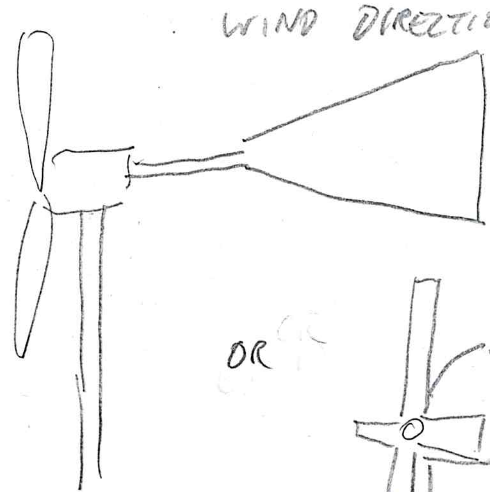
CHAPTER 5: CONTROL OF WIND TURBINES

SOMETIMES:

a) PASSIVE CONTROL BY MECHANICAL DESIGN, EG. VANE OR TAIL-ROTORS TO ORIENT TURBINE INTO WIND DIRECTION



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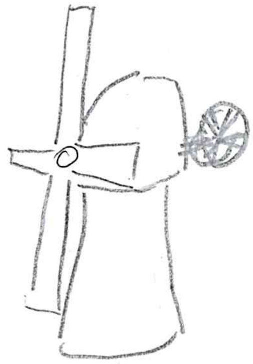
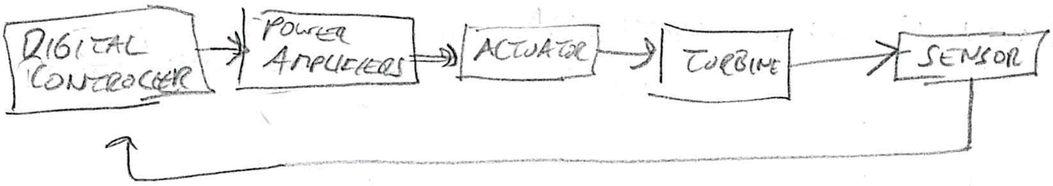


MOSTLY:

b) ACTIVE CONTROL BY SENSOR-ACTUATOR SYSTEMS, USUALLY USING DIGITAL CONTROLLERS



5.1 SENSORS & ACTUATORS IN WIND TURBINES

SENSORS

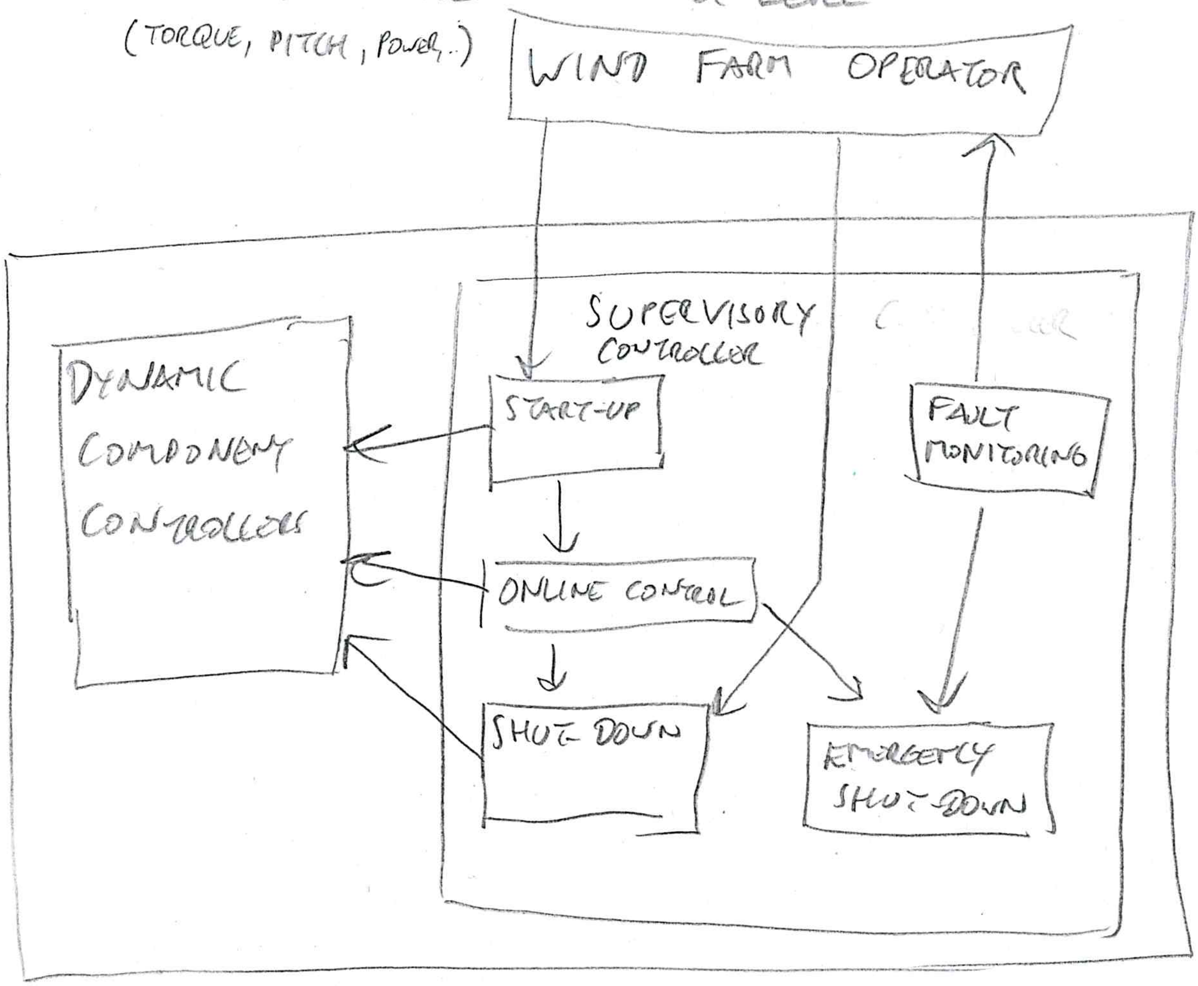
- GENERATOR SPEED, ROTOR SPEED, WIND SPEED, YAW RATE
- TEMPERATURES (GEARBOX OIL, GENERATOR WINDING, AMBIENT AIR, ...)
- BLADE PITCH, BLADE AZIMUTH, YAW ANGLE, WIND DIRECTION
- GRID POWER, CURRENT, VOLTAGE, GRID FREQUENCY, ...)
- TOWER TOP ACCELERATION, GEARBOX VIBRATION, SHAFT TORQUE, BLADE ROOT BENDING MOMENT ...
- ENVIRONMENT: ICING, HUMIDITY, LIGHTNING

ACTUATORS:

- GENERATOR
- MOTORS: PITCH, YAW,
- LINEAR MOTORS, MAGNETS, SOLID STATE SWITCHES
- HYDRAULIC PUMPS & PISTONS (HIGH POWER & SPEED)
- RESISTANCE HEATERS & FANS FOR TEMPERATURE CONTROL
- BRAKES (ROTOR, YAW)

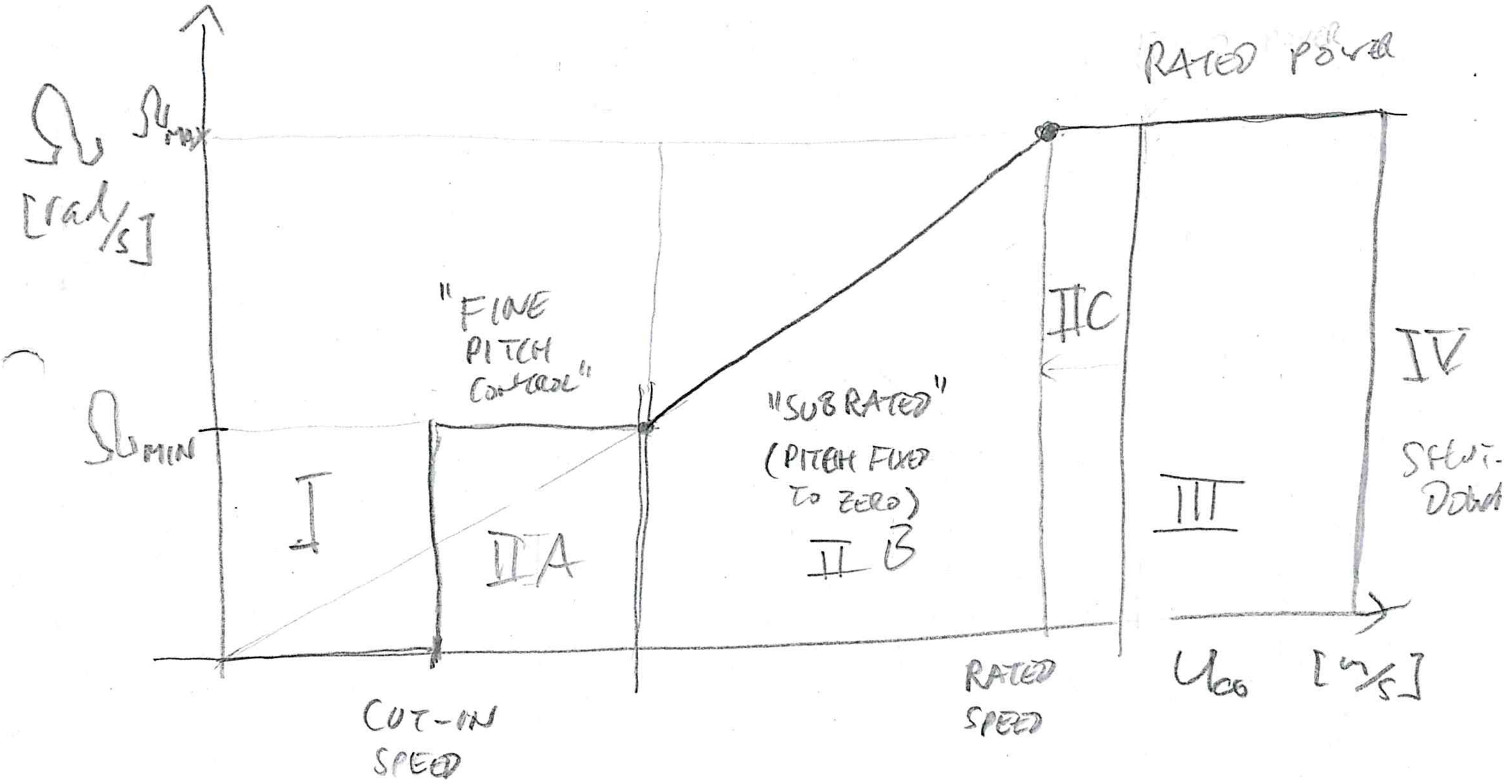
5.2 CONTROL SYSTEM ARCHITECTURE

USUALLY, "SUPERVISORY CONTROL" ON HIGH LEVEL FOR TURBINE OPERATING STATES, AND "DYNAMIC CONTROL" ON LOWER LEVEL (TORQUE, PITCH, POWER,..)



5.3 CONTROL OF VARIABLE SPEED TURBINES

ROTATION SPEED AS FUNCTION OF WIND SPEED, FOR VARIABLE SPEED, PITCH CONTROLLED TURBINE



AIM: MAXIMUM POWER PRODUCTION / COEFFICIENT $C_P(\lambda, \beta)$

PROBLEM: WIND SPEED ON ROTOR DISC NOT PERFECTLY KNOWN

POWER: $$\boxed{P = \frac{1}{2} \rho A u_\infty^3 \cdot C_p(\lambda, \beta)}$$

$\lambda = \frac{R\Omega}{u_\infty}$ TIP SPEED RATIO

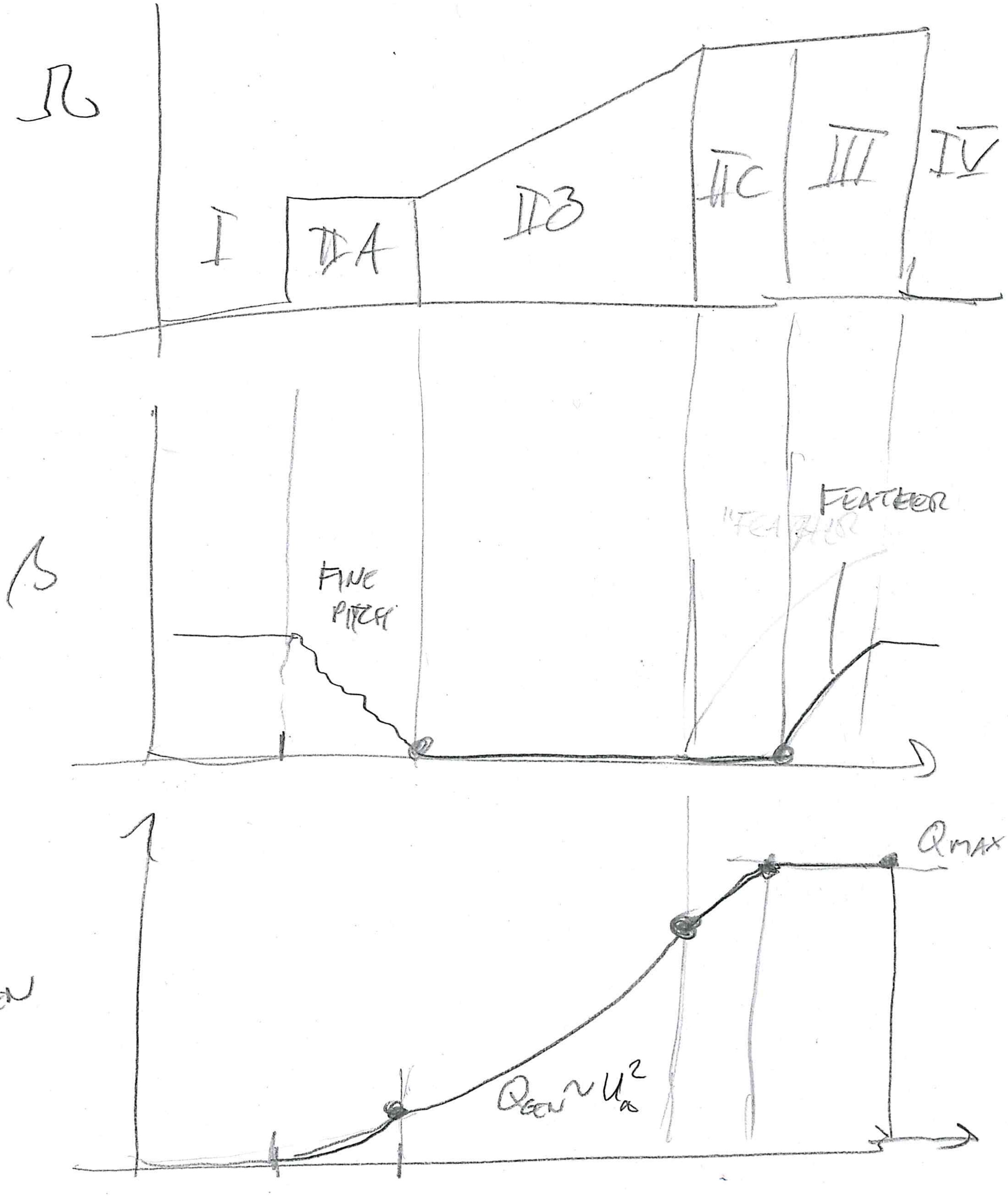
β : (COLLECTIVE) BLADE PITCH

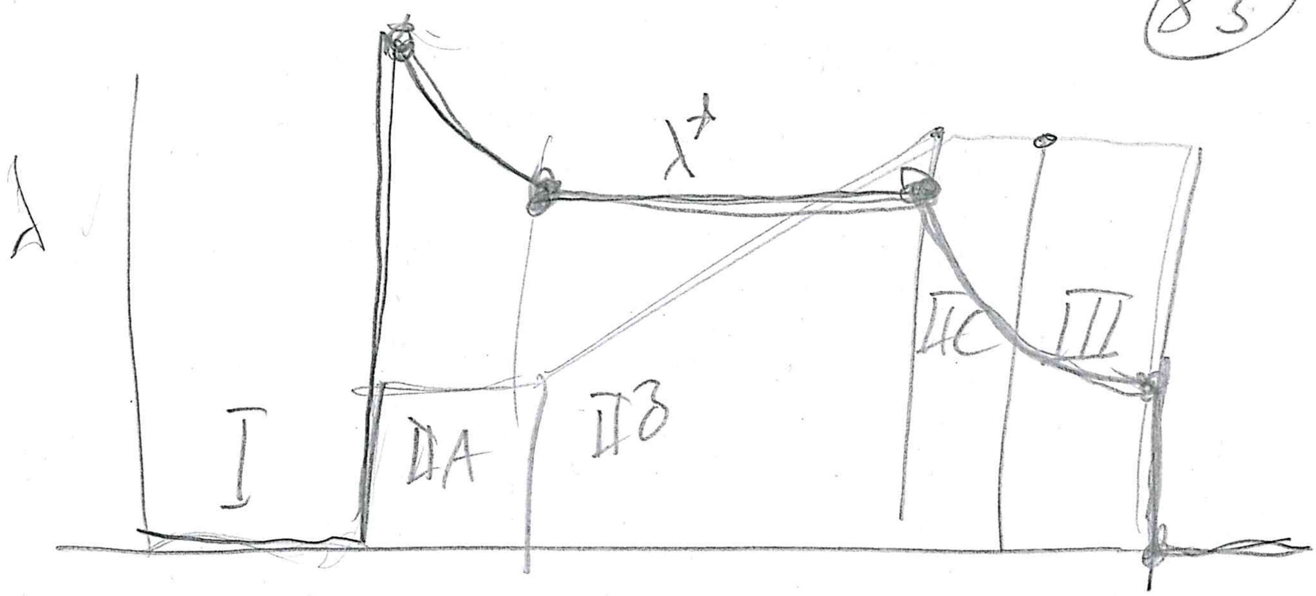
MAXIMUM OF C_P REACHED FOR λ^* AND β^* (USUALLY 0)

$C_p^* = C_P(\lambda^*, \beta^*)$ (eq. 7)

PITCH & TORQUE VS. WIND SPEED (82)
& λ

RECALL:





NOTE: THREE TYPES OF PITCH CONTROL:

a) COLLECTIVE PITCH (HERE)

b) CYCLIC PITCH
(DEPENDING ON AZIMUTH OF BLADE)
(LIKE HELICOPTERS)

c) INDIVIDUAL PITCH CONTROL
(EACH BLADE INDEPENDENTLY CONTROLLED)

IN REGION IIA, λ IS FIXED TO $\lambda_{FIX}^{I} = \frac{\Omega_{min} R}{U_{\infty}}$, AND β MAXIMIZES $C_P(\lambda_{FIX}, \beta)$

IN REGION IIB, $\lambda = \lambda^*$ AND $\beta = \beta^*$, (SUBRATED)

IN REGION IIC & III, λ IS AGAIN FIXED TO $\lambda_{FIX}^{III} = \frac{\Omega_{MAX} \cdot R}{U_{\infty}}$ AND β REGULATES POWER (III: AT MAXIMUM POWER)

5.4 TORQUE CONTROL AT SUBRATED POWER

TORQUE $Q_{GENERATOR}$ CAN BE CONTROLLED DIRECTLY AND SHOULD COUNTERACT AERODYNAMIC TORQUE Q_{AERO}. GIVEN ROTOR INERTIA I WE HAVE ODE FOR Ω:

$$I\dot{\Omega} = Q_{AERO} - Q_{GENERATOR}$$

Q_{AERO} DEPENDS ON u_∞ & Ω & β

AND IS GIVEN BY

$$P_{AERO} = \Omega \cdot Q_{AERO} \quad , \quad \Omega = \frac{\lambda}{R} \cdot u_\infty$$

$$Q_{AERO} = \frac{P_{AERO}}{\Omega} = \frac{1}{2} \rho (\pi R^2) u_\infty^3 \frac{C_P(\lambda, \beta) \cdot R}{u_\infty \cdot \lambda}$$

$$= \frac{1}{2} \rho \pi R^3 u_\infty^2 \underbrace{\left[\frac{C_P(\lambda, \beta)}{\lambda} \right]}_{=: C_Q(\lambda, \beta)}$$

$$= \underbrace{\frac{1}{2} \rho \pi R^3 u_\infty^2 \cdot C_Q\left(\frac{\Omega R}{u_\infty}, \beta \right)}_{=: Q_{AERO}(\Omega, u_\infty, \beta)}$$

HOW TO CHOOSE $Q_{GENERATOR}$, WHEN ONLY Ω IS MEASURED?

IDEA: FIND FUNCTION $Q_{GENERATOR}(\Omega)$ THAT BRINGS TURBINE TO OPTIMAL TIP SPEED RATIO λ^* (IN REGION IIB)

INTUITIVELY:
- HIGH Q_{GEN}, IF Ω TOO LARGE,
- SMALL Q_{GEN}, IF Ω TOO SMALL

IN ORDER TO STABILIZE ROTOR SPEED.

AT OPTIMUM $\Omega^* = \frac{\lambda^* \cdot u_\infty}{R}$ WE WOULD HAVE

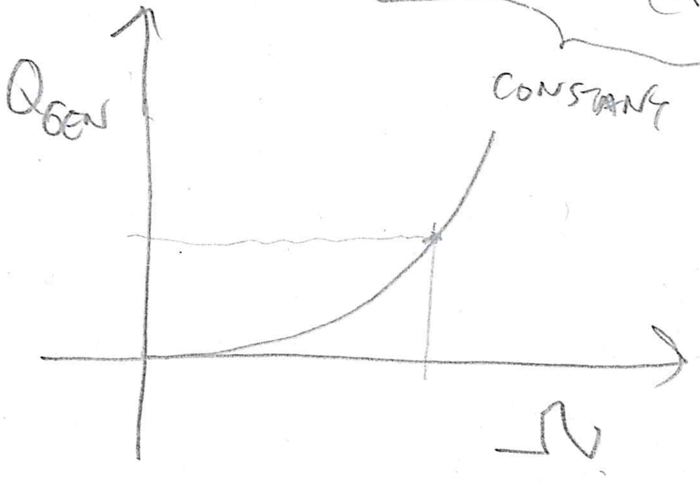
$$Q_{AERO}(\Omega^*, u_\infty, \beta^*) = Q_{GEN}(\Omega^*)$$

SO LET US GENERALLY TRY THE LAW

$$Q_{GEN}(\Omega) := Q_{AERO}\left(\Omega, \frac{R\Omega}{\lambda^*}, \beta^*\right)$$

$$= \frac{1}{2}\rho\pi R^3 \left(\frac{R\Omega}{\lambda^*}\right)^2 \frac{c_p(\lambda^*, \beta^*)}{\lambda^*}$$

$$= \underbrace{\frac{1}{2}\rho\pi R^5 \frac{c_p(\lambda^*, \beta^*)}{(\lambda^*)^3}}_{\text{CONSTANT } K_{GEN}} \cdot \Omega^2$$



(BOSSANYI, 2003)

"MAXIMUM POWER TRACKING TORQUE CONTROL"

IS THIS CONTROL LAW STABLE AT Ω^* ?

RECALL

$$\dot{\Omega} = f(\Omega) := \frac{1}{I}\left(Q_{aero}(\Omega, u_\infty, \beta^*) - Q_{gen}\right.$$

Q1) $f(\Omega^*) = 0$? (STEADY STATE ?)

IF $\Omega^* = \frac{\lambda^* u_\infty}{R}$ ~~ANTHEN~~, BY CONSTRUCTION

$$Q_{aero}(\Omega^*, u_\infty, \beta^*) = K_{GEN} \cdot (\Omega^*)^2$$

SUCH THAT INDEED $f(\Omega^*) = 0$

Q2) $\frac{df}{d\Omega}(\Omega^*) < 0$ (STABLE ?)

$$\frac{df}{d\Omega} = \frac{1}{I}\left(\frac{dQ_{aero}}{d\Omega} - \frac{dQ_{GEN}}{d\Omega}\right)$$

$$= \frac{1}{I}\left(\frac{1}{2}\rho\pi R^3 u_\infty^2 \frac{dC_Q}{d\lambda} \cdot \frac{d\lambda}{d\Omega} - 2 \cdot K_{GEN} \cdot \Omega\right)$$

$$\frac{dC_Q}{d\lambda} = \frac{d\left(\frac{C_P}{\lambda}\right)}{d\lambda} = \frac{\overbrace{\frac{dC_P}{d\lambda}}^{=0 \text{ DUE TO OPTIMALITY}} \cdot \lambda - C_P}{\lambda^2} = -\frac{C_P^*}{\lambda^{*2}} \quad \underline{\underline{\text{AT } \lambda^*}}$$

$$\frac{d\lambda}{d\Omega} = \frac{R}{u_\infty}$$

THUS

$$\frac{df}{d\Omega} = \frac{1}{I}\Big(\underbrace{\tfrac{1}{2}\rho\pi R^3 u_\infty^2 \left(-\frac{c_p^*}{\lambda^{*2}}\right)\frac{R}{u_\infty}}_{<0} \; \underbrace{-2K_{GEN}\Omega}_{<0}\Big)$$

< 0

IN MORE DETAIL, AT $\Omega = \Omega^* = \frac{\lambda^* u_\infty}{R}$

$$u_\infty = \frac{\Omega^* R}{\lambda^*}$$

WE GET

$$\frac{df}{d\Omega} = \frac{1}{I}\left(\tfrac{1}{2}\rho\pi R^5\right)\left(-\frac{c_p^*\Omega^*}{(\lambda^*)^3} - \frac{2c_p^*}{(\lambda^*)^3}\Omega^*\right)$$

$$= -\underbrace{\frac{\tfrac{1}{2}\rho\pi R^5}{I\cdot(\lambda^*)^3}\cdot 3c_p^*}_{=\text{CONST.}\ [-]}\,\Omega^*$$

I.E.
SETTLING TIME PROPORTIONAL TO $\frac{1}{\Omega^*}$ OR $\frac{R}{u_\infty}$

DIMENSIONAL CHECK:

$I \approx m R^2$, $m \approx \rho_B \cdot R^3$ THUS $I \approx \rho_B \cdot R^5$

ρ_B: BLADE DENSITY