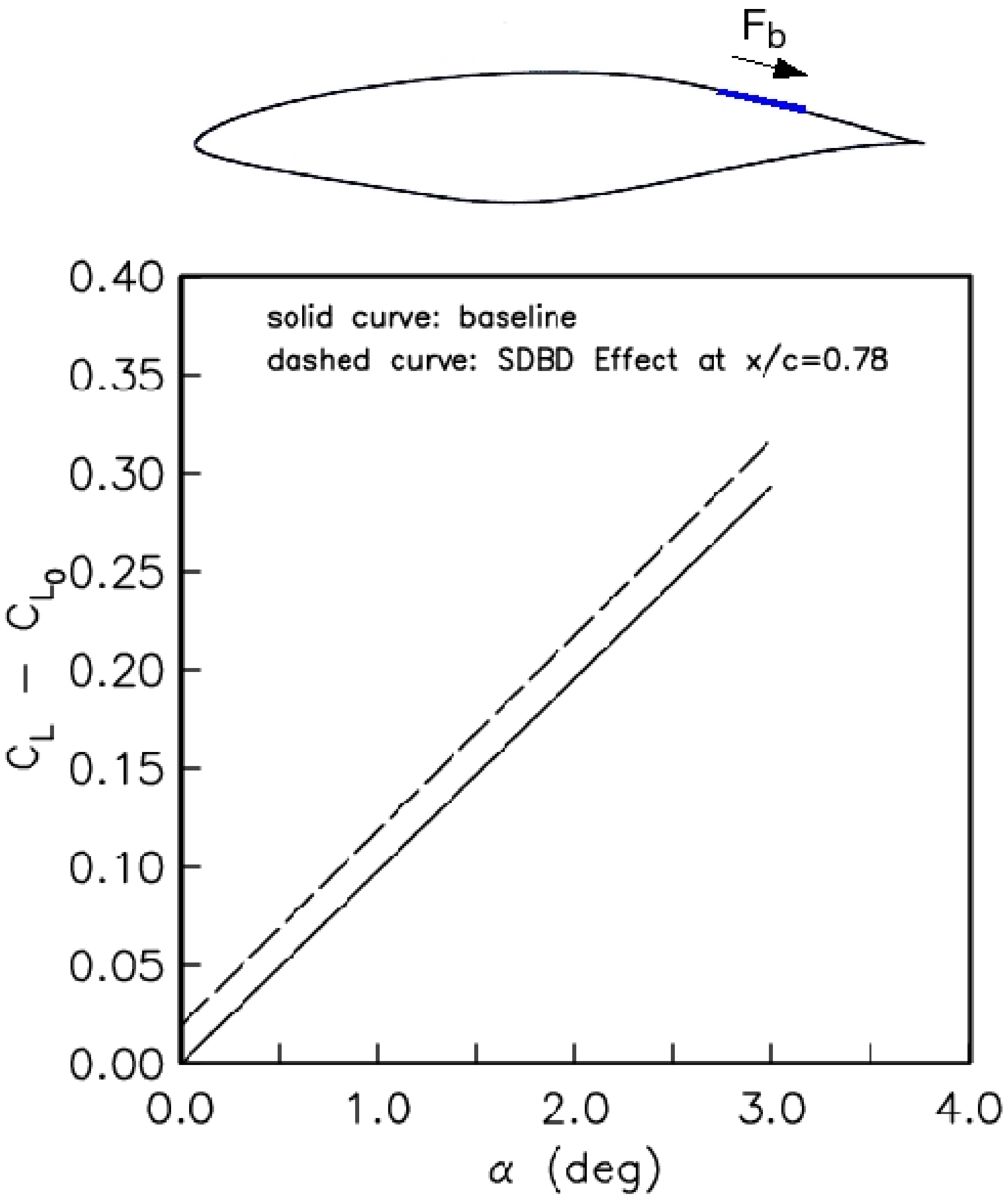

Figure 26: TE plasma actuator effect.

- Rotor tip extensions

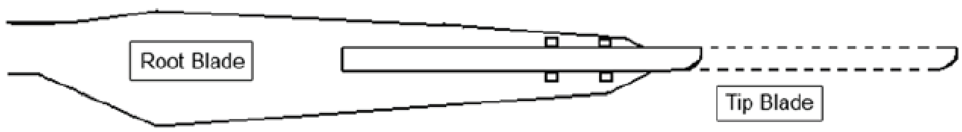

Figure 27: Rotor tip extensions.

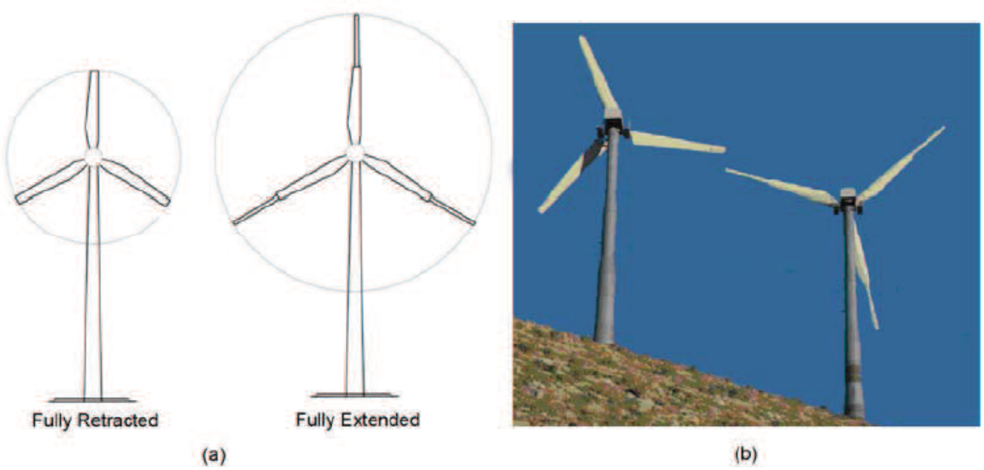

Figure 28: Rotor tip extensions.