Analysis of the FMI protocol as an alternative for the model-base certification of installations based on converters according to TG 4

Wind Energy Hamburg

Hamburg, Germany
25 Sept. 2024

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Content

- About FGW (Company and TG4)
- Functional Mock-UP interface protocol (FMI protocol)
- Test (Objectives and explanation)
- Modeling Full converter Wind Turbine Model
- Results
- Conclusions
- Questions

What makes FGW e.V. special

- Demands guidelines as a regulator for decentralized energies for 40 years.
- Development association as a neutral mediator in the industry.
- Creation of technical guidelines as instructions/recommendations in practice.
- 150 members represent the entire value chain.
- Well-structured network of experts for professional contacts and trusting cooperation.

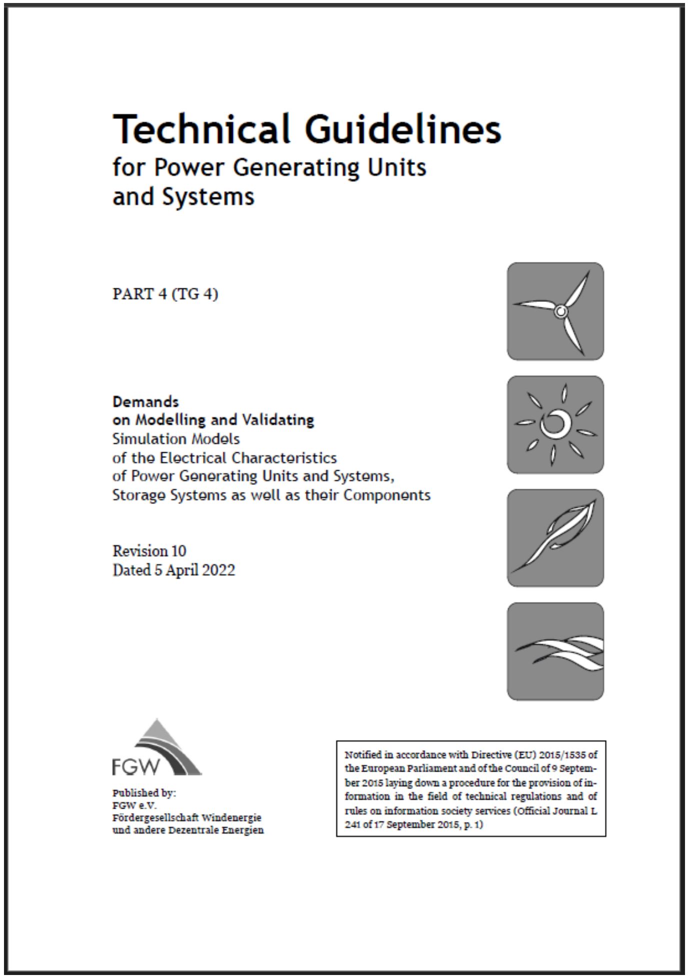
FGW webpage

What FGW e.V. does for the industry

- Guideline expertise in the field of decentralized energies.
- Reliable and targeted provision of information.
- Recommendations for national and international regulations and drafting of legal requirements.
- Active co-determination of the state of the art.
- Efficient and modern committee work.
- Needs-based, flexible and tried-and-tested working methods

Technical Guideline 4 (TG 4)

- Demands on Modelling and Validating Simulation Models of the Electrical Characteristics of Power Generating Units and Systems, Storage Systems as well as their Components.
- AG Einheitliche Schnittstelle.



Technical Guidelines
for Power Generating Units
and Systems

PART 4 (TG 4)

Demands
on Modelling and Validating
Simulation Models
of the Electrical Characteristics
of Power Generating Units and Systems,
Storage Systems as well as their Components

Revision 10
Dated 5 April 2022

Published by:
FGW e.V.
Fördergesellschaft Windenergie
und andere Dezentrale Energien

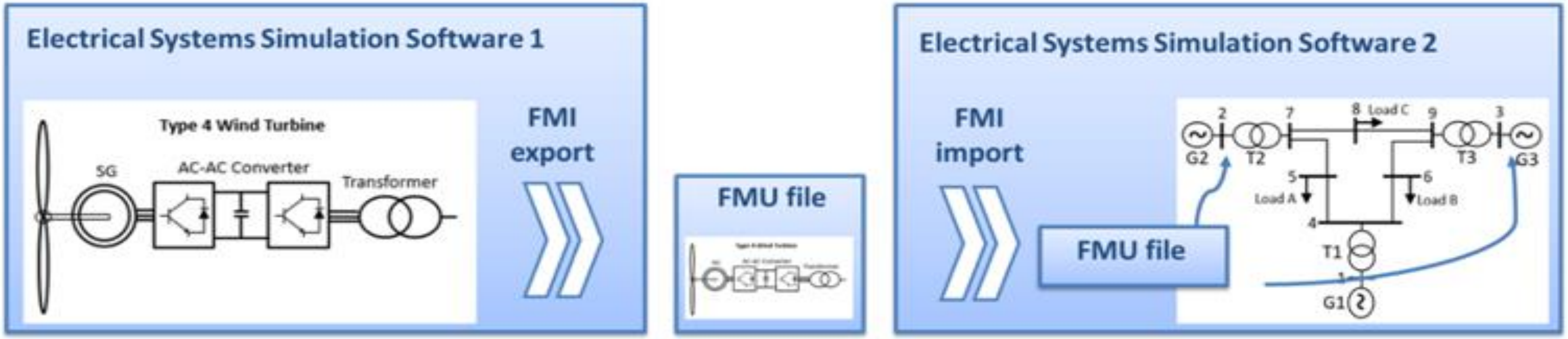
Notified in accordance with Directive (EU) 2015/1535 of the European Parliament and of the Council of 9 September 2015 laying down a procedure for the provision of information in the field of technical regulations and of rules on information society services (Official Journal L 241 of 17 September 2015, p. 1)

Functional Mock-Up Interface (FMI) protocol

- FMI: Characteristics
  - Free standard.
  - Improve interoperability between different simulation tools, enabling the **exchange of dynamic models** and the integration of various simulation environments.
  - Modelica Association Project (MAP) FMI. Since 2008.
  - Implemented in more than 170 programs.
  - https://fmi-standard.org/.

Objective

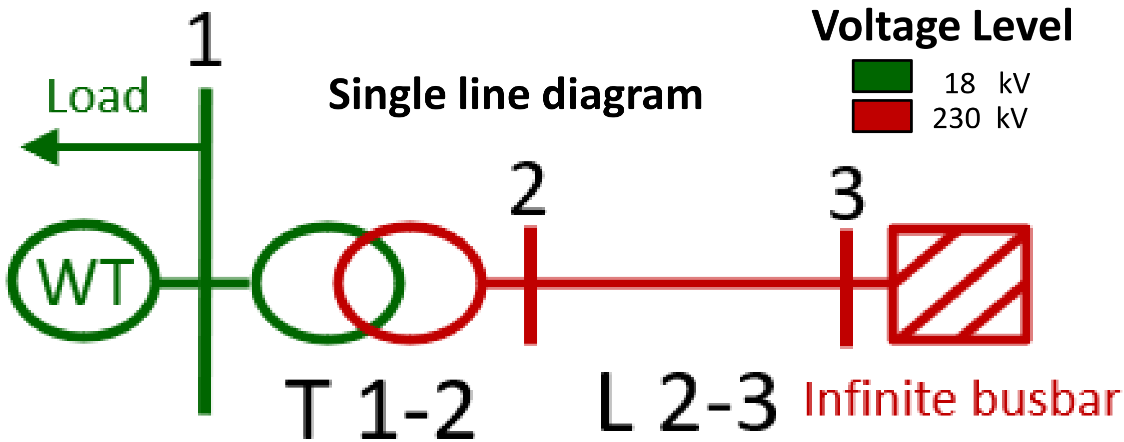
- General objective
  - Propose improvements in the technical guide TG 4.
    - Power-electronic based generators.
    - Is it possible to use/include the FMI protocol in the TG 4?.

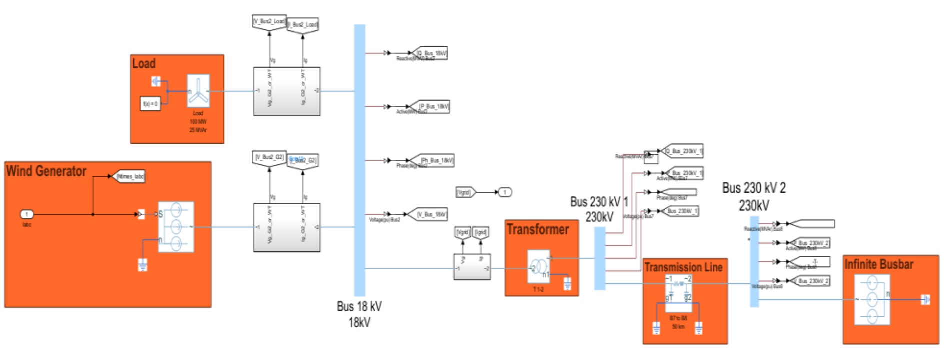


fmi Functional Mock-up Interface

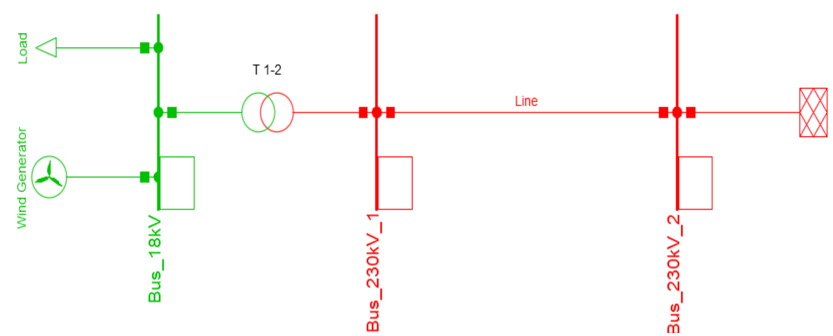
Modeling

- Grid





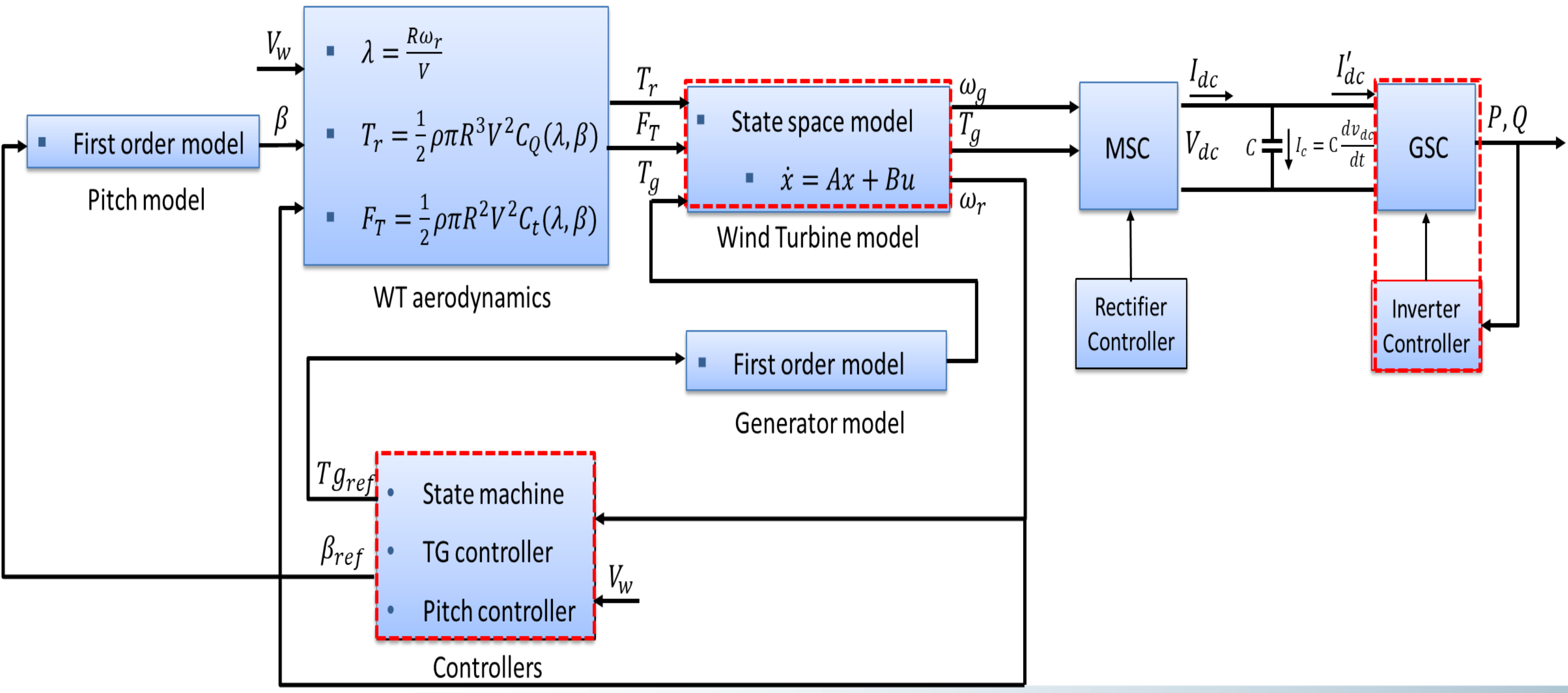
Simulink



Power Factory

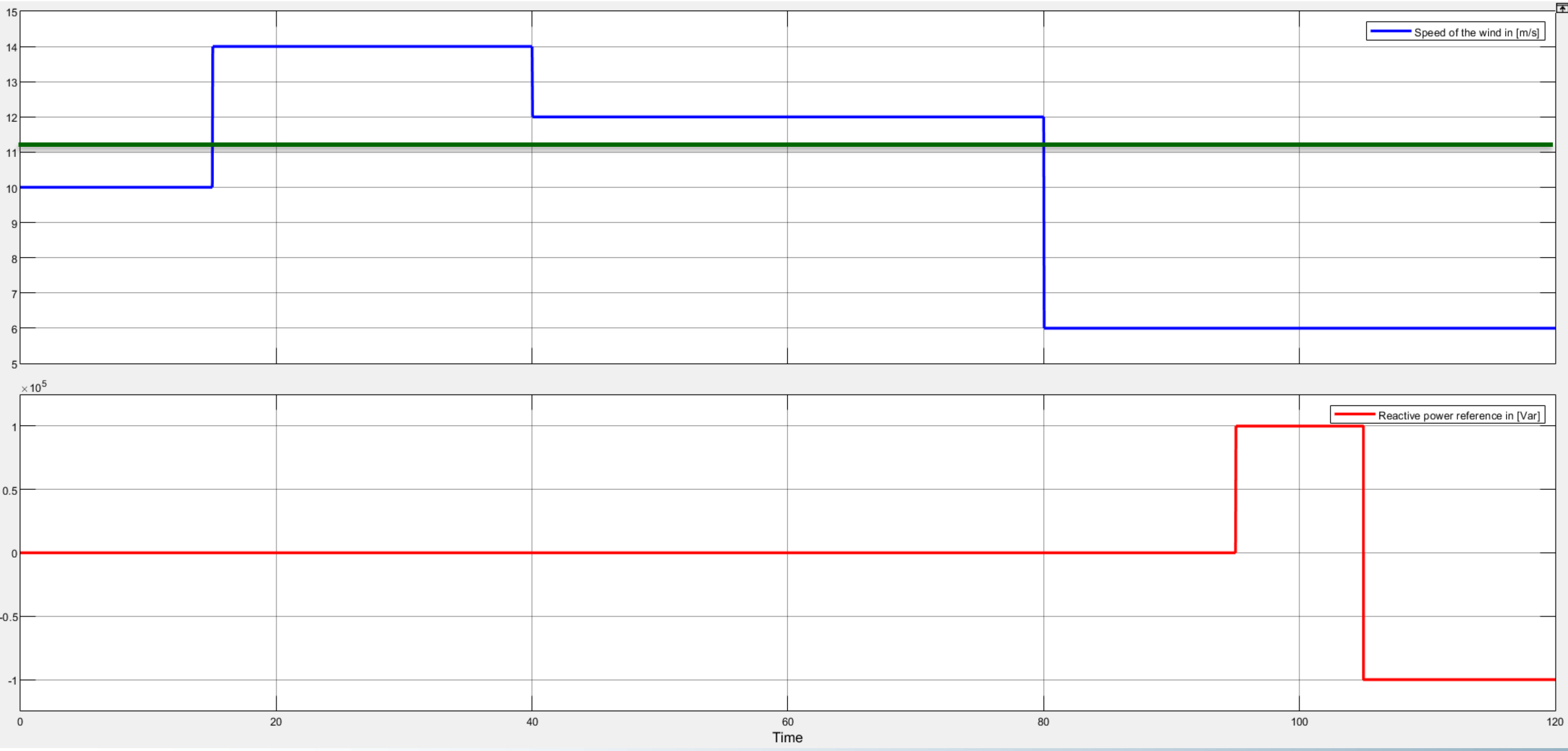
Modeling

- Type 4 Wind Turbine NREL 5.5 MW. Diagram.



Results

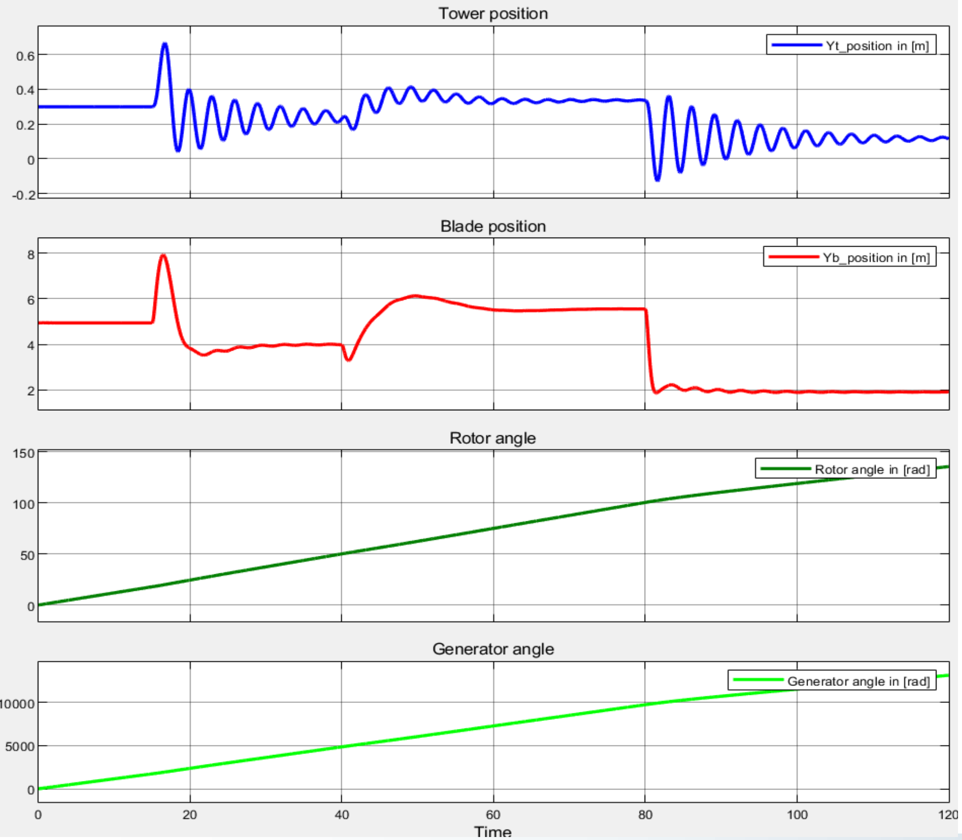
- Events: Wind speed variation and reactive power reference variation.



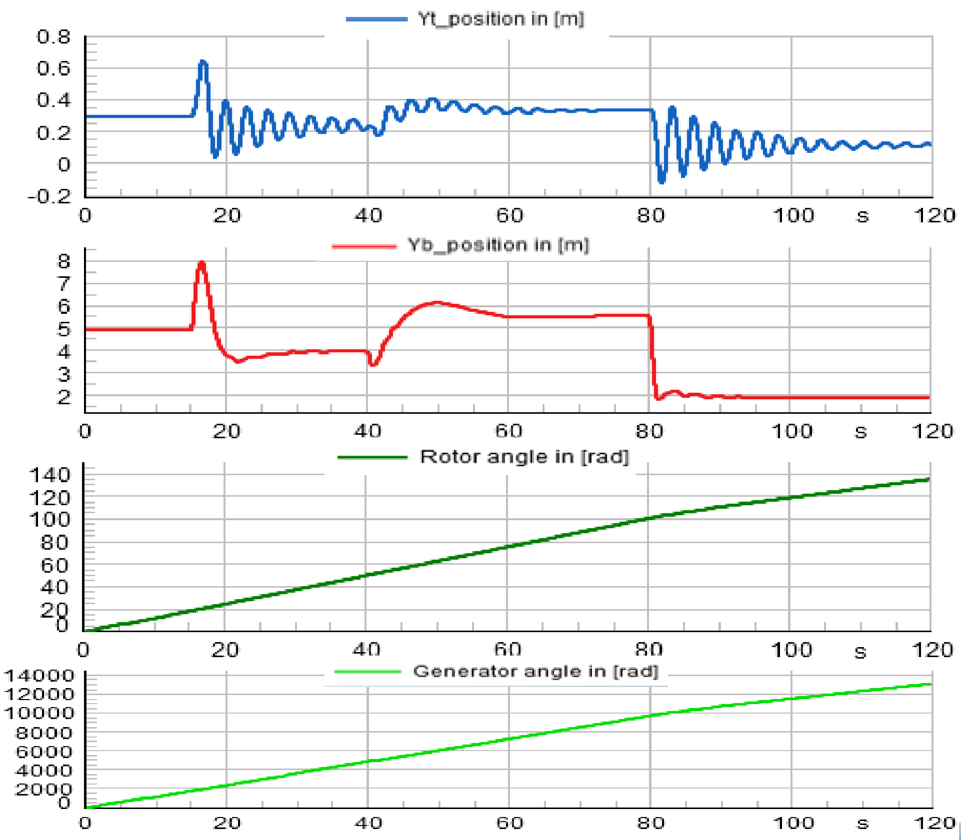
Results

- State space model: State space variables.

Simulink



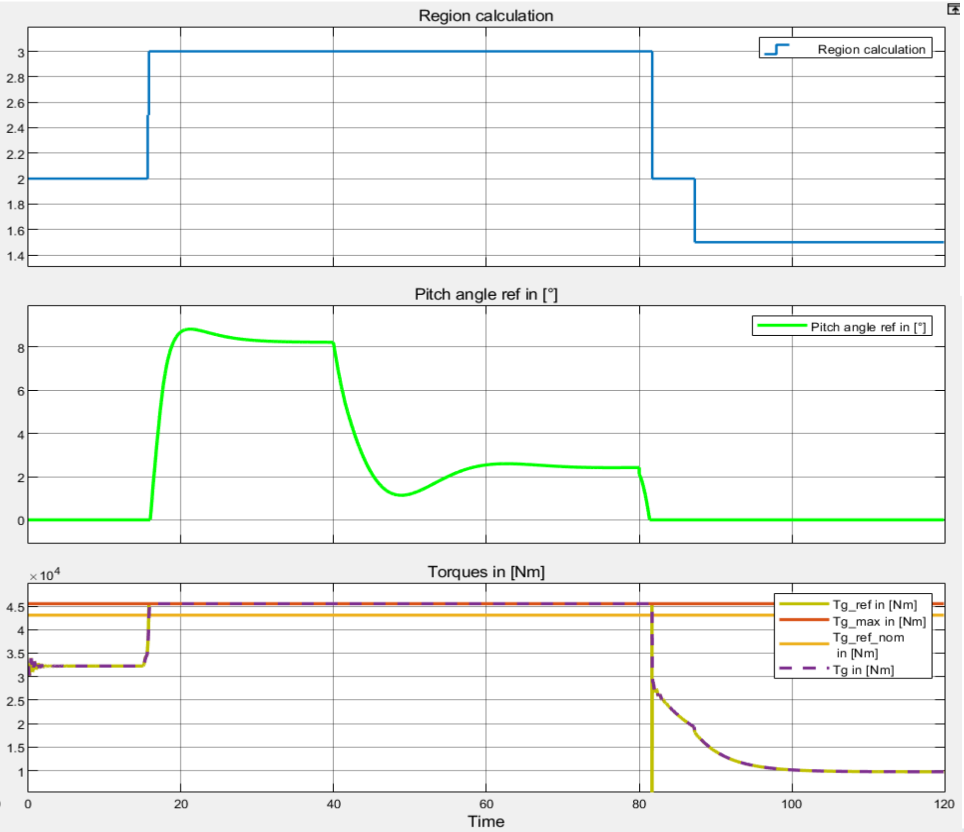
Power Factory



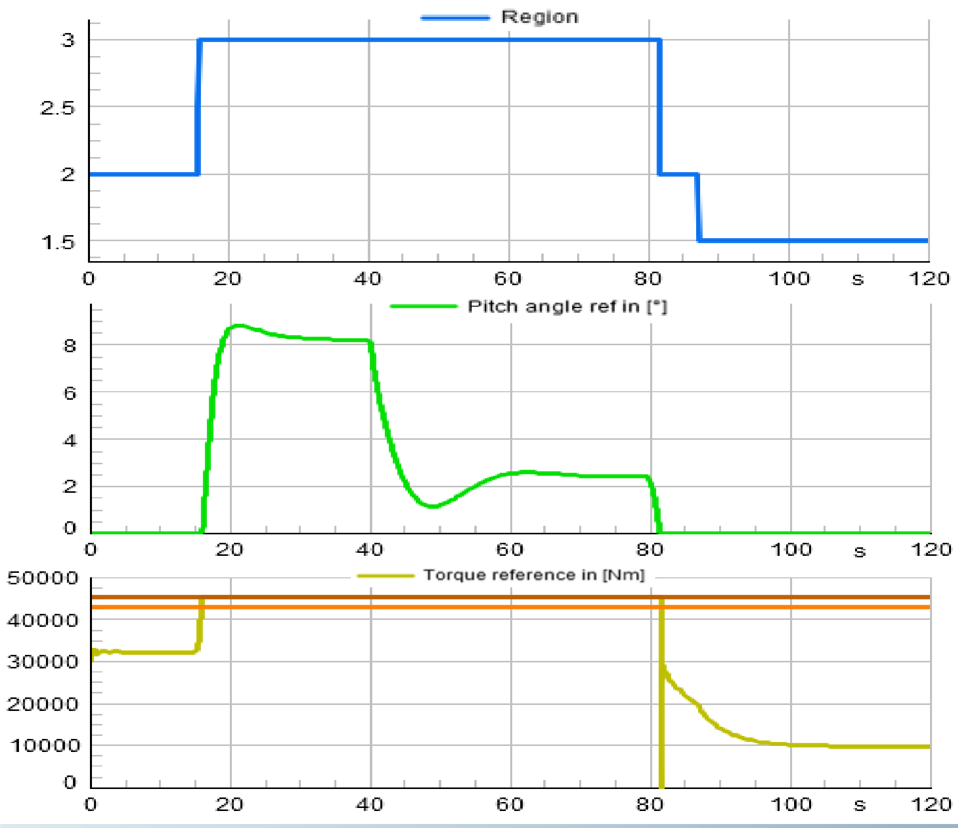
Results

- Pitch and torque-generator controllers.

Simulink

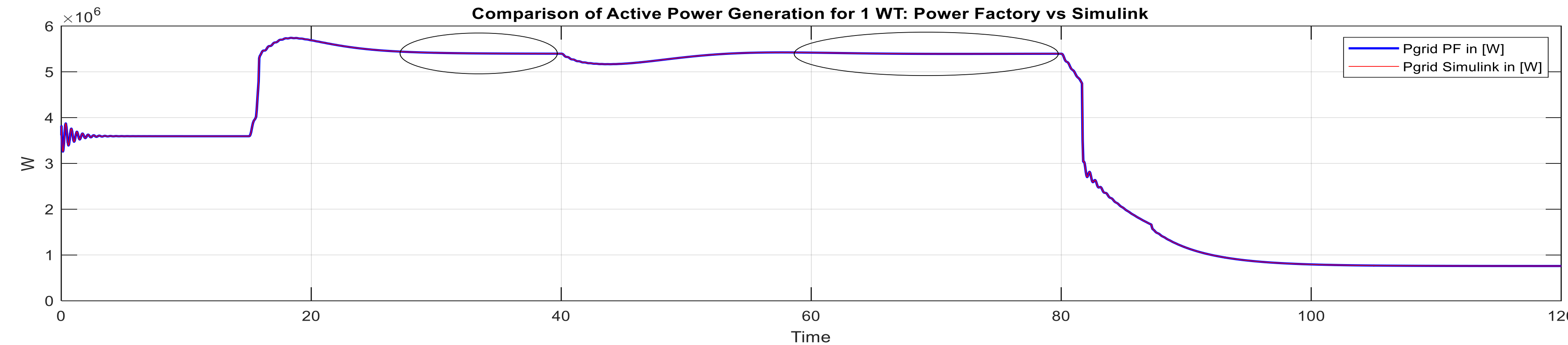


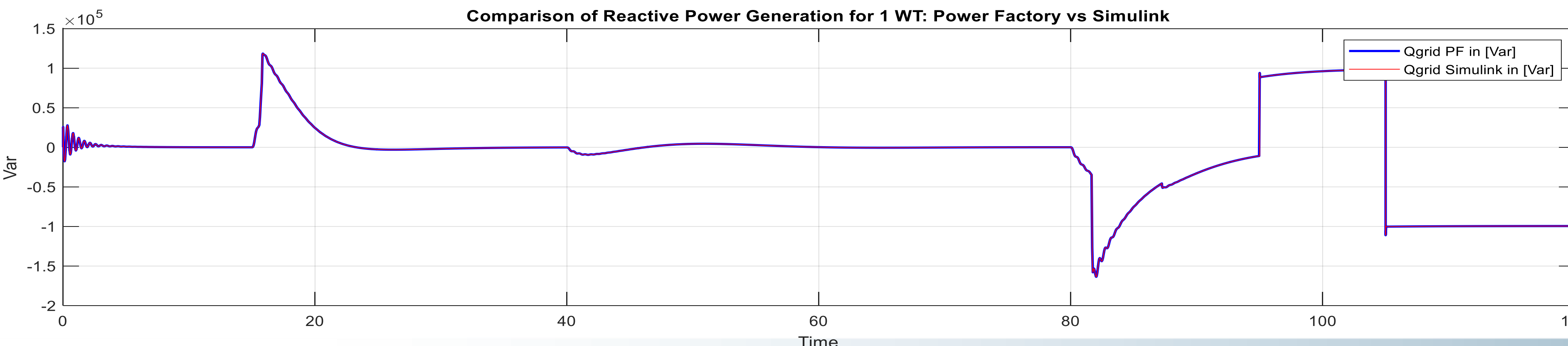
Power Factory



Results

- Grid Side Converter: Simulink and Power Factory, active and reactive power.





Conclusions

- Proposals for the TG 4
  - It is possible to propose the use of the FMI protocol as an alternative for the model-base certification of converter-based projects.
    - No differences were found in the observed variables.
    - Definition of the parameters, and input and output variables.

- Main limitations
  - More test considering other:
    - Programs,
    - Technologies,
    - Controllers,
    - Events.

Thank you for your attention
Questions?

Hamburg, Germany
25. September 2024

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Exhibit

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FMI alternatives

- IEC 61970-457: CIM for Dynamics Profile

Specifies a dynamics package which contains part of the CIM to support the exchange of models between software applications that perform analysis of the steady-state stability or transient stability of a power system. This one is not for free

- IEC 61400-27 interface

Defines standard electrical simulation models for wind turbines. Some power system simulation tools offer the possibility to import and export wind power plants models which were modeled using this standard. Such is the case with Power Factory, a program that already has this feature.

FMU

Simulink models can be exported to standalone co-simulation FMU in version 2.0 and 3.0.

The generated FMU package for FMI 2.0 contains the following files:

- modelDescription.xml
- model.png (optional)
- binaries\win64\modelname.dll, or binaries\linux64\modelname.so, or binaries\darwin64\modelname.dylib

The generated FMU package for FMI 3.0 contains the following files:

- modelDescription.xml
- terminalsAndIcons\icon.png (optional)
- binaries\x86_64-windows\modelname.dll, or binaries\x86_64-linux\modelname.so, or binaries\x86_64-darwin\modelname.dylib
- sources\buildDescription.xml

Parameters NREL WT 5.5 MW

Symbol	Value	Description	Unit
N	3	Number of blades	[Dimensionless]
R	63	Length of blades	[m]
rho	1.225	Air density	[kg/m3]
mT	436865	Effective mass of the nacelle-tower motion	[Kg]
kT	1981900	Stiffness constant of the tower	[N/m]
dT	70000	Damping constant of the tower	[Ns/m]
rB	21.975	Location of the mass in the equivalent model	[m]
mB	4435	Effective mass of the blade motion	[Kg]
kB	40000	Stiffness constant of the blades	[N/m]
kB_zentr	0.02	Stiffness constant in the center of the blades	[N/m]
dB	20000	Damping of the Blade	[Ns/m]
ngear	97	Gearbox Ratio	[Dimensionless]
Jr	38759227	Rotor inertia	[Kgm2]
Jg	534.1	Generator Inertia about High-Speed Shaft	[Kgm2]
kS	92214	Stiffness constant of the drive train	[N/m]
dS	660.5378	Damping constant of the drive train	[Ns/m]
tau_beta	0.1000	Pitch angle time constant	[s]
betaP_max	0.1745	Max pitch angle	[rad]
tau_g	0.0200	Generator time constant	[s]
Pr_R	5296610	Rated active power of the generator	[W]
omega_r_R	1.2671	Rated rotational speed of the rotor	[rad/s]
omega_g_R	122.9087	Rated rotational speed of the generator	[rad/s]
Tr_R	4180100	Rated torque of the rotor	[Nm]
Tg_R	43094.0000	Rated torque of the generator	[Nm]
v_R	11.2600	Rated speed of the wind	[m/s]
J_1DOF	43785000	Blade inertia constant of the 1 DoF model for the pitch control design	[kgm2]

Infinite busbar

- Simscape

Parameter	Value	Unit
Rated voltage (ph-ph RMS)	23	[kV]
Angle reference	0	[°]
Frequency	50	[Hz]
Short circuit power level	10000	[TW]
Source X/R ratio	20	[dimensionless]

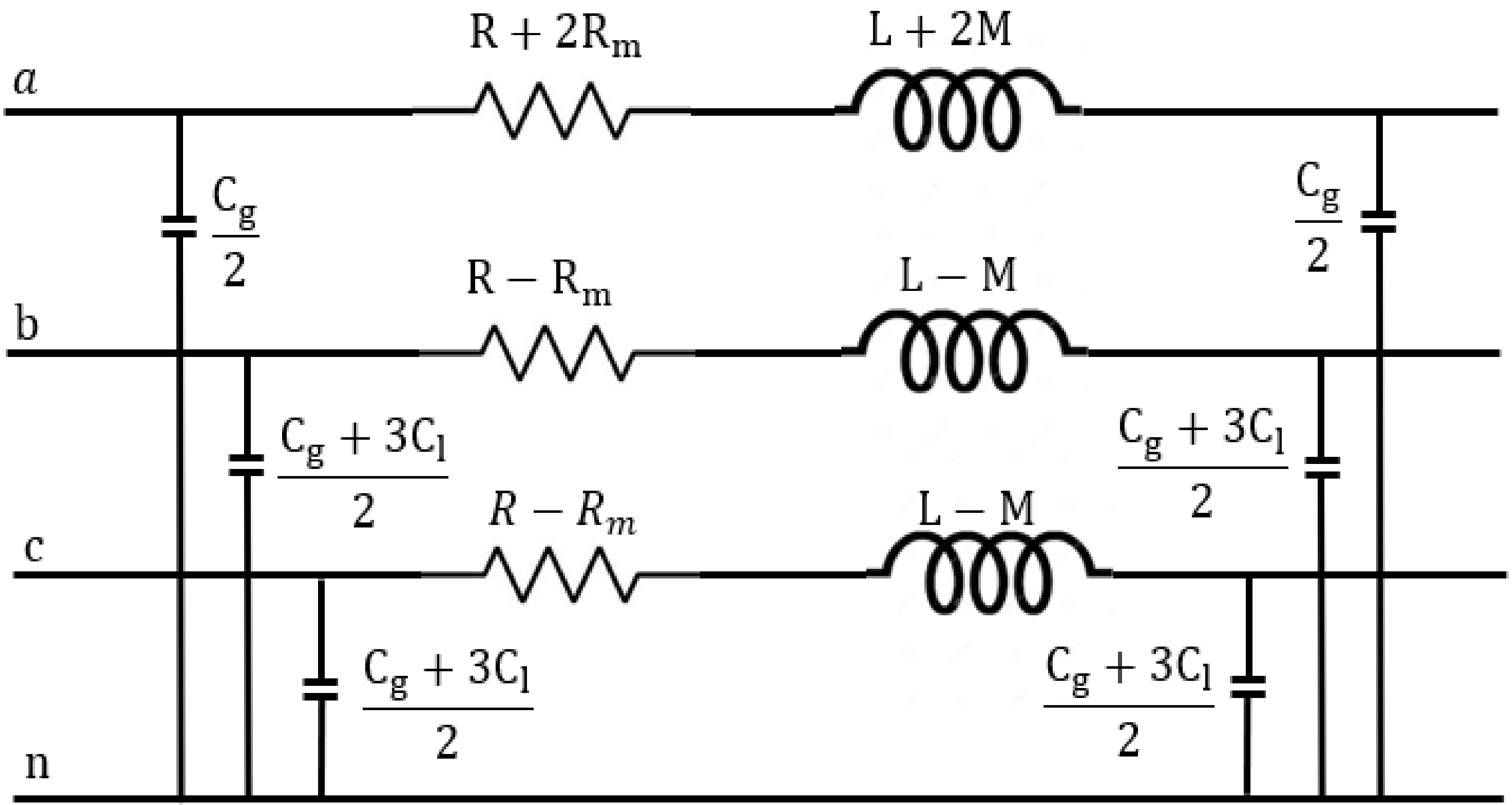
- Power Factory

Parameter	Value	Unit
Rated voltage	1	[p.u.]
Angle reference	0	[°]
Frequency	50	[Hz]
Short circuit power level (max)	100000	[MVA]
Source X/R ratio (max)	20	[dimensionless]

Transmission line

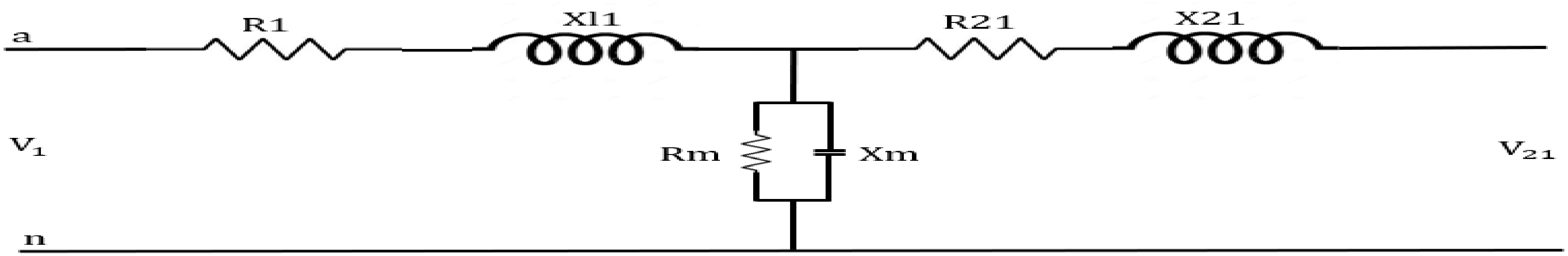
Transmission lines	Notation	2-3	2-3	Unit
Rated voltage	V	230	230	[kV]
Frequency	f	60	50	[Hz]
Base apparent power	Sb	100	100	[MW]
Base impedance	Zb	529	529	[Ohm]
Length	l	1	1	[km]
Lumped Resistance	Rl	0.189	0.189	[Ohm/km]
Lumped Inductance	Ll	2.723	2.723	[mH/km]
Lumped Mutual inductance	M	1.026	0.855	[mH/km]
Lumped Reactance	Xl	0.702	0.702	[Ohm/km]
Lumped Line to line capacitance	Cl	0.003	0.003	[uF/km]
Lumped Line to ground capacitance	Cg	0.007	0.007	[uF/km]
Lumped Mutual resistance	Rm	0.099	0.099	[Ohm/km]
Resistance	R	0.000	0.000	[pu]
Reactance	X	0.001	0.001	[pu]
Conductance series	G	80.851	115.725	[pu]
Susceptance series	Bs	-684.876	-816.911	[pu]
Capacitance shunt circuit 2 and 3[1]	Cg+3Cl	0.015	0.015	[uF/km]
Capacitance shunt circuit 2 and 3	Cg+3Cl	0.000	0.000	[F]
Capacitance shunt circuit 2 and 3	Cg+3Cl	0.000	0.000	[pu]
Susceptance shunt circuit 1	Bp	2.545	2.121	[uS/km]
Susceptance shunt circuit 1	Bp/2	1.273	1.060	[uS/km]
Susceptance shunt circuit 2 and 3	Bp	0.003	0.002	[uS/km]
Susceptance shunt circuit 2 and 3	Bp/2	0.001	0.001	[uS/km]

Transmission line



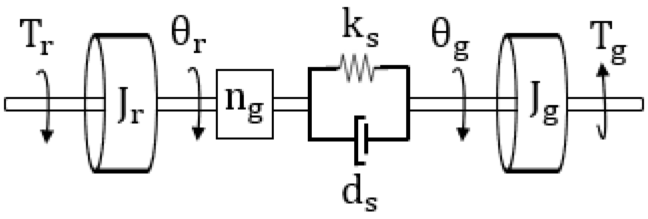
Transformer

Power Transformers	Symbol	T 1-2	T 1-2	Unit
Rated Apparent Power	St	100	100	[MVA]
Primary rated voltage	V_1	230	230	[kV]
Secondary rated voltage	V_2	18	18	[kV]
Rated Frequency	f	60	50	[Hz]
Primary winding resistance	R1	0.0001	0.0001	[pu]
Secondary winding resistance	R2	0.0001	0.0001	[pu]
Primary leakage reactance	Xl1	0.0313	0.0260	[pu]
Secondary leakage reactance	Xl2	0.0313	0.0260	[pu]
Shunt magnetizing resistance	Rm	500	500	[pu]
Shunt magnetizing reactance	Xm	500	500	[pu]
Transformation ratio	n	12.8	12.8	[pu]
Secondary winding resistance referred to the primary	R21	0.0163	0.0163	[pu]
Secondary leakage reactance referred to the primary	Xl21	5.1022	4.2519	[pu]

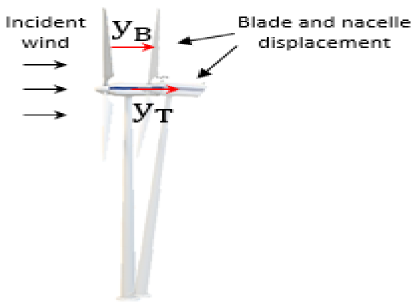


Modeling

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} + \frac{\partial P_D}{\partial \dot{q}_i} = f_i \qquad L = E_K - E_P$$



$$E_k = \underbrace{\frac{1}{2} m_T (\dot{y}_T)^2}_{\text{Tower}} + \underbrace{\frac{1}{2} N m_B (\dot{y}_{B,a})^2}_{\text{Blades}} + \underbrace{\frac{1}{2} J_r (\dot{\theta}_r)^2}_{\text{Rotor}} + \underbrace{\frac{1}{2} J_g (\dot{\theta}_g)^2}_{\text{Generator}}$$



$$E_P = \underbrace{\frac{1}{2} k_T (y_T)^2}_{\text{Tower}} + \underbrace{\frac{1}{2} N k_B (y_{B,a} - y_T)^2}_{\text{Blades}} + \underbrace{\frac{1}{2} k_s (\theta_r n_g - \theta_g)^2}_{\text{Drive train}}$$

$$P_D = \underbrace{\frac{1}{2} d_T (\dot{y}_T)^2}_{\text{Tower}} + \underbrace{\frac{1}{2} N d_B (\dot{y}_{B,a} - \dot{y}_T)^2}_{\text{Blades}} + \underbrace{\frac{1}{2} k_s (\dot{\theta}_r n_g - \dot{\theta}_g)^2}_{\text{Drive train}}$$

$$f = \begin{pmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{pmatrix} = \begin{pmatrix} F_T \\ F_T \\ T_r \\ -T_g \end{pmatrix}$$

Modeling

$$\dot{x}_m = A_m x_m + B_m u_m$$

$$A_m = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ -\frac{k_T}{m_T} & \frac{Nk_B}{m_T} & 0 & 0 & -\frac{d_T}{m_T} & \frac{Nd_B}{m_T} & 0 & 0 \\ \frac{k_T}{m_T} & Nk_B\left(-\frac{1}{m_T}-\frac{1}{Nm_B}\right) & 0 & 0 & \frac{d_T}{m_T} & Nd_B\left(-\frac{1}{m_T}-\frac{1}{Nm_B}\right) & 0 & 0 \\ 0 & 0 & -\frac{k_s n_g{}^2}{J_r} & \frac{k_s n_g}{J_r} & 0 & 0 & -\frac{d_s n_g{}^2}{J_r} & \frac{d_s n_g}{J_r} \\ 0 & 0 & \frac{k_s n_g}{J_g} & -\frac{k_s}{J_g} & 0 & 0 & \frac{d_s n_g}{J_g} & -\frac{d_s}{J_g} \end{bmatrix}$$

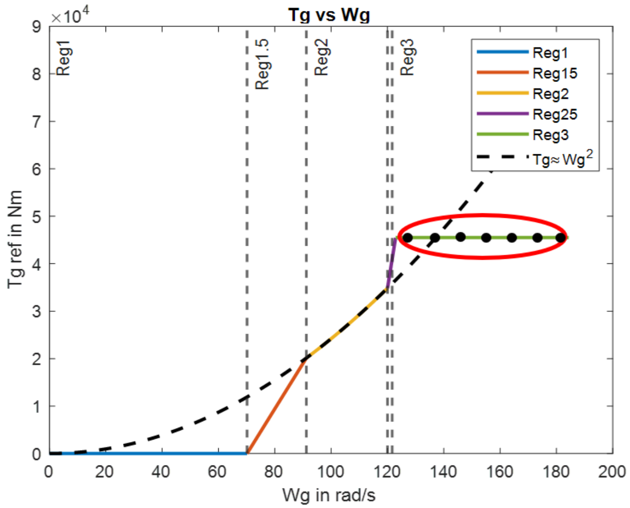
$$B_m = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \frac{1}{NmB} & 0 & 0 \\ 0 & \frac{1}{Jr} & 0 \\ 0 & 0 & -\frac{1}{Jg} \end{bmatrix}$$

$$x_m = \left[y_T \; y_B \; \theta_r \; \theta_g \; \dot{y}_T \; \dot{y}_B \; \dot{\theta}_r \; \dot{\theta}_g\right]^T$$

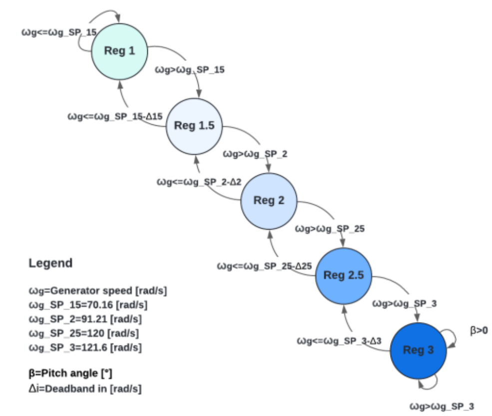
Modeling

Controllers: Pitch and generator-torque

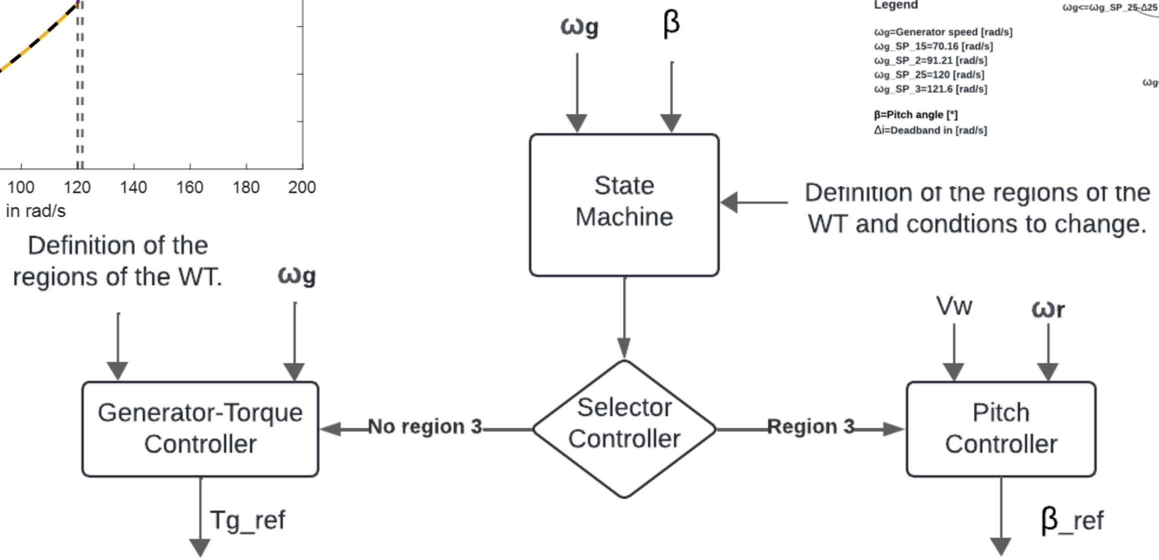
- Region definition



- State machine



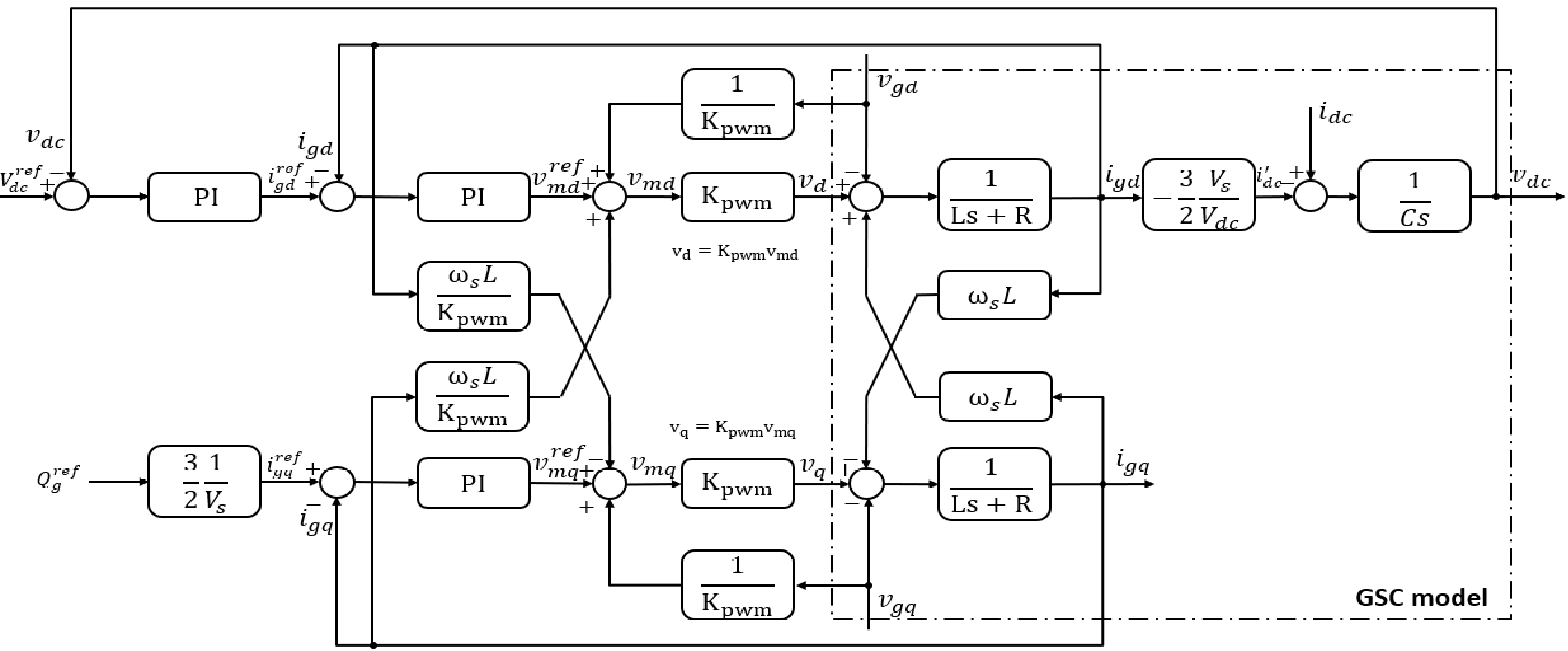
- Controller selector



Modeling

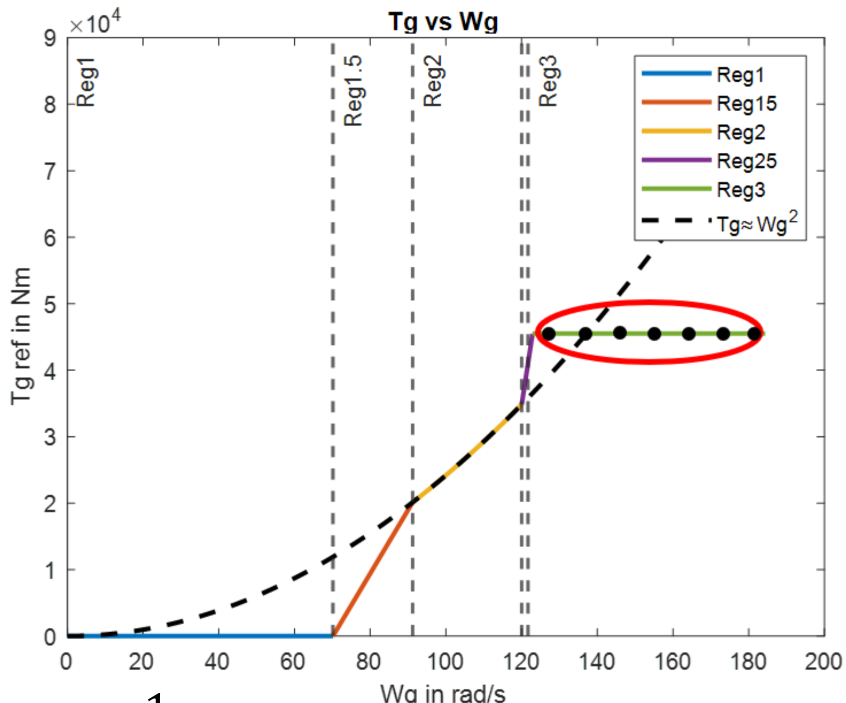
Controllers: GSC controller

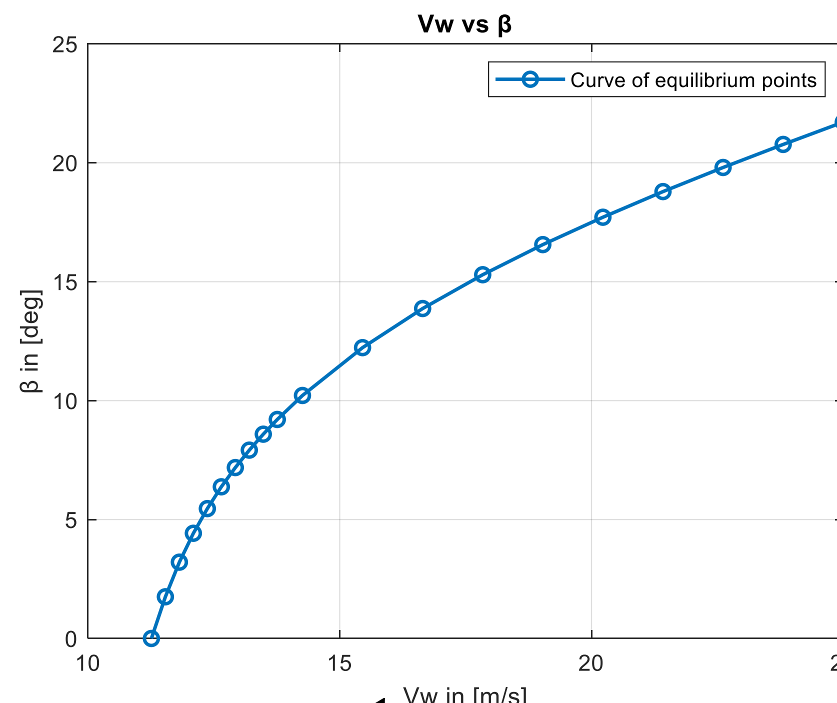
- Grid following



$i_{gd}^{ref} = G_{PI\_id1}(s)(V_{dc}^{ref} - v_{dc})$ $v_{md}^{ref} = G_{PI\_id2}(s)(i_{gd}^{ref} - i_{gd})$ $v_{md} = \frac{1}{K_{pwm}}(v_{gd} + v_{md}^{ref} + \omega_s L i_{gq})$ $G_{igd}(s) = \frac{i_{gd}}{v_d + \omega_s L i_{gq} - v_{gd}} = \frac{1}{Ls + R}$ $sCv_{dc} = I_{dc} + \frac{3}{2}\frac{v_{gd}}{V_{dc}} i_{gd}$

Modeling: Pitch controller





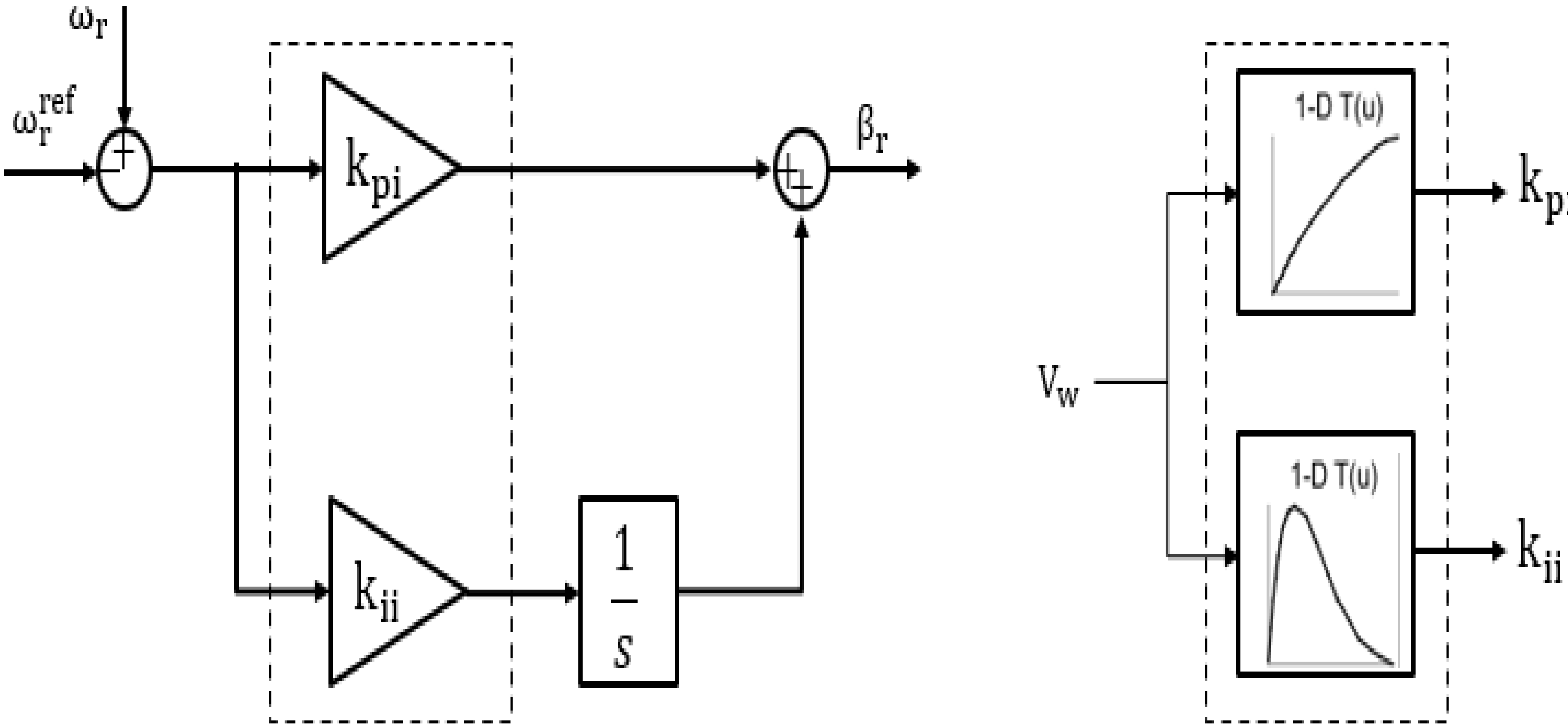
$$\dot{\omega_r} = \frac{1}{J}\left(T_r - T_g \times n_g\right)$$

$$T_r = \frac{1}{2}\rho\pi R^3 V_w^2 C_Q(\lambda, \beta)$$

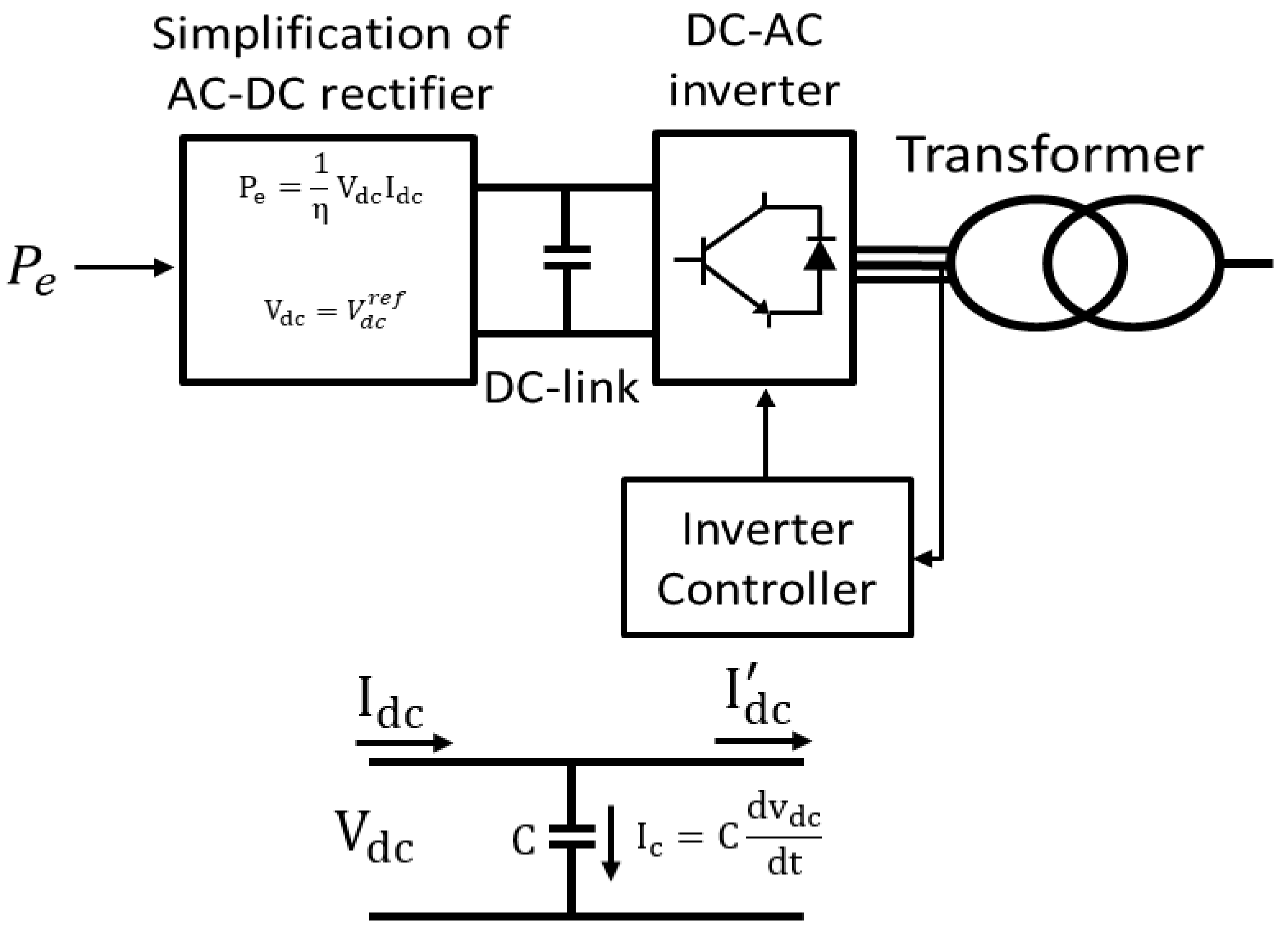
$$\tilde{C}_Q(\lambda, \beta) = c_1\left(c_2(\beta + c_3)^{1/2} + 1\right) + \frac{c_4\left(-\beta c_6 - \beta^{c_8} c_7 + c_5\lambda_i(\lambda, \beta) - c_9\right)e^{-c_{10}\lambda_i(\lambda,\beta)}}{\lambda} (\lambda > 0)$$

$$\Delta\dot{\omega}_{r_e} = k_{\lambda_e}\Delta\omega_r + k_{\beta_e}\Delta\omega_r + k_{V_{w_e}}\Delta V_w \qquad s\Delta\omega_{r_e}(s) = \left(k_{\lambda_e} + k_{\beta_e}\right)\Delta\omega_{r_e}(s) + k_{V_{w_e}}\Delta V_w(s)$$

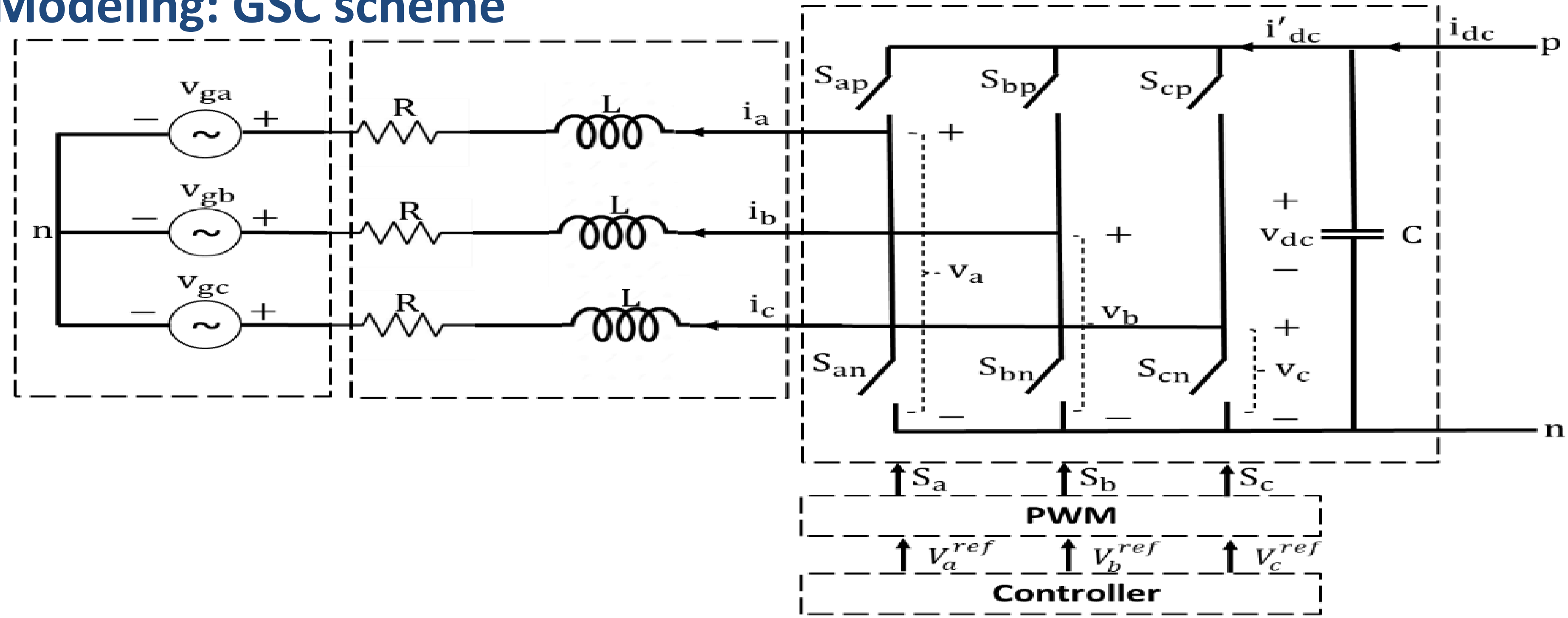
Modeling: Pitch controller



Modeling: MSC simplification and Idc calculation



Modeling: GSC scheme

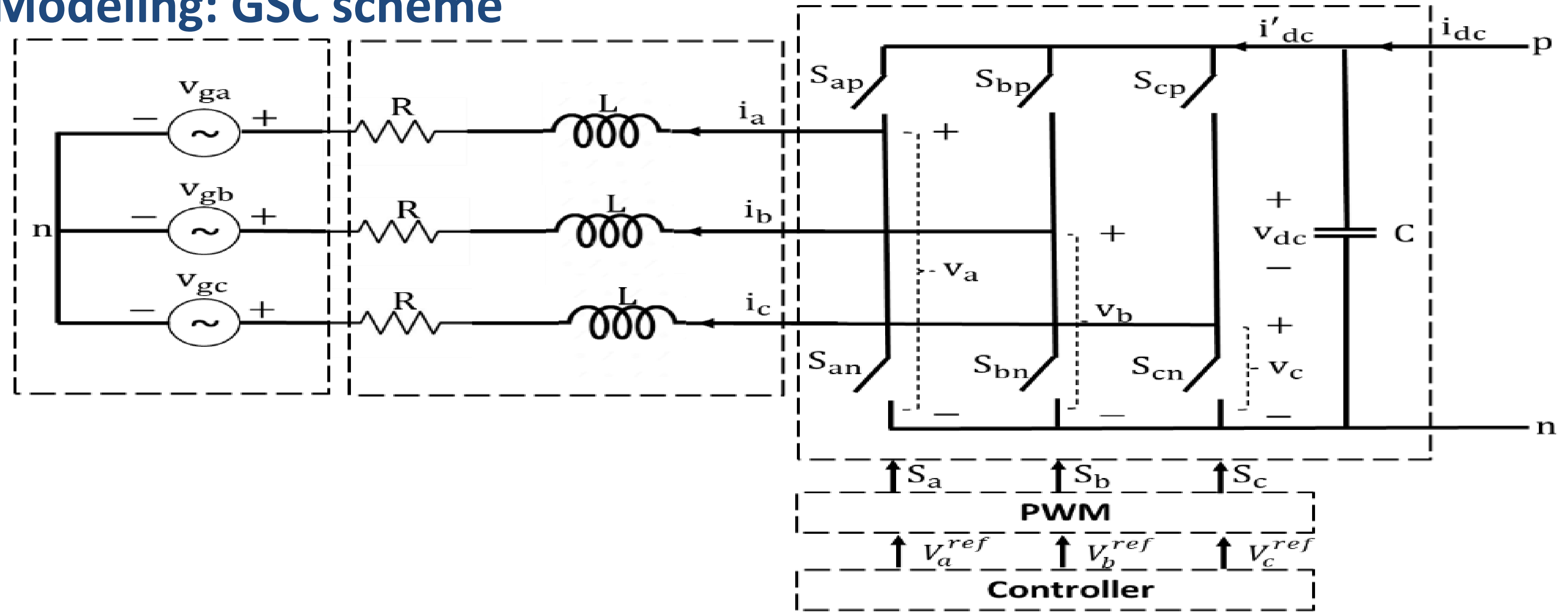


$$v_{pa} = -L\frac{di_a}{dt} - Ri_a + v_{an} \quad ; \quad v_{pb} = -L\frac{di_b}{dt} - Ri_b + v_{bn} \quad ; \quad v_{pc} = -L\frac{di_c}{dt} - Ri_c + v_{cn}$$

$$v_{pd} = -L\frac{di_d}{dt} - Ri_d + \omega_s L i_q + v_d \xrightarrow{Laplace} G_{ipd}(s) = \frac{i_d}{v_d + \omega_s L i_q - v_{pd}} = \frac{1}{Ls+R}$$

$$v_{pq} = -L\frac{di_q}{dt} - Ri_q - \omega_s L i_d + v_q \xrightarrow{Laplace} G_{ipq}(s) = \frac{i_q}{v_q - \omega_s L i_d - v_{pq}} = \frac{1}{Ls+R}$$

Modeling: GSC scheme



$$P_p = -\frac{3}{2}\mathrm{Re}\{\vec{v}_{pdq}\vec{i}^{*}{}_{pdq}\} = -\frac{3}{2}(v_{pd}i_{pd} + v_{pq}i_{pq}) \quad ; \quad Q_p = -\frac{3}{2}\mathrm{Im}\{\vec{v}_{pdq}\vec{i}^{*}{}_{pdq}\} = -\frac{3}{2}(v_{pq}i_{pd} - v_{pd}i_{pq})$$

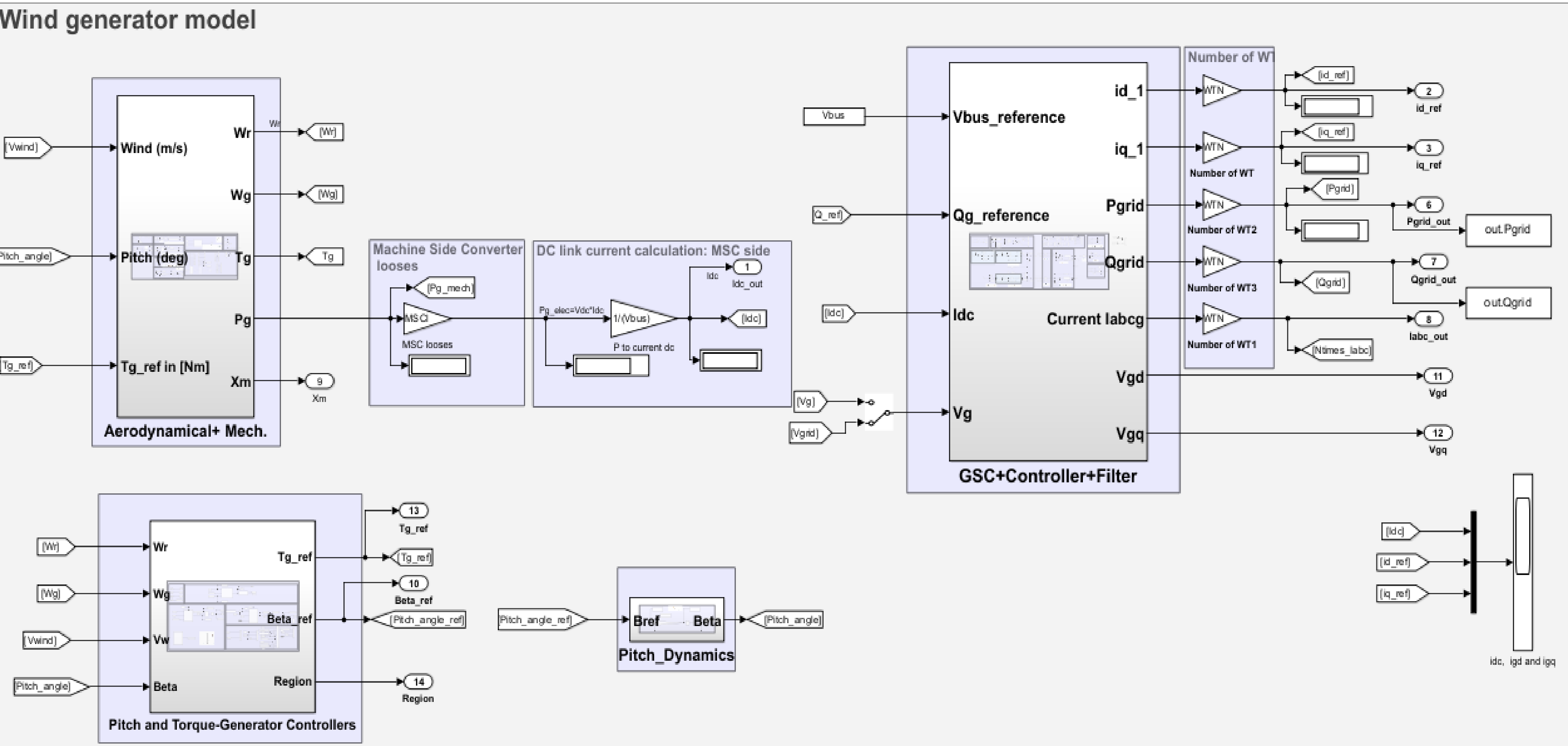
$$v_{pd} = v_{gd} = V_s \quad ; \quad v_{pq} = v_{gq} = 0$$

Modeling: GSC parameters

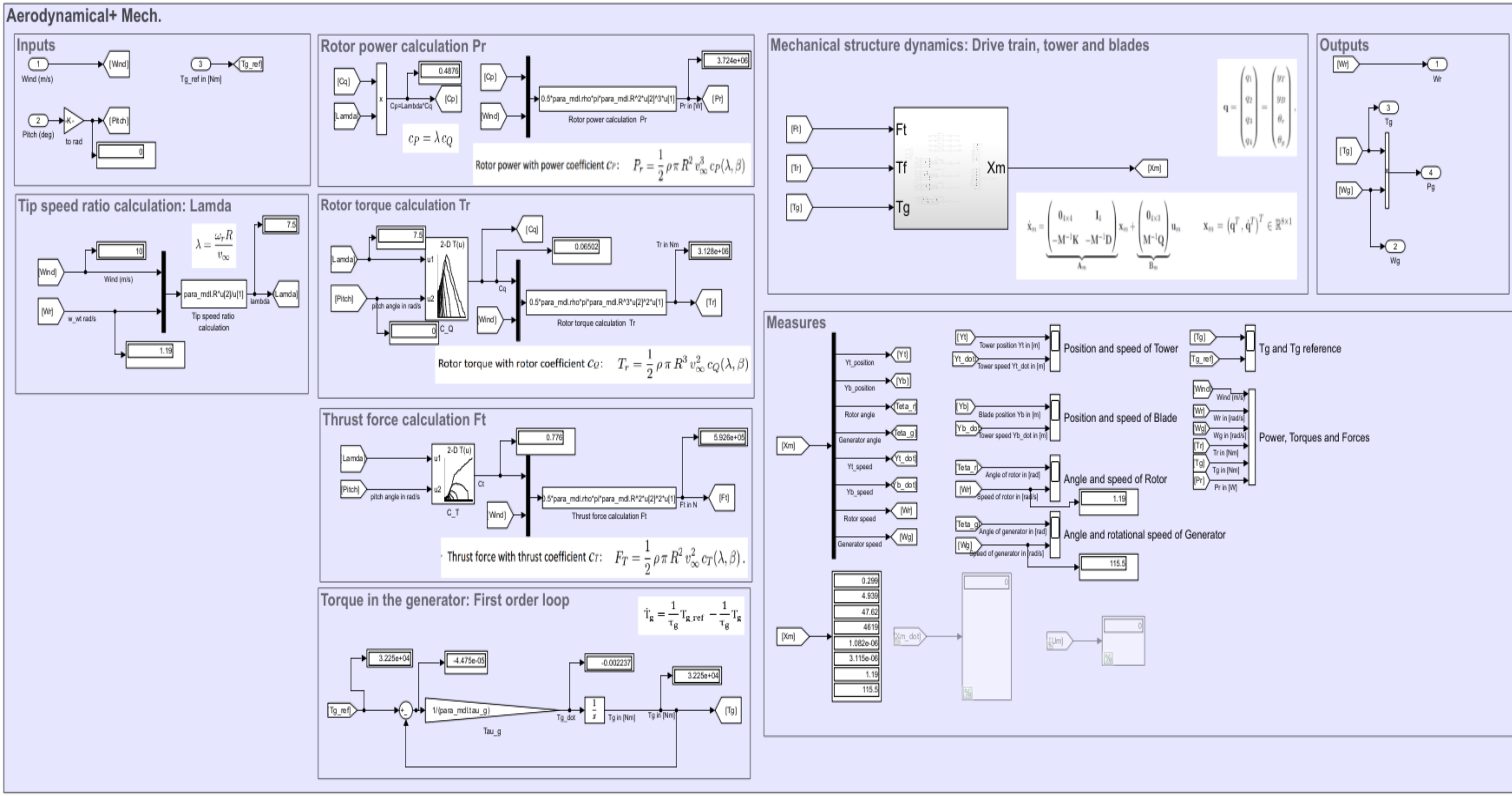
Parameter	Symbol	Value	Units
DC-Link rated voltage	V_{dc}^{ref}	1150	[V]
DC-Link capacitance	C_{dc}	15×10^{-3}	[F]
Grid side filter inductance	L	0.1×10^{-3}	[H]
Grid side filter inductance	R	0.001	[Ω]
PWM gain factor	K_{pwm}	0.9	[Dimensionless]
CCP[1] rated voltage (ph-ph RMS)	V_s	18000	[V]
Frequency of the system	f	50	[Hz]
Angular frequency	ω_s	100π	[rad/s]

Modeling

- Type 4 Wind Turbine NREL 5.5 MW. Simulink model.



Modeling: Wind Turbine



Modeling: State machine, pitch and GT controllers