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Wind Energy: Outline of Turbine Control

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Lecture Plan

Heading	Topics	Duration	Lecture
Intro to wind	Growth of wind and some pictures	20 mins	1
Energy Yield	Power curve; Wind Histogram; Load Factor	30 mins	1
Blade Aerodynamics	Airflow Components; Drag and lift; Rotation and Bending,	40 mins	1
Betz Limit	Stream tubes; Derivation	20 mins	1
Coursework	Describe task and show maps	10 mins	1
Outline of Turbine Control	Cp curves and tip-speed ratio; two control regions; optimal torque equation	30 mins	2
Electrical Generators	Full-converter and DFIG options; Drive train efficiency and control	30 mins	2
Wakes and Farm Layout	Wake examples; wind rose; turbine spacing; collector network	20 mins	2
Offshore Wind	UK examples; cable characteristics; HVDC	20 mins	2

The Case for Variable Speed Generators

Turbine blades have an optimal value of tip-speed ratio, λ at which they produce a maximum power coefficient C_P and maximum power.

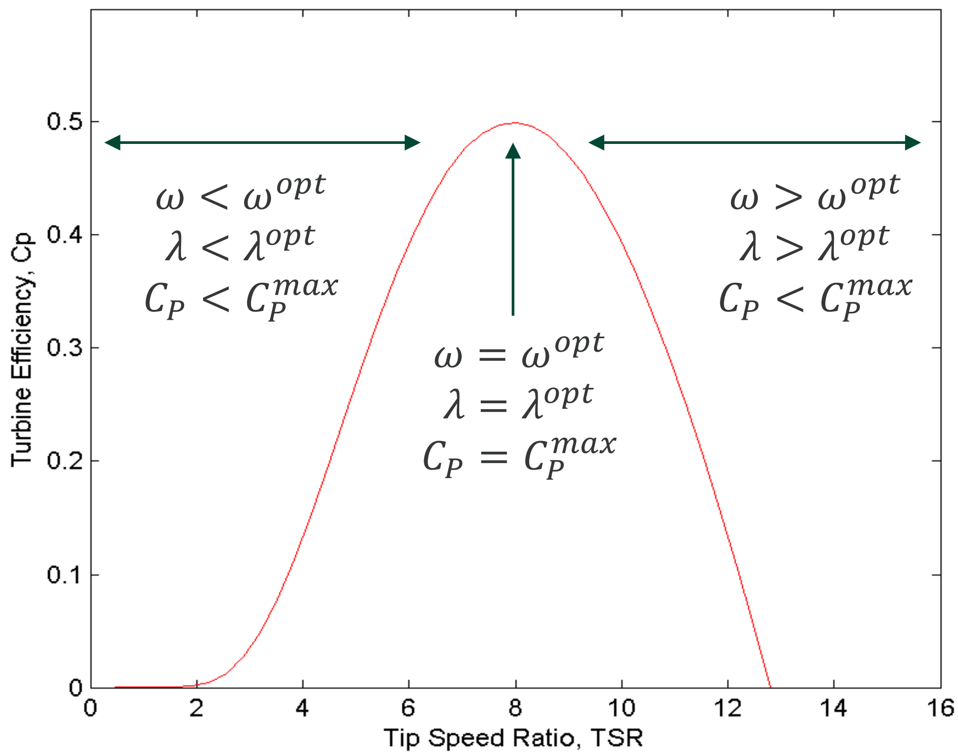
$$P_T = C_P \frac{1}{2} \rho A V^3$$

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

The optimal tip-speed ratio indicates the rotational speed that the blades should rotate at for a given wind speed.

$$\omega^{opt} = \lambda^{opt} \frac{V}{R}$$

Rotating at ω^{opt} ensures that the optimum angle of attack is maintained between the relative wind and the chord at each blade profile

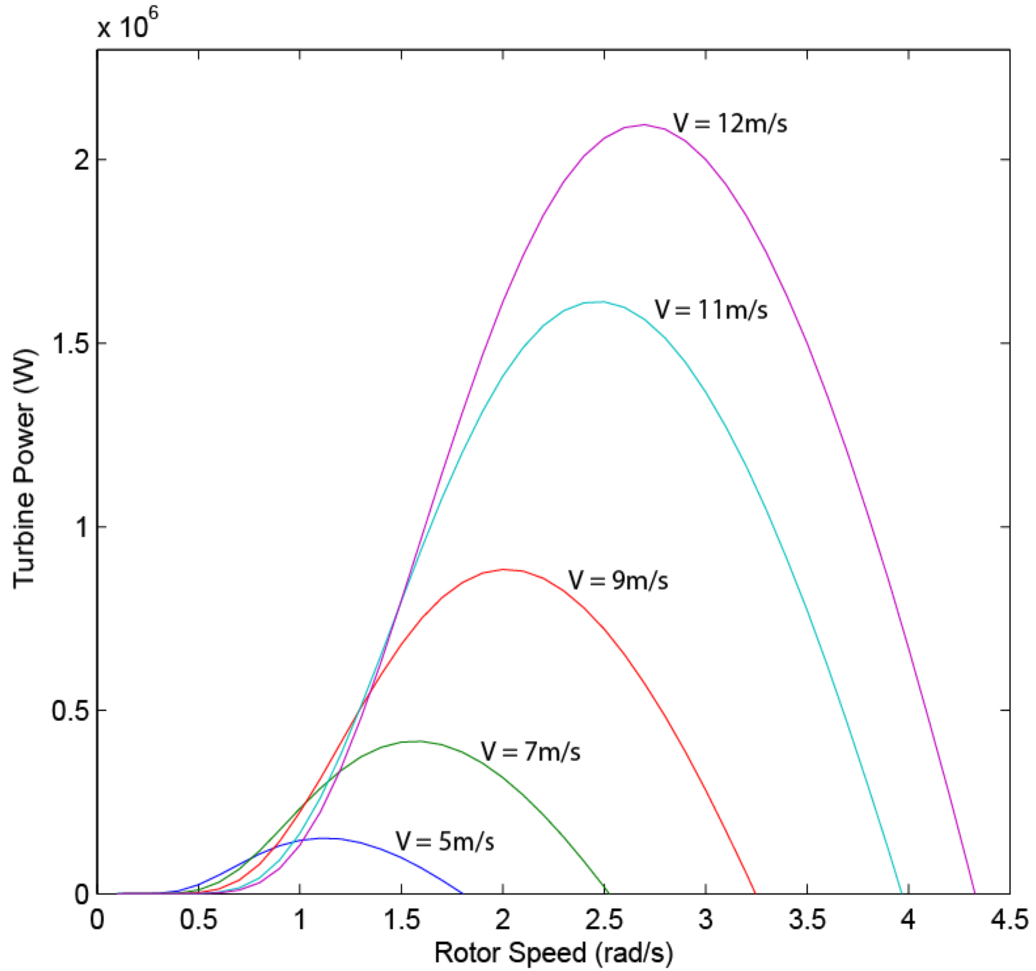


Power as a Function of Turbine Speed

If we "de-normalise", that is, don't plot against λ but against turbine speed, ω, we get a family of curves

For each wind speed we need to use a different rotational speed to achieve the maximum power (maximum C_P)

This is the case for "variable speed" wind turbines.



Power Control for a Wind Turbine

We have two principal ways to intervene in operation of a wind turbine to control the power yield:

1. We can alter the angle of attack of the blades by rotating the blade around its own longitudinal axis. This is called **pitch control**.

2. We can control the speed of the turbine by altering the current (and hence power) that is drawn from the generator by controlling the AC-to-DC converter. This is call **(generator) torque control.**

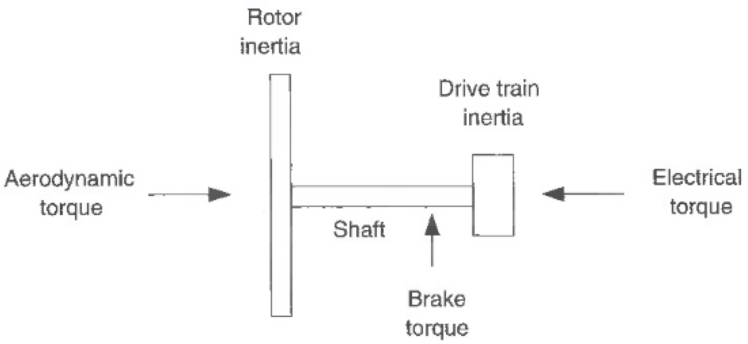
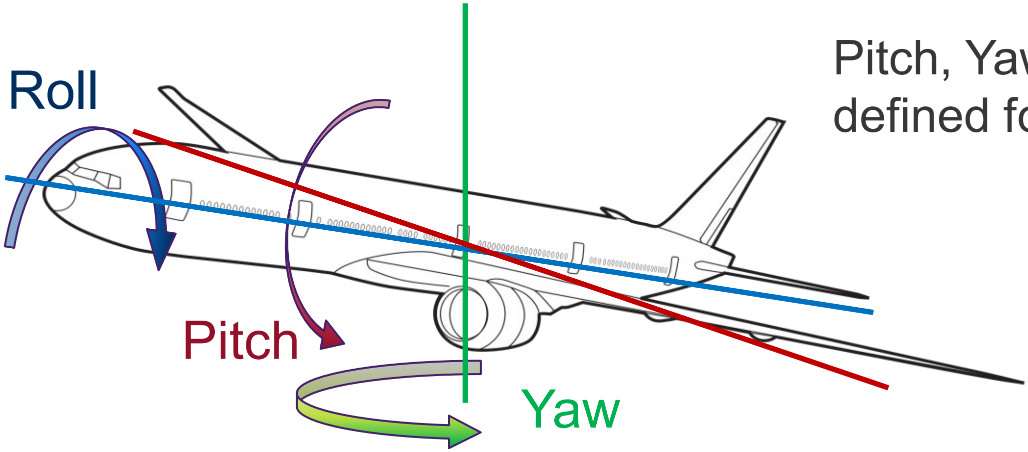


Figure 8.3 Simple wind turbine model

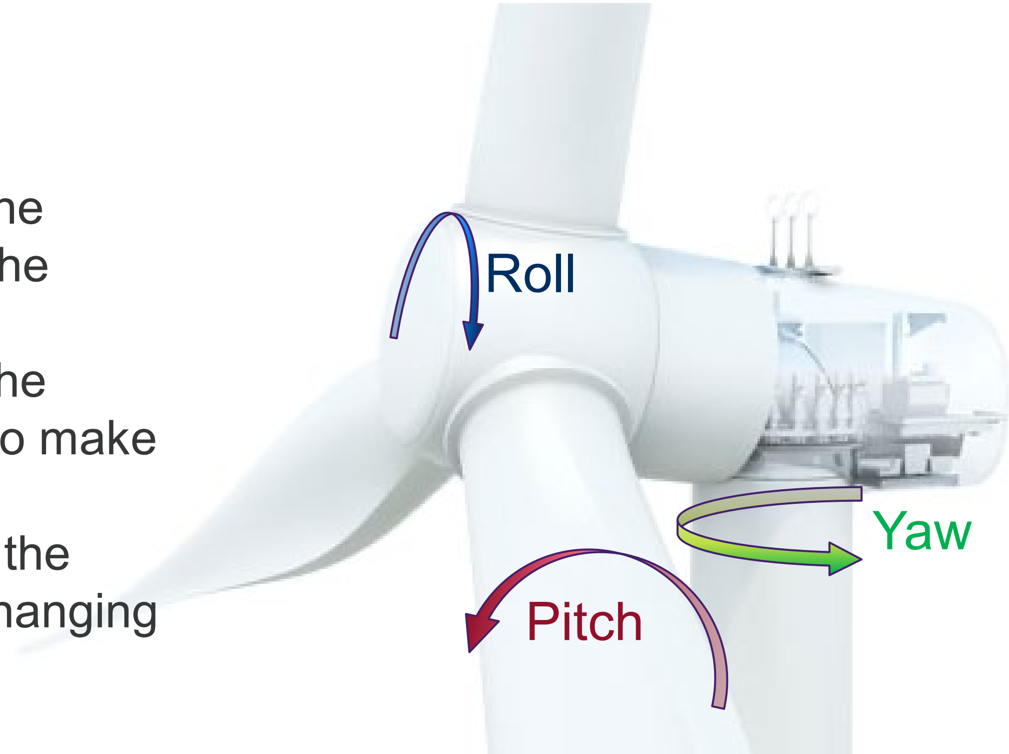
Definitions of Pitch, Yaw and Role



Pitch, Yaw and Roll were originally defined for ships and aircraft.

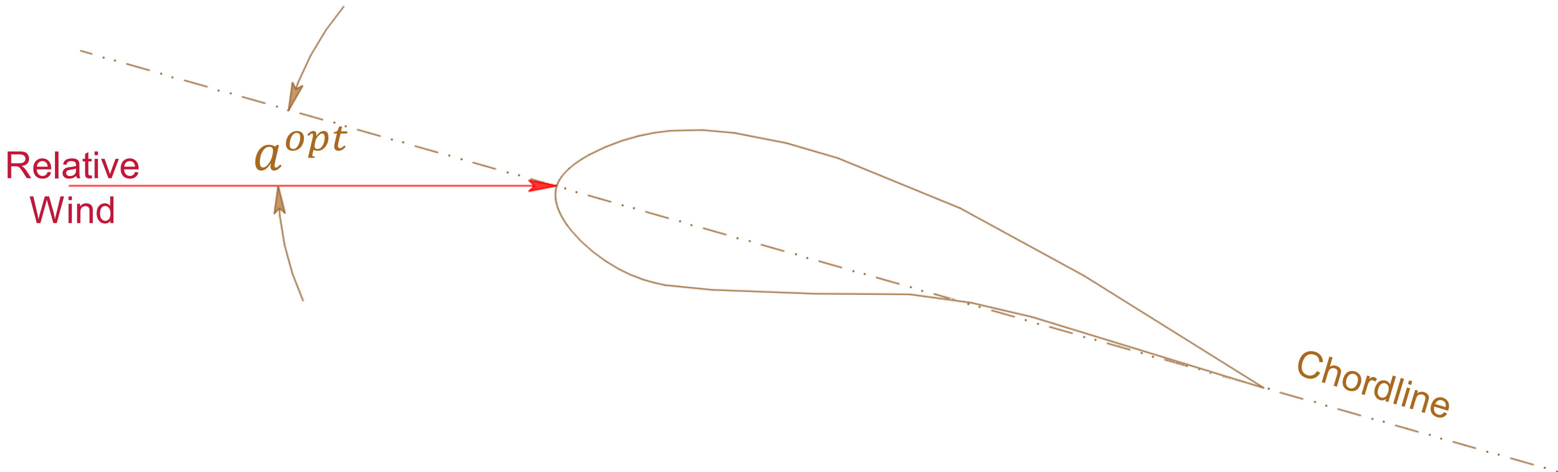
For a wind turbine:

- **Roll** is the direction of rotation of the blades around the nacelle to turn the generator.
- **Yaw** is the direction of rotation of the nacelle around the tower in order to make the blade disc face into the wind.
- **Pitch** is the direction of rotation of the blades around their own axis for changing the angle-of-attack.

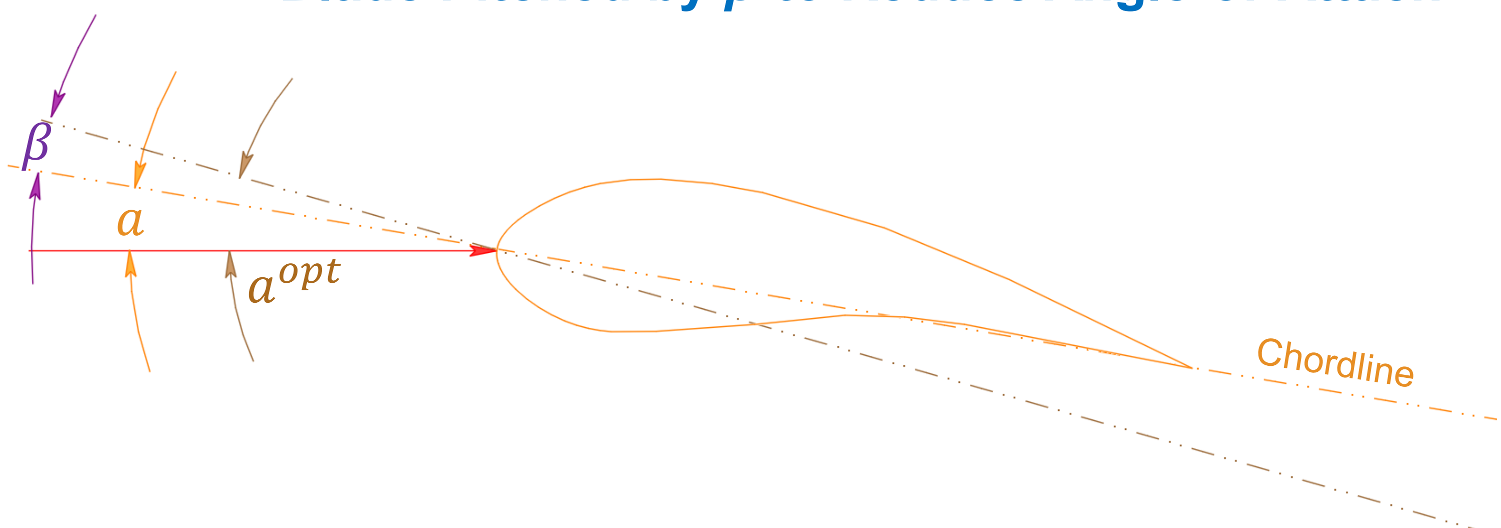


Blade Pitch Angle, β

Blade at Optimal Angle-of-Attack



Blade Pitched by β to Reduce Angle-of-Attack

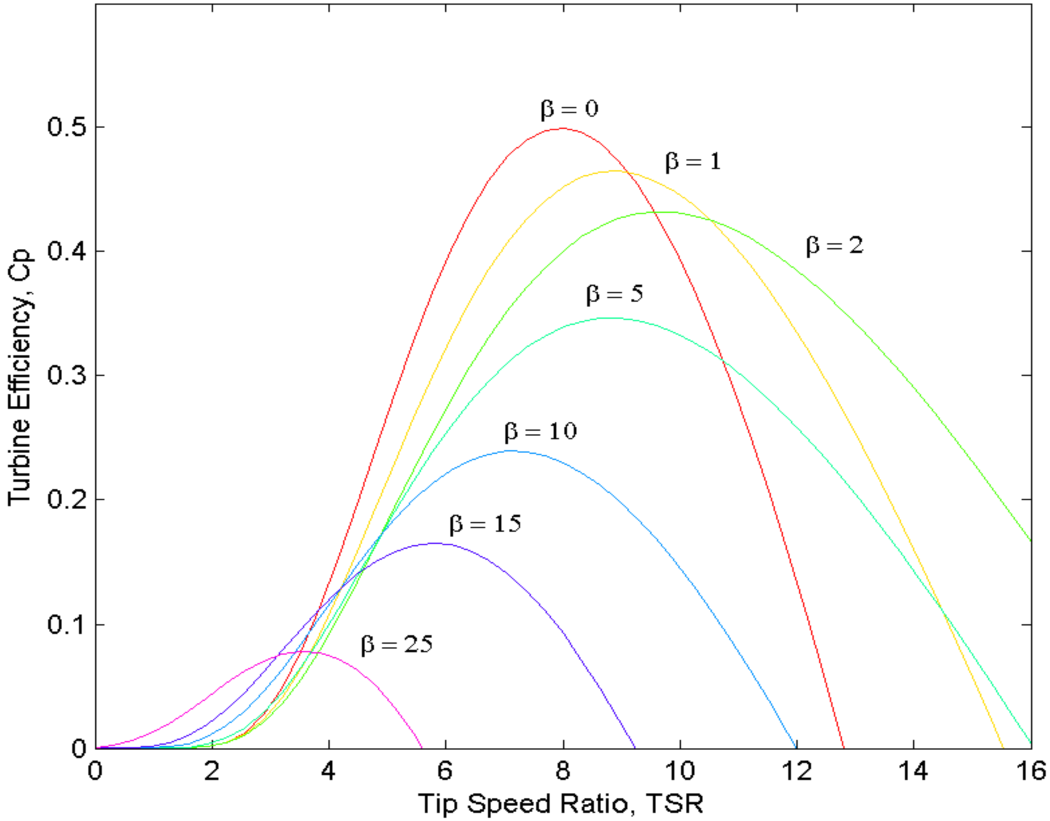


Blade Pitching for Control (high wind)

Pitching into the wind reduces the lift force and therefore reduces the power extraction.

Pitching is used to control speed and power under high wind speed conditions.

$$C_P = C_P(\lambda, \beta)$$



Pitching changes the peak and the shape of the curve of power against tip speed ratio, λ.

Turbine Control Regions

TORQUE CONTROL

Maximise Power

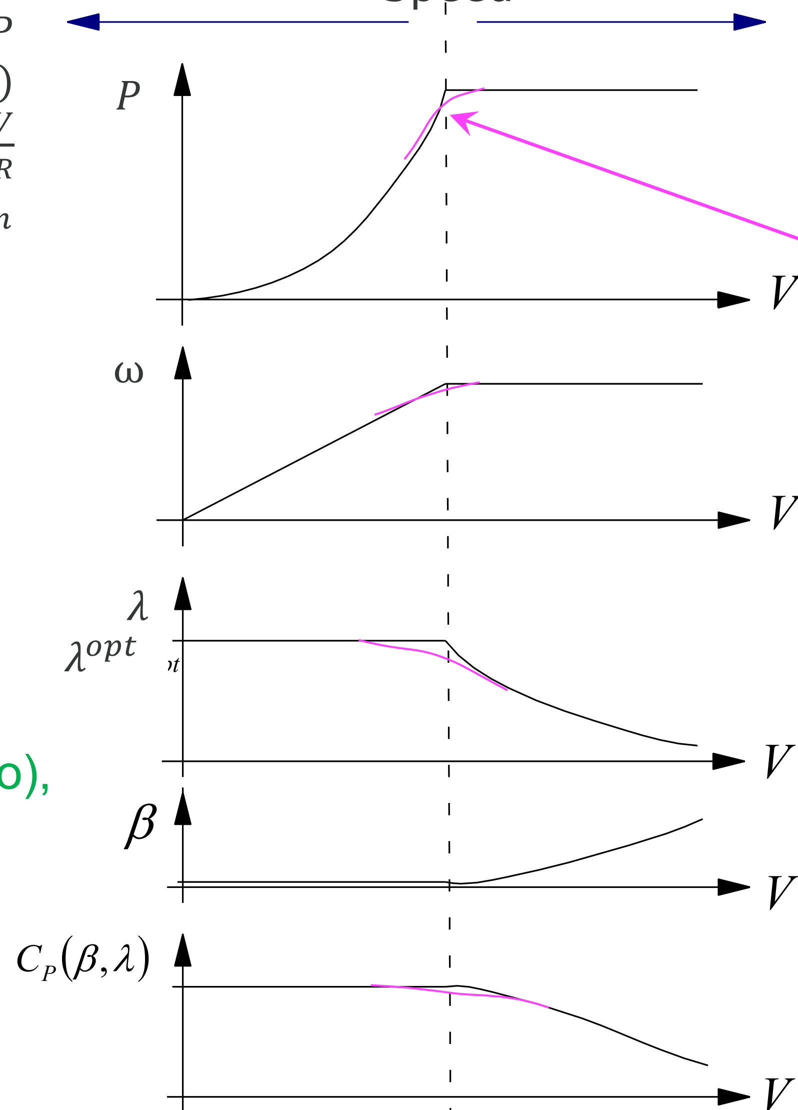
Base Speed

Limit Power

PITCH CONTROL

Maximise P
Hold $C_P = C_P(\lambda^{opt}, \beta^{opt})$
Control $\omega = \lambda^{opt} \frac{V}{R}$
by adjusting P_{Gen}

Set $P_{Gen} = P_{Rate}$
control $\omega = \omega_{Rated}$ by
adjusting β



A transition region is often used

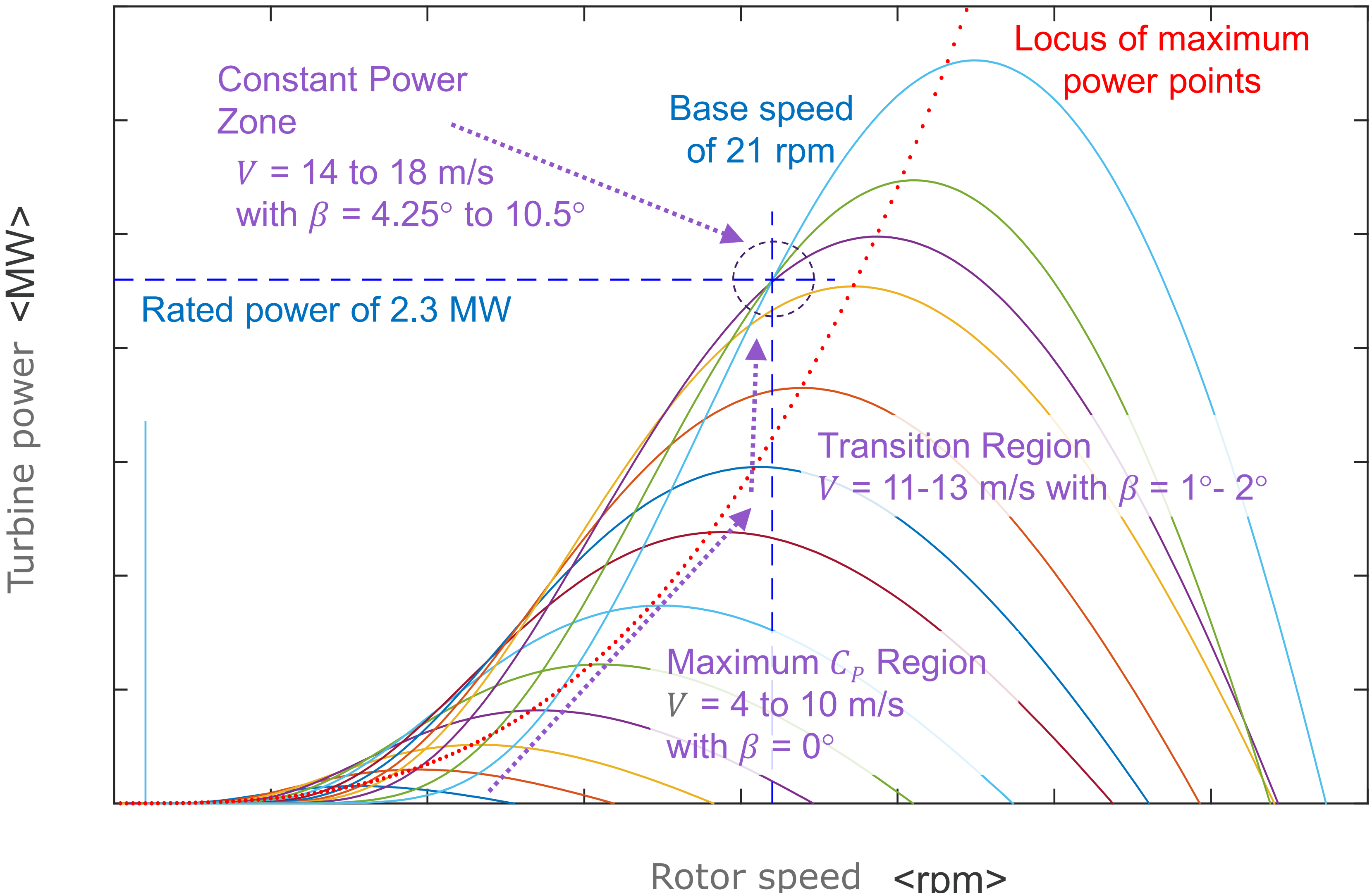
At low wind speeds, optimise the power extraction with optimal pitch, β^{opt} (typically zero), and optimal tip-speed ratio, λ^{opt}

At high wind speed, hold power at rated value using blade pitching and reduction of λ

Maximum C_P and Constant Power regions against Rotor Speed

Contour lines show wind speeds

Based on an Enercon E70: 70m diameter turbine and direct-drive generator



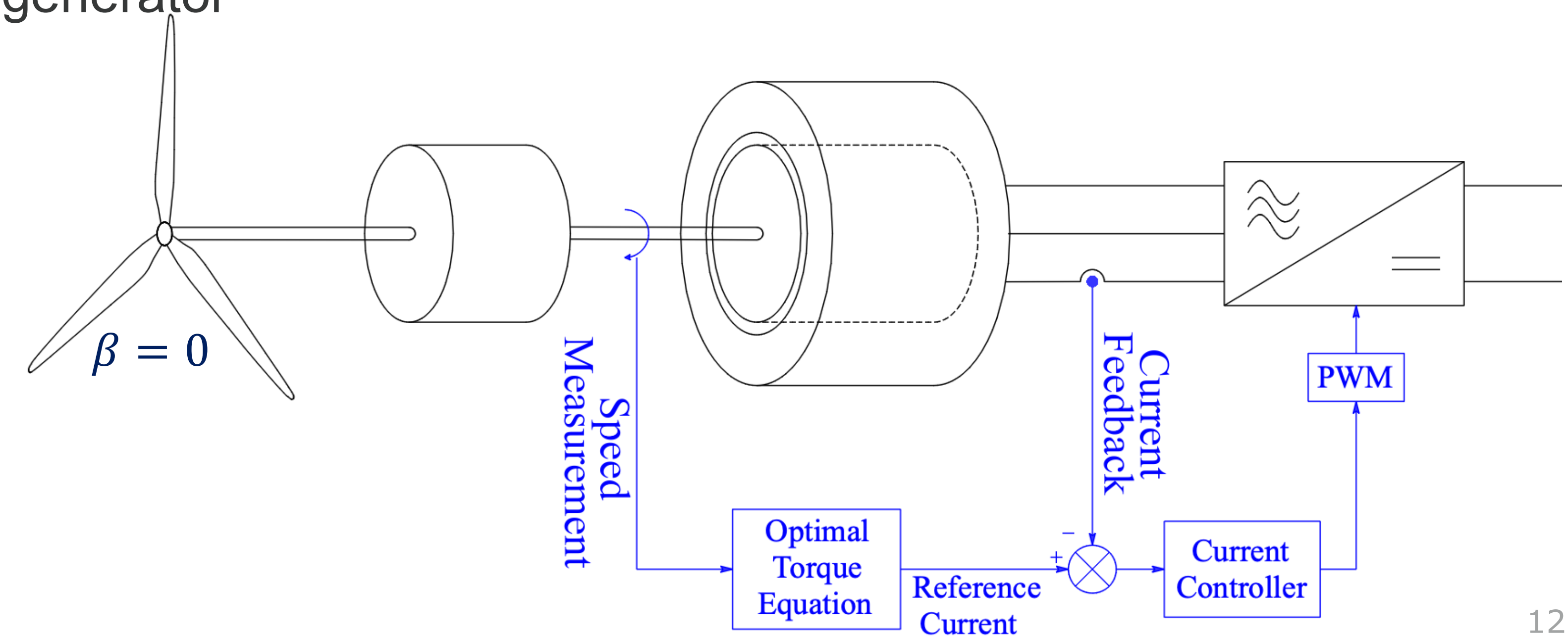
Power Optimisation Region (low wind)

To obtain maximum power we seek to operate at $C_P = C_P^{max}$

- Set the blades for maximum lift with $\beta = 0$
- Set the turbine rotational speed speed so that $\lambda = \lambda^{\mathrm{opt}}$ for the prevailing wind speed V.

We avoiding having to measure the wind speed by instead

- Determining an optimal relationship between torque and rotational speed
- Set the **generator reaction torque** by controlling the current drawn from the generator



Relationship between Torque and Power

In general

$$P = \tfrac{1}{2}\rho A_T C_P(\lambda, \beta)\, V^3$$

The maximum power points are when

$\beta = 0$ and $\omega = \lambda^{opt}\,\frac{V}{R}$

giving

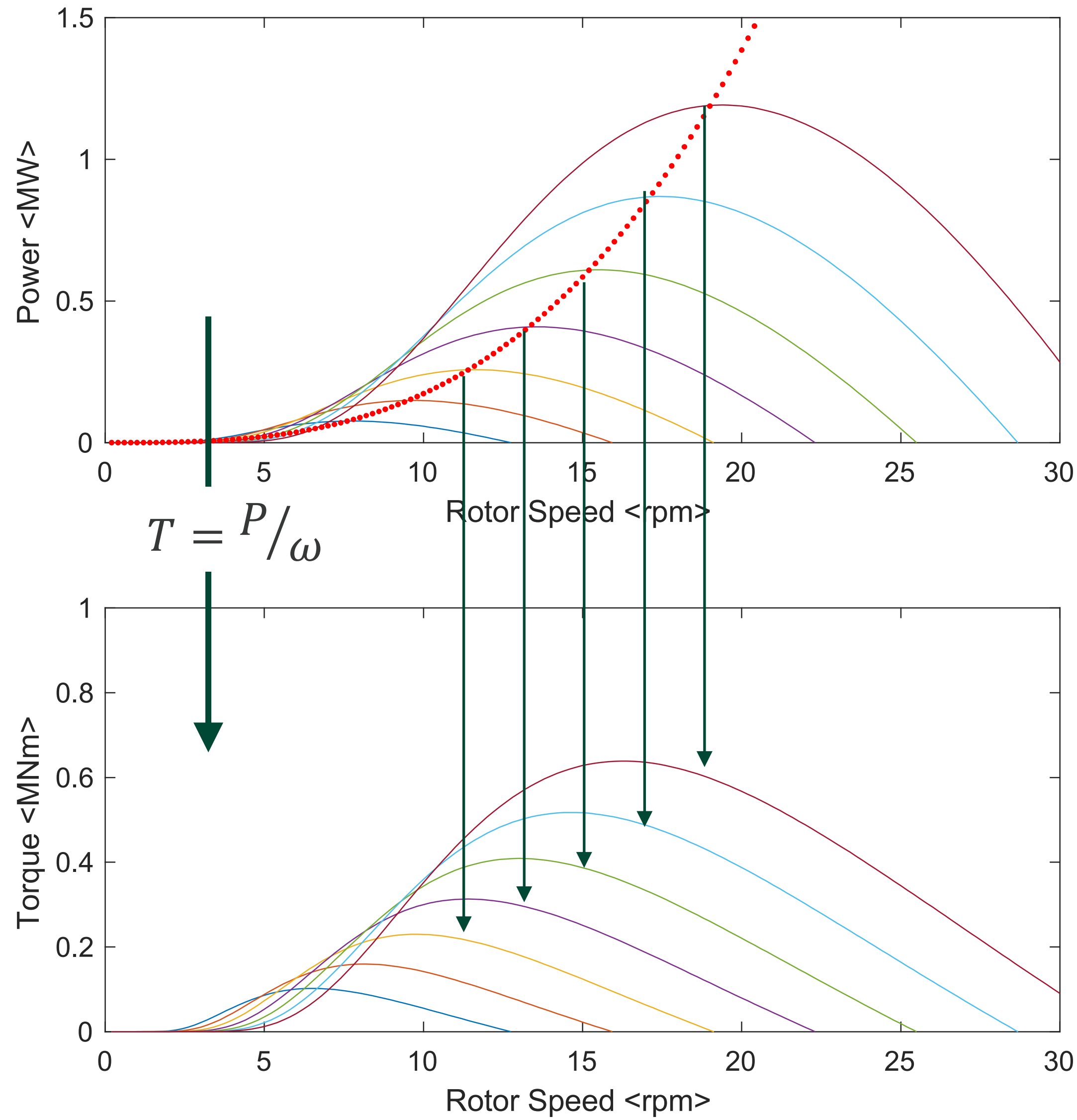
$$P = \tfrac{1}{2}\rho A_T C_P(\lambda^{opt}, 0)\, V^3$$

The torque exerted by the turbine can be found from

$P = T\omega$

$$T = \tfrac{1}{2}\rho A_T C_P\, \frac{V^3}{\omega}$$

Each maximum power point has an associated optimal torque



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Determination of Optimal Torque

- We first express expected turbine power in terms of $\lambda = {}^{\omega R}/_{V}$

$$P = ½\rho A_T C_P(\lambda, \beta)\, V^3 = ½\rho A_T C_P(\lambda, \beta)\frac{\omega^3 R^3}{\lambda^3}$$

- We then assume that $\beta = \beta^{opt}(= 0)$ and $\lambda = \lambda^{opt}$ will be used so that $C_p = C_P^{max}$. From that, find the expected torque at the maximum power point from $T = P/\omega$

$$P^{max} = ½\rho A_T C_P^{max}\frac{\omega^3 R^3}{\lambda^{opt^3}}$$

$$T^{MPP} = \frac{P^{max}}{\omega}$$

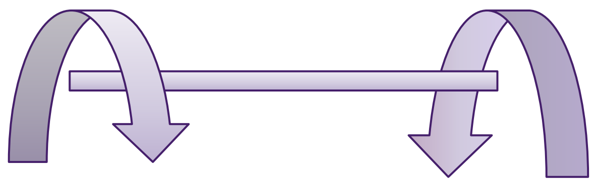
$$\boxed{T^{MPP} = ½\rho A_T C_P^{max}\frac{\omega^2 R^3}{\lambda^{opt^3}}}$$

Torque Balance

Consider the torques (rotational forces) acting on the shaft connecting the turbine blades to the generator.

Turbine Torque **Generator Reaction**

Turbine torque acts to accelerate the shaft clockwise (seen from this end)



Generator reaction torque acts against the turbine torque.

The shaft is in equilibrium if the turbine and generator torques match perfectly (that is, no acceleration if $T_T - T_G = 0$).

But is it a stable or unstable equilibrium?

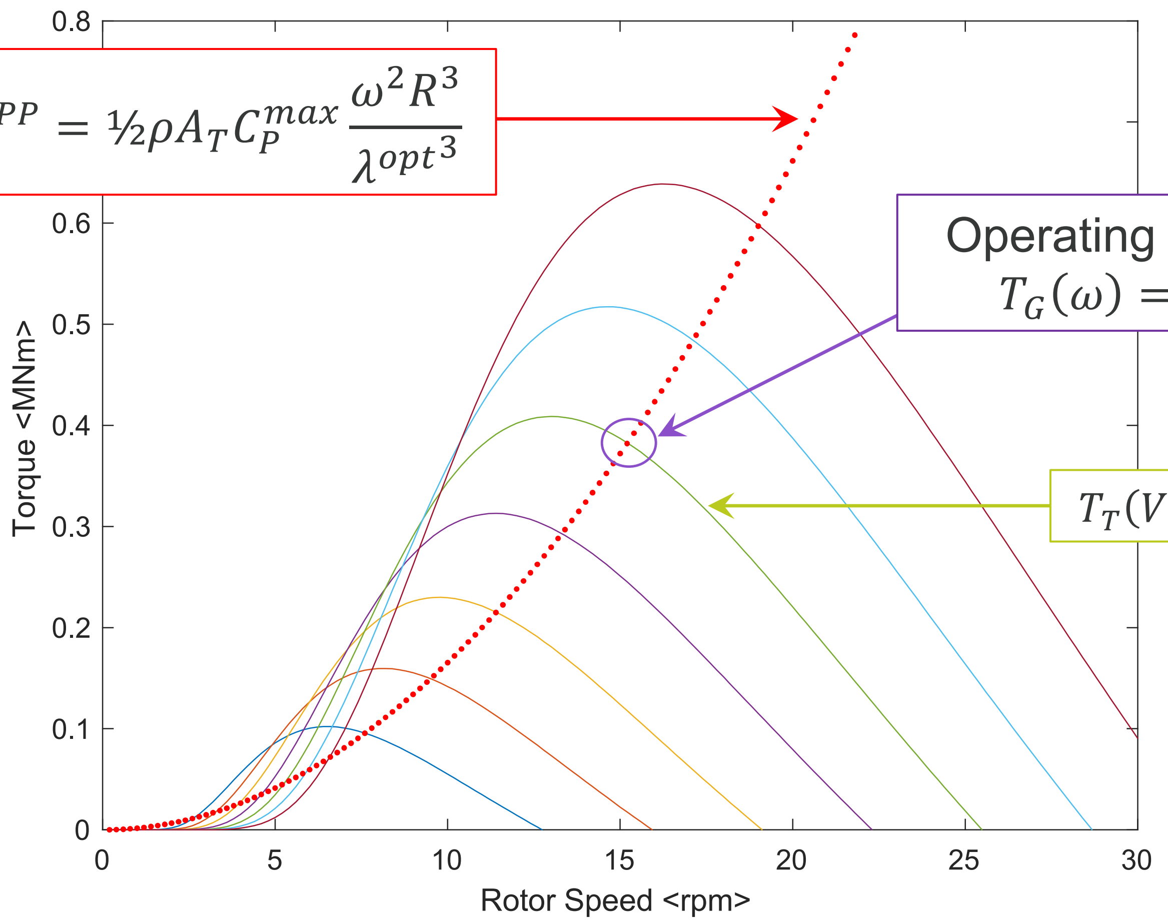
If the system is perturbed, does it return to its equilibrium point?

To answer that we have to know how the two torques change as a function of speed and how a perturbation affects their balance.

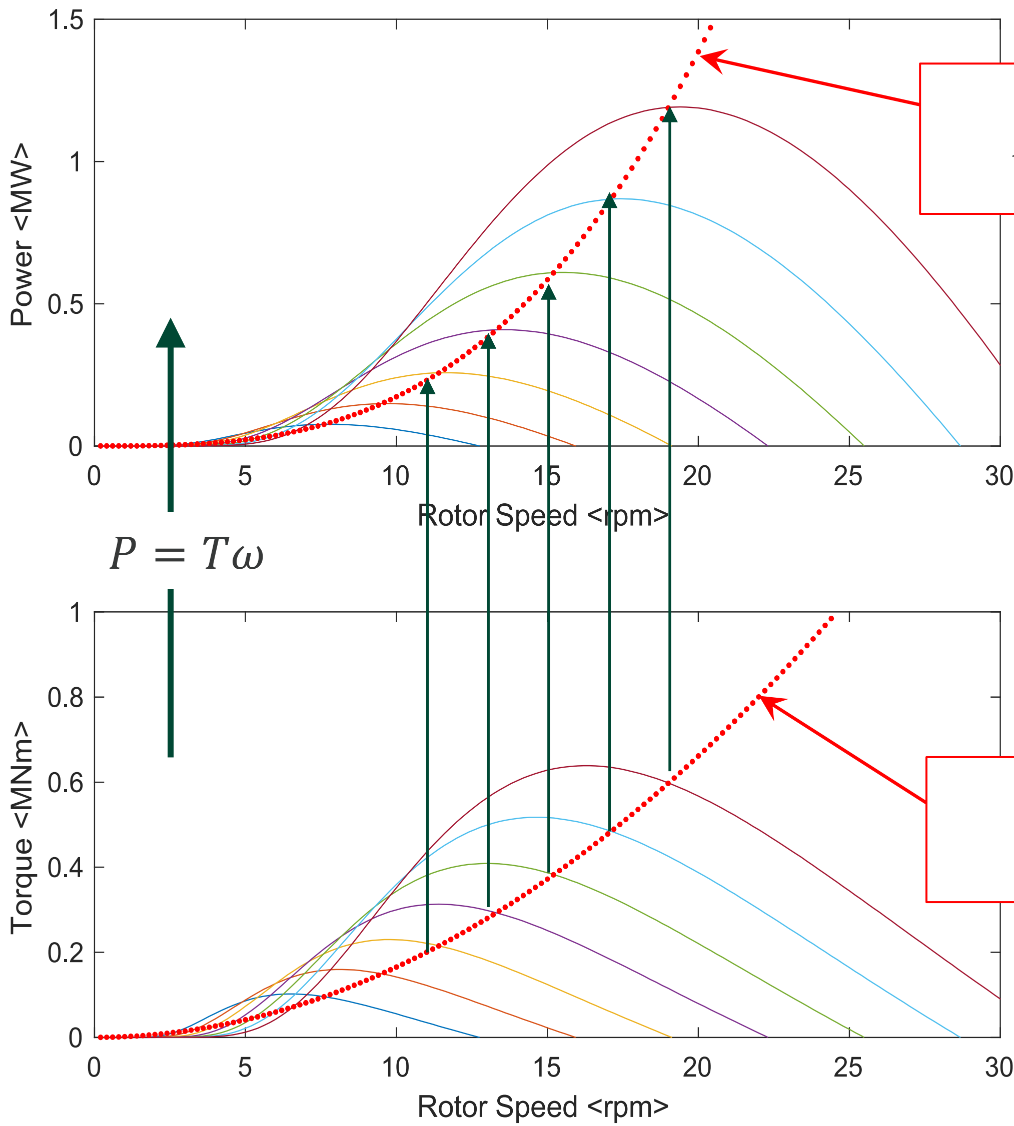
Operating Points in Optimal Power Region

Set generator torque equal to torque corresponding to maximum power points. Generator torque crosses each turbine torque curve creating series of equilibria for each wind speed that correspond to maximum power points.

$$T_G = T^{MPP} = ½\rho A_T C_P^{max} \frac{\omega^2 R^3}{{\lambda^{opt}}^3}$$



Torque Equilibrium Points Match the Maximum Power Points



$$P^{MPP} = ½\rho A_T C_P^{max} \frac{\omega^3 R^3}{\lambda^{opt^3}}$$

$$T^{MPP} = ½\rho A_T C_P^{max} \frac{\omega^2 R^3}{\lambda^{opt^3}}$$

Because the generator torque curve was calculated from the maximum power curve, each operating point at a torque equilibrium is the maximum power point for that wind speed.

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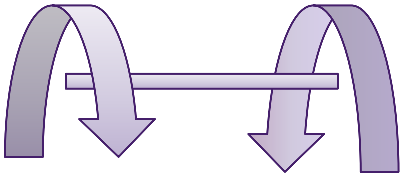
Stable Equilibrium

Turbine torque varies with wind speed, rotational speed and blade pitch.

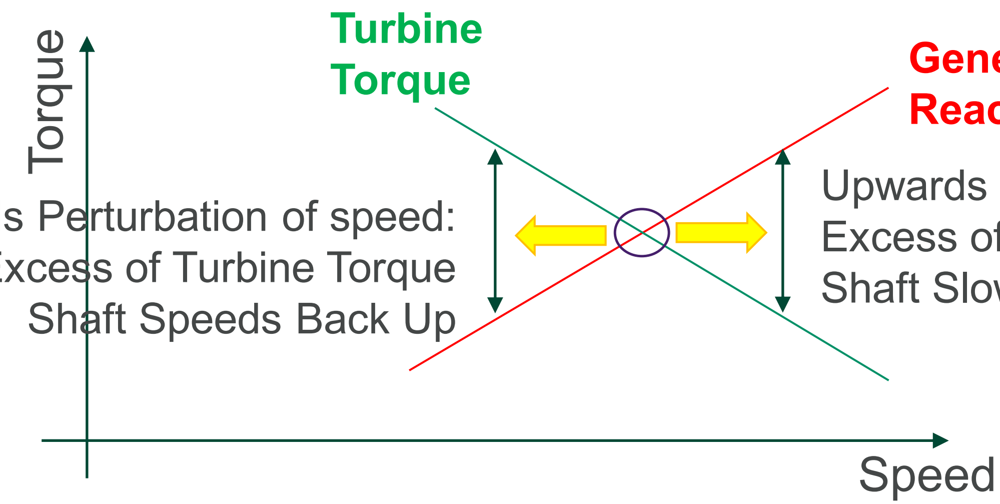
Turbine torque decreases with speed changes at max power



Generator reaction torque is set by the current that is drawn from the generator. It is controllable.

Generator reaction torque is set to increase with speed

$$T^{MPP} = ½\rho A_T C_P^{max} \frac{\omega^2 R^3}{\lambda^{opt\,3}}$$



Shaft speed will stabilise if the two torque characteristics cross in the right sense. Here they do. Perturbations in speed cause a net torque, $T_T - T_G$, that returns system to equilibrium.