Funded by:

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Modeling and Control of Solar PVs for Large Grid Disturbances and Weak Grids

Design of dynamic models and analysis tools for solar PVs under large grid disturbances and weak grid conditions

Lingling Fan

University of South Florida

November 17, 2021

Award #: DE-EE0008771

Other Contributors: Zhixin Miao, Shahil Shah, Przemyslaw Koralewicz, Vahan Gevorgian

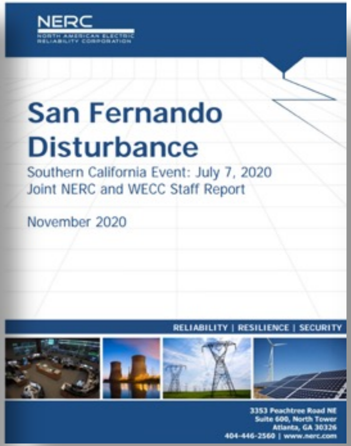
Motivation – "It is all about models!"

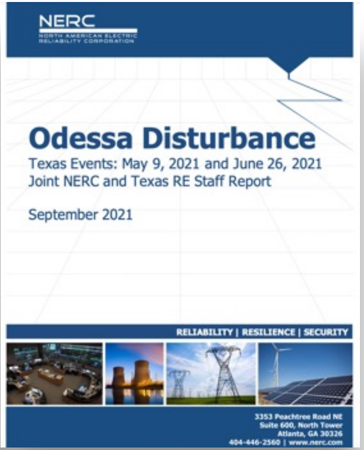
Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy


NERC
1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report
Southern California 8/16/2016 Event
June 2017
RELIABILITY | ACCOUNTABILITY
3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com


NERC
900 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report
Southern California Event: October 9, 2017
Joint NERC and WECC Staff Report
February 2018
RELIABILITY | ACCOUNTABILITY
3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com


NERC
April and May 2018 Fault Induced Solar Photovoltaic Resource Interruption Disturbances Report
Southern California Events: April 20, 2018 and May 11, 2018
Joint NERC and WECC Staff Report
January 2019
RELIABILITY | ACCOUNTABILITY
3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com


NERC
San Fernando Disturbance
Southern California Event: July 7, 2020
Joint NERC and WECC Staff Report
November 2020
RELIABILITY | RESILIENCE | SECURITY
3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com


NERC
Odessa Disturbance
Texas Events: May 9, 2021 and June 26, 2021
Joint NERC and Texas RE Staff Report
September 2021
RELIABILITY | RESILIENCE | SECURITY
3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com

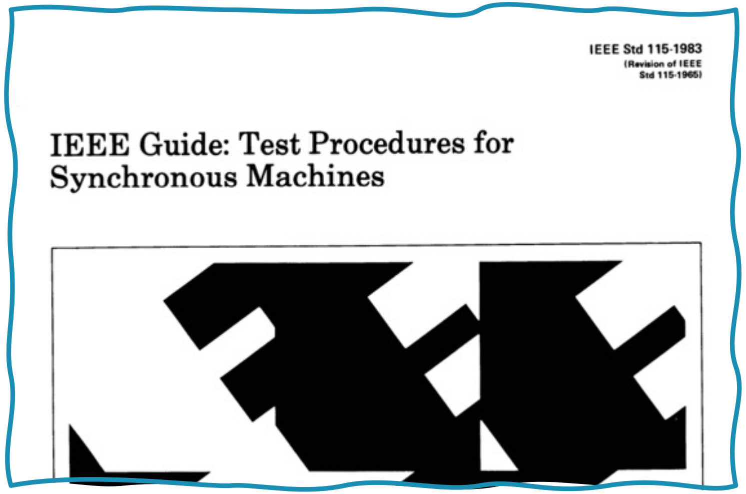
2016 California → 2017 California → 2018 California → 2020 California → 2021 Texas

"Without models, we are flying blind." --- Rich Bauer
"Are We Really Ready for High Penetration IBR Conditions?" --- Ryan Quint
"It is all about models!" – Andrew Isaacs

A peek at history:

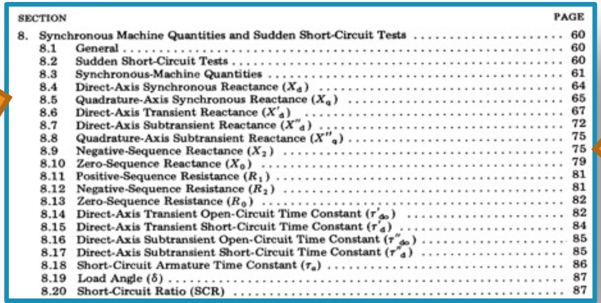
- With a complete knowledge of the synchronous machine physics, it takes another 100 years to develop/standardize synchronous generator models for system analysis.

IEEE std 115 was initiated in 1929
Version-1945, 1965, 1983, 1999, 2019

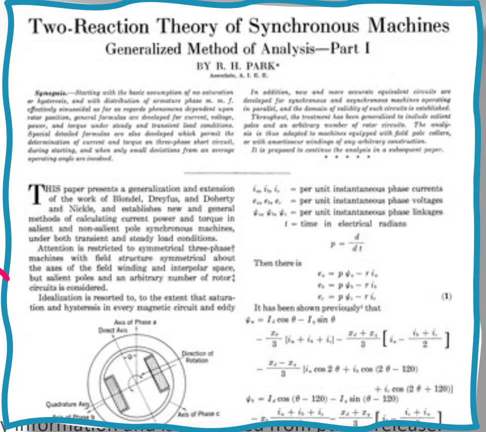


IEEE Std 115-1983
(Revision of IEEE Std 115-1965)

IEEE Guide: Test Procedures for Synchronous Machines



SECTION		PAGE
8.	Synchronous Machine Quantities and Sudden Short-Circuit Tests	60
8.1	General	60
8.2	Sudden Short-Circuit Tests	60
8.3	Synchronous-Machine Quantities	61
8.4	Direct-Axis Synchronous Reactance (X_d)	64
8.5	Quadrature-Axis Synchronous Reactance (X_q)	65
8.6	Direct-Axis Transient Reactance (X'_d)	67
8.7	Direct-Axis Subtransient Reactance (X''_d)	72
8.8	Quadrature-Axis Subtransient Reactance (X''_q)	75
8.9	Negative-Sequence Reactance (X_2)	75
8.10	Zero-Sequence Reactance (X_0)	79
8.11	Positive-Sequence Resistance (R_1)	81
8.12	Negative-Sequence Resistance (R_2)	81
8.13	Zero-Sequence Resistance (R_0)	82
8.14	Direct-Axis Transient Open-Circuit Time Constant (τ'_{do})	82
8.15	Direct-Axis Transient Short-Circuit Time Constant (τ'_d)	84
8.16	Direct-Axis Subtransient Open-Circuit Time Constant (τ''_{do})	85
8.17	Direct-Axis Subtransient Short-Circuit Time Constant (τ''_d)	85
8.18	Short-Circuit Armature Time Constant (τ_a)	86
8.19	Load Angle (δ)	87
8.20	Short-Circuit Ratio (SCR)	87



Two-Reaction Theory of Synchronous Machines
Generalized Method of Analysis—Part I
BY R. H. PARK*
Associate, A. I. E. E.

Synopsis.—Starting with the basic assumption of no saturation or hysteresis, and with distribution of armature phase m. m. f. effectively sinusoidal as far as regards phenomena dependent upon rotor position, general formulas are developed for current, voltage, power, and torque under steady and transient load conditions. Special detailed formulas are also developed which permit the determination of current and torque on three-phase short circuit, during starting, and when only small deviations from an average operating angle are involved.

In addition, new and more accurate equivalent circuits are developed for synchronous and asynchronous machines operating in parallel, and the domain of validity of such circuits is established.

Throughout, the treatment has been generalized to include salient poles and an arbitrary number of rotor circuits. The analysis is thus adapted to machines equipped with field pole collars, or with amortisseur windings of any arbitrary construction.

It is proposed to continue the analysis in a subsequent paper.

THIS paper presents a generalization and extension of the work of Blondel, Dreyfus, and Doherty and Nickle, and establishes new and general methods of calculating current power and torque in salient and non-salient pole synchronous machines, under both transient and steady load conditions.

Attention is restricted to symmetrical three-phase† machines with field structure symmetrical about the axes of the field winding and interpolar space, but salient poles and an arbitrary number of rotor‡ circuits is considered.

Idealization is resorted to, to the extent that saturation and hysteresis in every magnetic circuit and eddy

i_a, i_b, i_c = per unit instantaneous phase currents
e_a, e_b, e_c = per unit instantaneous phase voltages
ψ_a, ψ_b, ψ_c = per unit instantaneous phase linkages
t = time in electrical radians

$$p = \frac{d}{dt}$$

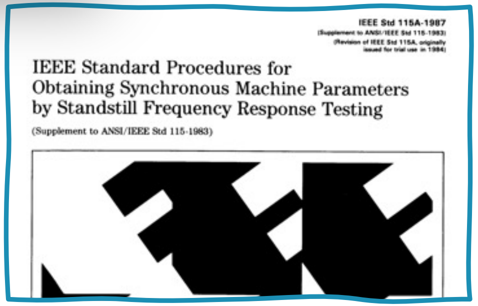
Then there is

$$e_a = p\,\psi_a - r\,i_a$$
$$e_b = p\,\psi_b - r\,i_b$$
$$e_c = p\,\psi_c - r\,i_c \qquad (1)$$

It has been shown previously[1] that

$$\psi_a = I_d \cos\theta - I_q \sin\theta - \frac{x_0}{3}[i_a + i_b + i_c] - \frac{x_d + x_q}{3}\left[i_a - \frac{i_b + i_c}{2}\right] - \frac{x_d - x_q}{3}[i_a \cos 2\theta + i_b \cos(2\theta - 120) + i_c \cos(2\theta + 120)]$$

$$\psi_b = I_d \cos(\theta - 120) - I_q \sin(\theta - 120)$$



IEEE Std 115A-1987
(Supplement to ANSI/IEEE Std 115-1983)
(Revision of IEEE Std 115A, originally issued for trial use in 1984)

IEEE Standard Procedures for Obtaining Synchronous Machine Parameters by Standstill Frequency Response Testing

(Supplement to ANSI/IEEE Std 115-1983)

In 1920s, machine model/circuits developed

Goals: Initiate the work on analytical modeling

- Developing **adequate** dynamic models (systems) for PV systems to **characterize** their interactions with the host grid, to **enhance stability** and **mitigate control interactions**.

- Common **misconceptions** about modeling and computer simulations
  - A complete reliance on software package: "click and run"
    - Garbage in garbage out; very challenging to master dynamic modeling
  - A complete distrust on computer simulation: No hardware experiments, no paper
    - Hardware is important when physics are not fully understood yet.
    - EMT simulation, is now a recognized means in power systems after decades of efforts from Dommel, BPA, Manitoba Hydro, Hydro Quebec.
  - The more details, the merrier
    - See the following.

2001, the proceedings of the IEEE

Modeling and Simulation of Power Electronic Converters

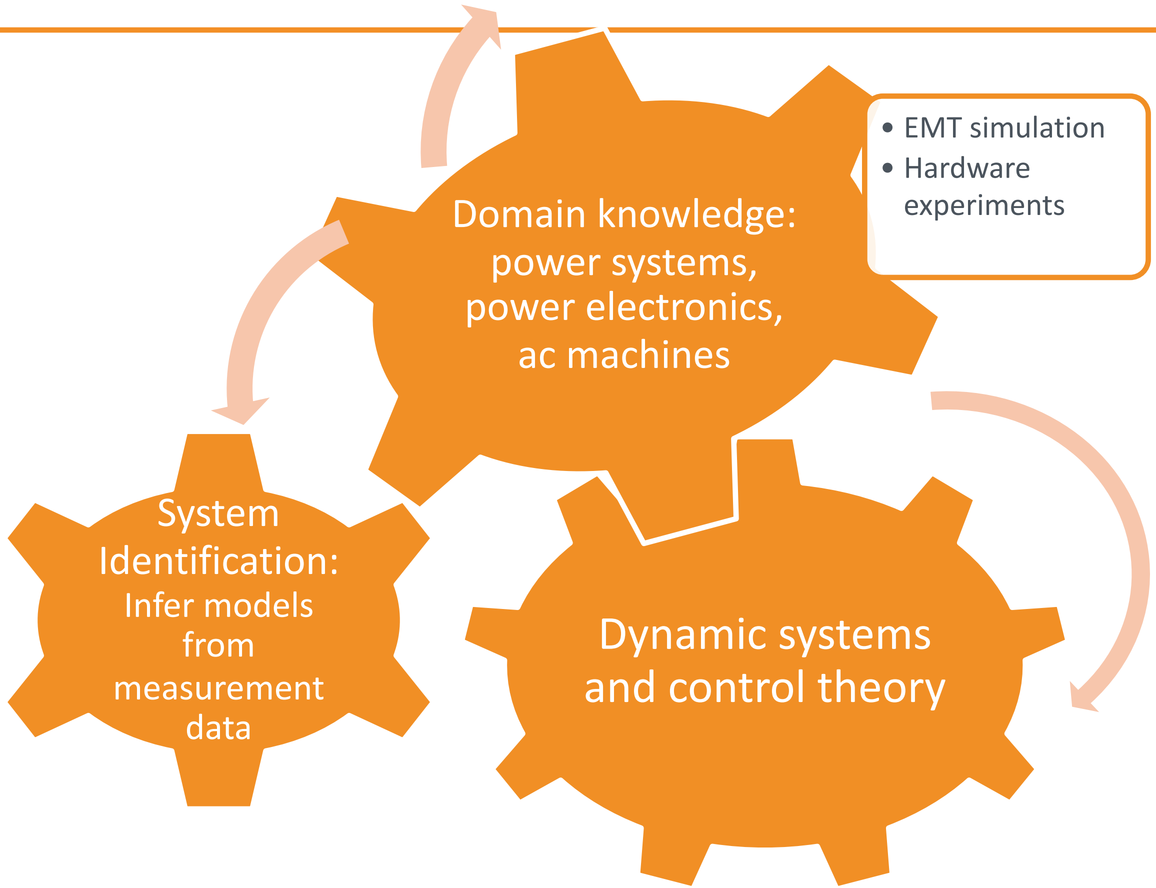
DRAGAN MAKSIMOVIĆ, MEMBER, IEEE, ALEKSANDAR M. STANKOVIĆ, MEMBER, IEEE, V. JOSEPH THOTTUVELIL, MEMBER, IEEE, AND GEORGE C. VERGHESE, FELLOW, IEEE

Invited Paper

…. Even if it were possible to simulate a full schematic with sufficient accuracy and efficiency, it is doubtful whether this capability alone would provide the basis for good design. Typically, **crucial insight and understanding are provided by hierarchical modeling, analysis, and simulation**, rather than working directly with a detailed schematic. The combination of these insights with hardware prototyping and experiments constitutes a powerful and effective approach to design.

Funded by:

Intellectual challenges of this project



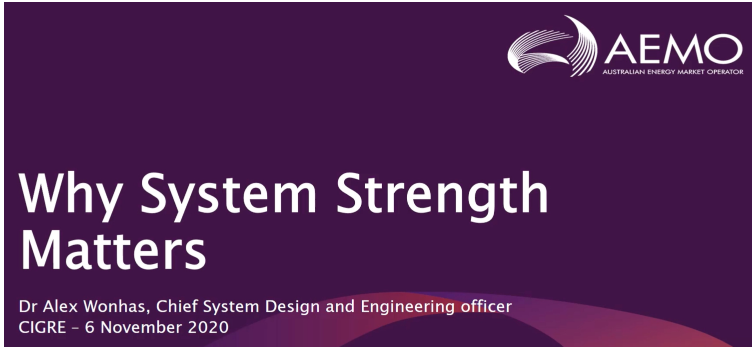
Outline

- Analytical model design
  - **Weak grid oscillation** analysis
    - Real-world events:
      - PESGM 2017 First Solar 7-Hz Oscillations
      - Australia West Murray 7-Hz oscillations, 19-Hz oscillations
  - *Demonstrate the analytical model design, validation and analysis procedure*
- Other research outcomes
  - On modeling
  - On measurement-based analysis

IBR weak grid integration

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

- AEMO “Grid Strength” workshop- Nov. 2020 (1100 registered attendees)
  - Alex Wonhas: “In my view, **system strength is arguably the final frontier that we have to master to make the energy transition happen**.”
  - Babak Badrzadeh: **Stability, protection, and power quality becomes a trinity problem**.



Dominion Energy 22-Hz oscillations

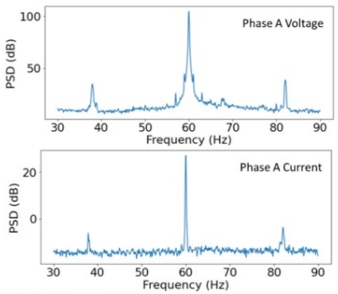


Fig. 17. PSD plots of voltage and current PoW data.

Australia 19-Hz oscillations

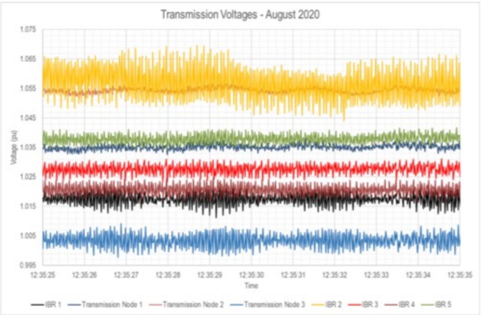
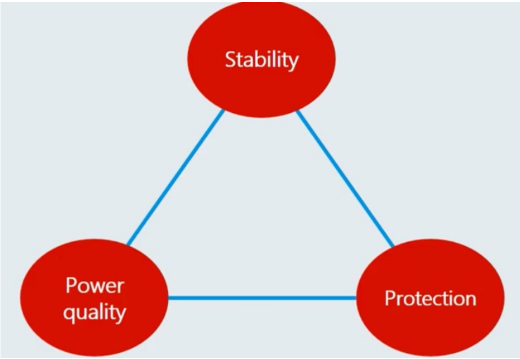


Fig. 15. AEMO 19-Hz oscillations - West Murray area.



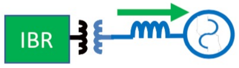
Can grid-forming converter solve the weak grid issue?

Funded by: SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy

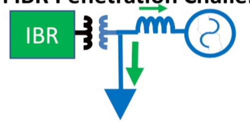
- Sebastian Achilles (GE Energy Consulting) ESIG webinars:
  - Nov. 11, 2021: Weak Grid connection of IBR: why are we still talking about this?
  - August 2017: Interconnection of Wind and Solar Power Plants to Weak Grids
- Important message: **Grid forming converter is not a magic bullet.**

SCR to evaluate Grid Following (GFL) and Grid Forming (GFM)

Power Transfer Challenges (PTC)



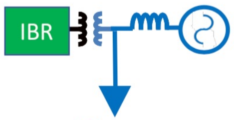
High IBR Penetration Challenges (HIPC)



Load Power [pu] (1)	SCR (2)	GFL (3)	GFM	Challenge
0	1.5+	☑	☑	
0	1.0 to 1.5	Could work	Could work	PTC
0	<1.0	☒ 🍎	☒	PTC
0.5	0.75+	☑	☑	
0.5	0.5 – 0.75	Could work	Could work	PTC and HIPC
0.5	<0.5	☒	☒	PTC and HIPC
1	<0.2	☒(4)	☑ 🍌	HIPC

(3) Advance commercially available GFL IBR technology
(4) May work in some conditions

(2) X = 1/SCR



(1) Load

Comparisons of 🍎 with 🍌 are not recommended
GFM main advantages are not related to Power Transfer constrained applications

ESIG

Source: Sebastian Achilles

Why analytical model?

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

For dynamic phenomena, we want to develop fundamental understanding, crucial insights, and find mitigation solutions. We need to rely on the classic nuts and bolts tool: **linear system analysis**.

Simulation model ≠ Analytical model

Analytical models:

- continuous, nonlinear, state variables constant at steady state.
- capable of large-signal simulation and small-signal analysis.

High Fidelity EMT model including converter switching sequences (discrete)

→ Averaging technique (1970s) →

EMT models with state variables are **sinusoidal** at steady state.

↓ abc to dq or Park's transformation (1920s) ↓

Models with state variables **constant** at steady state.

← Numerical perturbation ←

LTI model

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

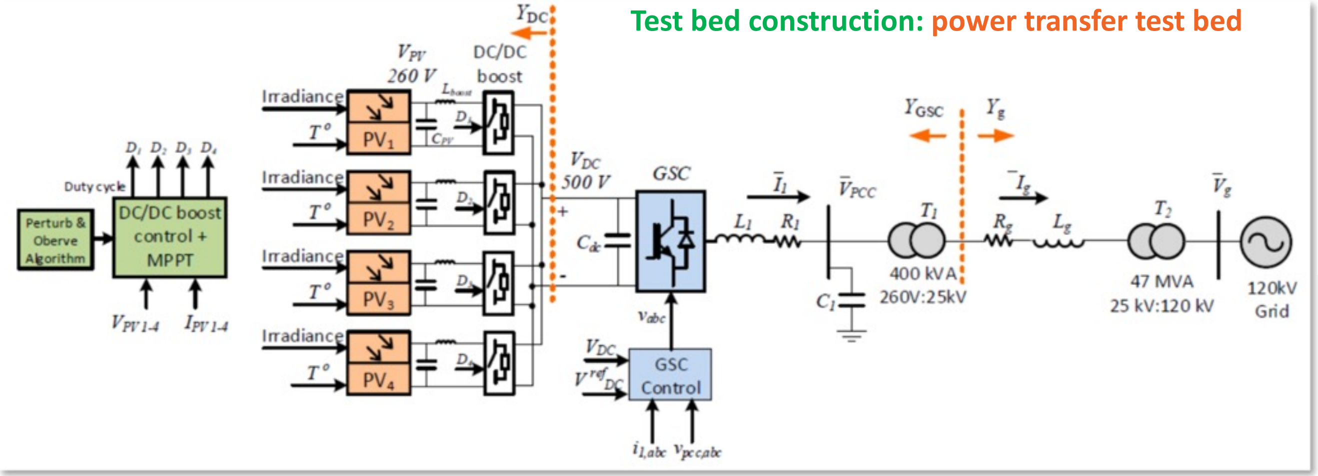
RMS-models (PSS/E, PSLF, Powerworld, TSAT) are analytical models.

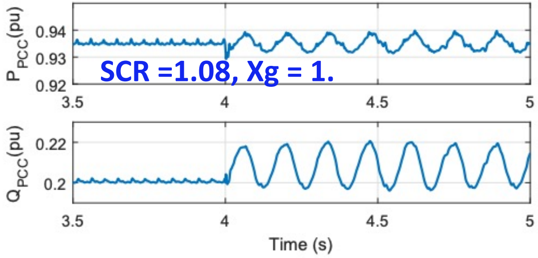
Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

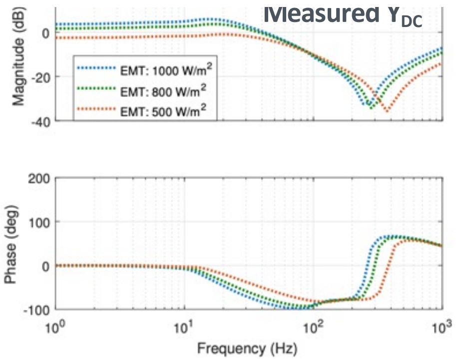
Analytical model design

EMT test bed → Analytical model design → Linear system analysis → Further simplification → More insights developed

Test bed construction: power transfer test bed







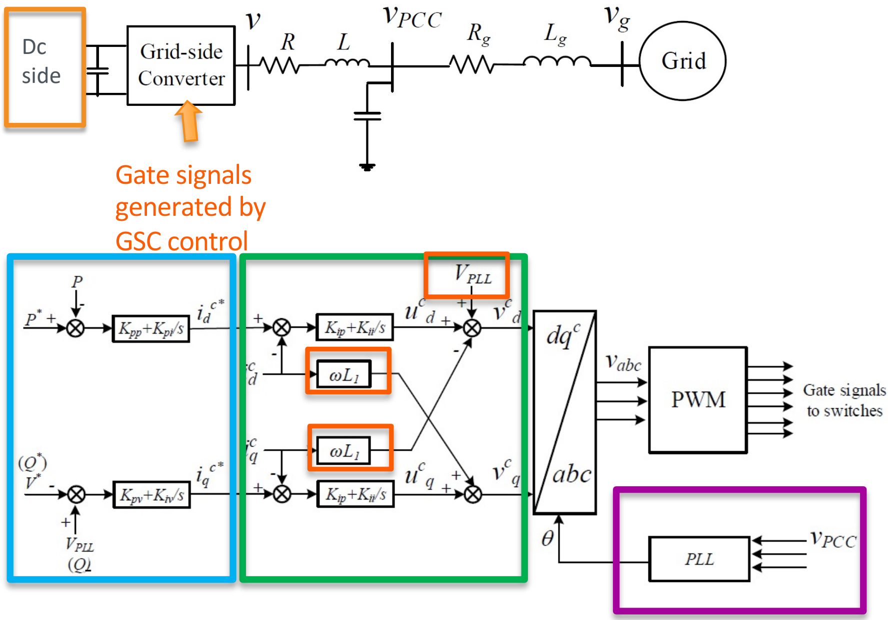
400-kW grid-connected PV farm detailed EMT testbed in MATLAB/SimScape

M. Zhang, Z. Miao, L. Fan, "**Reduced-Order Analytical Model of Grid-Connected Solar Photovoltaic Systems for Low-Frequency Oscillation Analysis**," *IEEE trans. Sustainable Energy, 2021*

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Essential part: inverter control

- Grid-following inverters (voltage source converters) have standard control structure. Several textbooks are available [1][2].
  - PCC voltage oriented vector control: **decoupled P(or Vdc)/Q control**: d-axis for P regulation, q-axis for Q regulation, d-axis aligned with the PCC voltage
  - Vector control consists of outer power/voltage control and **fast inner dq-axis current controls**
  - Vector control relies on phase-locked-loop (**PLL**) to sense PCC voltage frequency and angle for synchronization.
  - Decoupled from grid relying on **voltage feedforward and cross-coupling**

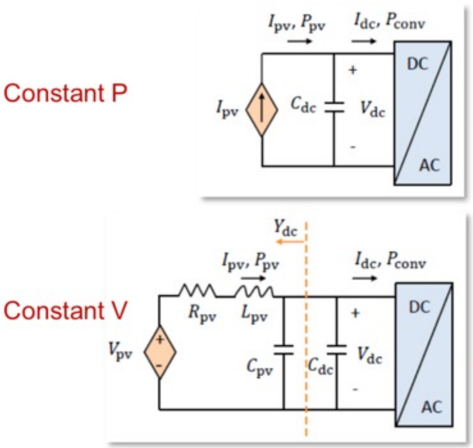


[1] Yazdani, Amirnaser, and Reza Iravani. Voltage-sourced converters in power systems. John Wiley & Sons, 2010.
[2] R. Teodorescu, M. Liserre, and P. Rodriguez, Grid Converters for Photovoltaic and Wind Power Systems, Joh Wiley & son, 2011.

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

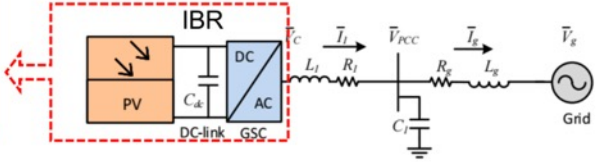
Analytical model design

EMT test bed → Analytical model design → Linear system analysis → Further simplification → More insights developed



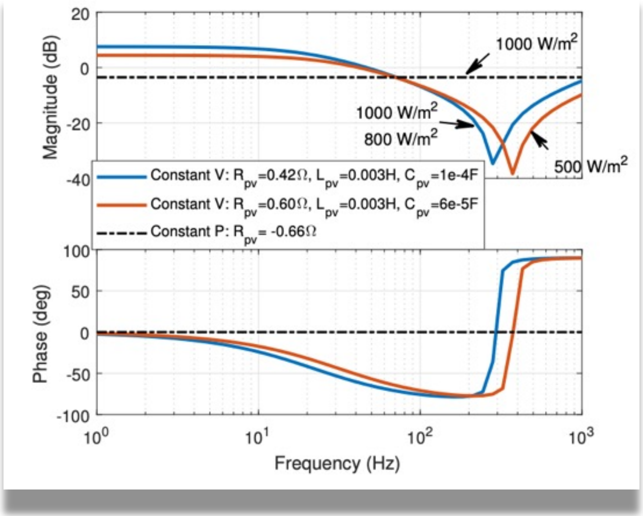
Different dc side assumptions

First simplification: dc-side dynamics



Simplified PV farm model topology

RLC circuit representation: Y_{DC}

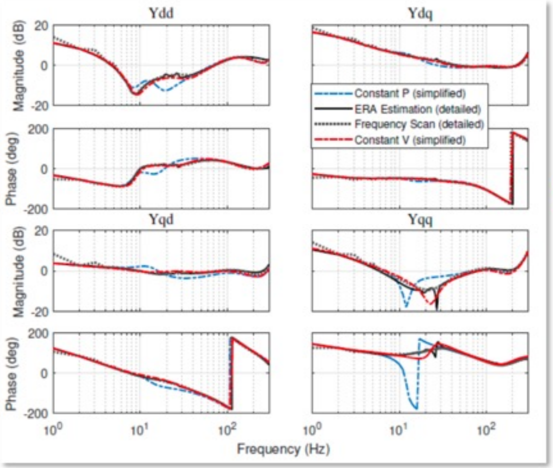


Is the RLC representation reasonable?

Analytical model design

EMT test bed → Analytical model design → Linear system analysis → Further simplification → More insights developed

Another round of validation: ac side frequency response comparison



Frequency-domain comparison on $Y_{VSC,dq}$

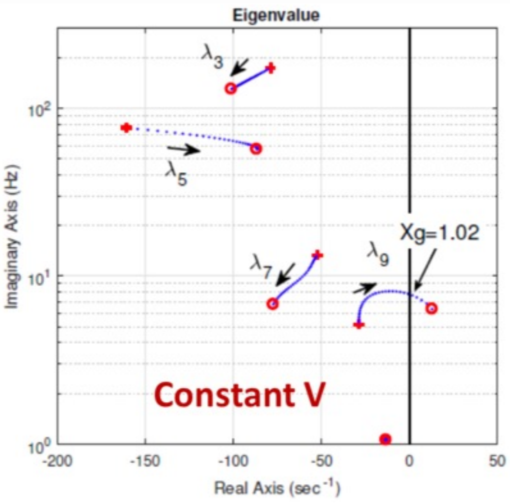


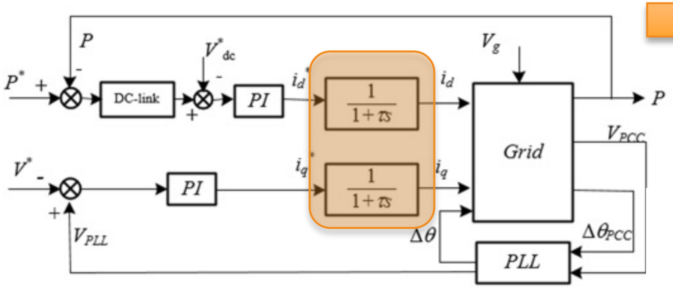
TABLE V: Participation factor table for the constant dc voltage model

State Variable	$\lambda_{1,2}$	$\lambda_{3,4}$	$\lambda_{5,6}$	$\lambda_{7,8}$	$\lambda_{9,10}$
V_{dc}^2	0.0002	0.0391	0.0353	**0.4985**	**0.2519**
i_{1d}^g	**0.3832**	0.0612	0.0968	0.0135	0.0047
i_{1q}^g	**0.1146**	**0.1605**	**0.1207**	0.0481	0.0087
i_{gd}^g	0.0469	**0.1242**	**0.3302**	0.0546	0.0193
i_{gq}^g	0.0161	**0.3067**	**0.4698**	**0.1089**	0.0482
$v_{PCC,d}^g$	**0.3892**	**0.1344**	**0.1207**	0.0333	0.0134
$v_{PCC,q}^g$	0.0943	**0.3279**	**0.1049**	0.0195	0.0029
θ	0.0118	0.0100	**0.1061**	**0.5326**	**0.3930**
$\Delta\omega$	0.0001	0.0003	0.0066	**0.1787**	**0.1694**
VFF	**0.1646**	**0.1192**	**0.4271**	**0.1413**	0.0526
V_{dc} PI	0.0000	0.0046	0.0093	**0.4236**	**0.1708**
V_{PCC} PI	0.0018	0.0152	**0.1170**	**0.4449**	**0.4296**
q-axis current PI	0.0012	0.0015	0.0182	0.0205	0.0159
d-axis current PI	0.0000	0.0003	0.0016	**0.4607**	0.0710
I_{pv}	0.0001	0.0013	0.0101	0.0420	0.0063

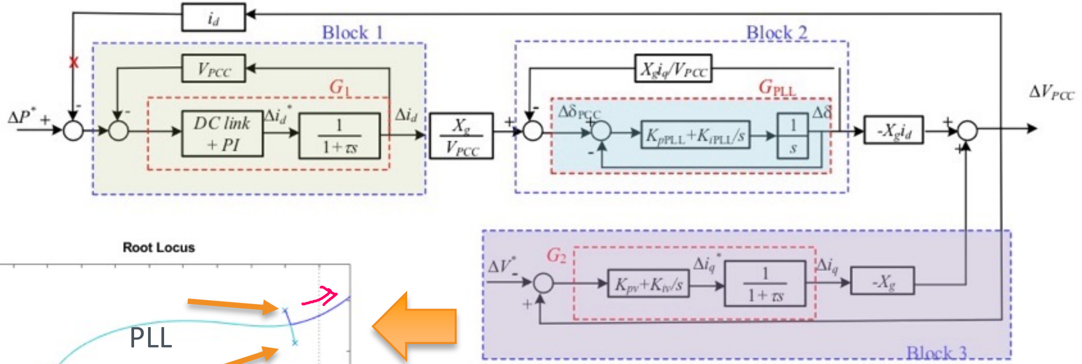
The weak grid mode is associated with PLL, Vdc and Vac control.

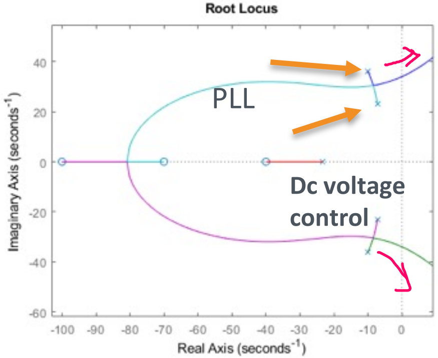
Analytical model design

EMT test bed → Analytical model design → Linear system analysis → Further simplification → More insights developed



Ignore current control, while focusing on outer control and PLL.





Weak grid stability → dynamic voltage stability

-- Lower grid strength, higher power transfer level make things worse.

-- mode frequency is related to dc voltage control bandwidth and PLL bandwidth

Funded by: SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy

Insights revealed→ enhancement designed

- Control design can be contemplated
  - Faster voltage control enhances stability
  - Decoupling power and voltage can enhance stability

Y. Li, L. Fan, and Z. Miao, "Stability Control for Wind in Weak Grids," IEEE Transactions on Sustainable Energy, vol. 10, no. 4, pp. 2094–2103, Oct. 2019, doi: 10.1109/TSTE.2018.2878745.

[7]

An inverter based solution that naturally scales with the IBR plant, thereby addressing the issue at the source rather than masking it at the Point of Connection (PoC), would be ideal. One proposed technique is a fast acting supplementary voltage control with sufficient bandwidth to functionally de-couple the IBR voltage from its active power output over a wider range of system impedances.

SMA: 5-7 Hz solar PV oscillation mitigation in AEMO

Practical experience with mitigation of sub-synchronous control interaction in power systems with low system strength

C. HARDT[1], D. PREMM[1], P. MAYER[2], F. MOSALLAT[2], S. GOYAL[3]
[1]SMA Solar Technology AG, Germany
[2]Manitoba Hydro International Ltd., Canada
[3]Powerlink Queensland, Australia

CIGRE Science & Tech, June 2021

Plant level controls typically operate on the basis of RMS measurement values and via IP based communication interfaces. This results in a lack of necessary bandwidth to adequately address relevant SSCI phenomena [18]. **Additional system strength support in the relevant frequency ranges can be provided by fast action of inverter level functions.** Regarding SSCI, such a function would be inverter level voltage control (ILVC), which may be optimized to provide damping to the frequency range of interest.

Research outcomes on modeling

- M. Zhang, Z. Miao, L. Fan, "**Reduced-Order Analytical Model of Grid-Connected Solar Photovoltaic Systems for Low-Frequency Oscillation Analysis**," *IEEE trans. Sustainable Energy, 2021.*

- L. Fan, Z. Miao, and M. Zhang, "**Subcycle Overvoltage Dynamics in Solar PVs**," *IEEE trans. Power Delivery, 2021*. (2017 Canyon 2 Fire event)

- L. Fan, Z. Miao, "**Root Cause Analysis of AC Overcurrent in July 2020 San Fernando Disturbance** ", *IEEE trans. Power Systems*, 2021.

- L. Fan, "**Inter-IBR Oscillation Modes**," *IEEE trans. Power Systems*, 2021

- IEEE PES IBR SSO Task force paper, "**Real-World Subsynchronous Oscillation Events in Power Grids with High Penetrations of Inverter-Based Resources**," request for revision, *IEEE trans. Power Systems*. (ERCOT, AEMO, Dominion Energy, Hydro One, State Grid China)

Research outcomes on measurements

- Measuring DQ admittance using harmonic injection takes time. Is there any efficient way to measure DQ admittance?
  - L. Fan and Z. Miao, "**Time-Domain Measurements-Based DQ-Frame Admittance Model Identification of Inverter-Based Resources**," IEEE trans. Power Systems, 2021
- Demonstration: Harmonic injection and time-domain method in a PHIL set up
  - L. Fan, Z. Miao, P. Koralewicz, S. Shah, and V. Gevorgian, "**Identifying DQ-Domain Admittance Models of a 2.3-MVA Commercial Grid-Following Inverter Via Frequency-Domain and Time-Domain Data**," *IEEE trans. Energy Conversion, 2021*
- With admittance, what can we do: Is modal analysis possible?
  - L. Fan and Z. Miao, "**Admittance-Based Stability Analysis**: **Bode Plots, Nyquist Diagrams or Eigenvalue Analysis**?" IEEE trans. Power Systems, vol. 35, no. 4, July 2020, 3312-3315.
- With admittance, what can we do: Is fast time-domain simulation possible?
  - M. Zhang, L. Bao, Z. Miao, L. Fan, P. Gomez, "**Measured Admittance Model for Dynamic Simulation of Inverter-Based Resources Using Numerical Laplace Transform**," accepted, 53rd NAPS 2021.

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Conclusions

- We are in an exciting era to integrate high penetrations of solar PVs. There are many challenges. The foremost one is grid reliability, specifically weak grid integration (final frontier).
- Design of **analytical models and tools** is key to develop crucial insights and develop grid reliability enhancement solutions. In addition, many tools can be used as leverage during the design: system identification, control theory, besides EMT simulation and hardware experiments.
- For power systems dynamics people, this is the **beginning** of our work on solar PV and IBR grid integration.