North America Dynamic Wind Generator Modeling Update

Based on work performed by the WECC Wind Generator Modeling Group and the IEEE Dynamic Performance of Wind Power Generation Working Group

US Membership to the IEC TF88 WG27

Abraham Ellis
Sandia National Laboratories
aellis@sandia.gov

Yuriy Kazachkov
Siemens-PTI
yuriy.kazachkov@siemens.com

Eduard Muljadi
National Renewable Energy Laboratory
eduard.muljadi@nrel.gov

Juan Sanchez-Gasca, Nicholas Miller
GE Energy - PSLF
juan1.sanchez@ge.com, nicholas.miller@ge.com

Robert Zavadil
EnerNex Corporation
bobz@enernex.com

Pouyan Pourbeik
Electric power Research Institute
PPourbeik@epri.com

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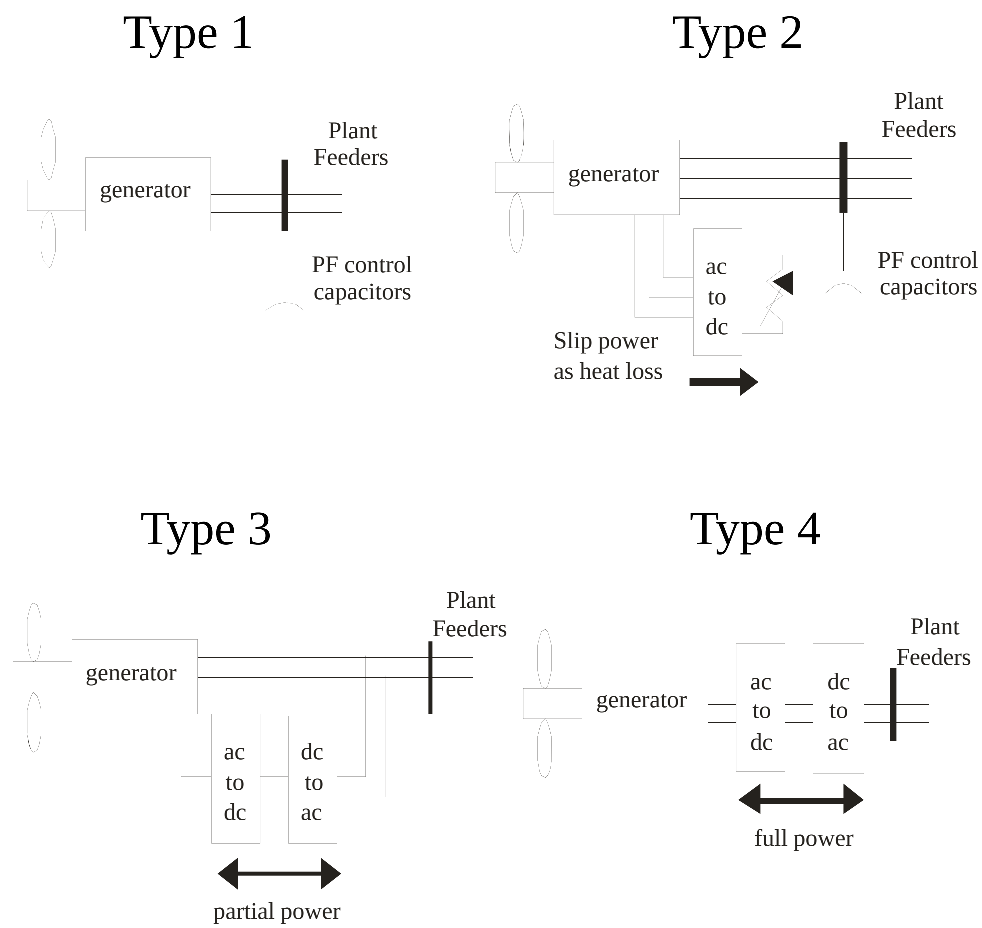
Presentation Contents

1. Status of WECC WGMG generic modeling effort and related activities in IEEE & NERC.
2. Review of WECC generic model structures, testing and verification
3. Simplified aerodynamic conversion representation for generic models
4. Model validation and parameter identification
5. Wind power plant network equivalent for power flow and dynamic simulations

Wind Turbine Generator Topologies

- **Four basic WTG types based on grid interface technology**

  - Type 1 – Fixed-speed, conventional induction generator
  - Type 2 – Variable slip, induction generators with variable rotor resistance
  - Type 3 – Variable speed, doubly-fed asynchronous generators with rotor-side converter
  - Type 4 – Variable speed, asynchronous generators with full converter interface



WECC Generic Model Implementation

- **Completed generic models implemented as standard-library models in PSSE/PSLF completed**

PSLF/17

Model Type	Type 1	Type 2	Type 3	Type 4
Generator	wt1g	wt2g	wt3g	wt4g
Excitation / Controller		wt2e	wt3e	wt4e
Turbine	wt1t	wt2t	wt3t	
Pitch Controller/Pseudo Gov.	wt1p	wt2p	wt3p	

PSSE/32

Generic model	WT1	WT2	WT3	WT4
Generator	WT1G	WT2G	WT3G	WT4G
El. Controller		WT2E	WT3E	WT4E
Turbine/shaft	WT12T	WT12T	WT3T	
Pitch control			WT3P	
Pseudo Gov/: aerodynamics	WT12A	WT12A		

- **Key Participants**
  - Siemens (PSSE), General Electric (PSLF), DOE (Sandia National Laboratories and NREL), Consultants, Universities, other stakeholders
- **Current focus**
  - Additional model validation, refinement, upgrade
  - Identification of generic model parameters

Partial List of WTG Types

Type 1	Type 2	Type 3	Type 4
Vestas NM72 1.65 MW, 50/60 Hz	Vestas V80 1.8 MW, 60Hz	GE 1.5 MW, 50/60 Hz	GE 2.5XL 2.0 MW, 50/60 Hz
Vestas V82 1.65 MW, 50/60Hz	Vestas V47 660 kW, 50/60 Hz	GE 3.6 MW, 50/60 Hz	Clipper 2.5 MW, 50/60 Hz
BONUS (now Siemens) 1.3 MW, 50/60 Hz	Gamesa G80 1.8 MW, 60 Hz	Gamesa G80 2 MW, 50 Hz	Enercon E66 1.8 MW, 50 Hz
BONUS (now Siemens) 2.3 MW, 50 Hz	Suzlon S88 2.1 MW, 50Hz	NORDEX N80 2.5 MW, 50Hz	Enercon E70 2.0 MW, 50 Hz
Mitsubishi MWT100a 1 MW, 60 Hz		REPower MD70 and MD77 1.5 MW, 50Hz	Siemens, 2.3VS82, 2.3MW, 50/60Hz
Suzlon S66 1.25 MW, 50 Hz		REPower MM70 and MM82 2.0 MW, 50Hz	Kennetech 33-MVS, 400kW, 60Hz
		Mitsubishi MWT-92/95 2.4 MW	
		Fuhrlaender FL 2.5 MW, 60 Hz	

Related Activities

- **IEEE DPWPG Task Force**
  - Verification, enhancement of WECC generic models
  - Paper on Specifications for Wind Power Plant models
  - Paper on Validation Procedures for Wind Power Plant models
  - Outreach (Tutorials)
  - Coordination with WECC, NERC (IVGTF), UWIG, CIGRE, IEC, …
- **UWIG/EnerNex (DOE funding)**
  - Develop user documentation for generic and turbine-specific wind turbine models; conduct training seminars
  - Verify performance of generic and vendor-specific models
  - Validate of models against field test results

Related Activities

- **NERC IVGTF Work Plan, Task 1.1 (Planning)**
  - Valid, generic, non-confidential, and public standard power flow and stability (positive-sequence) models [...] needed
  - Models should be readily validated and publicly available to power utilities and all other industry stakeholders
  - Model parameters should be provided by manufacturers
  - Common model validation standard [...] should be adopted
  - Review the Modeling, Data and Analysis (MOD) standards to identify any need modifications to address variable generation modeling and model validation

Good Progress, More Work Needed

- **Generic models emerging as the correct approach**
  - Pressure continues to build in North America, Europe
  - Several technical activities underway to validate, improve
  - Strong trend among manufacturers to replace custom models with adjusted generic models
- **Need to build on recent progress with generic models**
  - Include a more complete set of control options
    - Programmed inertia, frequency support features, LVRT details, etc.
  - Perform model validation, develop parameter sets
  - Develop model documentation and application guides
- **Coordination of related efforts is key**
- **Ultimate goal: full-featured, industry standard models**
  - In the meantime, manufacture models are still useful in cases where specific control features not available in the generic models have a substantial impact

Description of WECC Generic Models

References:

- Y. Kazachkov, S. Stapleton, “Do Generic Dynamic Simulation Wind Turbine Models Exist?”, WindPower 2005, Denver, Colorado, May 2005
- N. W. Miller, W. W. Price, J. J. Sanchez-Gasca, “Dynamic Model of GE’s 1.5 and 3.6 MW Wind Turbine Generators – Model Structure, Simulation Results, and Model Validation”, CIGRE Technical Brochure 328, *Modeling and Dynamic Performance of Wind Generation as it Relates to Power System Control and Dynamic Performance*, CIGRE WG C4.601, August, 2007
- WECC WGMG, “Generic Wind Plant Models for Power System Studies”, WindPower 2006, Pittsburgh, PA, June 2006
- WECC WGMG, “Development and Validation of WECC Variable Speed Wind Turbine Dynamic Models for Grid Integration Studies”, WindPower 2007, Los Angeles, CA, June 2007

WECC Generic Models

- **WECC WGMG Goals**
  - Specify generic, non-proprietary models for large-scale power system simulations (positive-sequence models)
  - Generic models are parametrically adjustable to any specific wind turbine of the same type in the market
  - Models are simplified, but major dynamic behavior is maintained
    - Find balance between simplification and performance. For example, representation of aerodynamic conversion should be simplified to avoid using proprietary *Cp* curves. Too much simplification is not good: a model does not perform well if aerodynamics is ignored (e.g. constant mechanical power)
  - Perform model testing and as much validation as possible
  - Implement in PSSE and PSLF with full documentation and default parameter sets

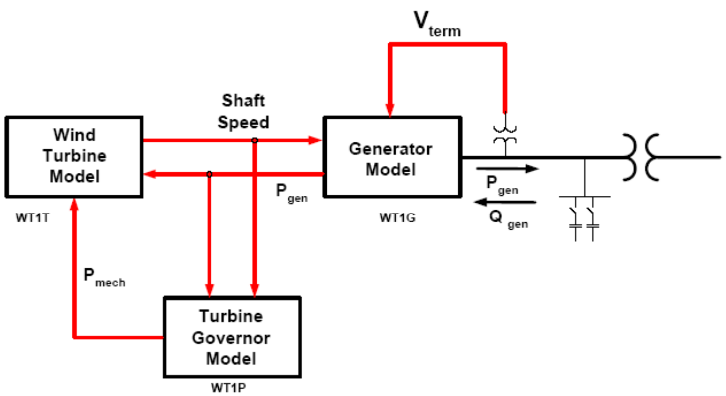
WECC Generic Models

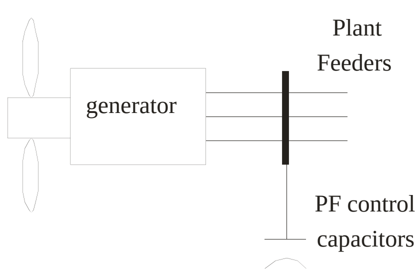
- **Technical Specifications**
  - Application: electrical disturbances (not wind disturbances), primarily grid faults external to the plant, typically 3 to 6 cycle duration.
  - Typical simulation time frame of interest are 20 to 30 seconds, with a ¼ cycle integration time step. Wind speed assumed to be constant.
  - Model able to handle oscillatory modes from dc to 5 Hz.
  - Initialize from power flow at full or partial power; able to handle user-specified wind speed
  - Speed and voltage protection modeled separately
  - Represent machine inertia and first shaft torsional mode characteristics
  - The models should be applicable to strong and weak systems with a short circuit ratio of 2.5 and higher at the point of interconnection
  - Shunt capacitors and any other reactive support equipment modeled separately with existing standard models

Response to Frequency Disturbances

- The generic WTG models were not developed with the intent of being accurate for the study of frequency excursions on the power system, or to reproduce the behavior of advanced power management features that are imminently becoming available from some WTG manufacturers (such as programmed inertia and 'spinning reserve' by spilling wind).
- We need to work further with Manufacturers to better understand response to frequency disturbances and thus improve the models.

WT1 Generic Model





Basic Description

Modules: WT1T, WT1P, WT1G

Generator model is conventional induction machine

Default model data provided in documentation (Mitsubishi MWT1000A)

Single or two-mass shaft model

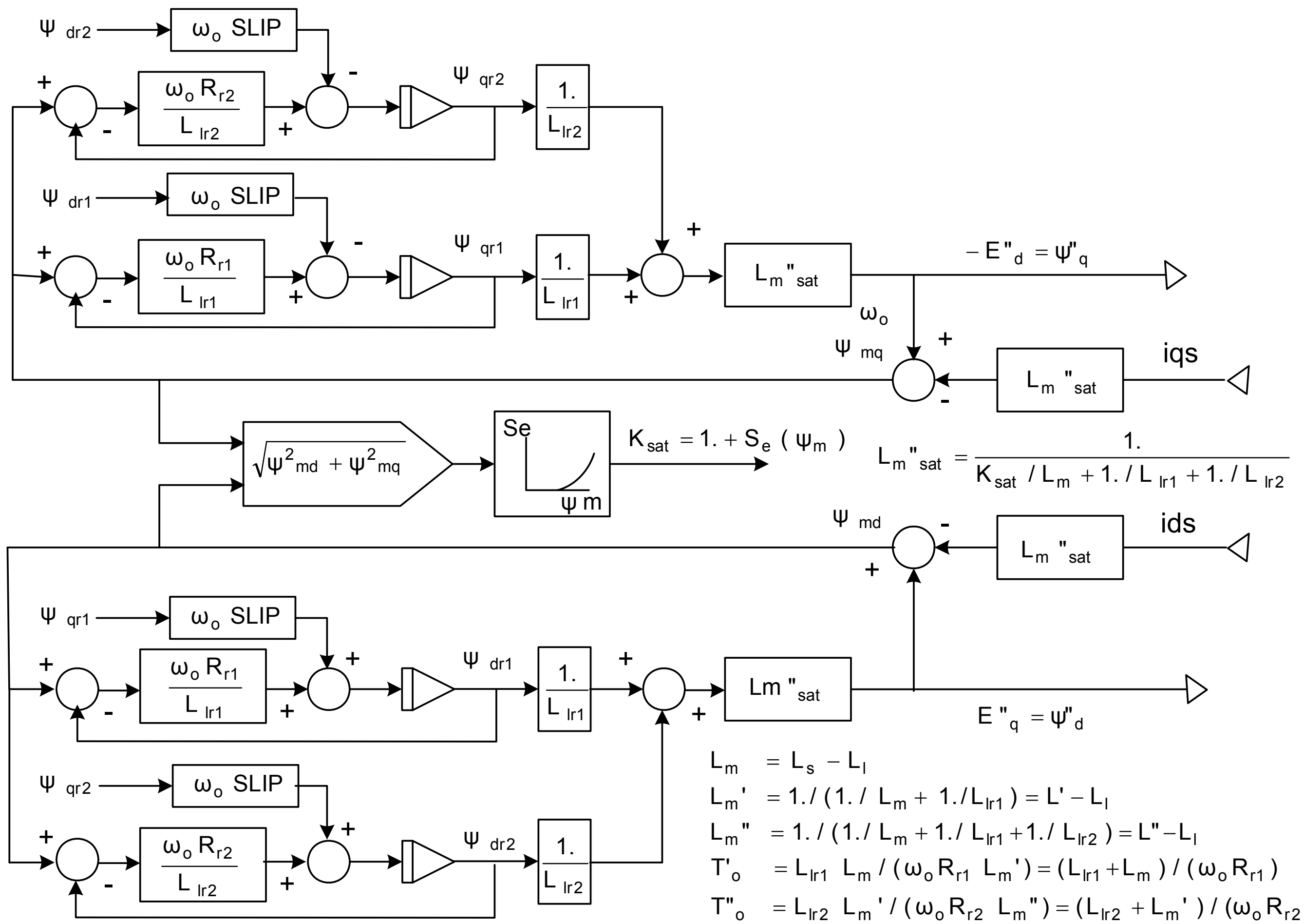
Power factor correction capacitor must be provided and initialized from load flow data

No special initialization or run-time script needed

No special adjustment needed for wind farm representation

WT1 Generic Model

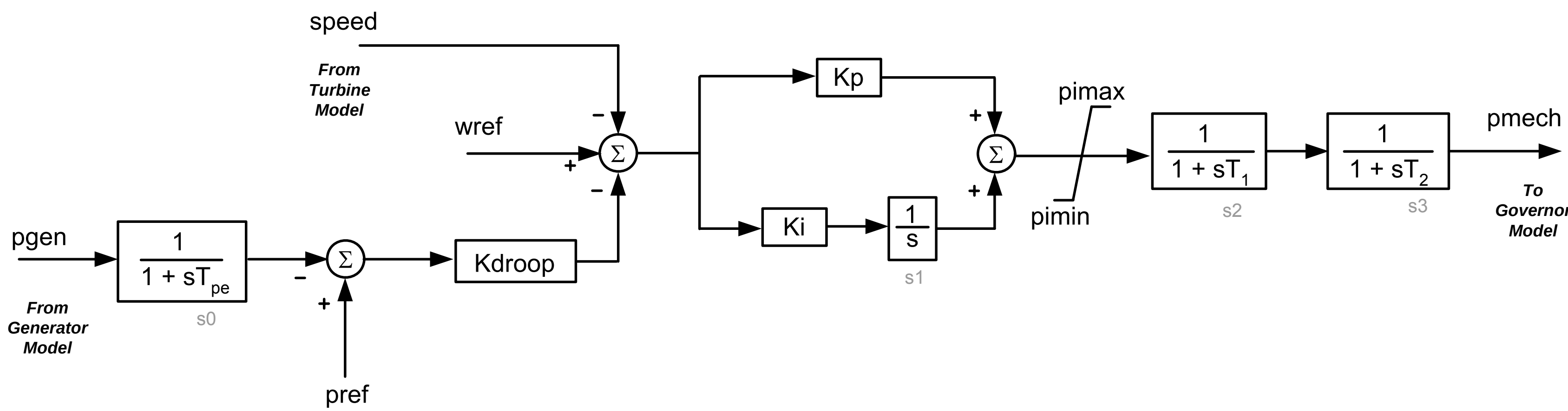
WT1G Induction Generator Model



Model simulates a one-cage model is used if Lpp **is equal to** Lp**. Otherwise, it simulates a two-cage induction generator. If** Lpp **or** Tppo **are 0., the model sets** Lpp **=** Lp**.**

WT1 Generic Model

WT1P
Pitch Control Model



Note: For disturbances involving frequency drops this is not necessarily accurate – should set <u>pimax</u> to rated turbine output to avoid any response from the turbine.

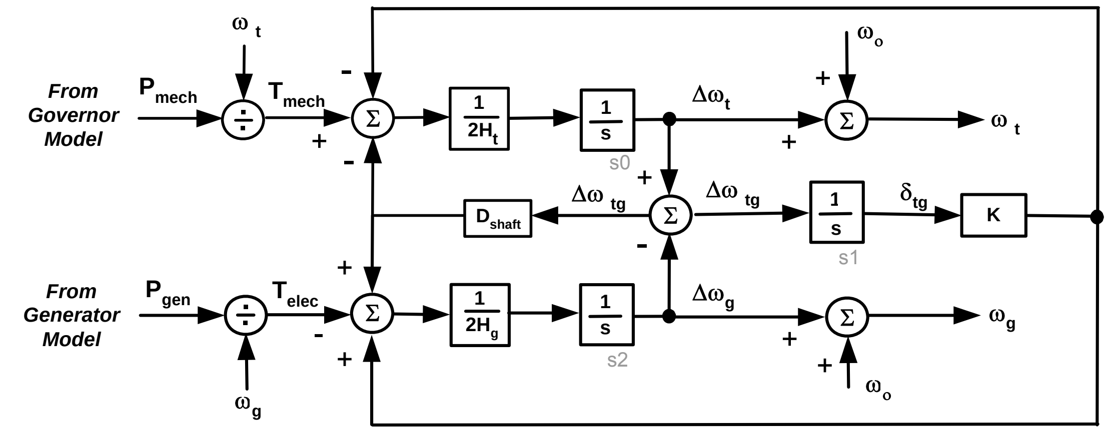
WT1 Generic Model

WT1T
Two-mass model

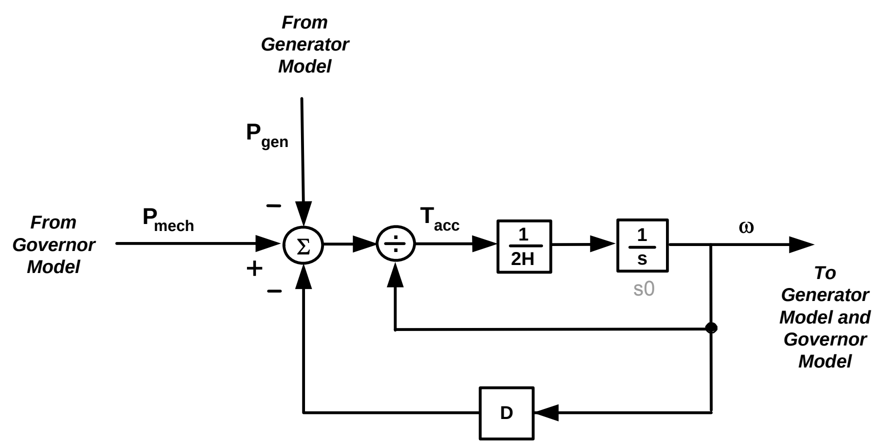
$H_t = H_{tfrac}\ H$

$H_g = H - H_t$

$K = 2\,(2\pi\ Freq1)^2\, H_t\, \frac{H_g}{H}$

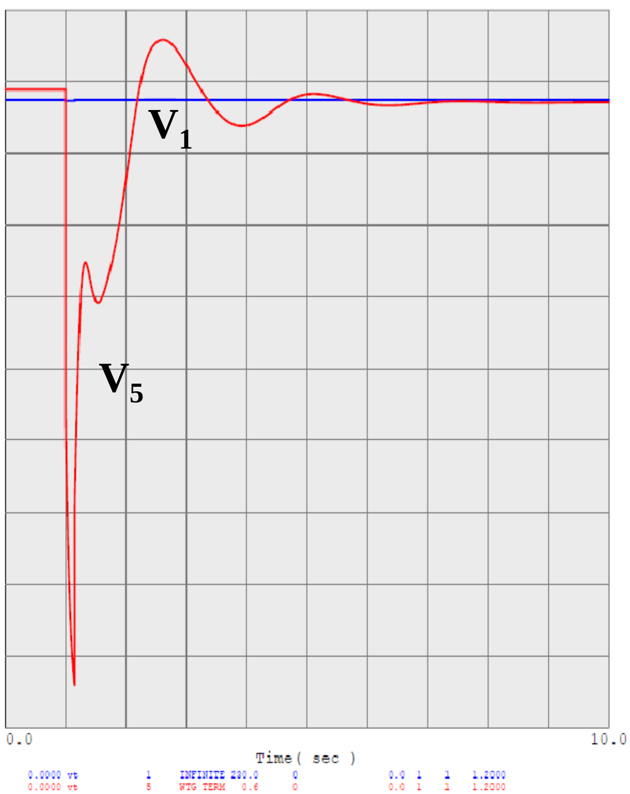


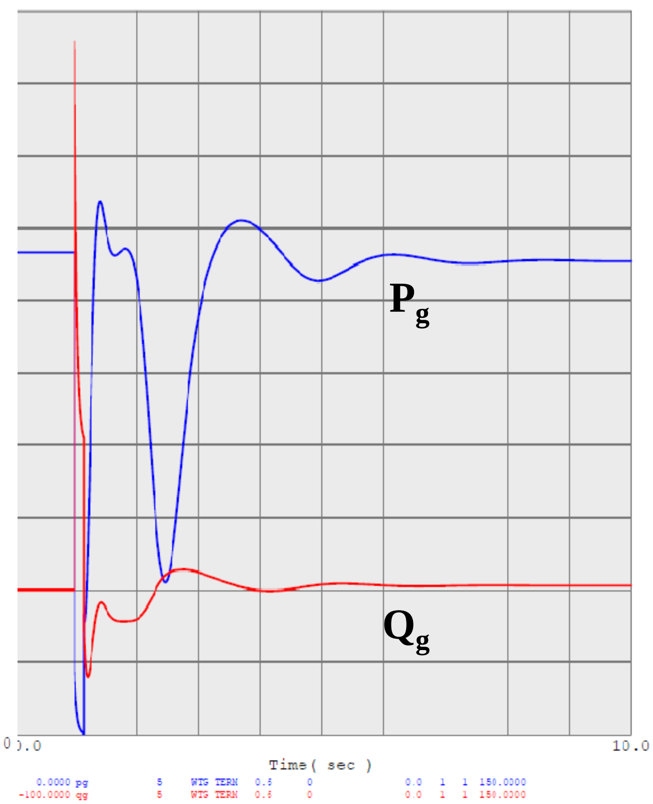
WT1T
Single mass model
(H_{tfrac} = 0)

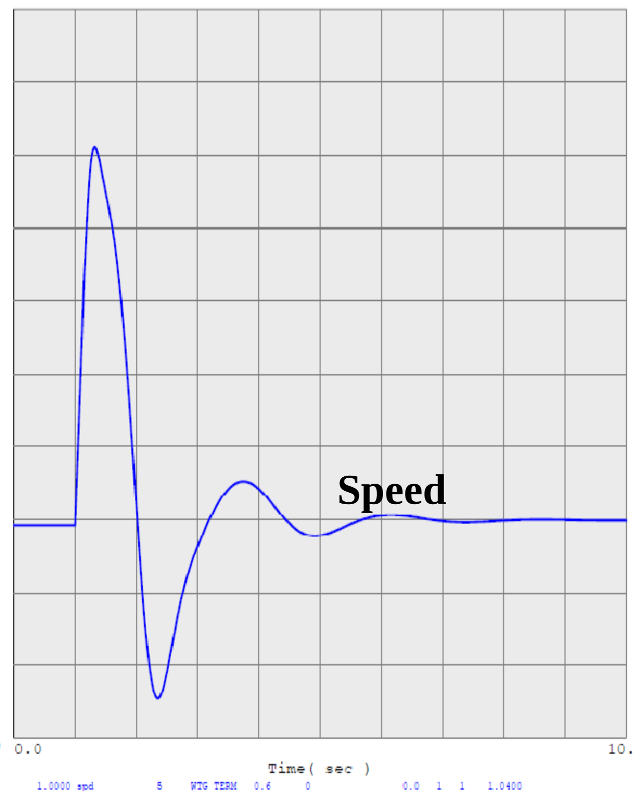


WT1 Fault Test

9-cycle, 3-phase fault at POI, clear fault by tripping line

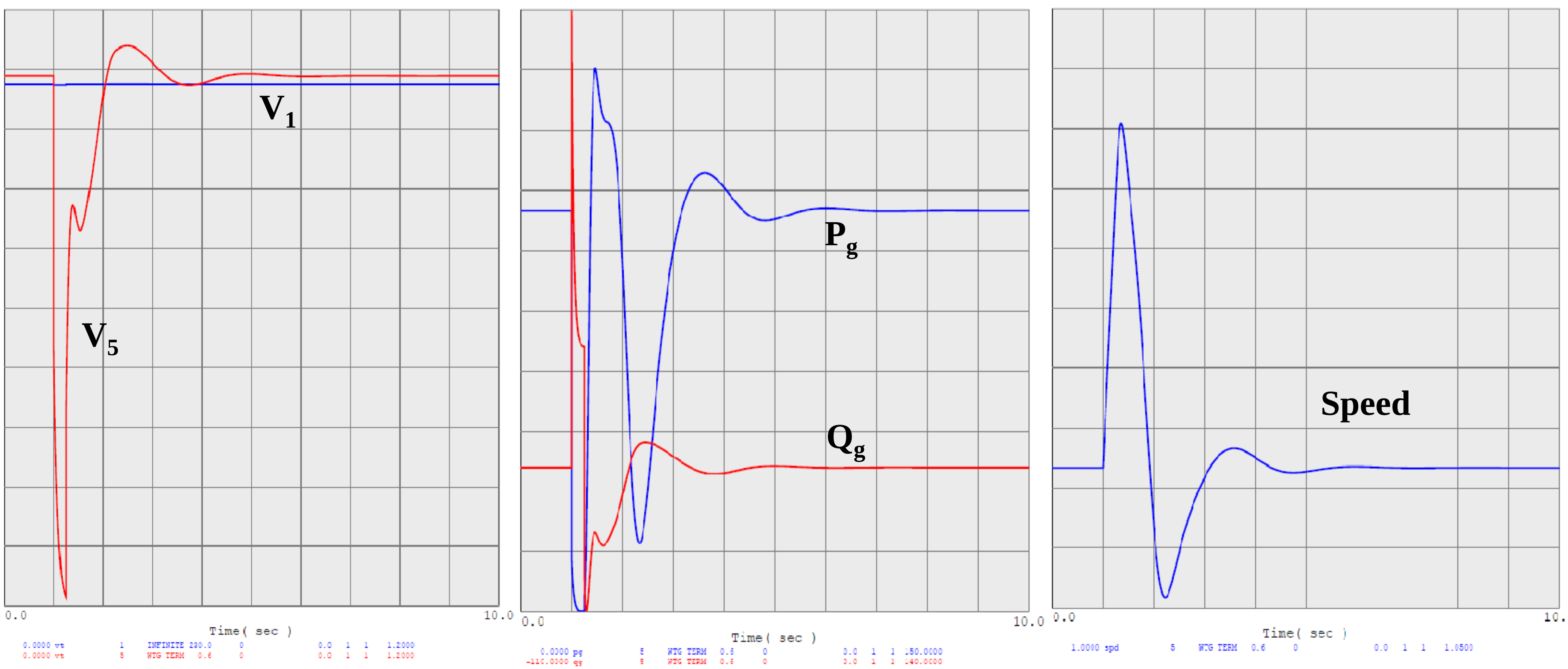






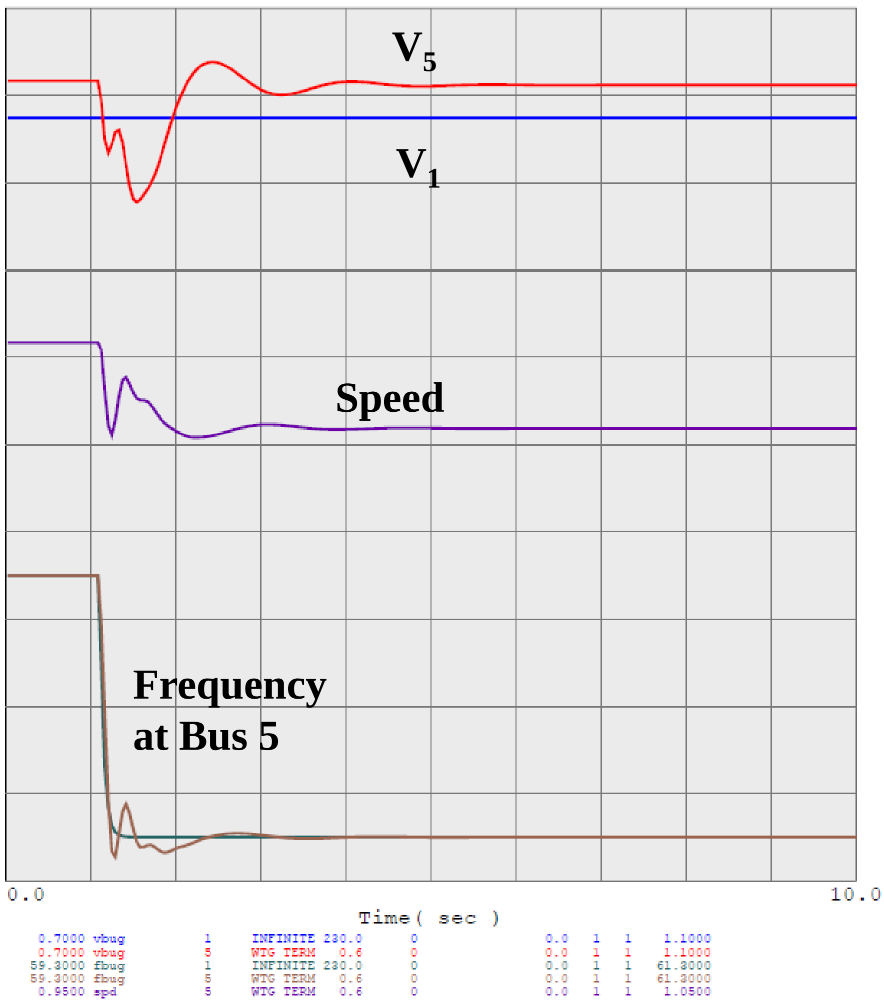
WT1 Fault Test

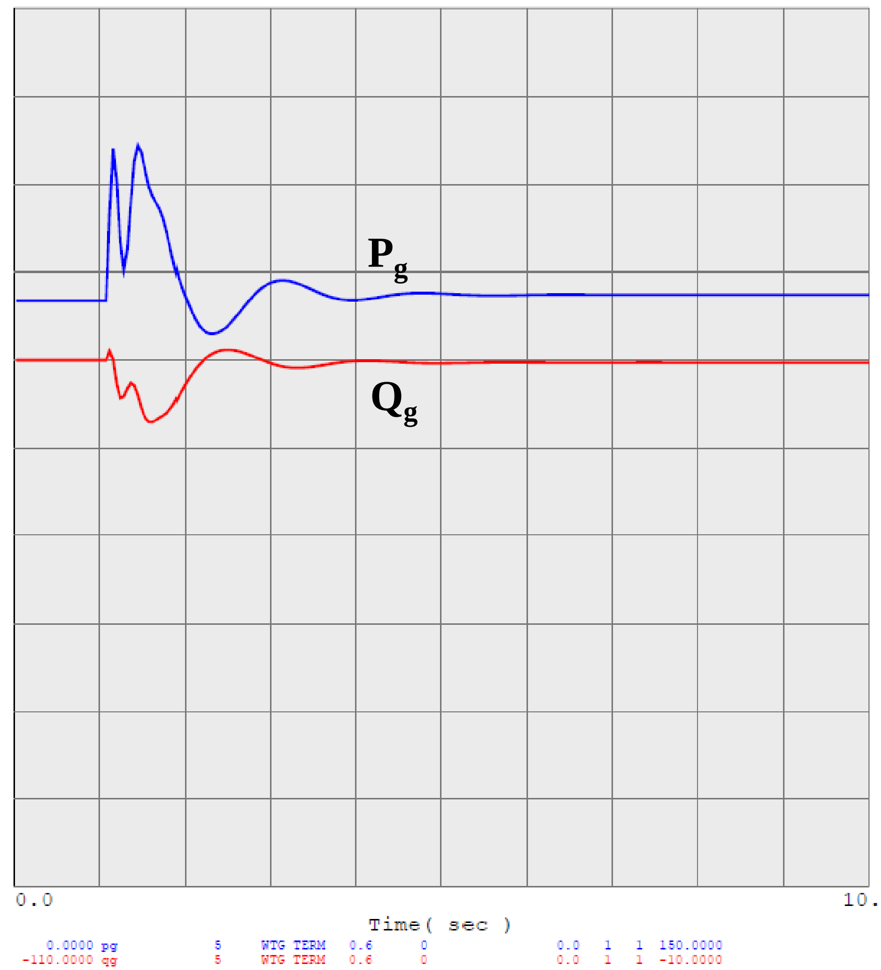
9-cycle, 3-phase fault at POI, Self-Clearing



WT1 Frequency Drop Test

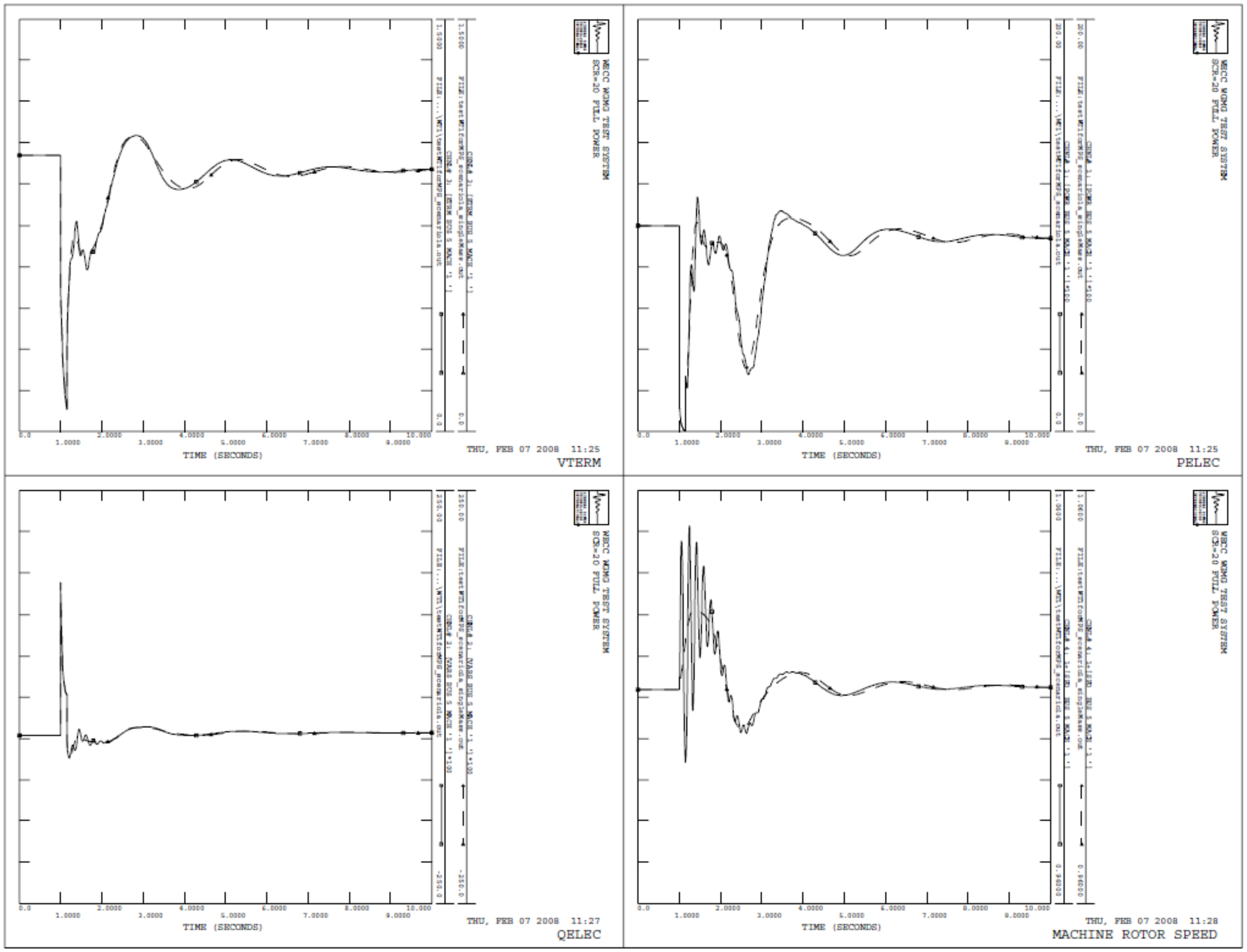
1% drop at t = 1 sec



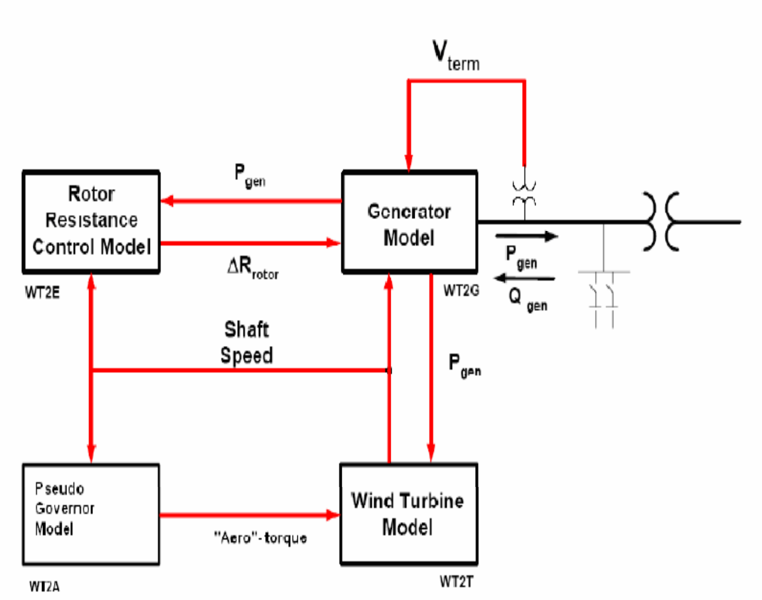


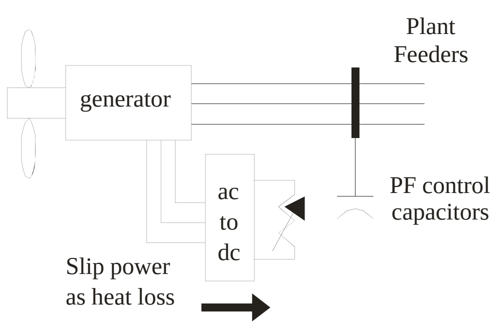
WT1 Model Comparison

Against Mitsubishi MWT1000A Manufacturer Model



WT2 Generic Model





Basic Description

Modules: WT2T, WT2E, WT2A/WT2P, WT2G

Generator model is conventional induction machine

Default model data provided in documentation (Vestas V80)

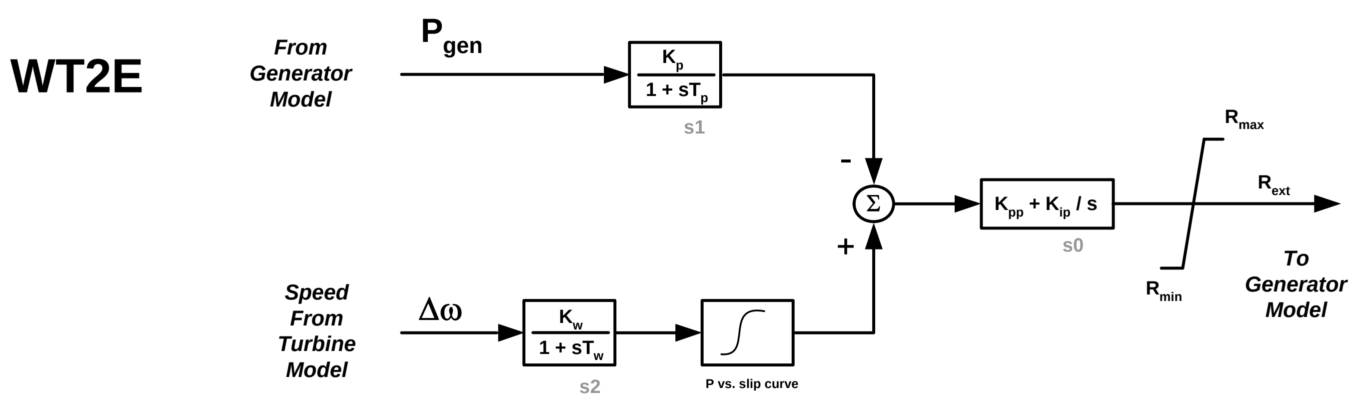
Single or two-mass shaft model

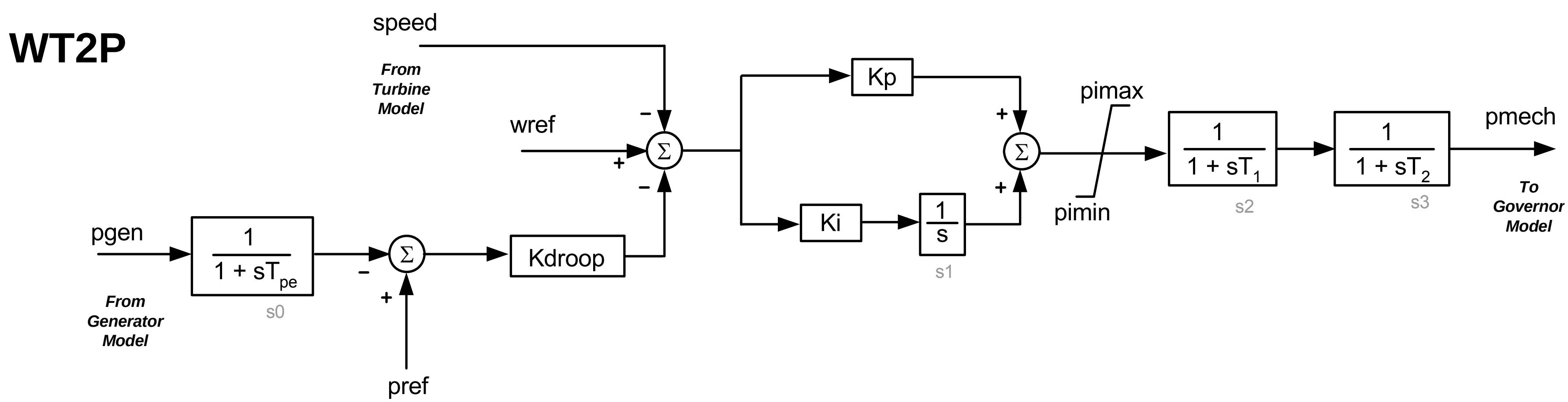
Power factor correction capacitor must be provided and initialized from load flow data

No special initialization or run-time script needed

No special adjustment needed for wind farm representation

WT2 Generic Model





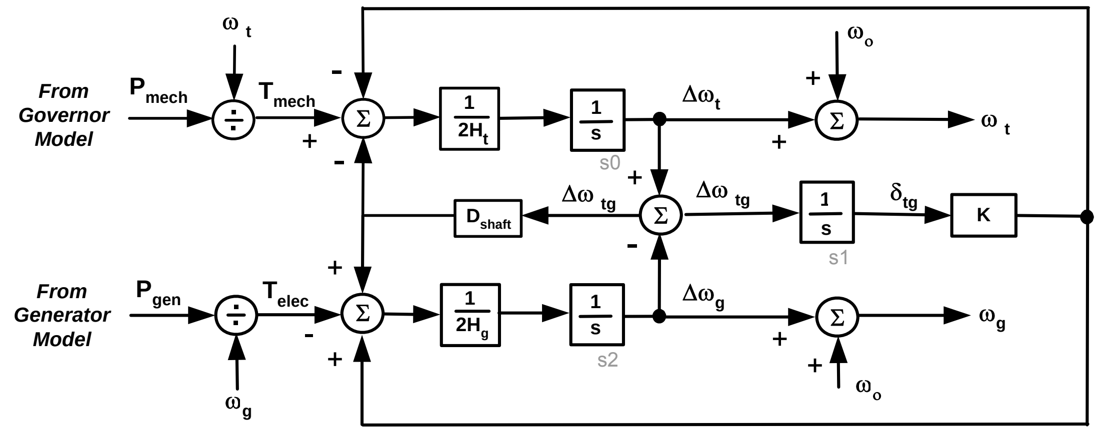
WT2 Generic Model

WT2T
Two-mass model

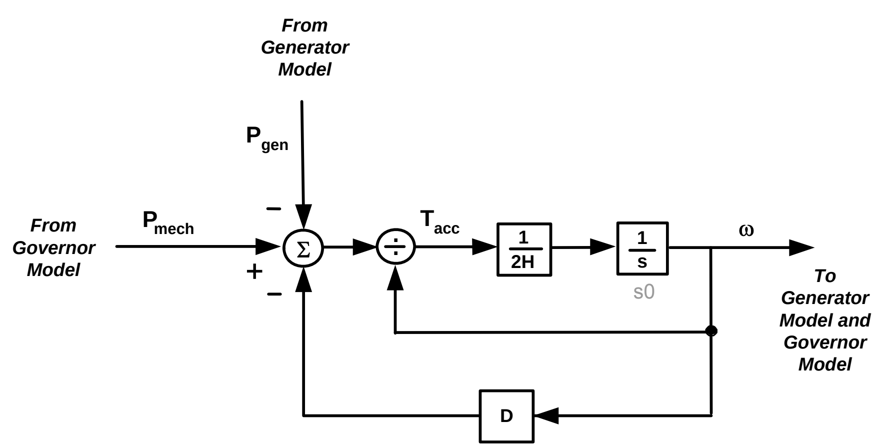
$H_t = H_{tfrac} H$

$H_g = H - H_t$

$K = 2 (2\pi\ Freq1)^2 H_t \frac{H_g}{H}$

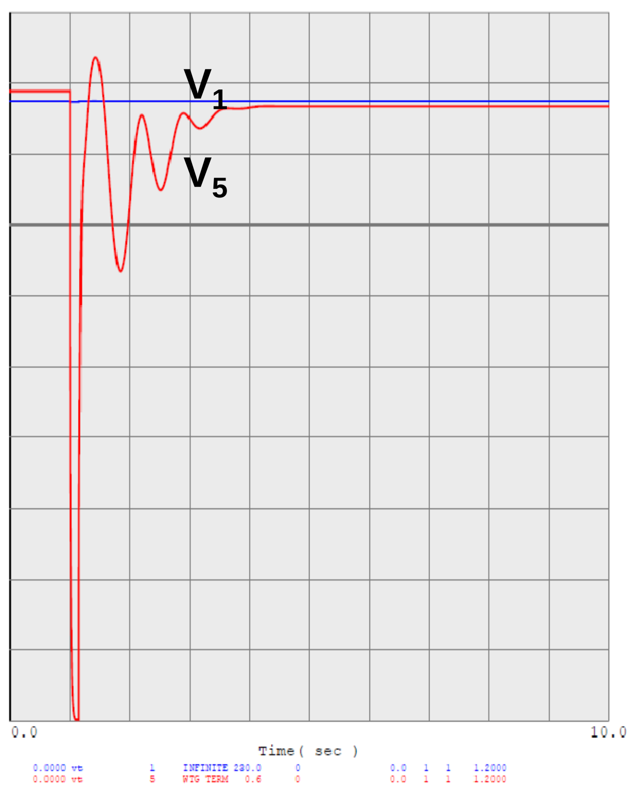


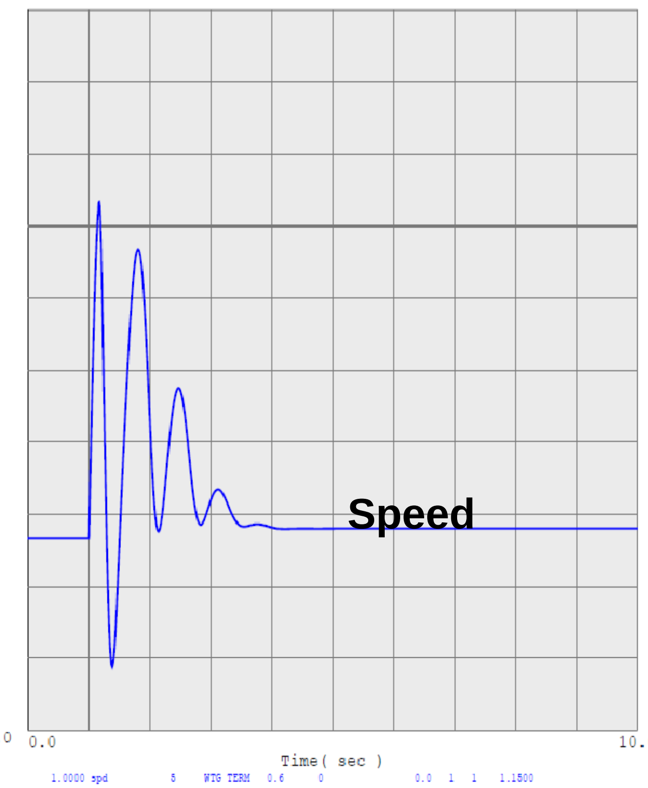
WT2T
Single mass model
(H_{tfrac} = 0)



WT2 Fault Test

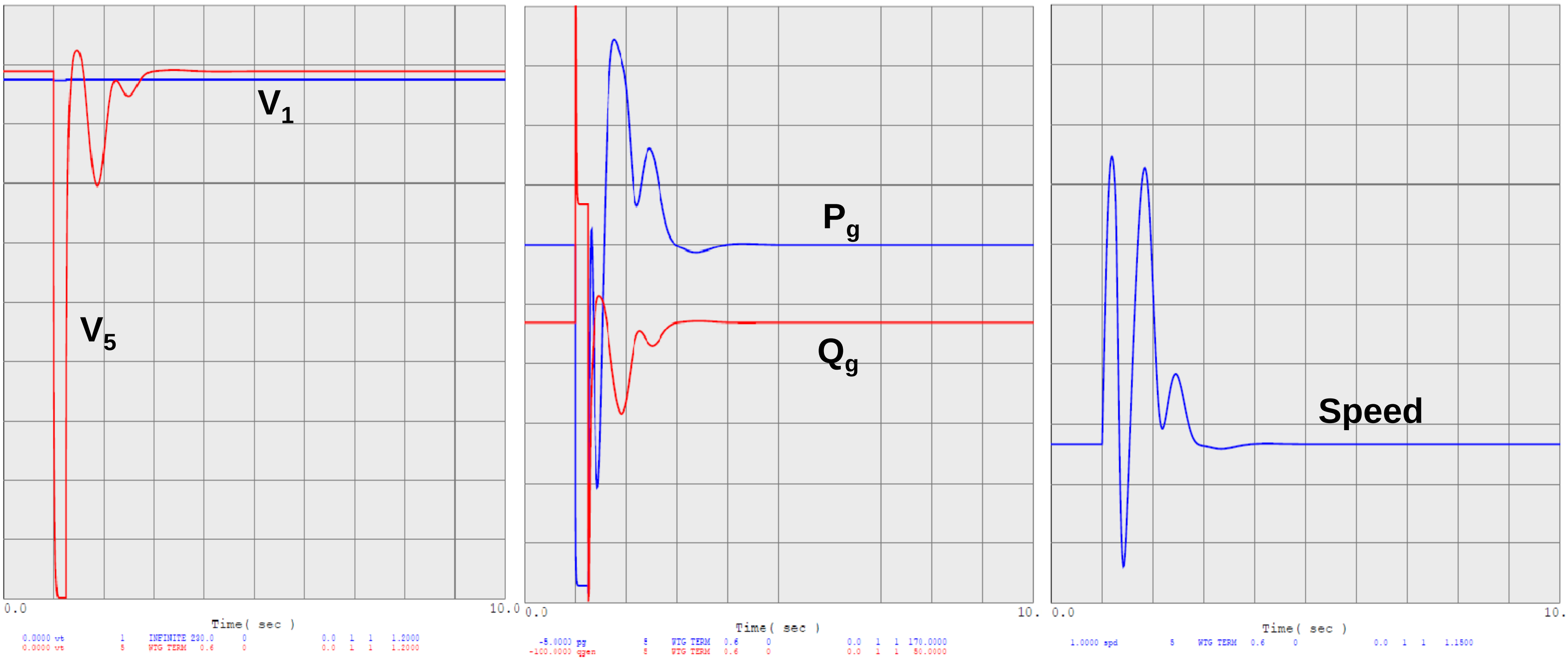
9-cycle, 3-phase fault at POI, clear fault by tripping line





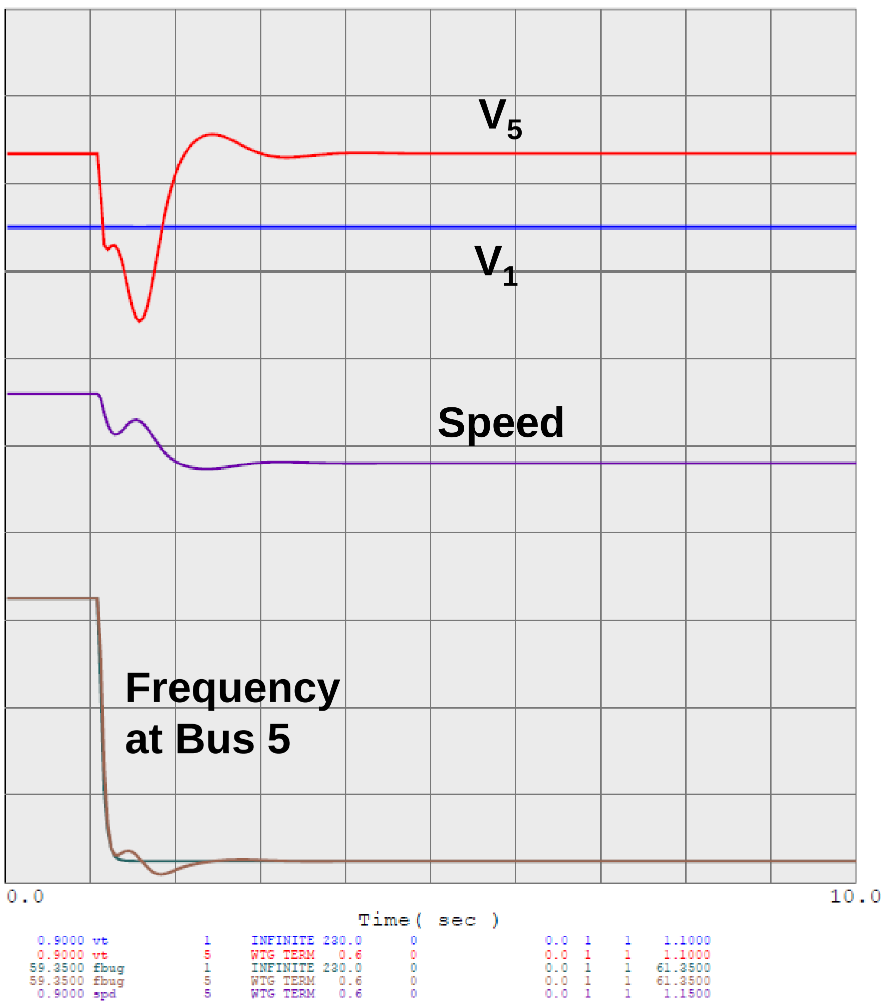
WT2 Fault Test

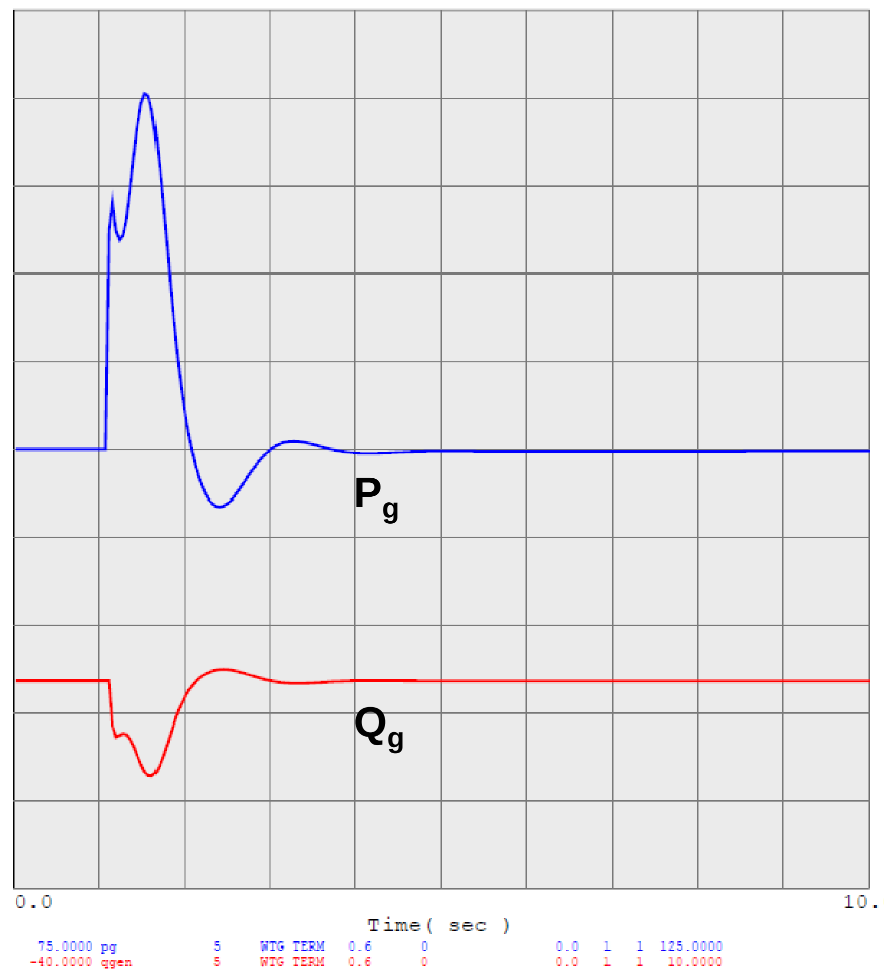
9-cycle, 3-phase fault at POI, self-clearing



WT2 Frequency Drop Test

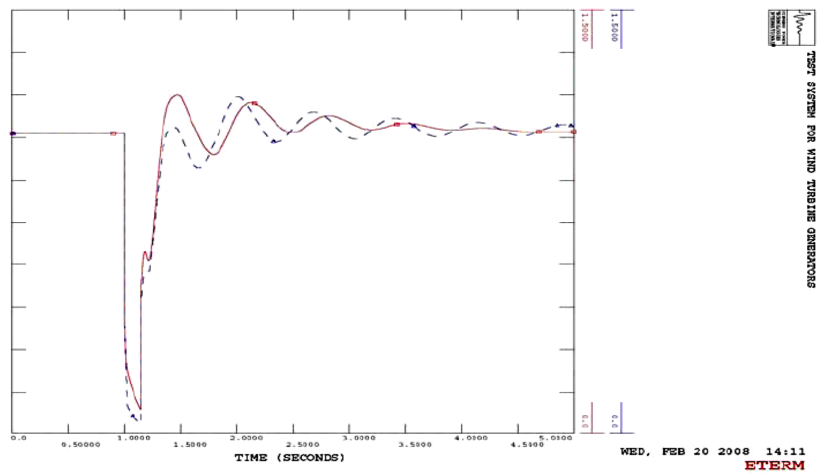
1% drop at t = 1 sec

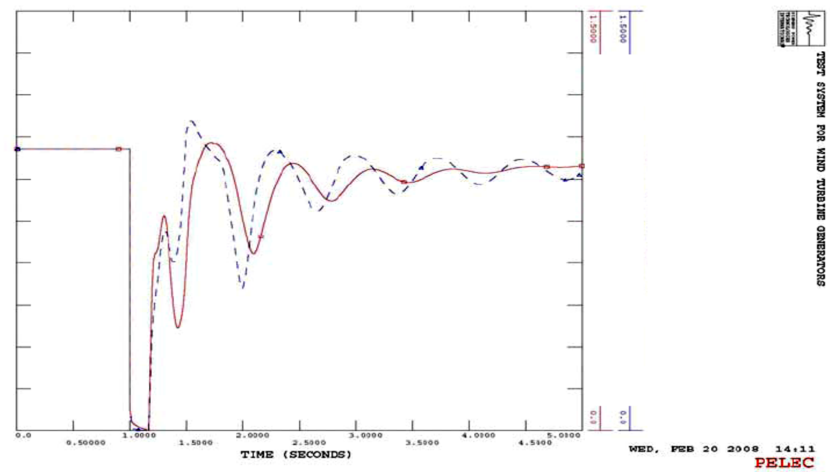


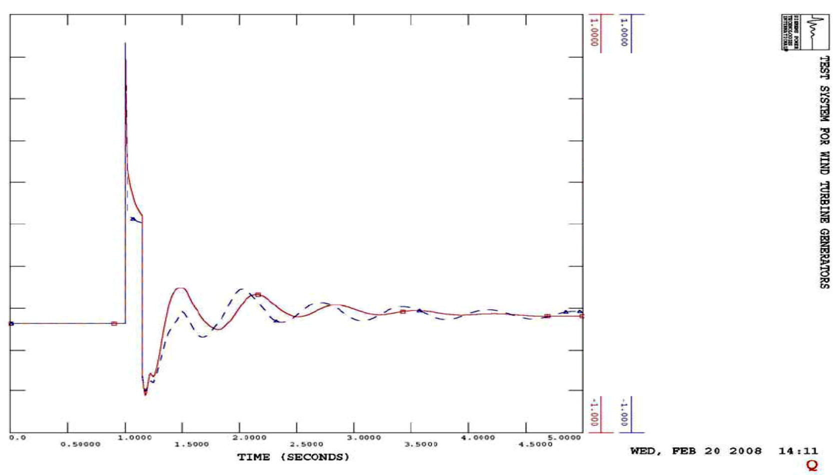


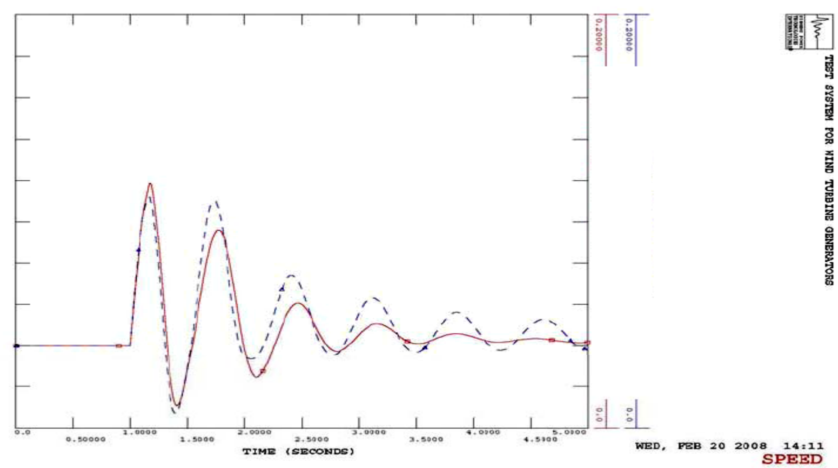
WT2 Model Comparison

Against Vestas V80 Manufacturer Model

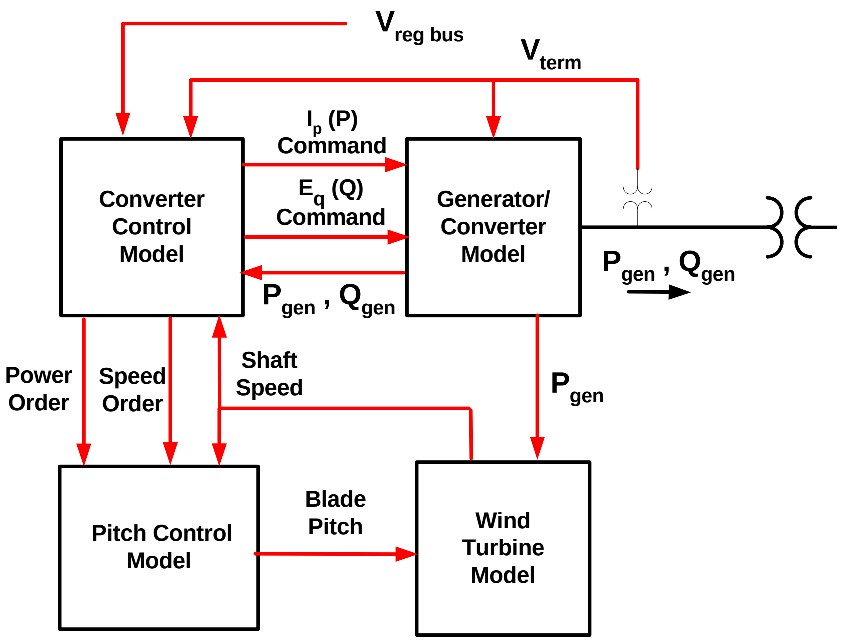


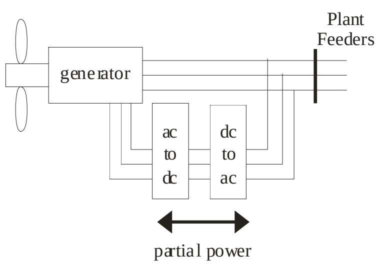






WT3 Generic Model





Basic Description

Modules: WT3T, WT3E, WT3P, WT3G

Generator is modeled as controlled current injection

Default model data provided in documentation (GE 1.5)

Single or two-mass shaft model

No special initialization or run-time script needed

Plant level reactive control options available for wind farm model (PF control, Q control and voltage control)

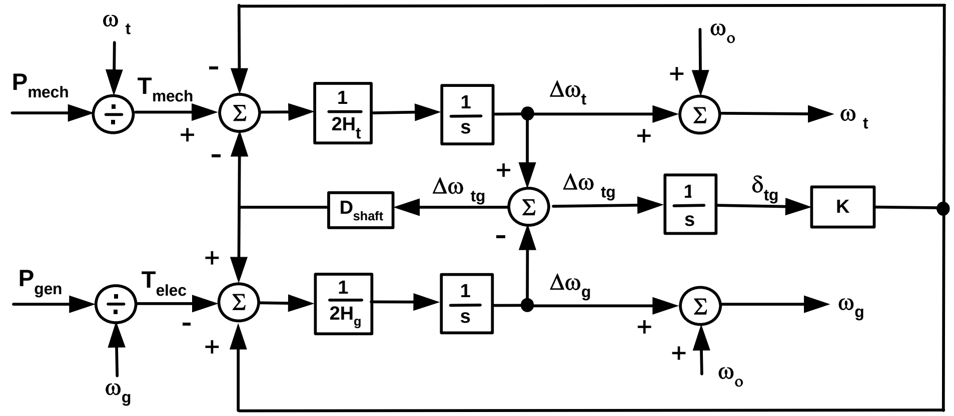
WT3 Generic Model

WT3T
Two-mass model

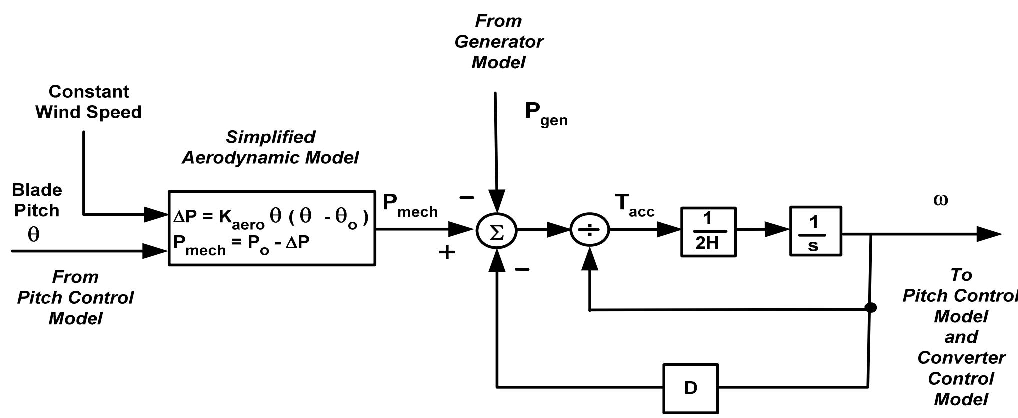
$H_t = H_{tfrac}\ H$

$H_g = H - H_t$

$K = 2\,(2\pi\ Freq1)^2\ H_t\ \frac{H_g}{H}$

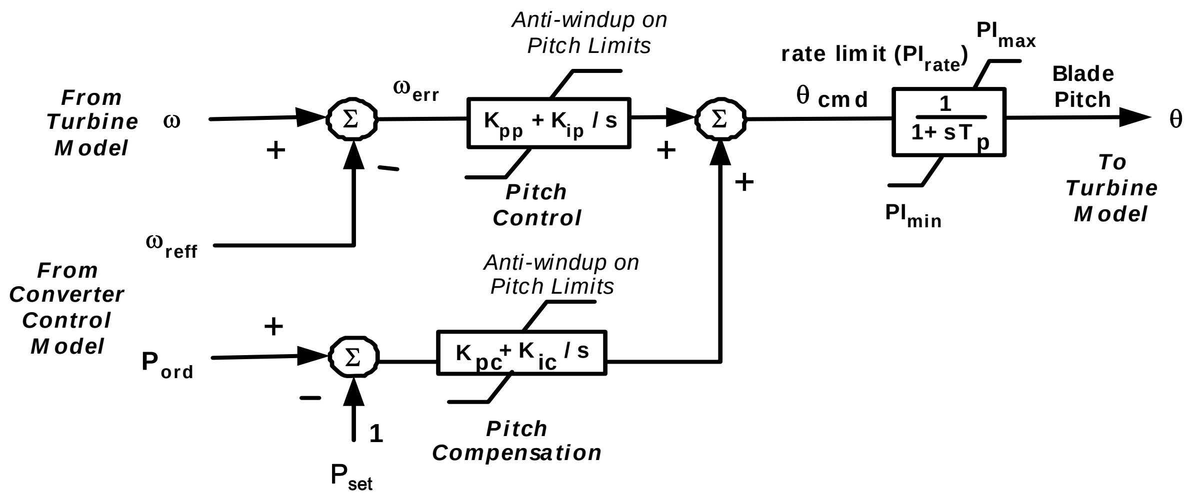


WT3T
Single mass model
(H_{tfrac} = 0)



WT3 Generic Model

WT3P
Pitch Control Model

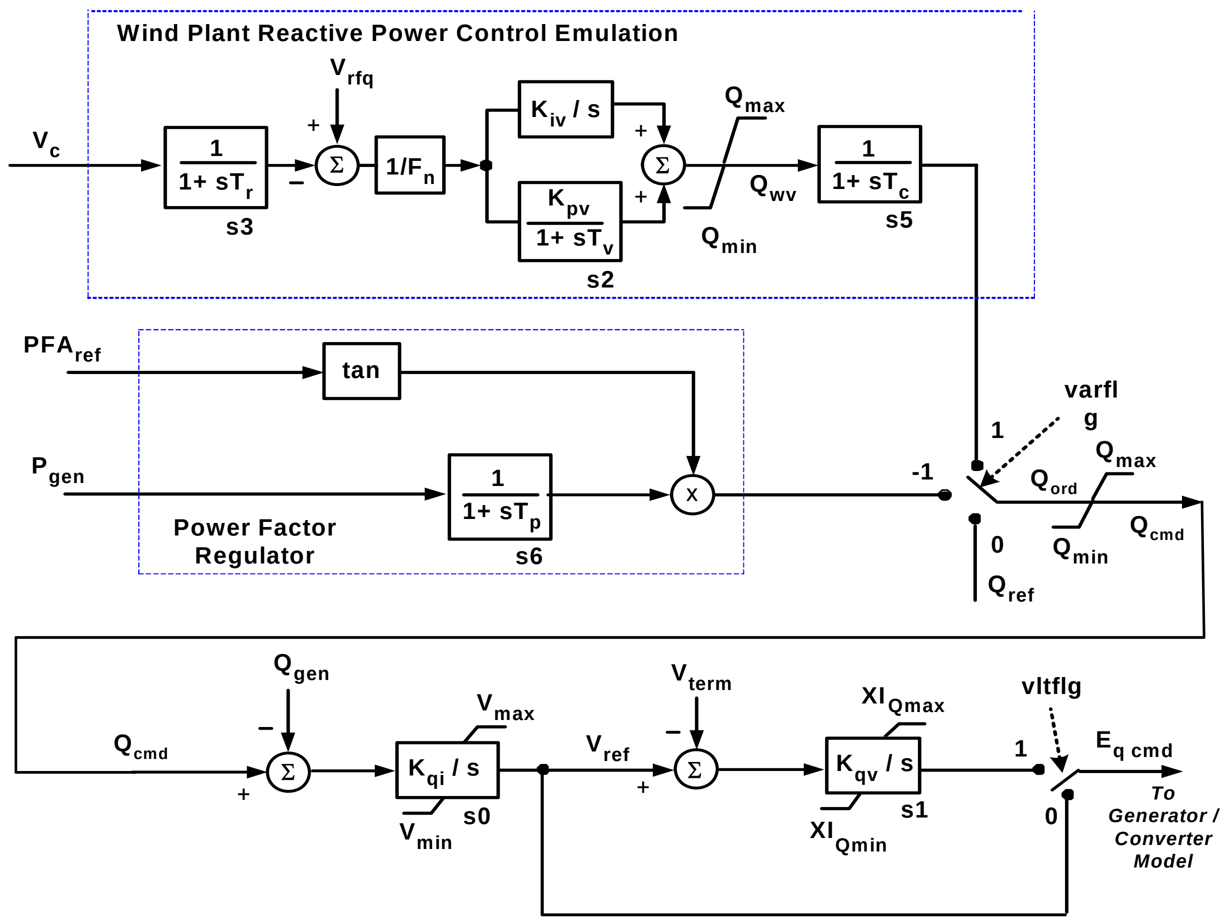


NOTE: P_{set} should normally be 1.0 unless it is controlled by a separate active power control model, e.g. to provide governing response. It must always be greater than or equal to the initial power output of the WTG.

WT3 Generic Model

WT3E

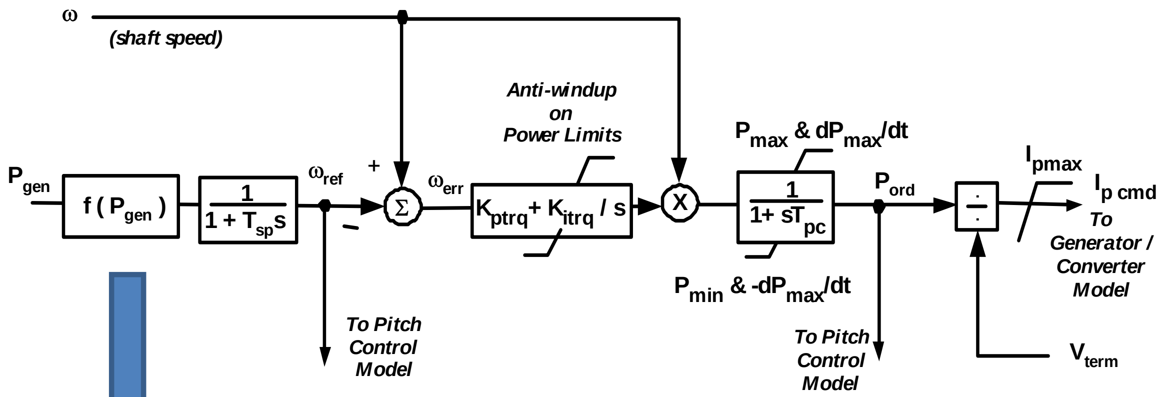
Reactive Power Control Model

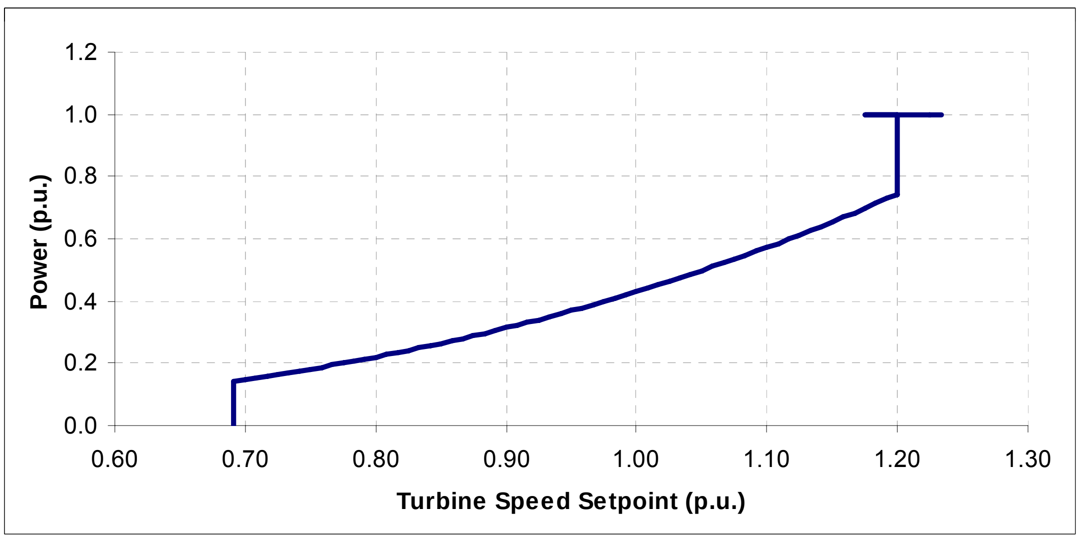


WT3 Generic Model

WT3E

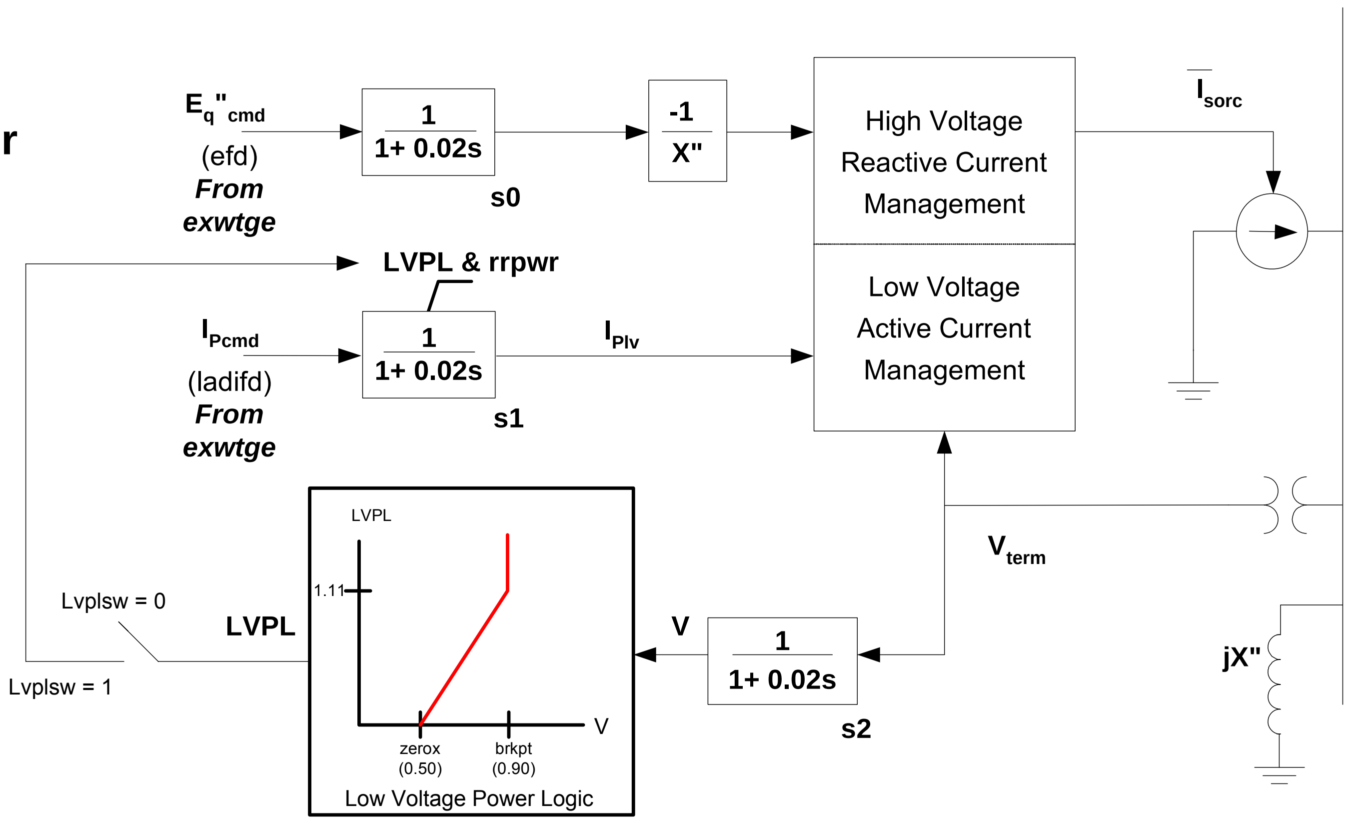
Active Power (Torque) Control Model





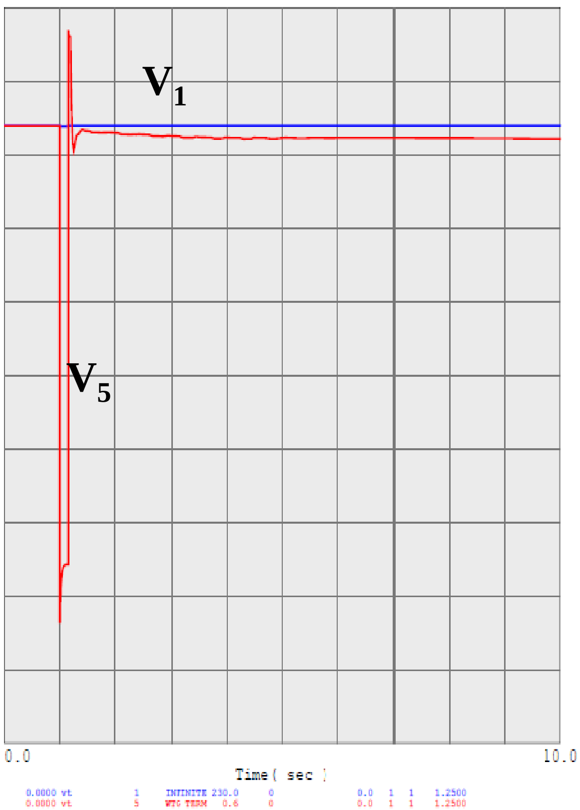
WT3 Generic Model

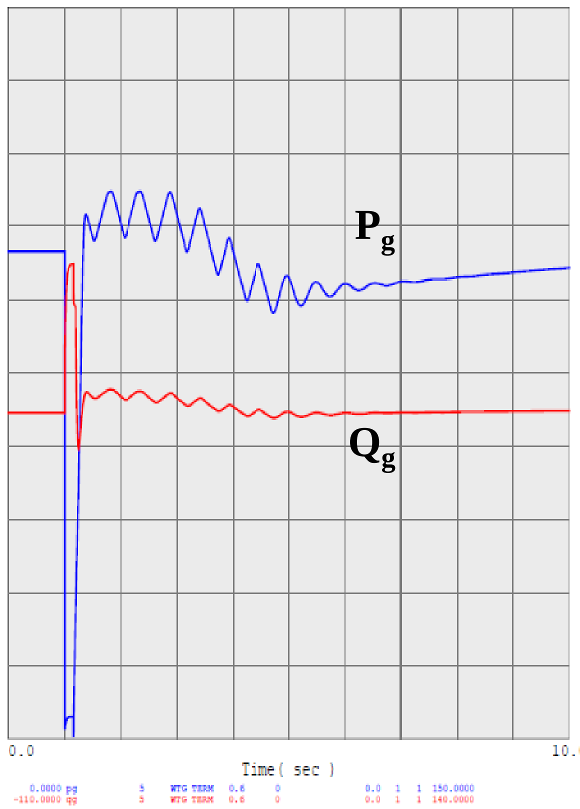
WT3G
Generator / Converter Model

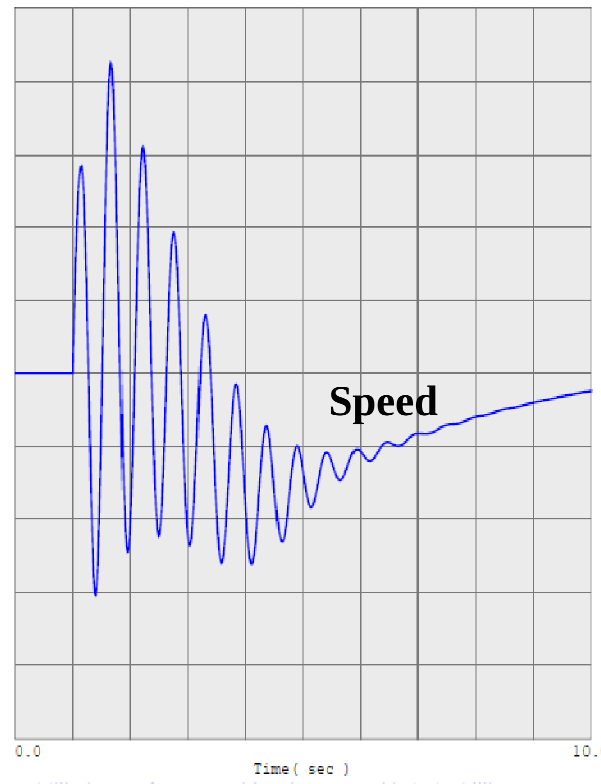


WT3 Fault Test

9-cycle, 3-phase fault at POI, clear fault by tripping line

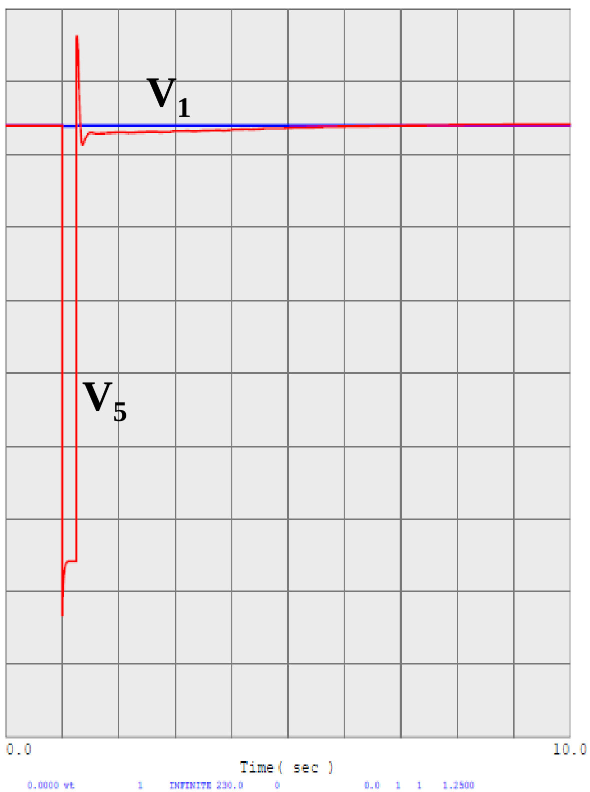


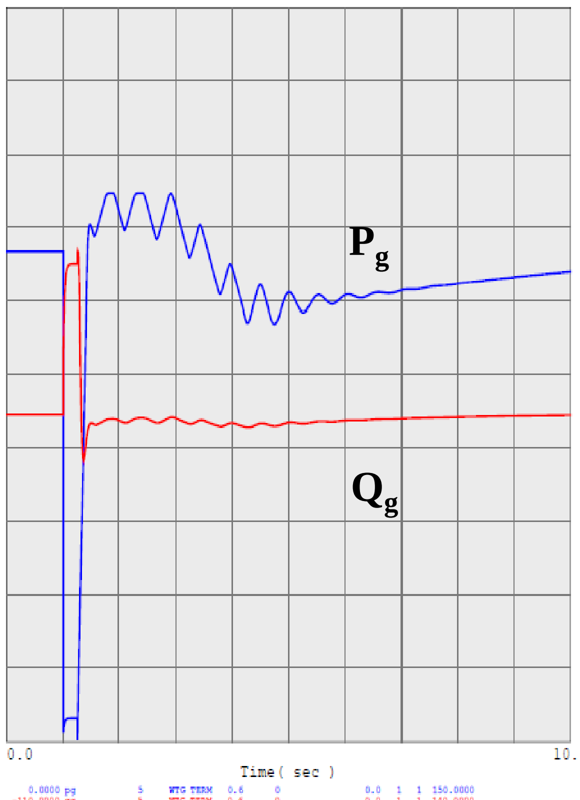


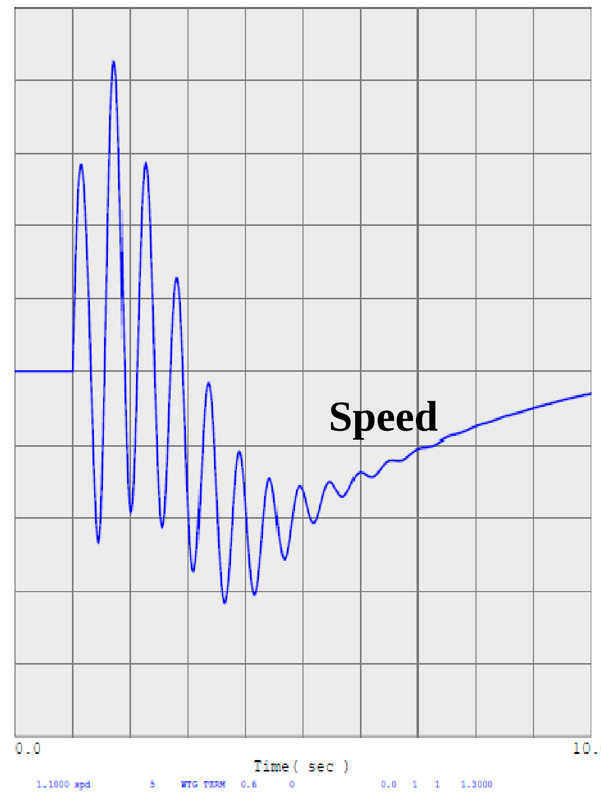


WT3 Fault Test

9-cycle, 3-phase fault at POI, self clearing

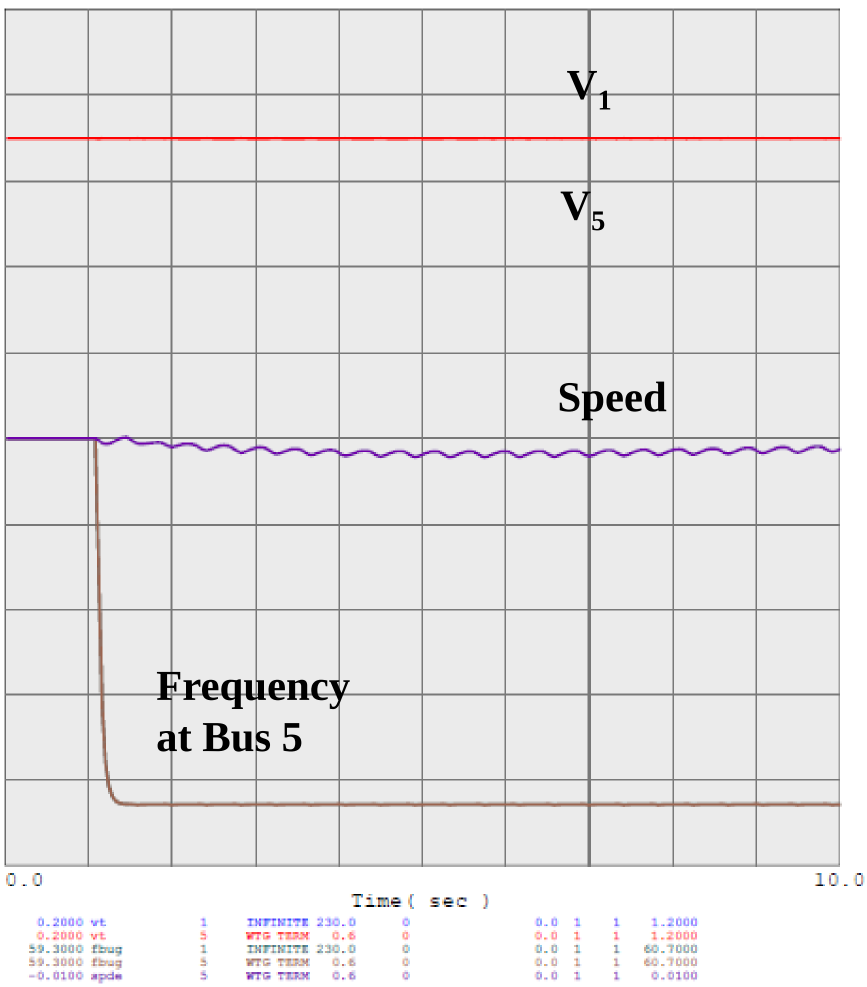


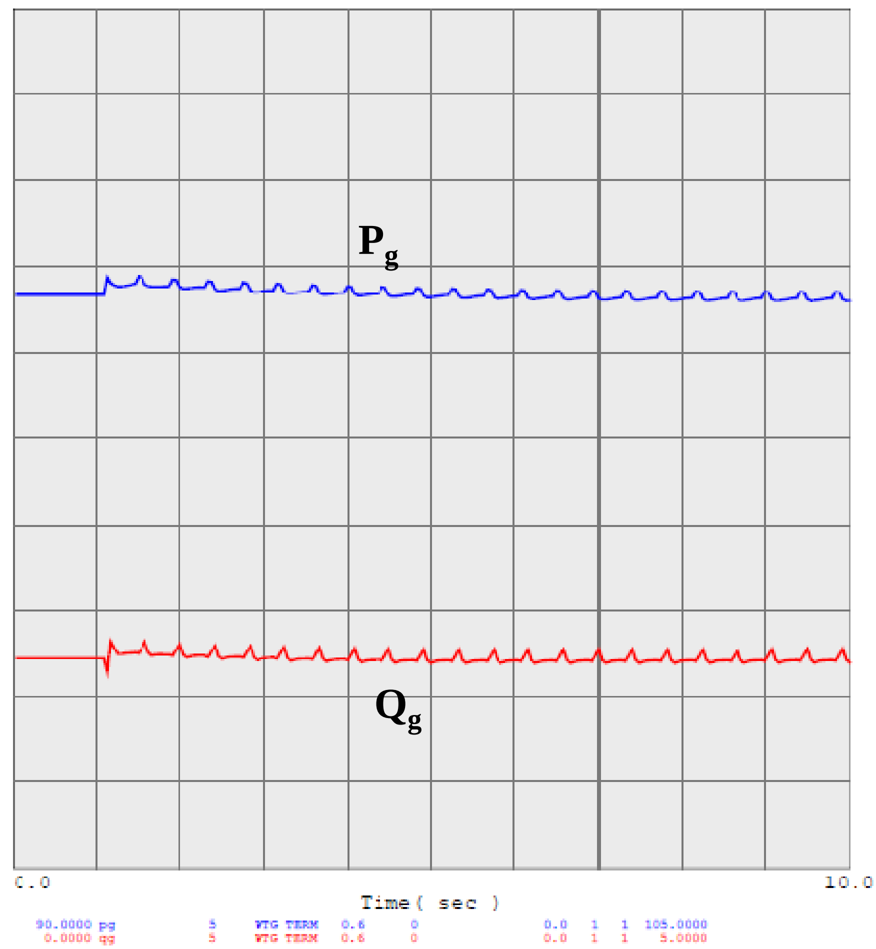




WT3 Frequency Drop Test

1% drop at t = 1 sec

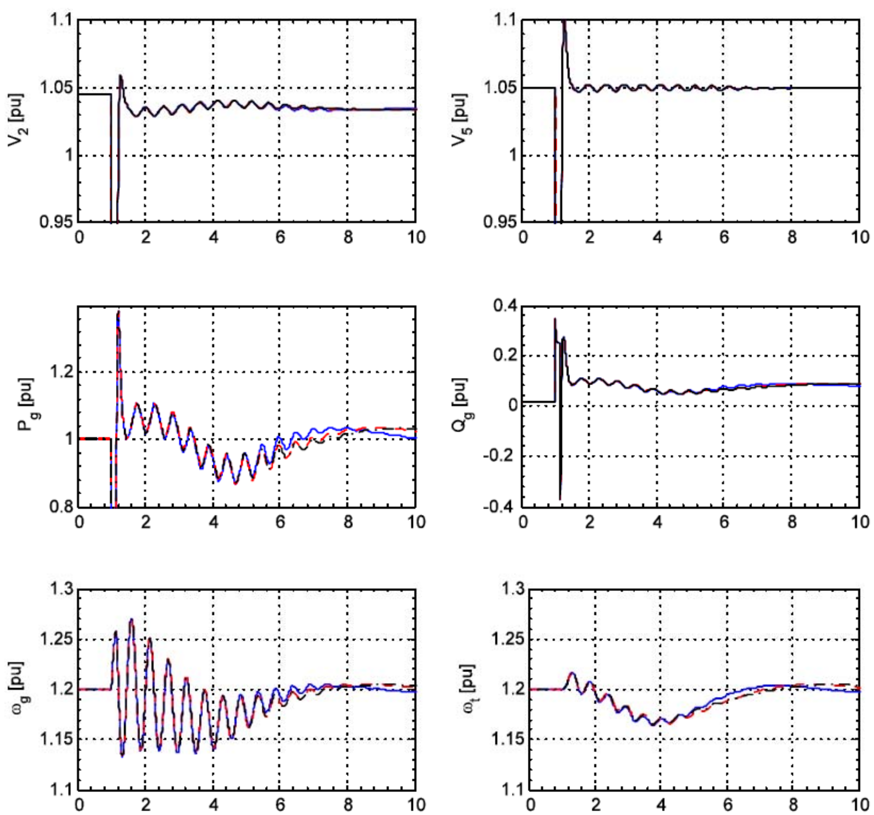




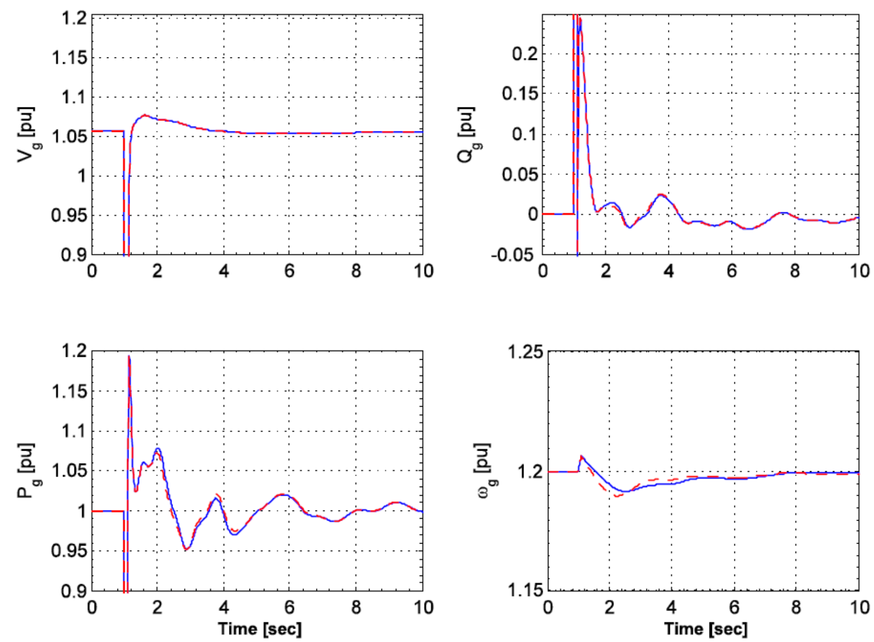
WT3 Model Comparison

Against GE1.5 Manufacturer Model

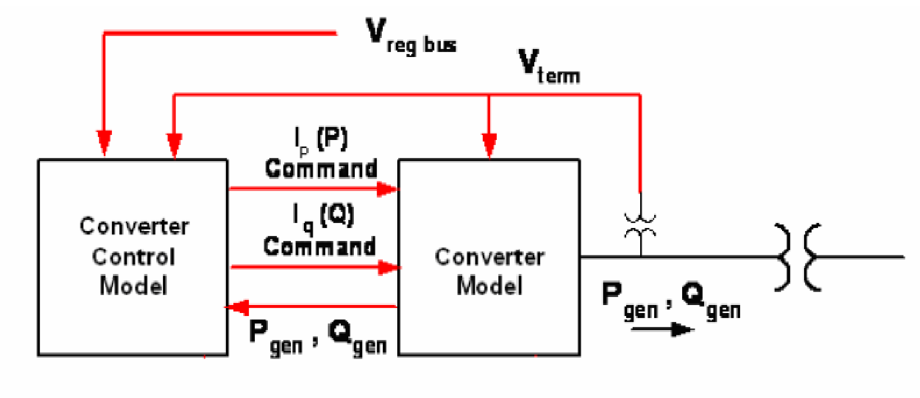
Small System

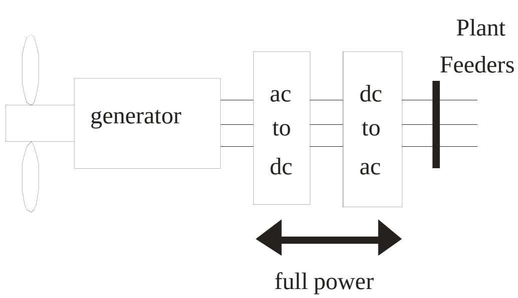


Large System



WT4 Generic Model





Basic Description

Modules: WT4T, WT4E, WT4G

No generator model. Just converter represented as controlled current injection

Default model data provided in documentation (GE 2.x)

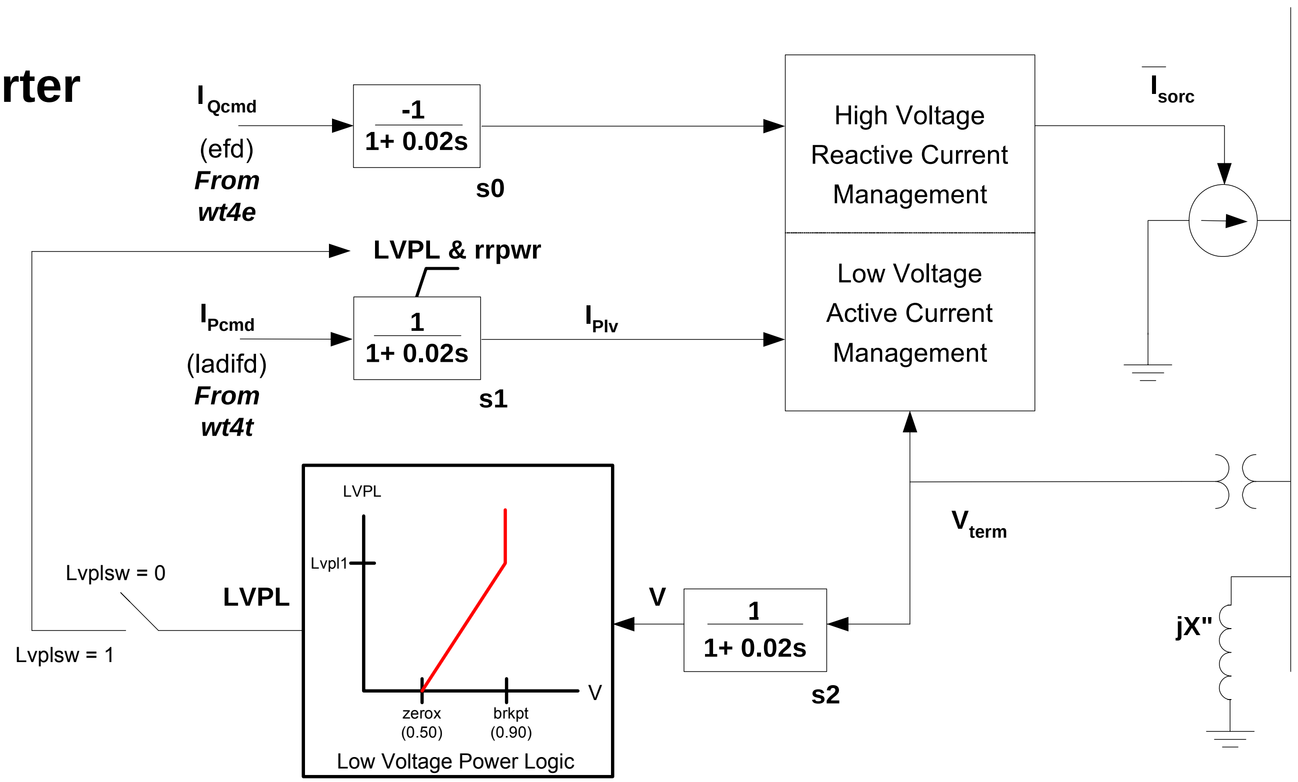
Machine dynamics not modeled (it decoupled from the grid by the converter)

No special initialization or run-time script needed

Plant level reactive control options available for wind farm model (PF control, Q control and voltage control)

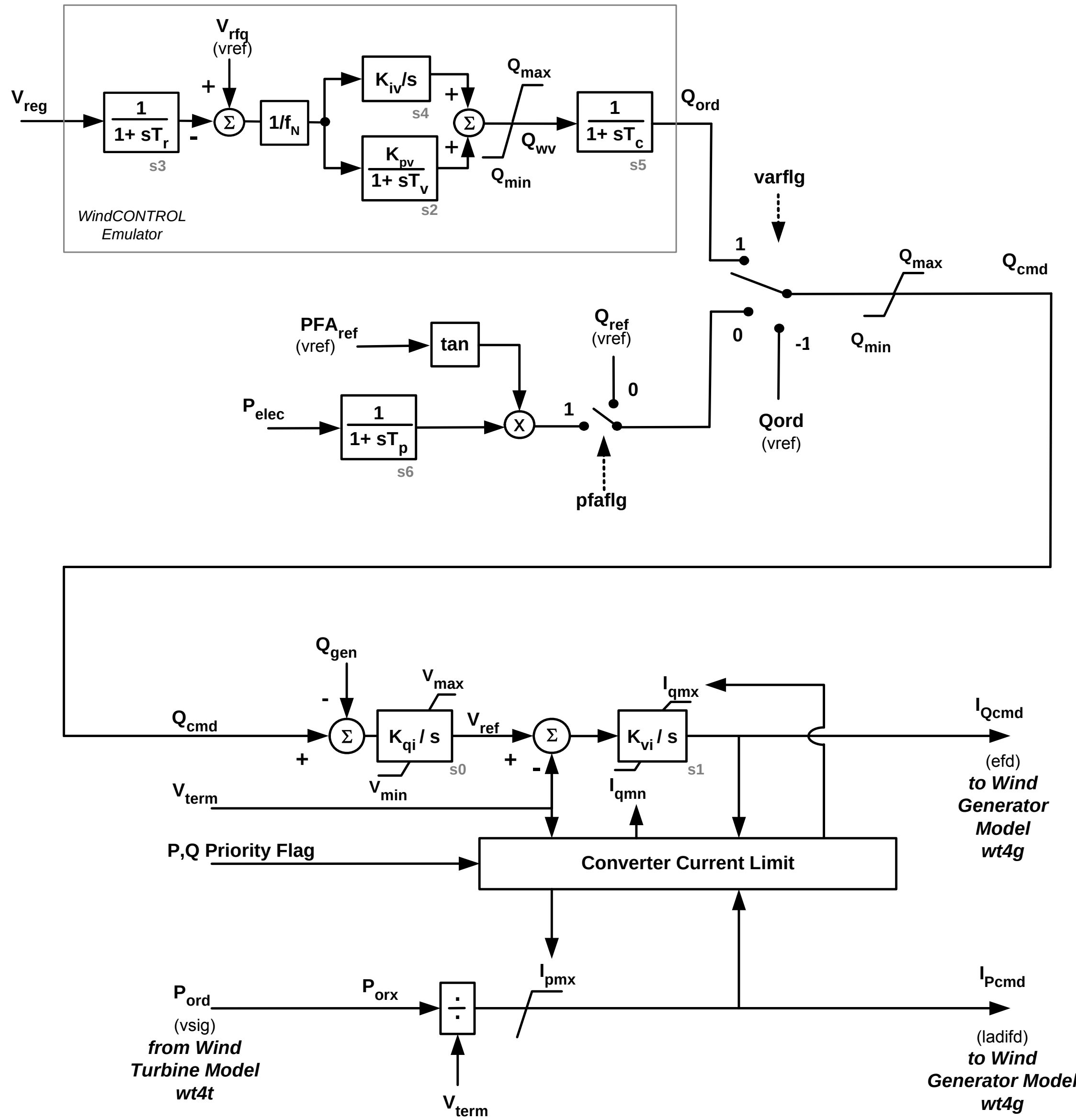
WT4 Generic Model

WT4G Generator/Converter Model



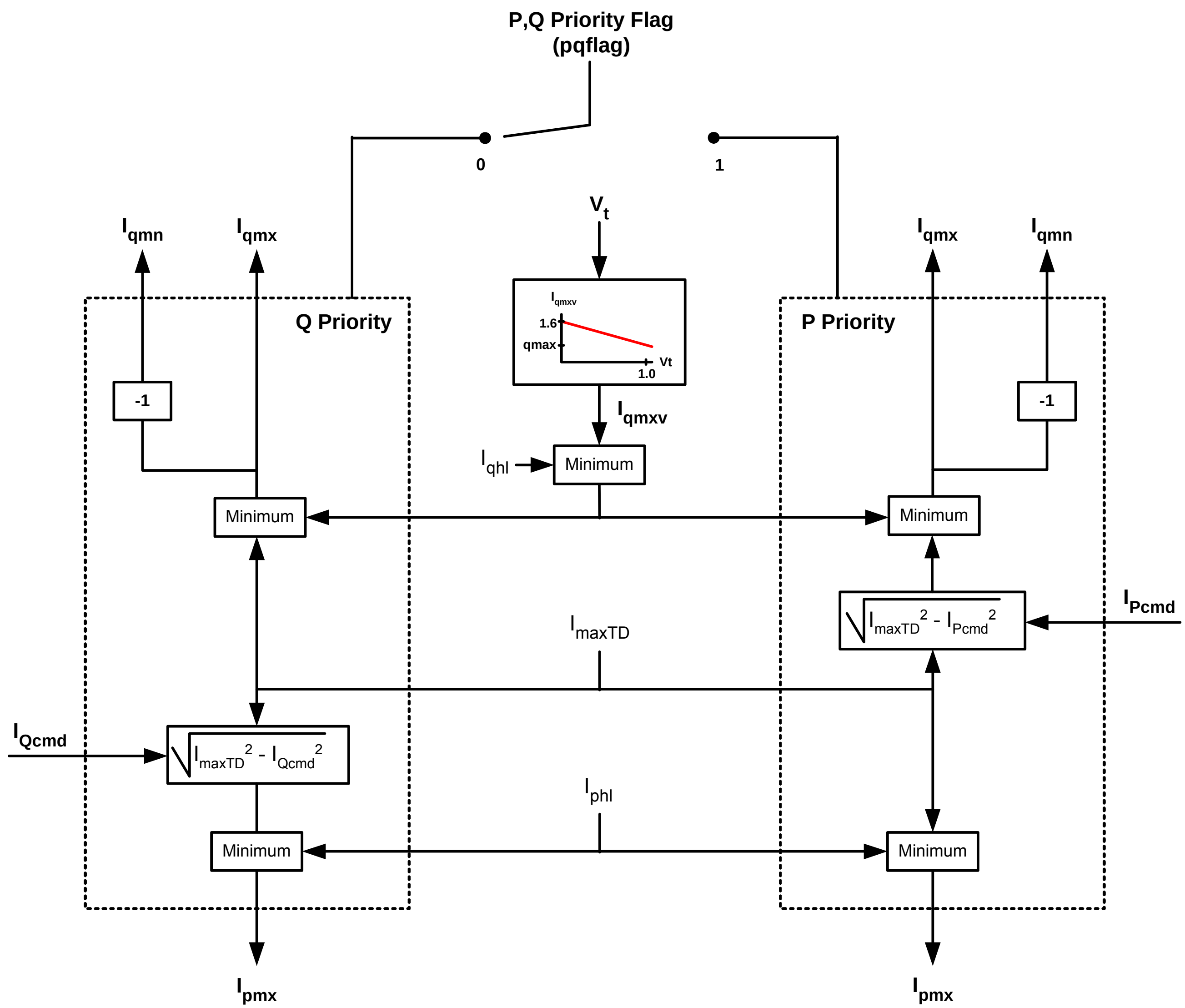
WT4 Generic Model

WT4E
Converter Electrical Control Model



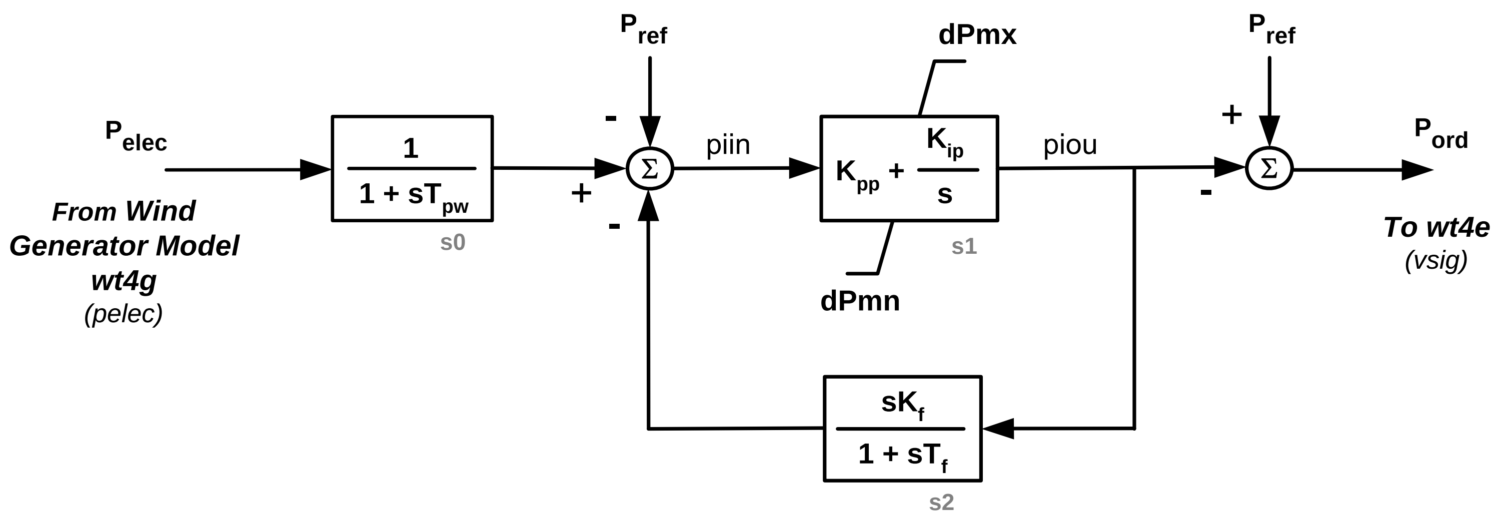
WT4 Generic Model

WT4E
Converter Current Limiter Model



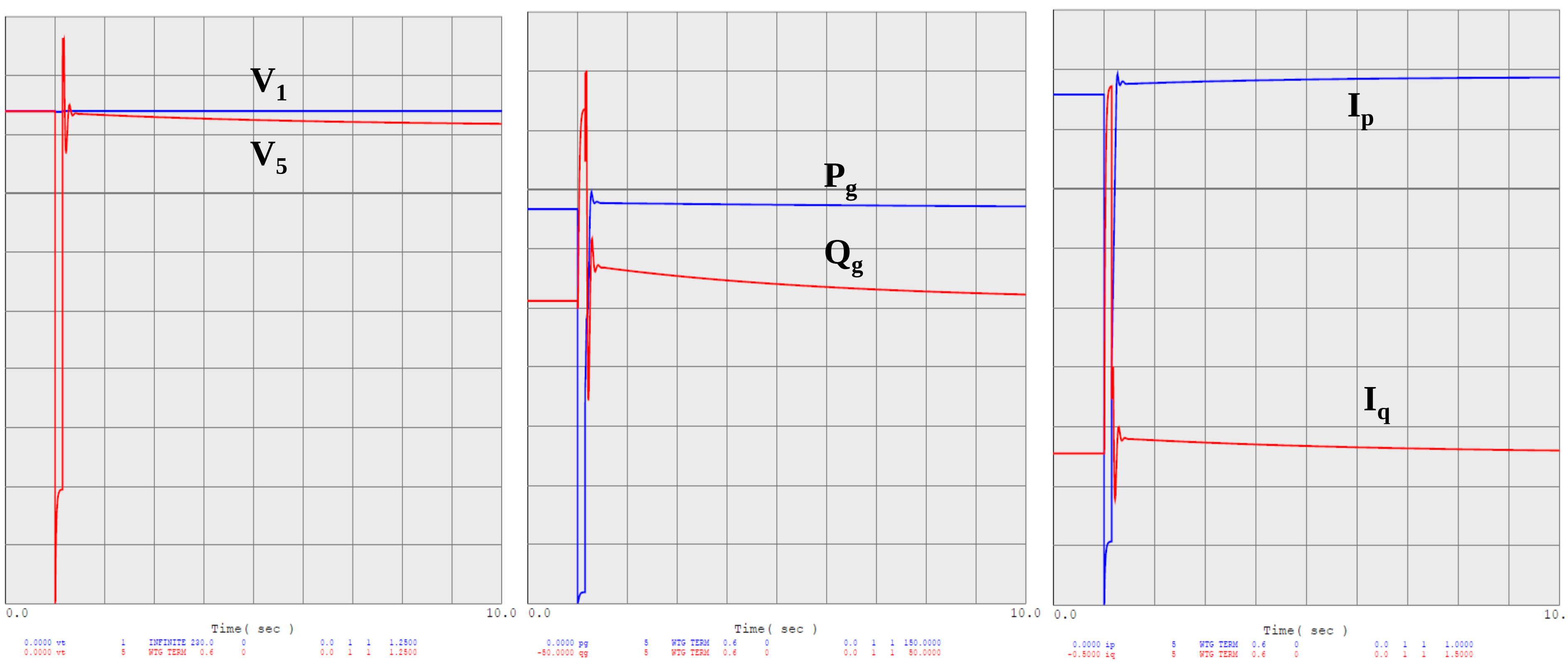
WT4 Generic Model

WT4T
Turbine Model



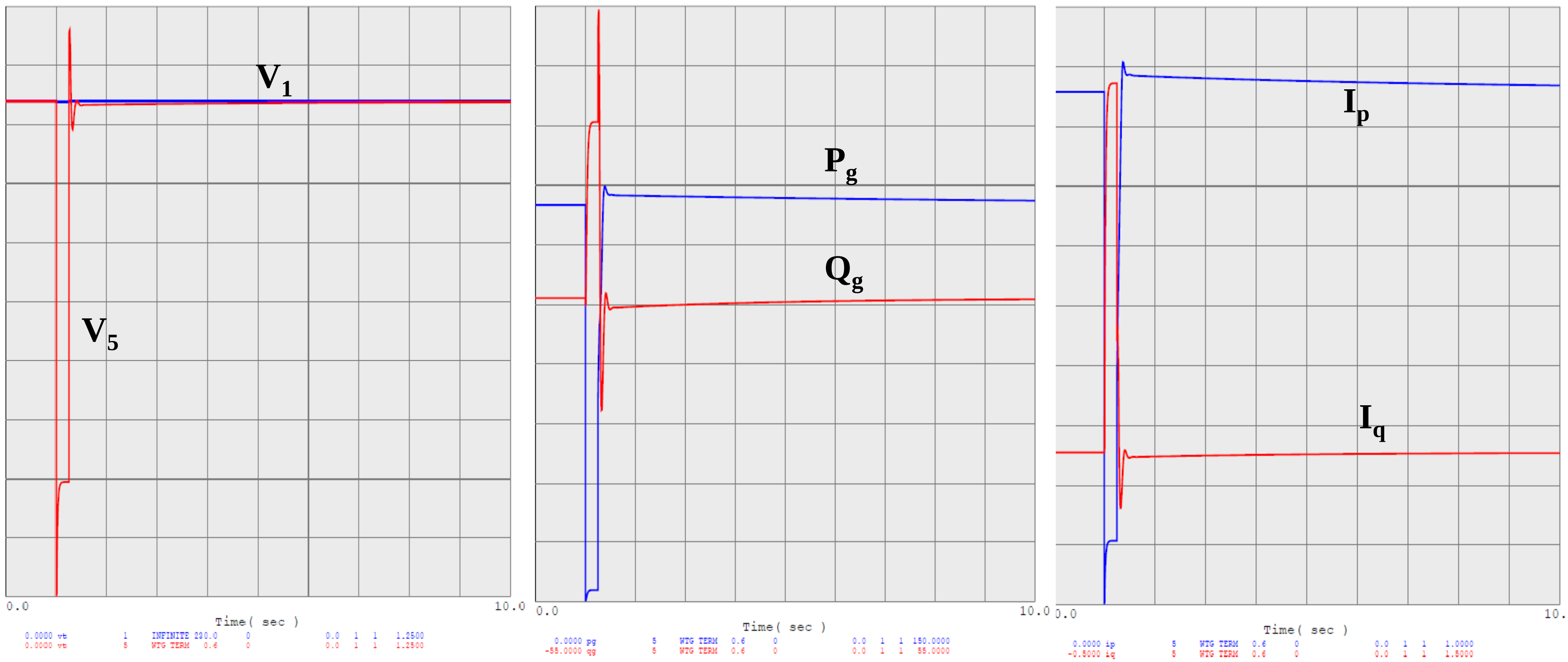
WT4 Fault Test

9-cycle, 3-phase fault at POI, clear fault by tripping line



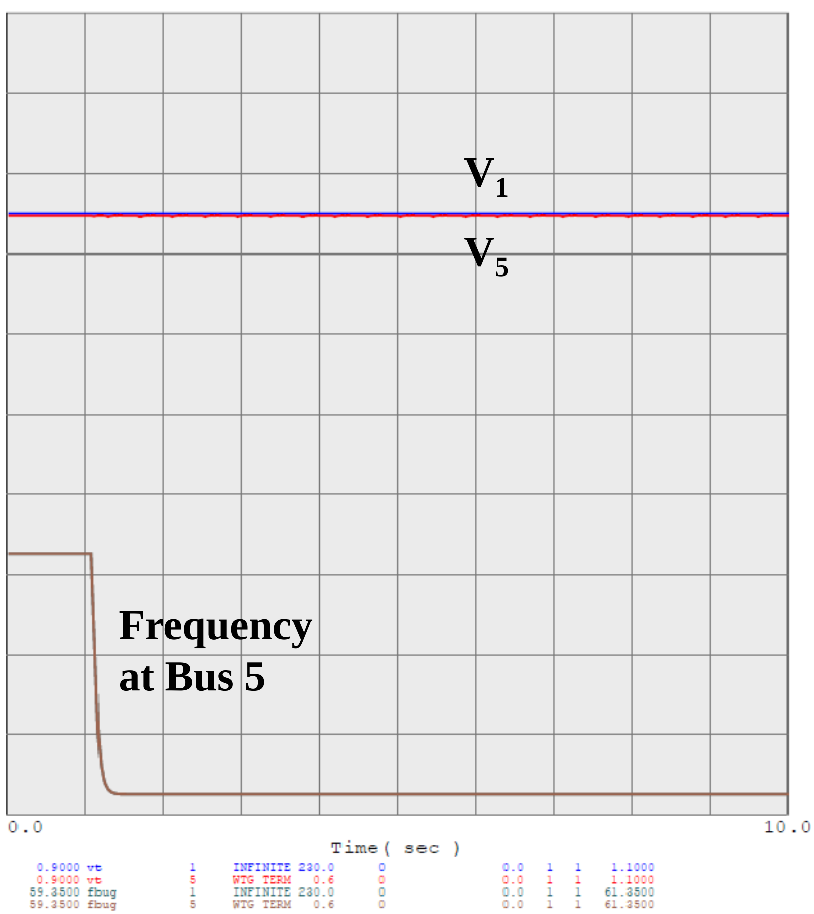
WT4 Fault Test

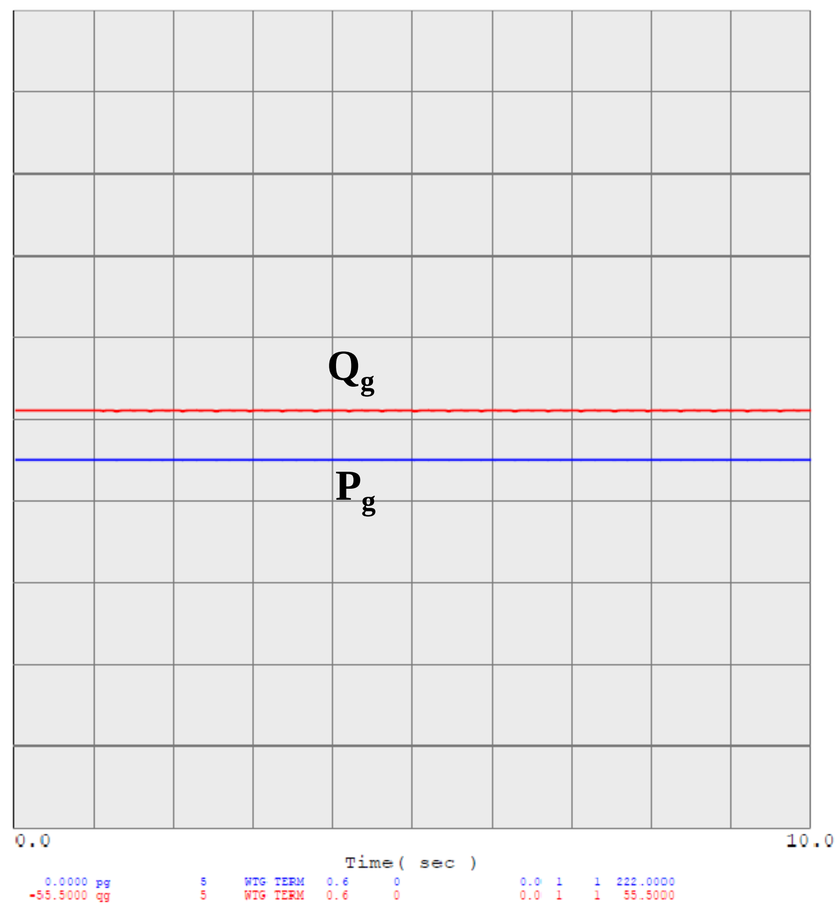
9-cycle, 3-phase fault at POI, clear fault by tripping line



WT4 Frequency Drop Test

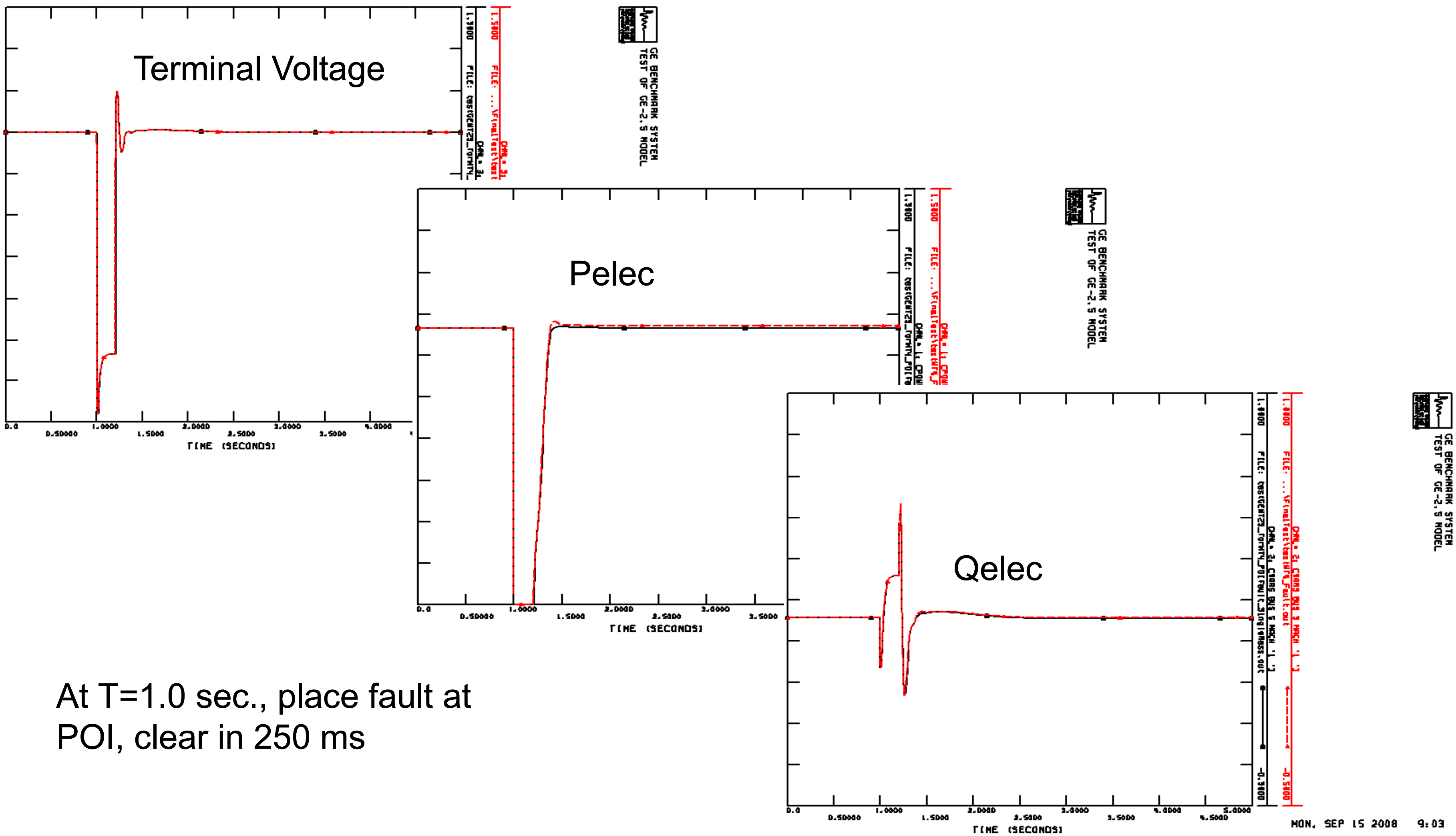
1% drop at t = 1 sec





WT4 Model Comparison

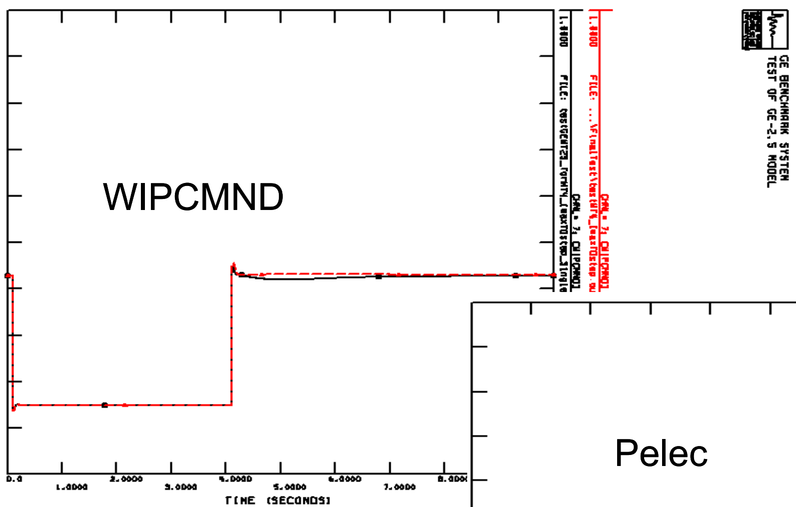
Against GE 2.5 MW Manufacturer Model

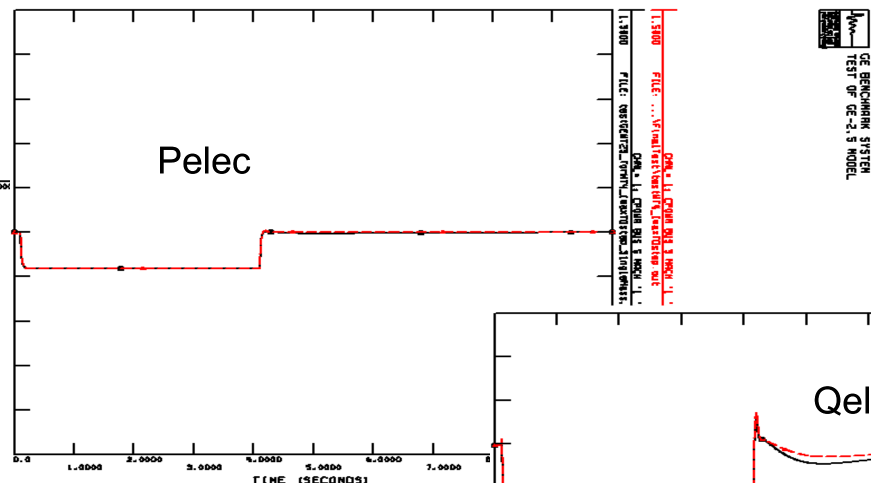


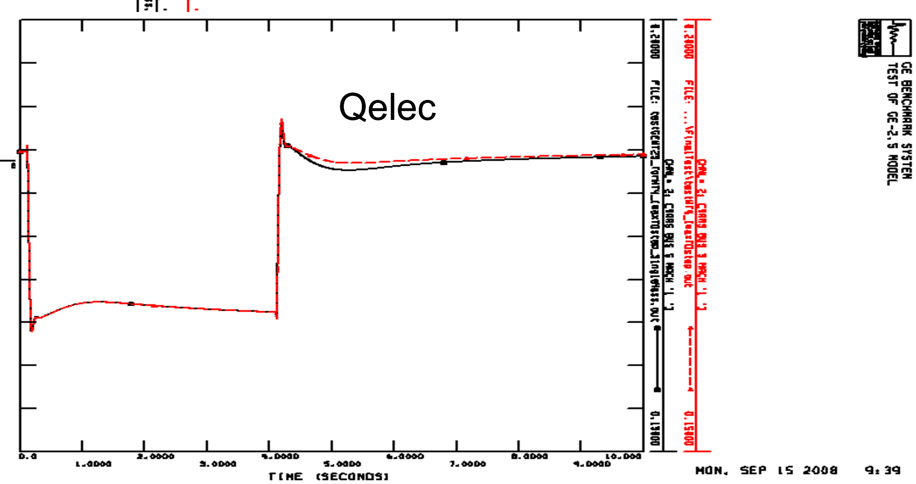
At T=1.0 sec., place fault at POI, clear in 250 ms

WT4 Model Testing

Against GE 2.5 MW Manufacturer Model





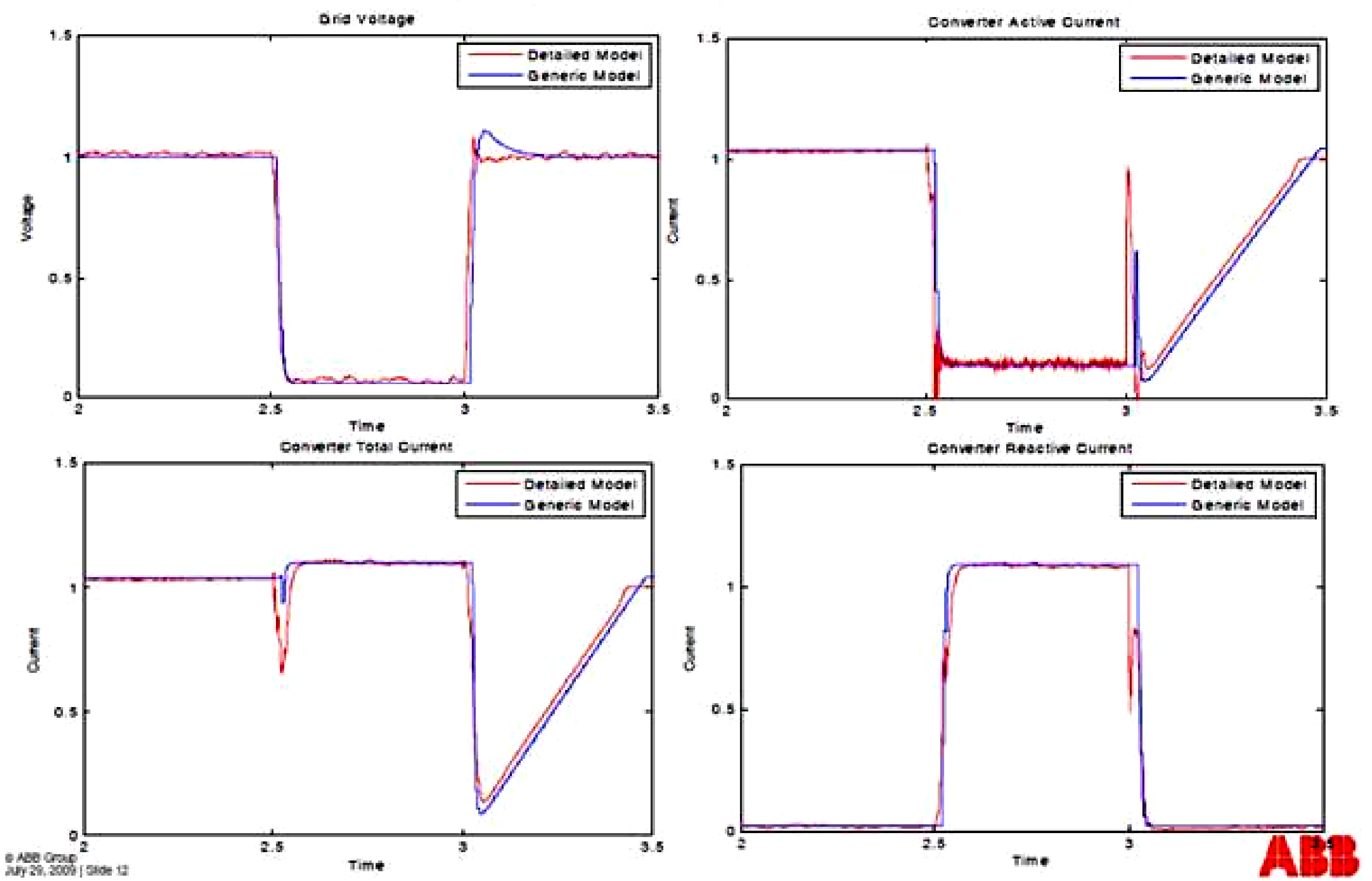


At T=0.1 sec., converter current limit was reduced from 1.7 p.u. to 0.8 p.u. and restored back to 1.7 p.u. at T=4.1 sec.

WT4 Model Verification

Against ABB Converter PSCAD Model

Full-converter WTD under 3-ph dip, Detailed model Ts=0.5 μs, Generic model Ts=5 ms

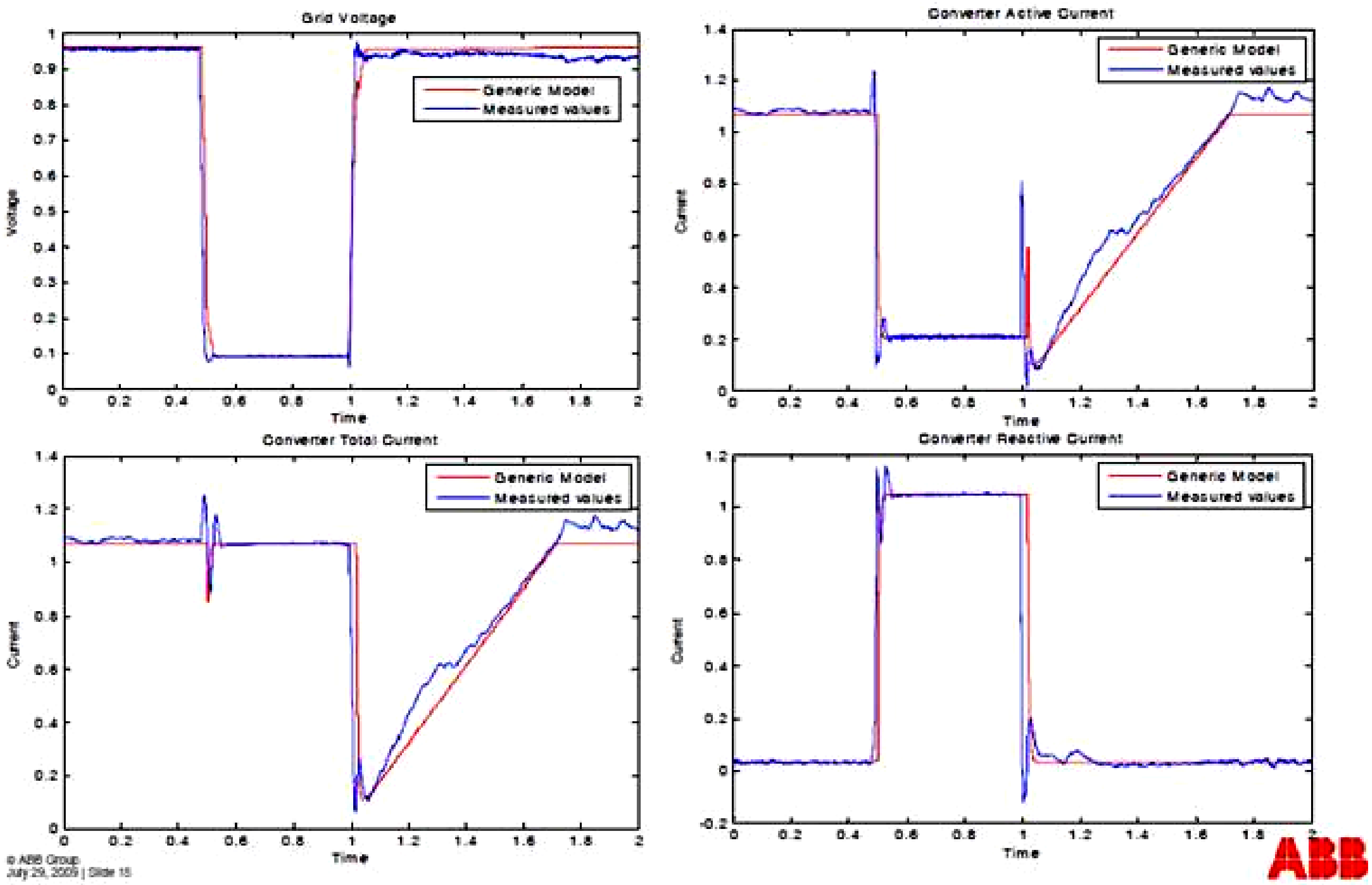


From "WECC - Model Specifications, Validation", presentation by Slavomir Seman, 7/29/09 at the IEEE PES General Meeting, Calgary, Canada.

WT4 Model Verification

Against ABB Converter Full Power Test

Full converter WTD under 3-ph dip , Generic model Ts = 5 ms



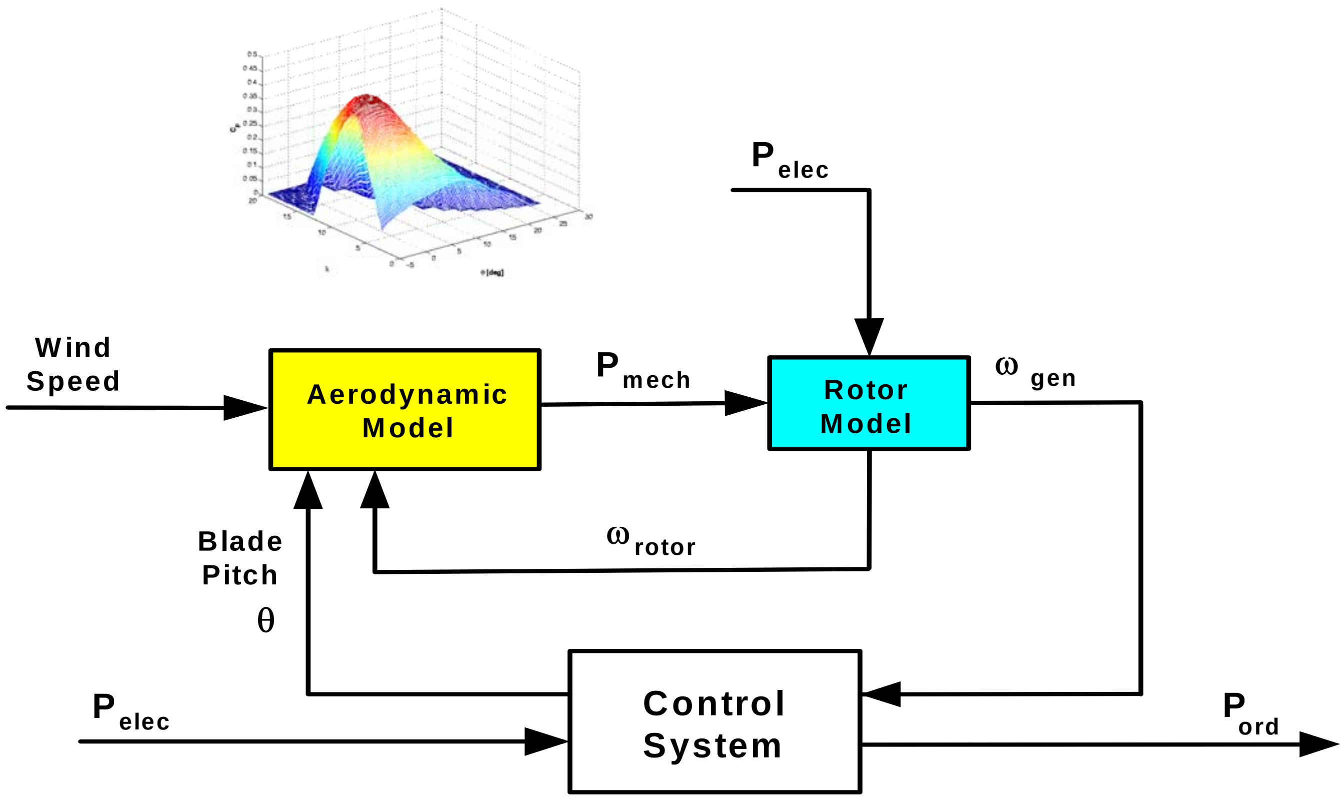
From "WECC - Model Specifications, Validation", presentation by Slavomir Seman, 7/29/09 at the IEEE PES General Meeting, Calgary, Canada.

On Aerodynamic Simplification used in WECC Generic Type 3 model

References:

- W. W. Price, J.J. Sanchez-Gasca, “Simplified Wind Turbine Generator Aerodynamic Models for Transient Stability Studies” Proc. IEEE PES PSCE, Atlanta, Georgia, October-November 2006
- M. Behnke, A. Ellis, Y. Kazachkov, T. McCoy, E. Muljadi, W. Price, J. Sanchez-Gasca, “Development and Validation of WECC Variable Speed Wind Turbine Dynamic Models for Grid Integration Studies”, AWEA WindPower, Los Angeles, California, June 2007

Aerodynamic Conversion



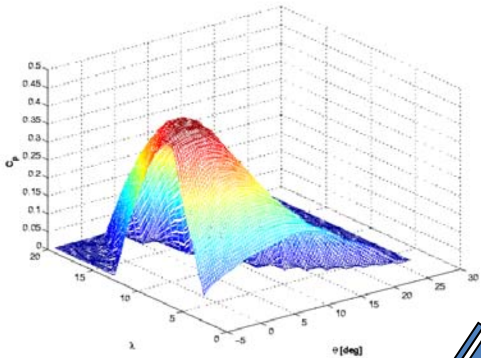
$$P_{mech} = \frac{\rho}{2} A_r v^3 C_p(\lambda, \theta)$$

Aerodynamic Simplification

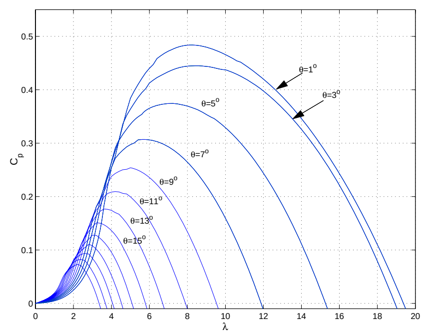
- Assume wind speed is constant for the duration of the typical period of interest in dynamic simulations (up to about 20 seconds)
- For variable speed Type 3 it was noticed that
  - Rate of change of mechanical power (P_{mech}) varies linearly with respect to pitch angle (θ) in the range $0 < \theta < 30$ deg
  - P_{mech} varies linearly with respect to wind speed (V_w) from cut-in to rated wind speed
  - θ varies linearly with respect to V_w for wind speeds above rated

Aerodynamic Model Simplification

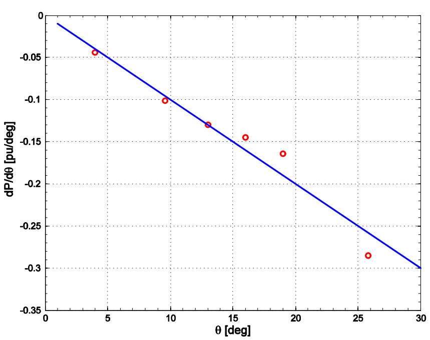
Detailed 3-D Cp Curve.



2-D Cp Curve used in detailed models



Linear relations allow for simplifications



Example for GE 1.5 WTG

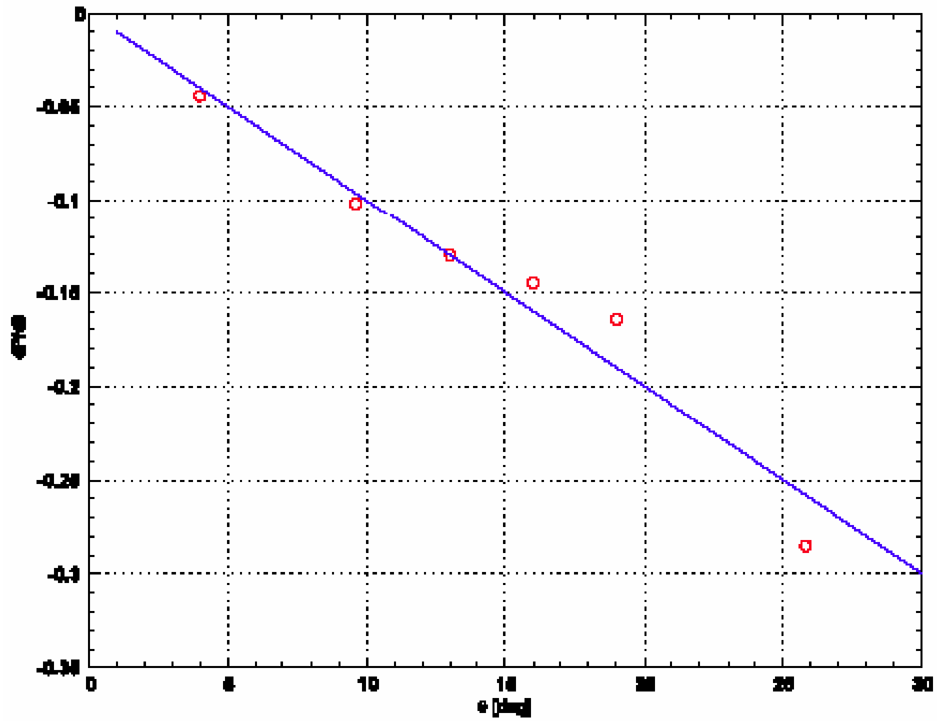


Figure 7. Rate of Change in Mechanical Power vs. Pitch Angle

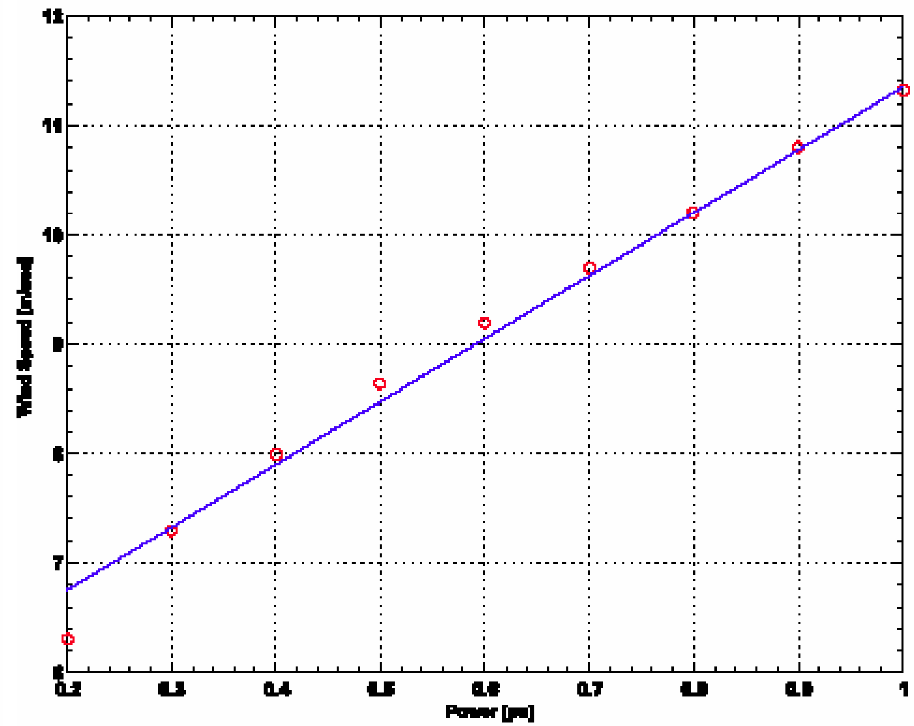


Figure 8. Wind Speed vs. Mechanical Power
Solid Line: Linear Fit Vw = 5.75*Pmech + 5.60

Example for GE 1.5 WTG

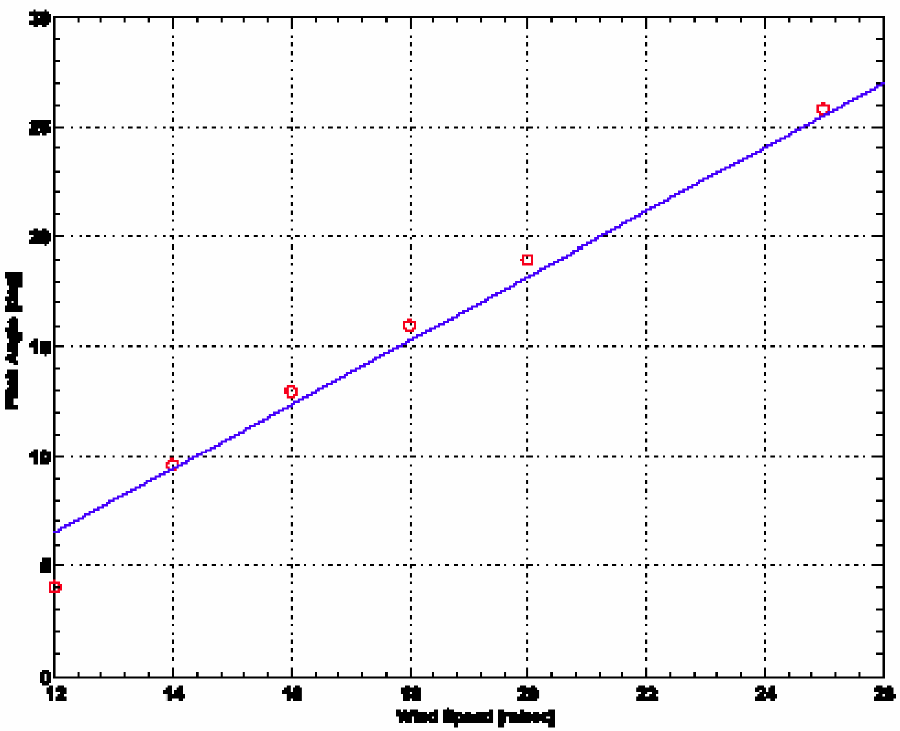


Figure 9. Pitch Angle vs. Wind Speed
*Solid Line: Linear Fit θ = 1.46*Vw – 11.0*

"Aerodynamic governor" model

$$Pm = Pm_o - \theta(\theta - \theta_o) / 100$$

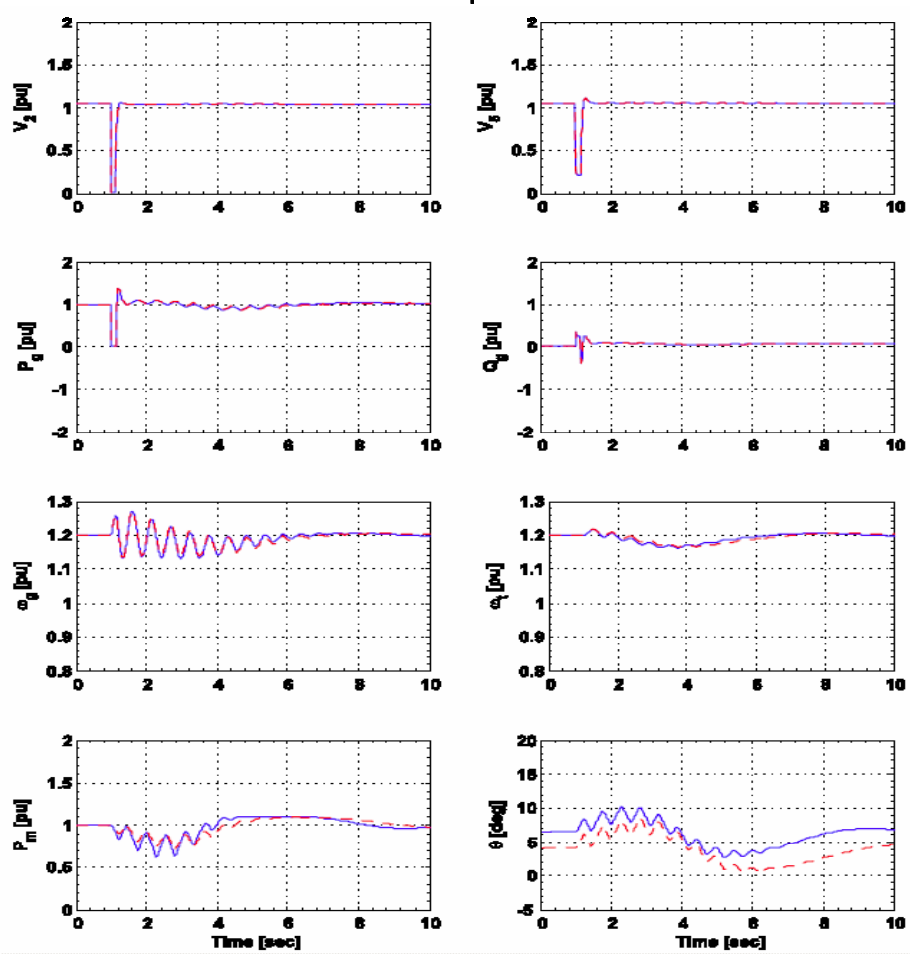
Initialization:

- Pm_o = *Pelec* (from power flow)
- Use Fig. 8 to find *Vw* for $\theta_o = 0$
- Use Fig. 9 to compute θ_o if
  Pe = Prated and user-input
  Vw is greater than rated wind speed

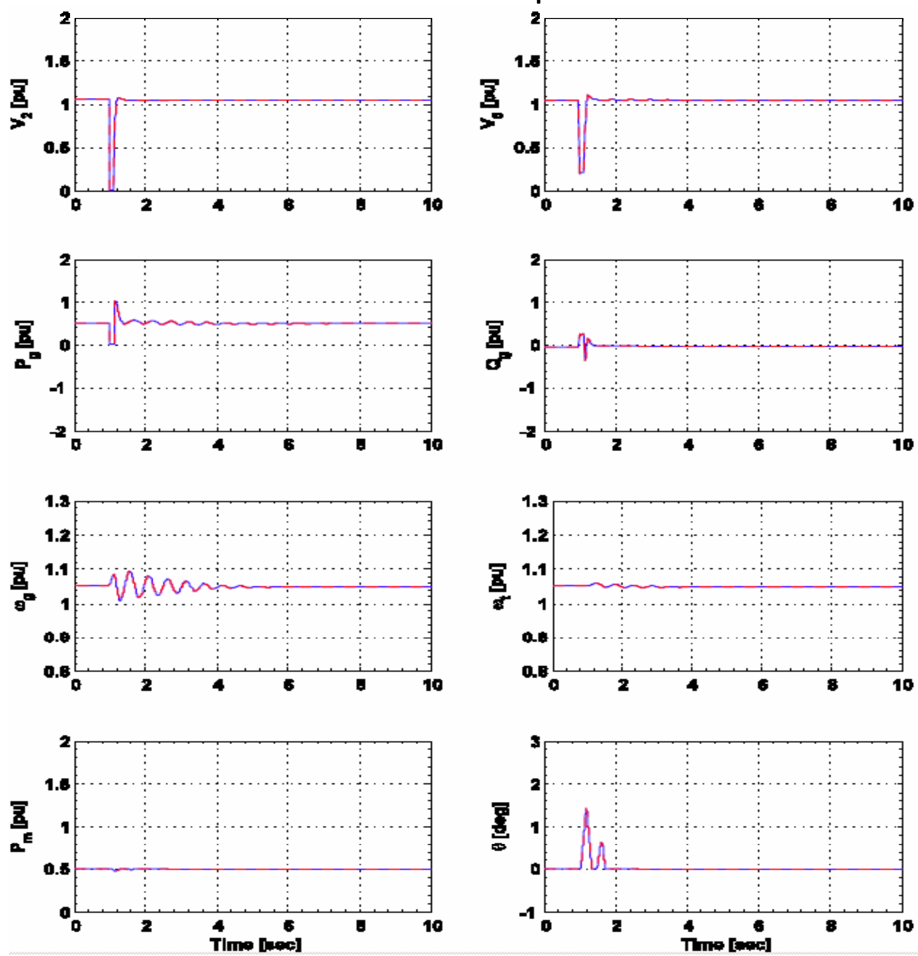
Testing of Aerodynamic Simplification

Against GE1.5 Manufacturer Model

At rated output



At 50% output



Blue = manufacturer standard model, Red = WECC WT3 generic model

On Identification of WTG Model Parameters and Model Validation Efforts

Efforts Underway in North America

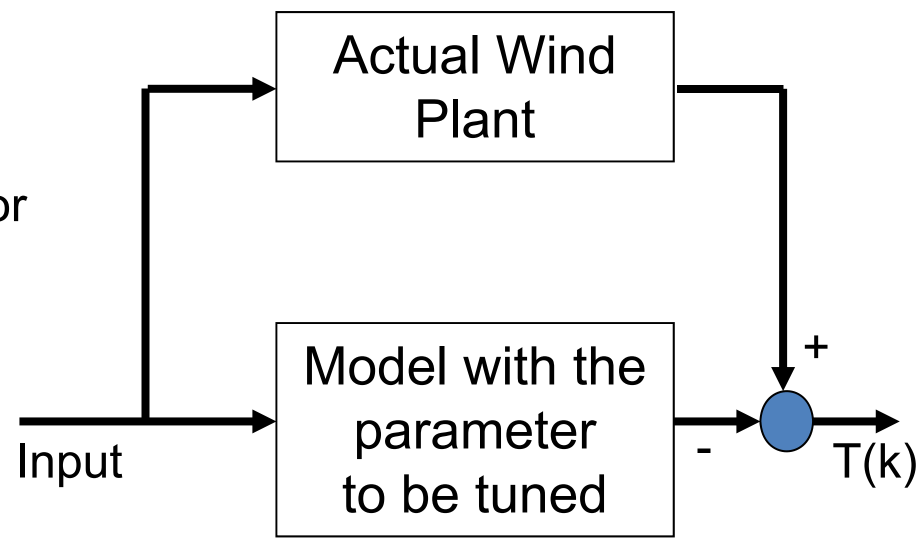
- NREL Model Parameter Identification Project
  - Tune parameters to match performance of manufacturer models) using parameter trajectory sensitivity approach
  - Parameters to be published in WECC WGMG guide
- IEEE DPWPGMG
  - Collaboration with several WTG manufacturers and industry stakeholders in the US and Europe
  - Develop specifications and test systems for model validation (underway)
- UWIG/EnerNex
  - Document generic model validation against measurements
- Hydro Quebec
  - Has done some work in this area
- PSLF and PSSE software developers and consultants

Parameter Sensitivity Approach

- The output of the simulation and the measured data can be used to find the total error of the measurement.

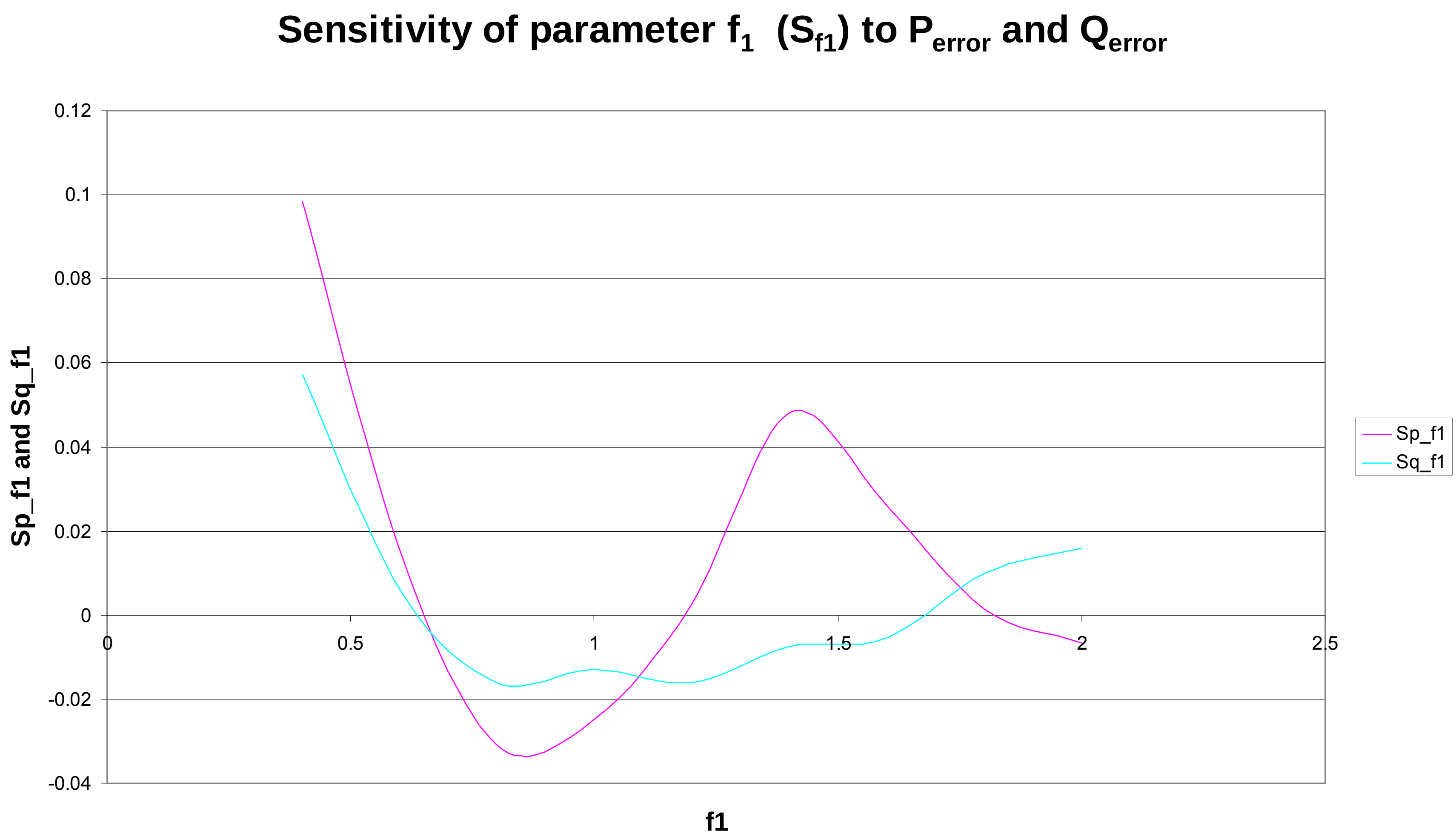
$$S_k^{T(k)} := \frac{dT(k)}{dk} \cdot \frac{k}{T(k)}$$

- $P_{err} = |P_{meas.} - P_{simulated}|$
- $Q_{err} = |Q_{meas.} - Q_{simulated}|$
- The error and the sensitivity parameter k1 with respect to the error can be computed.
- Use the other parameters k1, k2, k3, k4 etc
- The parameter sensitivity can be observed from the results.
- The trend can be used to drive the changes of the parameters.



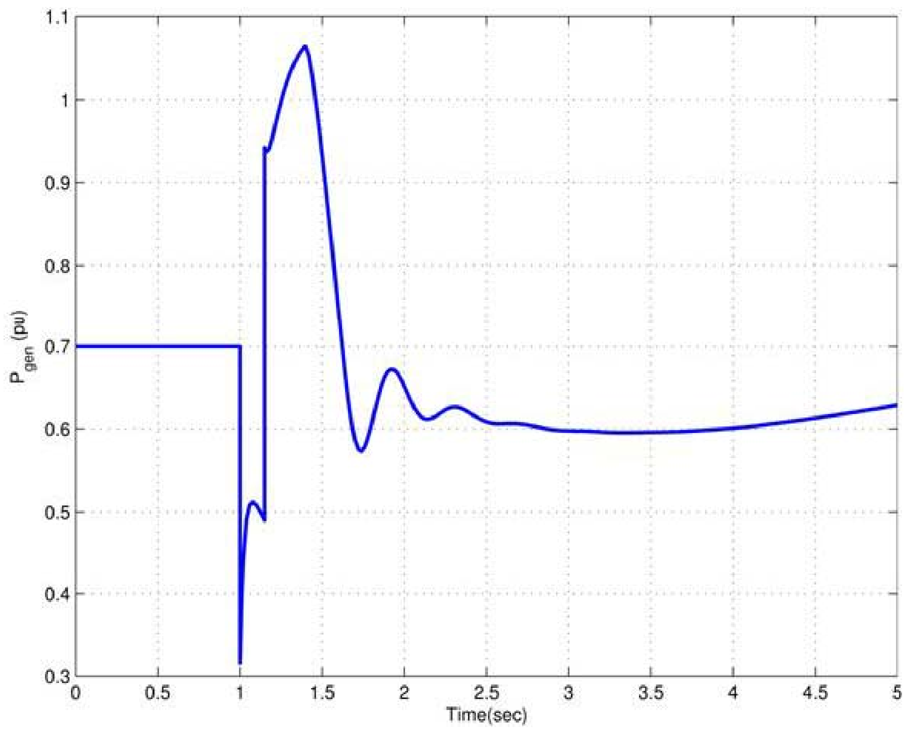
Parameter k

Parameter Sensitivity Approach

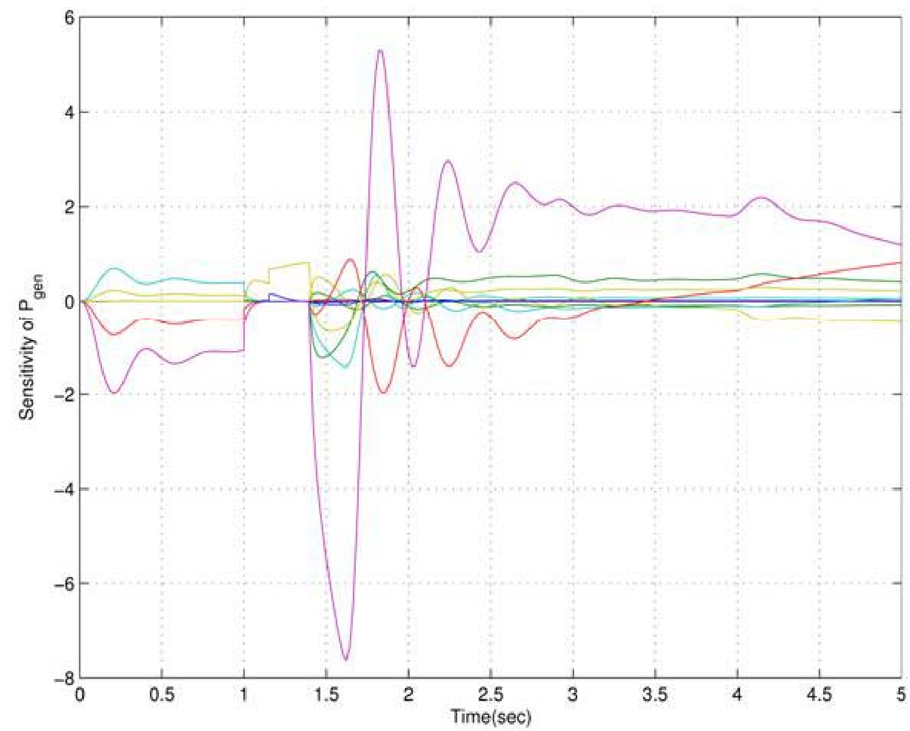


Parameter Sensitivity Approach

Example for WECC WT3 Generic Model



Response of P output



Sensitivity of P output to a range of parameters

- Qualitatively similar results for other outputs.
- Note that a lot of parameters have small and/or correlated influence.
- Sensitivities obtained as a by-product of running the simulation.

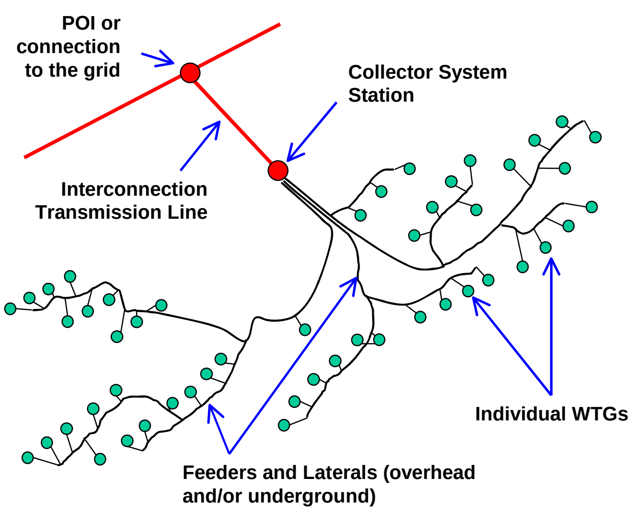
On Representation of Wind Farms With WECC Generic WTG Models

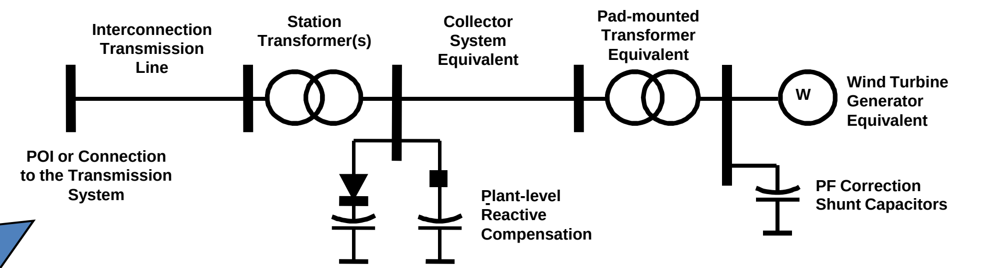
References:

- E. Muljadi, C.P. Butterfield, B. Parsons, A. Ellis, ”Characteristics of Variable Speed Wind Turbines Under Normal and Fault Conditions”, IEEE PES GM, Tampa, Florida, June 2007.
- J. Brochu, R. Gagnon, C. Larose, “Validation of the WECC Single-Machine Equivalent Power Plant”, Presented at the IEEE PSCE DPWPG-WG Meeting, Seattle, Washington, March 2009.
- WECC Wind Generation Power Flow Modeling Guide

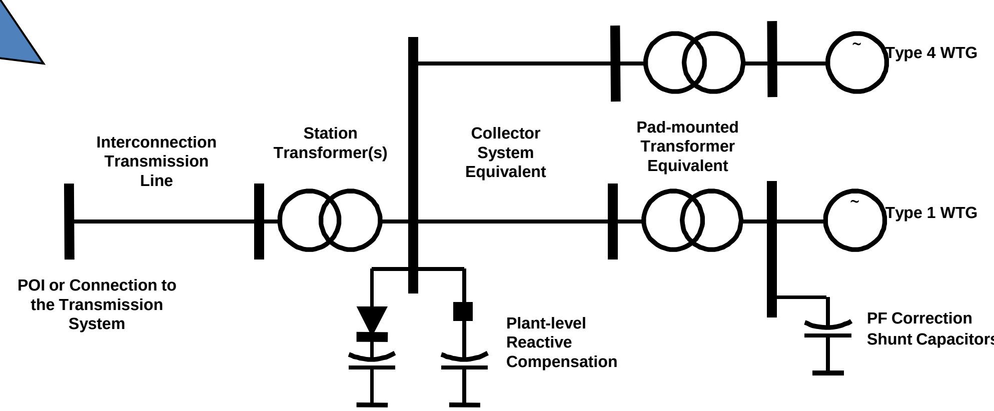
Wind Power Plant Representation

- WECC WGMG recommendation is to use a single-machine equivalent for power flow and dynamic representation of Wind Power Plants





…or in special cases (e.g., heterogeneous feeders or WTGs of different types)…



Equivalent Collector System

- Depends on feeder type (OH/UG) and WPP size
- Z_{eq} and B_{eq}, can be computed from WPP conductor schedule, if available
  - For radial feeders with N WTGs and I branches:

$$Z_{eq} = R_{eq} + jX_{eq} = \frac{\sum_{i=1}^{I} Z_i n_i^2}{N^2} \qquad B_{eq} = \sum_{i=1}^{I} B_i$$

  - Where n_i is the number of WTGs connected upstream of the $i\text{-}th$ branch
  - This can be implemented easily on a spreadsheet

Equivalent Collector System

- Example with $N=18$ and $I=21$:

From	To	R	X	B	n	$R\,n^2$	$X\,n^2$
1	2	0.0035	0.0263	0.0000	1	0.0035	0.0263
2	3	0.0018	0.0254	0.0013	2	0.0071	0.1015
3	4	0.0080	0.0226	0.0008	3	0.0722	0.2030
4	5	0.0023	0.0193	0.0005	4	0.0364	0.3080
5	51	0.0074	0.0248	0.0000	5	0.1861	0.6200
6	7	0.0031	0.0171	0.0014	1	0.0031	0.0171
7	8	0.0061	0.0143	0.0015	2	0.0244	0.0572
8	9	0.0069	0.0107	0.0004	3	0.0617	0.0965
9	51	0.0070	0.0033	0.0004	4	0.1113	0.0525
10	11	0.0078	0.0371	0.0003	1	0.0078	0.0371
11	12	0.0001	0.0005	0.0004	2	0.0005	0.0021
12	52	0.0083	0.0259	0.0004	3	0.0747	0.2330
13	14	0.0049	0.0349	0.0004	1	0.0049	0.0349
14	15	0.0041	0.0483	0.0008	2	0.0163	0.1931
15	16	0.0059	0.0116	0.0002	3	0.0528	0.1040
16	17	0.0079	0.0002	0.0003	4	0.1262	0.0029
17	18	0.0089	0.0146	0.0007	5	0.2224	0.3656
18	53	0.0018	0.0342	0.0008	6	0.0664	1.2302
51	52	0.0074	0.0034	0.0011	9	0.5957	0.2778
52	POI	0.0049	0.0456	0.0002	12	0.7102	6.5633
53	POI	0.0003	0.0338	0.0012	6	0.0125	1.2177
				0.0132		**2.3962**	**11.7438**
						0.0074	**0.0362**

Partial sum

Partial sum divided by total number of WTG (18 in this case) squared

Sum = B_{EQ}

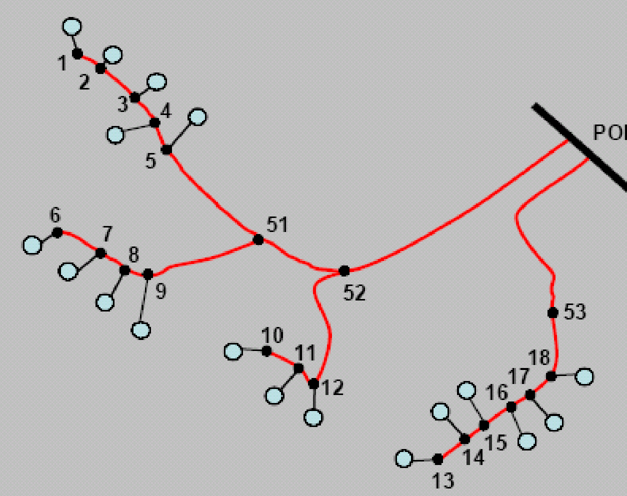
R_{EQ}

X_{EQ}

NOTES:

Branch R, X and B parameters are random numbers in this example.

Parameters should be in per-unit at 100 MVA and collector system kV.



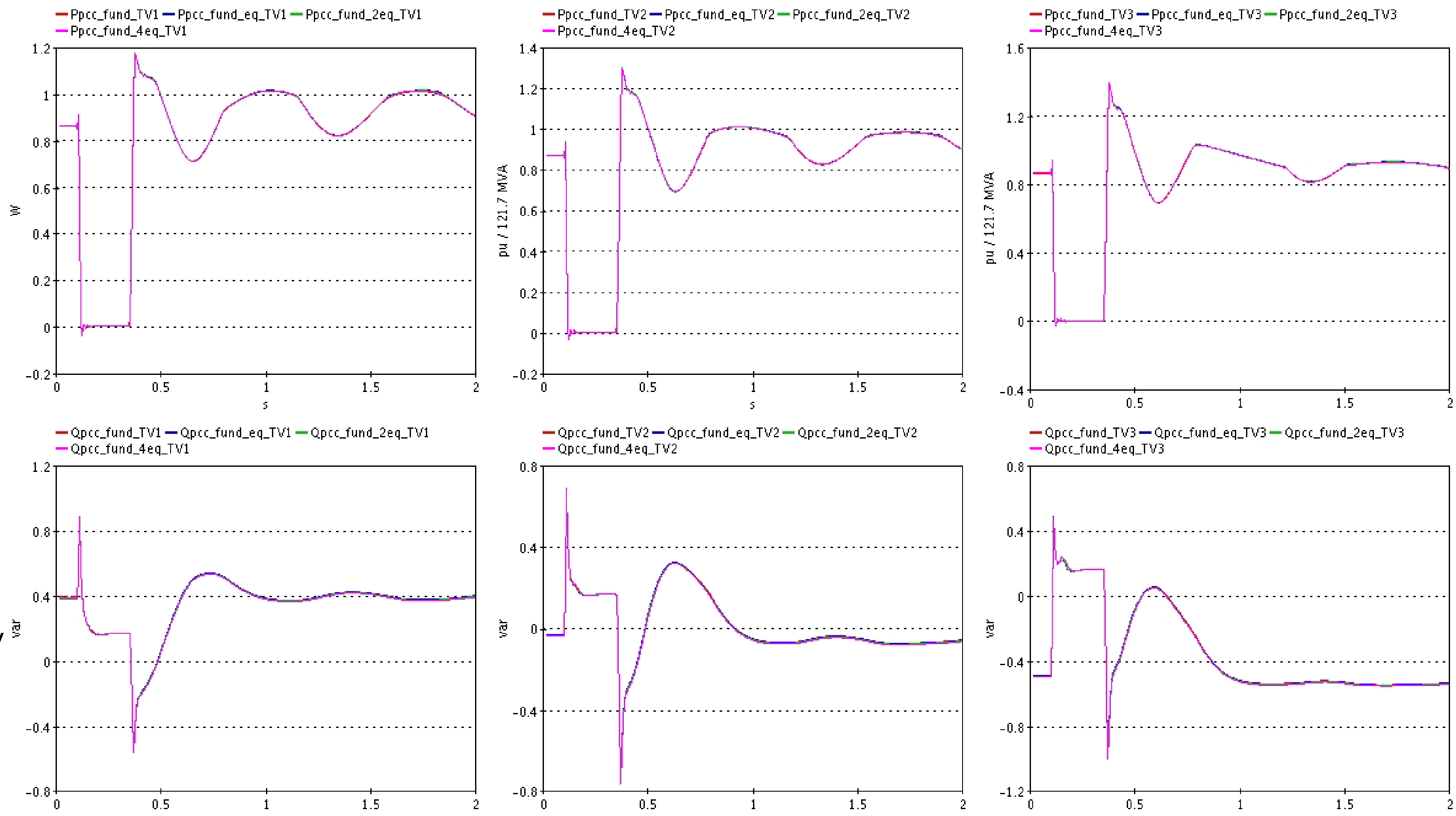
Detailed Vs. Single-Machine Representation

3-phase fault, all WTGs at 12 m/sec

Q_{WT} = 0.435 | 0 | -0.435

$P_{34.5\ kV}$

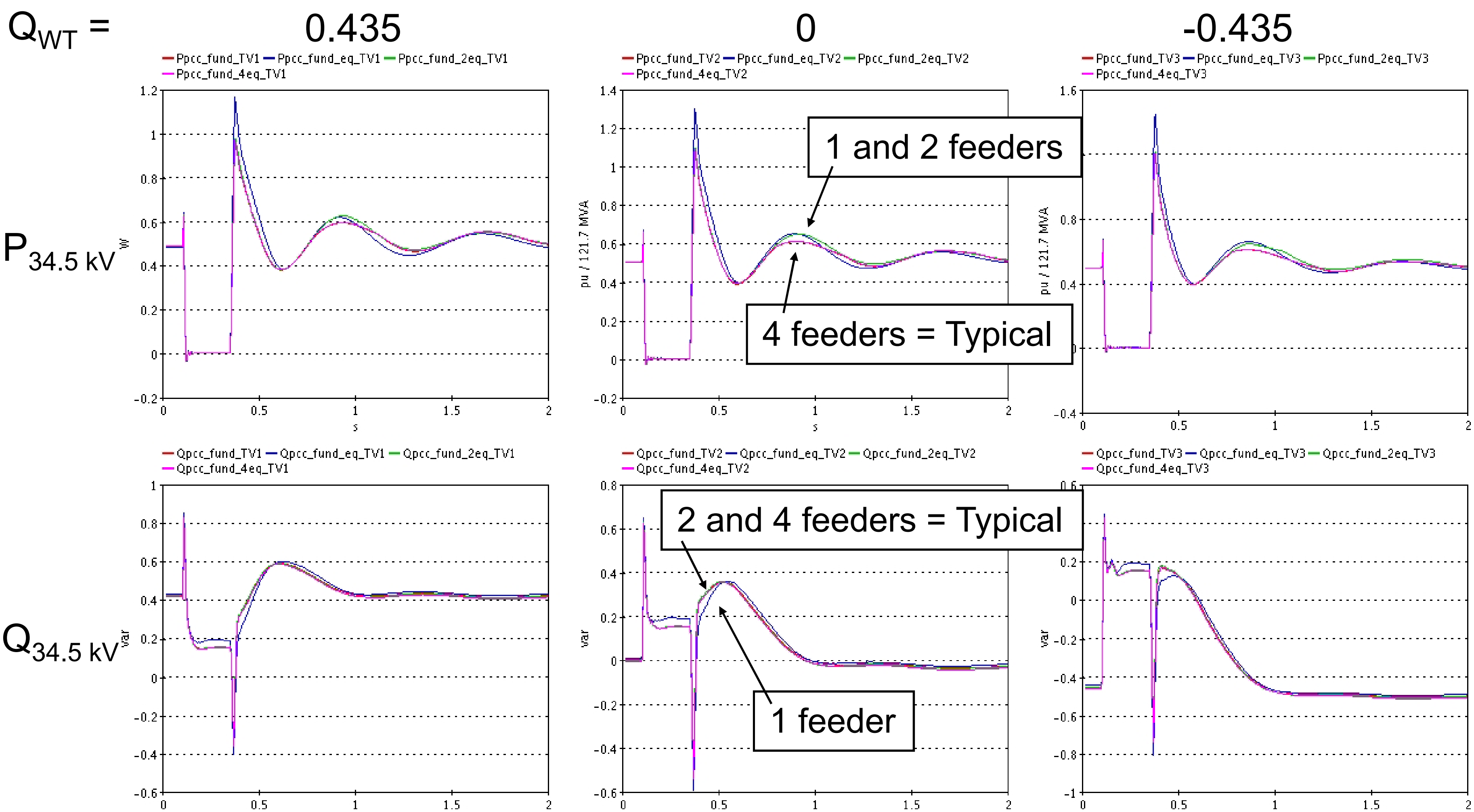
$Q_{34.5\ kV}$



From « Validation of the WECC Single-Machine Equivalent Power Plant », Presented DPWPG-WG Meeting at IEEE PSCE, March 2009 - Jacques Brochu, Richard Gagnon, Christian Larose, Hydro Quebec

Detailed Vs. Single-Machine Representation

3-phase fault, different wind speed for each feeder



From « Validation of the WECC Single-Machine Equivalent Power Plant », Presented DPWPG-WG Meeting at IEEE PSCE, March 2009 - Jacques Brochu, Richard Gagnon, Christian Larose, Hydro Quebec

Questions and Discussion