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ISGAN
INTERNATIONAL SMART GRID ACTION NETWORK

ISGAN
International Smart Grid Action Network
ISGAN Academy Webinar

Modeling and control of renewable-energy power plants for participation in a Dynamic Virtual Power Plant

29. 09. 2022,
Online Webinar

ISGAN in a Nutshell

ISGAN is the short name for the *International Energy Agency* (IEA) *Technology Collaboration Programme* (TCP) for a Co-operative Programme on Smart Grids (ISGAN – *International Smart Grids Action Network*).

It is also an initiative of the *Clean Energy Ministerial* (CEM) and was formally established at CEM2 in Abu Dhabi, in 2011 as an Implementing Agreement under a framework of the *International Energy Agency* (IEA).

The *International Smart Grid Action Network* (ISGAN) creates a strategic platform to support high-level government attention and action for the accelerated development and deployment of smarter, cleaner electricity grids around the world.

ISGAN
INTERNATIONAL SMART GRID
ACTION NETWORK

ISGAN in a Nutshell

ISGAN currently consists of 27 Contracting Parties.
Their nominated representatives form the Executive Committee headed by the Presidium, assisted by two co-Secretariats and the Operating Agent of ISGAN.

Co Secretariat

AIT AUSTRIAN INSTITUTE OF TECHNOLOGY

ISGAN Presidium

ISGAN Executive Committee

Co Secretariat

KSGI Korea Smart Grid Institute

ISGAN Vision

ISGAN's vision is to accelerate progress on key aspects of smart grid policy, technology, and investment through voluntary participation by governments and their designees in specific projects and programs. Its activities center foremost on those aspects of the smart grid where governments have regulatory authority, expertise, convening power, or other leverage, focusing on five principal areas:

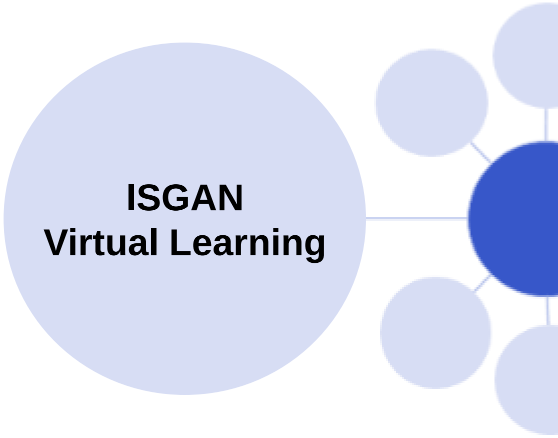
- Policy standards and regulation
- Finance and business models
- Technology system development
- Workforce skills and knowledge
- Users and consumers engagement

ISGAN facilitates dynamic knowledge sharing, technical assistance, peer review and, where appropriate, project coordination among its Contracting Parties.

ISGAN Value proposition

ISGAN Virtual Learning

- Offer the ISGAN community of high level engineers and decision makers a means of rational and efficient continuous technical skills complement and update in the field of smart grids
- ISGAN Virtual Learning proposes e-learning core modules dealing with the entire value chain of smart grid
- Fundamentals and further reading modules are also provided as appendices
- Webinars organized every two months or co-hosted with the Clean Energy Solutions Center



Operating Agent

ISGAN Website: www.iea-isgan.org

Modeling and control of renewable-energy power plants for participation in a Dynamic Virtual Power Plant

Webinar will present

- generic models
- local control schemes

of Renewable-energy Power Plants (RPP) for DVPP integration in the POwering SYstem flexibiliTY in the Future through Renewable Energy Sources (POSYTYF) project.

The speakers:

- Prof. Horst Schulte, Professor, HTW Berlin
- Florian Pöschke, Research Assistant, HTW Berlin
- Dr. Stephan Kusche, Research Assistant, HTW Berlin

Please, use the **Q&A tool** to pose questions, the speakers will answer at the end of the presentation.

The recording will be available through the **ISGAN YouTube channel.**

Agenda

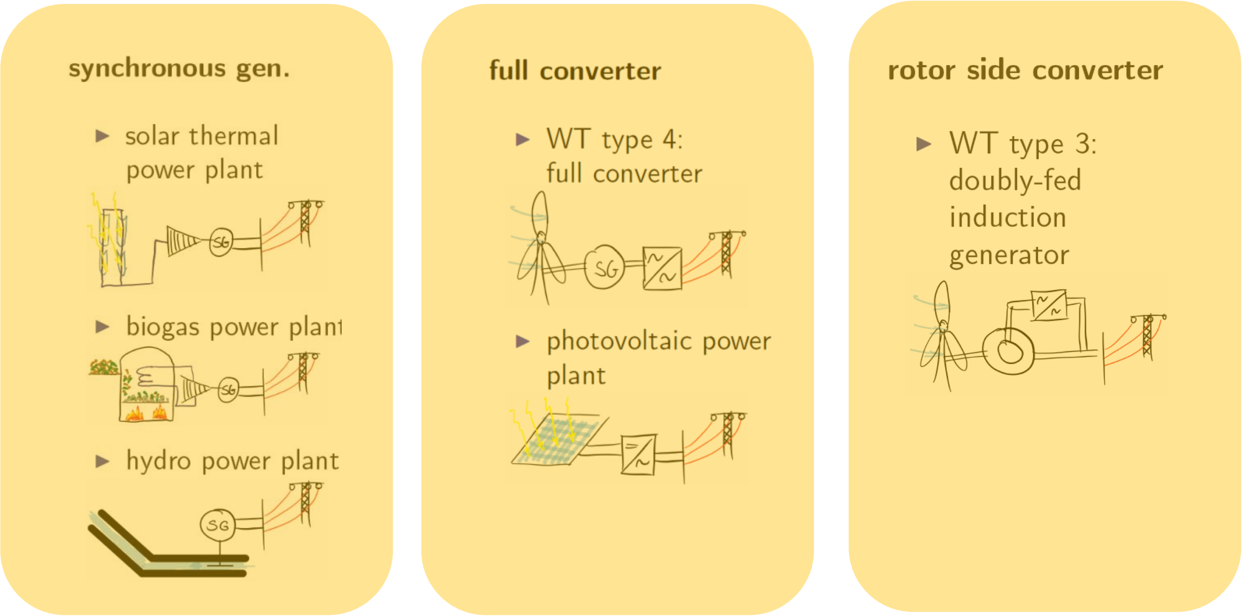
1. Introduction
2. Primary and secondary RPP models
3. Wind Turbine: Primary Conversion
4. WT Power converter: Secondary Conversion
5. PV power generation: Primary Conversion
6. Transfer functions of RPPs
7. Conclusion
8. Webinar Q&A

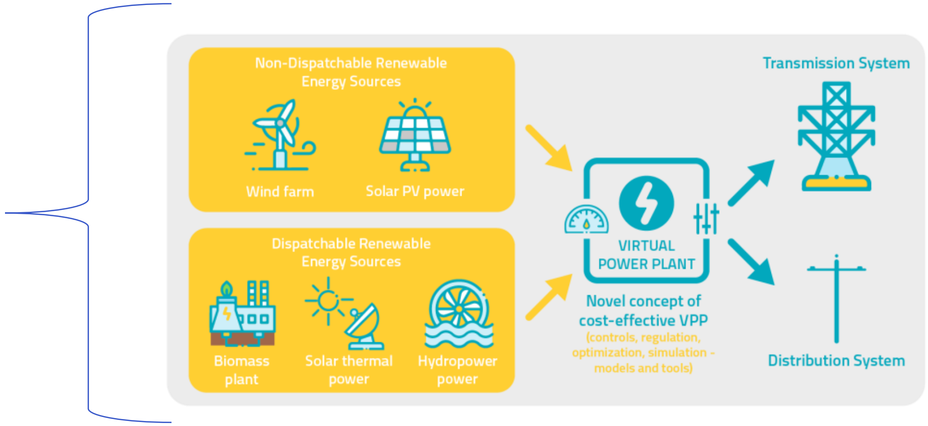
1. Introduction

Webinar presents

- generic models
- local control schemes

of Renewable-energy Power Plants (RPP) for DVPP integration.





1. Introduction

This includes different types of power plants as wind turbines, wind farms, PV systems, biogas-, hydropower, and solar thermal power plants.

Individual generating units are described in a unified model structure for local control design, simulation and the analysis of their dynamical characteristics.

Derived models are intended for the integration into a higher-level control design of DVPPs.

1. Introduction

Presentation addresses the following questions:

- What RPP dynamics are important when considering modeling for a DVPP level?
- Which functionalities need to be enabled?
- What are suitable models to described the dynamics?
- What are suitable reduced-order models for control design on a DVPP level?

1. Introduction

Modeling Framework

- Weighted convex combination of LTI state space models or affine state space models

$$\dot{\mathbf{x}} = \sum_{i=1}^{N_r} h_i(\mathbf{z}) \left(\mathbf{A}_i \, \mathbf{x} + \mathbf{B}_i \, \mathbf{u}\right),$$
$$\mathbf{y} = \sum_{i=1}^{N_r} h_i(\mathbf{z}) \, \mathbf{C}_i \, \mathbf{x}$$

$$\dot{\mathbf{x}} = \sum_{i=1}^{N_r} h_i(\mathbf{z}) \left(\mathbf{A}_i \, \mathbf{x} + \mathbf{B}_i \, \mathbf{u} + \mathbf{a}_i\right),$$
$$\mathbf{y} = \sum_{i=1}^{N_r} h_i(\mathbf{z}) \left(\mathbf{C}_i \, \mathbf{x} + \mathbf{c}_i\right)$$

- components $z_j \,, \quad j = 1, \ldots, l$ of premise vector may include

a) measured states $x_i \,, \quad i = 1, \ldots, n$

b) estimated states $\hat{x}_i \,, \quad i = 1, \ldots, n$

c) variable parameters θ_i

- convex sum condition

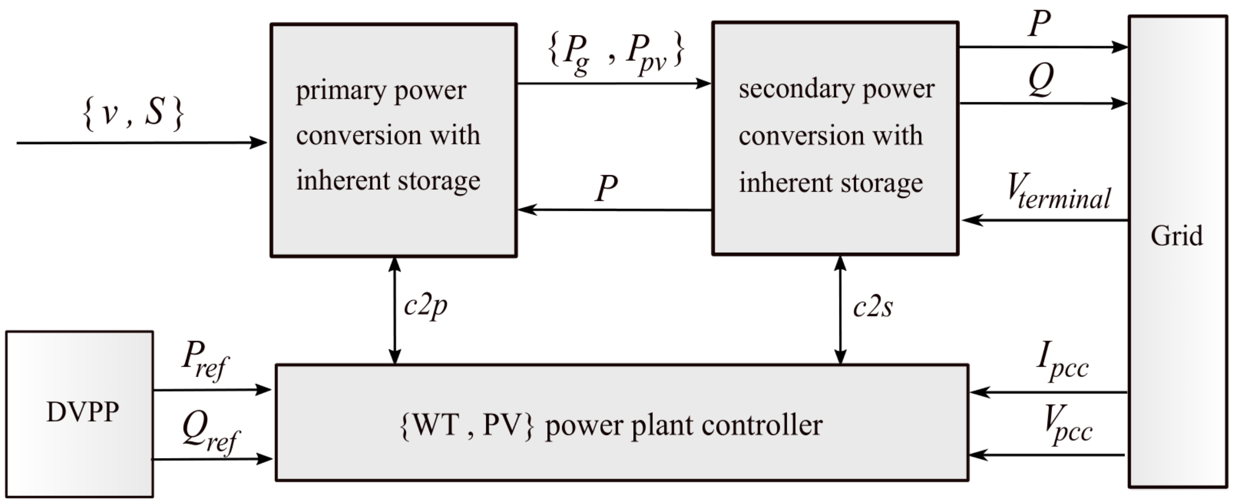
$$0 \leq h_i(\mathbf{z}) \leq 1 \,, \quad i = 1, 2, \ldots N_r \,, \qquad \sum_{i=1}^{N_r} h_i(\mathbf{z}) = 1 \quad \forall \mathbf{z}$$

2. Primary and secondary RPP models

For participations in the DVPP some functionalities are necessary:

- Commandable inputs from the DVPP to the RES:
  requested active and reactive power
- RES dynamics depending on applied control scheme
- Suitable closed loop RES models for design on the DVPP level

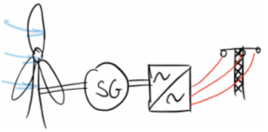
2. Primary and secondary RPP models



- Primary: wind turbine / PV generator plus DC-DC
- Secondary: grid- following / forming converter (GFOL/GFOR)

full converter

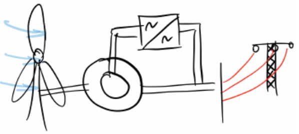
- WT type 4: full converter



- photovoltaic power plant

rotor side converter

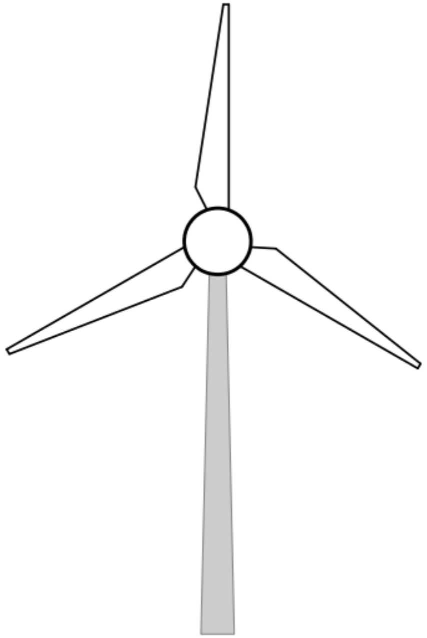
- WT type 3: doubly-fed induction generator

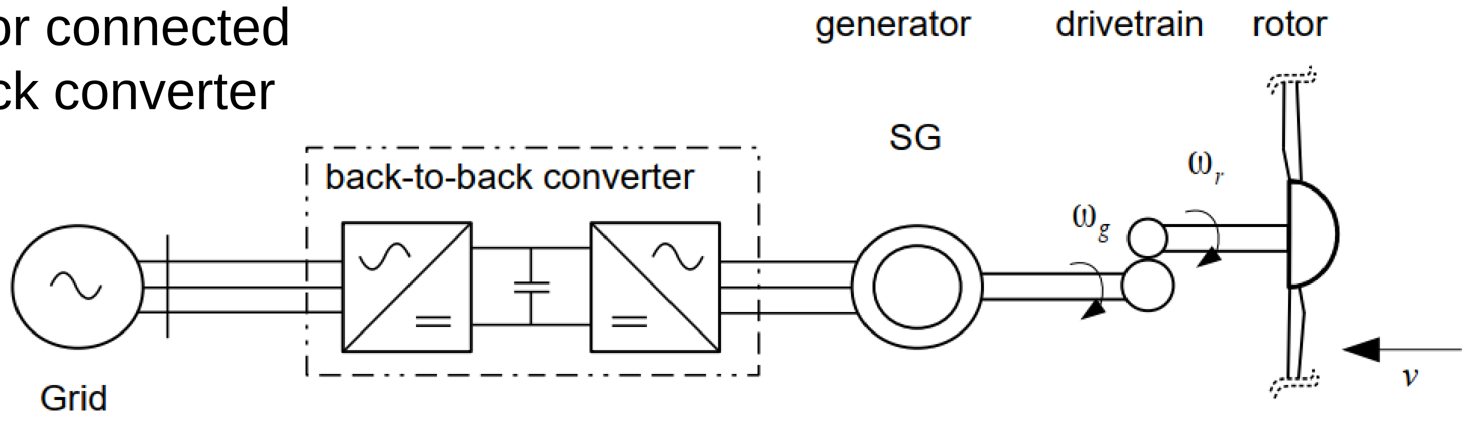


3. Wind Turbine: Primary Conversion

Objectives of Modeling

- Focus: providing a process for derivation of WT models suitable for both, control design and simulation studies
- Different types/sizes/designs of wind turbines available:
  - Three-bladed horizontal axis wind turbine
  - 5 MW reference onshore turbine
  - Type 4: synchronous generator connected to the grid using a back-to-back converter

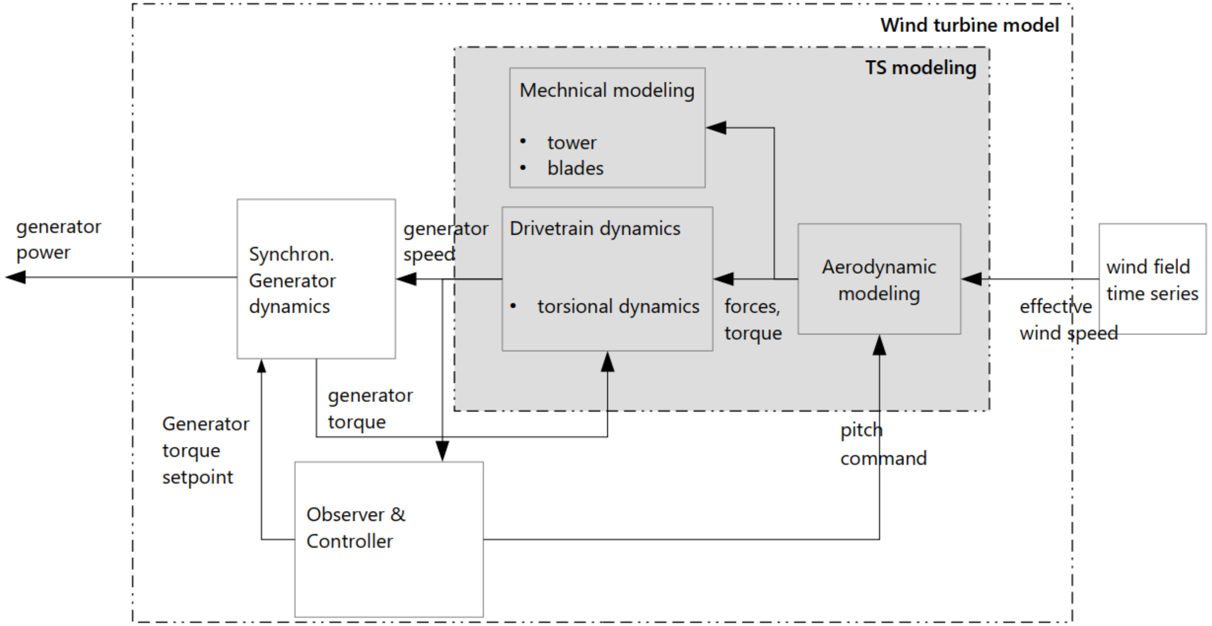




3. Wind Turbine: Primary Conversion

Overview

- Main *power dynamics* determined by rotation influenced by the nonlinear aerodynamics
- *Mechanical modeling*: loading
- *RE Source*: turbulent wind fields (generation characteristics)
- *Controller*: operating nonlinear turbine dynamics in large operating range
- *Observer*: wind speed reconstruction for monitoring and estimation of available power
- *Generator*: simple transfer function model

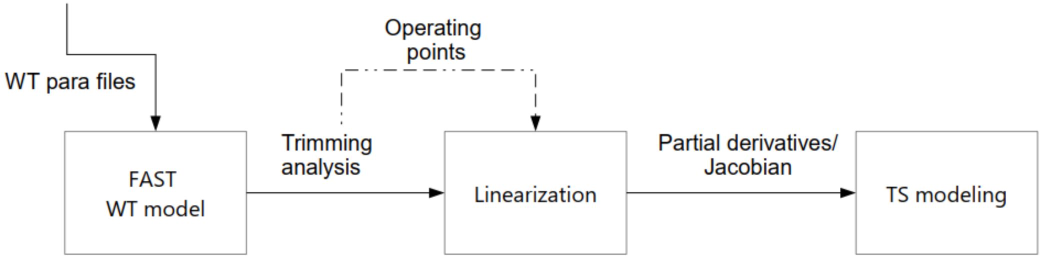


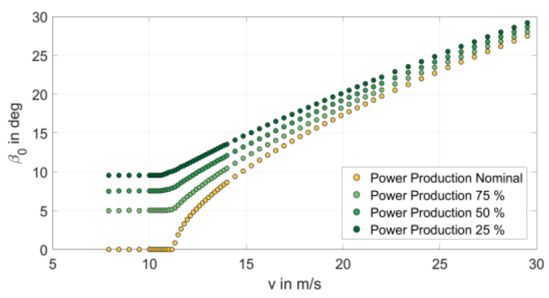
3. Wind Turbine: Primary Conversion

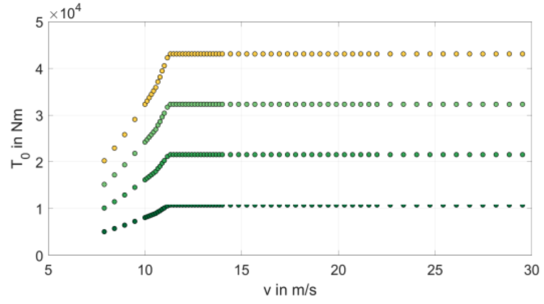
Linearization for TS modeling

Using aeroelastic simulators (FAST) as foundation for modeling

- suitable for certification of WTs, used in industry for load evaluation
- Inherits aerodynamics, tower, blades, drivetrain, (platform),..
- No electrical connection
- Modular approach to parametrize the turbine component
- Build-in linearization functionality

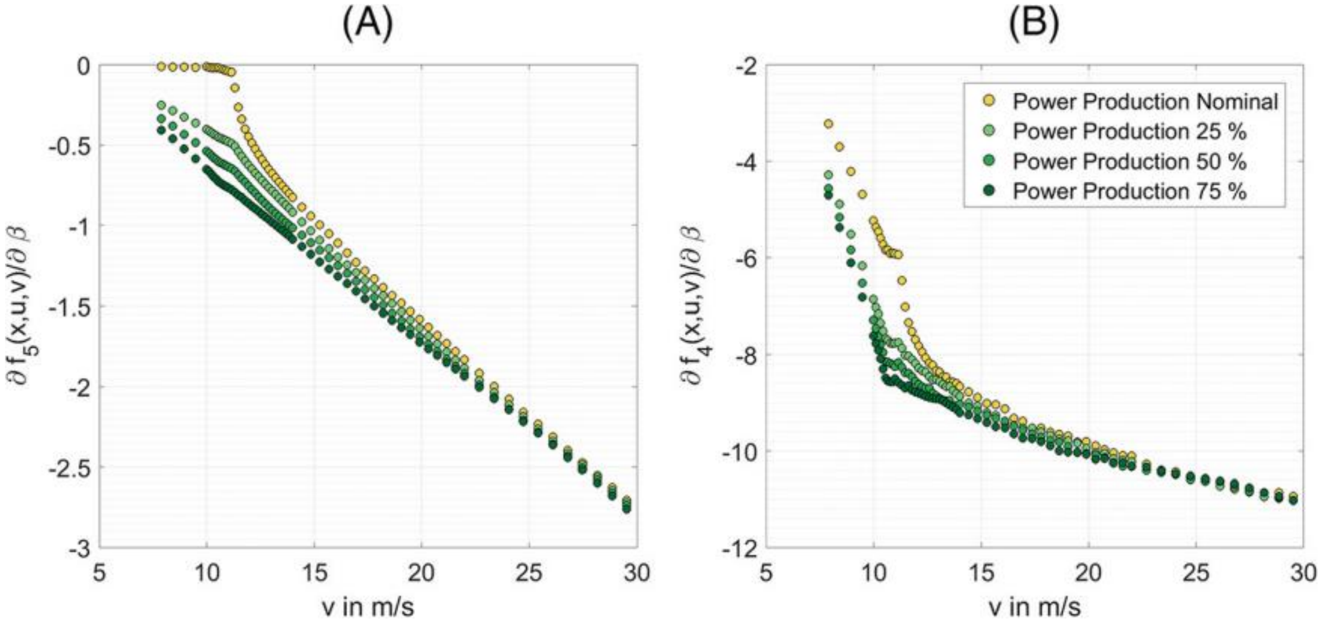


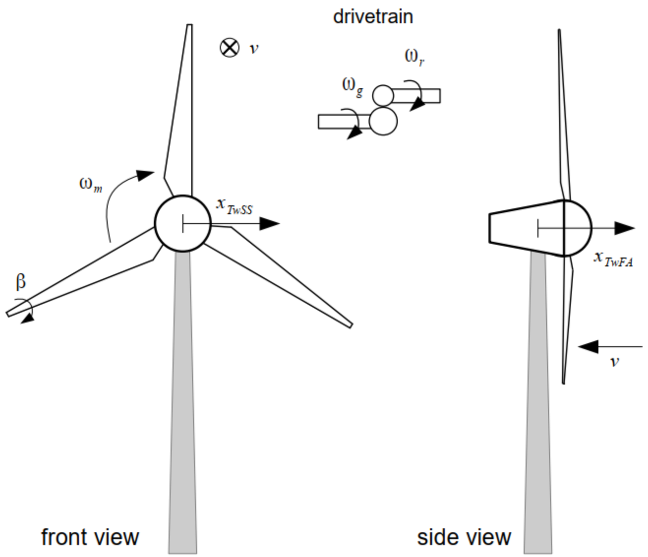




3. Wind Turbine: Primary Conversion

Nonlinear Wind Turbine Model in TS Form

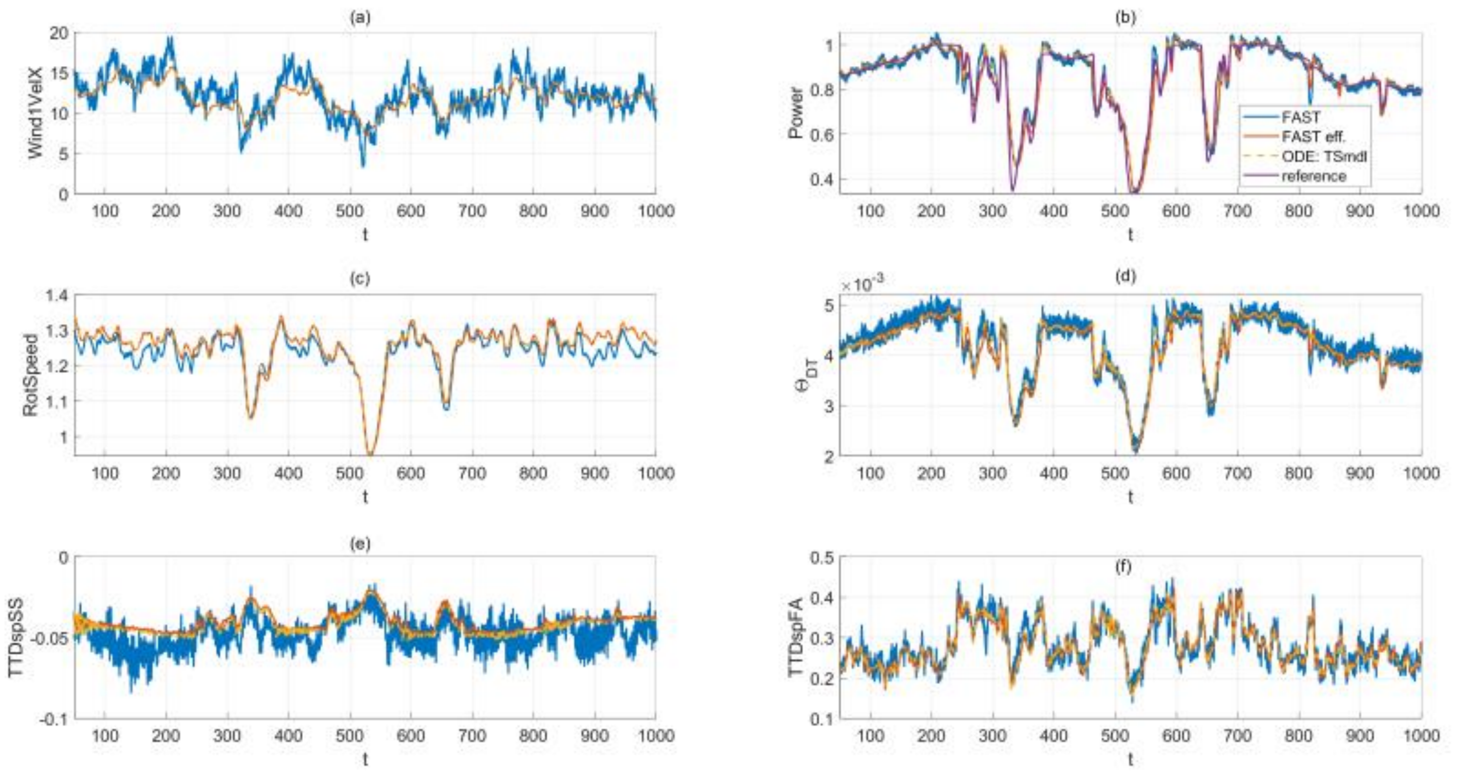




$$\dot{x} = \begin{bmatrix} \dot{x}_{\mathrm{TwSS}} \\ \ddot{x}_{\mathrm{TwSS}} \\ \dot{x}_{\mathrm{TwFA}} \\ \ddot{x}_{\mathrm{TwFA}} \\ \dot{\omega_r} \\ \dot{\omega_g} \\ \dot{\theta}_{\mathrm{DT}} \end{bmatrix} = \sum_{i=1}^{N} h_i(v,\ \Delta p)(A_i(x - x_{0i}) + B_i\underbrace{(u - u_{0i})}_{\begin{bmatrix} \beta - \beta_{0i} \\ T - T_{0i} \end{bmatrix}} + B_{di}(v - v_{0i}))$$

3. Wind Turbine: Primary Conversion

TS model validation against FAST 23DOF simulation



Suitable for simulation studies and control design

3. Wind Turbine: Primary Conversion

Wind speed observer design

- Wind speed *v* unmeasurable for control purposes!

$$\dot{x} = \sum_{i=1}^{N} h_i(v,\ \Delta p)(A_i(x - x_{0i}) + B_i(u - u_{0i}) + B_{di}(v - v_{0i}))$$

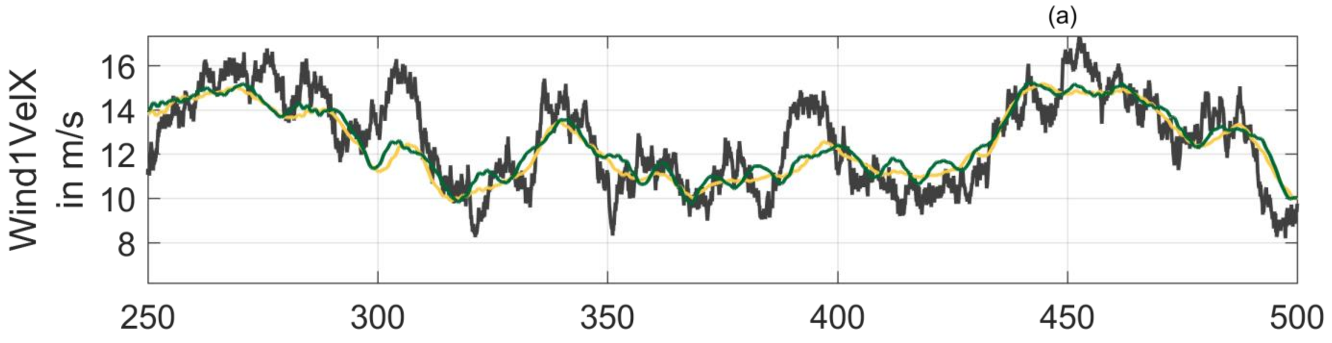
- Augment system description:

$$\dot{\chi} = \sum_{i=1}^{N} h_i(v,\ \Delta p)\left(\begin{bmatrix} A_i & B_{di} \\ 0 & -1/\tau \end{bmatrix} (\chi - \chi_{0i}) + \begin{bmatrix} B_i \\ 0 \end{bmatrix} (u - u_{0i})\right)$$

- Observer design for augmented system to estimate *v*!

3. Wind Turbine: Primary Conversion

Reduced-order models of power tracking



- Black: hub height component of turbulent wind field
- Yellow/green: wind speed estimation in different power tracking scenarios

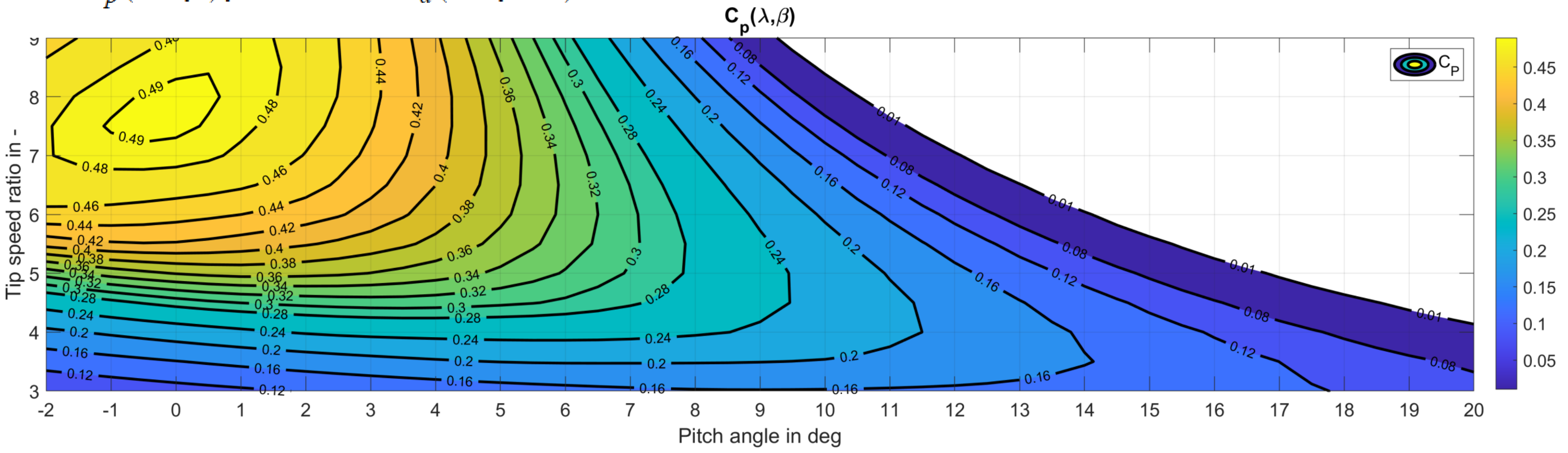
- Wind speed observer allows for:
  - Implementation of Condition monitoring systems ("digital twin")
  - Estimation of available power (DVPP)
  - (Possibly) optimized wind farm operation (load balancing, increasing energy yield)

3. Wind Turbine: Primary Conversion

Power tracking operation

- In general: power tracking operation of a wind turbine is not unique

$$p = 0.5\, c_p(\lambda, \beta)\, \rho \pi R^2 v^3 = T_a(\lambda, \beta, v)\, \omega$$



- Different dynamical properties?

3. Wind Turbine: Primary Conversion

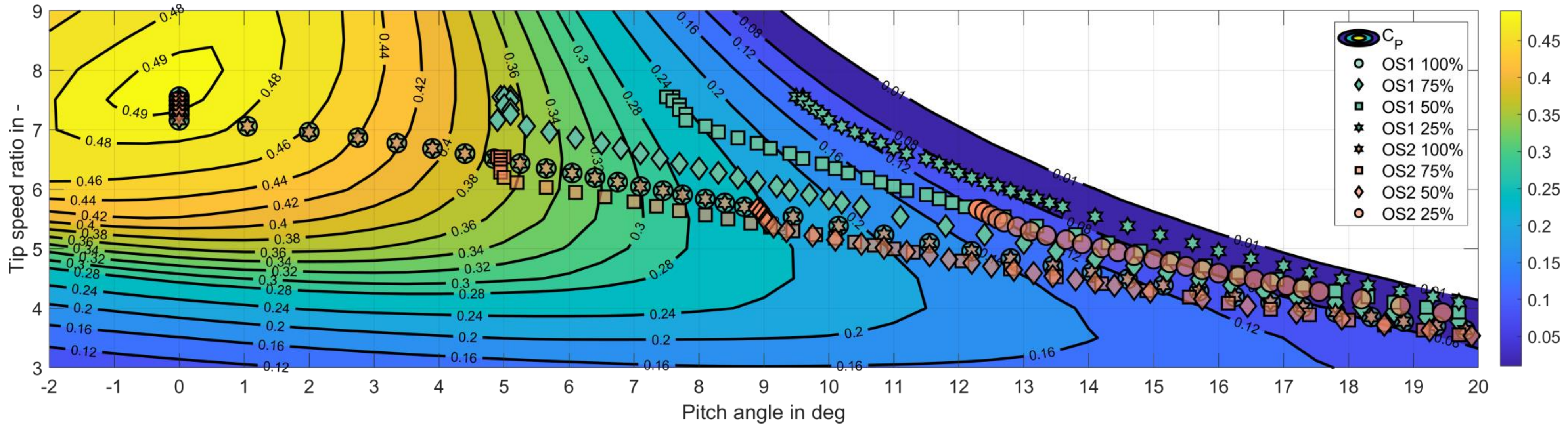
Power tracking operation

- Consideration of two different operating strategies (OS)

OS1: variation of torque only *OS2: variation of torque and rotational speed*

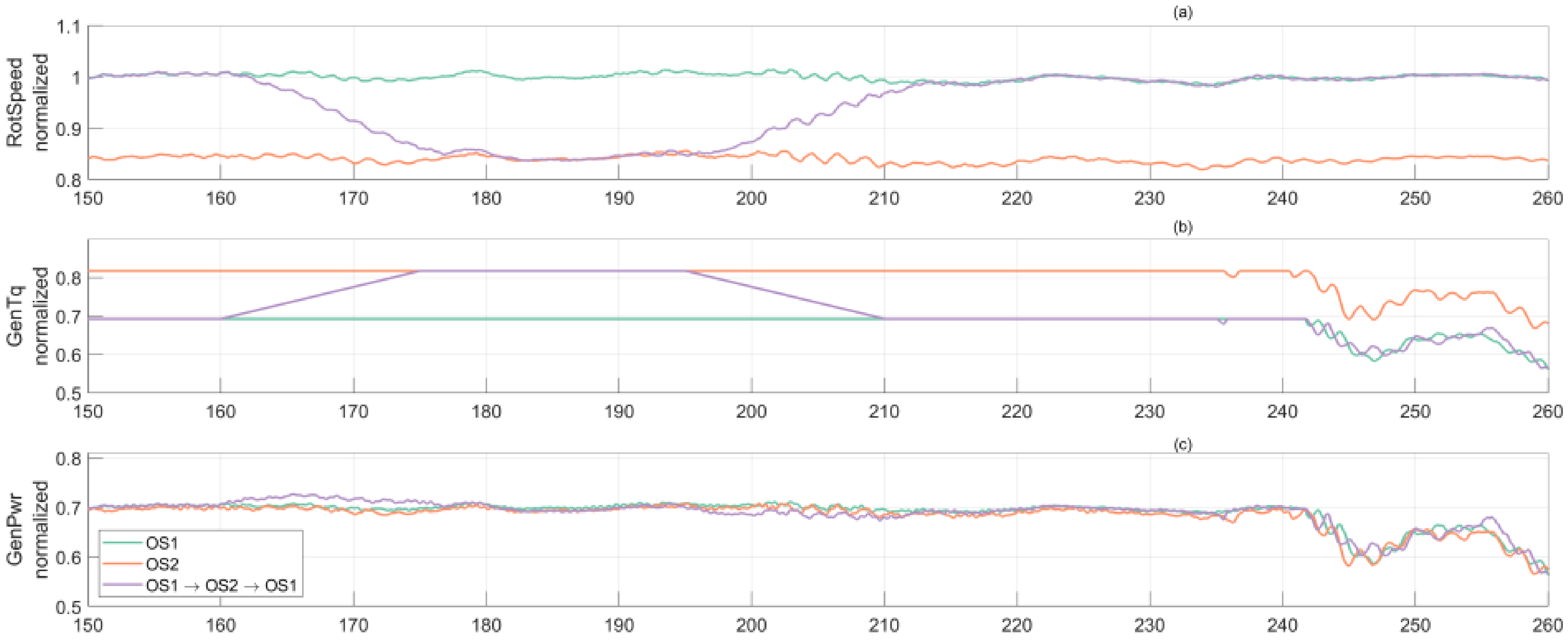
$$\text{OS1}: \begin{cases} p(v) = \omega_\text{R}(v)T_\text{g}(v) & \text{if } p_d = 1 \\ p(v) = \omega_\text{R}(v)\underbrace{p_d T_\text{g}(v)}_{=T(v,p_d)} & \text{if } p_d < 1 \end{cases}$$

$$\text{OS2}: \begin{cases} p(v) = \omega_\text{R}(v)T_\text{g}(v) & \text{if } p_d = 1 \\ p(v) = \underbrace{\sqrt{p_d}\omega_\text{R}(v)}_{=\omega(v,p_d)}\underbrace{\sqrt{p_d}T_\text{g}(v)}_{=T(v,p_d)} & \text{if } p_d < 1 \end{cases}$$



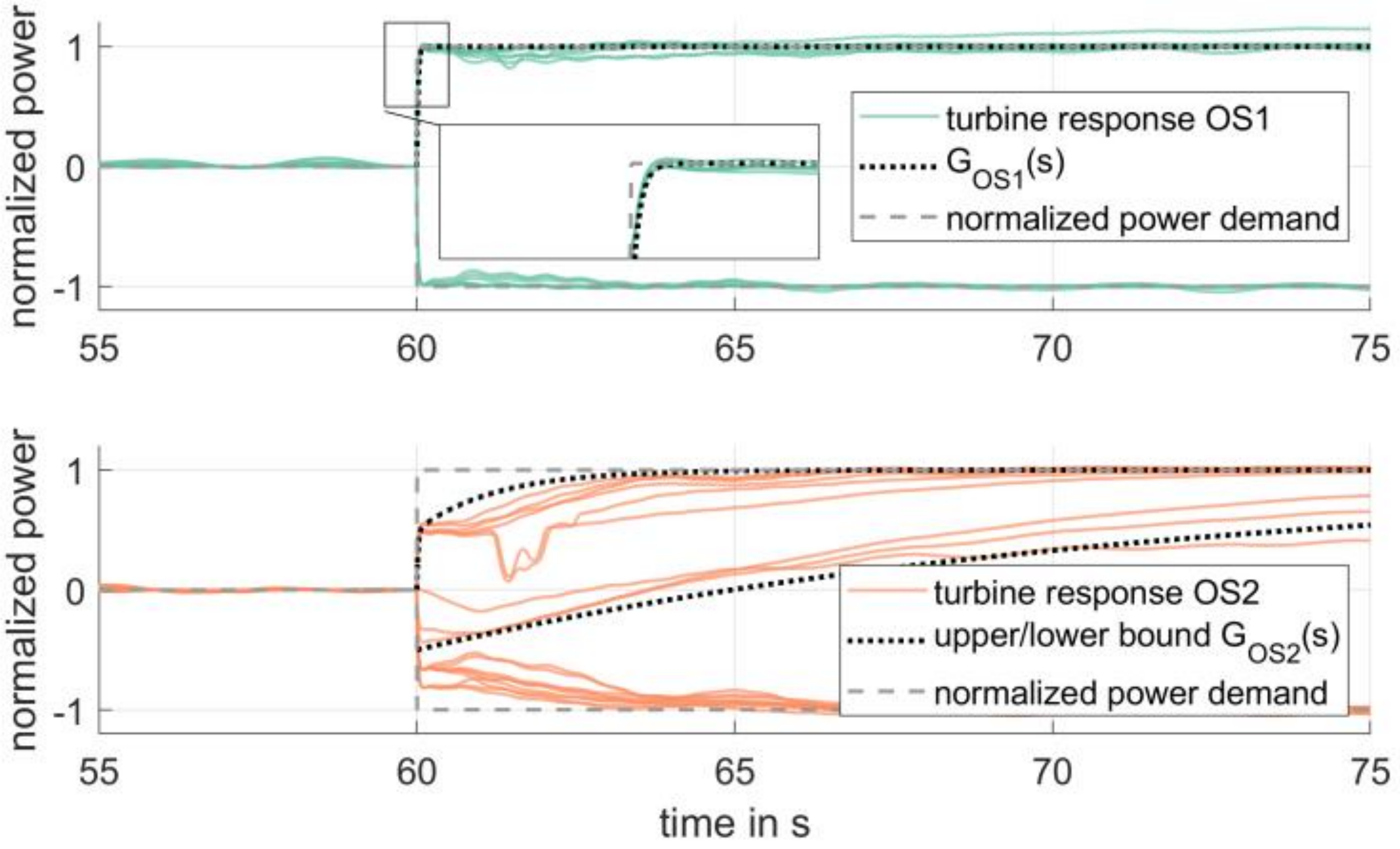
3. Wind Turbine: Primary Conversion

Power tracking operation



3. Wind Turbine: Primary Conversion

Reduced-order models of power tracking



$$G_{\mathrm{OS1}}(s) = \frac{1}{T_{\mathrm{OS1}}s + 1}$$

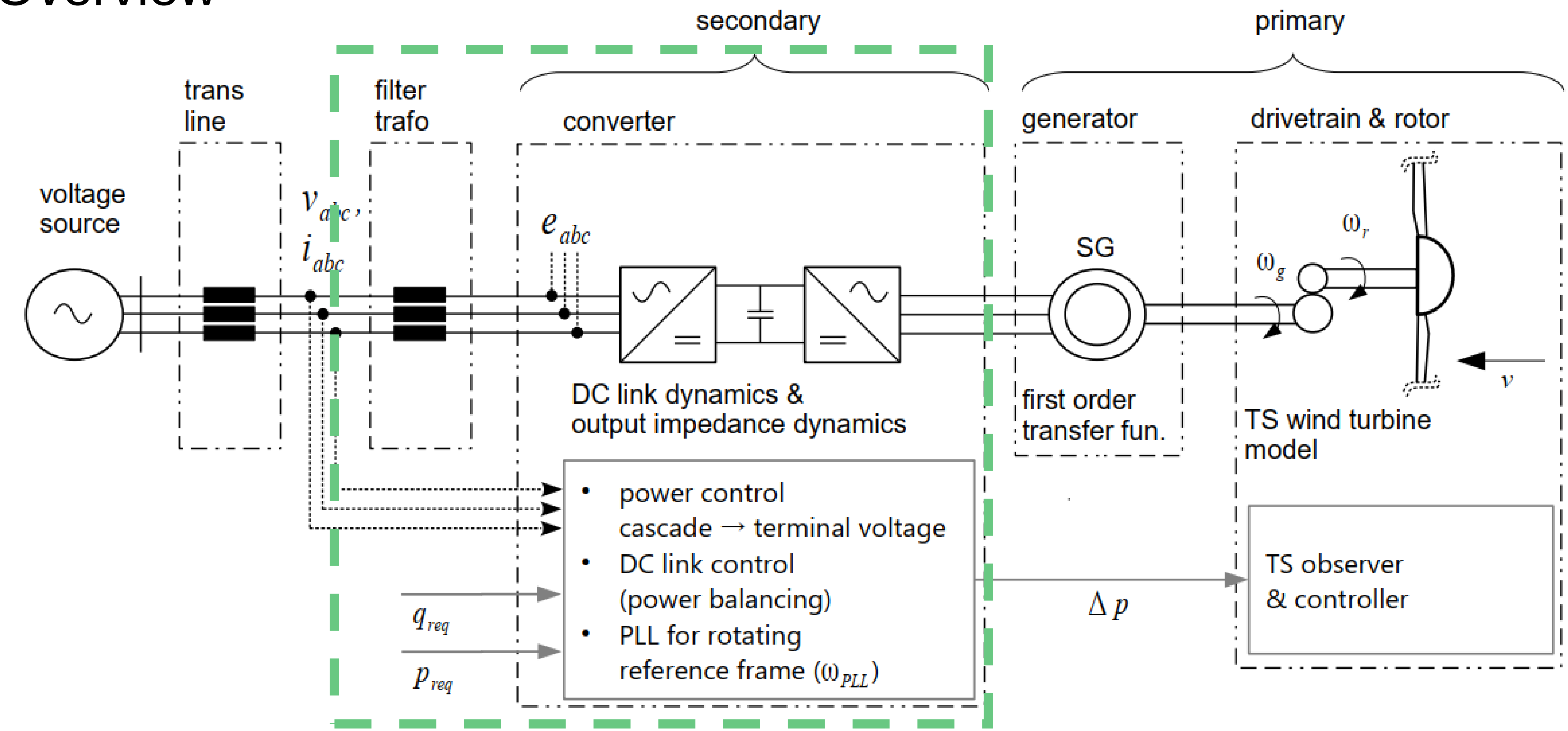
$$G_{\mathrm{OS2}}(s) = G_{\mathrm{I}}(s) + G_{\mathrm{II}}(s)$$

$$\text{with} \quad G_{\mathrm{I/II}}(s) = k_{\mathrm{I/II}} \frac{a_{\mathrm{I/II}}s + b_{\mathrm{I/II}}}{c_{\mathrm{I/II}}s + d_{\mathrm{I/II}}}$$

- OS1 power tracking determined by generator dynamics
- OS2 power tracking as combination of generator and rotational dynamics

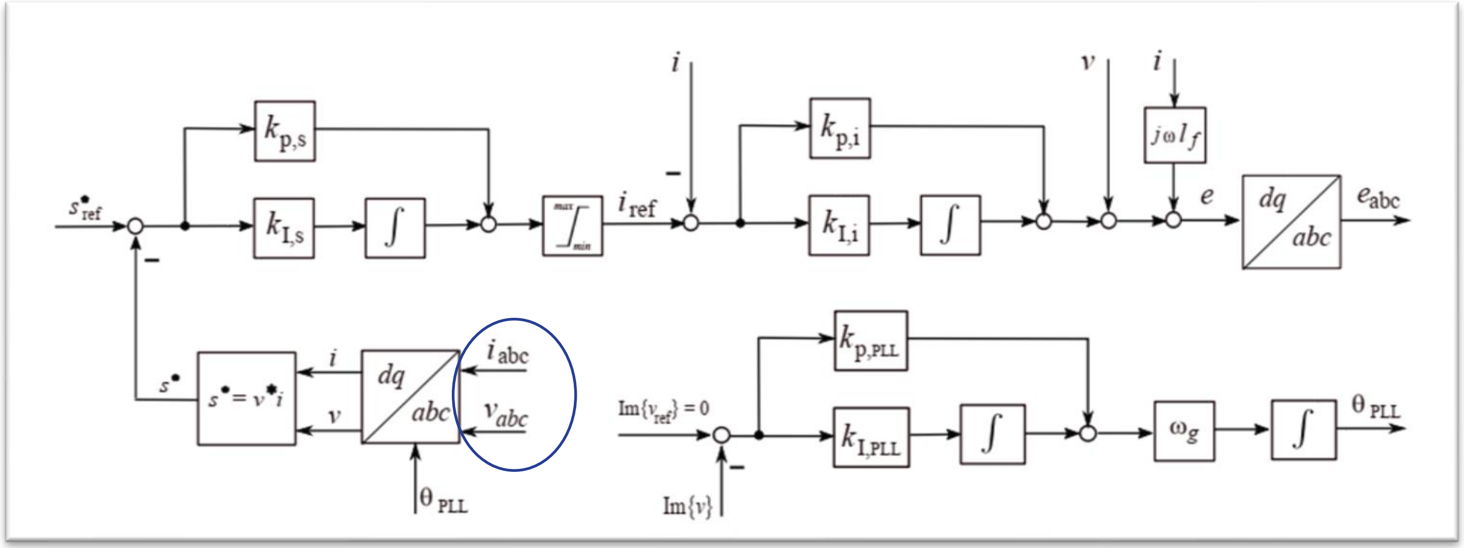
4. WT Power converter: Secondary Conversion

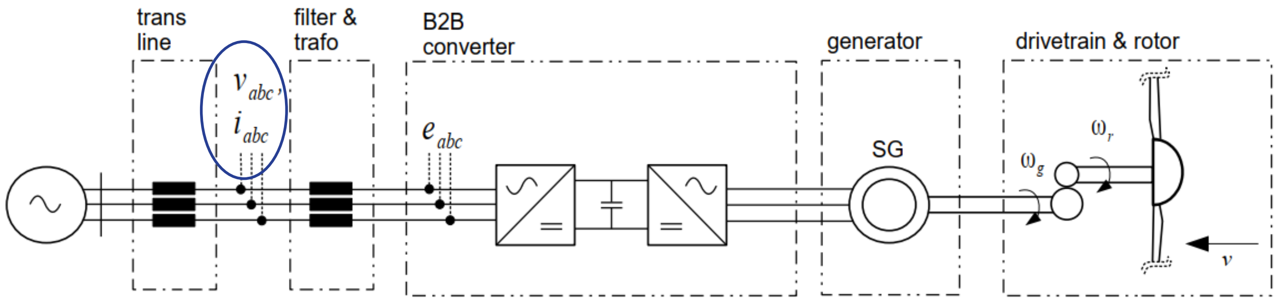
Overview



4. WT Power converter: Secondary Conversion

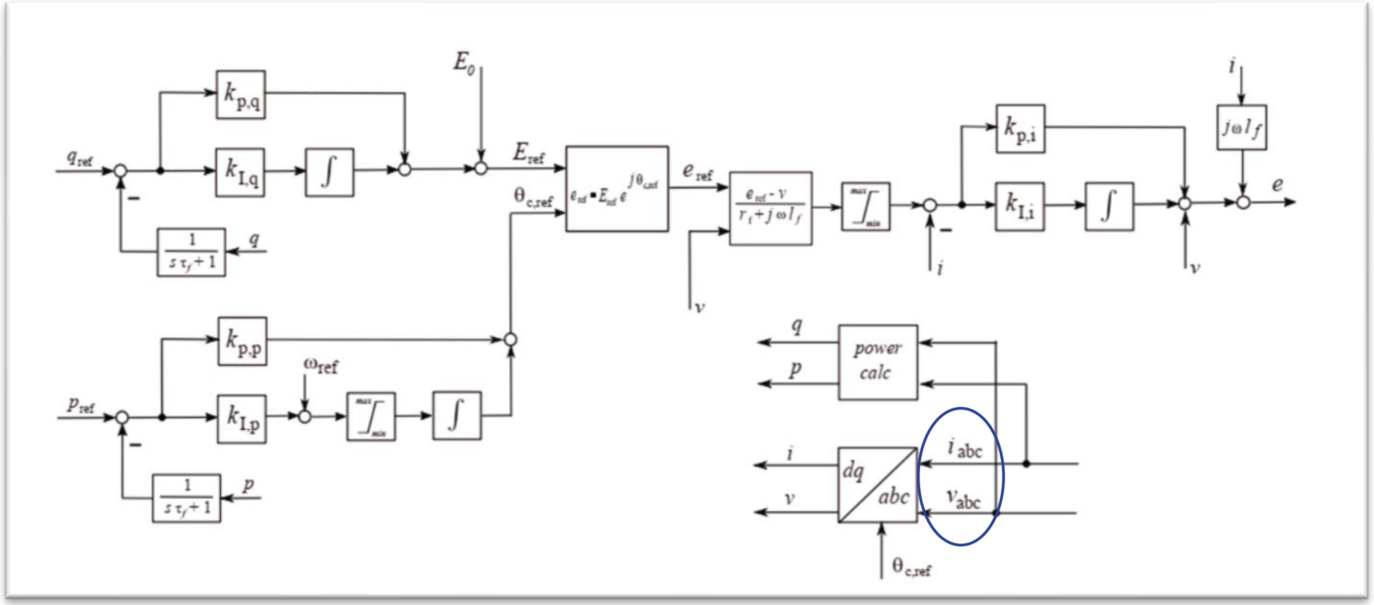
Control of grid-side converter: **G**rid **Fol**lowing (GFOL)

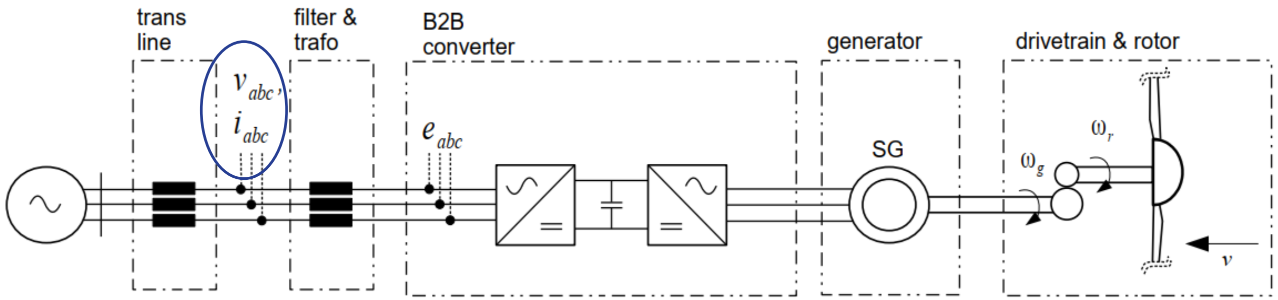




4. WT Power converter: Secondary Conversion

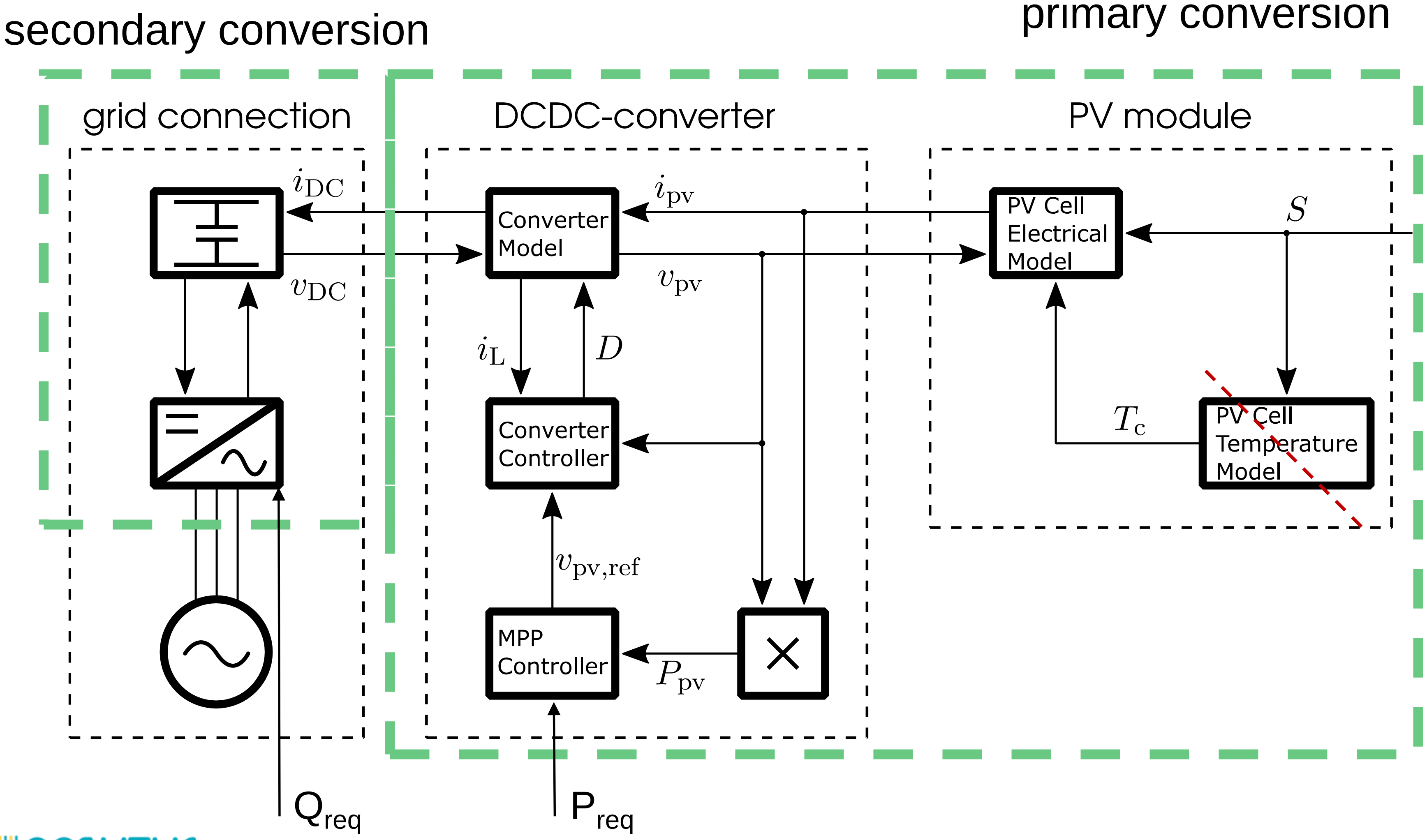
Control of grid-side converter: **G**rid **Forming** (GFOR)





5. PV power generation: Primary Conversion

Model overview

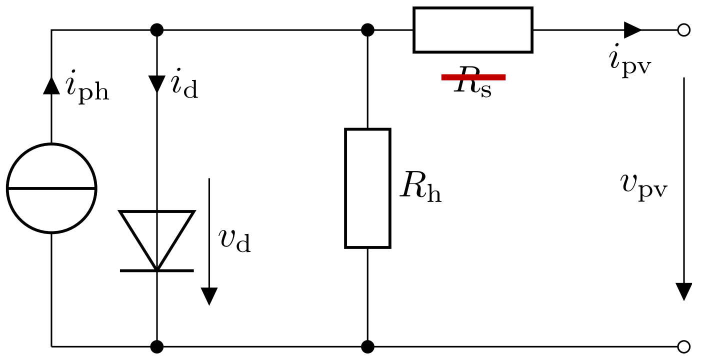


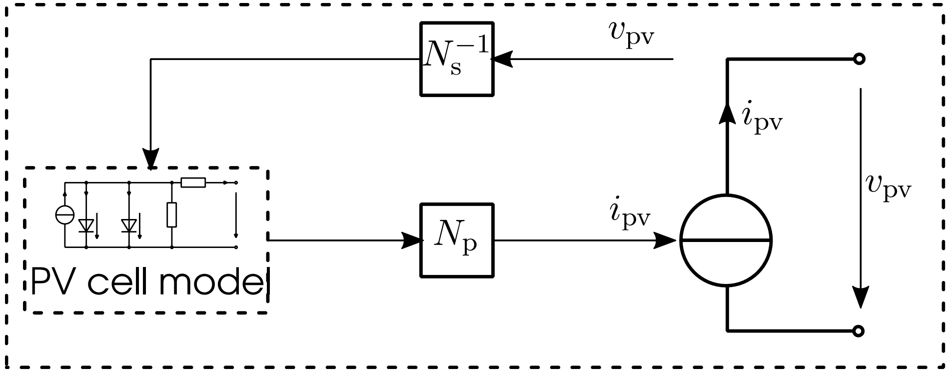
S	irradiation
i_{DC}, v_{DC}	DC current/voltage
i_{PV}, v_{PV}	PV array current/voltage
I_L	inductor current
D	duty cycle

5. PV power generation: Primary Conversion

Cell electrical model

Single Diode PV model





The governing equation (2) becomes:

$$i_{pv} = i_{ph} - i_s \left[\exp\left(\frac{1}{A_n} \frac{v_{pv}}{v_T} \right) - 1 \right] - \frac{v_{pv}}{R_h} = f(v_{pv}). \tag{3}$$

For the open-circuit $i_{pv} = 0$, it follows from (3) that the diode reverse-bias saturation current i_s can be expressed by the open-circuit voltage $v_{oc} = v_{pv}(i_{pv} = 0)$:

$$i_s = \frac{i_{ph} - \frac{v_{oc}}{R_h}}{\exp\left(\frac{1}{A_n} \frac{v_{oc}}{v_T} \right) - 1}. \tag{4}$$

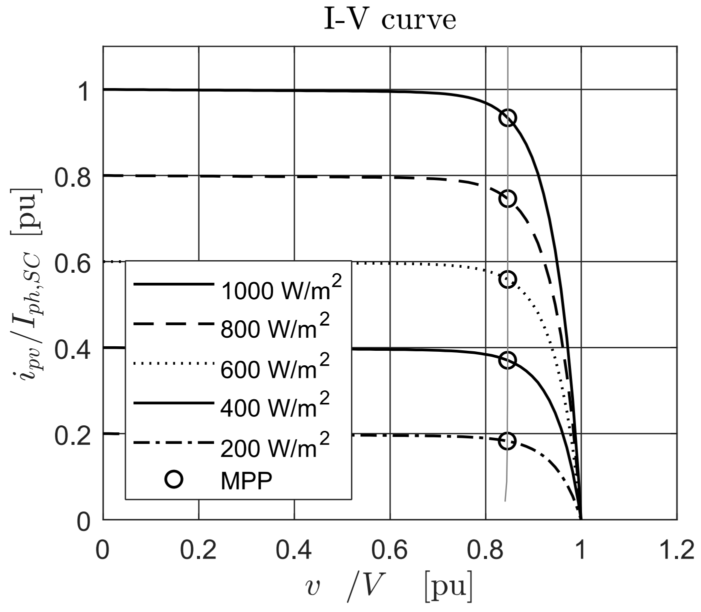
Derivations from the STC are addressed by the following correction formulas:

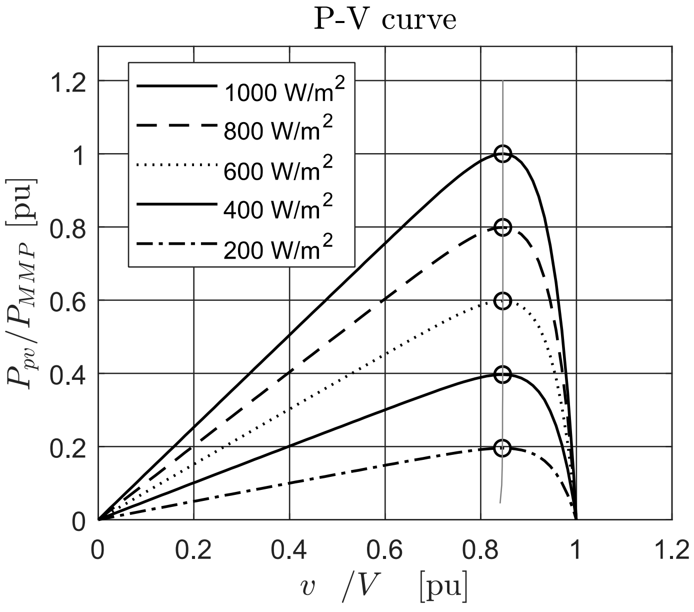
$$\frac{i_{ph}}{i_{ph}^{STC}} = \frac{S}{S^{STC}} \left[1 + \alpha_T (T_c - T_c^{STC}) \right], \quad \frac{v_{oc}}{v_{oc}^{STC}} = 1 + \beta_T (T_c - T_c^{STC}). \tag{5}$$

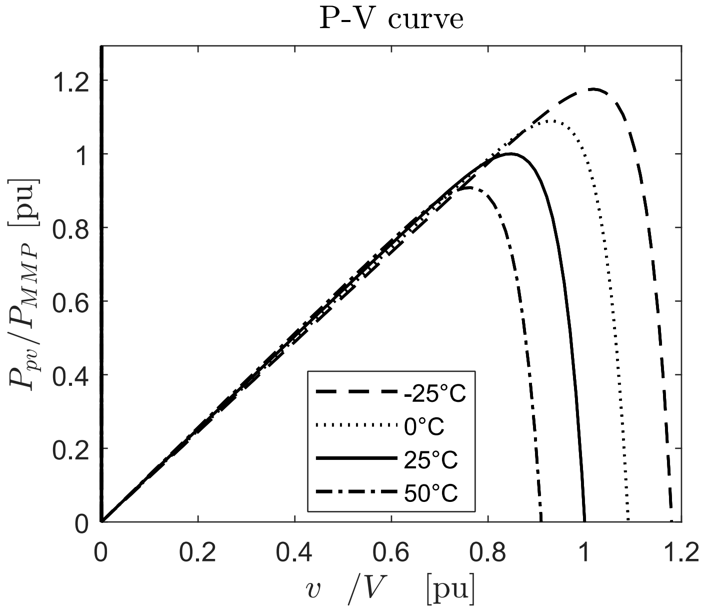
5. PV power generation: Primary Conversion

Cell characteristic

- produced power has linear dependency of irradiation
- MPP voltage has strong dependency of temperature

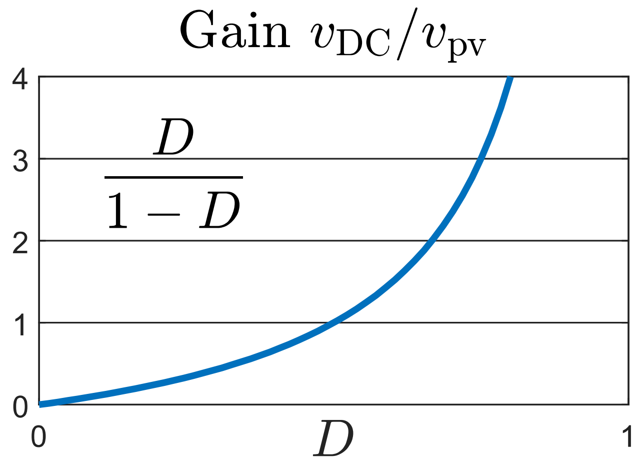


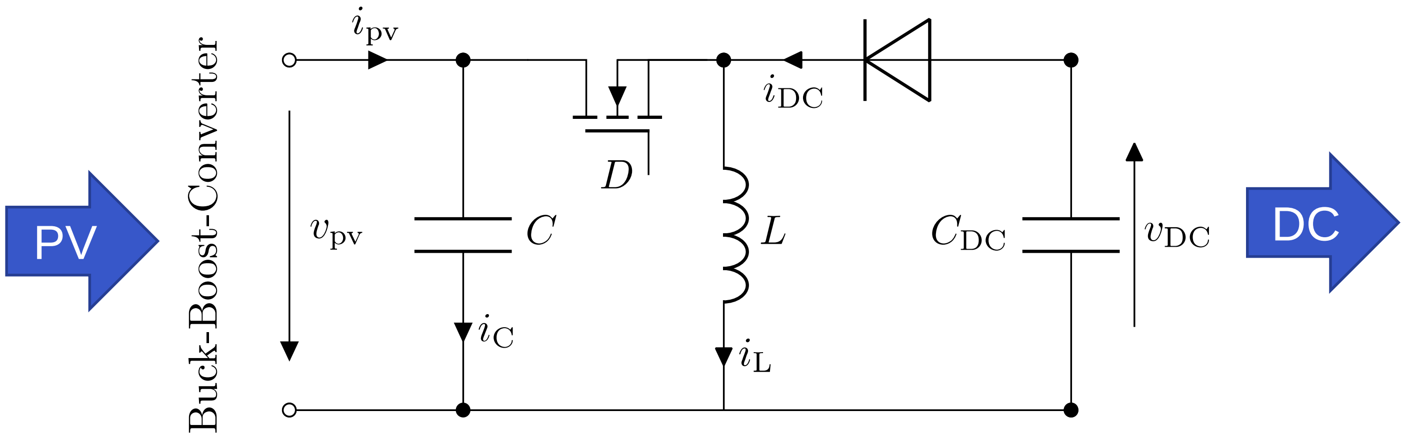




5. PV power generation: Primary Conversion

Buck-boost converter





duty cycle (input)

$$u = D$$

States vector

$$\mathbf{x} = (v_{pv}, i_L)^T$$

state space equation

$$\frac{dx_1}{dt} = \frac{f(x_1) - x_2 u}{C}$$

$$\frac{dx_2}{dt} = \frac{x_1 u - v_{DC}(1-u)}{L}$$

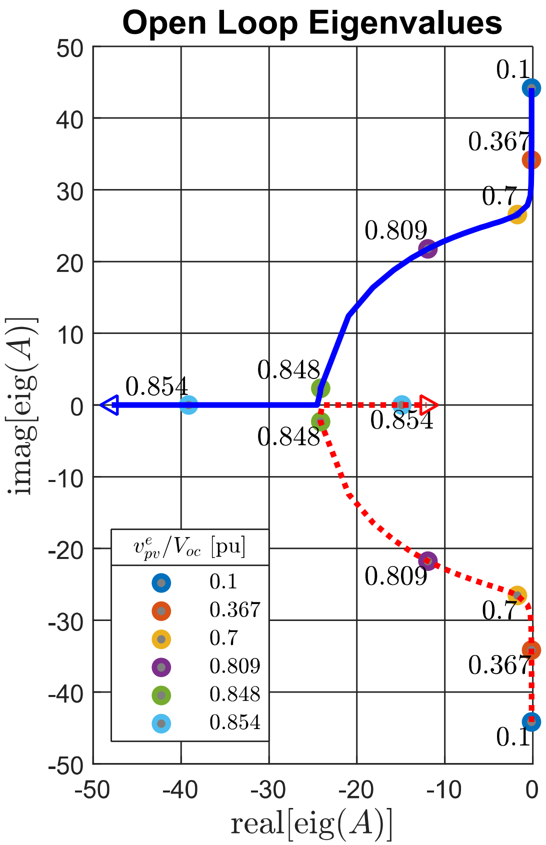
5. PV power generation: Primary Conversion

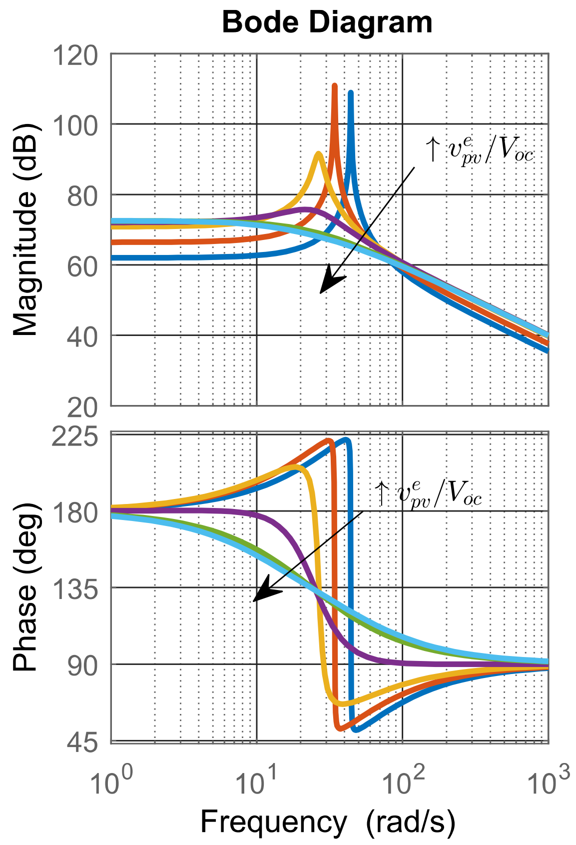
Buck-boost converter

$$\frac{d}{dt}\Delta\boldsymbol{x} = \begin{bmatrix} f'(v_{pv}^{e})/C & -D^{e}/C \\ D^{e}/L & 0 \end{bmatrix}\Delta\boldsymbol{x} + \begin{bmatrix} -i_{L}^{e}/C \\ (v_{DC}^{e}+v_{pv}^{e})/L \end{bmatrix}\Delta\boldsymbol{u}$$

Analysis of the converter coupled with the PV cell model shows different dynamics dependent of the choosen operation point

-> use TS modelling approach consisting of different linear models





5. PV power generation: Primary Conversion

Converter (Integral-state-space) controller

- I-state-space controller (linear controller):

$$\Delta D = \Delta u = -\mathbf{K}_x \Delta \mathbf{x} - K_\mathrm{I} \int_0^t (v_{\mathrm{pv,ref}} - v_{\mathrm{pv}}) d\tau$$

- I-state-space controller (TS controller)

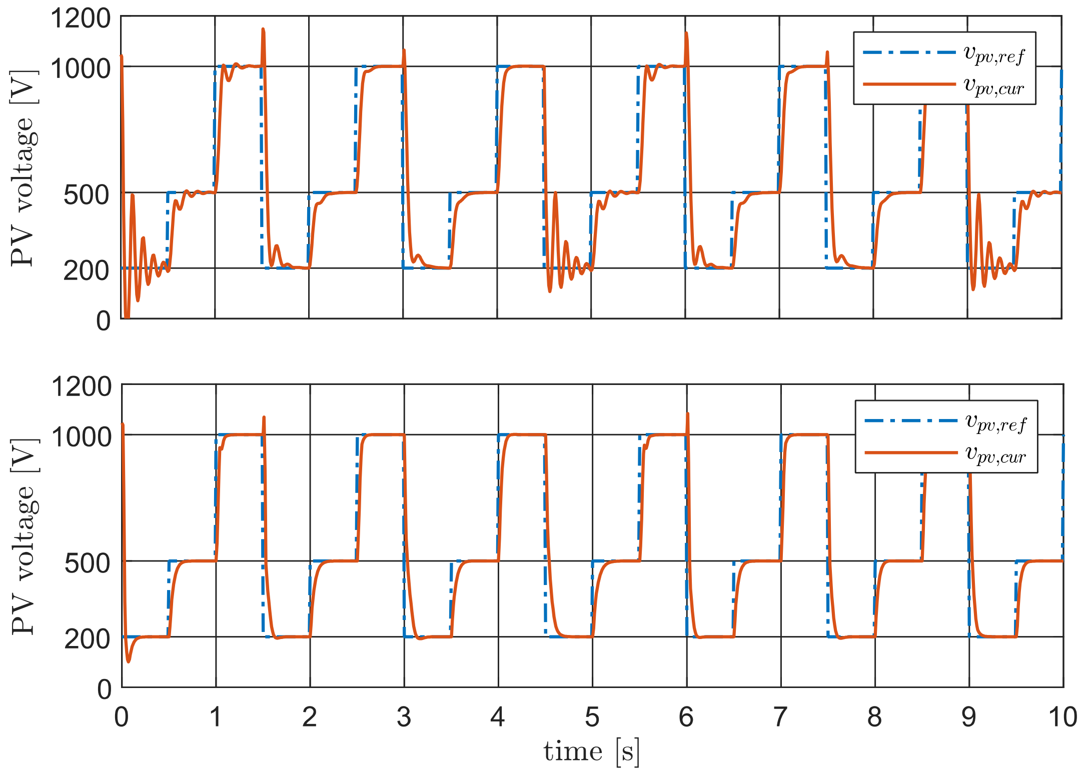
$$u = D = \sum_{i=1}^{N_r} h_i \left[D_i^e - \mathbf{K}_{x,i} (\mathbf{x} - \mathbf{x}_i^e) - K_{I,i} x_\mathrm{I} \right], \quad x_\mathrm{I} = \int_0^t (v_{\mathrm{pv,ref}} - v_{\mathrm{pv}}) d\tau$$

Premise variables

parameter	values
$v_{\mathrm{pv},i}^e / v_{\mathrm{pv,MPP}}$	$\{0.3, 0.6, 0.9\}$
S_i^e	$\{200, 333, 467, 600, 733, 867, 1000\}$ W/m^2
$T_{\mathrm{c},i}^e$	$\{273, 303, 333\}$ K

5. PV power generation: Primary Conversion

Controller validation (linear controller/ TS controller)



Values of the reference PV voltage, irradiation, and cell temperature (the premise variables) change their values abruptly every 0.5 seconds

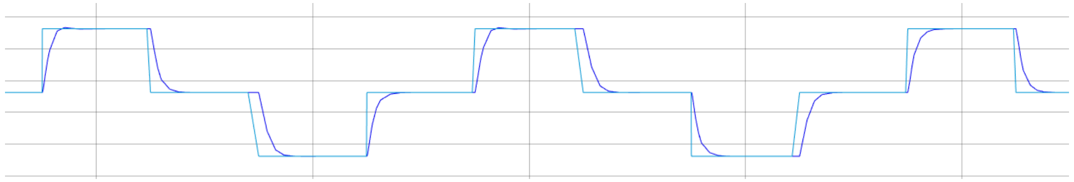
Controllers are tested with the nonlinear coupled system of converter and PV cell (linear top, TS bottom)

-> TS controller shows a better performance

5. PV power generation: Primary Conversion

MPPT and DPPT via P&O

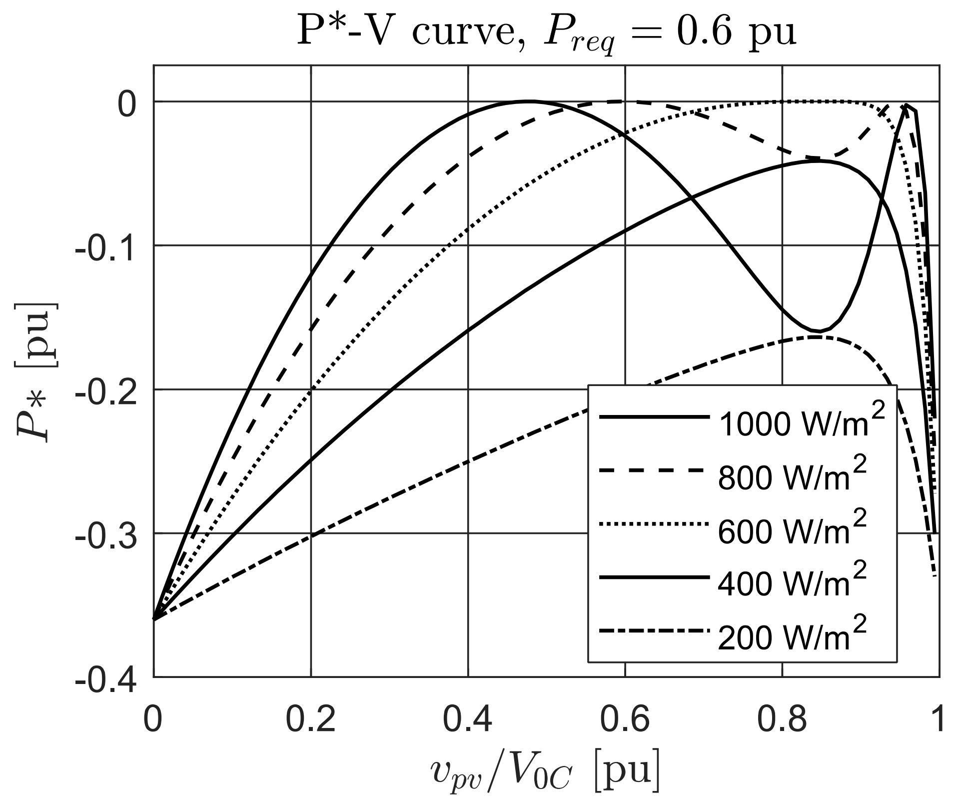
- Maximum Power Point Tracking can be achieved via the (dP-) Perturb and Observation algorithm



- Demand Power Point Tracking can utilize the P&O algorithm by slight variation of the power signal:

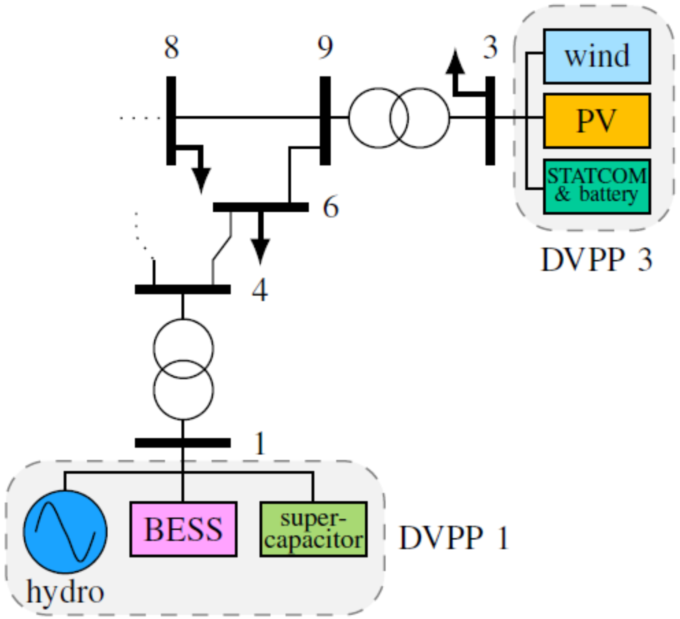
  $P_{PV*} = - |P_{PV} - P_{req}|$

- if the requested power is smaller than the available power, two distinguished maxima can be found

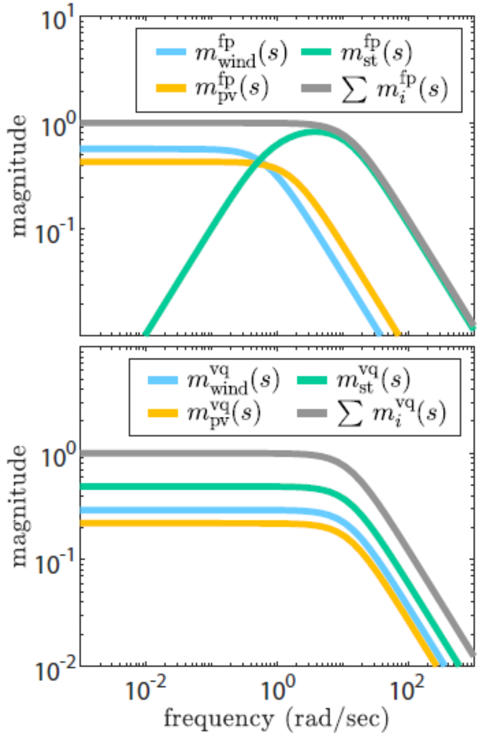


6. Transfer functions of RPPs

Transferfunction as plant models for higherlevel DVPP design*



(a) *Case study II:* IEEE nine-bus system with DVPPs at buses 1 and 3.



(b) Magnitude Bode plots of the ADPFs of the DVPP 3 devices.

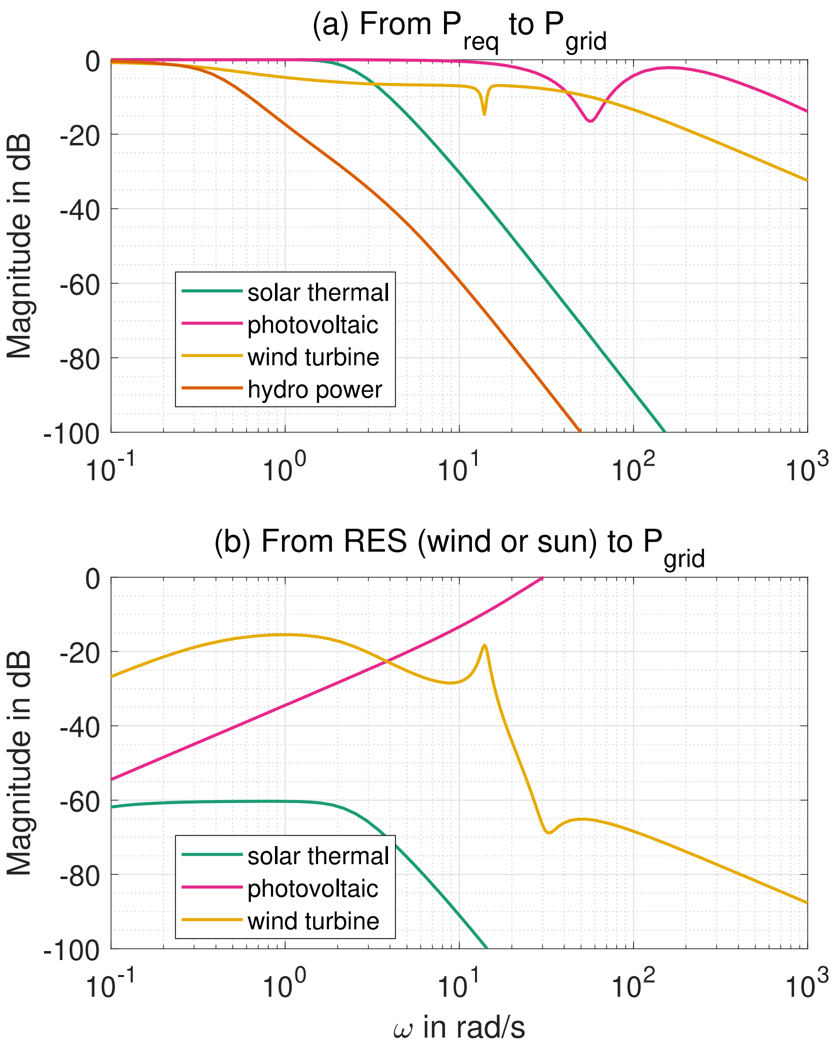
*published in V. Häberle, M. W. Fisher, E. Prieto-Araujo and F. Dörfler, "*Control Design of Dynamic Virtual Power Plants: An Adaptive Divide-and-Conquer Approach,"* in IEEE Transactions on Power Systems, vol. 37, no. 5, pp. 4040-4053, Sept. 2022

6. Transfer functions of RPPs

Method and results

- Numerical linearization
  - finite (central) difference approximations of various orders, coupled with a generalized (multiple term) Romberg extrapolation --> see Derivest Tool
  - applied to generated S-Functions

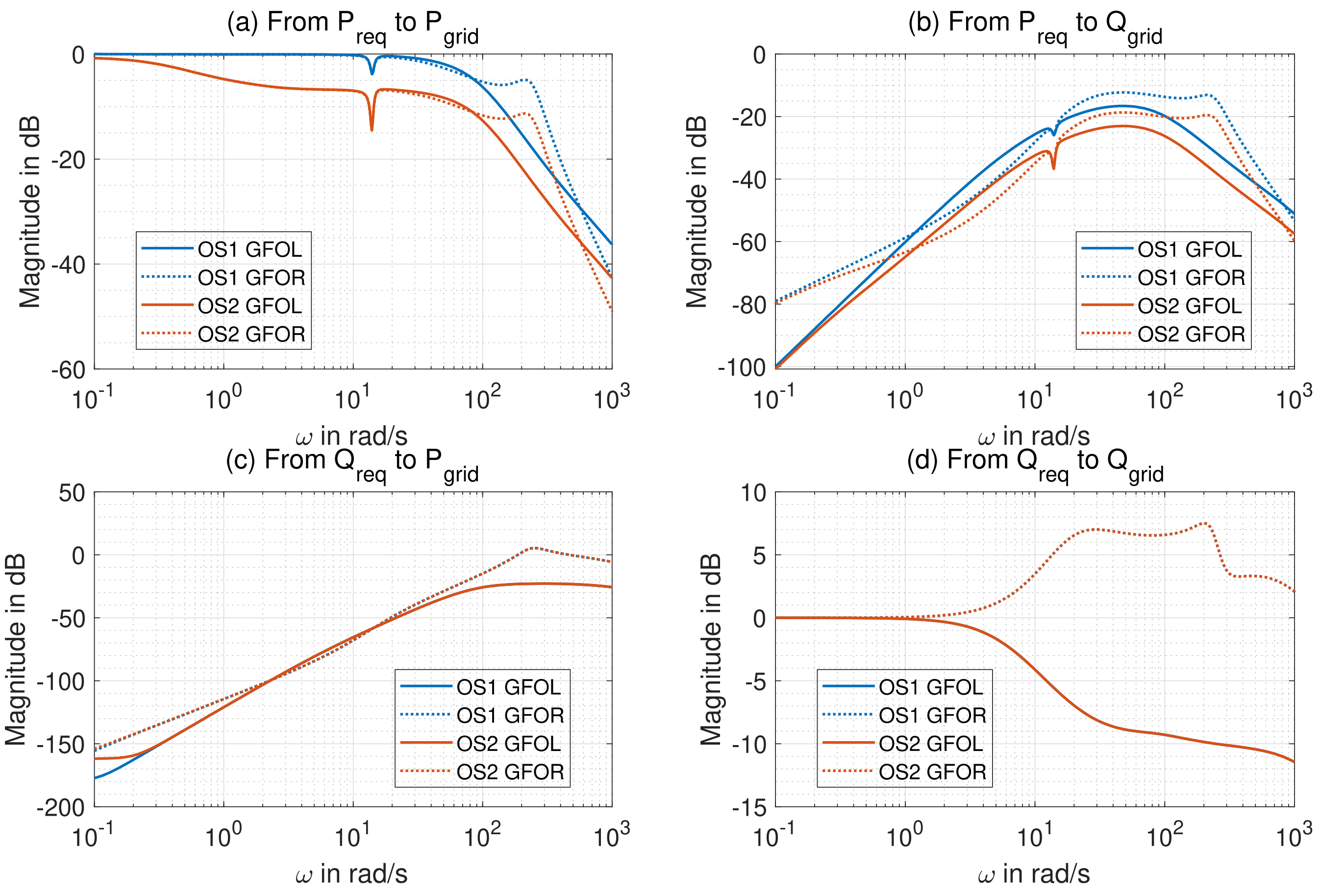
- Bode plots show approx. low pass behavior (P_{req} to P_{grid})
  - RES sorted by cut off frequencies: Hydro, solar thermal, wind farm, PV



- Distinct dynamical properties depending on type of RPP and its controls

6. Transfer functions of RPPs

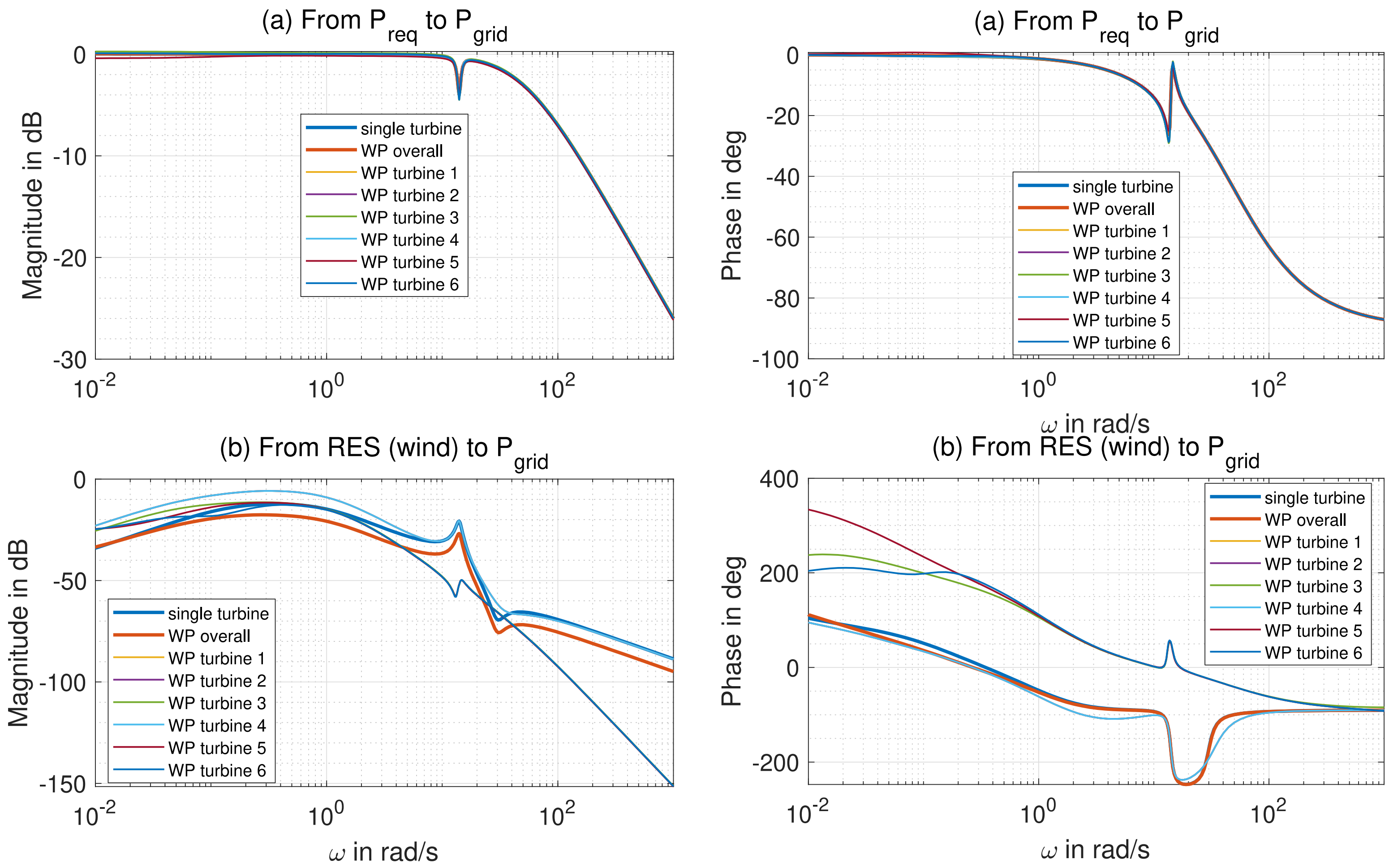
Results: Comparison of wind power plant dynamics with two power tracking operating strategies and converter types



- Operating strategy determines dynamical properties for wind turbines

6. Transfer functions of RPPs

Results: Dynamics of single wind power plants in a wind farm



- For active power: wind parks can be aggregated into single wind turbine model

7. Conclusion

- We have shown that the modeling of the primary power conversion and also the secondary gride side influences the overall closed-loop dynamics
- We have seen significant differences between the power plant types relevant to the DVPP and the associated converter concepts (GFOR, GFOL) of PV and wind power plants
- Suitable models to describe the RPP dynamics are
  - interpretable state-space models for simulation and model-based controller design (device level)
  - transfer functions of RPPs derived by numerical linearization at relevant operating points
  - sets of transfer functions can be transferred to LPV models for DVPP design via the TS approach using weighted convex blending.

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Webinar Q&A – Modeling and control of renewable-energy power plants for participation in a Dynamic Virtual Power Plant

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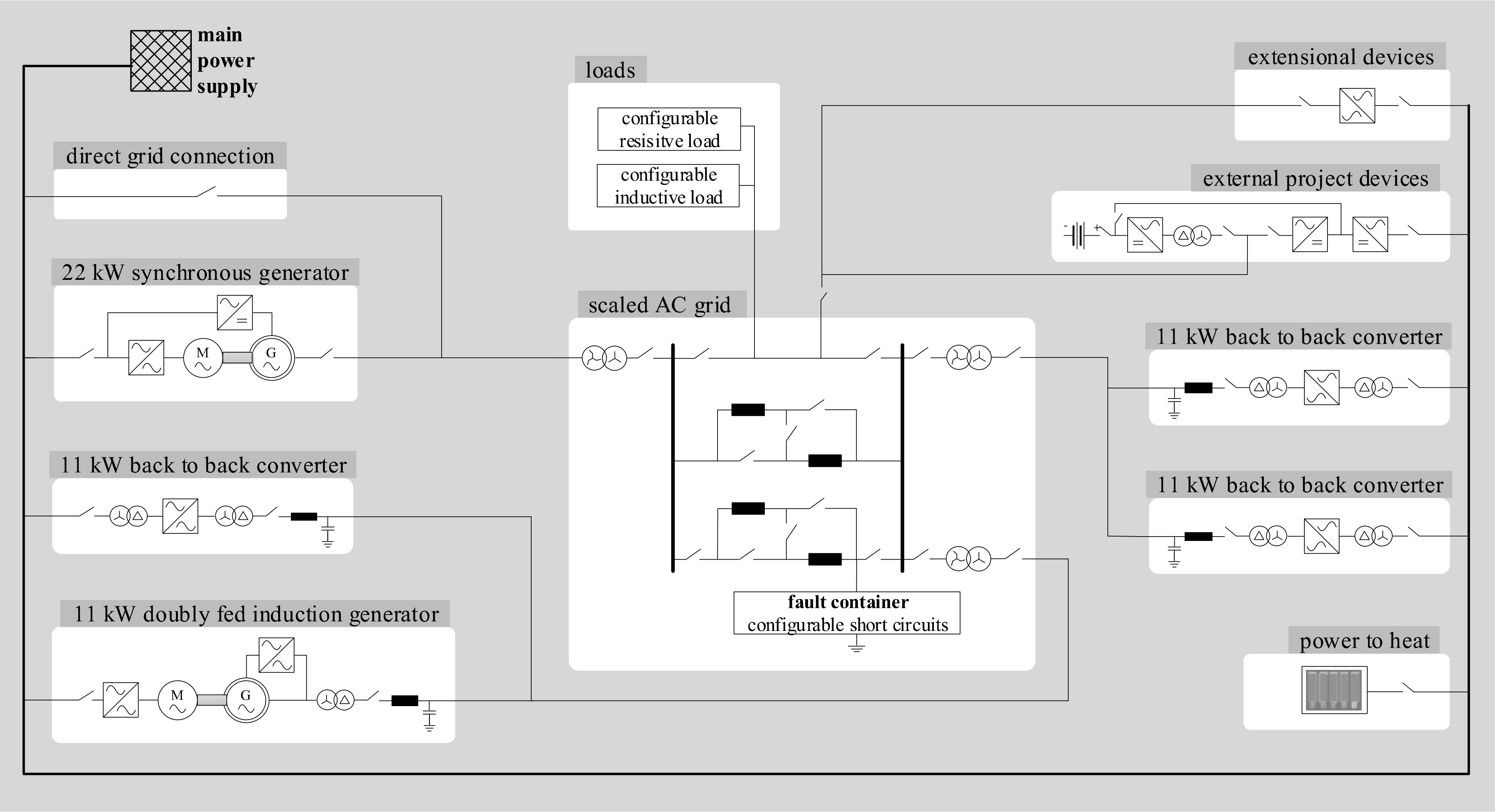
Appendix: Testbed system



Publications of interest

- Dynamic Virtual Power Plant: A New Concept for Grid Integration of Renewable Energy Sources, see https://ieeexplore.ieee.org/document/9885182
- POSYTYF project deliverables, WP2: Generic design of DVPPs at the device level, see https://posytyf-h2020.eu/english-version/deliverables
- Load mitigation and power tracking capability for wind turbines using linear matrix inequality-based control design, see https://doi.org/10.1002/we.2516
- Evaluation of different power tracking operating strategies considering turbine loading and power dynamics, see http://dx.doi.org/10.5194/wes-7-1593-2022
- Demanded Power Point Tracking of PV Power Plants without Battery Energy Storage, see https://doi.org/10.5445/KSP/1000138532
- Models implemented in Matlab availiable upon request horst.schulte@htw-berlin.de