OPWIND / STAS – wind farm control

Presentation at
Industry meets Science
25/10-2016

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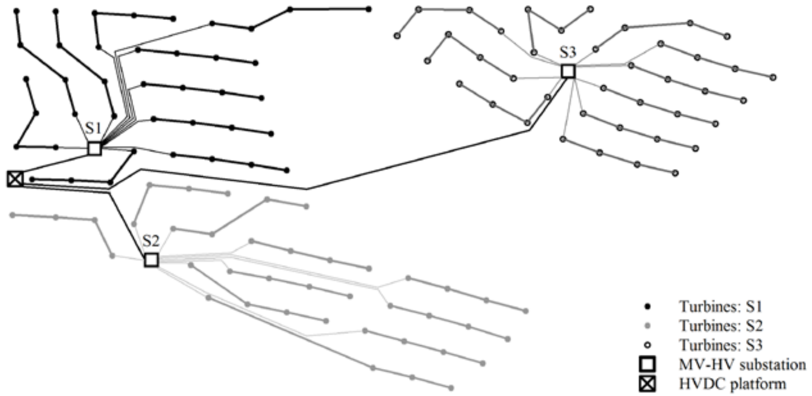
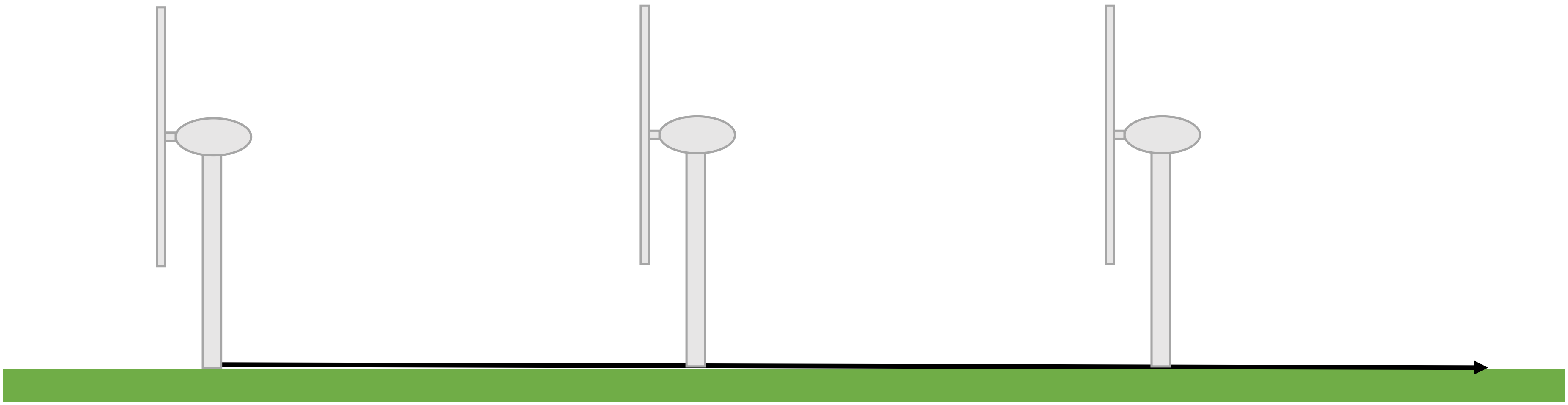
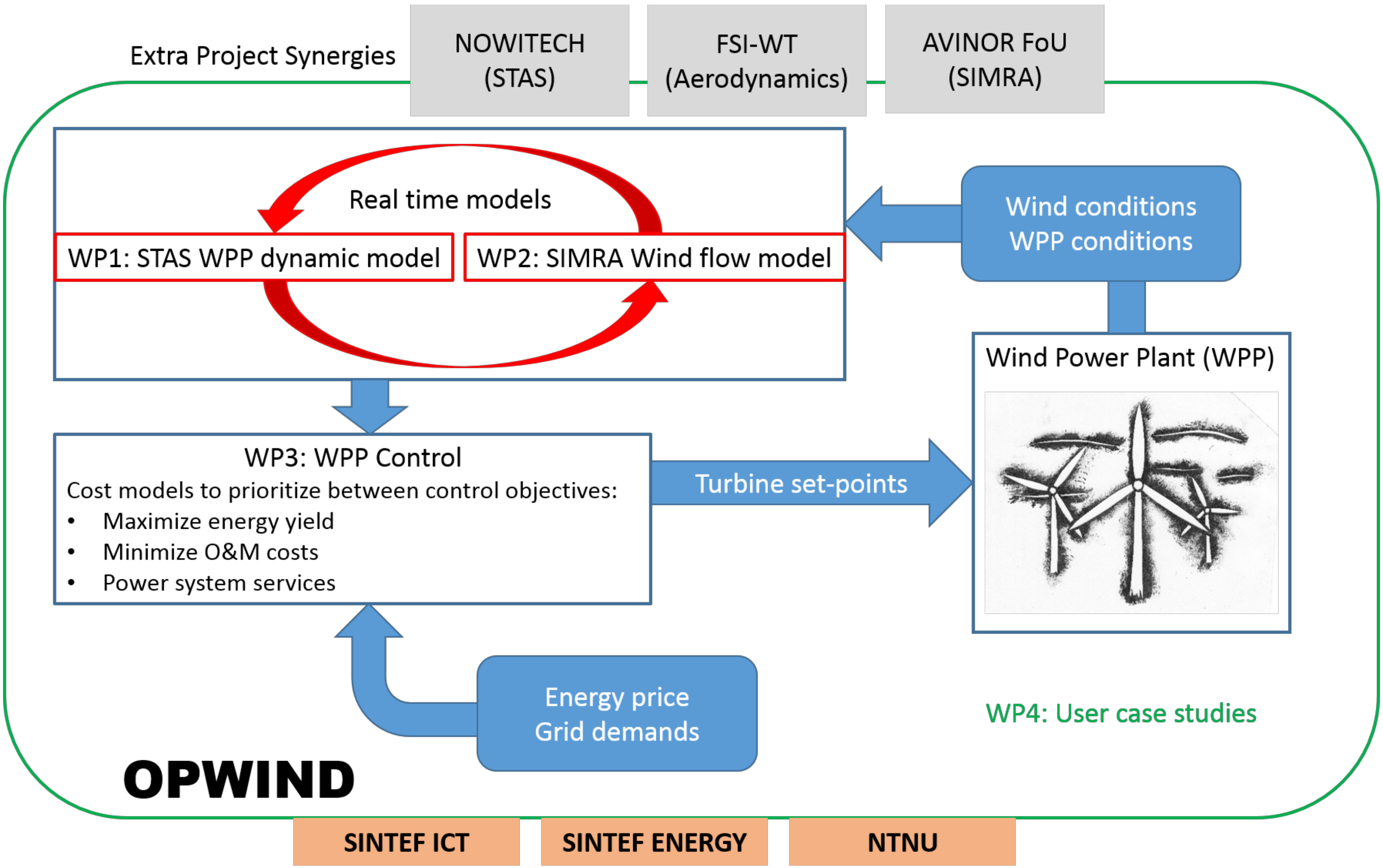
Wind farm control





- Safe and reliable
- Maximize energy output
- Minimize loads
- Deliver required power system services


Extra Project Synergies
NOWITECH (STAS)
FSI-WT (Aerodynamics)
AVINOR FoU (SIMRA)
Real time models
WP1: STAS WPP dynamic model
WP2: SIMRA Wind flow model
Wind conditions
WPP conditions
Wind Power Plant (WPP)
WP3: WPP Control
Cost models to prioritize between control objectives:
• Maximize energy yield
• Minimize O&M costs
• Power system services
Turbine set-points
Energy price
Grid demands
WP4: User case studies
OPWIND
SINTEF ICT
SINTEF ENERGY
NTNU

OPWIND KPN application 2017-2020

Primary objective:
To develop knowledge and tools for optimized operation and control of wind power plants, reducing costs and increasing profitability.

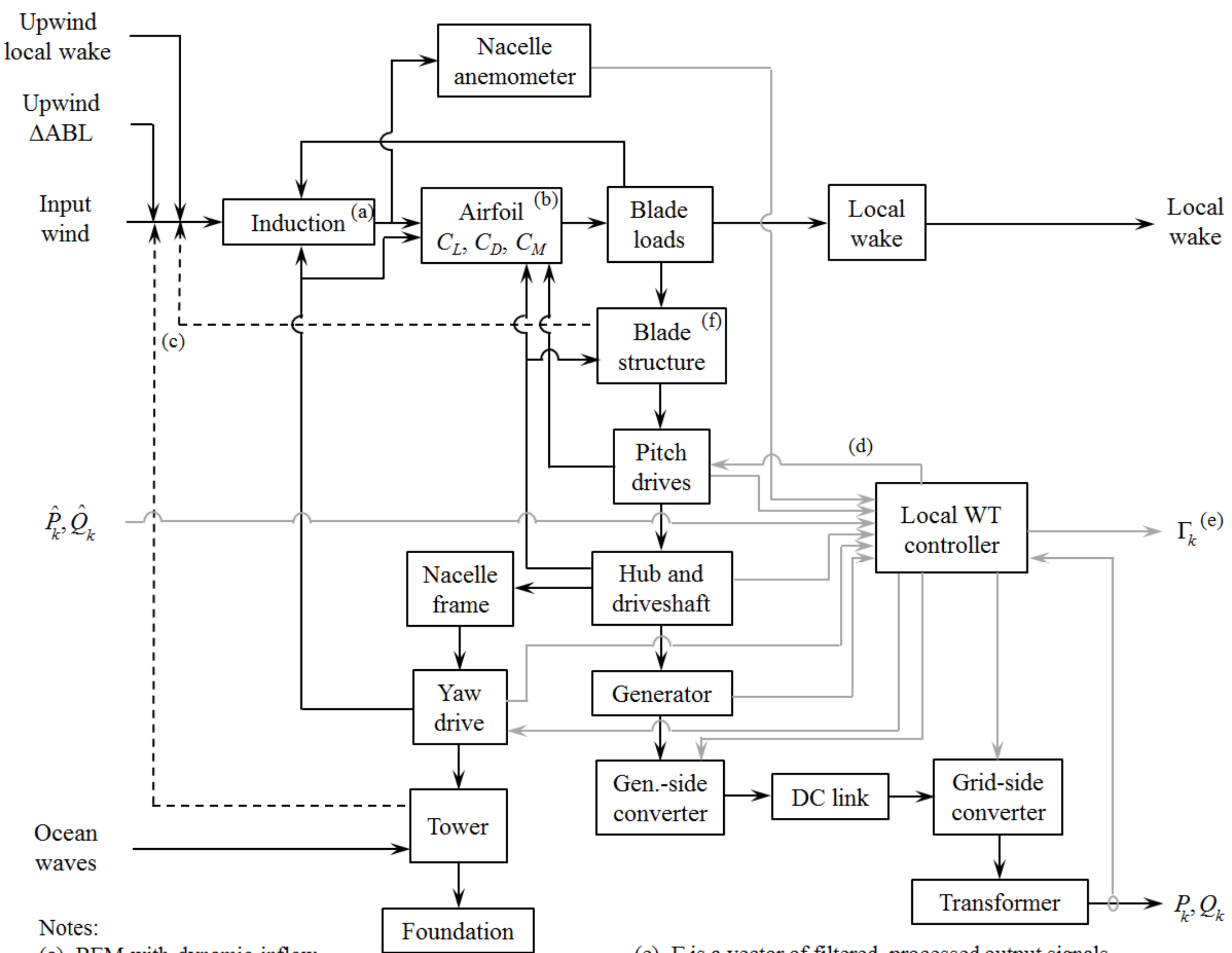
Secondary objectives:

- Develop a scalable, integrated state-space model of a wind power plant, for modal analysis, simulation, state observation, and control design at the plant level.
- Develop a real-time model for predicting the atmospheric flow through clusters of wind power plants.
- Develop a real-time wind power plant controller based on an integrated plant and flow model.
- Validate the developed tools and apply them for the analysis of user-defined case studies.

Research Challenges	State-of-the-art	Project Innovation
Dynamic modelling of wind power plants.	Discipline-oriented models with limited representations of other disciplines: incomplete dynamics.	An integrated model of a wind power plant, in a linear parameter-varying framework, with modal reduction to the essential degrees-of-freedom.
Real-time atmospheric flow models	Systems like "Wake4D", and lidar and radar based turbulence alert systems are in use in the aviation industry.	Reduced order modelling in combination with statistical reduction and simplified parameterization will be utilized to bring down the computational time of simulations relevant for wind power plant control.
Real-time wind power plant control.	Promising algorithms are available, but these are often formulated with overly simplified models. In the literature, focus is on either power production, load reduction, or grid services, not on the complete suite of plant control objectives. Small turbine arrays are used as demonstration cases.	Demonstration of algorithms with a proper dynamic model of the plant, analysis of parameter-varying implementations of linear control algorithms, real-time control of large wind power plants and plant clusters, case studies for OPWIND user partners.

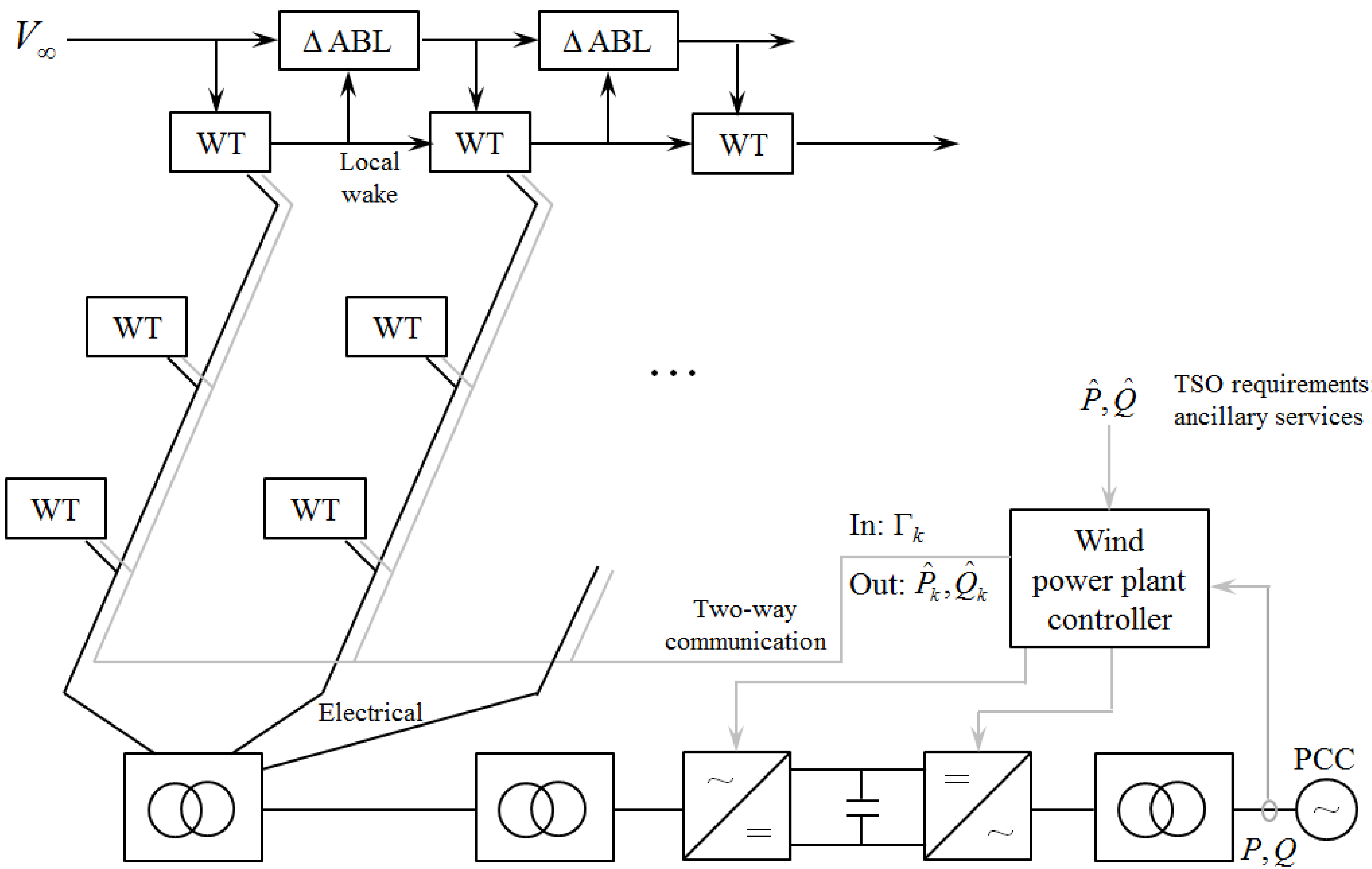
Turbine-level model for wind power plant system analysis

STAS Turbine



Notes:
(a) BEM with dynamic inflow
(b) Dynamic stall, Øye type model
(c) Aerodynamic damping, may be linearized and computed independently
(d) Black lines: physical connection. Grey: communication.
(e) Γ is a vector of filtered, processed output signals.
(f) Additional load, strain, or acceleration sensors could be installed in any of the mechanical components and fed to the local controller for active damping or inclusion in the output signal vector Γ.

STAS WPP



V_∞
Δ ABL
Δ ABL
WT
WT
WT
Local wake
WT
WT
WT
WT
. . .
$\hat{P}, \hat{Q}$
TSO requirements: ancillary services
In: Γ_k
Out: $\hat{P}_k, \hat{Q}_k$
Wind power plant controller
Two-way communication
Electrical
PCC
P, Q

Key points:

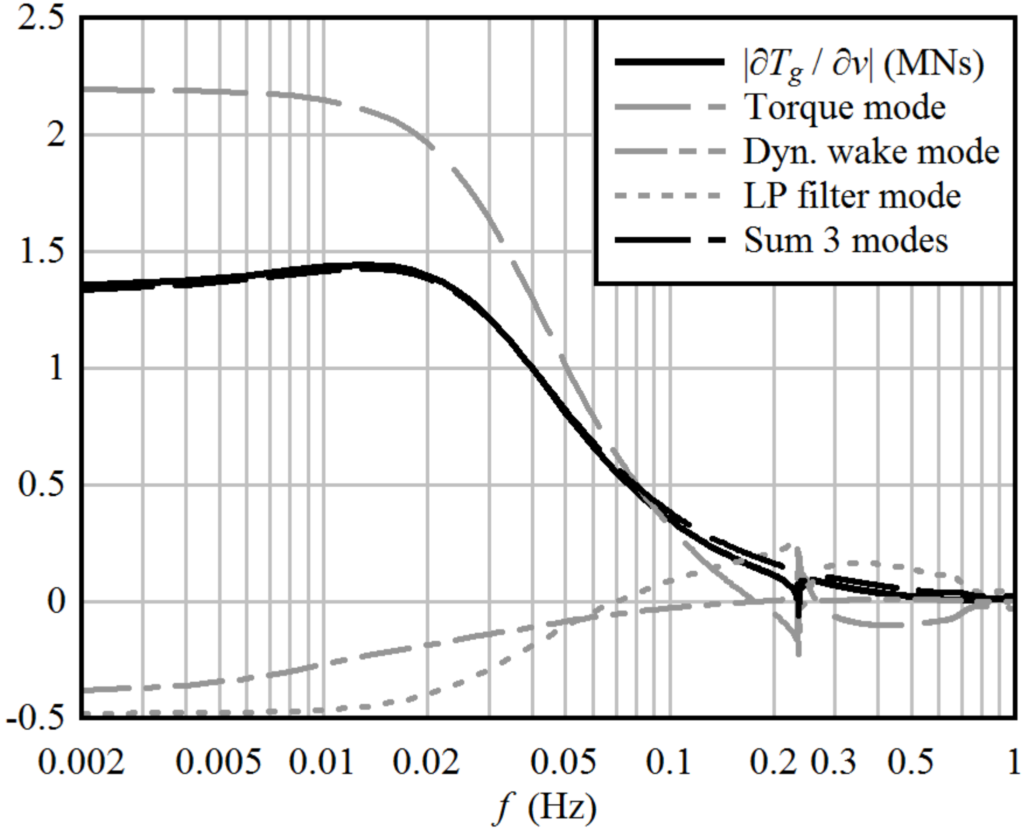
(1) It is possible to characterize the low-frequency response (below the first tower resonant frequency), including full structural, aerodynamic, and electrical systems, with three *system modes*.

(2) Preliminary investigations indicate that the response below 1 Hz can be represented by on the order of 10 modes.

Eigenvalues:	Torque control mode $\lambda = -0.179 + i0.111$ s^{-1}		Dynamic wake mode $\lambda = -0.073$ s^{-1}		Low-pass filter mode $\lambda = -1.124 + i0.027$ s^{-1}	
System DOF	$\|a\|$	θ/π	$\|a\|$	θ/π	$\|a\|$	θ/π
q_F	0.629	0.205	0.872	0.000	1.709	-0.184
q_f	9.222	0.137	12.034	0.000	35.127	-0.179
Ω	1.000	0.000	1.000	0.000	1.000	0.000
$\overline{\Omega}$	1.167	-0.033	1.061	0.000	9.272	-0.063
v_i	8.398	0.688	2.833	0.000	5.396	-0.182
s	1.065	0.383	9.516	0.000	0.744	-0.181

q_F: First fore-aft structural mode of the tower. q_f: First collective flapwise structural mode of the blades. Ω: Rotor speed. $\overline{\Omega}$: Measured and filtered rotor speed. v_i: Rotor-average axial induced velocity. s: Auxiliary state variable in the dynamic inflow equations.

Modal contributions to the net generator torque control action

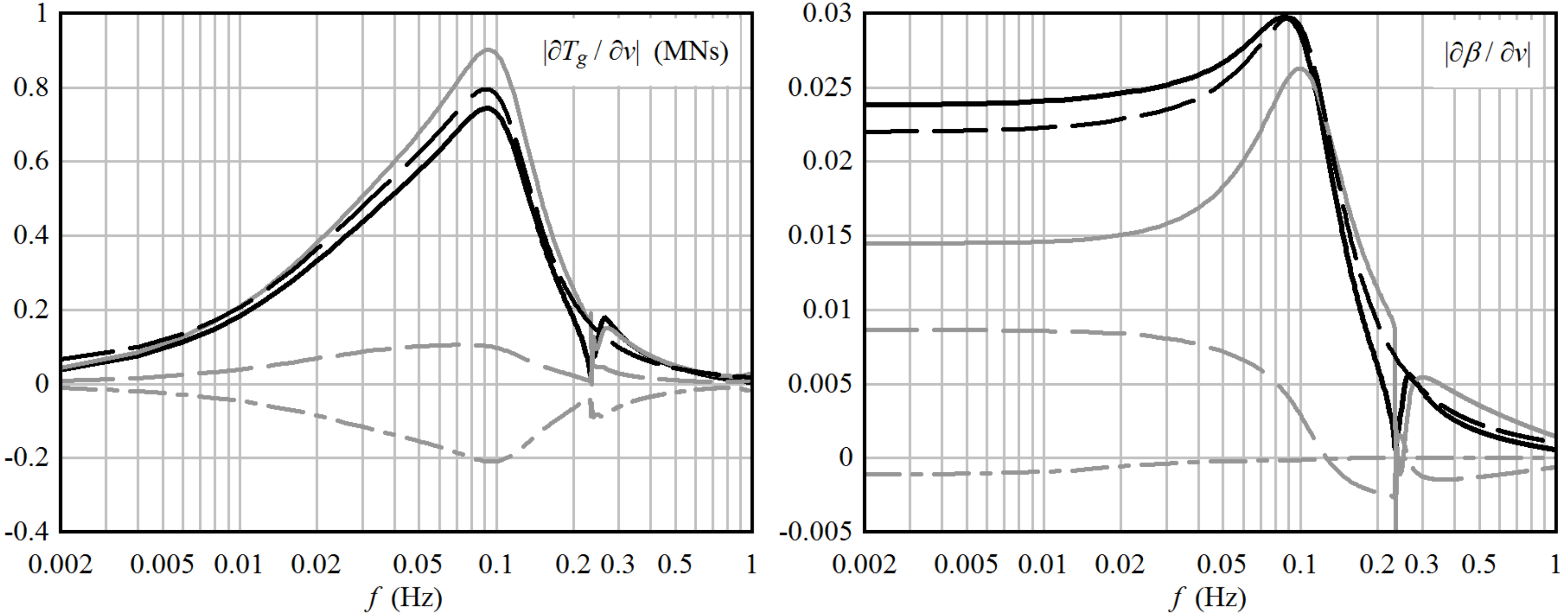


Above the rated windspeed

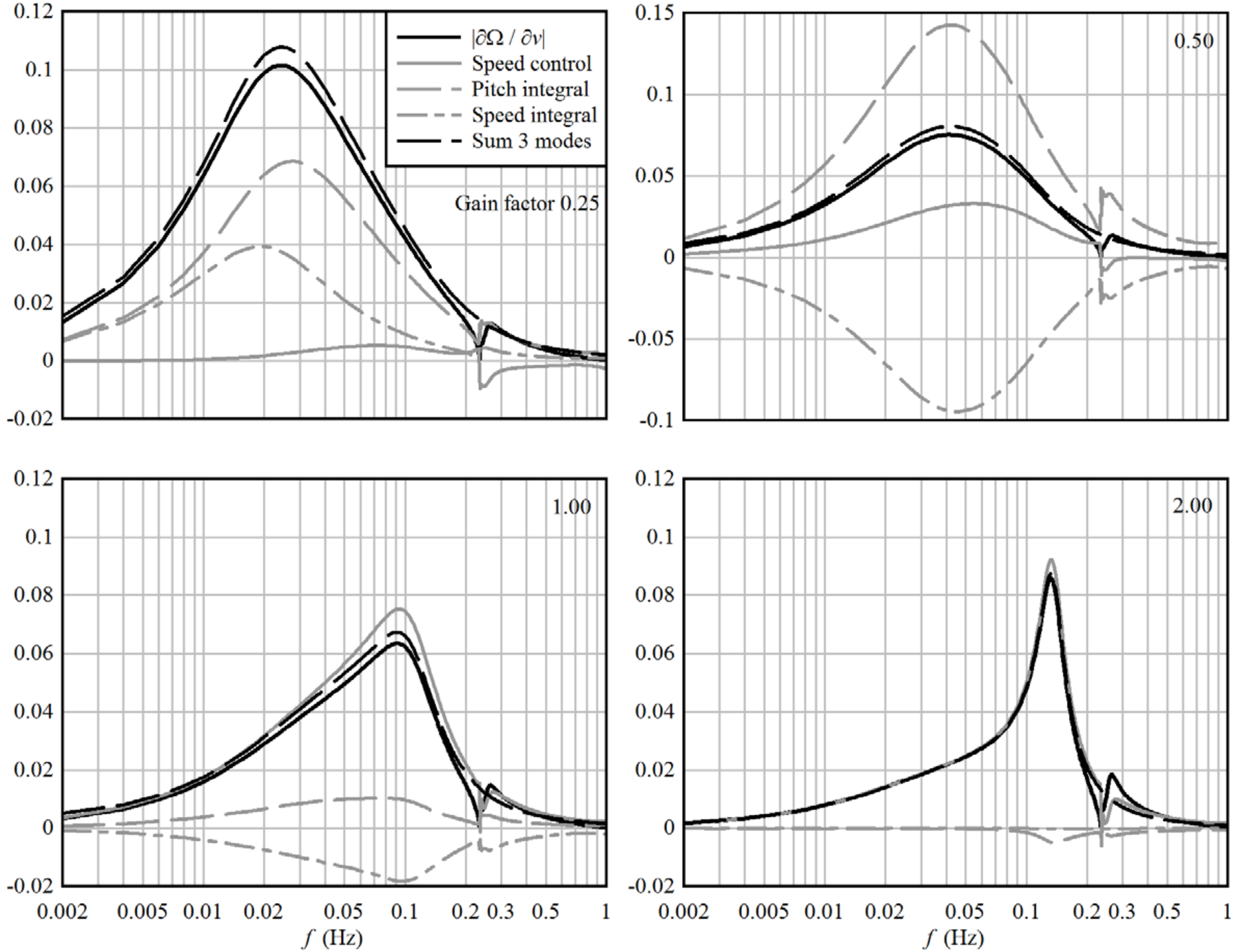
Eigenvalues:	Rotor speed control mode $\lambda = -0.274 + i0.628$ s^{-1}		Pitch integral mode $\lambda = -0.495$ s^{-1}		Speed integral mode $\lambda = -0.176 + i0.018$ s^{-1}	
System DOF	$\|a\|$	θ/π	$\|a\|$	θ/π	$\|a\|$	θ/π
q_F	3.141	0.621	1.747	1.000	0.651	0.979
q_f	38.346	0.595	32.842	1.000	6.092	0.898
β	0.520	0.679	0.554	1.000	0.077	0.290
Ω	1.000	0.000	1.000	0.000	1.000	0.000
$\bar{\Omega}$	1.060	-0.207	1.818	0.000	1.190	-0.006
v_i	6.172	-0.749	21.505	0.000	4.020	-0.788
s	0.937	-0.938	1.528	1.000	4.067	-0.876
α	0.774	0.626	0.799	1.000	0.259	0.954
$\int(\bar{\Omega} - \hat{\Omega})$	1.547	-0.838	3.675	1.000	6.735	-0.977
Eigenvalues:	(Blade coll. flap mode) $\lambda = -6.919 + i5.738$ s^{-1}		(Circulation lag mode) $\lambda = -4.437 + i0.431$ s^{-1}		(Low-pass filter mode) $\lambda = -1.654$ s^{-1}	
System DOF	$\|a\|$	θ/π	$\|a\|$	θ/π	$\|a\|$	θ/π
q_F	0.332	-0.789	1.167	-0.924	2.632	1.000
q_f	350.65	0.913	199.39	0.915	66.697	1.000
β	1.362	0.702	0.522	0.894	0.555	0.000
Ω	1.000	0.000	1.000	0.000	1.000	0.000
$\bar{\Omega}$	0.135	-0.752	0.327	-0.959	1.985	1.000
v_i	21.788	0.774	12.512	0.921	10.139	1.000
s	2.706	0.758	1.440	0.917	0.932	1.000
α	22.703	-0.068	53.220	0.667	2.580	1.000
$\int(\bar{\Omega} - \hat{\Omega})$	0.015	0.468	0.073	0.072	1.200	0.000

q_F: First fore-aft structural mode of the tower. q_f: First collective flapwise structural mode of the blades. β: Collective blade pitch angle. Ω: Rotor speed. $\bar{\Omega}$: Measured and filtered rotor speed. $\hat{\Omega}$: Commanded rotor speed. v_i: Rotor-average axial induced velocity. s: Auxiliary state variable in the dynamic inflow equations. α: Rotor-average dynamic angle-of-attack.

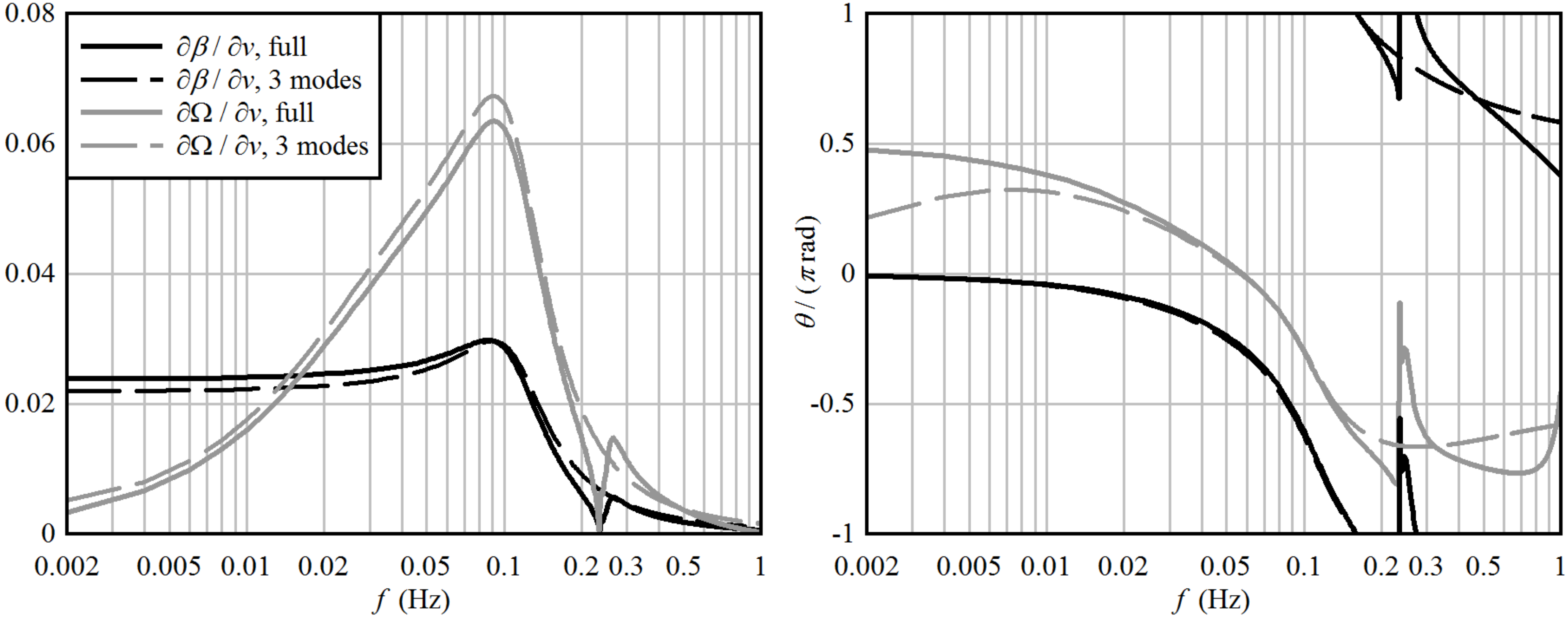
Modal contributions to the control actions



Modal contributions to the rotor speed response, as a function of gains



Rotor speed and blade pitch responses, including phase



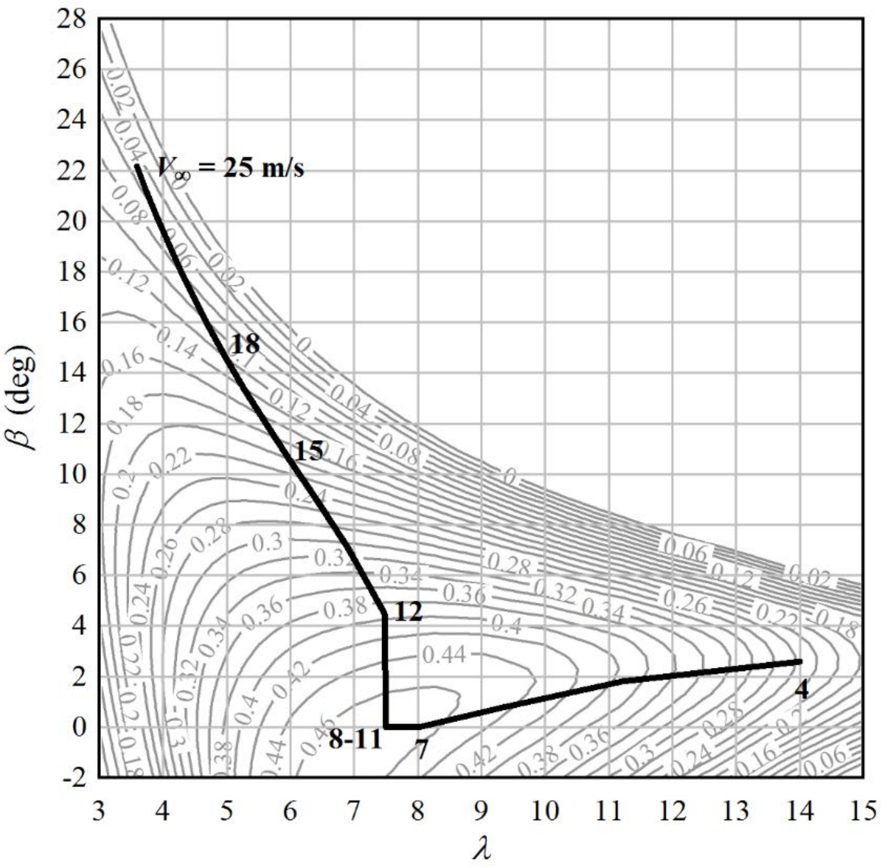
Key points:

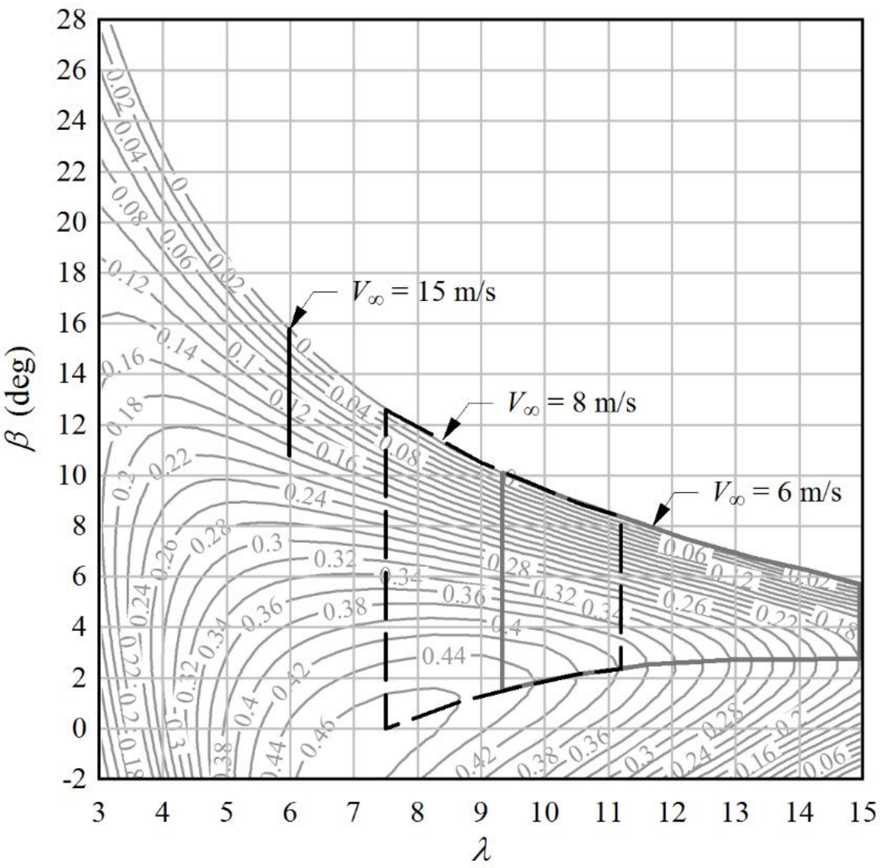
(1) A modern wind turbine is required to operate away from its nominal schedule, upon commands from the plant operator.

(2) Below the rated windspeed, there is considerable freedom in how the turbine can respond.

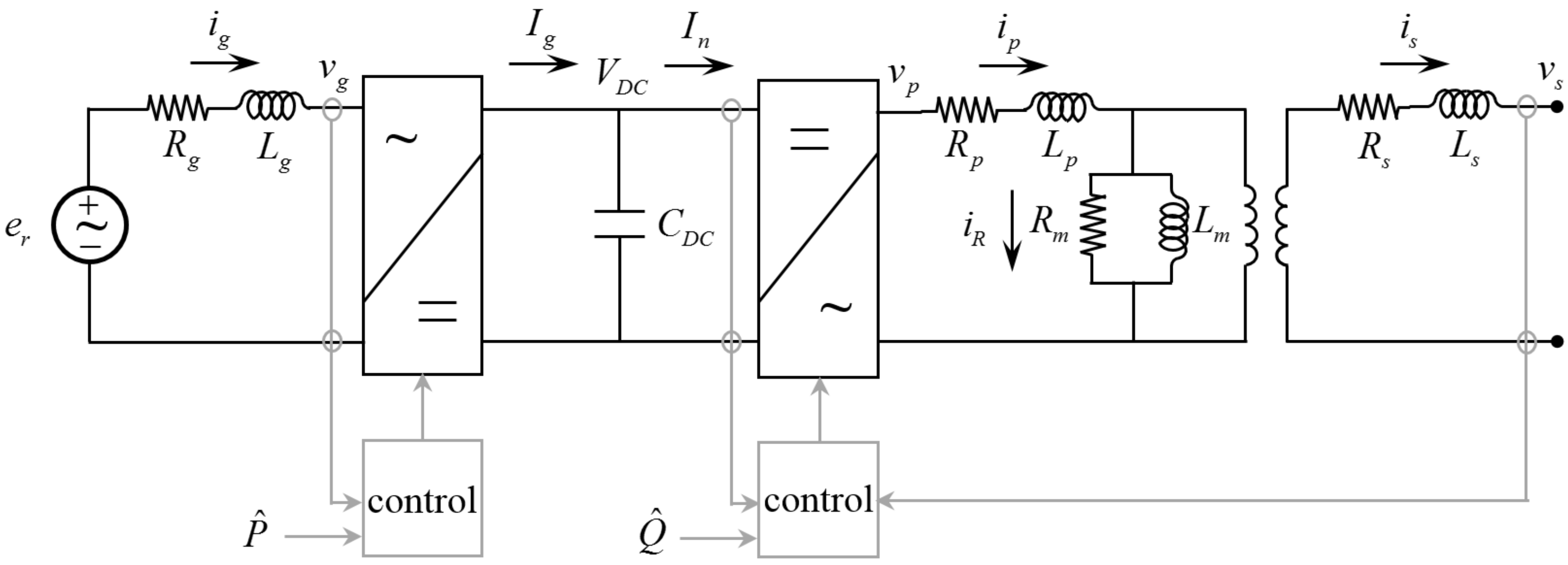
(3) The electrical and converter control dynamics constrain the bandwidth of the response, more than one might think.

(4) Constant-power operation destabilizes elastic resonant modes of the rotor. A virtual induction generator fixes the problem.


V_∞ = 25 m/s
18
15
12
8-11
7
4
β (deg)
λ


V_∞ = 15 m/s
V_∞ = 8 m/s
V_∞ = 6 m/s
β (deg)
λ

Wind turbine electrical components

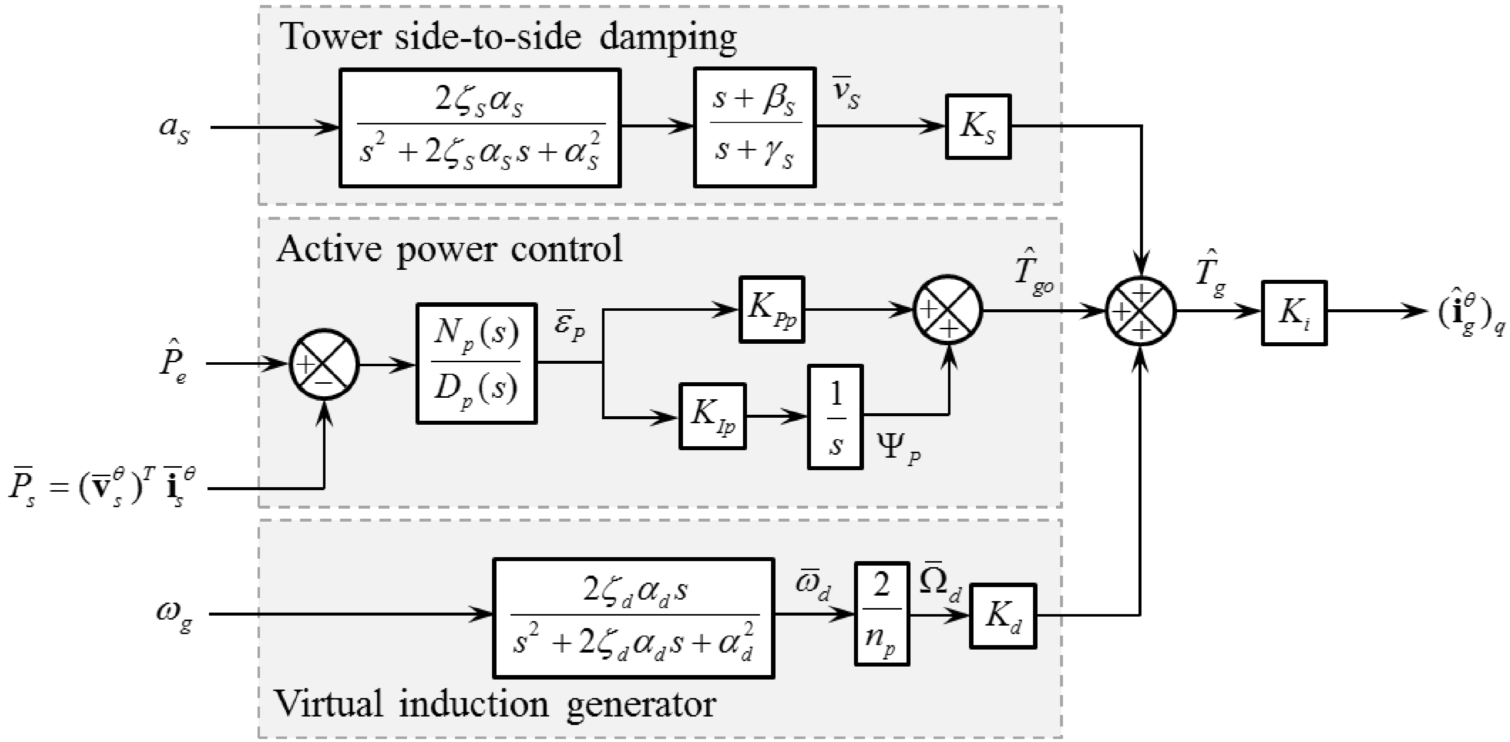


Inner-loop generator-side converter control

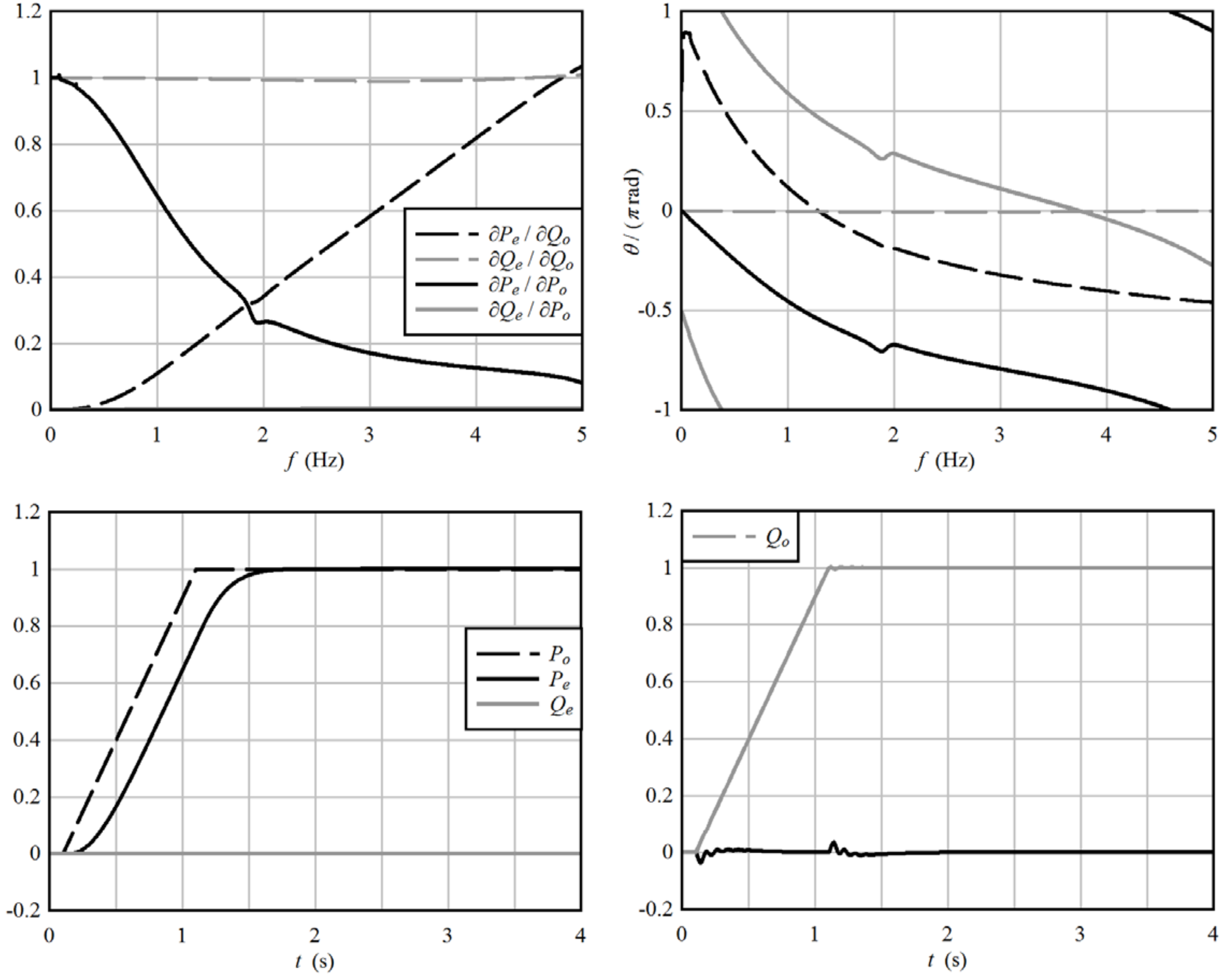
$$\mathbf{T}_a^\theta \boldsymbol{\Lambda}_g \mathbf{T}_\theta^a \frac{d\mathbf{i}_g^\theta}{dt} = -\left(\mathbf{T}_a^\theta \mathbf{R}_g \mathbf{T}_\theta^a + \omega_g \mathbf{T}_a^\theta \boldsymbol{\Lambda}_g \frac{d\mathbf{T}_\theta^a}{d\theta} \right) \mathbf{i}_g^\theta - \mathbf{v}_g^\theta - \mathbf{T}_a^\theta \frac{d\mathbf{T}_\theta^a}{d\theta} \boldsymbol{\lambda}_r^\theta \omega_g$$

$$\mathbf{v}_g^\theta = -\bar{\omega}_g \mathbf{T}_a^\theta \boldsymbol{\Lambda}_g \frac{d\mathbf{T}_\theta^a}{d\theta} \bar{\mathbf{i}}_g^\theta - \bar{\omega}_g \mathbf{T}_a^\theta \frac{d\mathbf{T}_\theta^a}{d\theta} \boldsymbol{\lambda}_r^\theta - \mathbf{K}_{Pg} \left(\hat{\mathbf{i}}_g^\theta - \bar{\mathbf{i}}_g^\theta \right) - \int_0^t \mathbf{K}_{Ig} \left(\hat{\mathbf{i}}_g^\theta - \bar{\mathbf{i}}_g^\theta \right) dt$$

Active power control with a virtual induction generator



Power command tracking control



Key points:

(1) A linear parameter-varying approach shows a lot of promise, for modelling large-scale wind power plants. Parts of the system that are nonlinear on short timescales (like control mode transitions) can be simulated, with the rest of the system modelled as LPV.

(2) 10 modes per turbine = 1000 modes for a GW-scale wind power plant, and further plant-level modal reduction is likely possible.

(3) The model can be used as an observer in a real-time controller, or as a fast desktop simulator.

(4) A reduced-order representation of the atmospheric flow is needed to complete the model.

Represent the system as a linear parameter-varying model

$$\frac{d\mathbf{x}}{dt} = \underbrace{\mathbf{A}(\mathbf{x},\mathbf{u},t)}\mathbf{x} + \underbrace{\mathbf{B}(\mathbf{x},\mathbf{u},t)}\mathbf{u}$$

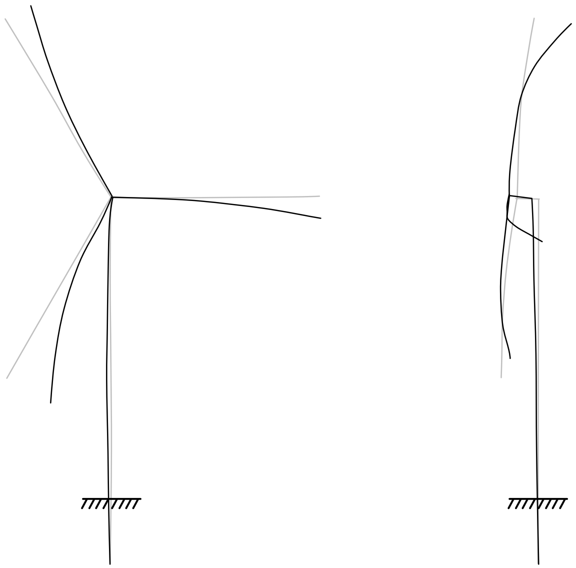
"Gradually" varying

$$\mathbf{y} = \overbrace{\mathbf{C}(\mathbf{x},\mathbf{u},t)}\mathbf{x} + \overbrace{\mathbf{D}(\mathbf{x},\mathbf{u},t)}\mathbf{u}$$

... and compute the system modes.

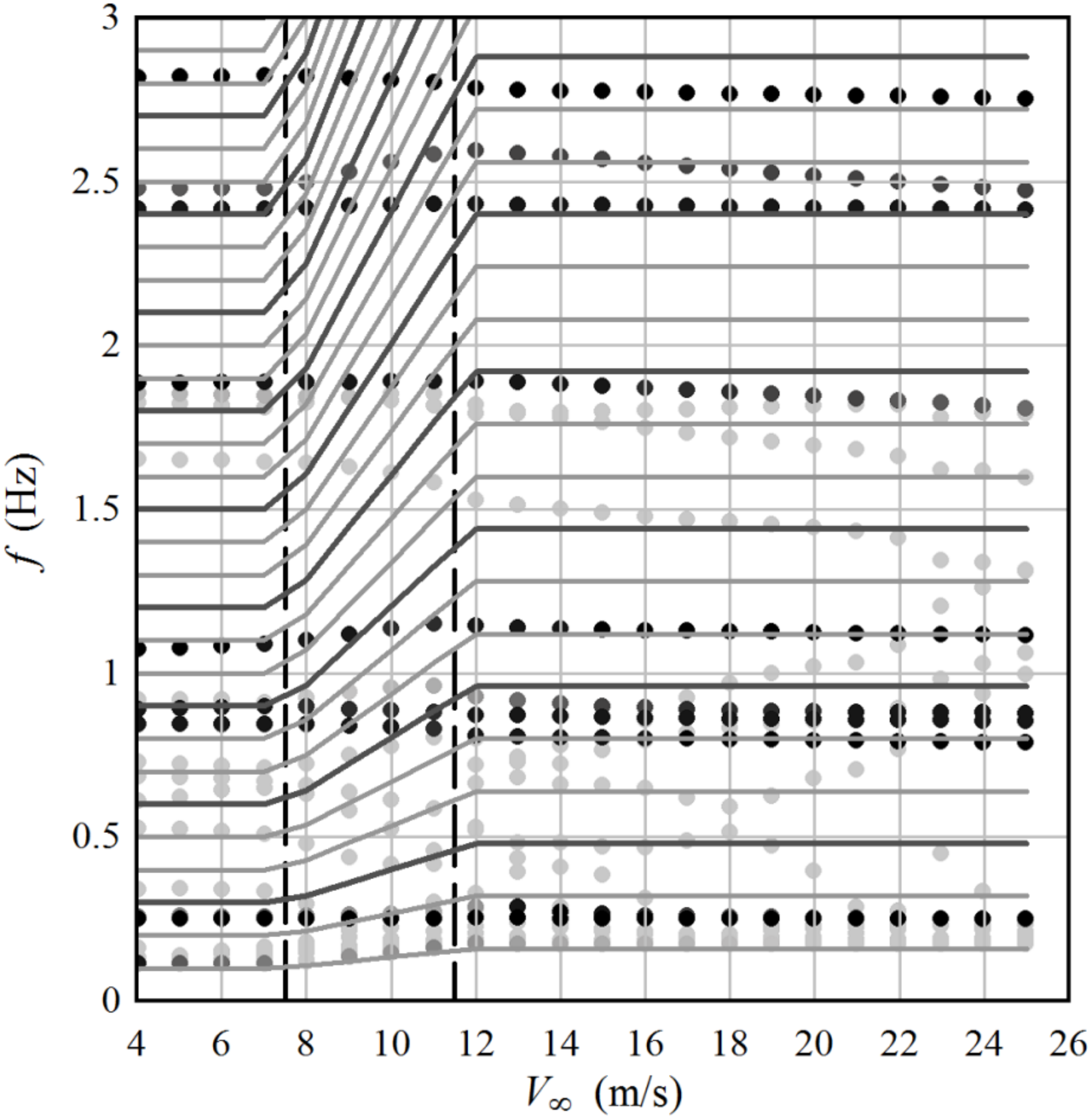
$$(i\omega\mathbf{I} - \mathbf{A})\mathbf{\Phi} = \mathbf{0}$$

Example of system modes for a single wind turbine.
The modes also contain electrical, aerodynamic, and control contributions!



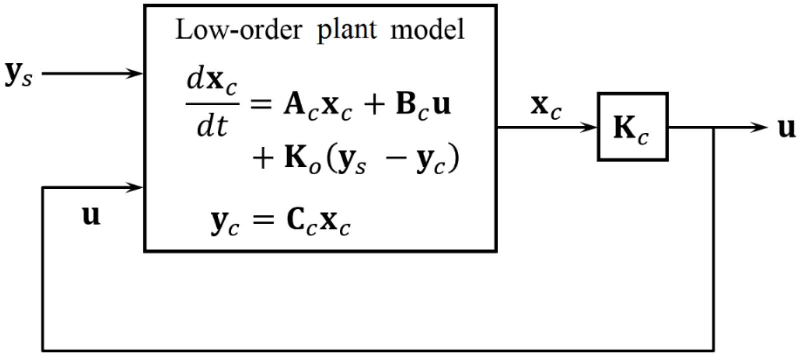
Use participation factors, or energy considerations, to select the modes which are relevant for wind power plant control actions.

Modal analysis: frequency, damping, and possible resonant interactions



The model can be used both as a real-time optimal controller and as a fast desktop simulator

Real-time control and condition monitoring:



Desktop simulation: