INTERCONNECTION INNOVATION e-XCHANGE
U.S. DEPARTMENT OF ENERGY

EMT Bootcamp for BES IBR Studies Part 2: System Impact Assessment

| 9/14/23

An initiative spearheaded by the Solar Energy Technologies Office and the Wind Energy Technologies Office

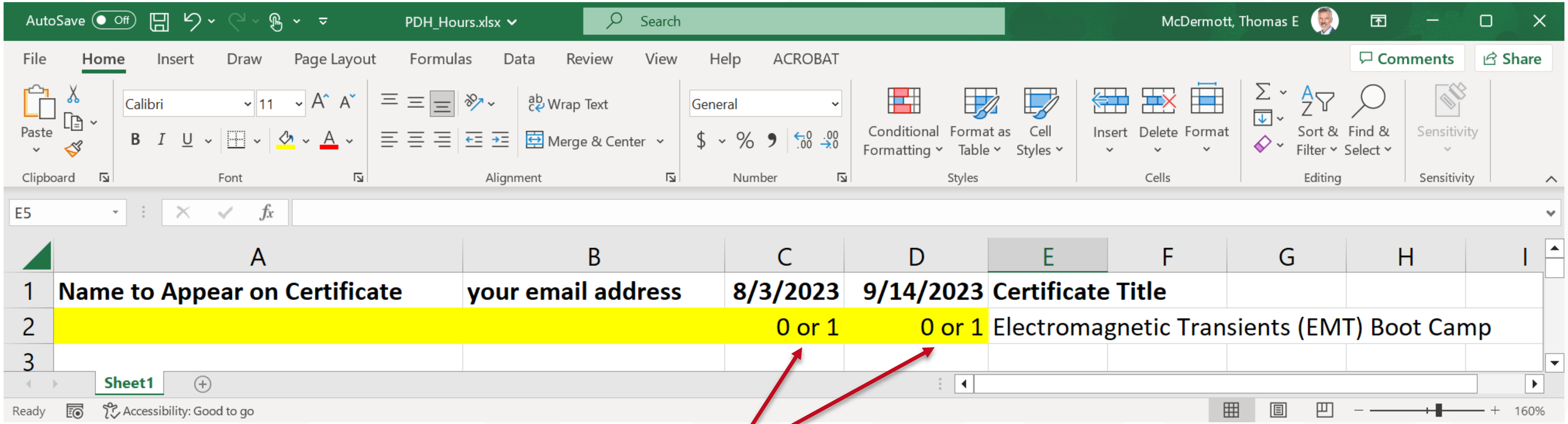
Thomas.McDermott@pnnl.gov

System-Level Session Agenda

- Course Completion Certificates from NERC
- Downloading Example Files
- NERC Guidelines for Use of EMT Models
  - Link: https://www.nerc.com/comm/RSTC/Pages/EMTTF.aspx and
    https://www.nerc.com/comm/RSTC_Reliability_Guidelines/Reliability_Guideline-EMT_Modeling_and_Simulations.pdf
  - Comparison to IEEE P2800.2 Subgroup 3 Tests under Development
- Workflow Management for System Impact Studies
  - PSSE File Inputs
  - Common Information Model, IEC 61970-301 (network) and -302 (dynamics)
  - Dynamic Link Library (DLL) Models
- Technical Discussion: average, switching, and DC bus modeling
- Hands-on Sessions:
  - This meeting ends for all at 2:30 Eastern time; please join your tool-specific meeting then
  - Running IBR study cases in the IEEE 39-bus system
  - Tool-specific automation examples
  - Repository of Materials: https://github.com/pnnl/i2x/tree/develop/emt-bootcamp

Course Completion Certificates for 4-8 Hours.

1. Download: https://github.com/pnnl/i2x/blob/develop/emt-bootcamp/PDH_Hours.xlsx
2. Complete the highlighted cells:

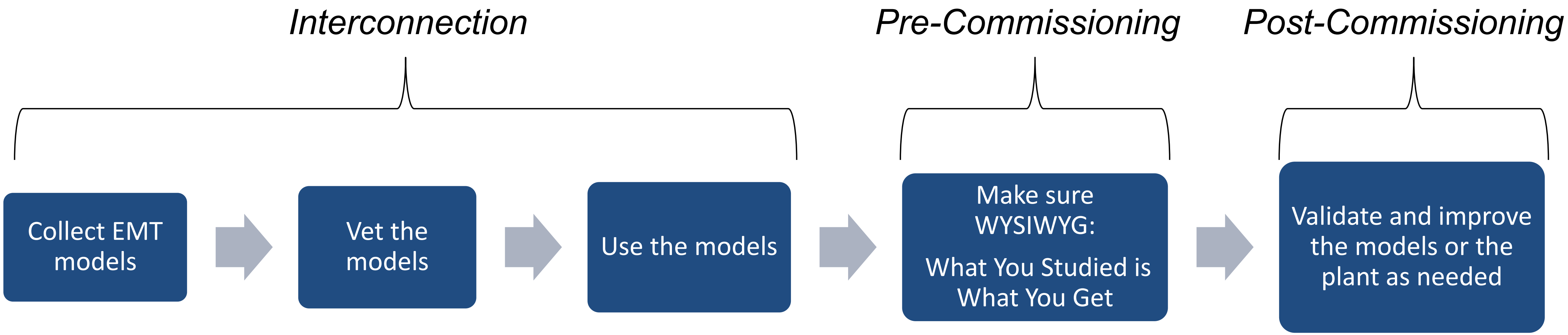


Enter a **1** for each session you attended

3. Email the xlsx file to Thomas.McDermott@pnnl.gov by 9/22/2023
4. You will receive an e-signed certificate from Ryan Quint of NERC
5. It’s your responsibility to determine suitability for any state PE licensing requirements

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

EMT Model Life Cycle



Source: Aung Thant, NERC Webinar, 6/27/2023

EMT Modeling Adoption Visualized in Stages

Stage 1
Establishing EMT Model Requirements

Stage 2
EMT Model Quality Verification

Stage 3
EMT Model-based Plant Performance Assessment

Stage 4
Screening and Integration in Interconnection Process

Stage 5
Conducting Interconnection & Planning Studies
(where necessary)

Source: Aung Thant, NERC Webinar, 6/27/2023

EMT Modeling Adoption Visualized in Stages

Odessa disturbances,
San Fernando disturbance,
2021 CA disturbances

EMT SAR
Project 2022-04

IEEE 2800.2

EMT Guideline Goal

NERC Disturbance Reports
- *Instantaneous AC OV, OC*
- *PLL loss of sync.*
- *Phase jump*
- *Unbalanced AC & DC*
- *DC OV*

Stage 1
Establishing EMT Model Requirements

Stage 2
EMT Model Quality Verification

Stage 3
EMT Model-based Plant Performance Assessment

Stage 4
Screening and Integration in Interconnection Process

Stage 5
Conducting Interconnection & Planning Studies (where necessary)

Published EMT Guideline Scope

Chapter 1
- Recommended EMT Model Requirements
- Sample Checklist

Chapter 2
- Principles of Model Quality
- Verification Processes
- Attestations – unit models & plant model
- Unit Model Validation

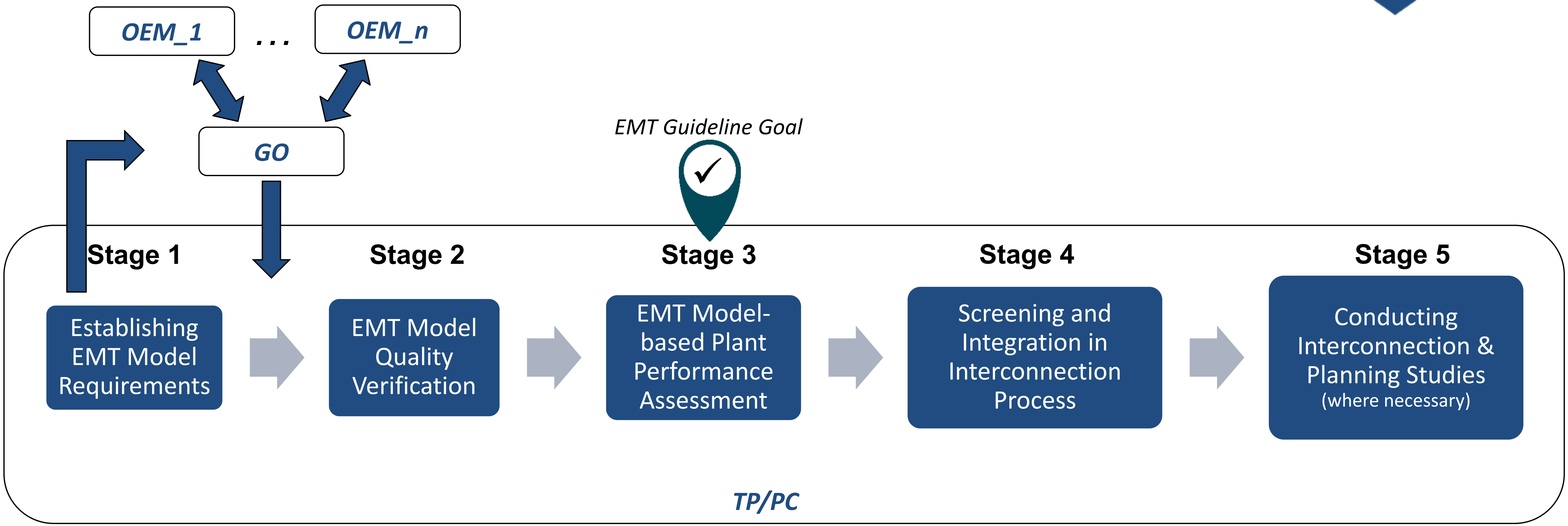
Chapter 3
- Model Adequacy Tests
- Functional Tests
- Disturbance Ride-through Performance Tests

Chapter 4
- EMT Study Use Cases
- Common situations needing an EMT study

New EMT Guideline Scope (Work item 2 of NERC EMTTF)

Source: Aung Thant, NERC Webinar, 6/27/2023

EMT Modeling Visualized by Functional Entities



Source: Aung Thant, NERC Webinar, 6/27/2023

Recommended EMT Model Requirements

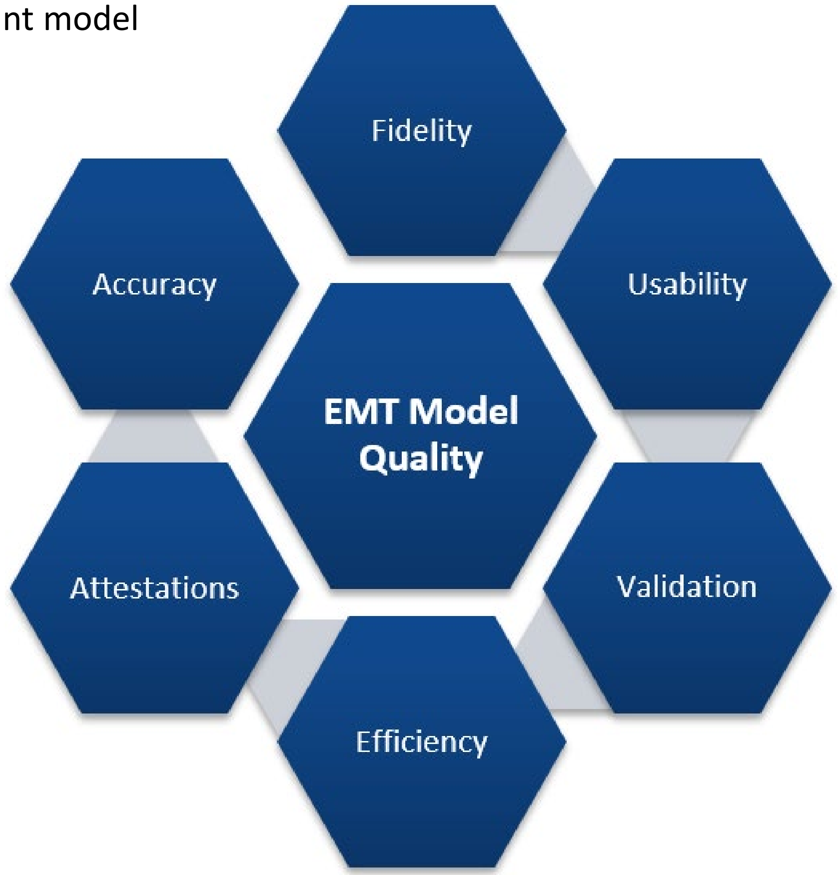
- Establish EMT modeling requirements per FAC-002 for all new IBR resources
- Create a “checklist” of EMT model requirements for GO and equipment manufacturers
- Require high quality EMT models as a prerequisite of interconnection
- Require the EMT models accurately represent all pertinent controls, and protections that could affect the electrical output of the facility during and after grid disturbances
- Require all submitted EMT models include
  - Attestations by the equipment manufacturers and
  - Attestations by GO that aggregate model represents the entire plant and includes site-specific models, settings, protections, and controls
- Include change management requirements and protocols regarding how changes should be reflected in EMT models by the GO
- Clearly define the purview and duration of EMT simulations

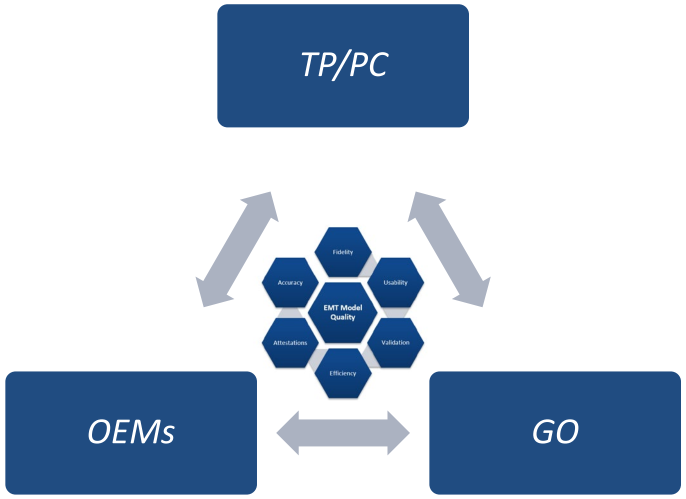
Source: Aung Thant, NERC Webinar, 6/27/2023

Chapter 2: Principles of Model Quality

Chapter 2

- **Principles of Model Quality**
- Verification Processes
- Attestations – unit models & plant model
- Unit Model Validation



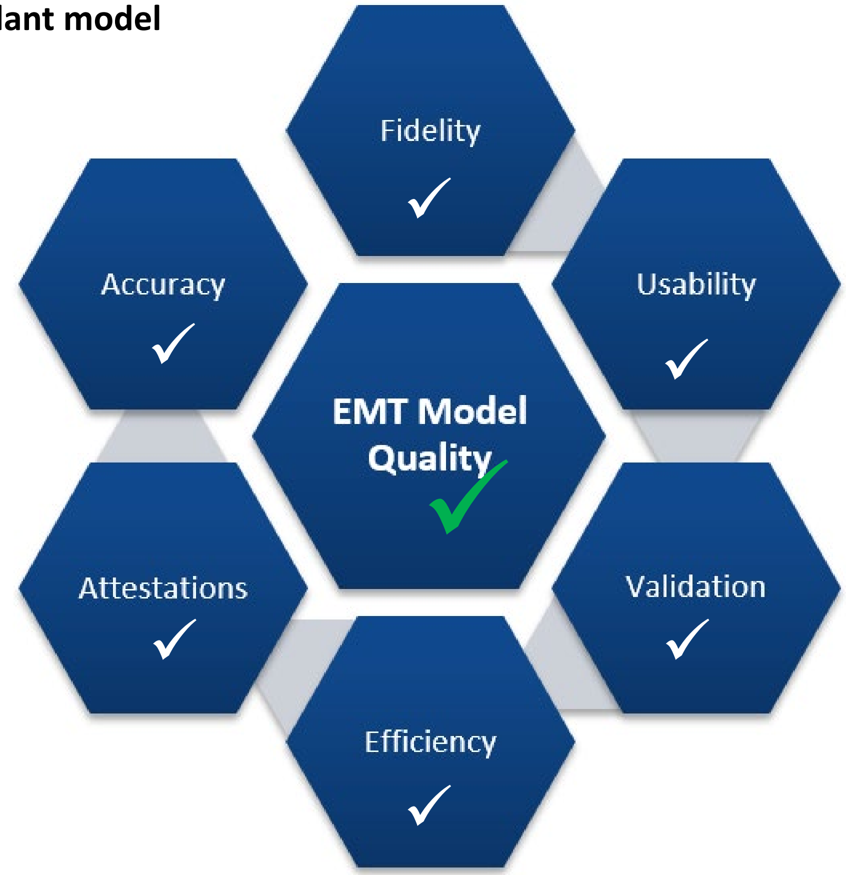


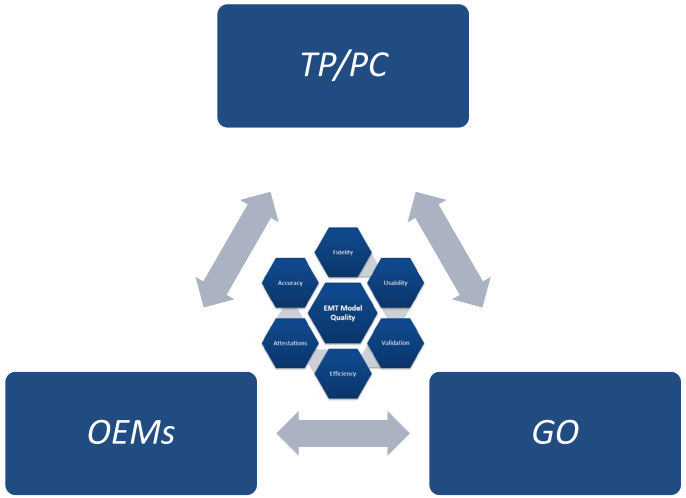
Source: Aung Thant, NERC Webinar, 6/27/2023

Chapter 2: Model Quality Verification

Chapter 2

- Principles of Model Quality
- **Verification Processes**
- **Attestations – unit models & plant model**
- **Unit Model Validation**





Source: Aung Thant, NERC Webinar, 6/27/2023

Chapter 2: Model Quality Verification Processes

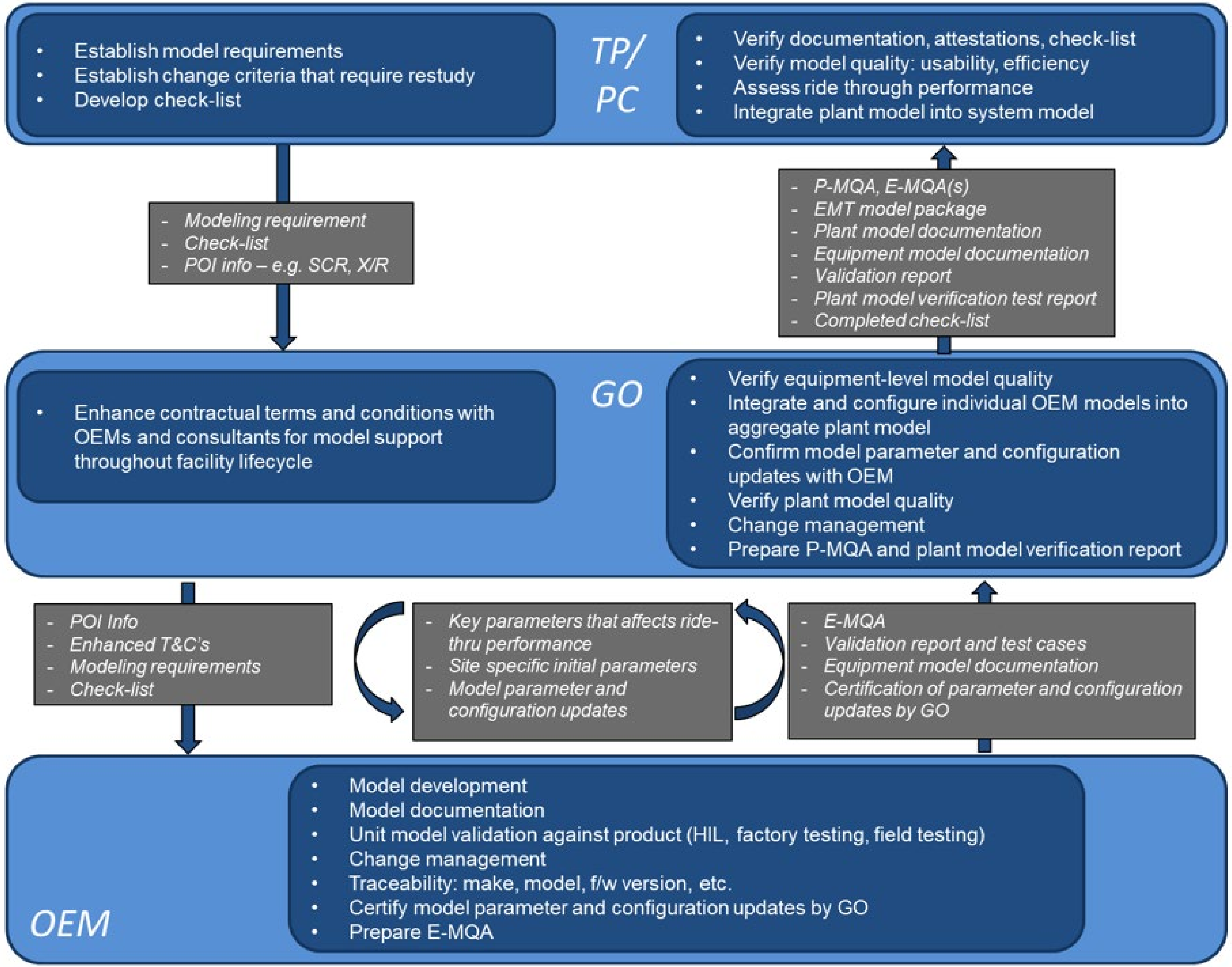
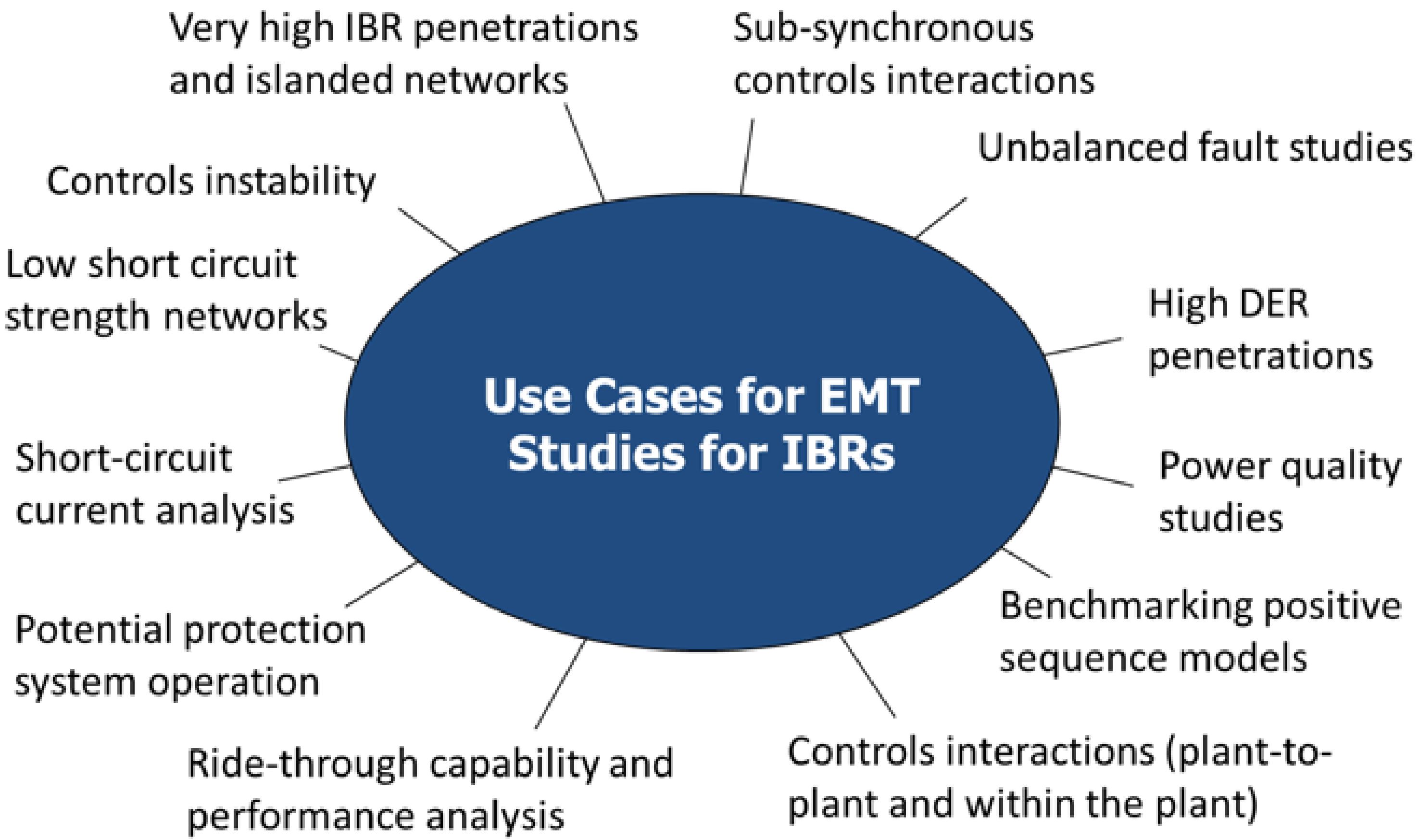


Figure 2.2: Model Quality Verification Processes, pg. 18

Source: Aung Thant, NERC Webinar, 6/27/2023

Chapter 4: EMT Study Use Cases



Source: Aung Thant, NERC Webinar, 6/27/2023

Chapter 5 and Appendices

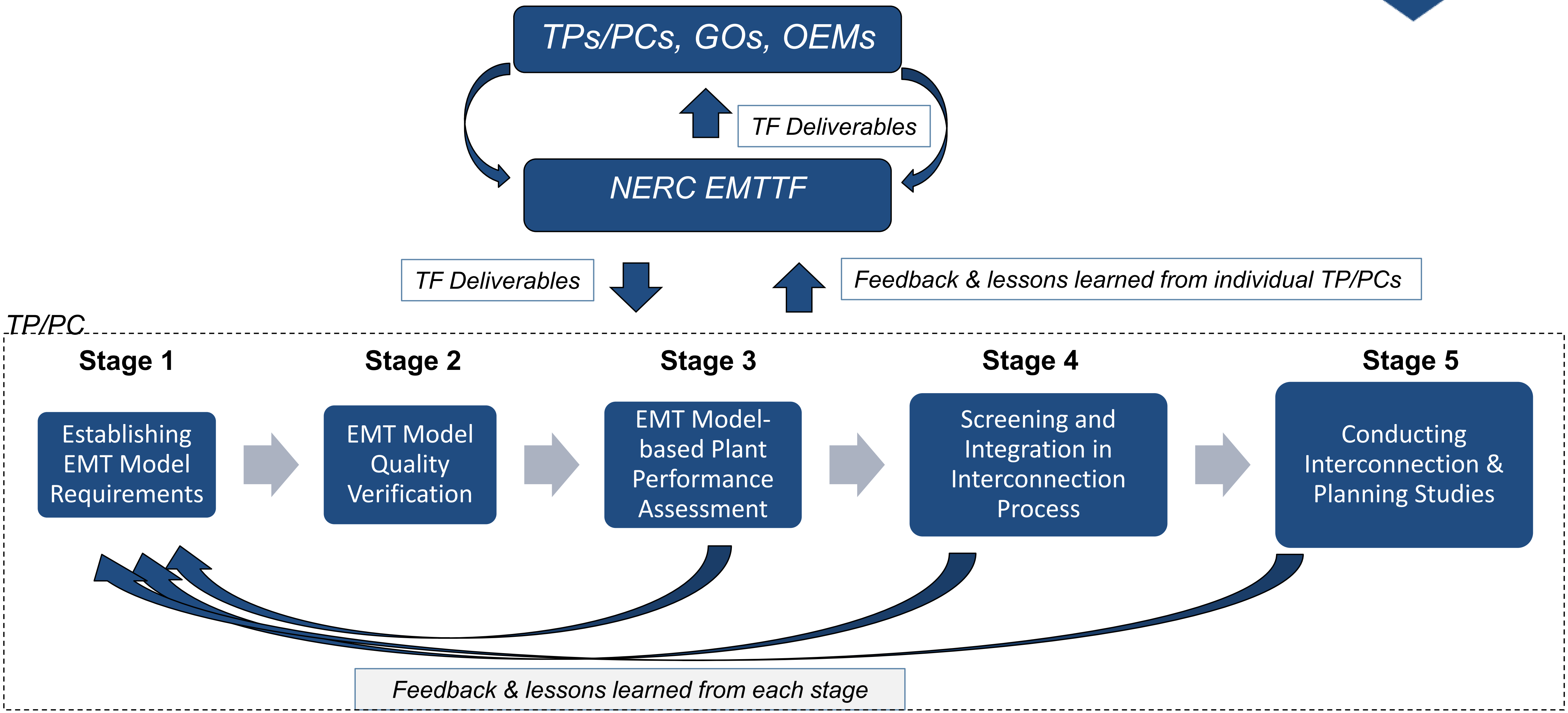
- Chapter 5: Other Relevant Topics
  - **Benchmarking Positive Sequence Dynamic Models against the EMT Model**
  - Resourcing for Future EMT Study Needs
  - Applicability and Use of IEEE 2800 Guidance
- Appendix A: EMT Model Terminology
  - Generic versus Equipment Specific Models
  - Equipment-Specific **Model Types**
    - Transparent EMT Models
    - "Black Box" EMT Models
    - "Real Code" EMT Models
  - Detailed and Aggregate EMT Modeling
- Appendix B: **References for EMT Model Requirements**

Key Takeaways

- Help industry close EMT modeling knowledge gaps
- Provide a foundation of knowledge for new modeling requirements and practices
- Guidance to make quality-vetted EMT models available to TPs and PCs for the purposes of reliability studies – interconnection studies per FAC-002 and planning assessments per TPL-001
- Help industry close current gaps between interconnection studies and installed equipment

Source: Aung Thant, NERC Webinar, 6/27/2023

EMTTF Supporting EMT Adoption Across NA

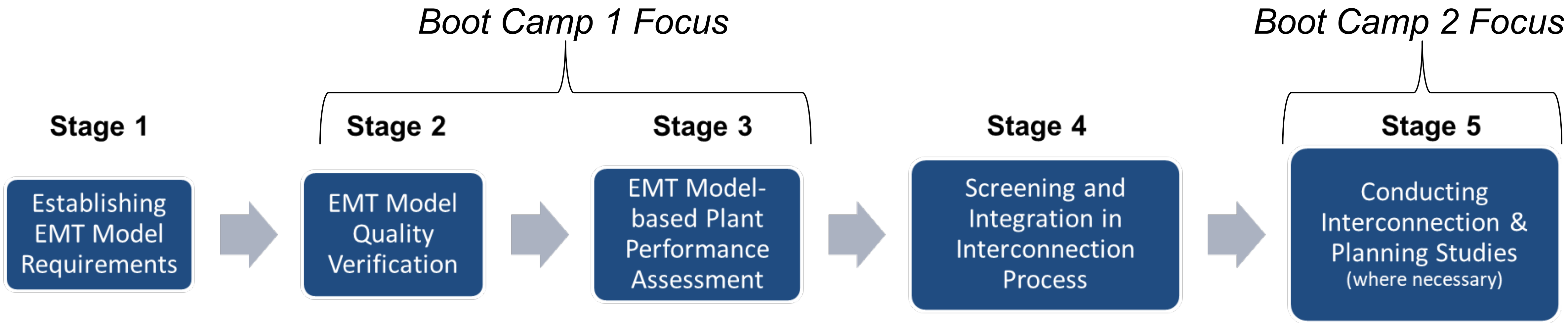


Source: Aung Thant, NERC Webinar, 6/27/2023

Upcoming Events

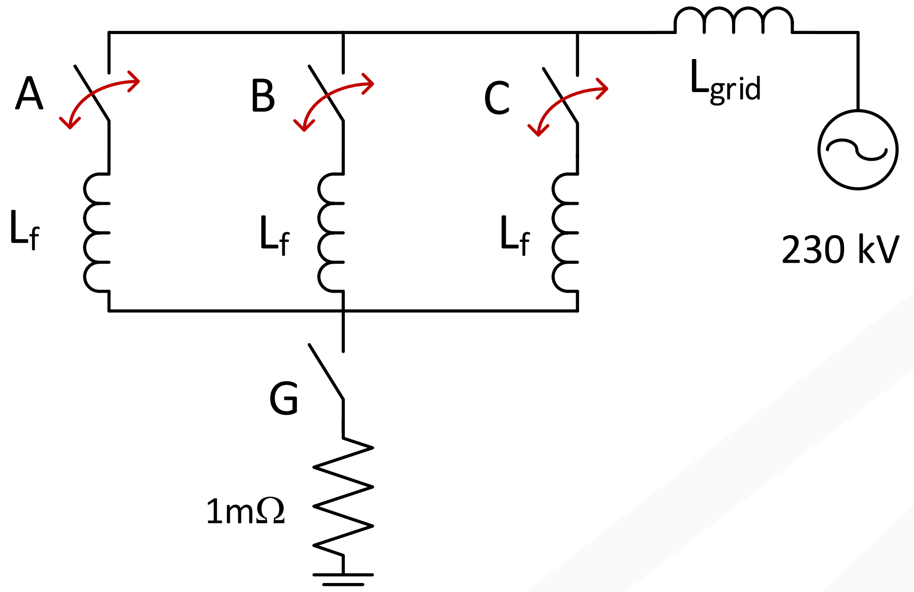
- EMT Modeling Boot Camps (Virtual)
  - co-hosted by U.S. Department of Energy Interconnection Innovation e-Xchange (i2X) and NERC

Date	Time	Session
July 27, 2023	1 – 3 pm Eastern	Pre-session
August 3, 2023	1 – 5 pm Eastern	Boot Camp 1: Individual IBR Plant Performance Assessment
September 14, 2023	1 – 5 pm Eastern	Boot Camp 2: System Impact Assessment



Source: Aung Thant, NERC Webinar, 6/27/2023

Systematic fault simulations applied to a strong grid.



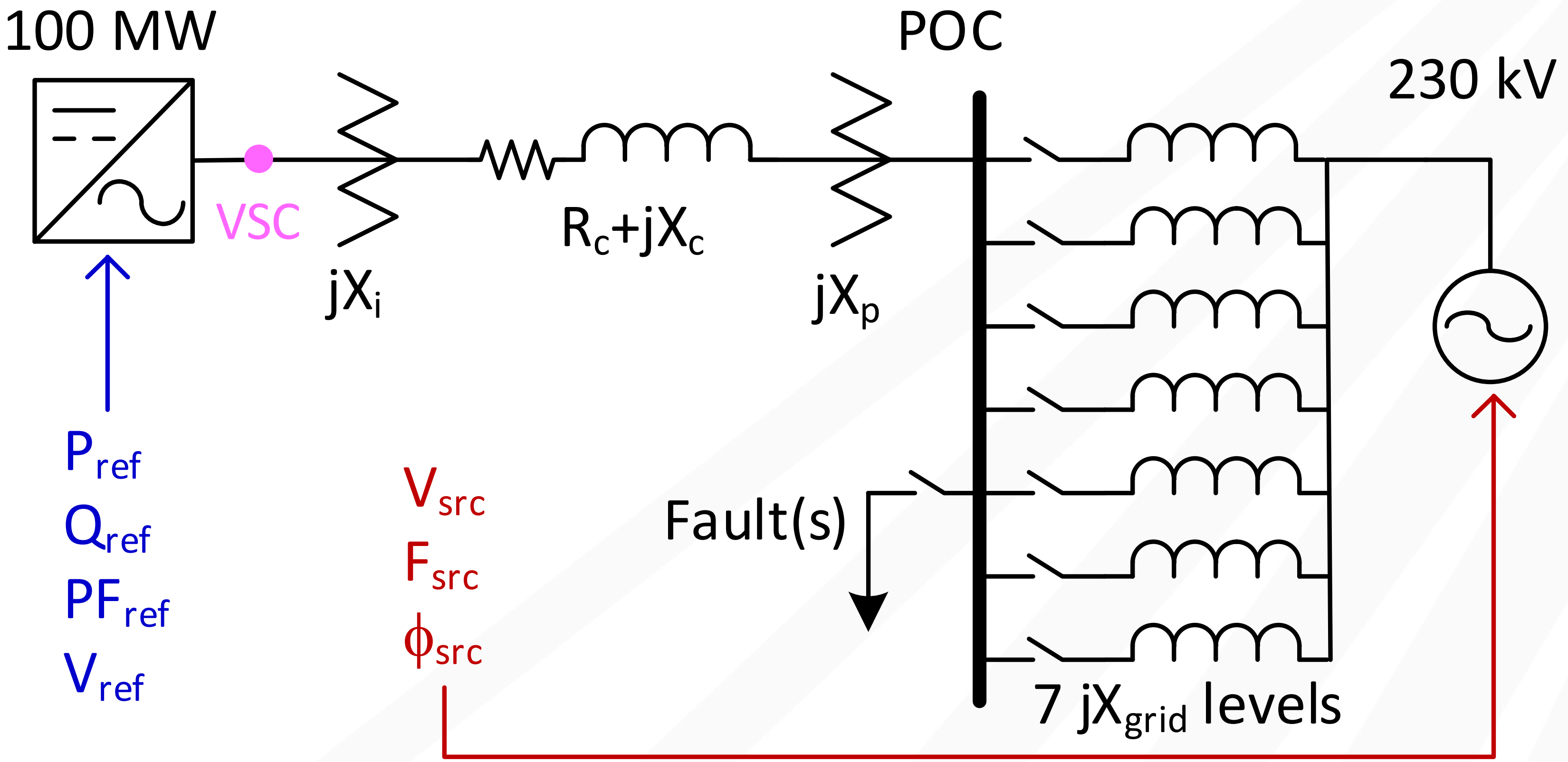
- Initial conditions don't change
- No facilities removed from service after the fault clears
- Fault duration is 0.3s, ride-through is not required for some faults

$$Z_{grid} = 10\angle 85° = 0.8716 + j9.9619$$

$$L_{grid} = 9.9619 / 377 = 0.0264$$

Phases	Retained Voltage	Lf [H]
ABCG	80%	0.1057
ABCG	50%	0.0264
ABCG	25%	0.0088
ABCG	1%	0.0001
AG	80%	0.1057
AG	50%	0.0264
AG	25%	0.0088
AG	1%	0.0001
BC	80%	0.1057
BC	50%	0.0264
BC	25%	0.0088
BC	1%	0.0001

Plant model testing framework on a weak grid; IEEE P2800.2 SG3 contemplates testing at SCR = 2.5, details in D0.5, clause 7.



For SCR=2.5 at the VSC terminal (reactance values at 230 kV)

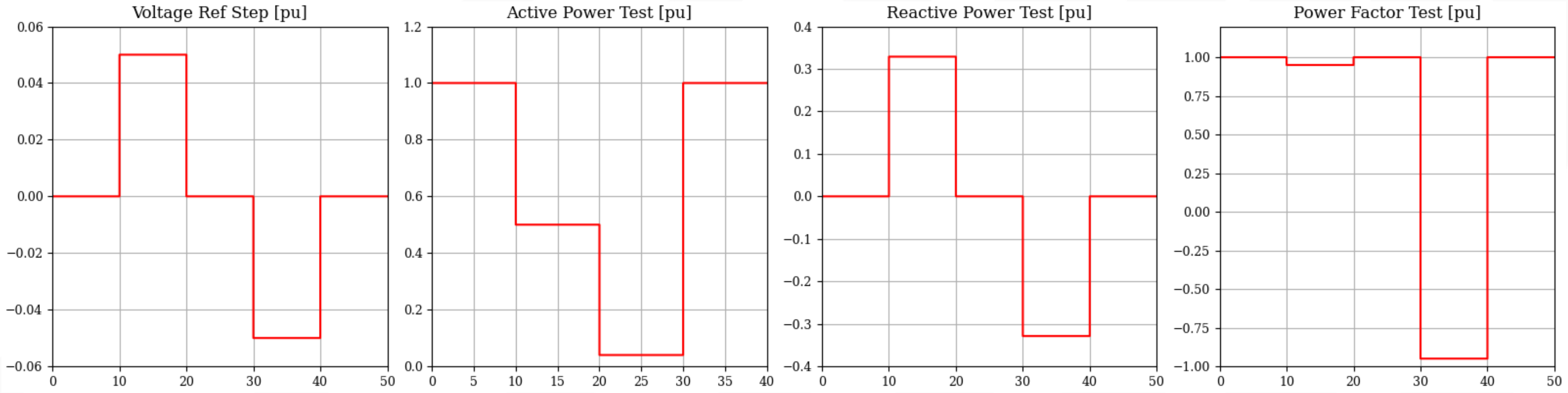
Example	Xi	Xc	Xp	Xgrid	Xtotal	SCMVA
Solar	10.58	0.00	63.48	137.54	211.60	250.0
Wind	30.23	6.42	63.48	111.47	211.60	250.0

Maximum SCR at VSC when Xgrid≈0:

Example	Xplant	SCMVA
Solar	74.06	714.3
Wind	100.13	528.3

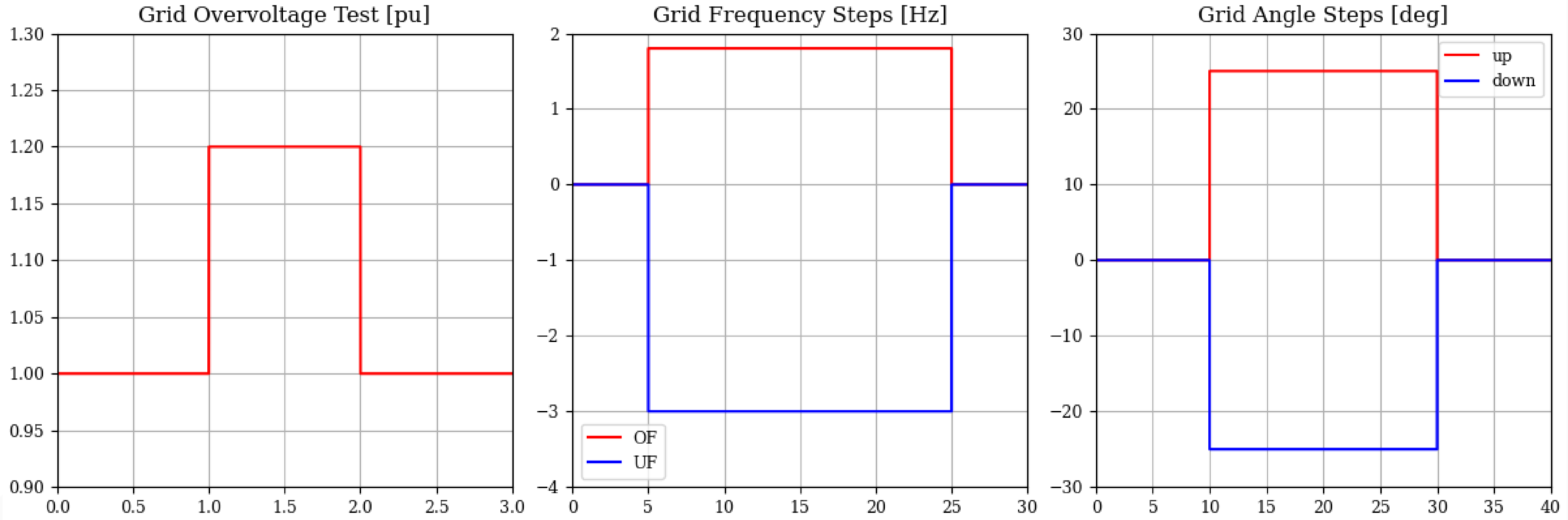
Model initialization, undervoltage, and control step tests are automated with IBR control references and fault parameters.

- **fs**: 14 flat-start tests to initialize *from zero* in 10s, remain stable for 10s
  - P = inverter continuous rating (ICR) and P_{min}, 7 variations each:
    - V_{ref}=1; Q_{ref}=[0.3287, 0, -0.3287]; pf_{ref}=[0.95, 1.0, -0.95]
- **uv**: 15 undervoltage ride-through tests, fault duration=0.16s, all at P=ICR
  - 3 fixed Q values of 0.3287, 0, -0.3287 pu
  - 5 fault types [3ϕ sag to 50% voltage, 3ϕg, 1ϕg, 2ϕg, 2ϕ]
- **st**: 4 control reference change tests plotted below



P2800.2 grid overvoltage, frequency change, and angle jump tests are implemented with controlled grid sources.

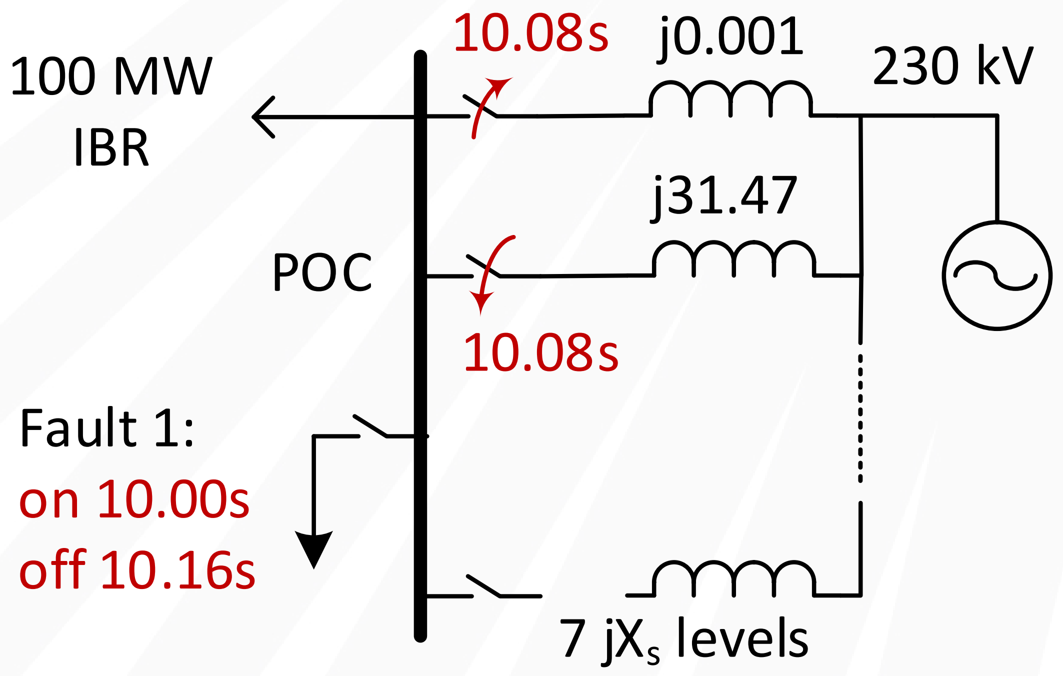
- **ov**: 3 overvoltage ride-through tests at P=ICR and 3 fixed Q values:
  - Q = 0, +0.3287, -0.3287
- **fr**: 4 frequency ride-through tests, over/under at P=ICR and P_{min}, fixed Q=0
- **an**: 4 angle ride-through tests, positive/negative at P=ICR and P_{min}, fixed Q=0



Short-circuit ratio (SCR) ramp-down tests transition between impedances during faults at 5-second intervals.

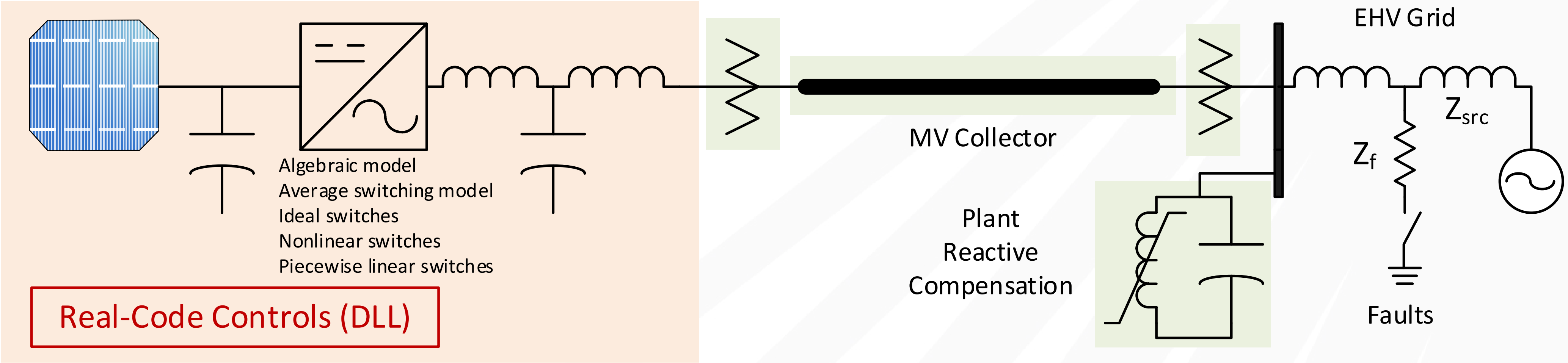
P2800.2/D0.5, Clause 7.3.5.1.2
POC SCR Change Informational Tests
Stable operation expected until SCR=2.5

Range [s]	SCR	X @ 230 kV
0-5	20	26.45
5-10	10	52.90
10-15	5	105.80
15-20	4	132.25
20-25	3	176.33
25-30	2.5	211.60
30-35	2	264.50
35-40	1.5	352.67
40-45	1	529.00



This test is simulated manually, with sequenced faults and changes in source impedance.

Comparing NERC EMT Task Force and IEEE P2800.2 emphases.



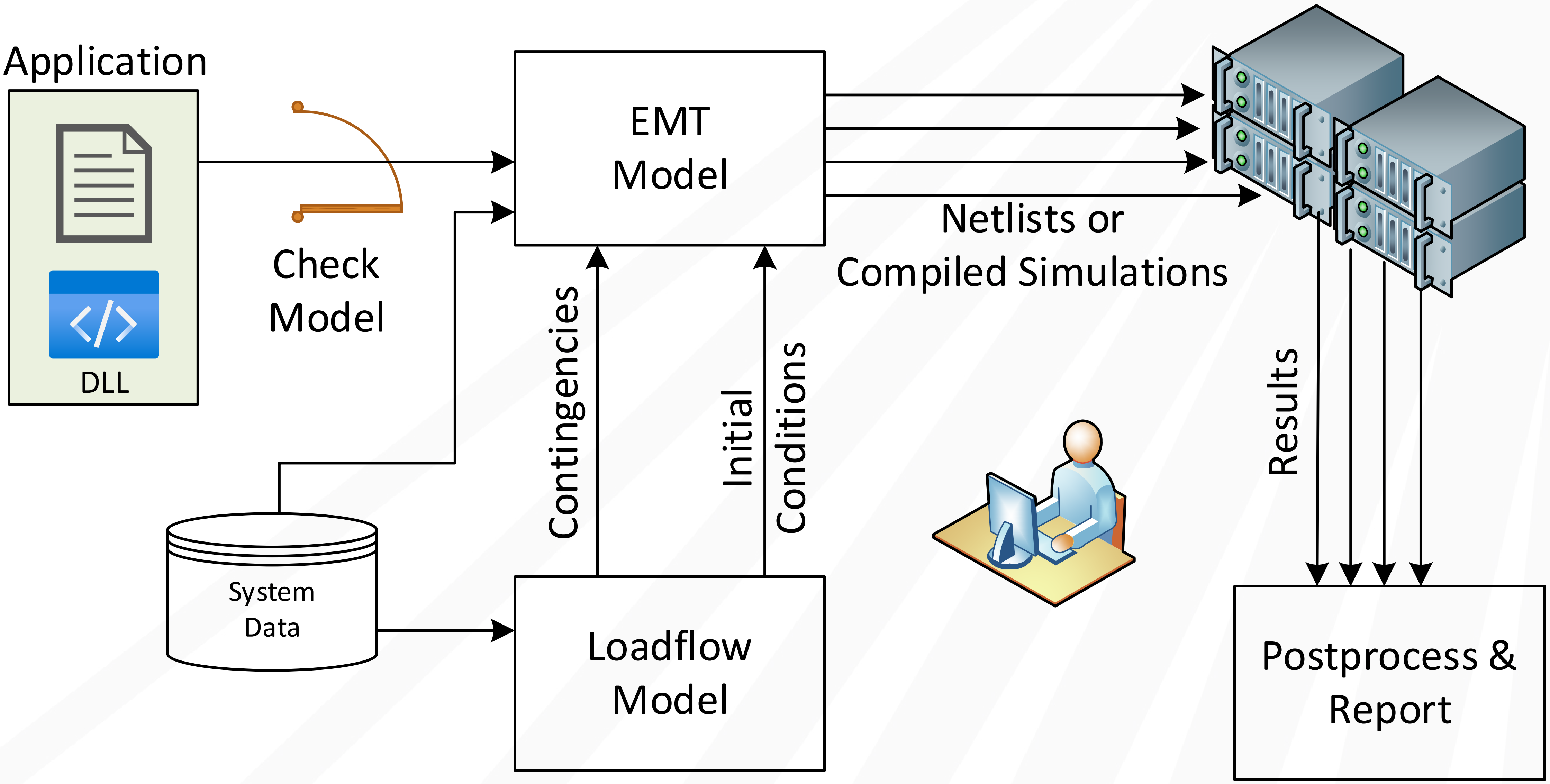
P2800.2 Emphasis

1. Conformance of the hardware and controls to IEEE 2800-2022 requirements
2. Models to match unit and plant commissioning tests, also use in design evaluations

NERC EMT Task Force Emphasis includes P2800.2, plus

1. Establish EMT modeling and IBR performance criteria, including ride-through, for new interconnection requirements.
2. Verifying model quality & accuracy, and conformance to new iX requirements.
3. Additional requirements on model accuracy and usability, adjustable and observable parameters, documentation, numerical robustness, Δt flexibility, etc.

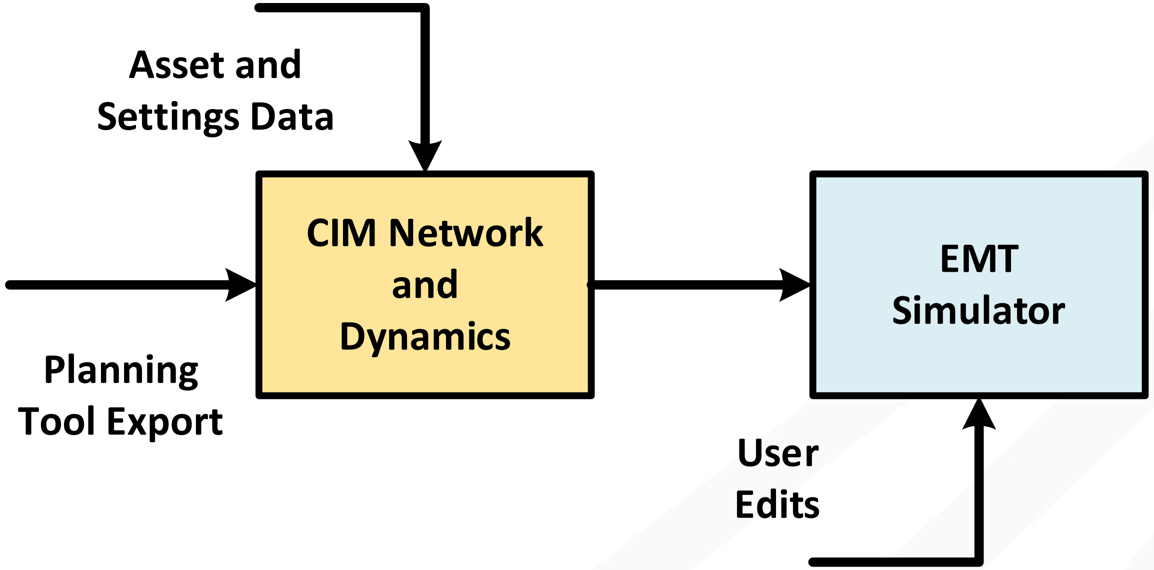
Study engineers build and check models, organize simulations, and analyze the results.



PSSE files can help build the balance-of-system model for EMT.

- Many/most commercial EMT tools can import from PSSE files:
  - **RAW** – positive sequence network bus and branch data for power flow
  - **SEQ** – zero-sequence and negative-sequence data for short circuit solution
  - **DYR** – dynamics data (machines, exciters, governors, stabilizers, IBR)
  - **LOC** – bus locations for visualization
- Points to remember:
  - There may be some gaps in data for controls, non-linearities, etc.
  - Manual edits to the EMT model files will be decoupled from the original PSSE files
  - EMT tools may operate differently from PSSE, PSLF, PowerWorld, and TSAT

Common Information Model (CIM) has been used to maintain and exchange bulk electric system models, including dynamics.



https://openei.org/wiki/File:CIM_EMT_Article.pdf

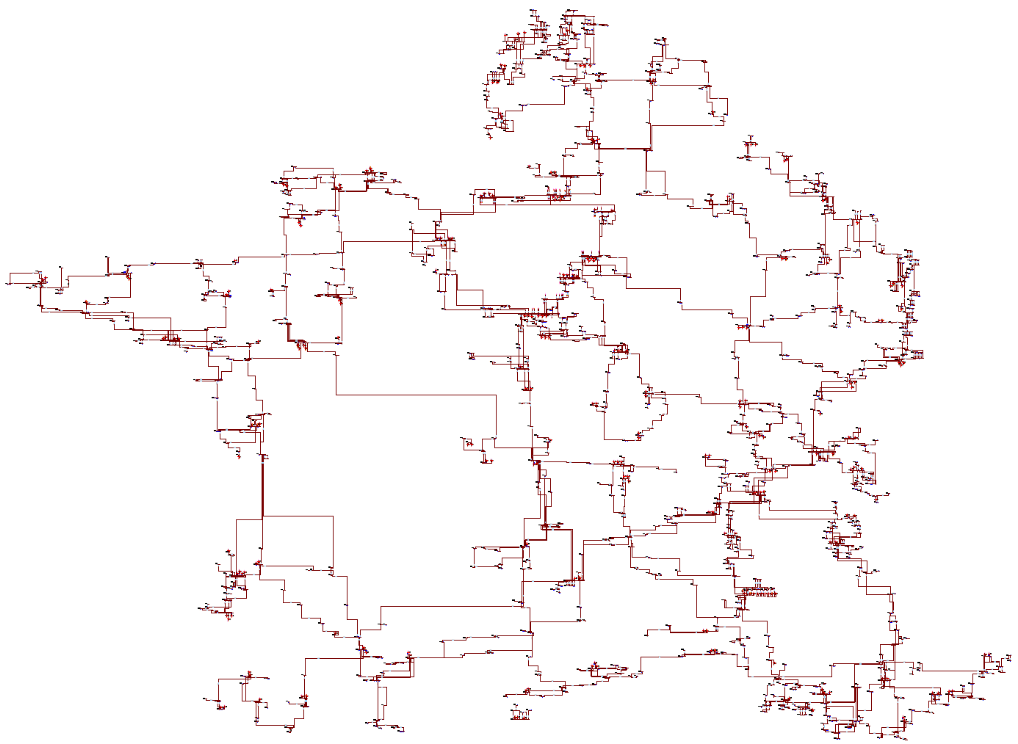


Fig. 5 French 225 kV grid after CIM import in EMTP

https://www.ipstconf.org/papers/Proc_IPST2017/17IPST099.pdf

- ENTSO-E (35 countries)
- ERCOT since 2009
- AEP, SCE, others adopting
- Sustained effort by EPRI

CIM can represent line impedances and coupling in detail; unbalanced distribution system models have been exchanged.

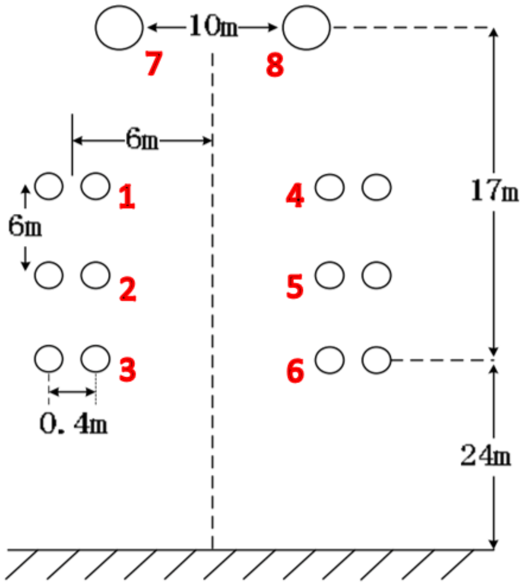
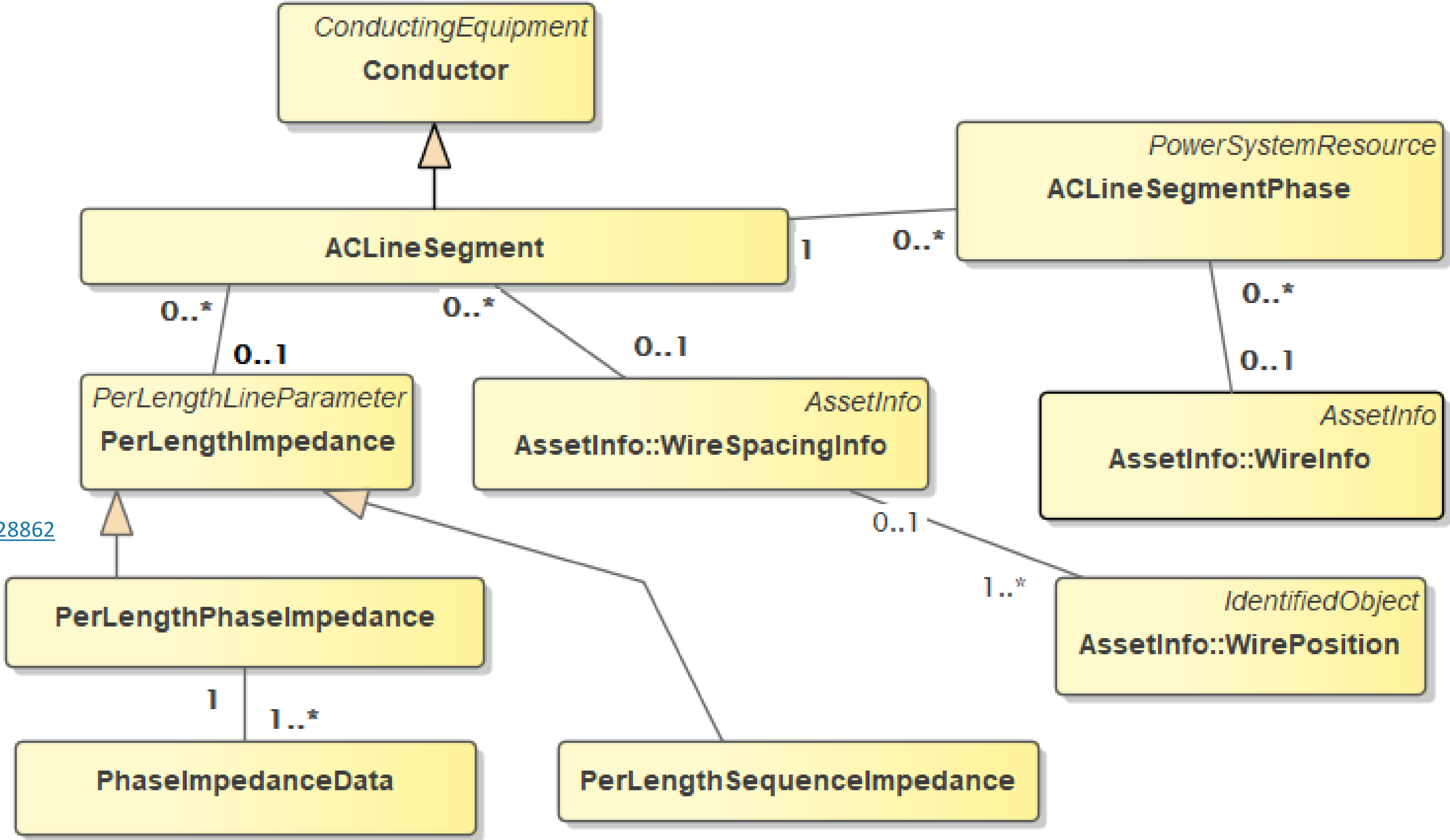
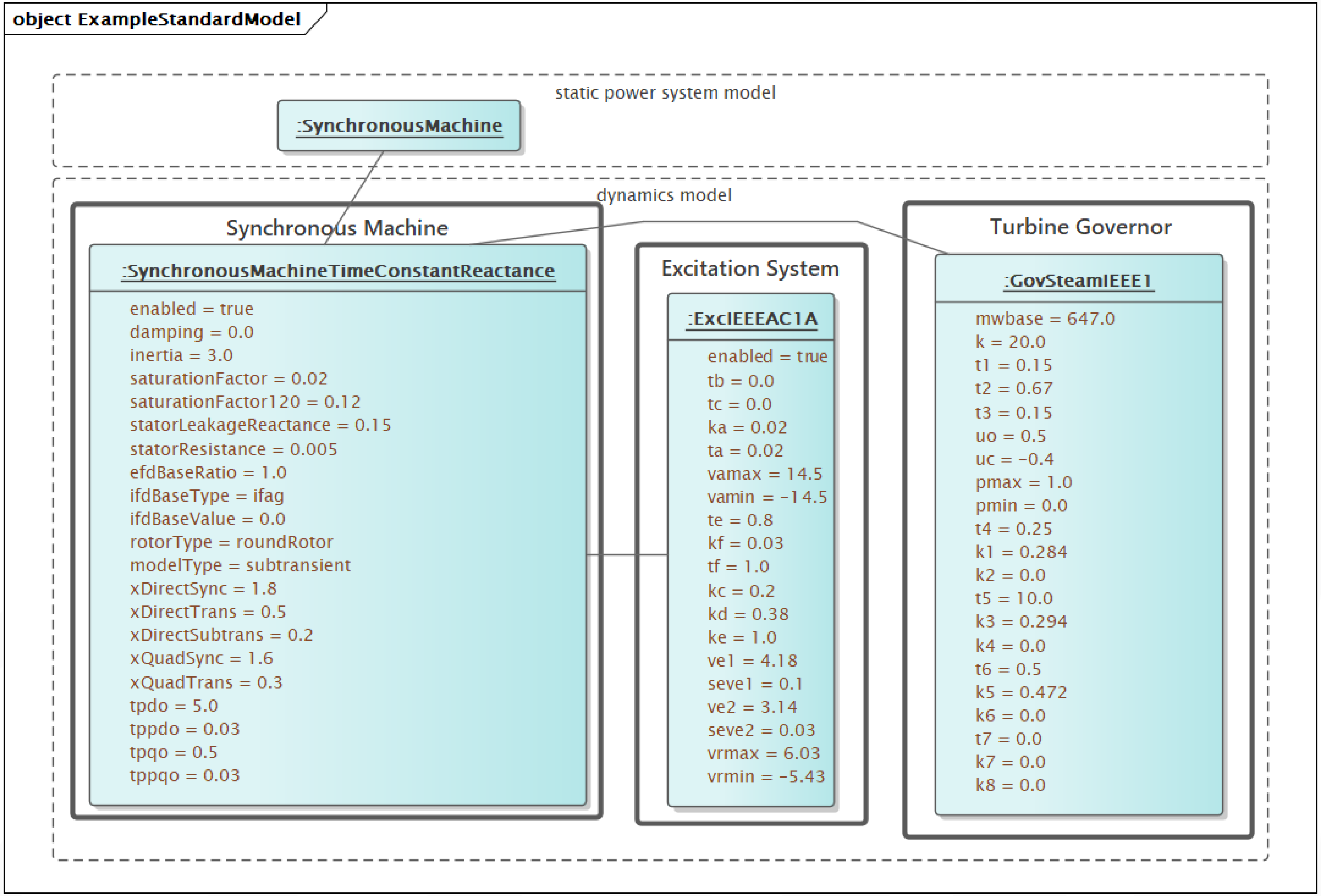


Fig.2 DCTL Tower Parameters

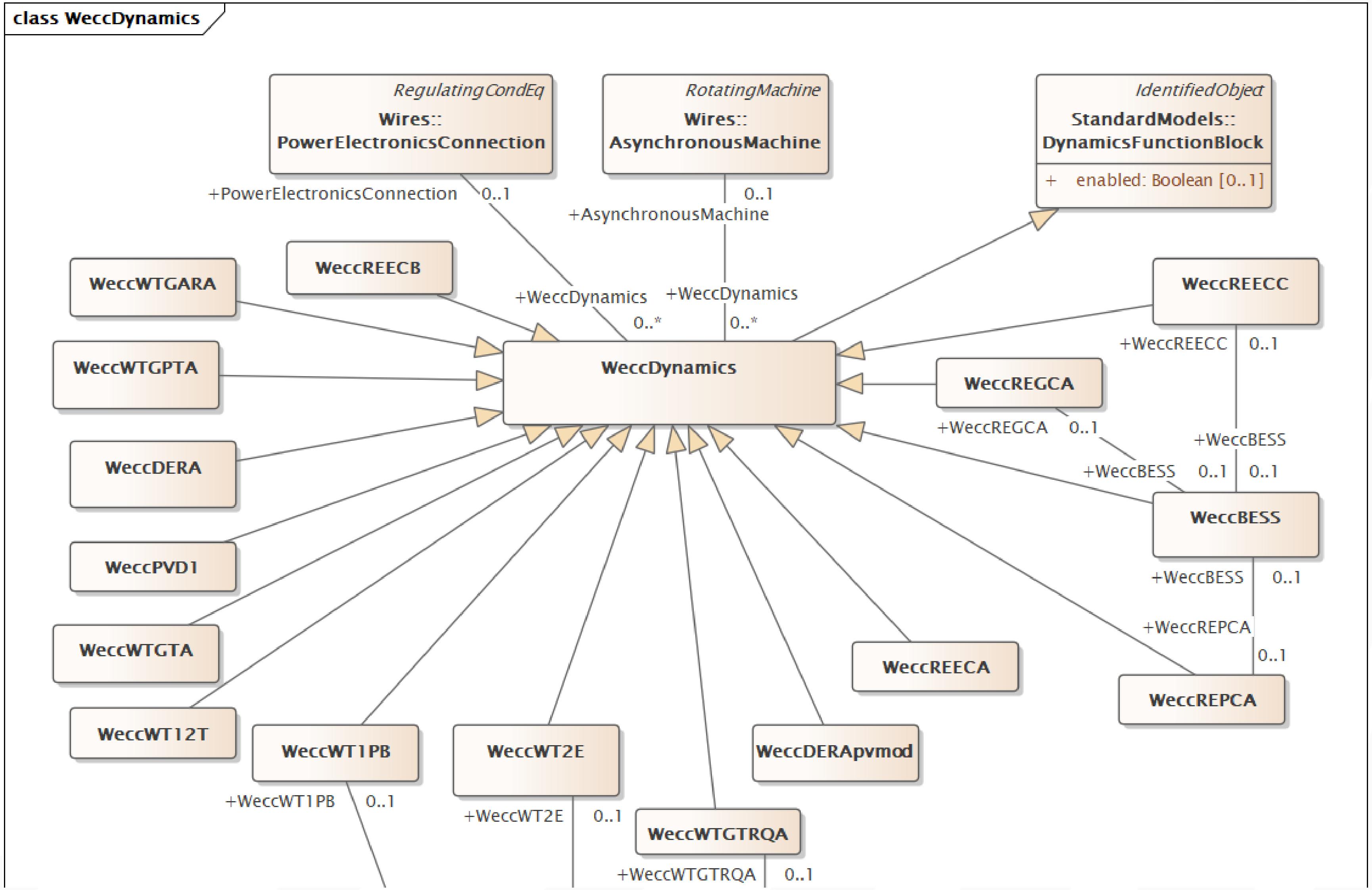
Ref: https://doi.org/10.1109/ISGTEurope.2014.7028862



IEC 61970-302:2018 (CIM Dynamics) already supported machines.

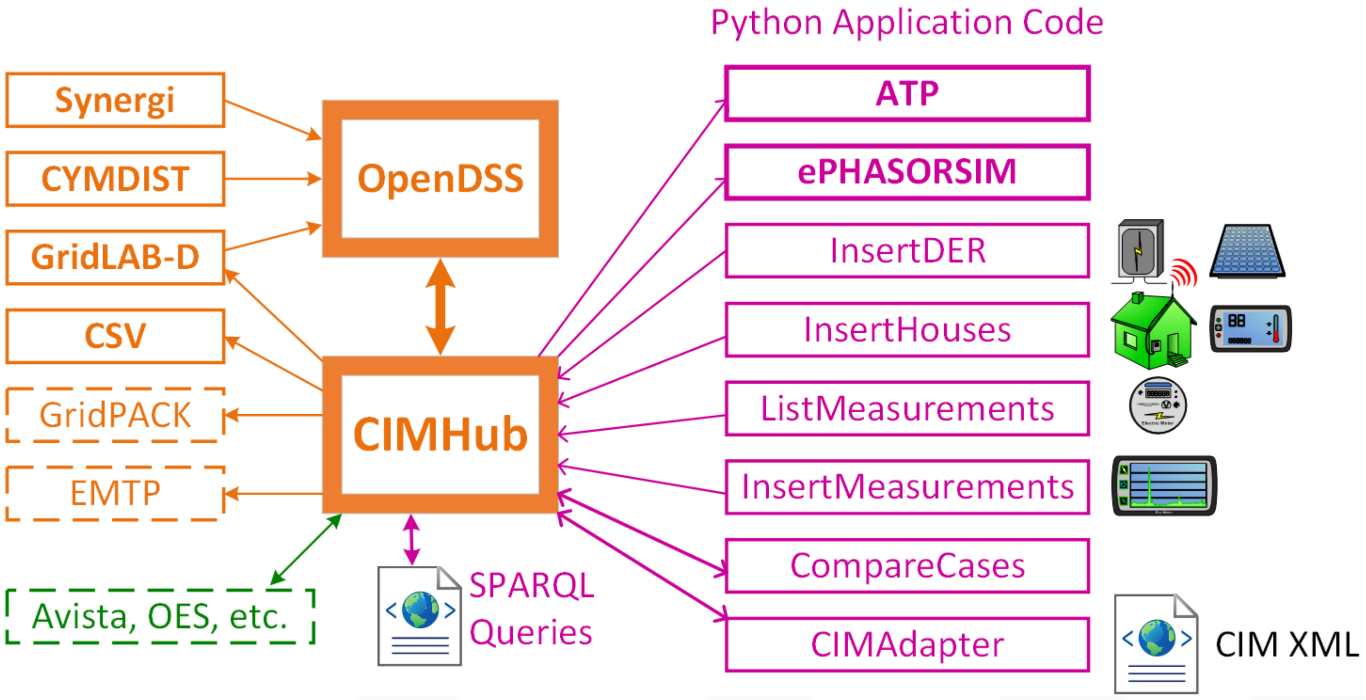


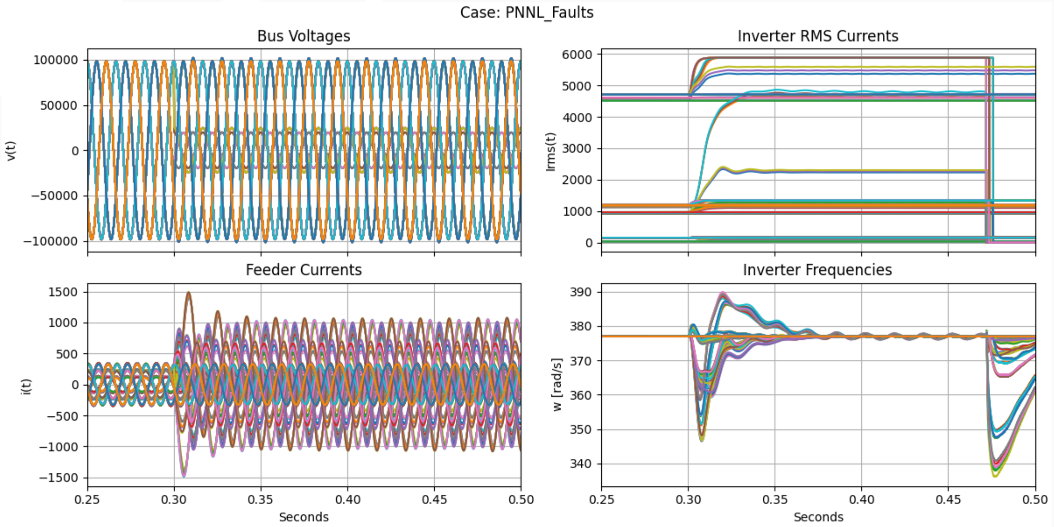
WECC renewable models were added for 61970-302:2022



https://webstore.iec.ch/preview/info_iecfdis61970-302%7Bed2.0%7Den.pdf

DER models were added to IEC 61970-302:2022 and IEEE 1547.2 (in ballot resolution). These models support EMT simulation of DER.



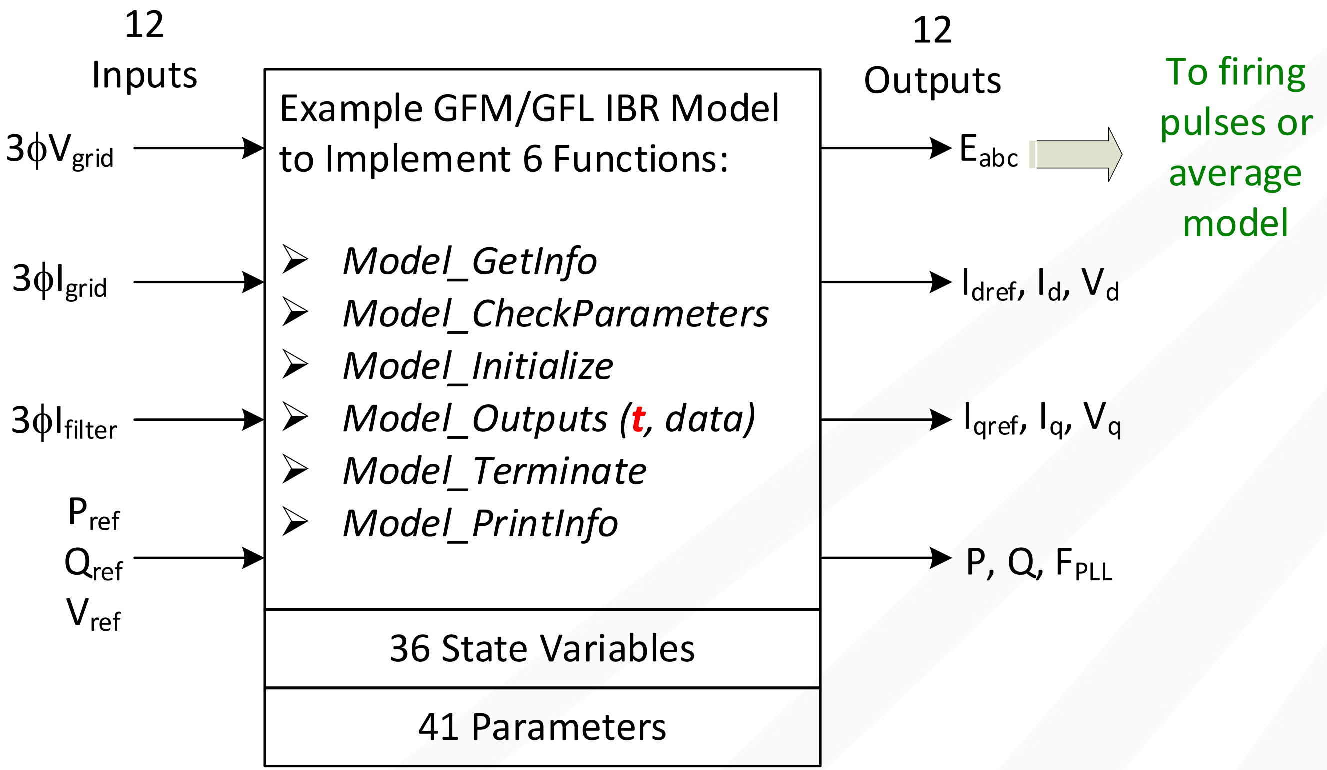


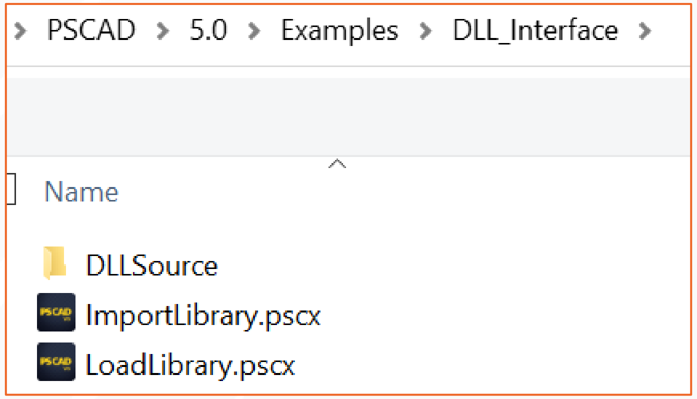
Name	Type	V_{LL} [kV]	#Loads	#DER	Load [MW]
IEEE 13x	Radial	4.16	9	4	3.4
IEEE 123x	Radial	4.16	114	14	3.8
EPRI DPV J1	Radial	12.47	1384	13	11.6
IEEE 9500	Variable	12.47	1275	12	12.3
IEEE LVN	LV Network	13.20	624	8	42.2
Smart DS	Radial	12.47	4173	928	42.2
Avista CEF2	2 Feeders	13.20	582	4	10.1
PNNL Campus	2 Substations	12.47	743	3	16.4
Nantucket	8 Feeders	13.20	13,794	62	50.6

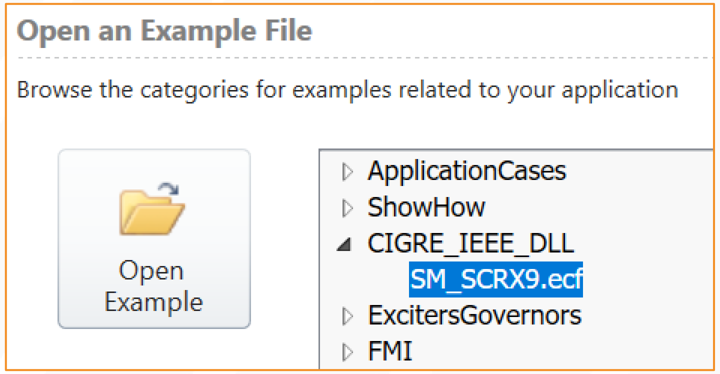
CIM DER UML: https://cimhub.readthedocs.io/en/latest/CDPSM.html#der-models-from-ieee-1547-2018

CIMHub Code and Models: https://github.com/GRIDAPPSD/CIMHub/tree/feature/SETO

Dynamic Link Library (DLL) real-code model interfaces were developed by a joint IEEE AMPS / Cigre B4.82 task force.







Past IEEE/B4.82 presentations: http://www.electranix.com/ieee-pes-tass-realcodewg/

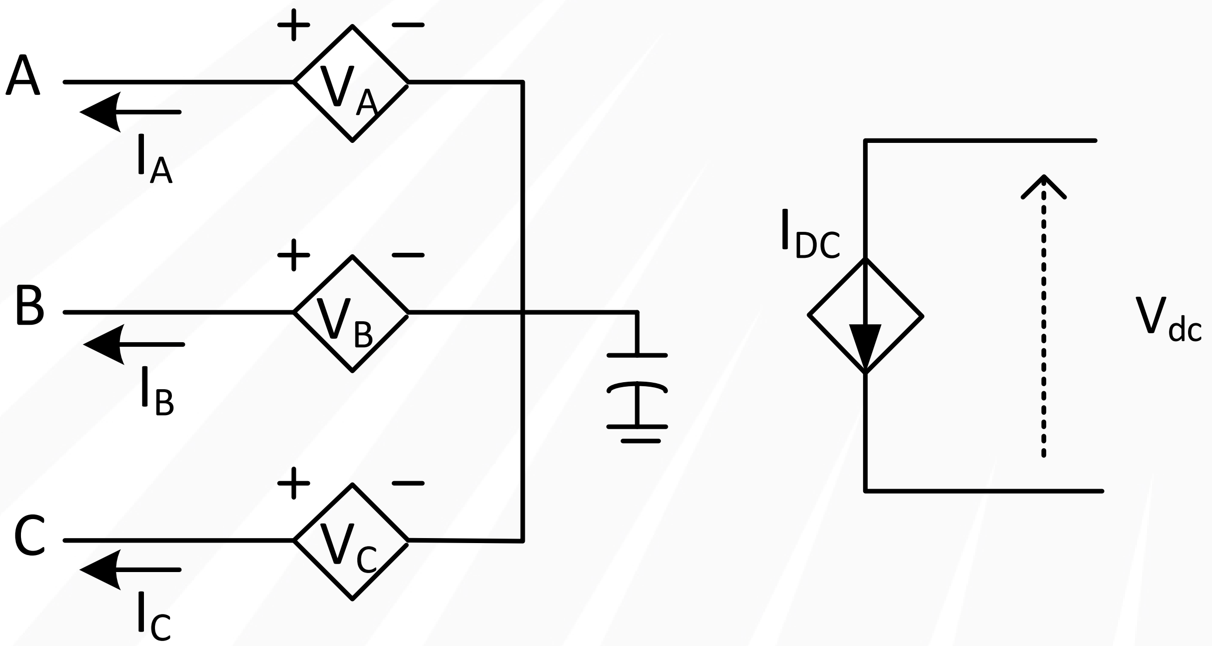
Some more Cigre Technical Brochures

1. TB 039, “Guidelines for representation of network elements when calculating transients”, 1990.
2. TB 295, “Relay software models for use with electromagnetic transient analysis program”, 2006.
3. TB 736, “Power system test cases for EMT-type simulation studies”, 2018.
4. TB 881, “EMT simulation models for large-scale system impact studies in power systems having a high penetration of inverter-connected generation”, 2022.

Average models use energy-conserving, controlled sources to produce the reference phase voltages.

Control modulation indices:

$$m_a = \sin(\omega t)$$
$$m_b = \sin(\omega t + 2\pi / 3)$$
$$m_c = \sin(\omega t - 2\pi / 3)$$



AC voltage sources:

$$V_A = \frac{m_a V_{DC}}{2}$$

$$V_B = \frac{m_b V_{DC}}{2}$$

$$V_B = \frac{m_c V_{DC}}{2}$$

DC current source:

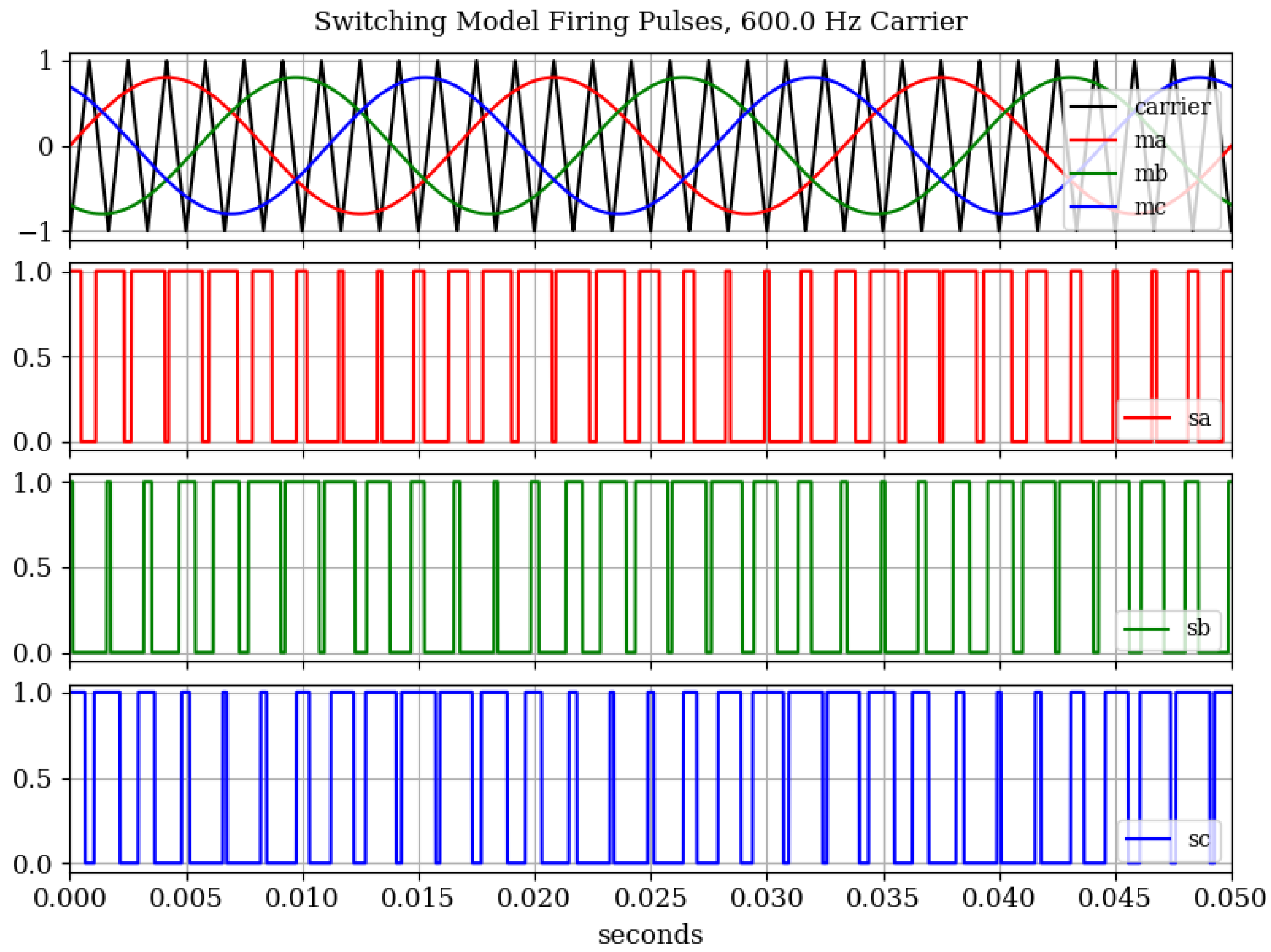
$$I_{DC} = \frac{m_a I_A + m_b I_B + m_c I_C}{2}$$

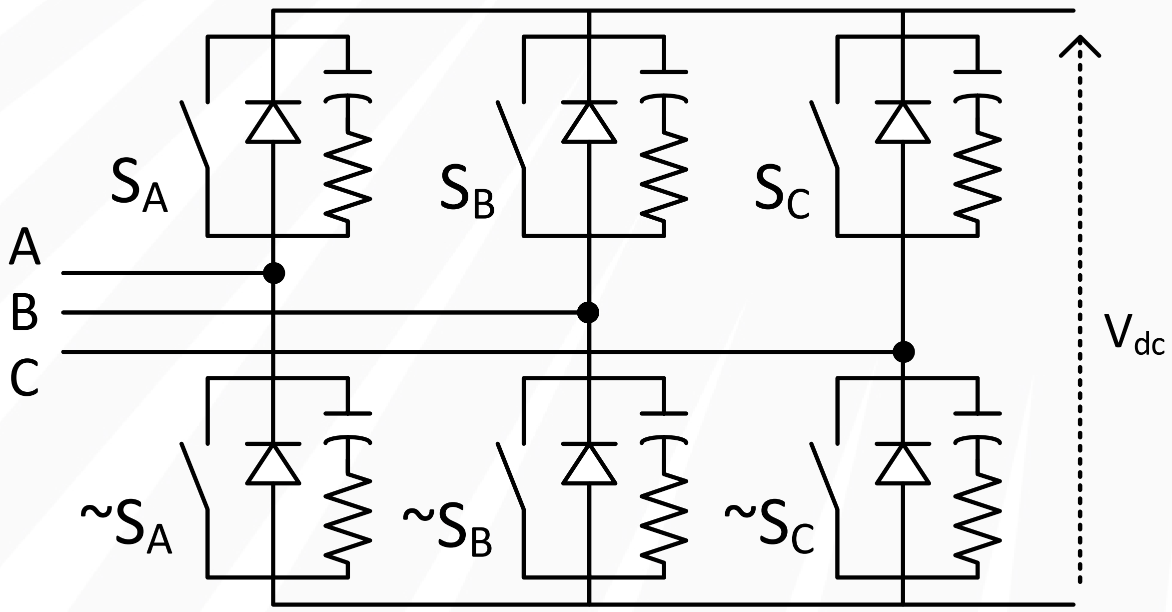
Check power balance:

$$I_A V_A + I_B V_B + I_C V_C = I_{DC} V_{DC}$$

Ref: Yazdani and Iravani, pp. 119-121

Switching (detailed) models are driven by the same reference voltages, or modulation indices, as the average models.



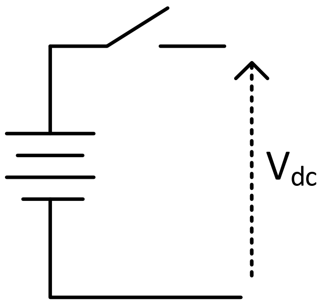


$S_A = m_A >$ carrier

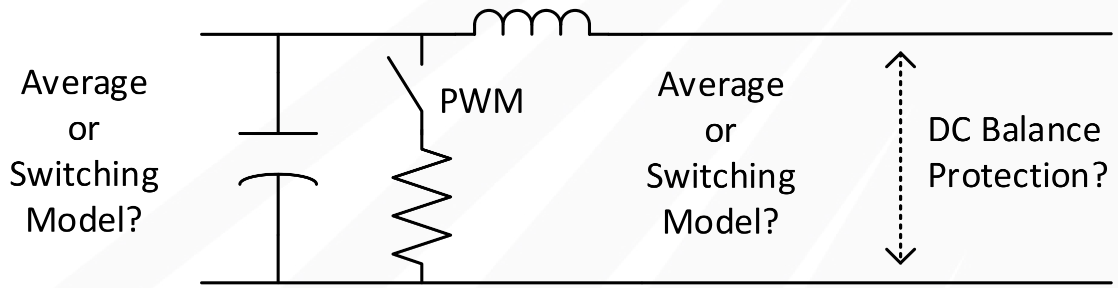
$S_B = m_B >$ carrier

$S_C = m_C >$ carrier

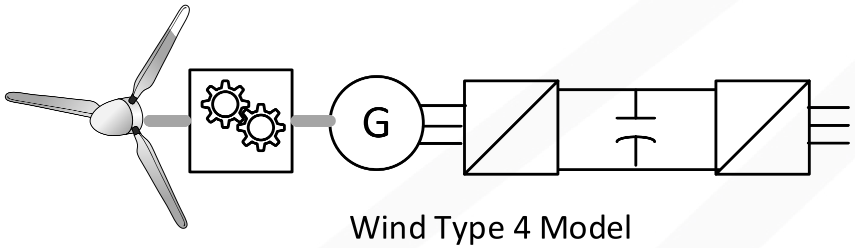
DC bus modeling may be necessary to represent control system dynamics and protective functions accurately.



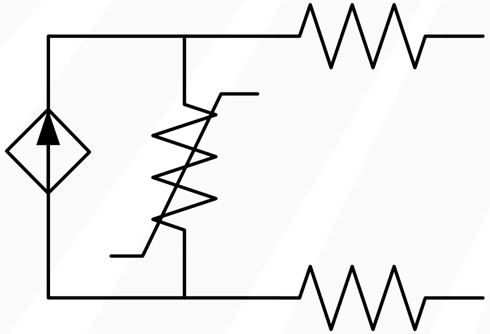
Idealized



Chopper?



Wind Type 4 Model



Nonlinear PV Model

Converter model reference: https://doi.org/10.1109/ACCESS.2021.3086420
PV model references: https://doi.org/10.1109/TSTE.2012.2202294 and https://doi.org/10.1109/TPEL.2009.2013862
Battery model reference: https://doi.org/10.1109/ACCESS.2019.2957698

Important Links and Instructions

- This meeting now "ends for all"
- Please join your tool-specific meeting from 2:30 – 5:00 Eastern time
    - That meeting will be on a separate invitation that you should have received
- Instructions, models, slides, videos, and other material: https://github.com/pnnl/i2x/tree/develop/emt-bootcamp
- Direct questions about software operation to your tool vendor
- Post questions about the bootcamp materials here:
    - https://github.com/pnnl/i2x/issues/16
    - You may benefit from the experience of others this way