# ESIG Webinar Series

## Update on Dynamic Model Development and Validation for Converter-based Resources

**Bob Zavadil**, Chief Operating Officer, EnerNex
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December 17, 2019

ESIG
ENERGY SYSTEMS INTEGRATION GROUP

NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

# Modeling and Verification for BPS-Connected Inverter-based Resources

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Senior Manager, NERC
Energy Systems Integration Group (ESIG) Webinar
December 2019

**RELIABILITY | RESILIENCE | SECURITY**




# Disclaimer

- *Materials presented here…*
  - *Are not intended as compliance guidance.*
  - *Are intended to describe the technical aspects of inverter-based resource modeling and verification.*
  - *Are based on my experience and engagement with industry stakeholders, and may not necessarily be the opinions of NERC.*
- *Questions related to compliance can be directed to NERC Compliance Assurance department.*

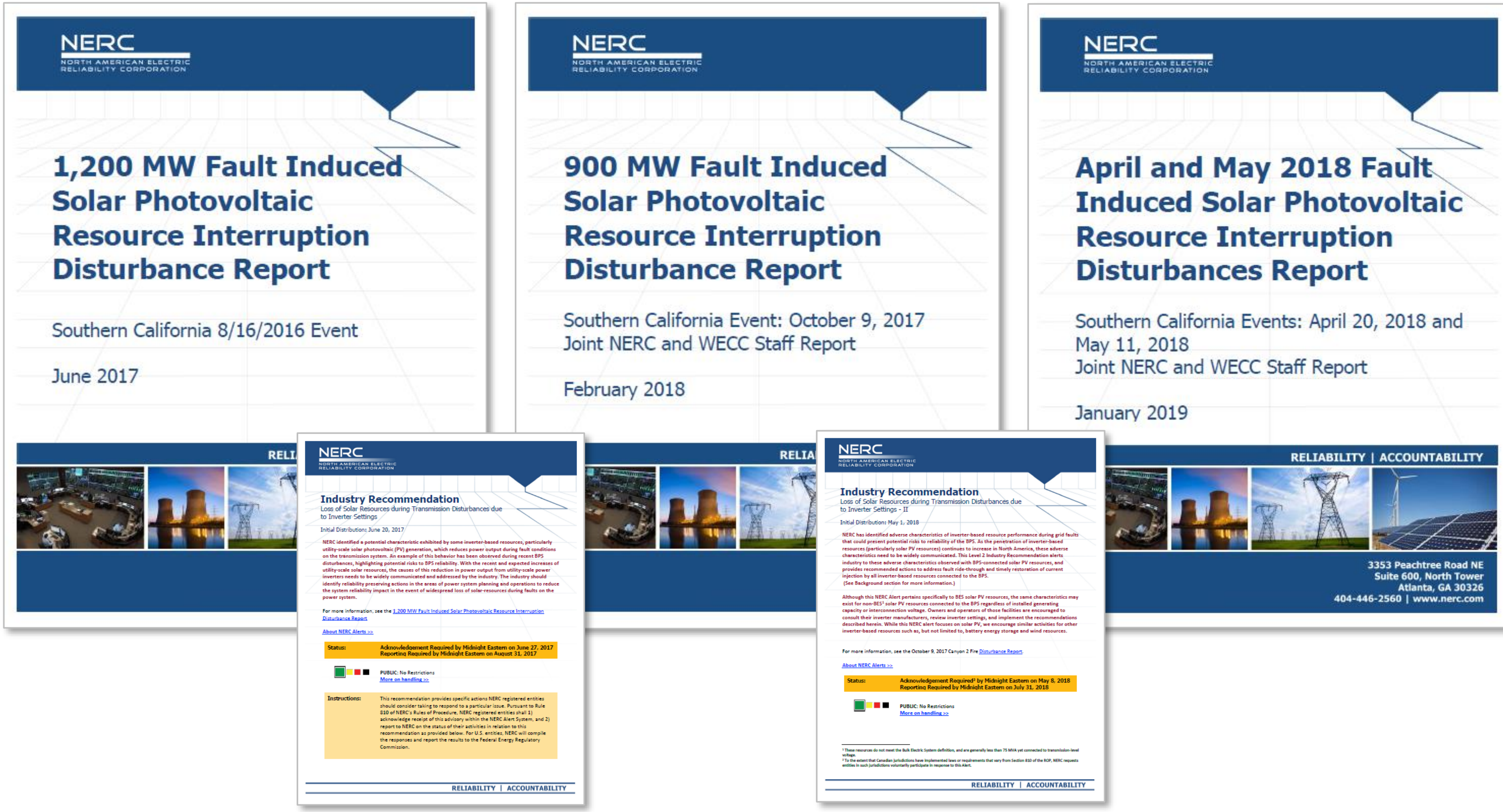
# Big Picture Perspective

**The bulk power system and its technologies are RAPIDLY changing…**

**It is INCUMBENT upon us as stewards of reliability to ADAPT to these changes…**

**To ensure RELIABLE OPERATION of the bulk power system moving forward…**

# NERC Disturbance Reports of Solar PV Events



# NERC Reliability Guidelines

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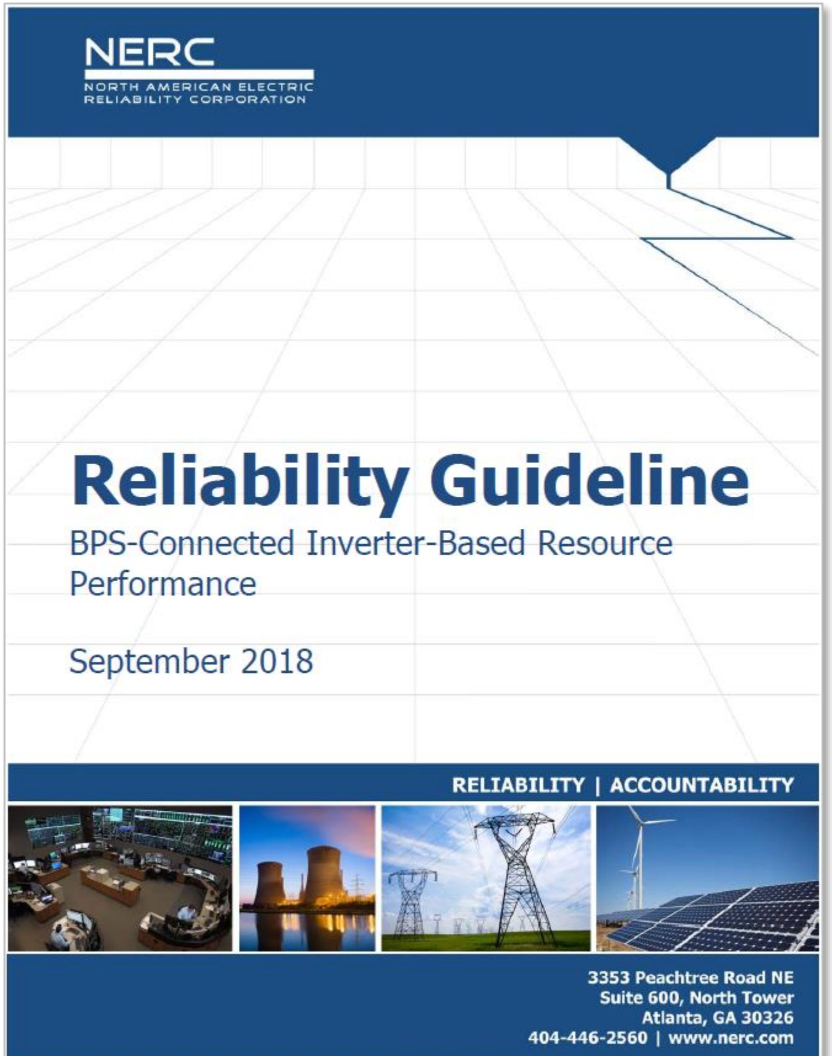
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Reliability Guideline

BPS-Connected Inverter-Based Resource Performance

September 2018

RELIABILITY | ACCOUNTABILITY

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Suite 600, North Tower
Atlanta, GA 30326
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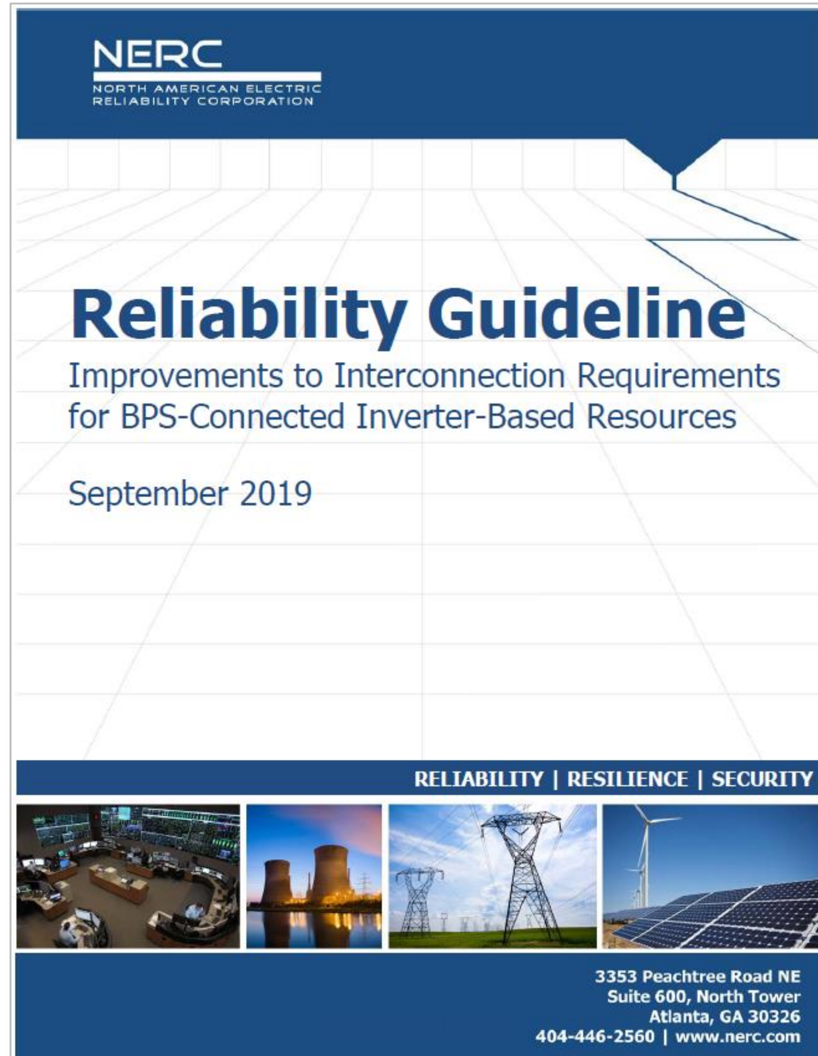
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Reliability Guideline

Improvements to Interconnection Requirements for BPS-Connected Inverter-Based Resources

September 2019

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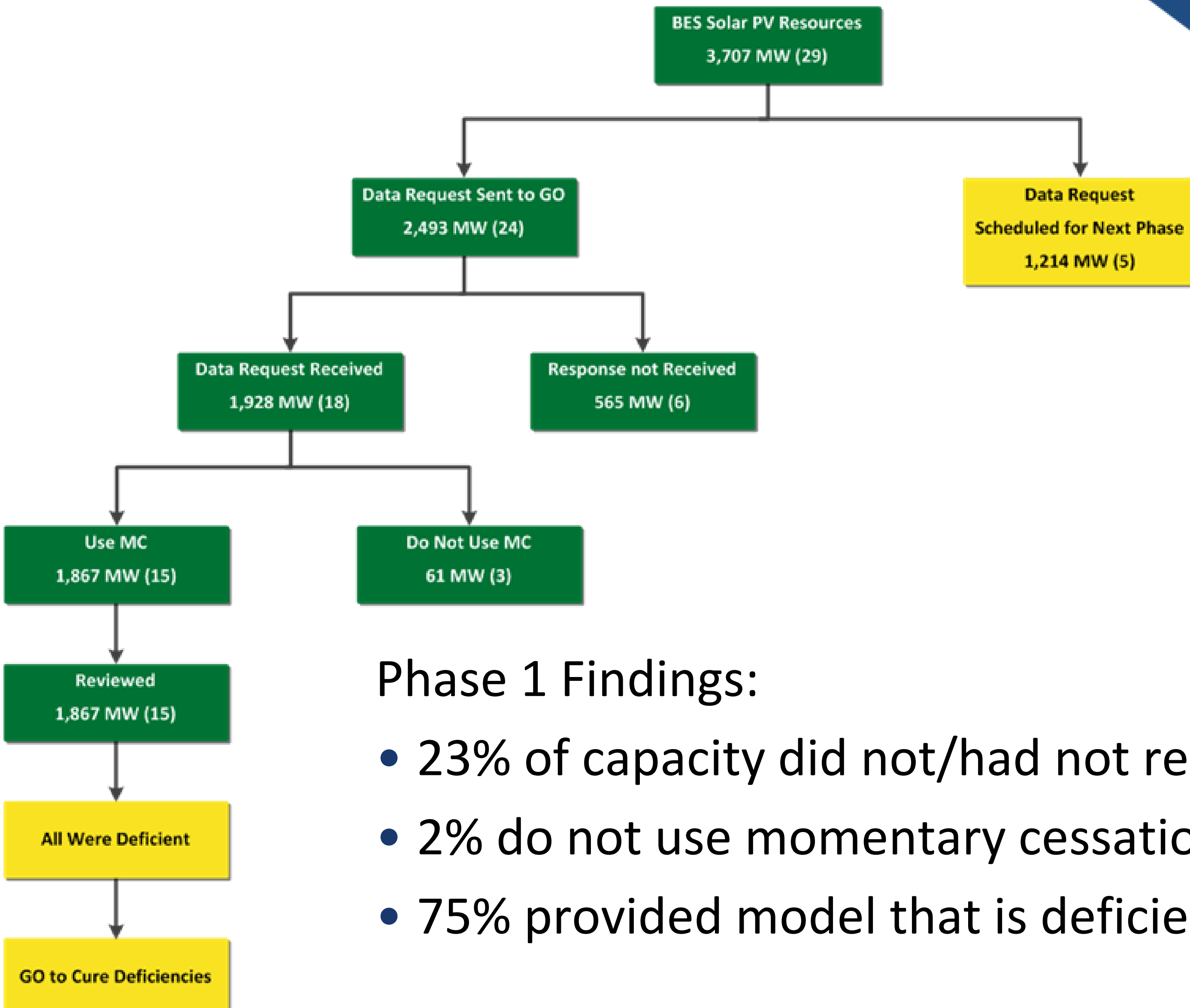
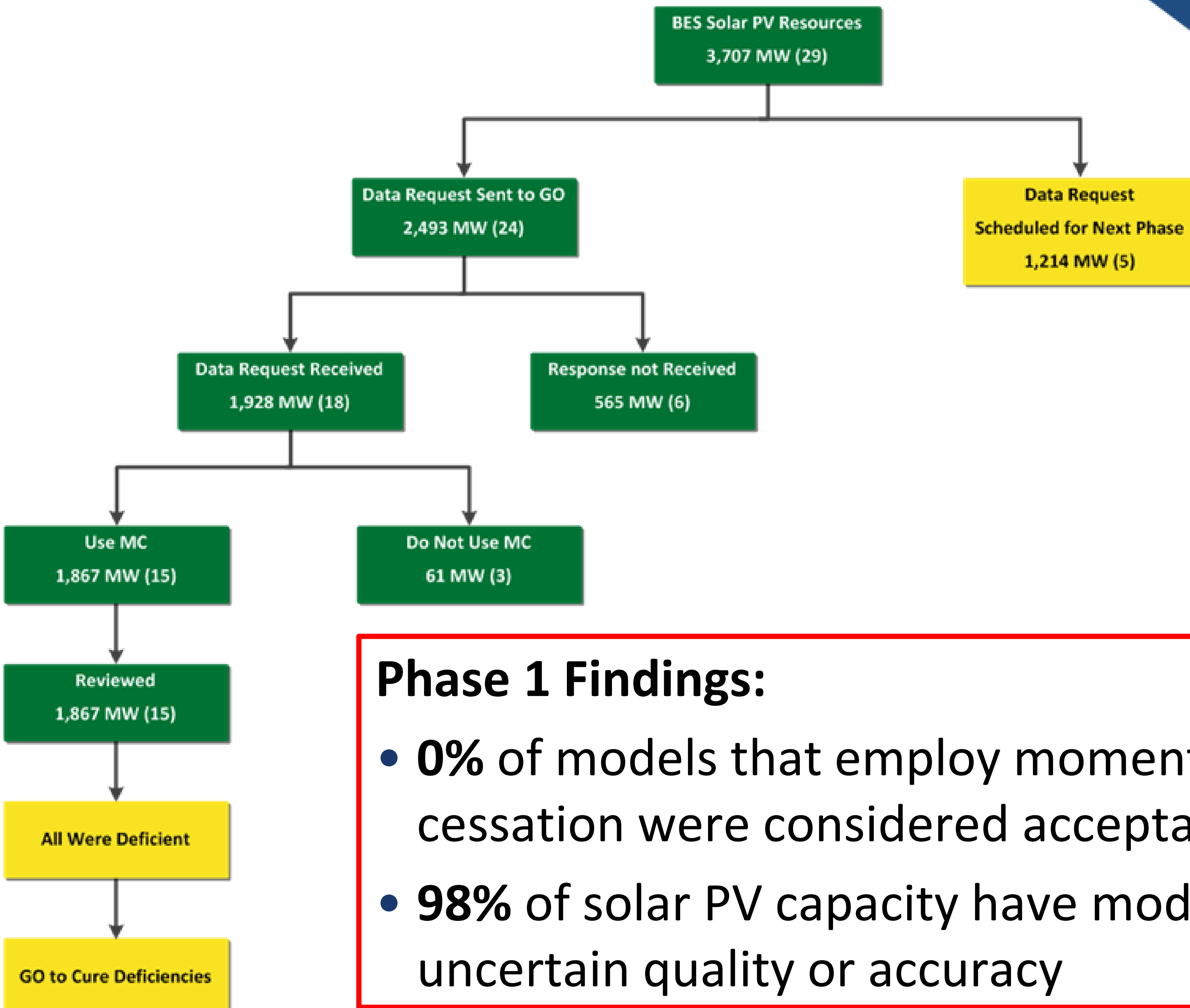
# SCE Modeling Improvements Update September 2019




Phase 1 Findings:

- 23% of capacity did not/had not responded
- 2% do not use momentary cessation
- 75% provided model that is deficient

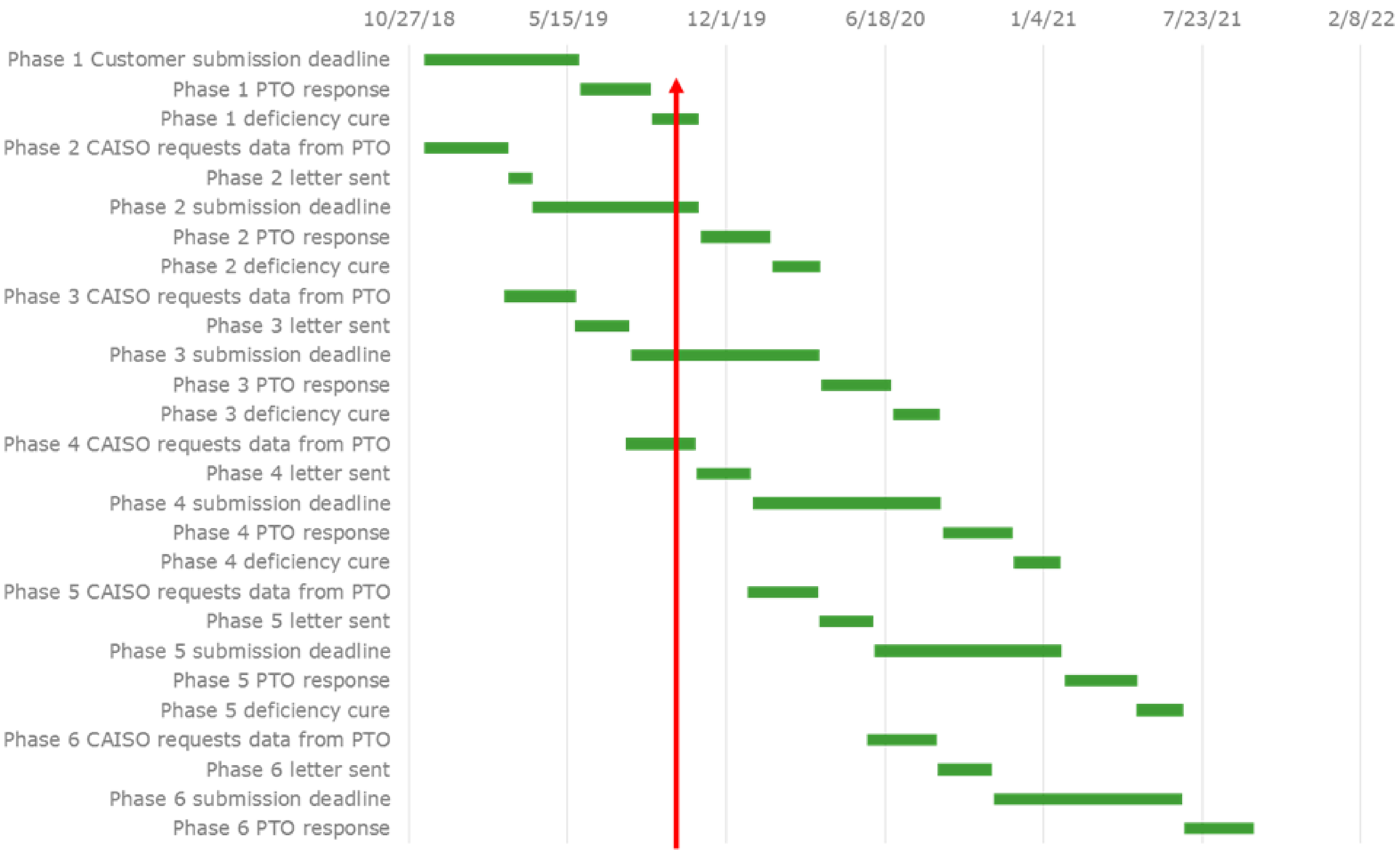
# SCE Modeling Improvements Update September 2019




## Phase 1 Findings:

- **0%** of models that employ momentary cessation were considered acceptable
- **98%** of solar PV capacity have models with uncertain quality or accuracy

# PG&E Timeline for Modeling Improvements



# Predominant Issues for Modeling BPS Solar PV Resources

- Models fail basic model quality checks – incorrect data format, initialization, flat run, positive damping
- Mismatch between model and actual installed settings – incorrect parameterization
  - The reec_a model parameters does not match actual settings provided in NERC Alert by GO
- Actual resource uses momentary cessation but is modeled using *reec_b* rather than *reec_a*
  - *reec_b* does not suitably capture momentary cessation;
  - WECC has published a white paper describing the steps to convert the dynamic models from reec_b to reec_a; however, it is apparent that these recommendations are not being applied widely by industry.

# Predominant Issues for Modeling BPS Solar PV Resources (cont.)

- Suspicious data – exact same default parameters used across many resources; often match software manuals
  - Unlikely that every control setting exactly the same for many plants; each plant should be tuned during interconnection for optimal performance
- Uncoordinated parameters for VDL tables, Vdip, and Ip and Iq prioritization – fairly complex and requires expert to make changes to model due to parameter interactions
- Anecdotal evidence that multiple plants making changes to control settings without providing dynamic model to TP/PC, nor requesting approval from transmission entity before making these changes.
  - GOs/GOPs stated that changes were not considered “material modifications” and therefore can be made without prior approval or notification.

# Predominant Issues for Modeling BPS Solar PV Resources (cont.)

- Lack of information available for TPs/PCs to verify whether dynamic models match actual installed equipment
  - Lack of detail in MOD-026-1 and MOD-027-1 test reports
  - Unknown type of data provided during interconnection process
  - NERC Alert was first time data on actual installed equipment collected
- Interconnection timeline crunch – modeling challenge
  - Receiving updated dynamic models after interconnection proved fruitless
- Studies with up-to-date models for BPS-connected IBR and DER not being widely performed
  - IRPTF studies: accurate BPS IBR models, DER not considered
  - DER studies: Accurate DER models; BPS IBR using incorrect models

# Predominant Issues for Modeling BPS Solar PV Resources (cont.)

- EMT models often not provided during interconnection study process; extremely difficult to acquire after in-service date
  - Challenge for systems with rapid evolution of generation technologies
  - Without EMT models, TPs/PCs faced with using assumptions for resource performance (may miss potential reliability risks)
- Limitations in rms positive sequence stability simulations
  - Inability to identify common stability issues during high-penetration inverter-based resource conditions
  - Controls interactions, controls instability, subsynchronous control interactions (SSCI), low short circuit strength grids
  - EMT not commonly performed during annual planning process

# Timeline of Models Submitted

**Feasibility Study**
- Little information known about plant
- Expected plant design (basic), powerflow
- TP/PC sets requirements

**System Impact Study**
- More information known about plant
- Expected plant design (detailed), dynamics
- TP/PC sets requirements

**Commissioning**
- As built designs, plant information, settings
- May deviate from expected models slightly
- Updates need to be provided to TP/PC asap

**MOD-032 Case Creation**
- Regular data submittal process
- Most up-to-date plant data and models
- TP/PC review of data submitted

**MOD-026 and MOD-027 Verification**
- Verification of actual plant performance and docs
- TP review of report and data submitted
- Latest expected performance from resource

**MOD-033 Verification**
- TP/PC verification of wide-area performance
- Direction to GO to check model/settings

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# FERC Interconnection Process
# Interconnection Request

Attachment A to Appendix 1
Interconnection Request

## LARGE GENERATING FACILITY DATA

### UNIT RATINGS

kVA ____________ °F _________ Voltage _____________
Power Factor ________
Speed (RPM) ________ Connection (e.g. Wye) _____________
Short Circuit Ratio ________ Frequency, Hertz ____________
Stator Amperes at Rated kVA _________ Field Volts _______________
Max Turbine MW ____________ °F ______

Primary frequency response operating range for electric storage resources:
Minimum State of Charge: ____________

Maximum State of Charge: ____________

### COMBINED TURBINE-GENERATOR-EXCITER INERTIA DATA

Inertia Constant, H = ____________________ kW sec/kVA
Moment-of-Inertia, $WR^2$ = ____________________ lb. $ft.^2$

### REACTANCE DATA (PER UNIT-RATED KVA)

| | DIRECT AXIS | | QUADRATURE AXIS | |
|---|---|---|---|---|
| Synchronous – saturated | $X_{dv}$ | _______ | $X_{qv}$ | _______ |
| Synchronous – unsaturated | $X_{di}$ | _______ | $X_{qi}$ | _______ |
| Transient – saturated | $X'_{dv}$ | _______ | $X'_{qv}$ | _______ |
| Transient – unsaturated | $X'_{di}$ | _______ | $X'_{qi}$ | _______ |
| Subtransient – saturated | $X''_{dv}$ | _______ | $X''_{qv}$ | _______ |
| Subtransient – unsaturated | $X''_{di}$ | _______ | $X''_{qi}$ | _______ |
| Negative Sequence – saturated | $X2_v$ | _______ | | |
| Negative Sequence – unsaturated | $X2_i$ | _______ | | |
| Zero Sequence – saturated | $X0_v$ | _______ | | |
| Zero Sequence – unsaturated | $X0_i$ | _______ | | |

### WIND GENERATORS

Number of generators to be interconnected pursuant to this Interconnection Request:
____________

Elevation: ____________ _____ Single Phase _____ Three Phase

Inverter manufacturer, model name, number, and version:

List of adjustable setpoints for the protective equipment or software:

Note: A completed General Electric Company Power Systems Load Flow (PSLF) data sheet or other compatible formats, such as IEEE and PTI power flow models, must be supplied with the Interconnection Request. If other data sheets are more appropriate to the proposed device, then they shall be provided and discussed at Scoping Meeting.

### Solar Generation

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# NERC Consideration for "Material Modification"

## B. Requirements and Measures

**R1.** Each Transmission Planner and each Planning Coordinator shall study the reliability impact of: (i) interconnecting new generation, transmission, or electricity end-user Facilities and (ii) materially modifying existing interconnections of generation, transmission, or electricity end-user Facilities. The following shall be studied: *[Violation Risk Factor: Medium] [Time Horizon: Long-term Planning]*

**1.1.** The reliability impact of the new interconnection, or materially modified existing interconnection, on affected system(s);

**1.2.** Adherence to applicable NERC Reliability Standards; regional and Transmission Owner planning criteria; and Facility interconnection requirements;

**1.3.** Steady-state, short-circuit, and dynamics studies, as necessary, to evaluate system performance under both normal and contingency conditions; and

### Guidelines and Technical Basis

Entities should have documentation to support the technical rationale for determining whether an existing interconnection was "materially modified." Recognizing that what constitutes a "material modification" will vary from entity to entity, the intent is for this determination to be based on engineering judgment.

# FERC Definition of "Material Modification"

**Material Modification** shall mean those modifications that have a material impact on the cost or timing of any Interconnection Request with a later queue priority date.

Customer; and (c) a Permissible Technological Advancement for the Large Generating Facility after the submission of the Interconnection Request. Section 4.4.6 specifies a separate technological change procedure including the requisite information and process that will be followed to assess whether the Interconnection Customer's proposed technological advancement under Section 4.4.2(c) is a Material Modification. Section 1 contains a definition of Permissible Technological Advancement.

**Permissible Technological Advancement** [Transmission Provider inserts definition here].

# "Material Modification"

## NERC FAC-002-2 Consideration ≠ FERC LGIP/SGIP Consideration

**NOTE THE SAME INTENTION OR PURPOSE**

- Don't you want to re-study the potential BPS impact of any changes to the facility that may have an impact on the electrical performance for the facility?
  - Changes to inverter type/size and inverter controls
  - Changes to plant-level controller settings
  - Changes to dynamic reactive support

# Applicable NERC Facility Interconnection Standards

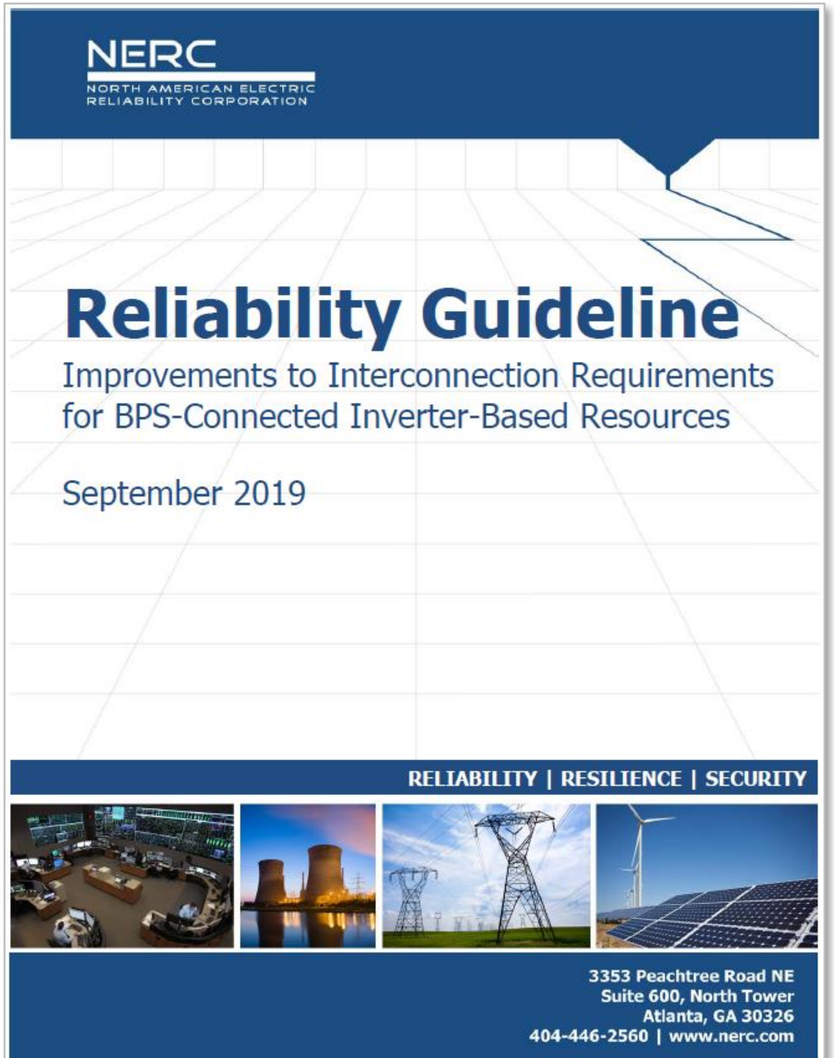
## FAC-001-3: Facility Interconnection Requirements

**R1.** Each Transmission Owner shall document Facility interconnection requirements, update them as needed, and make them available upon request. Each Transmission Owner's Facility interconnection requirements shall address interconnection requirements for: *[Violation Risk Factor: Lower] [Time Horizon: Long-term Planning]*

## FAC-002-2: Facility Interconnection Studies

**R1.** Each Transmission Planner and each Planning Coordinator shall study the reliability impact of: (i) interconnecting new generation, transmission, or electricity end-user Facilities and (ii) materially modifying existing interconnections of generation, transmission, or electricity end-user Facilities. The following shall be studied: *[Violation Risk Factor: Medium] [Time Horizon: Long-term Planning]*

# Improvements to Interconnection Requirements for BPS-Connected IBR




**NOTICE:**

**ACTIONABLE RECOMMENDATIONS CONTAINED WITHIN!**

- Strong recommendations to improve interconnection requirements AND interconnection study process
- All TOs/TPs/PCs should be considering this guideline and adopting its recommendations, as applicable

# NERC MOD-026-1 and MOD-027-1

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**Standard MOD-026-1 — Verification of Models and Data for Generator Excitation Control System or Plant Volt/Var Control Functions**

**A. Introduction**

1. **Title:** Verification of Models and Data for Generator Excitation Control System or Plant Volt/Var Control Functions
2. **Number:** MOD-026-1
3. **Purpose:** To verify that the generator excitation control system or plant volt/var control function[1] model (including the power system stabilizer model and the impedance compensator model) and the model parameters used in dynamic simulations accurately represent the generator excitation control system or plant volt/var control function behavior when assessing Bulk Electric System (BES) reliability.
4. **Applicability:**
   - **4.1. Functional Entities:**
     - 4.1.1 Generator Owner
     - 4.1.2 Transmission Planner
   - **4.2. Facilities:**

     For the purpose of the requirements contained herein, Facilities that are directly connected to the Bulk Electric System (BES) will be collectively referred to as an "applicable unit" that meet the following:
     - 4.2.1 Generation in the Eastern or Quebec Interconnections with the following characteristics:
       - 4.2.1.1 Individual generating unit greater than 100 MVA (gross nameplate rating).
       - 4.2.1.2 Individual generating plant consisting of multiple generating units that are directly connected at a common BES bus with total generation greater than 100 MVA (gross aggregate nameplate rating).
     - 4.2.2 Generation in the Western Interconnection with the following characteristics:
       - 4.2.2.1 Individual generating unit greater than 75 MVA (gross nameplate rating).
       - 4.2.2.2 Individual generating plant consisting of multiple generating units that are directly connected at a common BES bus with total generation greater than 75 MVA (gross aggregate nameplate rating).

[1] Excitation control system or plant volt/var control function:

a. For individual synchronous machines, the generator excitation control system includes the generator, exciter, voltage regulator, impedance compensation and power system stabilizer.

b. For an aggregate generating plant, the volt/var control system includes the voltage regulator & reactive power control system controlling and coordinating plant voltage and associated reactive capable resources.

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**Standard MOD-027-1 — Verification of Models and Data for Turbine/Governor and Load Control or Active Power/Frequency Control Functions**

**A. Introduction**

1. **Title:** Verification of Models and Data for Turbine/Governor and Load Control or Active Power/Frequency Control Functions
2. **Number:** MOD-027-1
3. **Purpose:** To verify that the turbine/governor and load control or active power/frequency control[1] model and the model parameters, used in dynamic simulations that assess Bulk Electric System (BES) reliability, accurately represent generator unit real power response to system frequency variations.
4. **Applicability:**
   - 4.1. Functional entities
     - 4.1.1 Generator Owner
     - 4.1.2 Transmission Planner
   - **4.2. Facilities**

     For the purpose of the requirements contained herein, Facilities that are directly connected to the Bulk Electric System (BES) will be collectively referred to as an "applicable unit" that meet the following:
     - 4.2.1 Generation in the Eastern or Quebec Interconnections with the following characteristics:
       - 4.2.1.1 Individual generating unit greater than 100 MVA (gross nameplate rating).
       - 4.2.1.2 Individual generating plant consisting of multiple generating units that are directly connected at a common BES bus with total generation greater than 100 MVA (gross aggregate nameplate rating).
     - 4.2.2 Generation in the Western Interconnection with the following characteristics:
       - 4.2.2.1 Individual generating unit greater than 75 MVA (gross nameplate rating).
       - 4.2.2.2 Individual generating plant consisting of multiple generating units that are directly connected at a common BES bus with total generation greater than 75 MVA (gross aggregate nameplate rating).
     - 4.2.3 Generation in the ERCOT Interconnection with the following characteristics:

[1] Turbine/governor and load control or active power/frequency control:

a. Turbine/governor and load control applies to conventional synchronous generation.

b. Active power/frequency control applies to inverter connected generators (often found at variable energy plants).

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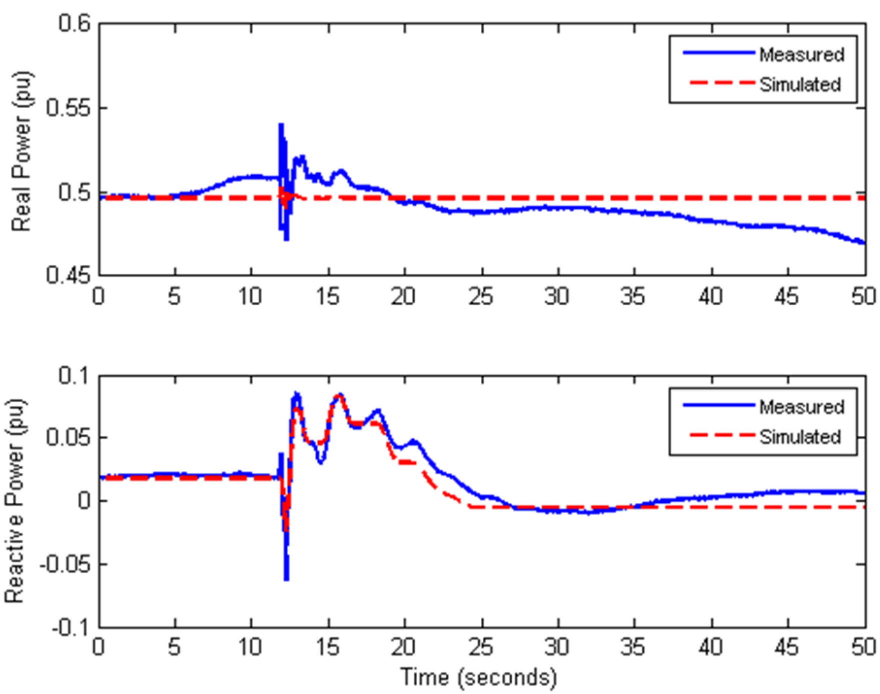
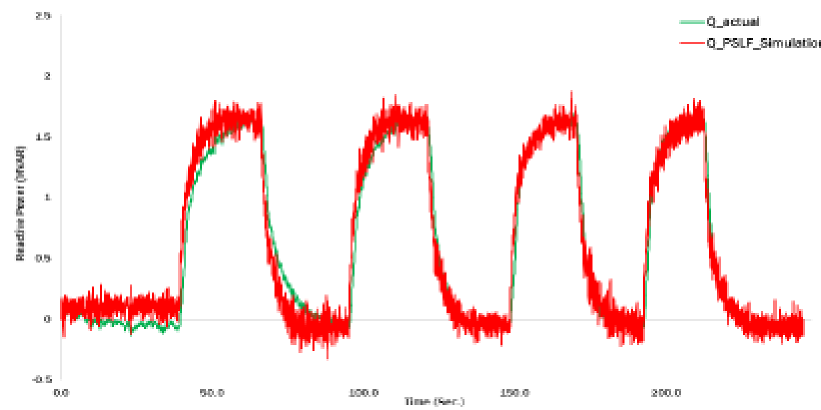
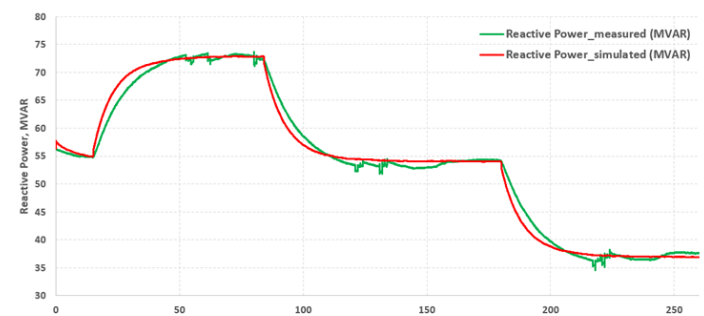
# Small Disturbance Verification

- Captures response to small grid disturbances such as frequency excursions and small voltage swings
- Commonly used for verification testing
- Neglects large disturbance behavior (i.e., faults)




Sources: IEEE©2016, First Solar

# Expectations for Verification Reports

17.2 REGCAU1

**Renewable Energy Generator/Converter Model**

| | | |
|---|---|---|
| This model is located at system bus | #______ | IBUS, |
| Machine identifier | #______ | ID, |
| This model uses CONs starting with | #______ | J, |
| and STATEs starting with | #______ | K, |
| and VARs starting with | #______ | L, |
| and ICONs starting with | #______ | M. |

| CONs | # | Value | Description |
|---|---|---|---|
| J | | | |
| J+1 | | | |
| J+2 | | | |
| J+3 | | | |
| J+4 | | | |
| J+5 | | | |
| J+6 | | | |
| J+7 | | | |
| J+8 | | | |
| J+9 | | | |

18.2 REECAU1

**Generic Renewable Electrical Control Model**

| | | |
|---|---|---|
| This model is located at system bus | #______ | IBUS, |
| Machine identifier | #______ | ID, |
| This model uses CONs starting with | #______ | J, |
| and STATEs starting with | #______ | K, |
| and VARs starting with | #______ | L, |
| and ICONs starting with | #______ | M. |

| CONs | # | V |
|---|---|---|
| J | | |
| J+1 | | |
| J+2 | | |
| J+3 | | |
| J+4 | | |
| J+5 | | |
| J+6 | | |
| J+7 | | |
| J+8 | | |
| J+9 | | |
| J+10 | | |

22.1 REPCAU1 & REPCTAU1

**Generic Renewable Plant Control Model**

| | | |
|---|---|---|
| This model is located at system bus | #______ | IBUS, |
| Machine identifier | #______ | ID, |
| This model uses CONs starting with | #______ | J, |
| and STATEs starting with | #______ | K, |
| and VARs starting with | #______ | L, |
| and ICONs starting with | #______ | M. |

| CONs | # | Value | Description |
|---|---|---|---|
| J | | | Tfltr, Voltage or reactive power measurement filter time constant (s) |
| J+1 | | | Kp, Reactive power PI control proportional gain (pu) |
| J+2 | | | Ki, Reactive power PI control integral gain (pu) |
| J+3 | | | Tft, Lead time constant (s) |
| J+4 | | | Tfv, Lag time constant (s) |
| J+5 | | | Vfrz, Voltage below which State s2 is frozen (pu) |
| J+6 | | | Rc, Line drop compensation resistance (pu) |
| J+7 | | | Xc, Line drop compensation reactance (pu) |
| J+8 | | | Kc, Reactive current compensation gain (pu) |
| J+9 | | | emax, upper limit on deadband output (pu) |
| J+10 | | | emin, lower limit on deadband output (pu) |
| J+11 | | | dbd1, lower threshold for reactive power control deadband (<=0) |
| J+12 | | | dbd2, upper threshold for reactive power control deadband (>=0) |
| J+13 | | | Qmax, Upper limit on output of V/Q control (pu) |
| J+14 | | | Qmin, Lower limit on output of V/Q control (pu) |

*Source: PTI*

- Thorough explanations:
  - Models selected and why
  - Model data sheets (or model) with values entered
  - Explanation of derivation for **<u>EVERY</u>** parameter
    - Commissioning, verification, or factory test reports
    - Communication with manufacturer
    - Engineering judgement
  - Small disturbance expectations
  - Large disturbance expectations
  - Model limitations and capabilities

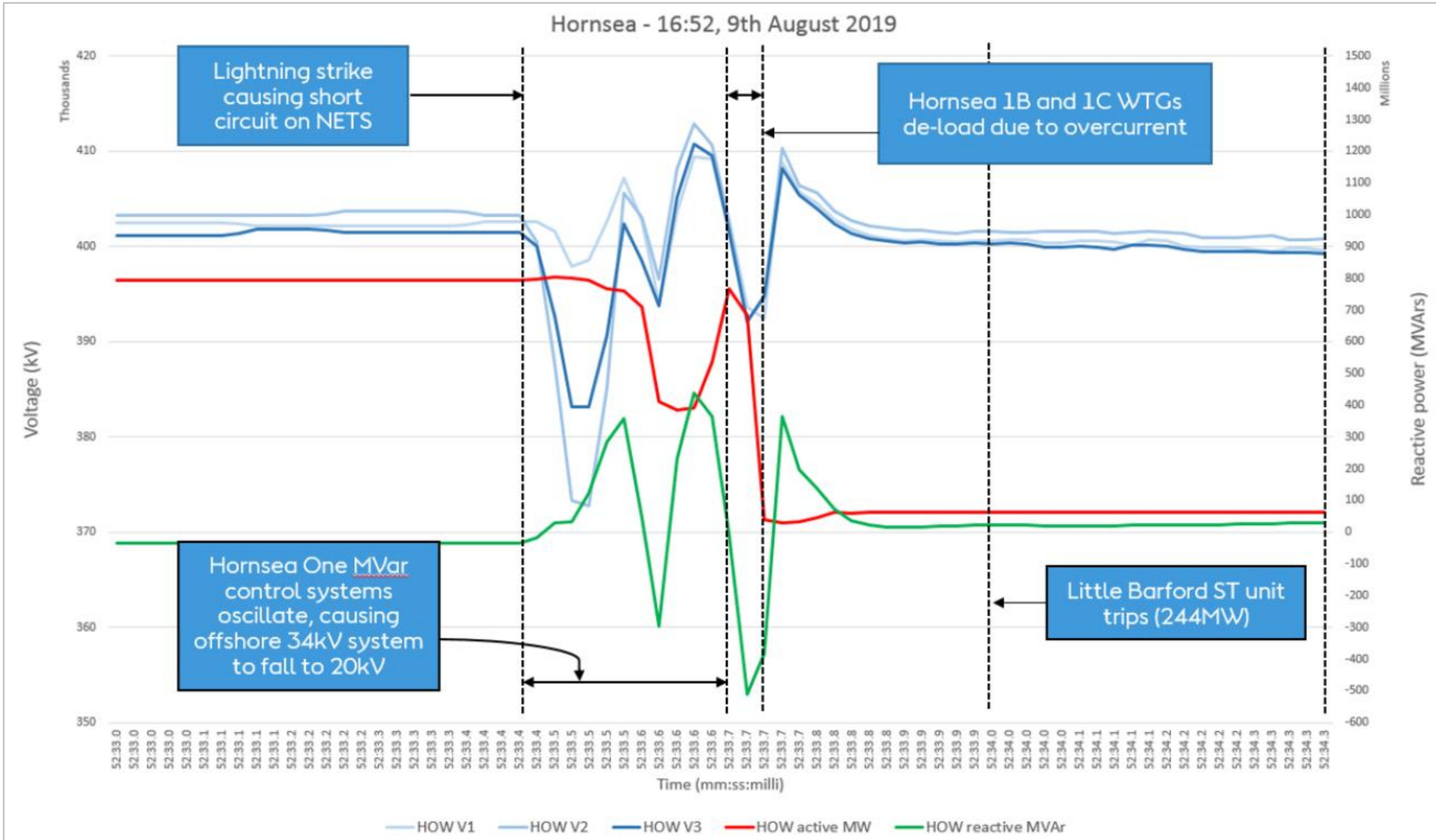
# Large Disturbance Testing

## *Do we have a gap?**

*Gap = ...

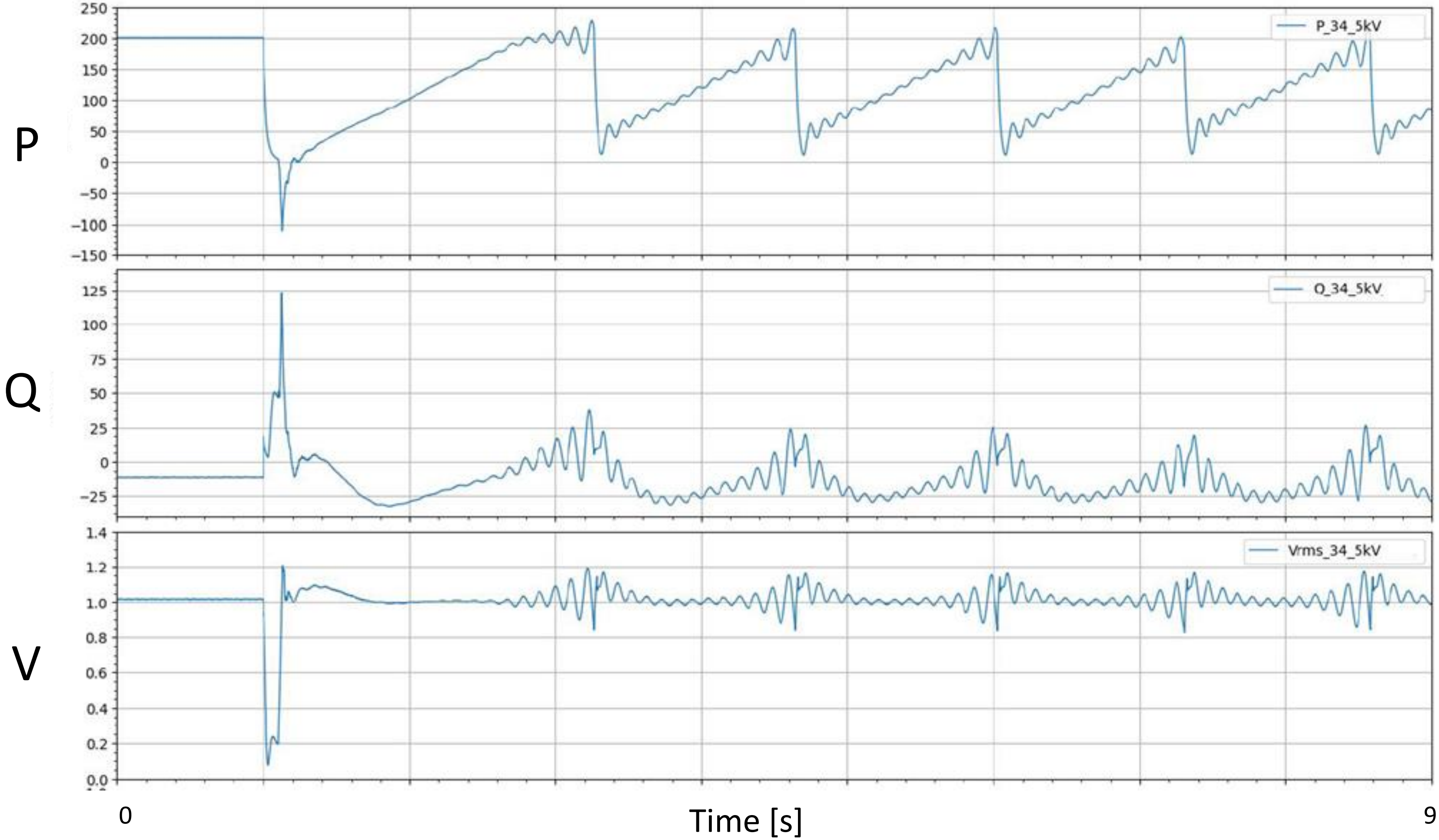
- Evolving technologies and resources
- Evolving models and study needs
- No requirement for spec sheets or settings
- Small disturbance testing only
- Lack of detail in test reports
- Need for more thorough review of models and parameterization

# UK Grid Disturbance
# Example of "Weak Grid" Condition




Source: OFGEM

# Growing Need for EMT Modeling



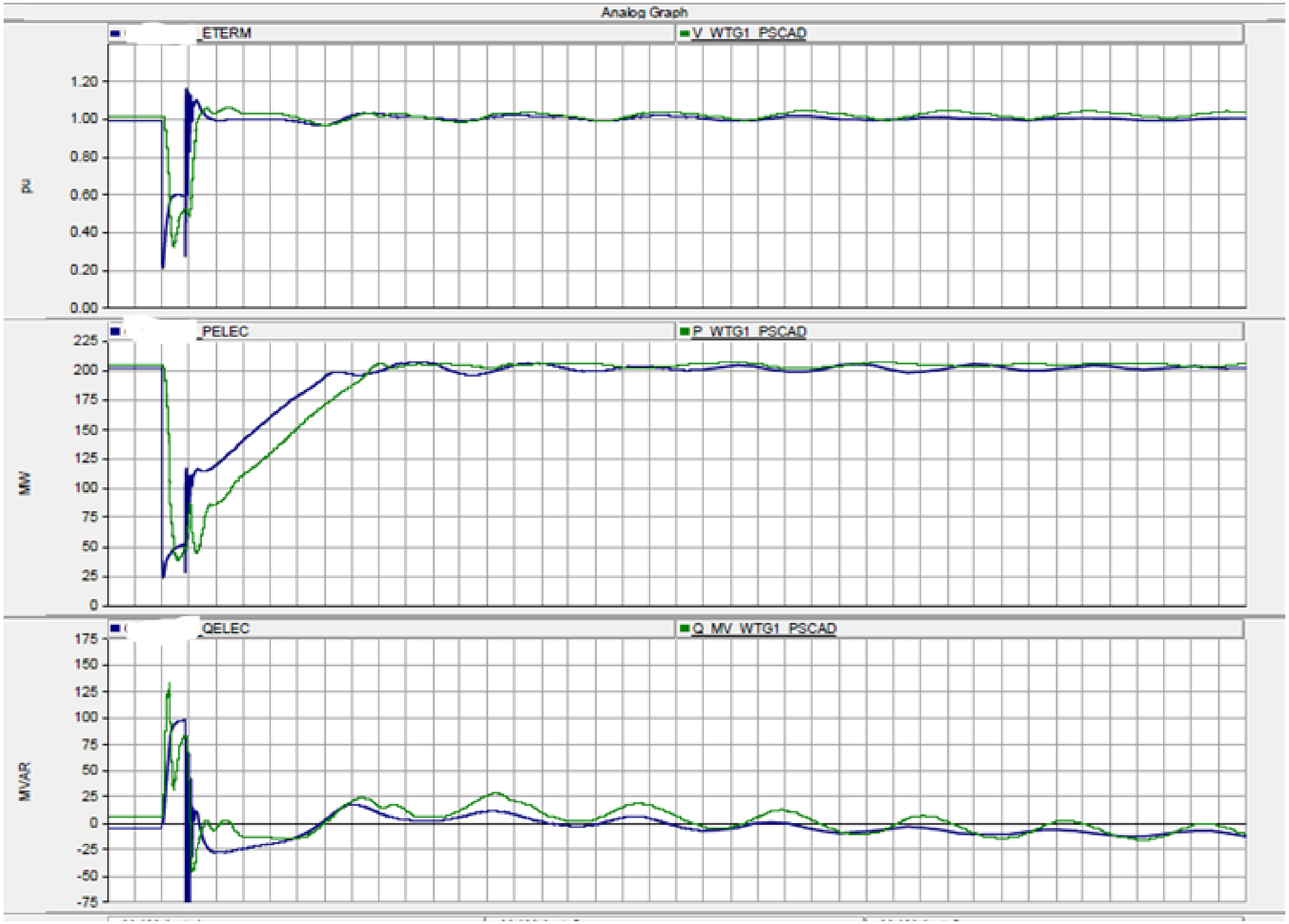

*Source: Electranix*

# EMT Model Benchmarking

V

P

Q

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*Source: Electranix*

# Cannot Stress Enough…

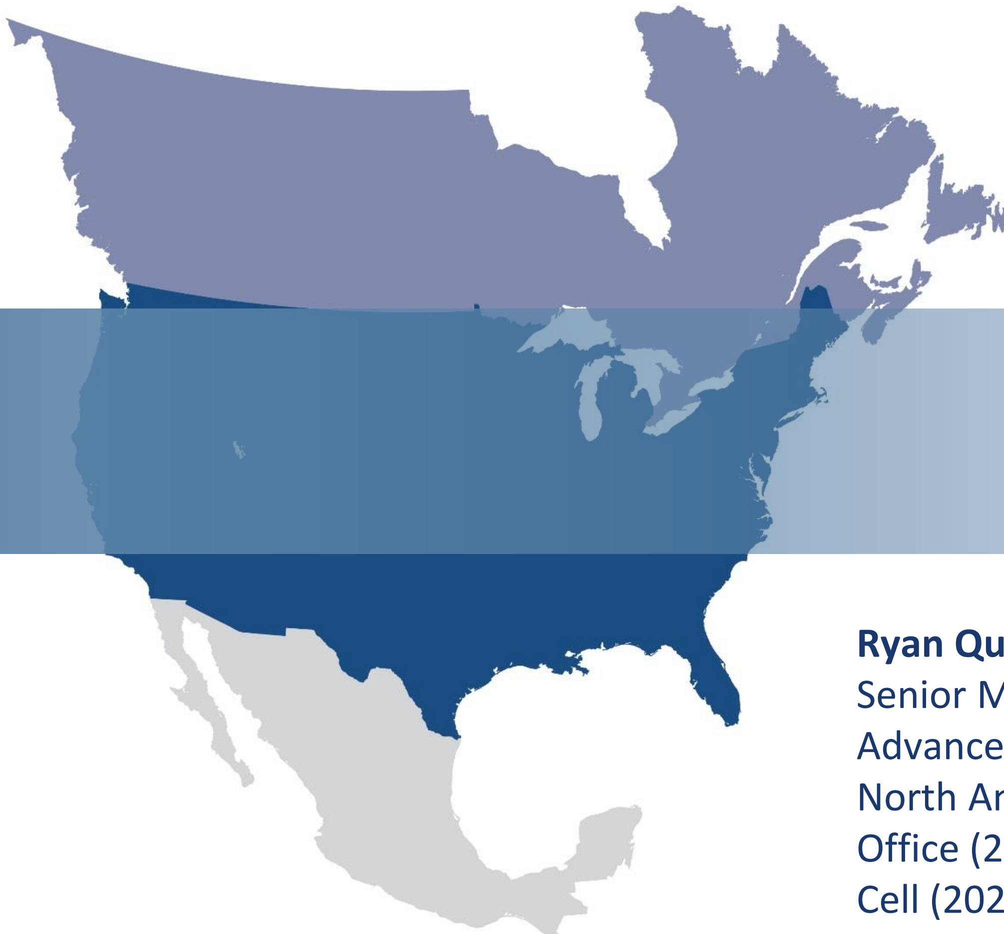
**The bulk power system and its technologies are RAPIDLY changing…**

**It is INCUMBENT upon us as stewards of reliability to ADAPT to these changes…**

**To ensure RELIABLE OPERATION of the bulk power system moving forward…**

# Get Engaged with NERC Activities

- Reliability Guidelines (here)
- NERC Inverter-Based Resource Performance Task Force (here)
- NERC Power Plant Modeling and Verification Task Force (here)
- Guideline: Recommended Performance for BPS-Connected IBR (here)
- Guideline: Improvements to Interconnection Requirements (here)
- Blue Cut Fire Disturbance Report (here)
- Canyon 2 Fire Disturbance Report (here)
- Palmdale Roost and Angeles Forest Disturbance Report (here)
- NERC Alert: Loss of Solar Resources I (here)
- NERC Alert: Loss of Solar Resources II (here)
- Summary of ERO Activities for IBR (here)
- IEEE P2800 (here)



# Thank You!

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# RENEWABLE PLANT MODEL VALIDATION – STATUS & OUTLOOK

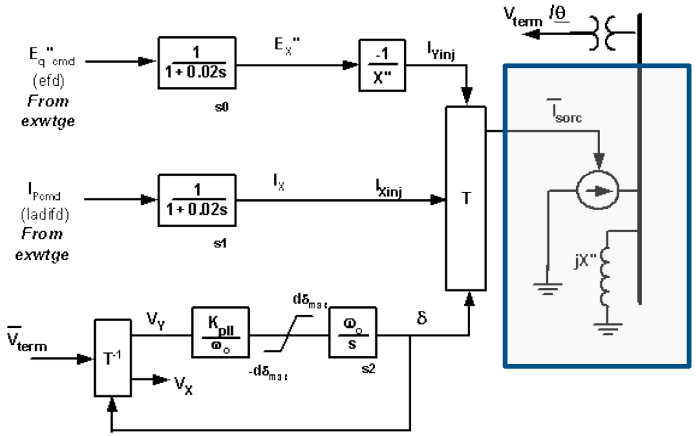
SOME THOUGHTS ON "GRID-FOLLOWING" VS. "GRID-FORMING" INVERTERS

17 DECEMBER 2019

EnerNex

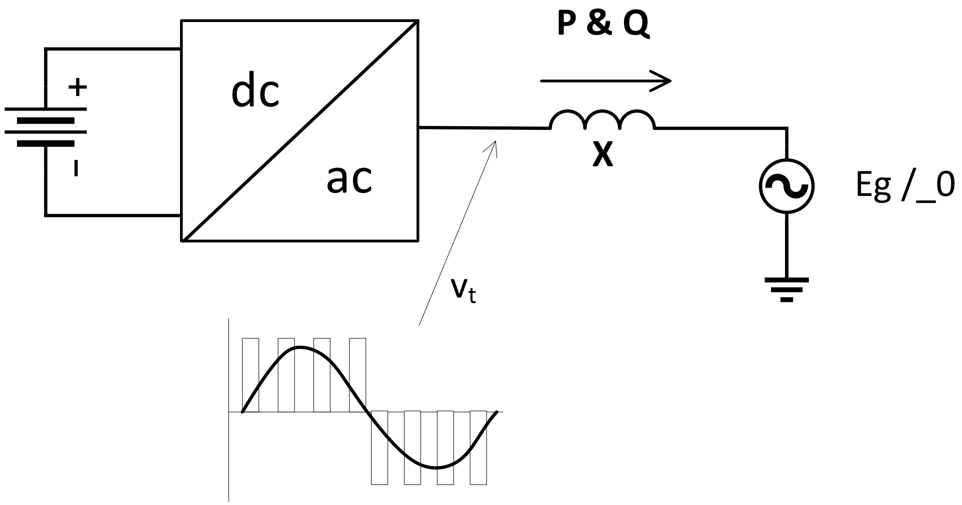
A CESI Company

- "Inverter-Based Resources" drawing significant attention in industry (e.g. Ryan's presentation)
- We are now approaching 15 years of expanding our technical analysis capabilities to accommodate growing renewable penetrations (much of it inverter-based)
  - 2nd generation of generic models for bulk system planning tools
  - Increasing application of EMT models
- Some early concepts remain –
  - Fundamental control concept is independent control of P & Q (in steady state)
  - Inject real and reactive currents into grid
  - Small, individual IBRs synchronize to grid voltage; i.e. they operate independent of grid frequency (don't care), unless additional feedback is added (synthetic inertia)



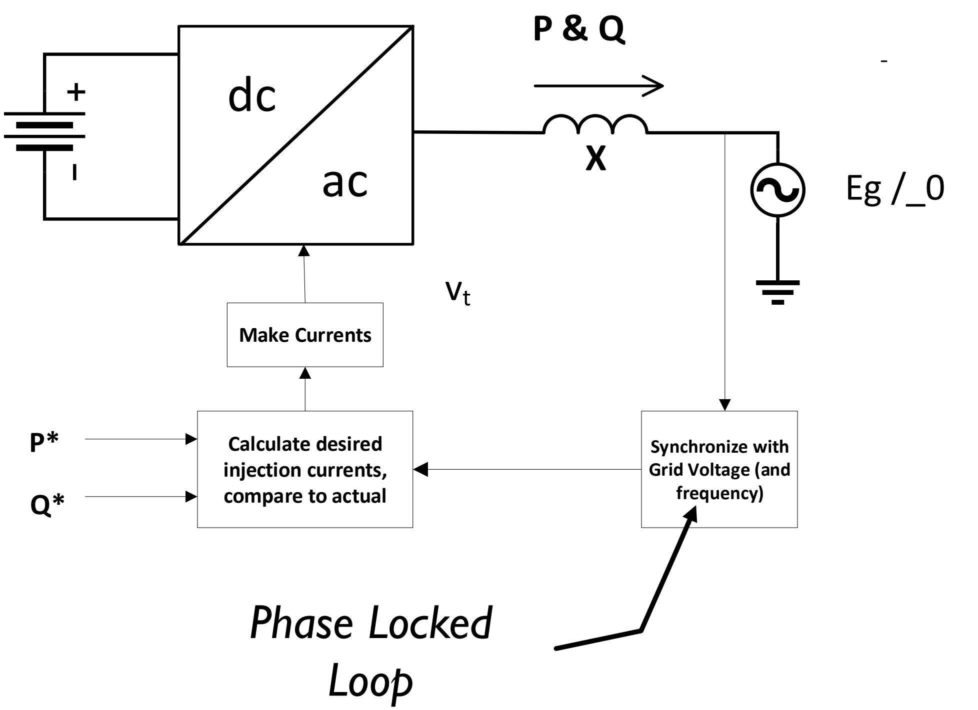
# FUNDAMENTAL VOLTAGE-SOURCE CONVERTER OPERATION

- Voltage on dc link is manipulated to create ac voltage
- Synthesized voltage drives currents through grid tie
  - Output filter
  - GSU transformer
- Voltage at immediate terminals of converter (before output filter/inductance) is comprised of a fundamental component and switching noise
  - Sometimes is computed directly in control loops (conventional PWM scheme for switch control)
  - May not be explicit in control – e.g. hysteresis current modulation



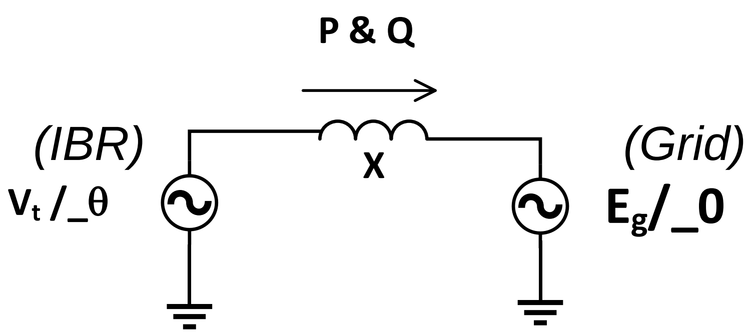
# GRID "FOLLOWING" INVERTERS – BASIC OPERATION

- Quadrature currents to effect desired P & Q are computed from
  - Interface voltage magnitude
  - Voltage angle as ascertained by PLL
- Actual & desired currents are compared
- Switch operation adjusted to compensate for errors
- PLL will "follow" the grid voltage



# FUNDMENTAL POWER CONTROL IN AC SYSTEMS

- Power transfer over a pure inductance is determined by phasor voltages at terminals
- Note that current does not appear in control equations
- IBR voltage (prior to output inductance) is the "V" behind the "Z"




$$P = \frac{V_t E_g}{X} \cdot \cos\theta$$

$$Q = \frac{E_g}{X} \cdot (V_t \cos\theta - E_g)$$

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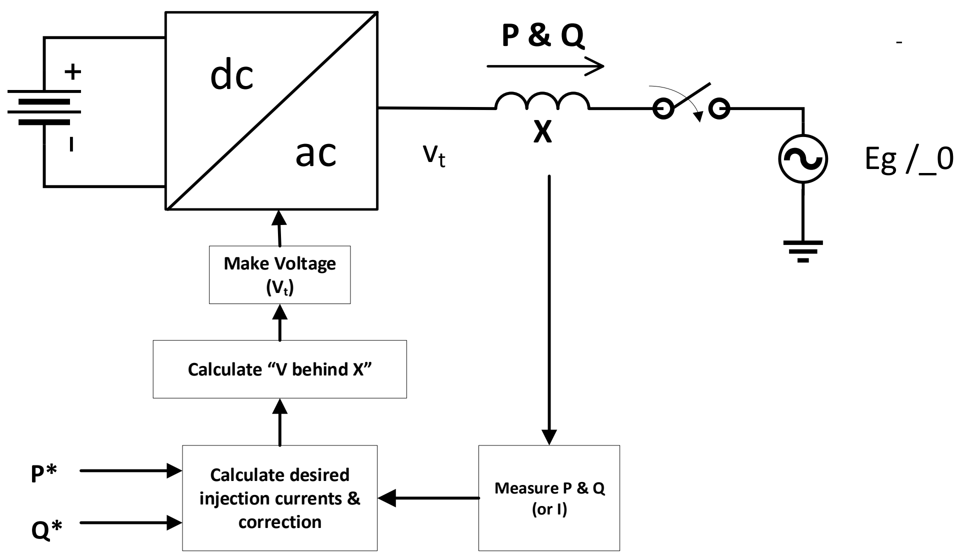
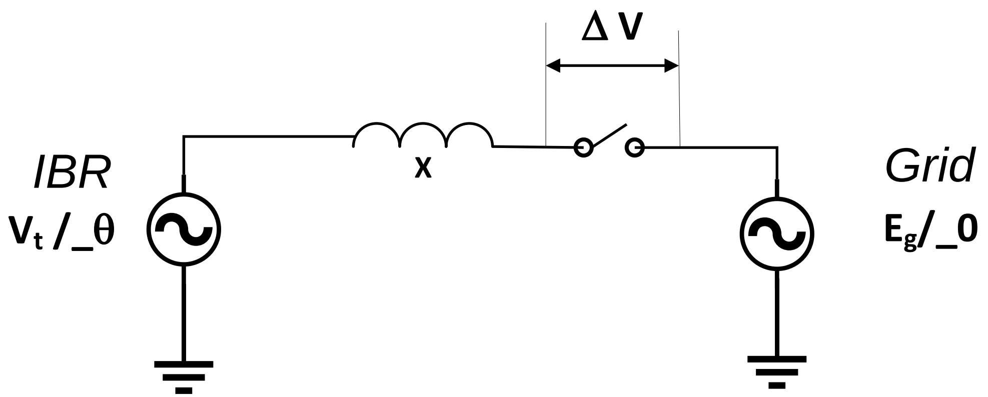
# SIMPLE GRID "FORMING" INVERTER

- Modified control loops in VSC
- Primary control variable is Vt
- Deviations between actual P & Q and desired P & Q are translated into magnitude and phase adjustments for Vt
- How to synchronize?



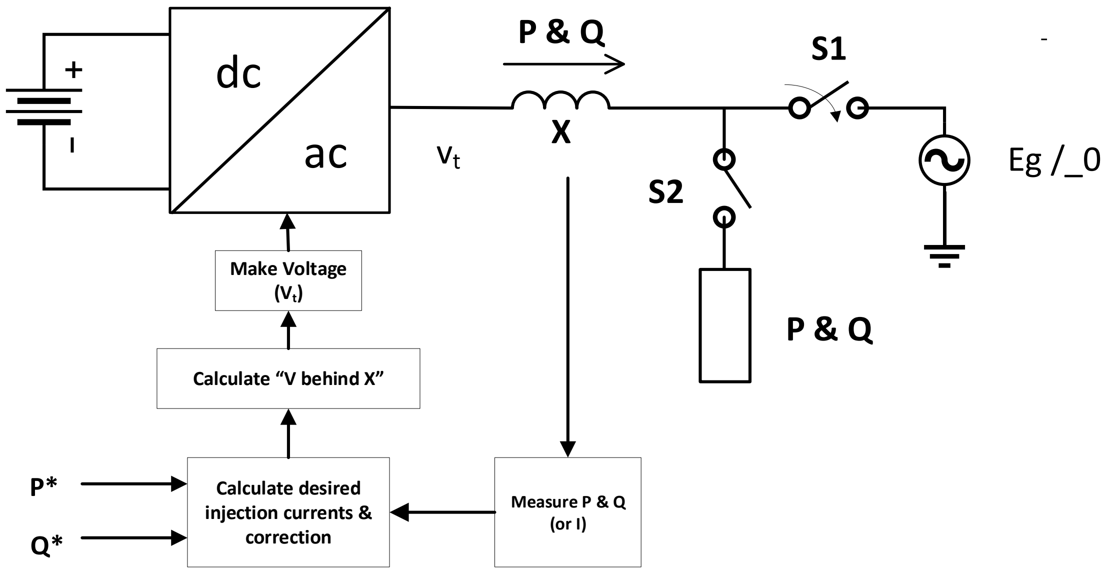
# GRID SYNCHRONIZATION – THE "OLD FASHIONED" WAY

- Connecting a Grid-forming inverter to system just like conventional generator synchronization
- Steps
  - Precise GPS timing for internal control used as reference
  - With no output current, magnitude and phase of Vt are adjusted so that ΔV is zero
  - When ΔV is zero, switch is closed
  - Vt then adjusted (magnitude & phase) to achieve desired P & Q



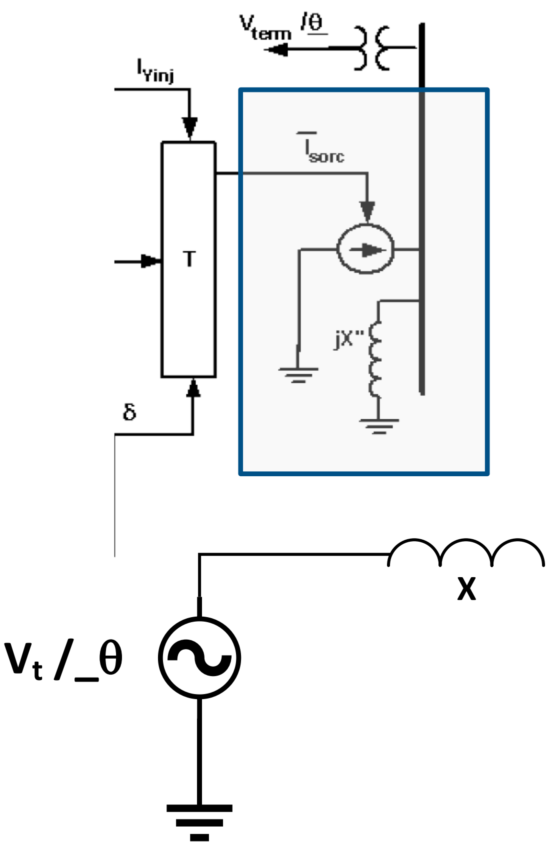
# ILLUSTRATION – ISLANDED OPERATION WITH GRID-FORMING CONTROL

- In figure at right, assume initially that
  - S1 is closed, S2 is open
  - IBR is transferring P & Q to grid
  - Eg is steady (no V or f disturbances)
- If S2 is closed, current through S1 will go to zero
  - Still grid-tied
  - Local load served completely by IBR
- When S1 is opened, local island system will continue _stable_ operation



# SUMMARY

- Grid-following & Grid-forming inverters/IBRs are actually very close cousins
- Much ongoing research on control strategy, grid impacts for high to very high IBR penetrations
- Potentially some short-term consequence for modeling
  - In current bulk system analysis tools, PLL is "idealized"
  - IBR is interfaced to network as a current source (top diagram)
  - Industry has experience some modeling convergence issues that may be related to the form of the interface for grid-following inverters
  - A "V-behind-Z" interface is more conventional, and could help to address these numerical stability issues (TBD, of course)



*Thanks*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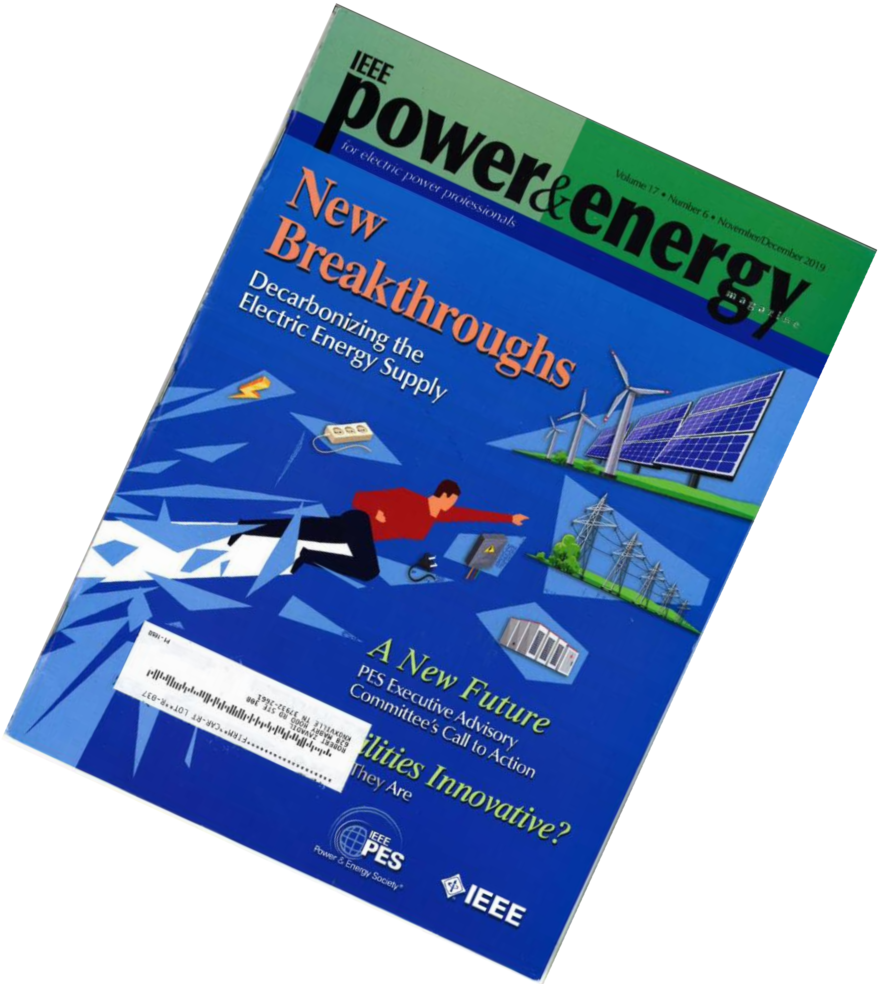

# Q & A

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