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PV Plant Modeling and Model Validation

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Sandia National Laboratories

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Outline

- WECC REMTF
- Power Flow Model
- Dynamic Model
- Model Validation
  - Procedure
  - Examples

WECC REMTF & Wind Models

Approved, Under Development

- WT1/2 wind plants

Module	Use
WTxG	Generator
WTxT	Turbine
WTxP/A	Pitch control/aero
WT2E	Rotor resistance

- Distributed PV

Module	Use
PVD1	Discrete (large) DG
PVD2	Enhanced discrete DG
CMPLDW(g)	Distributed generation (PV)
CMPLDW+	Distributed generation

- Inverter interface (PV, WT3/4 plants, storage)

Module	Use
REPC_A	Plant controller
REPC_B	Enhanced plant controller
REEC_A	Electrical controls (Wind)
REEC_B	Electrical controls (PV)
REEC_C	Energy storage
REGC_A	Generator/Converter
WTGT_A	Drive Train
WTGAR_A	Aerodynamics
WTGPT_A	Pitch Control
WTGTQ_A	Torque Control

All dynamic models except for CMPLDW require explicitly generator representation in power flow

WECC REMTF Model Documentation

- Technical specs, Application guides, Validation guides
- Where to find updated WECC/REMTF documents?
  - https://www.wecc.biz/PCC/Pages/MVWG.aspx under "Approved Documents" and "Approved Model Specifications"
- Recent papers presented at 2015 IEEE PES GM

Generic Photovoltaic System Models for WECC – A Status Report

WECC Renewable Energy Modeling Task Force

Abstract **– This paper describes generic models of photovoltaic (PV) systems developed for implementation in Western Electric Coordinating Council (WECC) base cases. The scope encompasses both transmission-connected, central station PV plants and distributed PV systems. These models were added to the WECC Approved Dynamic Model Library in March of 2014.**

Index Terms **– Distributed generation, dynamic models, photo-voltaic generation (PV), wind turbine generator (WTG).**

The generation mix in the undergoing rapid transfor of system-wide power flo accurate representation modeling effort began, guidelines on the topic of flow and dynamic data se set of best practices for re

Generic Wind Turbine Generator Models for WECC – A Second Status Report

WECC Renewable Energy Modeling Task Force

Abstract **– This paper describes the latest generic wind turbine generator models of types 3 and 4 developed for implementation in the Western Electricity Coordinating Council (WECC) base cases.**

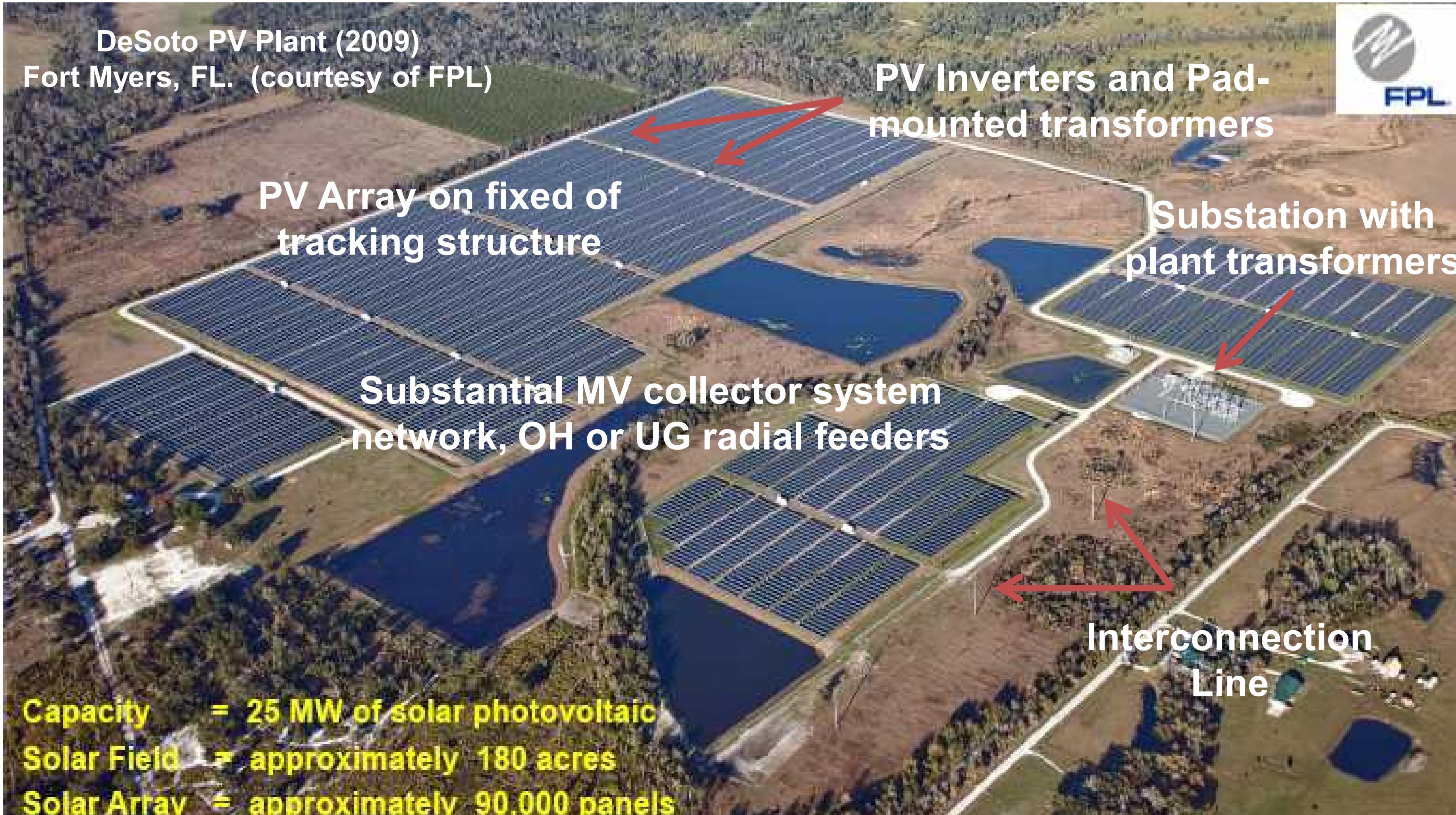
Key Words – Generic wind turbine models, wind power.

I. INTRODUCTION

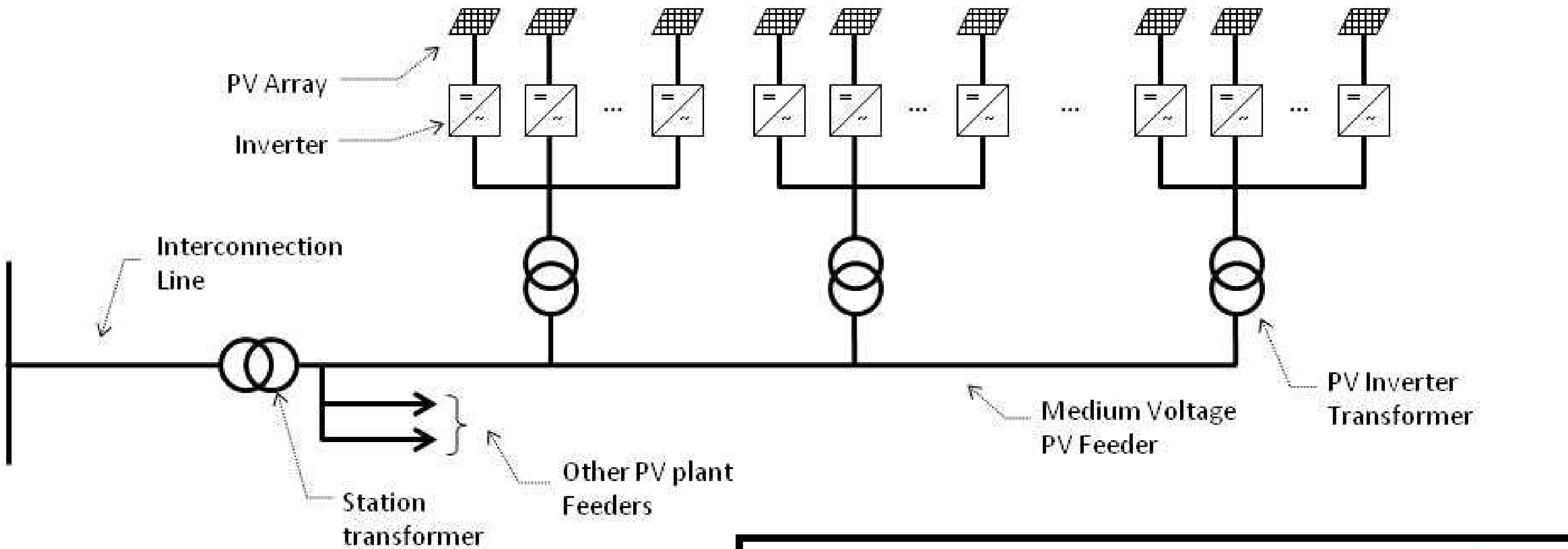
second generation g-WTG models have recently been implemented in several transient stability programs used for planning studies in North America and have also been added to the list of models sanctioned by WECC for planning studies [3], [4].

The purpose of this paper is to provide a concise description of

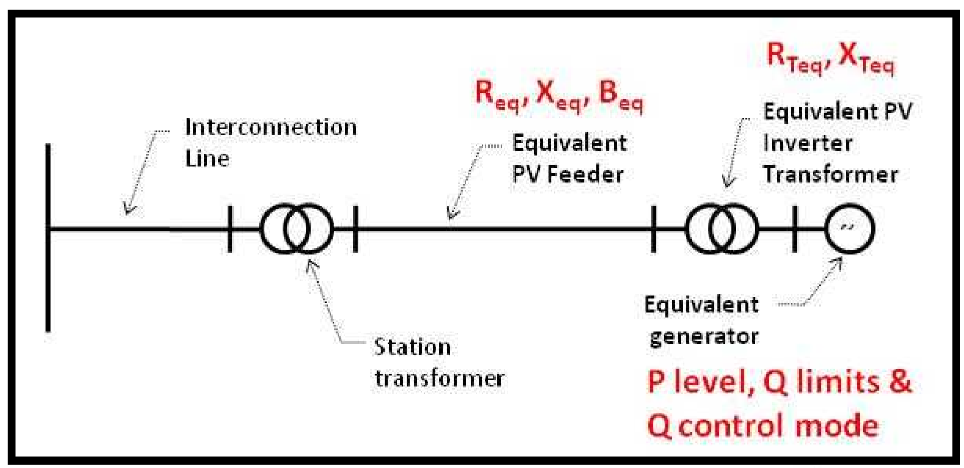
What is in a PV Plant?



Power Flow Representation

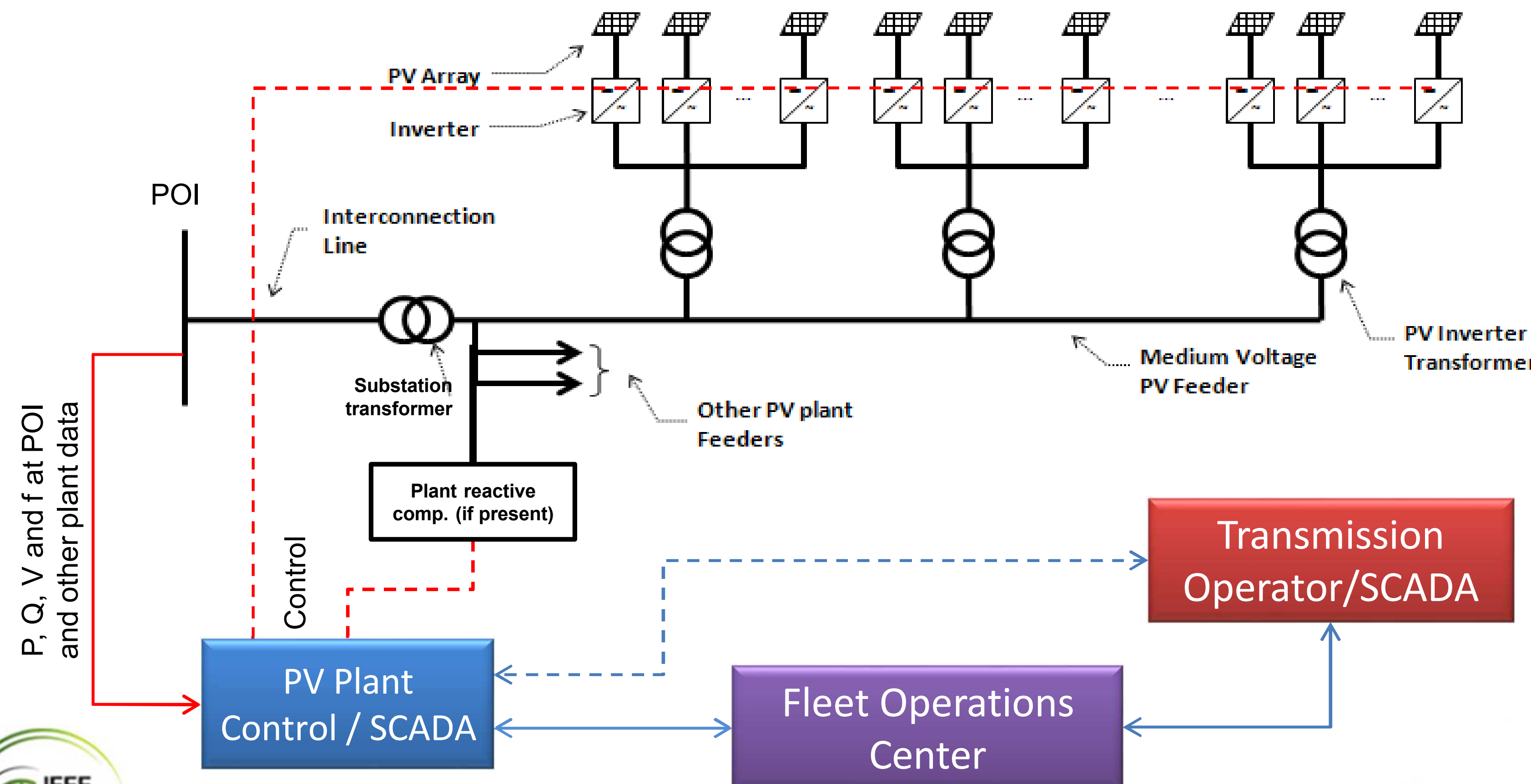


Single-machine equivalent
Could be a *few*-machine equivalent

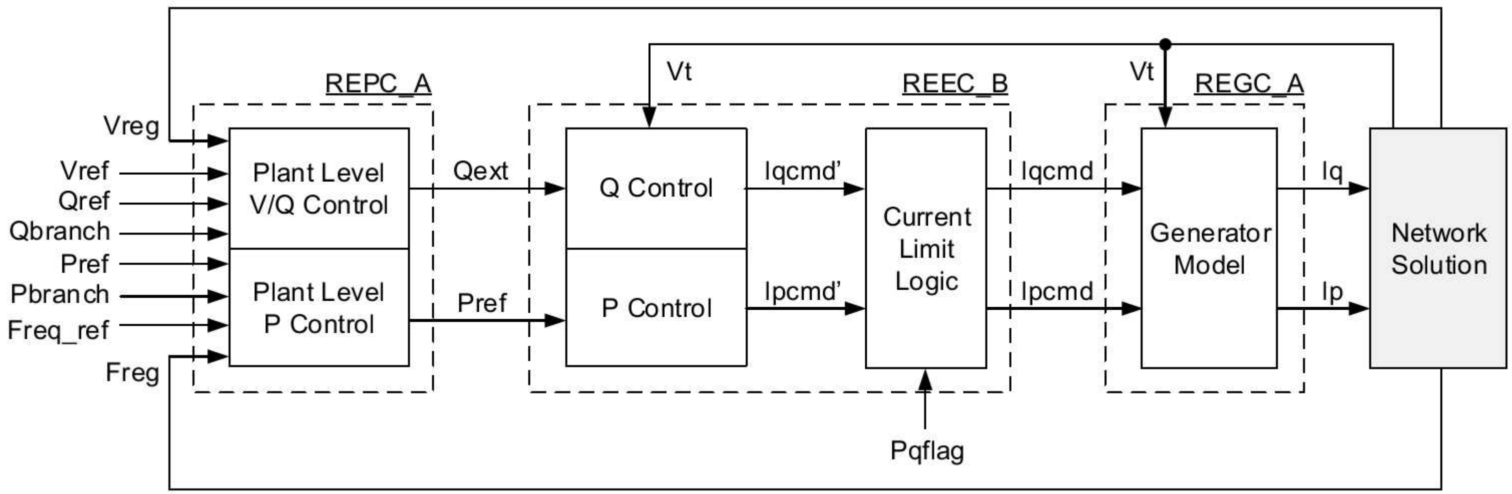


PV Plant Control / SCADA

- Coordinate operation of inverters and other controllable assets inside the plant (custom integration typically needed)

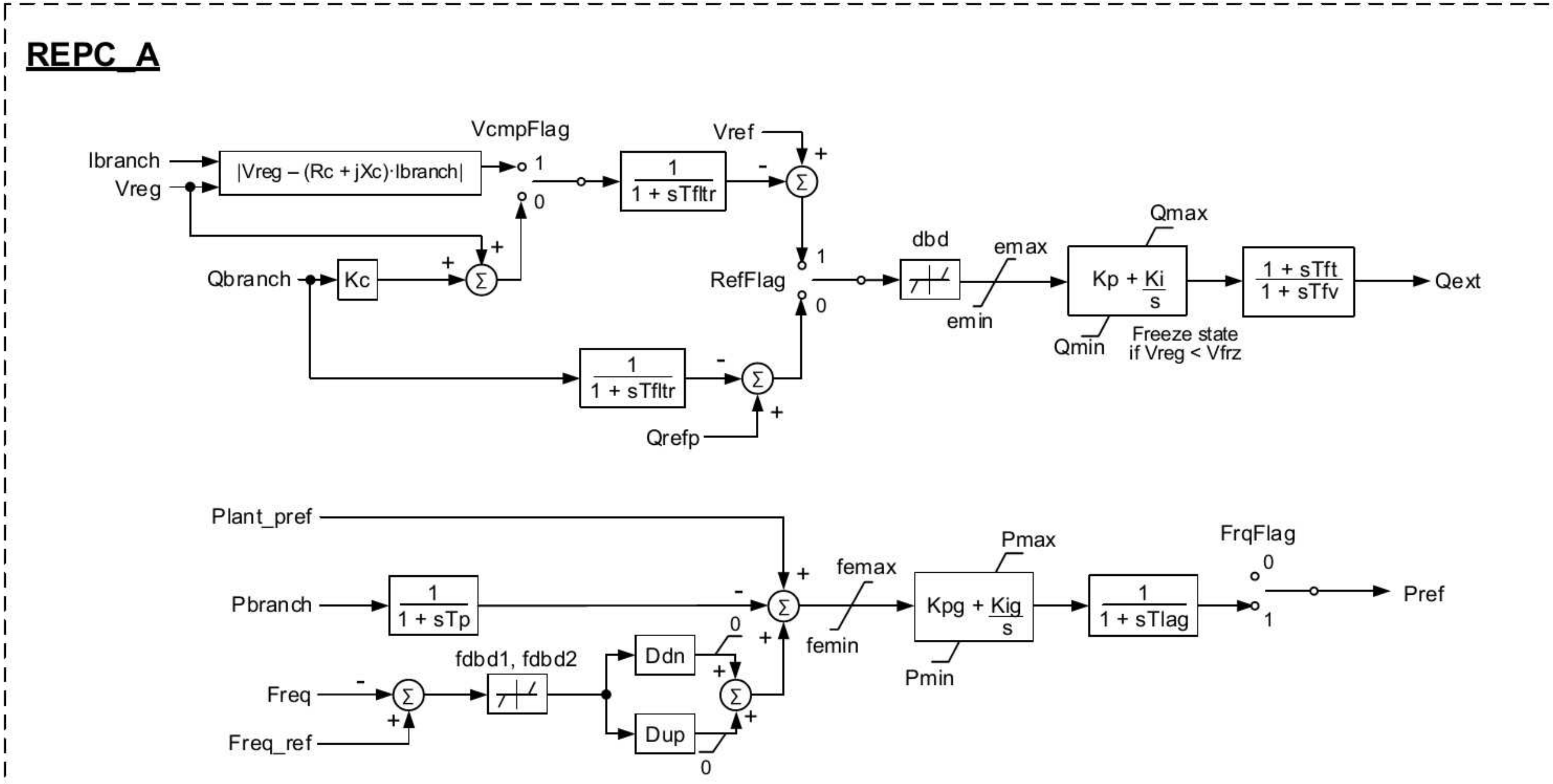


WECC/REMTF Dynamic Model

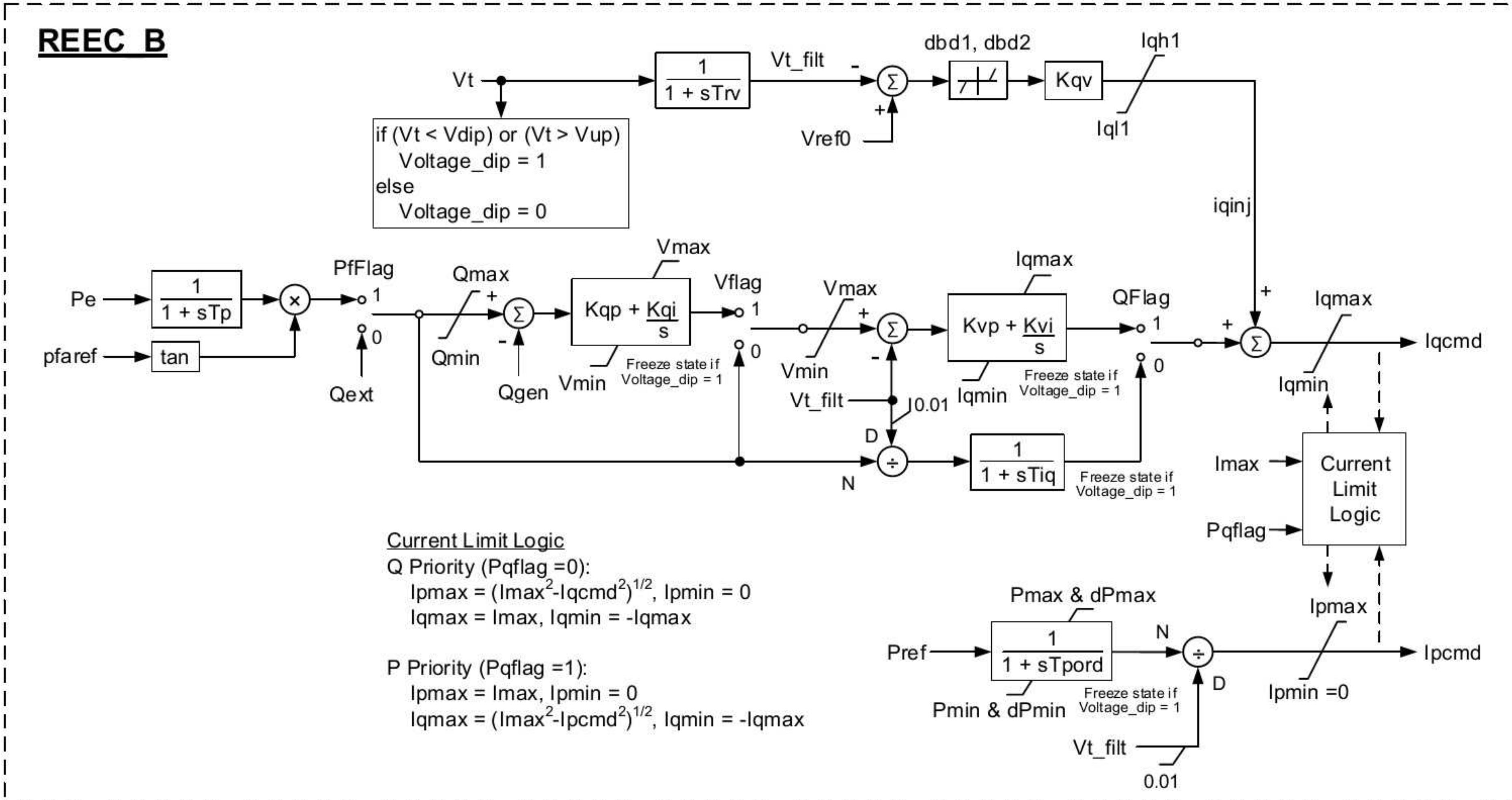


- REPC_A generates the real and reactive power references based on the plant-level control scheme
- REEC_B translates the real and reactive power references into current commands
- REGC_A reconciles the current commands with the network solution to yield current injections

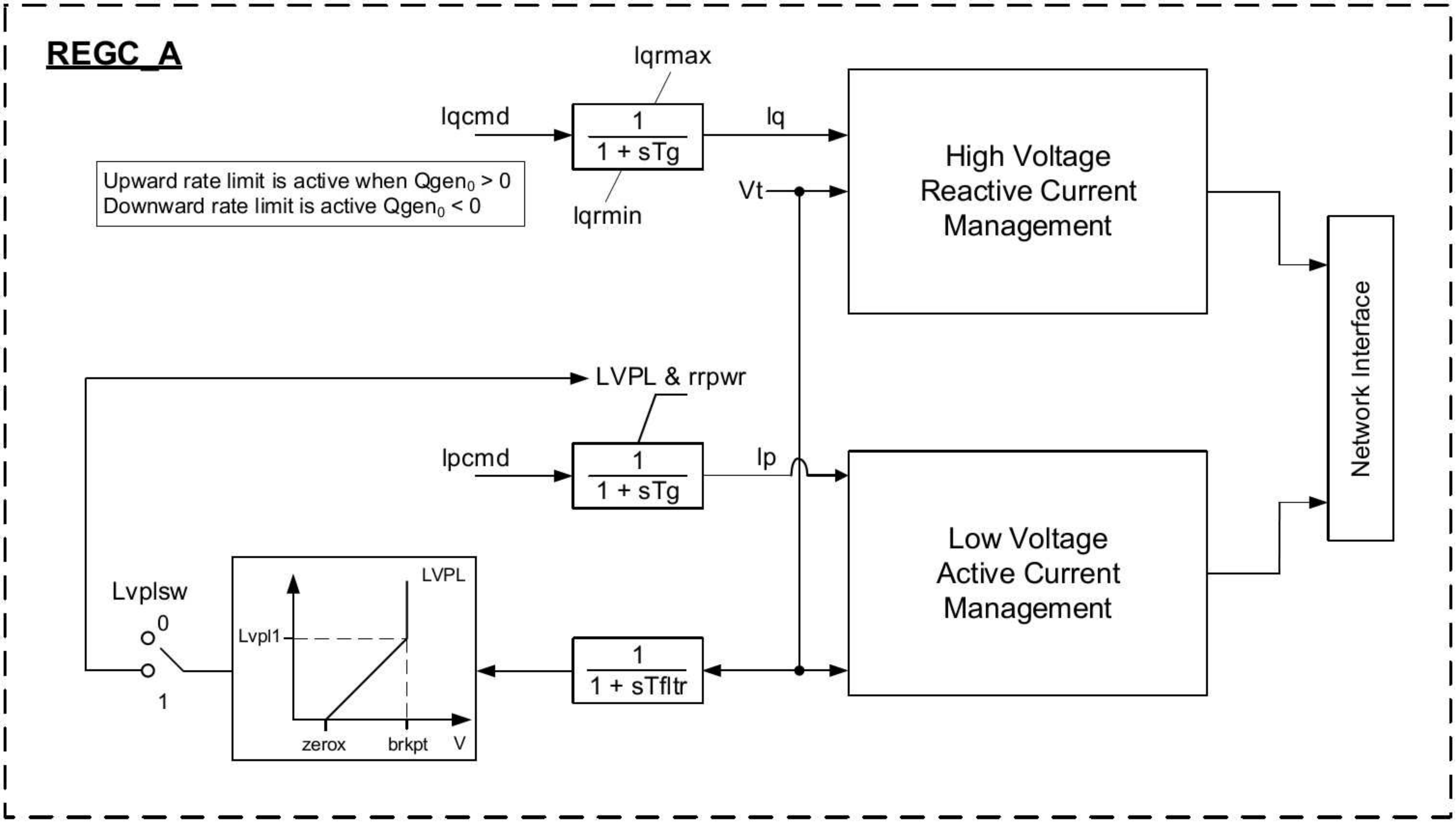
REPC_A Block Diagram



REEC_B Block Diagram



REGC_A Block Diagram



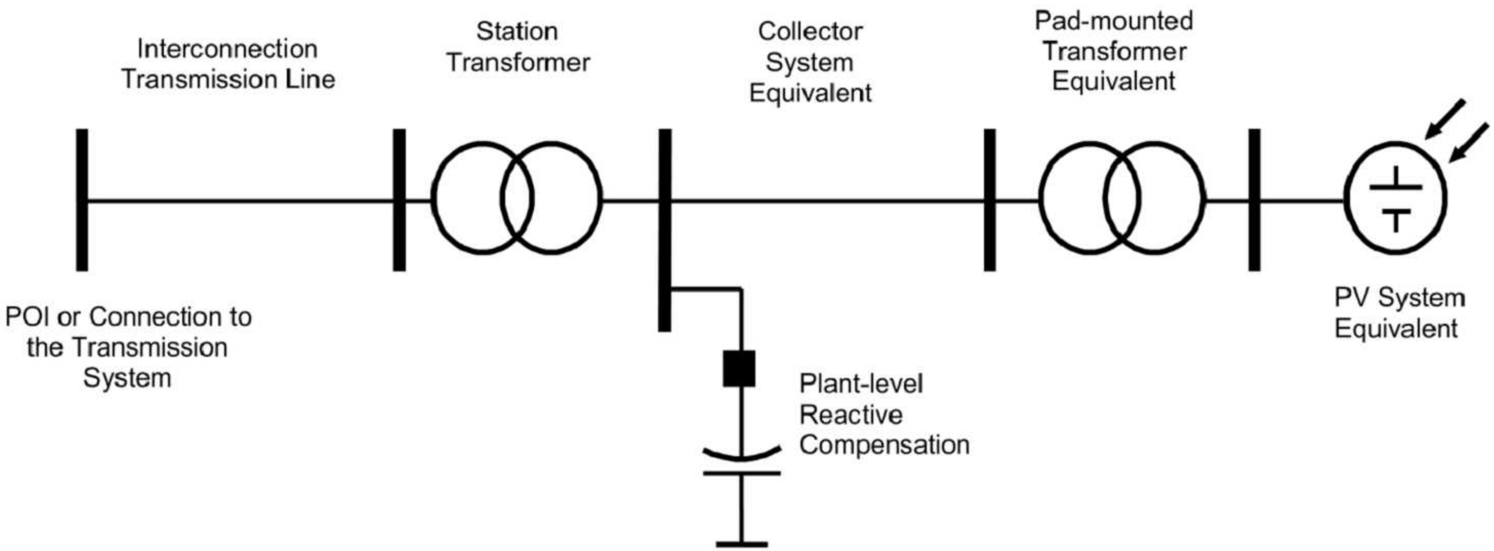
Model Validation – Overview

- Model validation is the process by which we reconcile a model with measured output
  - Typically, we try to match the output (active and reactive power) for a given input (voltage, freq.)
  - Can the model parameters be logically tuned?
- There is little industry experience with PV plant model validation
  - However, validation is still required per NERC MOD-026/027 and regional standards/policies
  - *REMTF published a technical guideline on the subject. The charts that follow are extracted from that document*

Recommended Steps for REXX

1. Establish a power flow model for the plant
2. Define the plant's mode of operation (e.g., local vs. plant-level control, etc.)
3. Set appropriate dynamic model flag combination
4. Determine appropriate dynamic model invocation
5. Adjust *tunable* parameters
   - Tunable parameters selected based on operation mode
6. Perform parameter estimation such that the modeled and measured are deemed to sufficiently agree

Power Flow Representation



- Must be set up prior to tuning the dynamic model
- Common mistakes include connecting the equivalent generator to a high-voltage bus
  - *Refer to WECC PV Plant Power Flow Modeling Guide*

Defining the Mode of Operation

Functionality	Required models	pfflag	vflag	qflag	refflag
Plant level Q control	REEC_B + REPC_A	0	N/A	0	0
Plant level V control	REEC_B + REPC_A	0	N/A	0	1
Plant level Q control & Local coordinated Q/V control	REEC_B + REPC_A	0	1	1	0
Plant level V control & Local coordinated Q/V control	REEC_B + REPC_A	0	1	1	1

- List of commonly employed modes of operation for plant-level control
- The designation “N/A” means that the parameter flag has no impact on the mode of operation
- We also developed an easy-to-follow guide to setting the parameter flags…

Flag Setting Procedure for REEC_B

1) Set **pfflag** = 0. Local power factor control should not be used with the plant controller module.
2) Does the Qref Volt/VAR output of the plant controller correspond to a voltage reference?
   - If yes, set **vflag** = 0 and **qflag** = 1. Skip to Step 6.
3) Does the Qref Volt/VAR output of the plant controller correspond to a reactive power reference?
   - If yes, set **vflag** = 1. Go to Step 4.
4) Does the plant employ local coordinated Q/V control using the series PI loops depicted in Figure 11?
   - If yes, set **qflag** = 1. Skip to Step 6.
5) Does the plant compute a reactive current command by dividing the reactive power reference by a voltage?
   - If yes, set **qflag** = 0. In this configuration, the series PI loops depicted in Figure 11 are bypassed.

Verification of Flag Combination

REEC_B			REPC_A	Notes
pfflag	vflag	qflag	refflag	No.
0	0	0	0	1
0	0	0	1	2
0	0	1	0	3
0	0	1	1	4
0	1	0	0	5
0	1	0	1	6
0	1	1	0	7
0	1	1	1	8
1	0	0	0	9

Key
Valid
Invalid

- Clearly indicates whether or not a given flag combination makes sense from a control perspective
- In this case, we see that local power factor control should not be used with the plant controller module

Dynamic Model Invocation

Plant Controller Invocation Variations:

```
Regulate the terminal bus (bus 5):
repc_a 5 "PV TERM " 0.600 "1 " : #9 / etc.

Regulate the to-bus (bus 2):
repc_a 5 "PV TERM " 0.600 "1 " 2 "PV HIGH " 230.00 : #9 / etc.

Regulate the point defined by |Vmon_i – (rc + jxc)*Ibranch|:
repc_a 5 "PV TERM " 0.600 "1 " !  !  !  !  ! 5 "PV TERM " 0.600 4 "PV LOW2 "
      34.5 "1 " : #9 / etc.
```

- It is not sufficient to set the parameter flags correctly
- The dynamic model invocation must be consistent with the selected mode of operation
- Notably, the regulated bus and monitored branch

Identifying Tunable Parameters

REEC_B			REPC_A	Tunable Parameters	
pfflag	vflag	qflag	refflag	Local	Plant
0	0	0	0	Kqv	Kp, Ki
0	0	0	1	Kqv	Kp, Ki
0	0	1	0	Kqv, Kvp, Kvi	Kp, Ki
0	0	1	1	Kqv, Kvp, Kvi	Kp, Ki
0	1	0	0	Kqv	Kp, Ki
0	1	0	1	Kqv	Kp, Ki
0	1	1	0	Kqv, Kqp, Kqi, Kvp, Kvi	Kp, Ki
0	1	1	1	Kqv, Kqp, Kqi, Kvp, Kvi	Kp, Ki

- REXX model has 45 to 75 dynamic model parameters
- It’s critical to fix as many as possible (typical ranges)
- Recommended to restrict membership in the set of tunable parameters to control gains (see above)

Parameter Sensitivity

Parameter sensitivity to real and reactive power response.

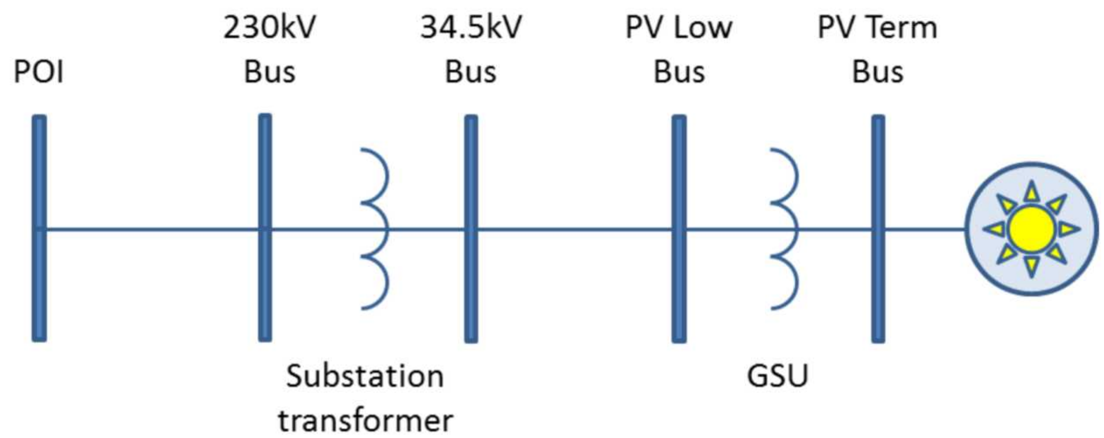
Real Power		Reactive Power	
REEC_B	REPC_A	REEC_B	REPC_A
-	Kpg	Kqv	Kp
-	Kig	Kqp	Ki
-	Ddn	Kqi	-
-	Dup	Kvp	-
-	-	Kvi	-

- The real and reactive power control loops are independent (for the most part…)
- Categorized potential free parameters according to whether they affect the real or reactive response
- Can be broken down further into 4 quadrants…

Parameter Sensitivity Cont.

- Real power response to voltage variations
  - Key models: REGC_A
  - Key parameters: lvplsw, zerox, lvpl1, brkpt, lvpnt0, lvpnt1
- Real power response to frequency variations
  - Key models: REPC_A
  - Key parameters: frqflag, kpg, kig, Ddn, Dup
- Reactive power response to voltage variations
  - Key models: REPC_A + REEC_B
  - Key parameters: kp, ki, kqv, kqp, kqi, kvp, kvi
- Reactive power response to frequency variations
  - Key parameters: N/A

Parameter Estimation Example



- Plant-level *voltage control* with coordinated local Q/V control
- Example created with simulated data for demonstration purposes
- Captured data on both sides of the station transformer to use as proxy PMU measurements

Parameter Estimation Example

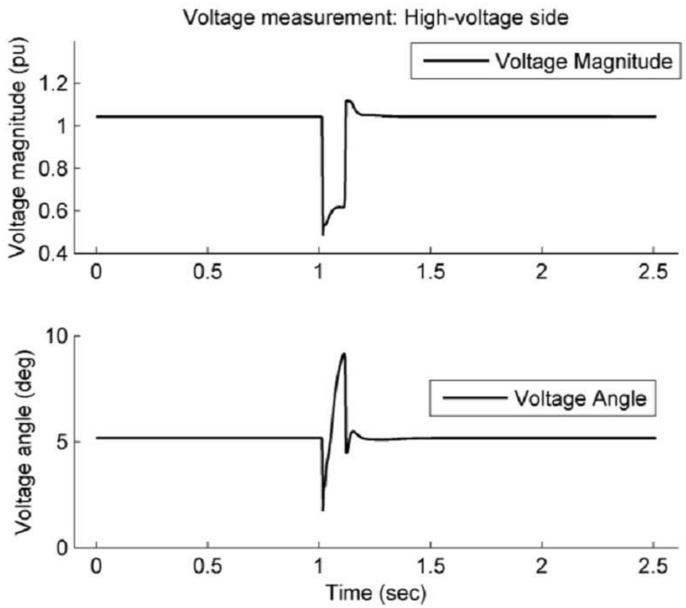


Figure 4. Inputs – Station voltage measurements.

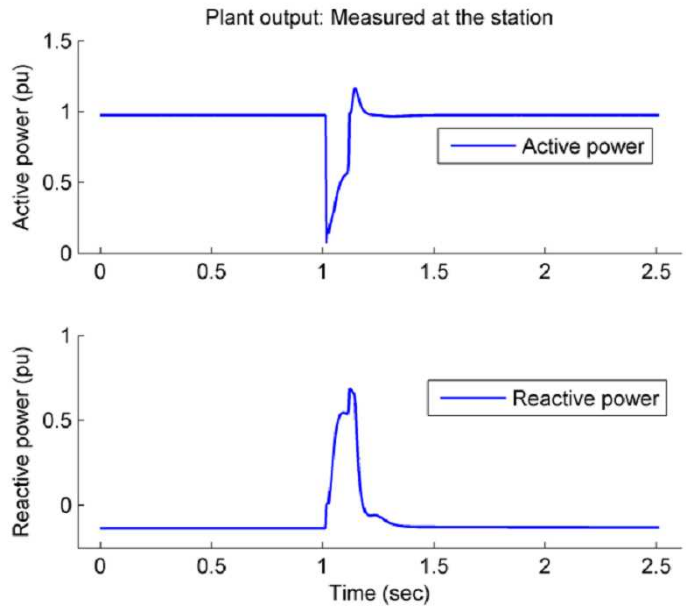


Figure 5. Outputs – Plant real and reactive power.

- Disturbance was a 6-cycle fault, resulting in a 50% voltage dip
- The key measured outputs were P and Q at the POI

Parameter Estimation Example

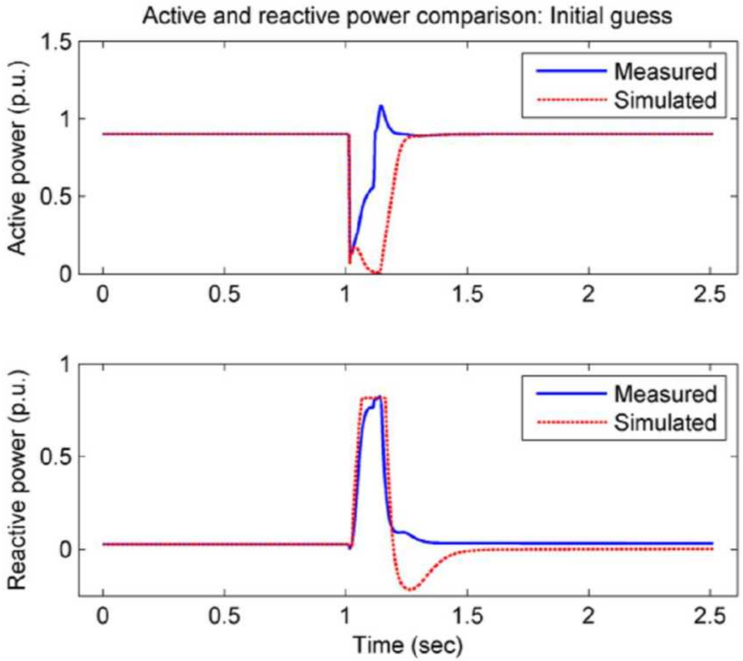


Figure 6. Initial guess output comparison.

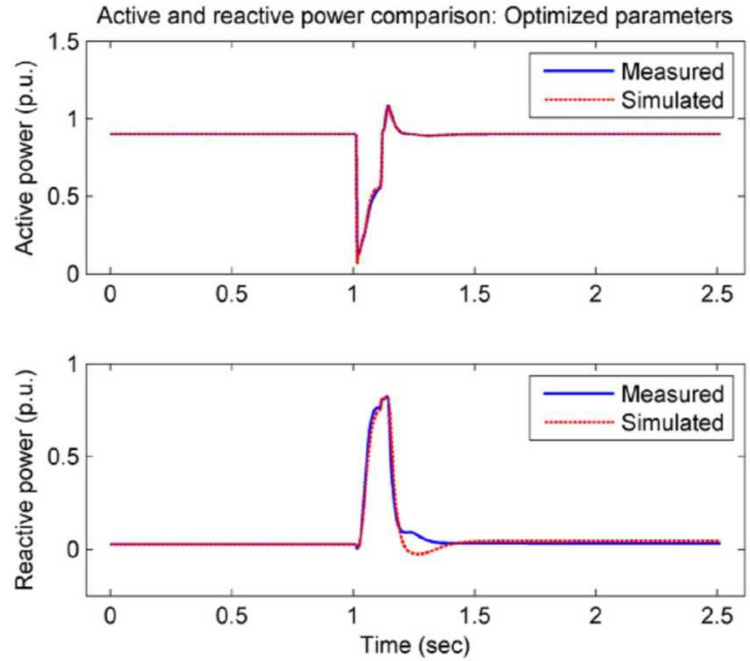


Figure 7. Optimized parameter output comparison.

- The level of residual error in the reactive power response represents what is achievable (and considered acceptable) considering field data accuracy

Parameter Estimation Example

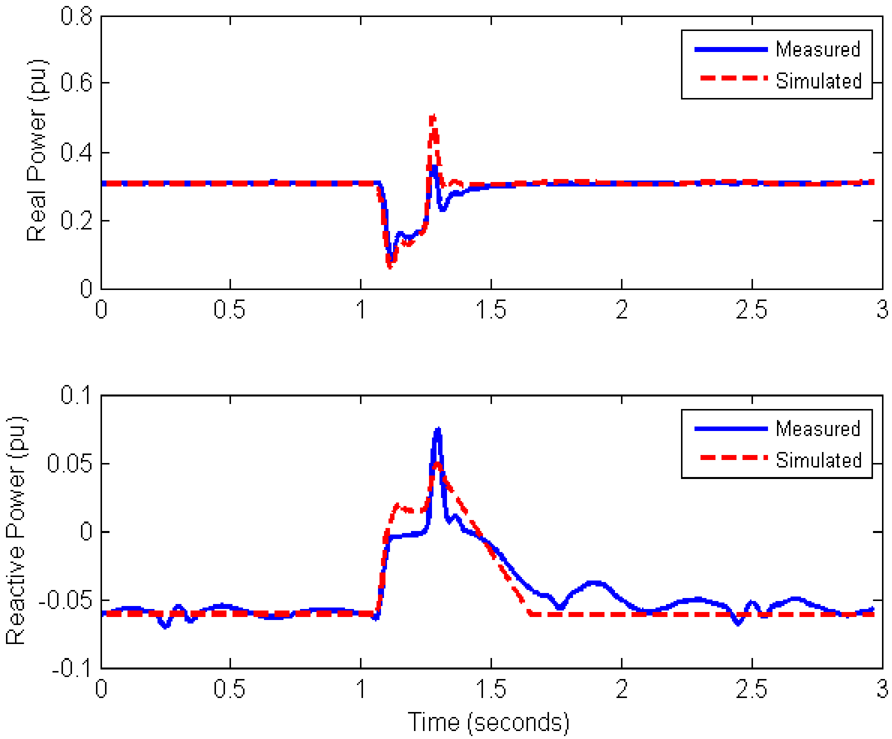
Initial, actual, and optimized model parameters.

Model	Param.	Initial guess	Actual	Estimated
REPC_A	Kp	15.0	10.0	10.9
	Ki	1.0	5.0	4.3
REEC_B	Kqv	0.0	0.0	0.0
	Kqp	0.0	0.1	0.0
	Kqi	0.0	0.1	0.0
	Kvp	12.0	5.0	4.1
	Kvi	2.0	1.0	1.2

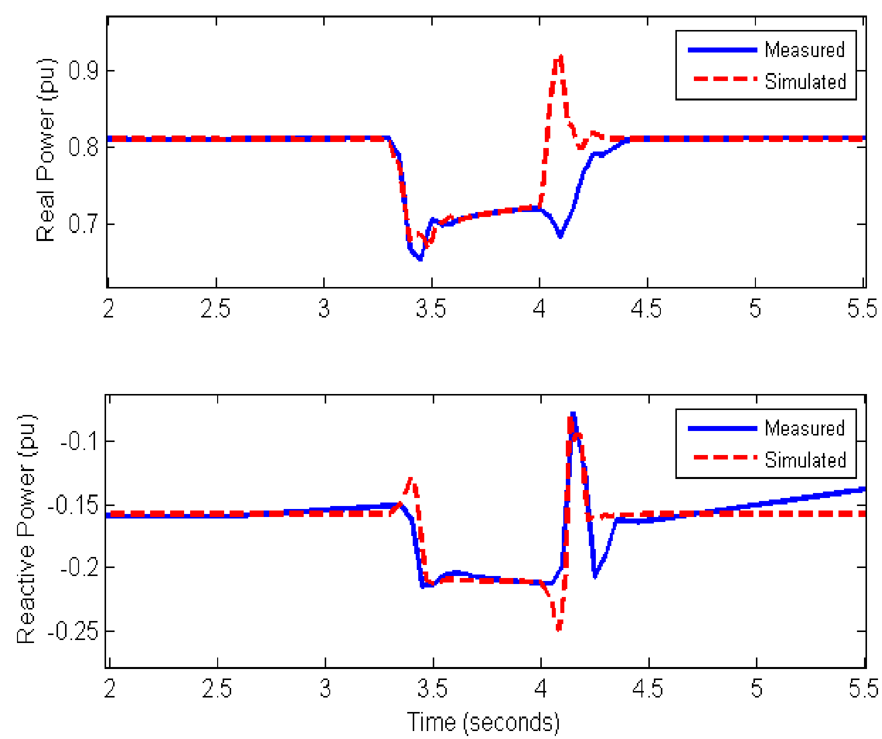
- Example, we can see not only how well the fits match, but how close the parameter values are
- In this example, we started with a blind parameter set and used the Nelder-Mead (downhill simplex) algorithm for parameter estimation

Examples of PV Model Validation

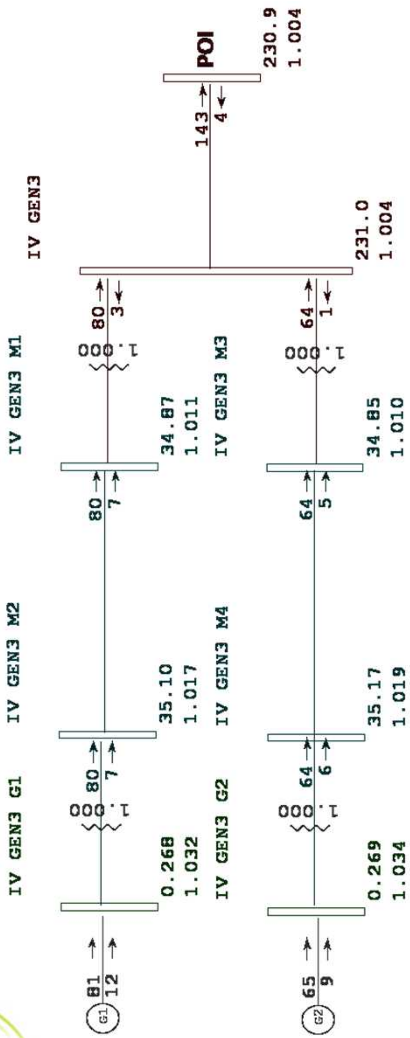
- Against Lab Test
  - 3-phase, 50kW PV inverter

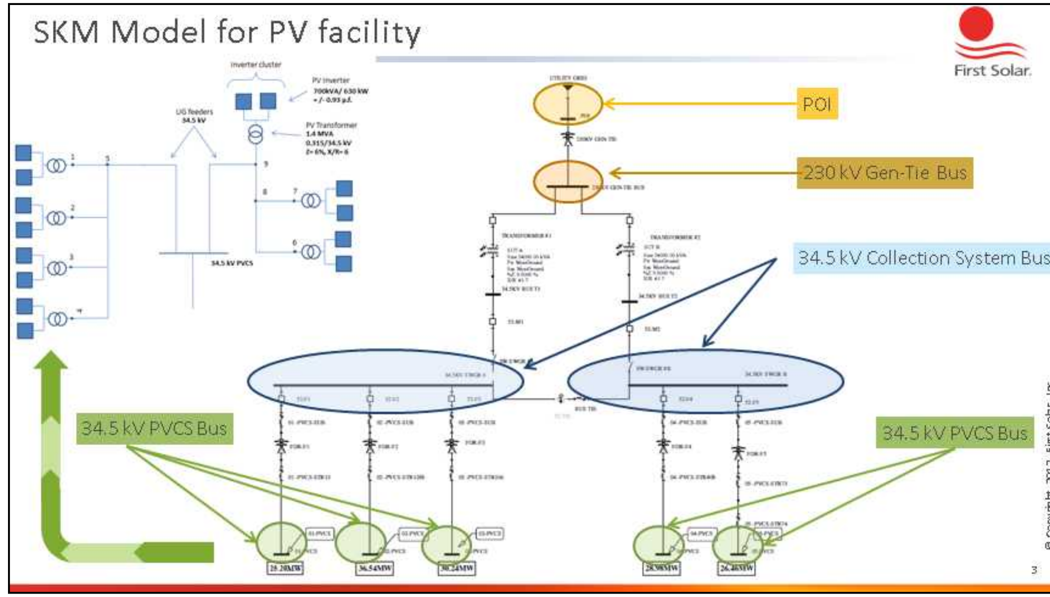


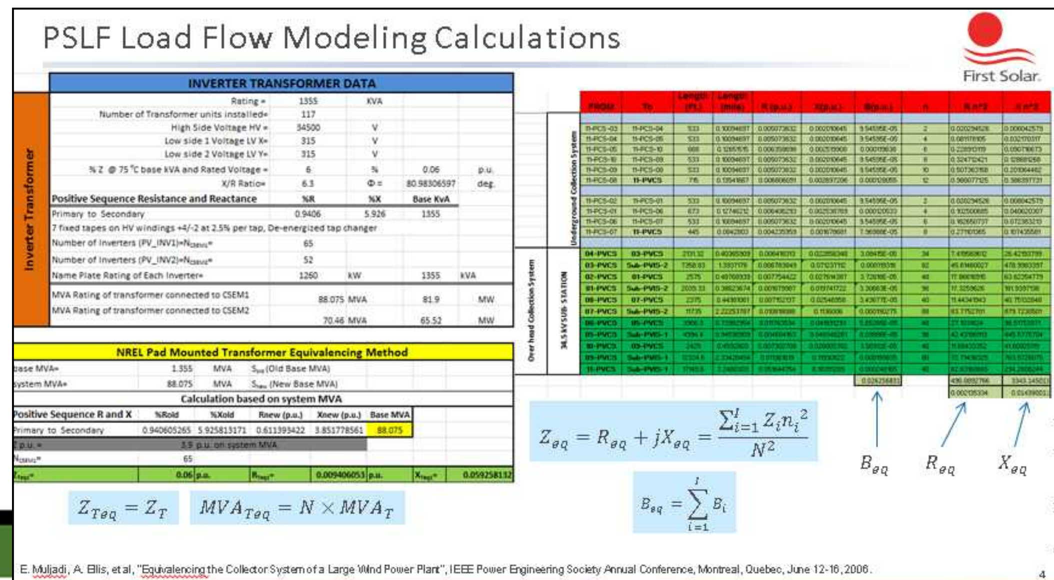
- Against PMU data
  - From 20 MW plant. Difference during fault clearing due to DC dynamics (not modeled)



PV Plant Model Validation







PSLF Load Flow Modeling Calculations

First Solar.

INVERTER TRANSFORMER DATA (Inverter Transformer)

Rating =	1355	KVA		
Number of Transformer units installed=	117			
High Side Voltage HV =	34500	V		
Low side 1 Voltage LV X=	315	V		
Low side 2 Voltage LV Y=	315	V		
% Z @ 75 °C base kVA and Rated Voltage =	6	%	0.06	p.u.
X/R Ratio=	6.3	Φ =	80.98306597	deg.
Positive Sequence Resistance and Reactance	%R	%X	Base KvA	
Primary to Secondary	0.9406	5.926	1355	
7 fixed tapes on HV windings +4/-2 at 2.5% per tap, De-energized tap changer				
Number of Inverters (PV_INV1)=N_{CSEM1}=	65			
Number of Inverters (PV_INV2)=N_{CSEM2}=	52			
Name Plate Rating of Each Inverter=	1260	kW	1355	kVA
MVA Rating of transformer connected to CSEM1	88.075	MVA	81.9	MW
MVA Rating of transformer connected to CSEM2	70.46	MVA	65.52	MW

NREL Pad Mounted Transformer Equivalencing Method

base MVA=	1.355	MVA	S_{old} (Old Base MVA)			
system MVA=	88.075	MVA	S_{new} (New Base MVA)			
Calculation based on system MVA						
Positive Sequence R and X	%Rold	%Xold	Rnew (p.u.)	Xnew (p.u.)	Base MVA	
Primary to Secondary	0.940605265	5.925813171	0.611399422	3.851778561	88.075	
Z p.u. =		3.9 p.u. on system MVA				
N_{CSEM1}=		65				
Z_{Teq}=	0.06	p.u.	R_{Teq}=	0.009406053	p.u.	X_{Teq}= 0.059258132

	FROM	To	Length (Ft.)	Length (mile)	R (p.u.)	X(p.u.)	B(p.u.)	n	R n^2	X n^2
Underground Collection System	11-PCS-03	11-PCS-04	533	0.10094697	0.0050073632	0.002010645	9.54595E-05	2	0.020294526	0.008042579
	11-PCS-04	11-PCS-05	533	0.10094697	0.0050073632	0.002010645	9.54595E-05	4	0.081178105	0.032170317
	11-PCS-05	11-PCS-10	668	0.12651515	0.006358698	0.002519908	0.000119636	6	0.22891319	0.09071673
	11-PCS-10	11-PCS-09	533	0.10094697	0.0050073632	0.002010645	9.54595E-05	8	0.324712421	0.128681268
	11-PCS-09	11-PCS-08	533	0.10094697	0.0050073632	0.002010645	9.54595E-05	10	0.507363158	0.201064462
	11-PCS-08	11-PVCS	716	0.13541667	0.006806091	0.002697206	0.000128055	12	0.980077125	0.388397731
	11-PCS-02	11-PCS-01	533	0.10094697	0.0050073632	0.002010645	9.54595E-05	2	0.020294526	0.008042579
	11-PCS-01	11-PCS-06	673	0.12746212	0.006406293	0.002538769	0.000120533	4	0.102500685	0.040620307
	11-PCS-06	11-PCS-07	533	0.10094697	0.0050073632	0.002010645	9.54595E-05	6	0.182650737	0.072383213
	11-PCS-07	11-PVCS	445	0.0842803	0.004235359	0.001678681	7.96988E-05	8	0.27107065	0.107435581
Over head Collection System / 34.5 kV SUB-STATION	04-PVCS	03-PVCS	2131.32	0.40365303	0.006410313	0.022858348	3.08415E-05	34	7.410569812	26.42153799
	03-PVCS	Sub-PVIS-2	7358.83	1.3937179	0.006783849	0.07123712	0.00010536	82	45.61460027	478.3983357
	02-PVCS	01-PVCS	2575	0.48768939	0.007754422	0.027694387	3.72016E-05	48	17.86661916	63.62254779
	01-PVCS	Sub-PVIS-2	2035.33	0.38623674	0.001679987	0.019741722	3.30663E-05	38	17.3259626	181.9337198
	08-PVCS	07-PVCS	2375	0.44981061	0.00715237	0.02546958	3.43077E-05	40	11.44341043	40.75102048
	07-PVCS	Sub-PVIS-2	11735	2.22253787	0.010816886	0.1136006	0.000180275	88	83.7752701	879.7230801
	06-PVCS	05-PVCS	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	40	[illegible]	[illegible]
	05-PVCS	Sub-PVIS-1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	38	[illegible]	[illegible]
	10-PVCS	09-PVCS	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	40	[illegible]	[illegible]
	09-PVCS	Sub-PVIS-1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	60	[illegible]	[illegible]
	11-PVCS	Sub-PVIS-1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	40	[illegible]	[illegible]
							0.024256833		436.0892766	3343.145651
									0.002135334	0.016439001

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

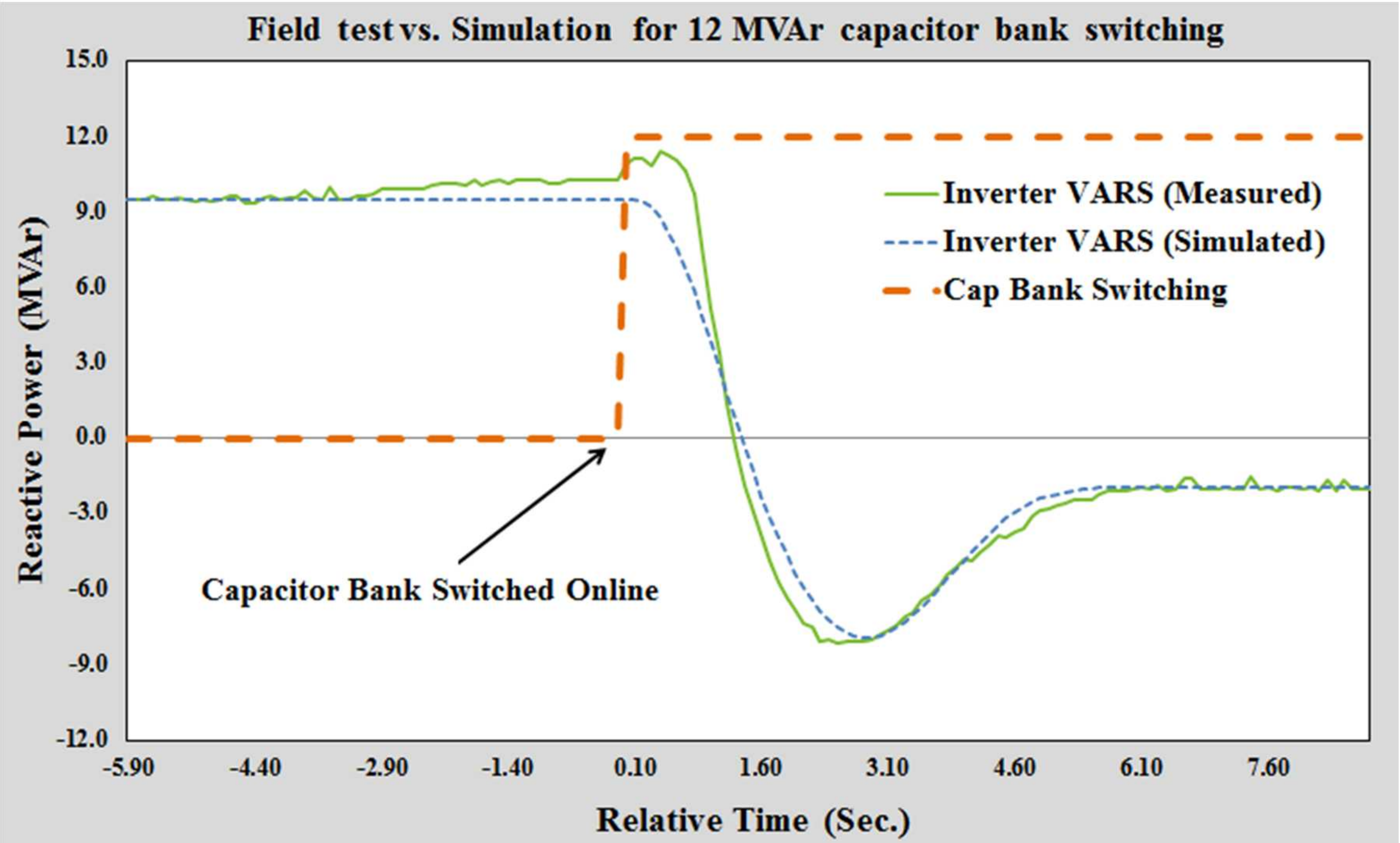
B_{eq} R_{eq} X_{eq}

$$B_{eq} = \sum_{i=1}^{I} B_i$$

$$Z_{Teq} = Z_T \qquad MVA_{Teq} = N \times MVA_T$$

E. Muljadi, A. Ellis, et al, "Equivalencing the Collector System of a Large Wind Power Plant", IEEE Power Engineering Society Annual Conference, Montreal, Quebec, June 12-16, 2006.

Staged Test – 34 kV Cap Switching



Summary

- Setting up the models correctly is half the battle
  - Parameterizing them is the other half
- There is no substitute for engineering judgment
  - We do not prescribe tests for “goodness of fit”
- It’s important that the modeled output agrees with measured data for various disturbances
  - Reserve some data for evaluation, rather than model training
- See the WECC Central Station PV Plant Model Validation Guideline for more information

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