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VARIABLE-SPEED VARIABLE-PITCH CONTROL FOR A WIND TURBINE SCALE MODEL

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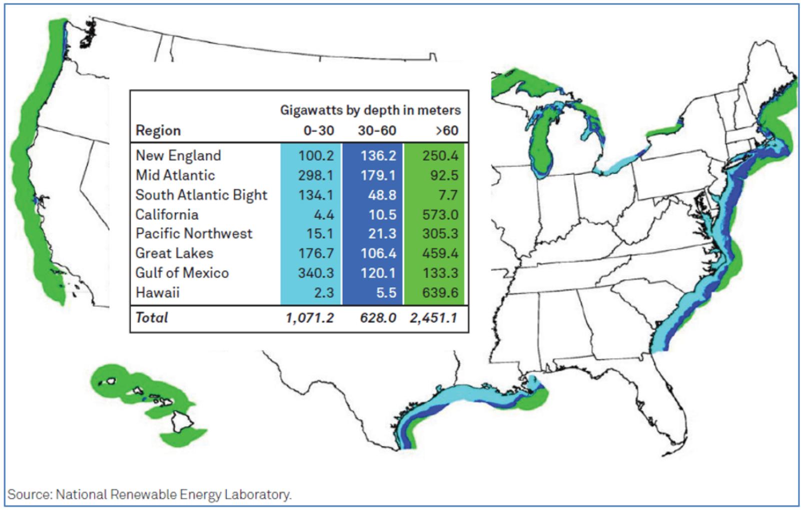
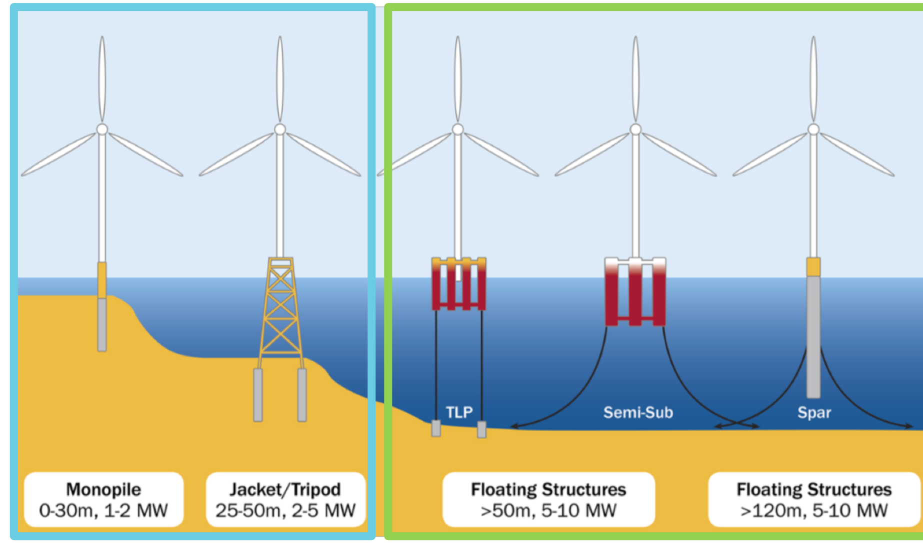


Region	Gigawatts by depth in meters 0-30	30-60	>60
New England	100.2	136.2	250.4
Mid Atlantic	298.1	179.1	92.5
South Atlantic Bight	134.1	48.8	7.7
California	4.4	10.5	573.0
Pacific Northwest	15.1	21.3	305.3
Great Lakes	176.7	106.4	459.4
Gulf of Mexico	340.3	120.1	133.3
Hawaii	2.3	5.5	639.6
Total	*1,071.2*	*628.0*	*2,451.1*

Source: National Renewable Energy Laboratory.



- Offshore wind energy LCOE is still high
- Floating offshore wind energy is a potential game changer for LCOE reduction
  - Greater energy production
  - Increased range of possible installation sites
  - Lower installation costs
- Deep seas represent a significant fraction of exploitable wind energy in Europe and worldwide

FOWTs WIND TUNNEL TESTING

- Experimental data required to calibrate/validate numerical simulation tools
- Scale model testing:
  - Lower costs than full-scale experiments
  - Control of environmental conditions
  - Lower uncertainties
- Hybrid/HIL testing
  - Rotor loads (including control) reproduced by a wind turbine scale model
  - Hydrodynamic loads and platform motion from numerical computations
  - 6-DOFs robot moves the wind turbine model in real-time

CONTROL SCALING

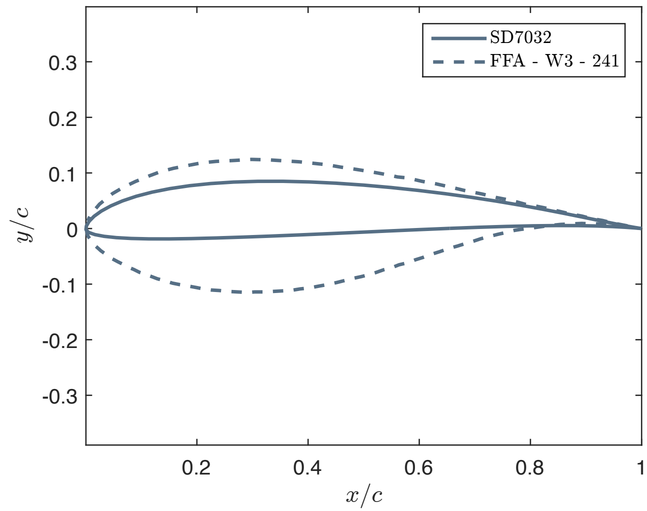
SCALE MODEL CONTROL

- Required to improve experiment fidelity
- Reproduction of rotor dynamics and control induced loads
- Direct investigation of FOWT control problem

- Non-ideal model scaling
- Low Reynolds flow
- Not possible to achieve target response with a scaled controller

WIND TURBINE SCALE MODEL

Scale	Expression	Value
Length	λ_L	75
Velocity	λ_v	3



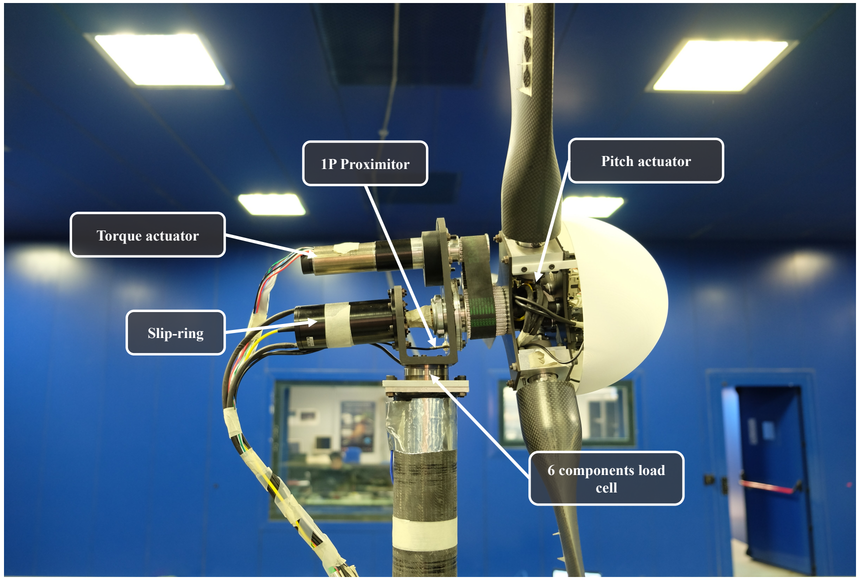
ROTOR

Performance scaling: low-Re blades

- Match thrust coefficient
- Match scaled weight
- Match first flapwise frequency

MECHATRONIC CONFIGURATION

- Similar to the full-scale turbine with torque and pitch actuators
- Onboard sensors acquired in real-time
- Embedded Control and Monitoring system

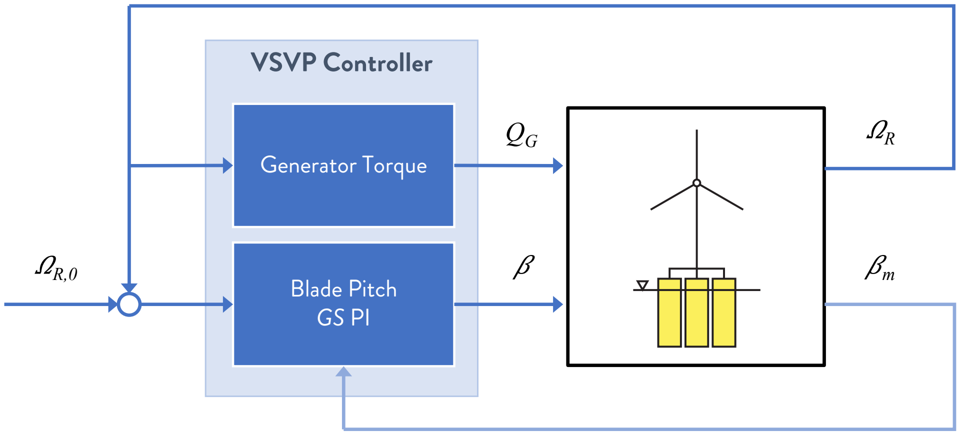


PARTIAL LOAD

- Constant pitch angle $\beta = 5°$
- Variable generator torque

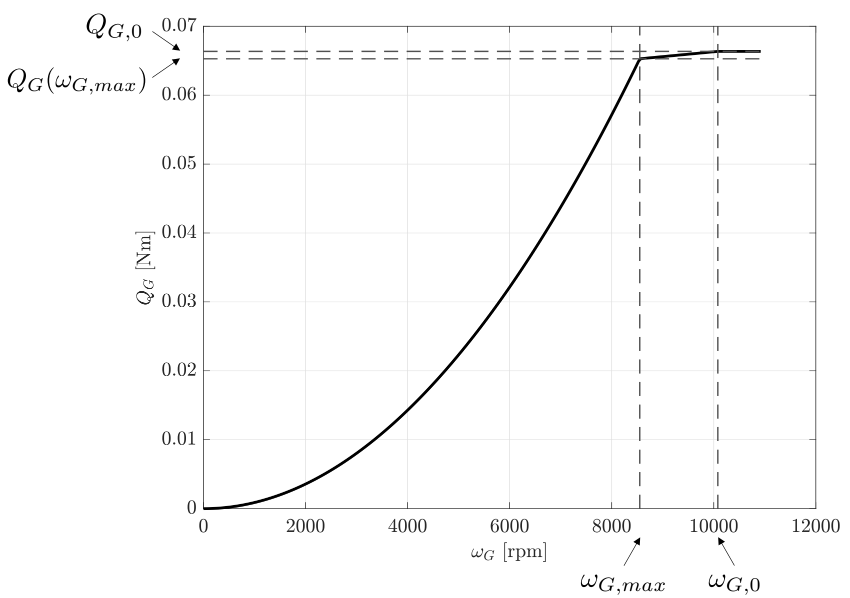
$$Q_G = K_G \omega_G^2$$

- K_G chosen to maximize power coefficient



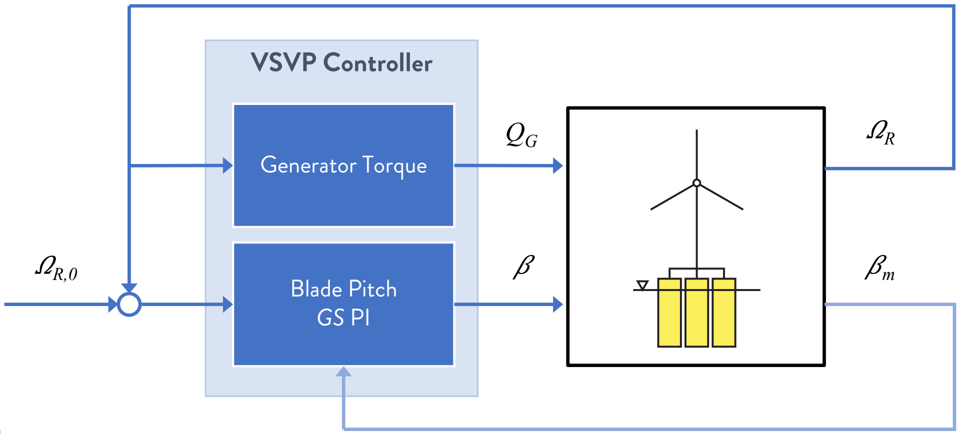
TRANSITIONS

- No region 1.5
- Linear transition to reach rated torque (no-PI torque controller)



FULL LOAD

- Constant torque
- Variable collective pitch angle
- Generator speed and generator power feedback



$$\beta = \left(k_P^{\omega} e_{\omega} + k_I^{\omega} \int e_{\omega} dt\right) + \left(k_P^{P} e_P + k_I^{P} \int e_P dt\right)$$

GAIN SCHEDULING

- Quadratic aerodynamic gains scheduling
- Additional non-linear gain scheduling for large speed excursions

$$\eta_A = \frac{1}{1 + \frac{\beta}{KK_1} + \frac{\beta^2}{KK_2}}$$

$$\eta_{NL} = 1 + \frac{e_{\omega}^2}{(\omega_2 - \omega_0)^2}$$

DRIVETRAIN NON-IDEALITIES

Largely due to commercially available components and mechatronic design

- Not possible to have scaled generator/transmission
- Technological limits for blades realization

EFFECTS

- WT controller works on HSS feedback
- Drivetrain inertia directly affects rotor dynamics and pitch controller response

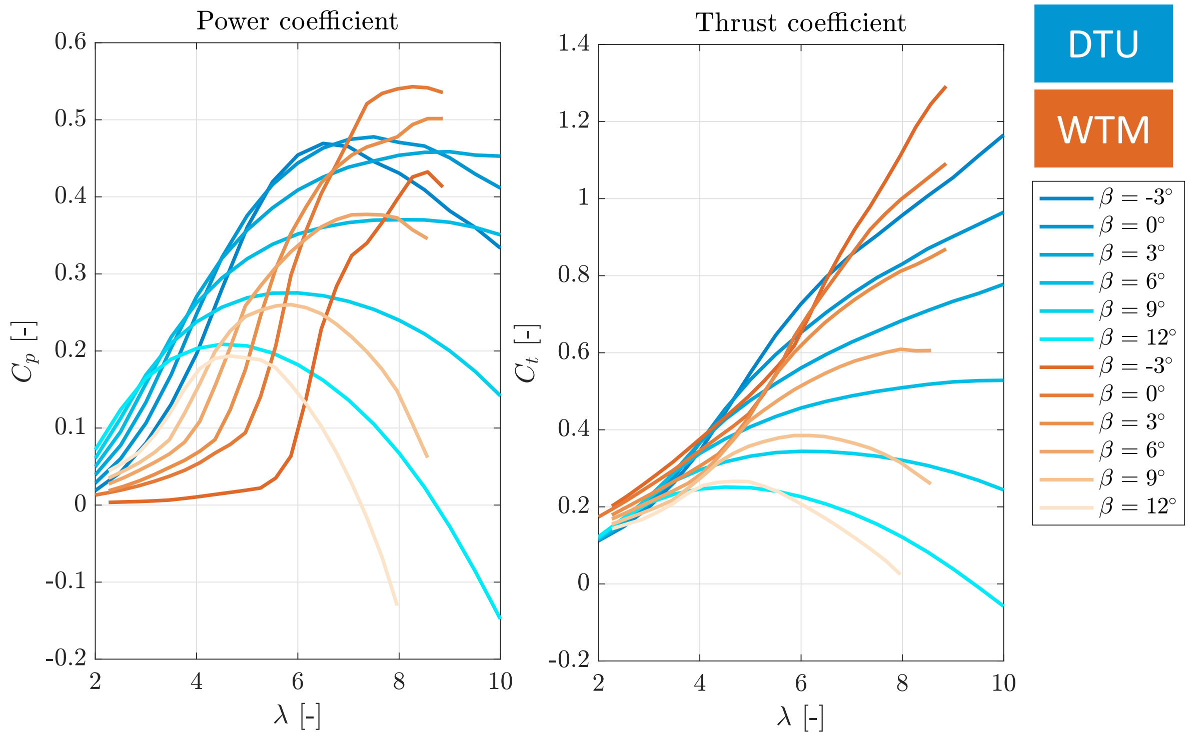
DRIVETRAIN PROPERTIES		
	DTU	WTM
Transmission ratio	50	42
LSS inertia	0.066	0.279
HSS inertia	6.323e-7	6.438e-6
Mechanical efficiency	1	0.735
Electrical efficiency	0.94	0.894

POWER COEFFICIENT

- Lower than target for small β and low values of λ
- Max C_p of 0.54 at $\beta = 0°$ and $\lambda = 8.26$
- Influence on the WT start-up
- Above-rated: lower β to keep power at rated

THRUST COEFFICIENT

- Closer to target
- Some differences for small β and low values of λ

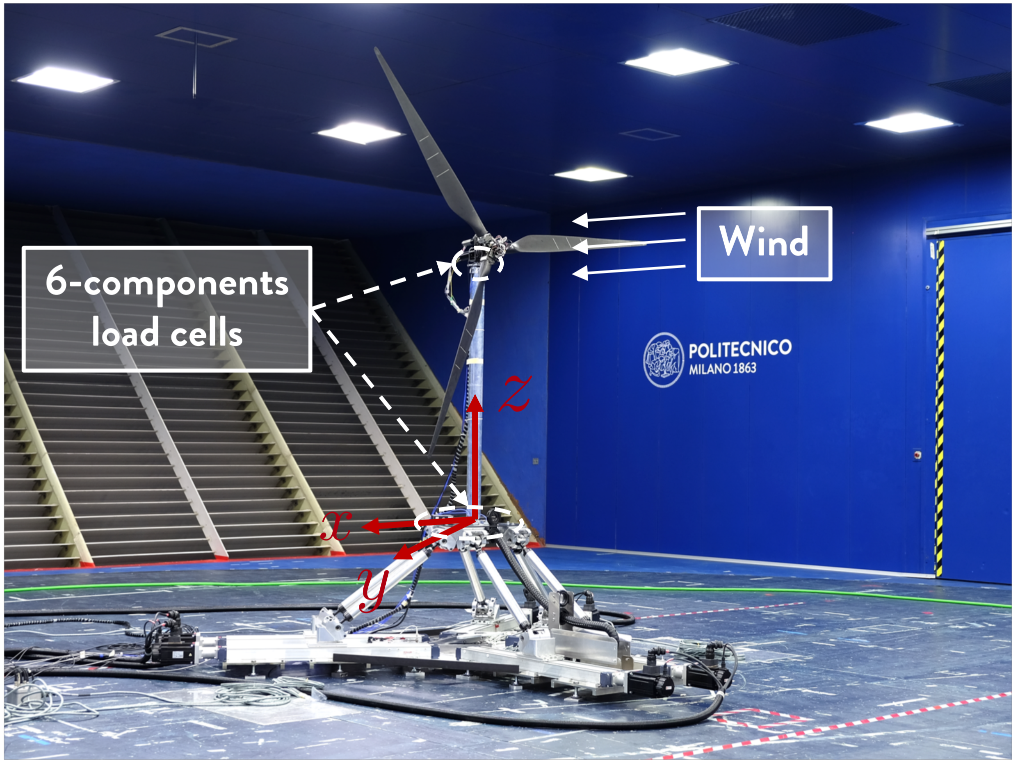


SCALE MODEL TESTING

- Laminar wind conditions
- Load measurements from two load cells

- **Steady-state tests**
  - Full-scale wind speed from 9 to 25 m/s
  - Average loads and control inputs at regime

- **Dynamic tests**
  - Sinusoidal surge motion at different frequencies and amplitudes
  - Below and above rated mean wind speeds



CONTROLLER SETTINGS

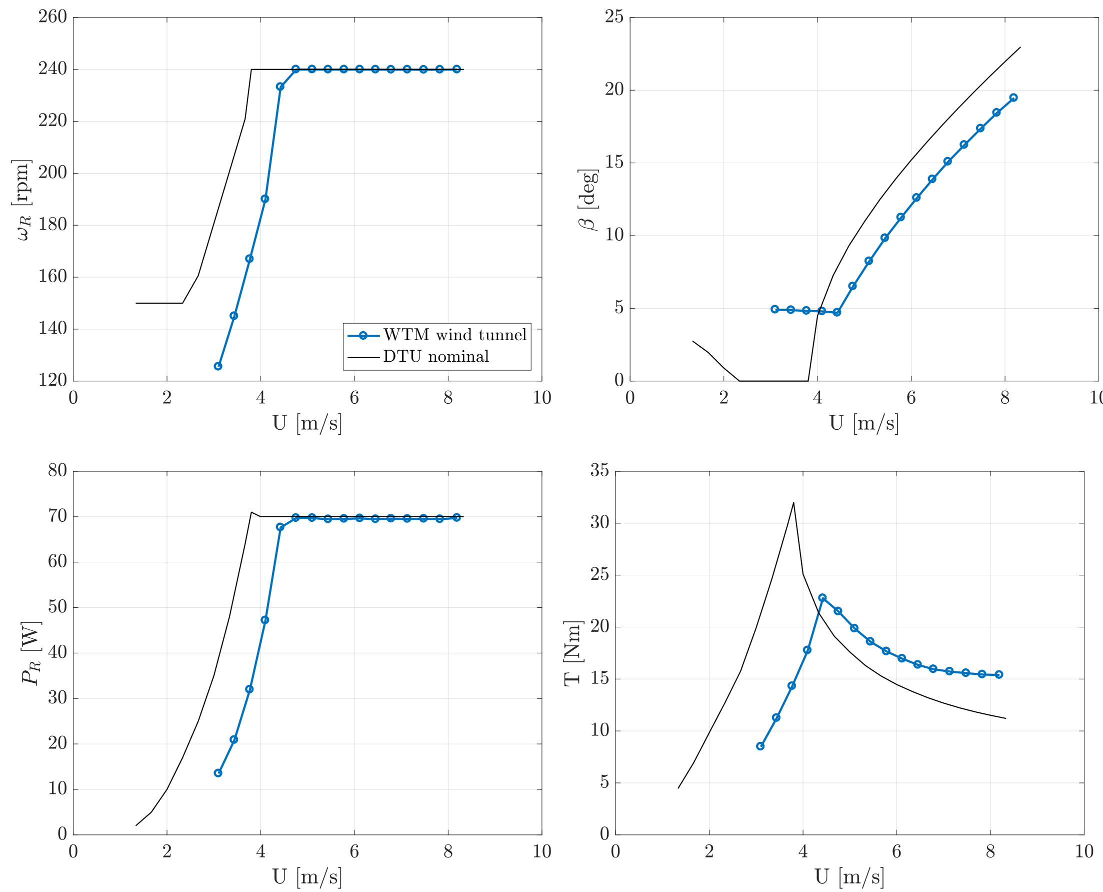
- Based on the public definition of the LIFES50+ OO-Star Wind Floater Semi 10MW

1. Original parameters were scaled
2. Parameters referred to HSS were corrected for different efficiency/transmission ratio
3. Increased below-rated pitch angle
4. Modified generator torque constant (max C_p for $\beta = 5°$)

Parameter	Symbol	Unit	Value
Rated generator speed	$\omega_{G,0}$	rpm	10080
Region 2 transition speed	$\omega_{G,max}$	rpm	8550
Rated generator power	$P_{G,0}$	W	70.044
Generator torque constant	K_G	$Nm/(rad/s)^2$	$8.143 \cdot 10^{-8}$
Minimum pitch angle	β_{min}	deg	5
Proportional speed gain	k_P^{ω}	s	$1.831 \cdot 10^{-4}$
Integral speed gain	k_I^{ω}	$-$	$2.095 \cdot 10^{-4}$
Proportional power gain	k_P^P	rad/W	$8.265 \cdot 10^{-4}$
Integral power gain	k_I^P	$rad/(Ws)$	$2.070 \cdot 10^{-2}$
Linear gain scheduling factor	KK_1	deg	198.329
Quadratic gain scheduling factor	KK_2	deg^2	693.222
Speed for doubled gains	ω_2	rpm	13104

PARTIAL LOAD

- Rated reached at 14 m/s
- Steady-state angular speed lower than target
- Low λ and increased β lead to decreased power and low thrust force



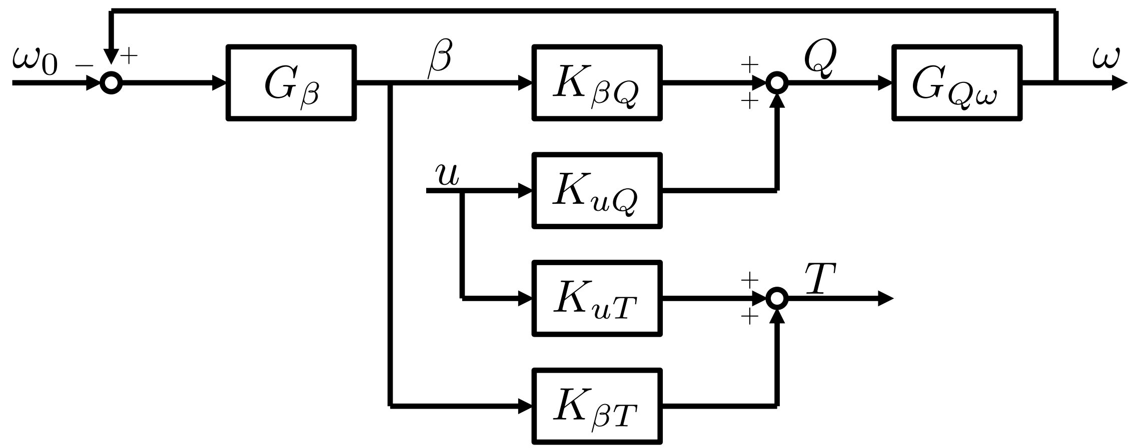
FULL LOAD

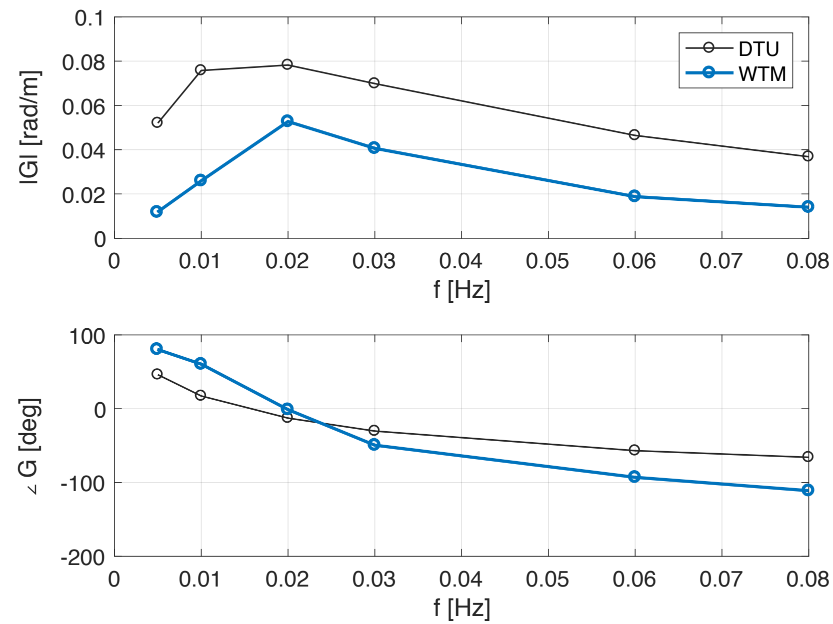
- Pitch angle always lower than target
- Increased thrust force: WTM rotor designed to have target thrust at DTU 10MW nominal pitch angles

IDEAL CLOSED-LOOP

- Pitch controller disturbance rejection function
- Above-rated mean wind speed: 18 m/s

$$G(f) = \frac{\omega_R(f)}{u(f)} = \frac{G_{u\omega}}{1 - G_\beta G_{\beta\omega}}$$





- $G_{u\omega}$ depends both on the drivetrain mechanical properties and on rotor aerodynamics
- G_β is the PI-pitch controller transfer function
- $G_{\beta\omega}$ depends both on the drivetrain mechanical properties and on rotor aerodynamics

CONCLUSIONS