OAK RIDGE National Laboratory

Emerging Needs for a Generic IBR Model in EMT Domain

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Electromagnetic Transient Simulation Workshop

Oak Ridge National Lab

Oak Ridge, August 24, 2023

Classification: public

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U.S. DEPARTMENT OF ENERGY

Acknowledgement

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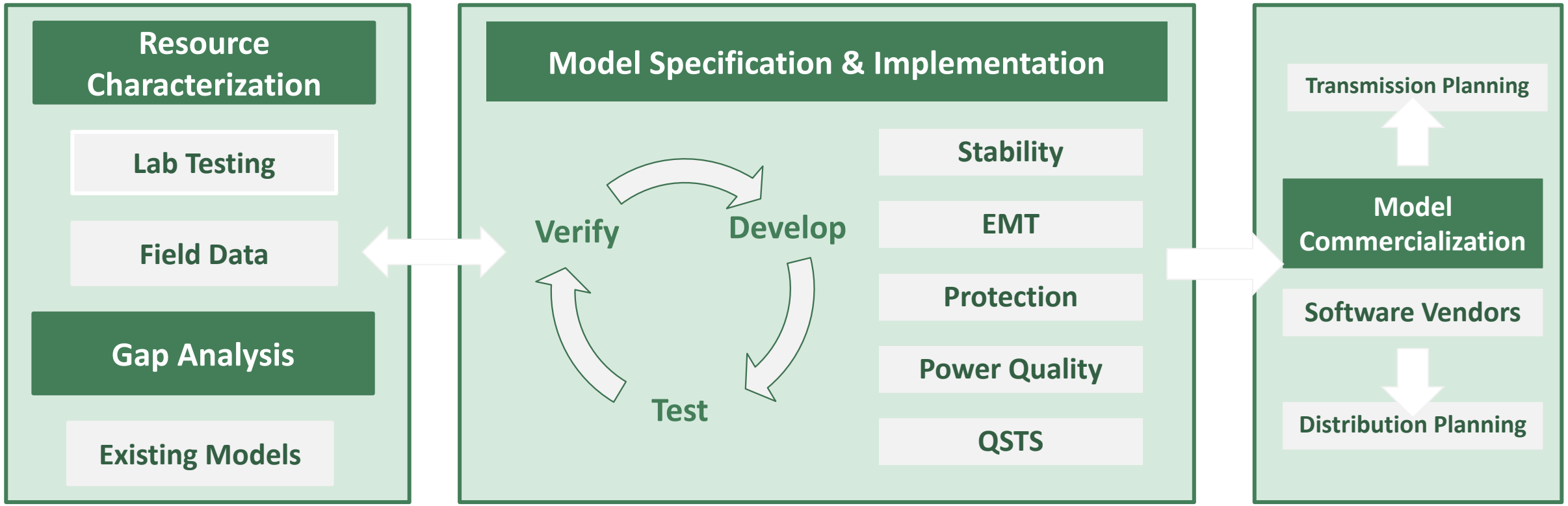
Content

- Background & Motivation
- Proposed Generic EMT Model for PV and Storage—Specification & Validation Example
- Example Use Case related to FERC Order 2023—Improvements to Generator Interconnection Procedures and Agreements
- Remaining Gaps & Challenges

PV-MOD Project Overview https://www.epri.com/pvmod

Validated; publicly available models for various types of studies, reports detailing the research, close collaboration with industry stakeholders (NERC, WECC, IEEE, etc.)



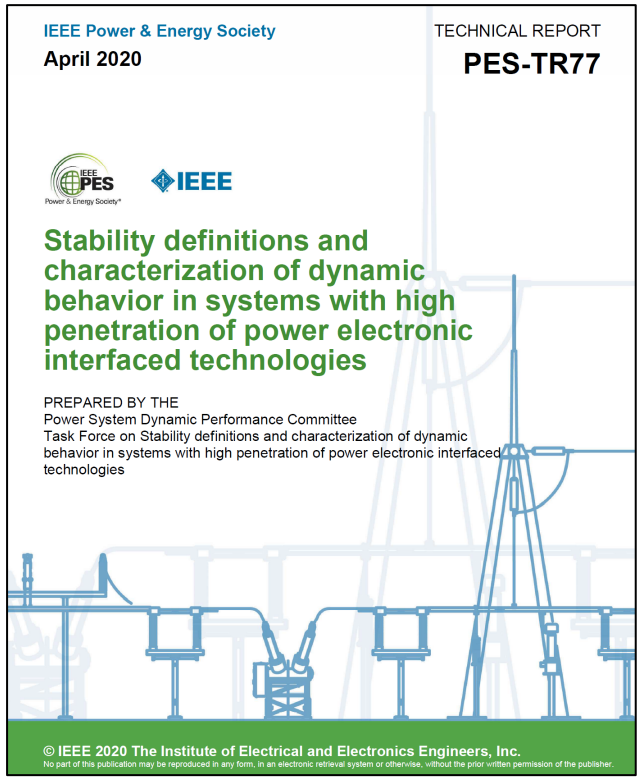
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

This deliverable is, in part, supported by the U.S. Department of Energy, Solar Energy Technologies Office under Award Number DE-EE0009019 *Adaptive Protection and Validated MODels to Enable Deployment of High Penetrations of Solar PV (PV-MOD)*.

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

This deliverable is, in part, supported by the North American Electric Reliability Corporation (NERC) under EPRI contract 20011165 *Inverter-Based Resources Dynamic Response Characterization for Bulk Power System Protection, Planning, and Power Quality*.

Need for EMT models of IBRs



"Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies," Technical Report April, 2020. [Online]. Available: https://resourcecenter.ieee-pes.org/publications/technical-reports/PES_TP_TR77_PSDP_stability_051320.html

"IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems," in *IEEE Std 2800-2022* , vol., no., pp.1-180, 22 April 2022, doi: 10.1109/IEEESTD.2022.9762253.

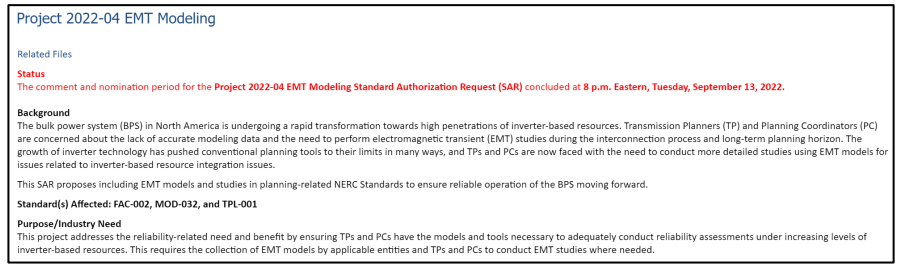
https://www.nerc.com/pa/rrm/ea/Pages/Major-Event-Reports.aspx

MOD-026-2 – Verification of Dynamic Models and Data for BES Connected Facilities

A. Introduction

1. **Title:** Verification of Dynamic Models and Data for BES Connected Facilities
2. **Number:** MOD-026-2
3. **Purpose:** To verify that the dynamic models and associated parameters used to assess Bulk Electric System (BES) reliability represent the in-service equipment of BES Facilities including generating Facilities, transmission connected dynamic reactive resources, and high-voltage direct current (HVDC) systems.

https://www.nerc.com/pa/Stand/Pages/Project-2020_06-Verifications-of-Models-and-Data-for-Generators.aspx



https://www.nerc.com/pa/Stand/Pages/Project2022-04EMTModeling.aspx

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Need for Generic Models
Transmission planning perspective

- Futuristic studies
- Development and communication of grid-specific performance requirements
- Investigation of site-specific requirements
- Existing facilities where EMT models are not available
- Education

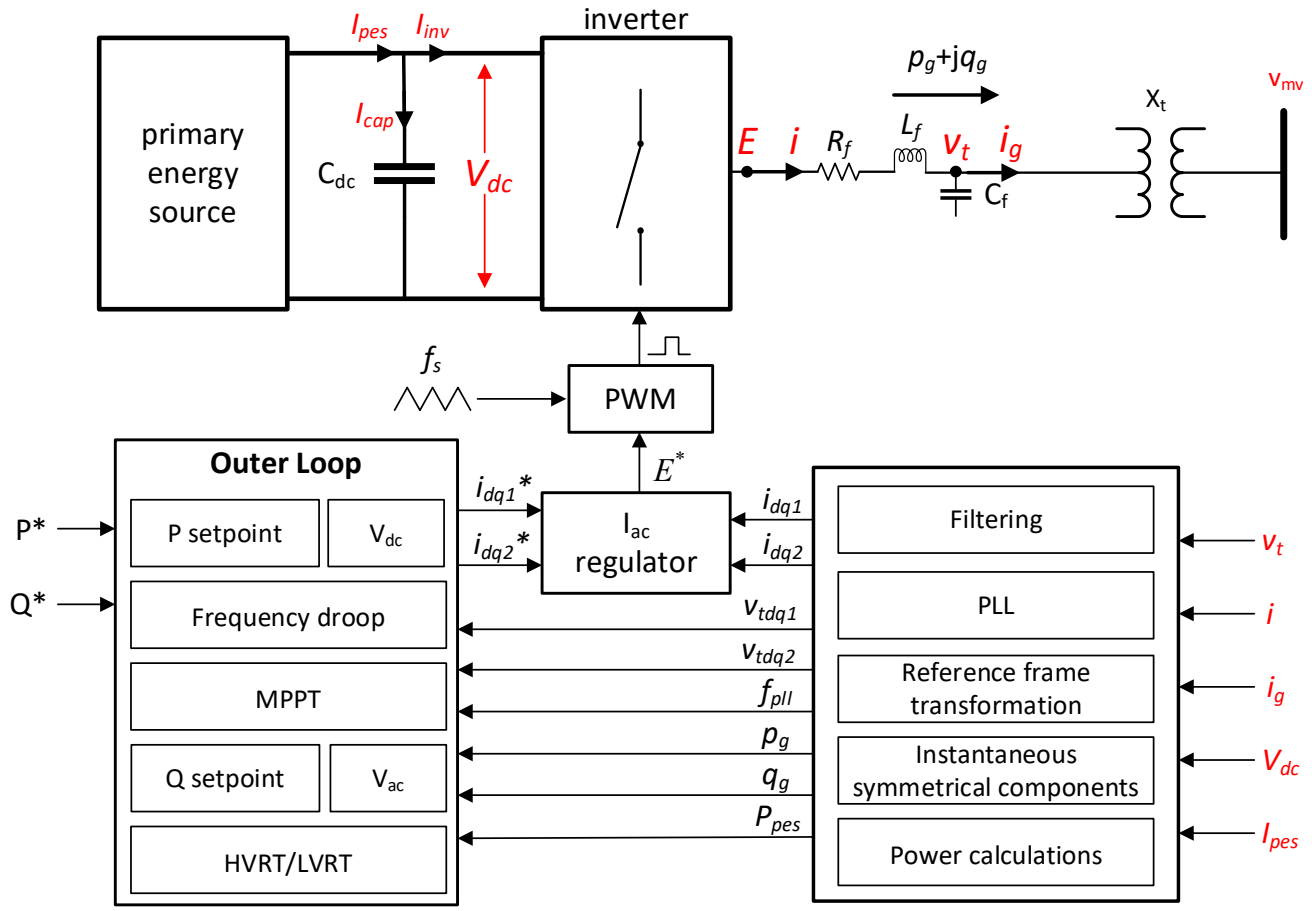
But … the model should be reasonable

Generic EMT Model for PV and Storage
Based on IEEE Std 2800-2022 performance requirements

- Include control that allows the IBR to meet the IEEE Std 2800-2022 performance requirements
- Include varying levels of modeling simplifications
  - DC dynamics
  - Converter model
- Ensure the model is reasonable
  - Comparisons to commercial inverter responses

Ref: Generic Photovoltaic Inverter Model in an Electromagnetic Transients Simulator for Transmission Connected Plants: PV-MOD Milestone 2.7.3. EPRI, Palo Alto, CA: 2022
https://publicdownload.epri.com/PublicAttachmentDownload.svc/AttachmentId=82135

Generic EMT model
PV or storage inverter model

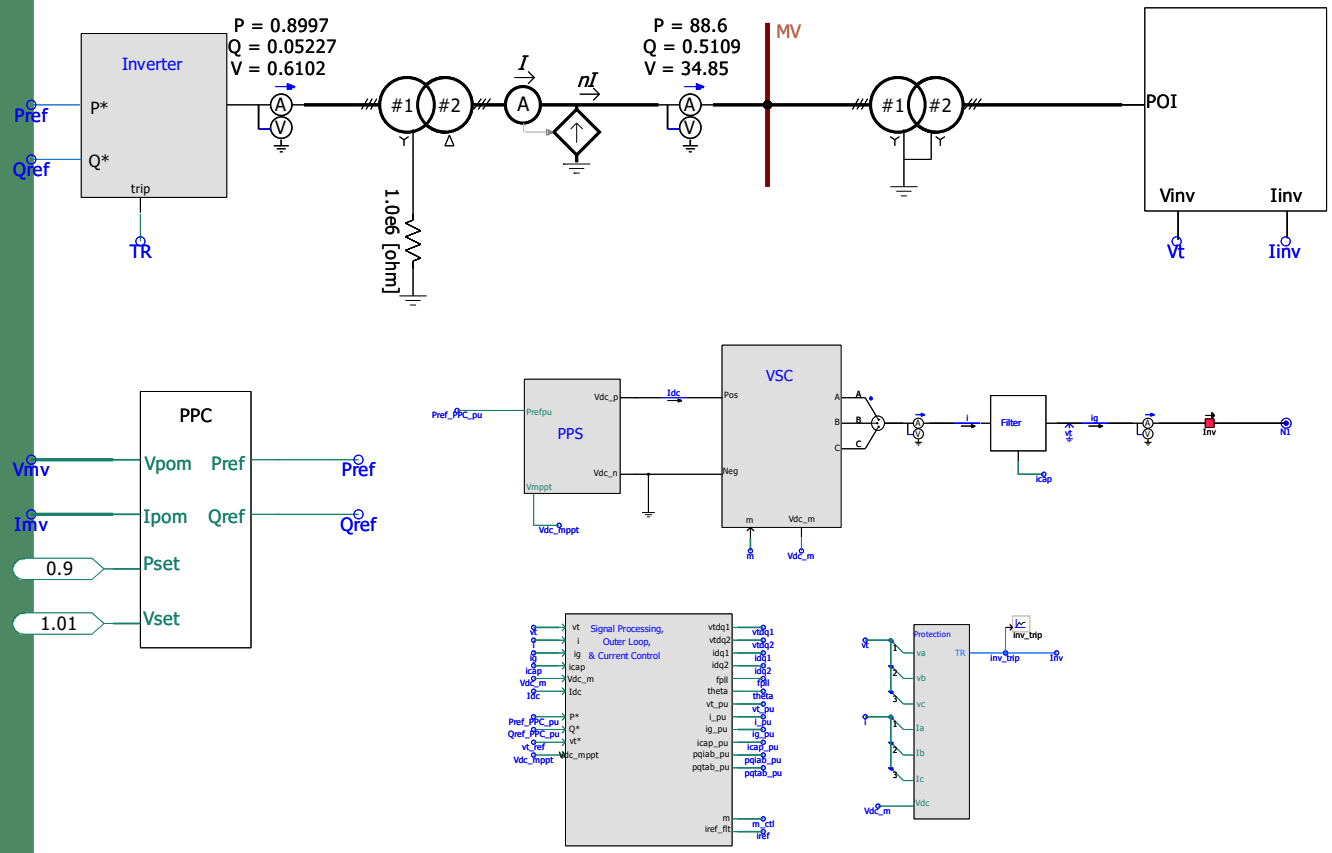


Generic inverter model

- → Current-controlled, PWM VSC
- → Control implemented in dual dq frames: positive and negative sequences
- → Controllers developed based on IEEE 2800-2022 FRT response requirements
- → Setpoint controllers: Vdc, P, Vac, and Q

Ref: Generic Photovoltaic Inverter Model in an Electromagnetic Transients Simulator for Transmission Connected Plants: PV-MOD Milestone 2.7.3. EPRI, Palo Alto, CA: 2022
https://publicdownload.epri.com/PublicAttachmentDownload.svc/AttachmentId=82135

Generic EMT model
Implemented in PSCAD™



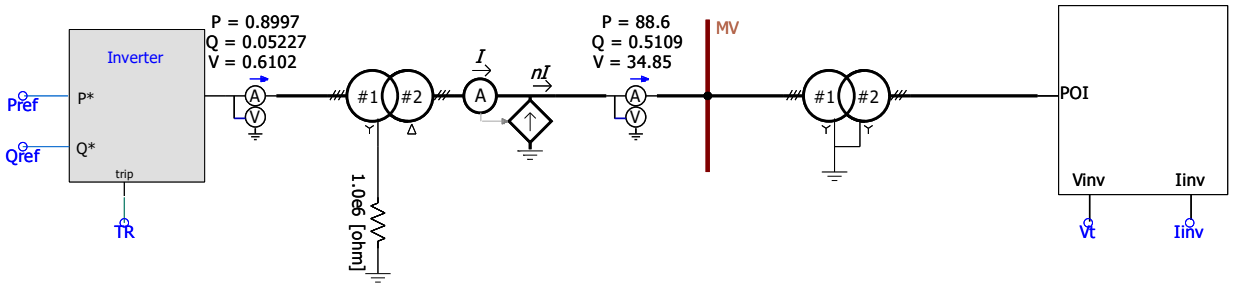
0. inverter data	
Sinv: Inverter rated aparant power (VA)	1e6
VLL_base: inverter rated RMS voltage line-line (V)	600
fnom: nominal frequency	60.0
Lf: LC filter inductance	0.0001
Rf: LC filter resistance	0.00075
Cf: LC filter capacitance (uF)	147
Rd: LC filter damping resistance	0.05 [ohms]
Cdc: DC link capacitor capacitance (uF)	0.1e6
Vdc_nom: DC link voltage nominal	1200
fs: PWM switching frequency (switching model)	3060.0
tstart_up: Start-up time	2.0
1. control configuration	
Vsp_flg (1: enable inverter term. voltage control,	0
Qsp_CL_flg (1: closed loop Q control, 0: open loo	0
qt_flg (1: Q control at terminal after LC filter, 0: Q	1
Vdc_flg (1: enable Vdc control, 0: voltage source	0
PV_flg (1: enable PV array I-V characteristic, 0: co	0
MPPT_flg (1: enable MPPT for Vdc*, requires VI-fl	0
f_flg (1: to enable frequency-droop control, 0: dis	0
2. reactive power - voltage control	
Qmax: reactive power maximum limit	0.4
Qmin: reactive power minimum limit	-0.4
iq1_max: reactive current maximum limit	99
iq1_min: reactive current minimum limit	-99
Kqp: Q closed-loop propotional gain	0
Kqi: Q closed-loop integral gain	40
Kvp: terminal voltage control proportional gain	0
Kvi: terminal voltage control integral gain	100
vt_ref: terminal voltage control reference setpoint	1.0
Tv: Voltage LPF time constant	0.01
3. Vdc control	
kp_vdc:Vdc propotional gain	5.18
ki_vdc: Vdc integral gain	52.91
4. frequency-droop	
fdbd1: deadband for frequency droop control (< (	-0.0006
fdbd2: deadband for frequency droop control (> (	0.0006
Dup: 1/Droop for low frequency	20.0
Ddn: 1/Droop for high frequency	20.0
Tfrq: 1st order LPF time constant for PLL frequenc	0.1

5. FRT	
Ilim_pu: current limit	1.0
ipri_flg: current priority (1: iq, 0: ip)	1
Vlvrt: threshold for LVRT	0.9
Vhvrt: threshold for HVRT	1.1
V1_frt_dbstep_flg: set FRT V1 deadband as step	0
Kqv1_lvrt: LVRT V1 proportional gain	2
Kqv1_hvrt: HVRT V1 proportional gain	2
iq1i_flg	1
Kqv 2: FRT V2 proportional gain	2
V2_db: V2 FRT dead band	0.1
V2_frt_dbstep_flg: set FRT V1 deadband as step	1
DelI_flg	1
6. PLL	
kp_pll: Propotional gain for PLL	40
ki_pll: Integral gain for PLL	4
limpllmax: PLL integrator windup limit	70
7. signal processing	
Iflt_flg: Current filter flag (1: enable)	1
Tflt_i: Current LPF time constant	0.00001
Vflt_flg: Voltage filter flag (1: enable)	1
Tflt_v: Voltage LPF time constant	0.00001
8. current control	
kp_cur: Proportional gain current controller	0.9
ki_cur: Integral gain current controller	900.0
limcurmax: anti-windup upper limit	99999
limcurmin: anti-windup lower limit	-99999
ip_ramp_up: Ramp rate for increasing active curre	1.0
Vff_flg: (1: enable voltage feedforward, 0: disable	0
Tvff: Vff LPF time constant	0.0001

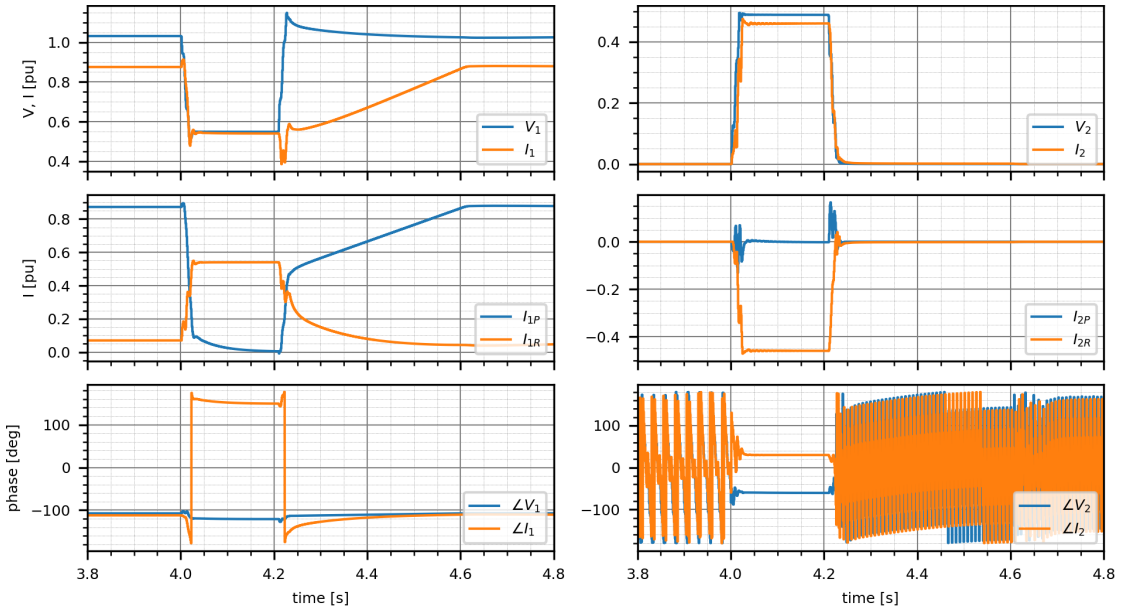
Ref: PRE-SW: Generic Photovoltaic Inverter Model in an Electromagnetic Transients Simulator for Transmission Connected Plants (PVMOD-EMT-IBR) v1.0 Beta. EPRI, Palo Alto, CA: 2023. 3002025889 Online: https://www.epri.com/research/products/000000003002025889

Generic EMT model

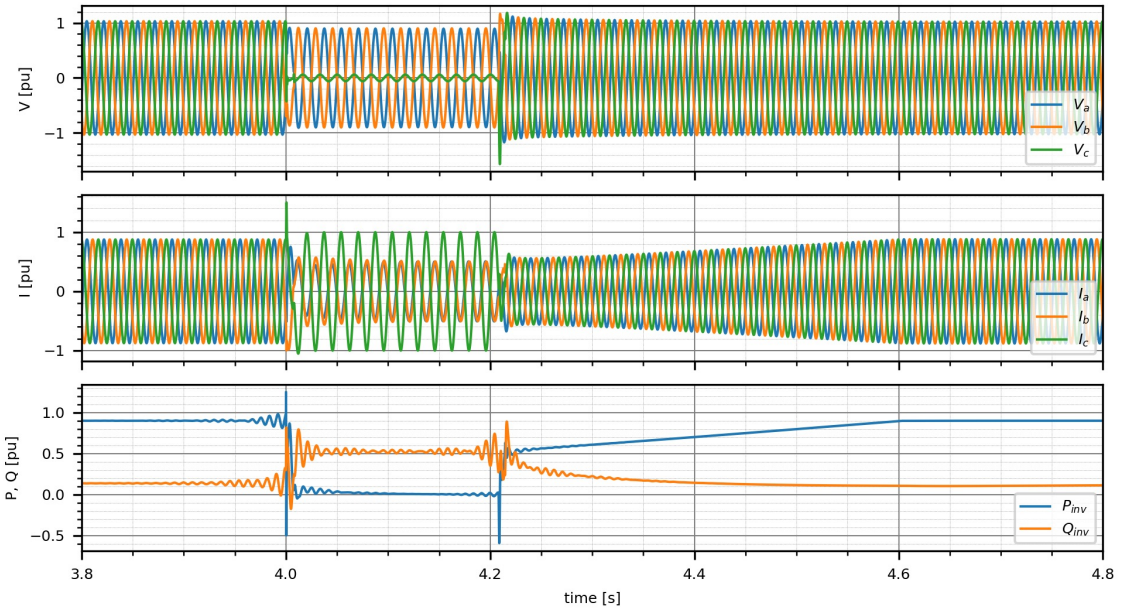
FRT response tests: B-C fault at POI example



B-C fault: Fundamental Freq. Symmetrical Components



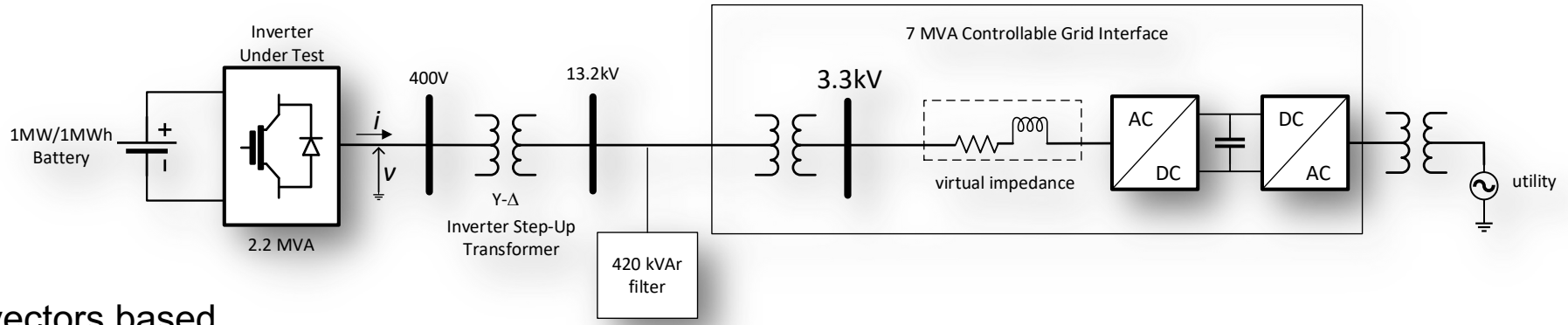
Instantaneous voltage, current, active power, and reactive power



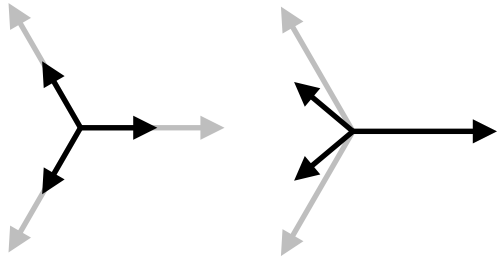
Ref: W. Baker, M. Patel, A. Haddadi, E. Farantatos, J. Boemer, "Inverter Current Limit Logic based on the IEEE 2800-2022 Unbalanced Fault Response Requirements", *2023 IEEE Power Engineering Society General Meeting*

Validation example
Laboratory testing of a 2.2 MVA commercial battery inverter

Laboratory test circuit



Voltage vectors based on IEEE Std 1668-2017



Varying residual voltage in faulted phases at the 13.2 kV bus

Fault type	Faulted Phase(s) Residual 13.2 kV Voltage [pu]
LLLG	0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9
LL (B-C)	0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9

1. NREL test facility: https://www.nrel.gov/docs/fy19osti/72886.pdf
2. Draft Test Plan and Candidate Inverter List: Adaptive Protection and Validated MODels to Enable Deployment of High Penetrations of Solar PV (PV-MOD). EPRI, Palo Alto, CA: 2023. Milestones 1.3.2 and 1.3.3 report for DOE. Online: https://publicdownload.epri.com/PublicAttachmentDownload.svc/AttachmentId=82091 and https://www.epri.com/pvmod
3. W. Baker, D. Ramasubramanian, A. Huque, J. Boemer, V. Gevorgian, P. Koralewicz, E. Mendiola, "Validation of the Fault Ride-Through Response of a Generic EMT Inverter Model by Laboratory Testing", *2023 IEEE Power Engineering Society General Meeting*

Validation example

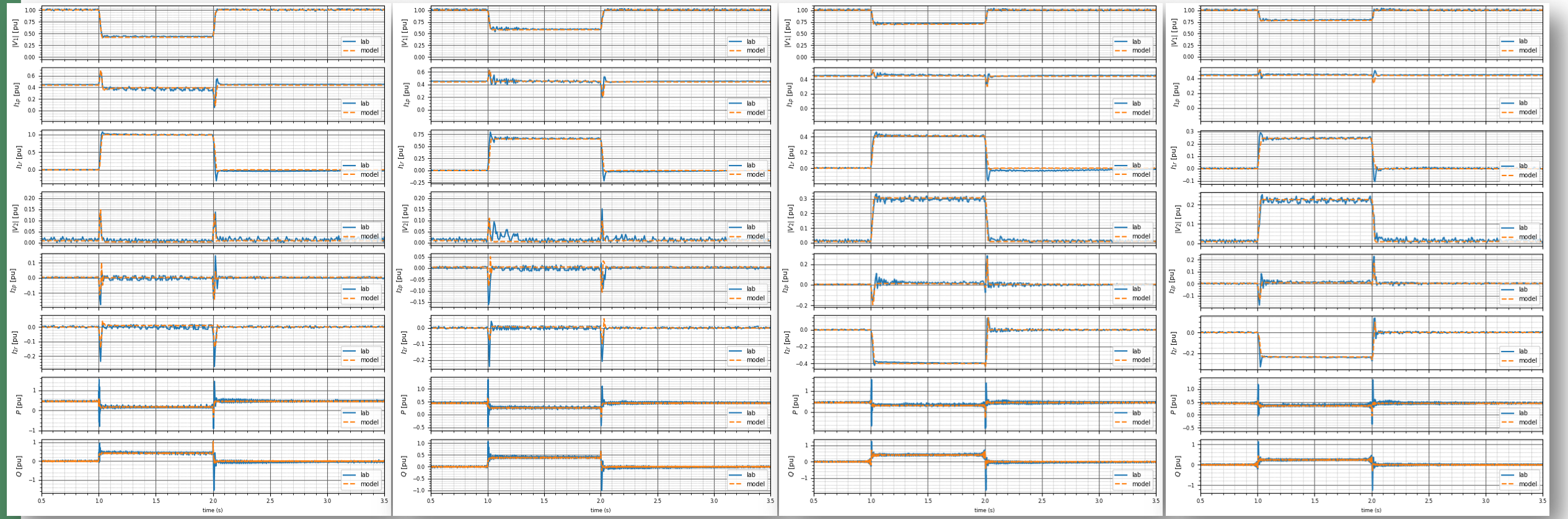
Comparison of the EMT model's response ('model') to the measured response of the IUT ('lab') to balanced and unbalanced faults

LLLG fault with $|\mathbf{V_1}|$=0.4 pu

LLLG fault with $|\mathbf{V_1}|$=0.6 pu

B-C fault with $|\mathbf{V_2}|$=0.3 pu

B-C fault with $|\mathbf{V_2}|$=0.22 pu

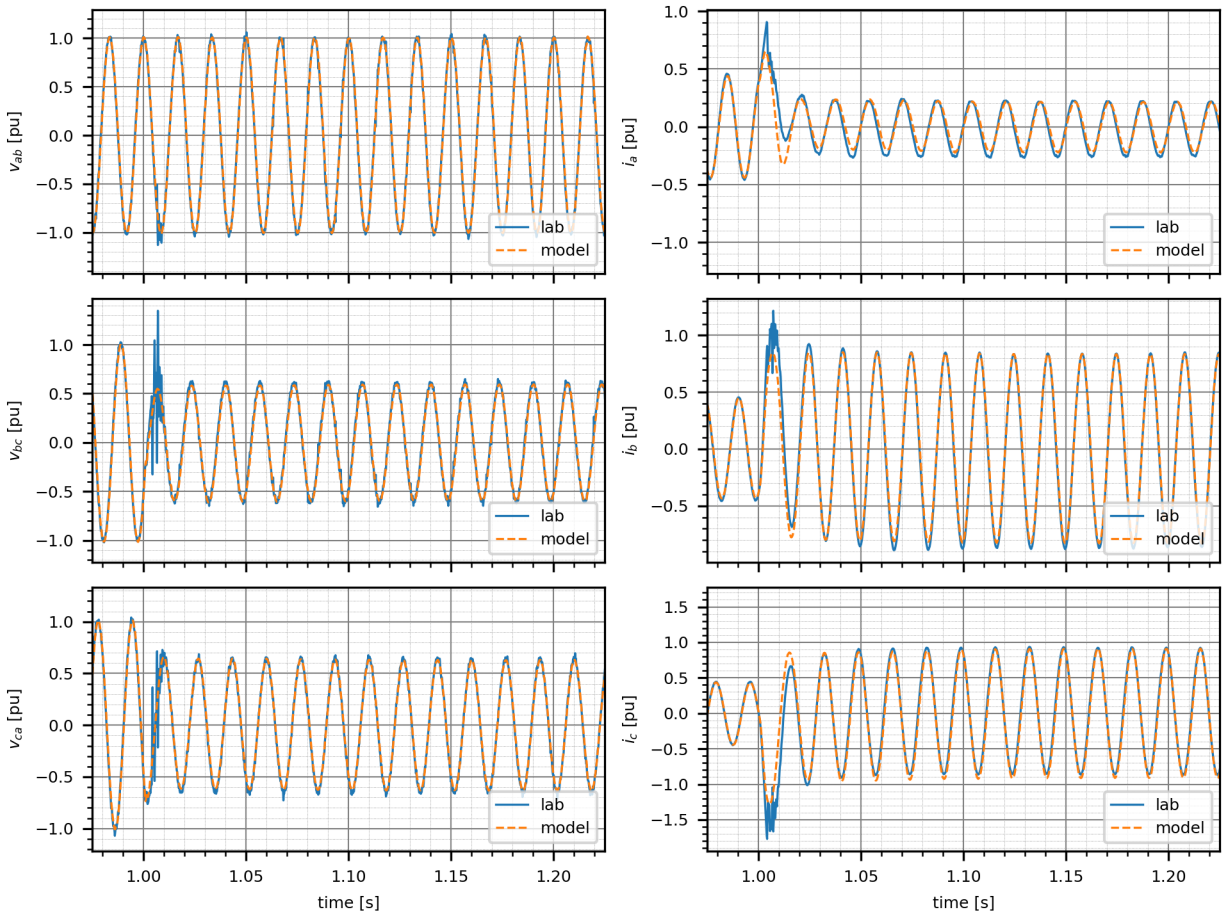


Ref: W. Baker, D. Ramasubramanian, A. Huque, J. Boemer, V. Gevorgian, P. Koralewicz, E. Mendiola, "Validation of the Fault Ride-Through Response of a Generic EMT Inverter Model by Laboratory Testing", *2023 IEEE Power Engineering Society General Meeting*

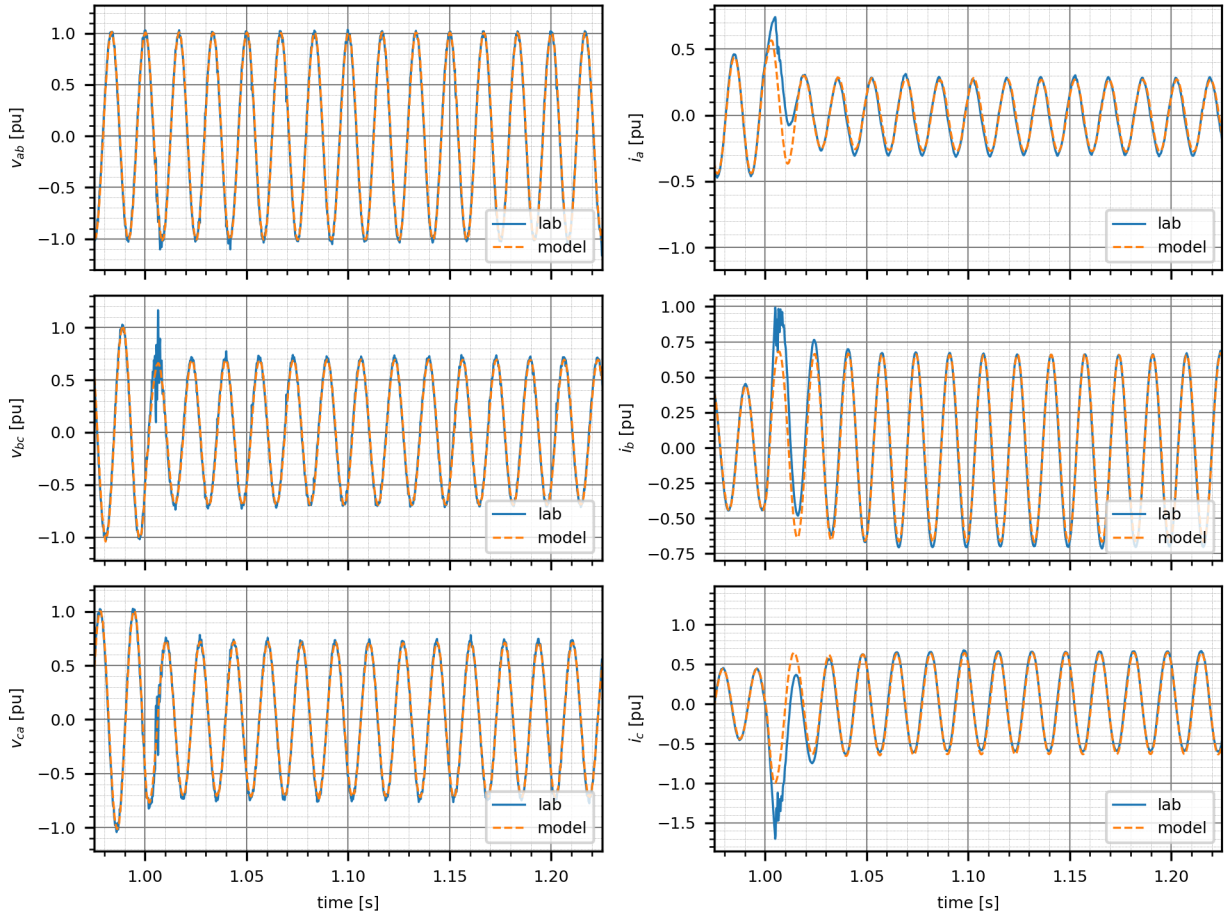
National Laboratory

Validation example

Instantaneous line-line voltage and current at fault inception



B-C fault 30% retained voltage



B-C fault 50% retained voltage

Ref: W. Baker, D. Ramasubramanian, A. Huque, J. Boemer, V. Gevorgian, P. Koralewicz, E. Mendiola, "Validation of the Fault Ride-Through Response of a Generic EMT Inverter Model by Laboratory Testing", *2023 IEEE Power Engineering Society General Meeting*

Validation example
Summary

- The generic EMT inverter model provides a reasonable prediction of the commercial inverter's FRT response for various fault types, fault severity, and initial operating conditions.

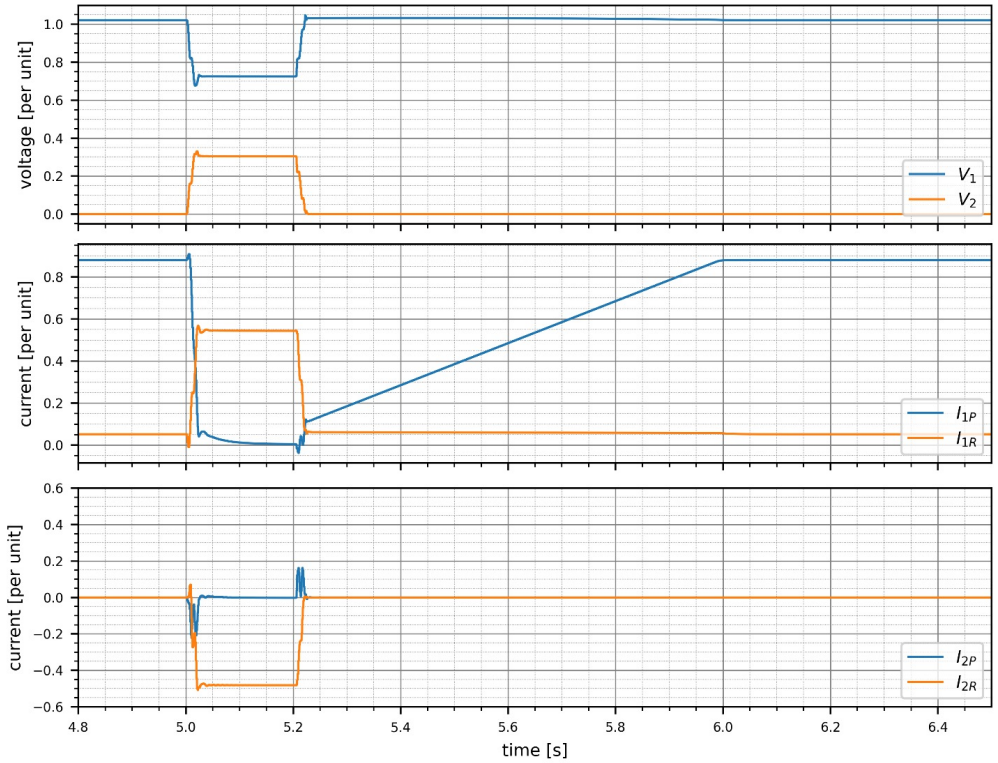
- Differences in the transient periods are observed as expected.
  - Details of the commercial inverter's design and control are unknown.
  - All details of the test circuit are not known.

- Expectation is that inverter models developed by the inverter OEMs should be much more accurate.

Example Use Case
IBR Performance Requirements

- Example IBR response for a LL fault

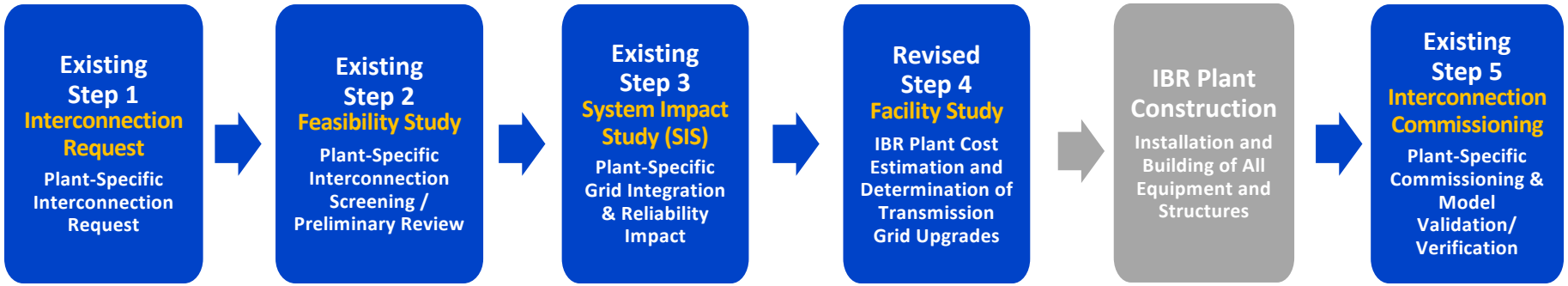
- Helps the *communication of performance requirements* to the IBR developer



Ref: Southern Company Interconnection Requirements for Transmission Connected Inverter-Based Resources.
Online: http://www.oasis.oati.com/woa/docs/SOCO/SOCOdocs/SOCO_IBR_Interconnection-Technical-Requirements_Effective_08-06-2023.pdf

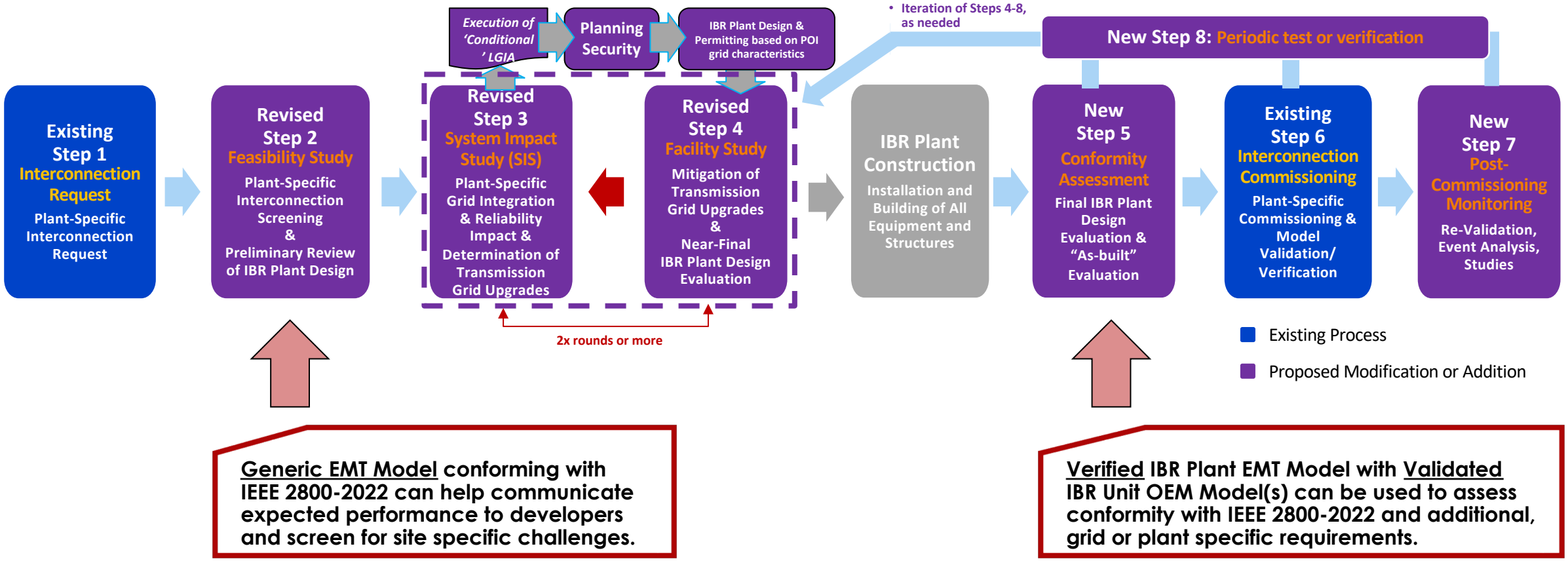
Example Use Case

Existing Interconnection Procedure as shaped by the FERC Large Generator Interconnection Process



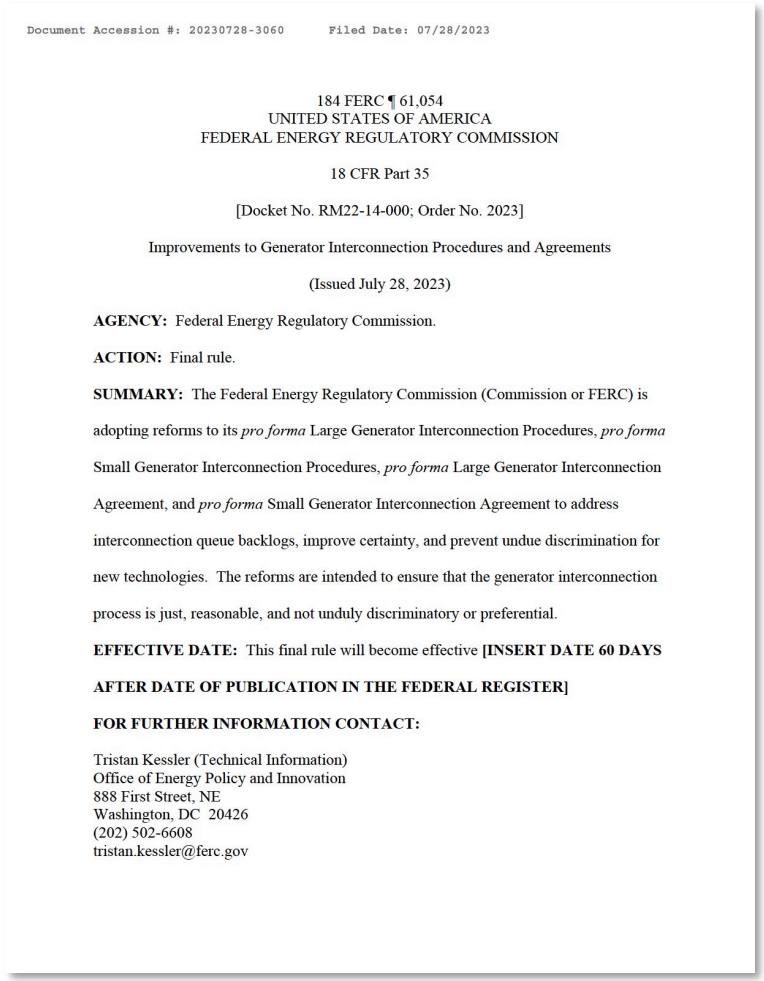
Further Reading:
J. Boemer, A. Shattuck, J. Matevosyan, *"Need for North American Interconnection Process Review"*, ESIG Blog Article, December 13, 2022.

Example Use Case
Recommended Improvements to the Interconnection Process



But:
FERC Ruled with Order 2023 on July 28, 2023, and declined to incorporate IEEE 2800-2022 by reference (for now).

FERC Order 2023 on Improvements to Generator Interconnection Procedures and Agreements (RM22-14)



Document Accession #: 20230728-3060 Filed Date: 07/28/2023

184 FERC ¶ 61,054
UNITED STATES OF AMERICA
FEDERAL ENERGY REGULATORY COMMISSION

18 CFR Part 35

[Docket No. RM22-14-000; Order No. 2023]

Improvements to Generator Interconnection Procedures and Agreements

(Issued July 28, 2023)

AGENCY: Federal Energy Regulatory Commission.

ACTION: Final rule.

SUMMARY: The Federal Energy Regulatory Commission (Commission or FERC) is adopting reforms to its *pro forma* Large Generator Interconnection Procedures, *pro forma* Small Generator Interconnection Procedures, *pro forma* Large Generator Interconnection Agreement, and *pro forma* Small Generator Interconnection Agreement to address interconnection queue backlogs, improve certainty, and prevent undue discrimination for new technologies. The reforms are intended to ensure that the generator interconnection process is just, reasonable, and not unduly discriminatory or preferential.

EFFECTIVE DATE: This final rule will become effective **[INSERT DATE 60 DAYS AFTER DATE OF PUBLICATION IN THE FEDERAL REGISTER]**

FOR FURTHER INFORMATION CONTACT:

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- Issued July 28, 2023 (link), EPRI is currently reviewing and plans to host a summary webinar soon

Scope per NOPR

- Implement a first-ready, first-served study process
  - Interconnection information access
  - Cluster Study
  - Allocation of Cluster Study Costs
  - Allocation of Cluster Network Upgrade Costs
  - Shared Network Upgrades
  - Increased Financial Commitments and Readiness Requirements
  - Transition Process
- Improve interconnection queue processing speed
  - Elimination of the reasonable effort standard
  - Affected Systems
  - Optional Resource Solicitation Study
- Incorporate technological advancements
  - Increasing Flexibility in the Generator Interconnection Process
  - Incorporating Alternative Transmission Technologies into the Generator Interconnection Process
- Update modeling and performance requirements for system reliability
  - Modeling and Performance Requirements for Non-Synchronous Generating Facilities

➢ ***FERC declined to incorporate IEEE 2800-2022 by reference and to include plant conformity assessment into interconnection process.***

Remaining Gaps & Challenges

Related to Generic EMT Model Development

- Comprehensive validation and testing of EPRI's proposed model against IEEE 2800-2022 performance requirements is ongoing.
- Implementation and benchmarking of EPRI's proposed model in other EMT modeling software like EMTP-RV, PowerFactory, OpenDSS, etc. is ongoing.
- Continuous improvement and alignment with IEEE 2800-2022 and future revisions of the standard is necessary.

Related to Generic EMT Model Application

- IEEE 2800-2022 not yet broadly adopted by many ISOs/RTOs.
- Potential value of IEEE 2800-2022 not fully recognized by FERC.
- Revision of NERC Reliability Standards may consider IEEE 2800-2022 but will likely take many years.
- Neither EPRI's nor any other entity's proposed generic, IEEE 2800 conforming EMT model is "officially recognized".

References

- Model Specification
  - Generic Photovoltaic Inverter Model in an Electromagnetic Transients Simulator for Transmission Connected Plants: PV-MOD Milestone 2.7.3. EPRI, Palo Alto, CA: 2022 Online: https://publicdownload.epri.com/PublicAttachmentDownload.svc/AttachmentId=82135
  - W. Baker, M. Patel, A. Haddadi, E. Farantatos, J. Boemer, "Inverter Current Limit Logic based on the IEEE 2800-2022 Unbalanced Fault Response Requirements", *2023 IEEE Power Engineering Society General Meeting*
- Model prototype in PSCAD™
  - *PRE-SW: Generic Photovoltaic Inverter Model in an Electromagnetic Transients Simulator for Transmission Connected Plants (PVMOD-EMT-IBR) v1.0 Beta.* EPRI, Palo Alto, CA: 2023. 3002025889 Online: https://www.epri.com/research/products/000000003002025889
- Model Validation
  - Draft Test Plan and Candidate Inverter List: Adaptive Protection and Validated MODels to Enable Deployment of High Penetrations of Solar PV (PV-MOD). EPRI, Palo Alto, CA: 2023. Milestones 1.3.2 and 1.3.3 report for DOE. Online: https://publicdownload.epri.com/PublicAttachmentDownload.svc/AttachmentId=82091
  - W. Baker, D. Ramasubramanian, A. Huque, J. Boemer, V. Gevorgian, P. Koralewicz, E. Mendiola, "Validation of the Fault Ride-Through Response of a Generic EMT Inverter Model by Laboratory Testing", *2023 IEEE Power Engineering Society General Meeting*
- FERC Order 2023: Improvements to Generator Interconnection Procedures and Agreements
  - FERC Transmission Reform Paves Way for Adding New Energy Resources to Grid. News Release. FERC. July 27, 2023. Online: https://www.ferc.gov/news-events/news/ferc-transmission-reform-paves-way-adding-new-energy-resources-grid

Thank You!

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