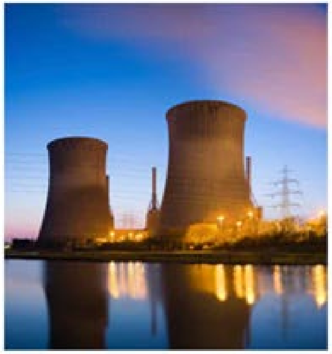
NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Battery Energy Storage Systems and Hybrid Power Plants

NERC Inverter-Based Resource Performance Working Group
Informational Webinar
July 15, 2021

RELIABILITY | RESILIENCE | SECURITY



NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Webinar Outline

Welcome	Allen Schriver, NextEra, IRPWG Chair Julia Matevosyan, ERCOT, IRPWG Vice Chair
Reliability Guideline Overview	Ryan Quint, NERC
Equipment Manufacturer Perspectives	Prashant Kansal, Tesla Siddharth Pant, General Electric
Plant Developer, Owner, and Operator Perspectives	Rachana Vidhi, NextEra Venkat Konala, Urban Grid
Transmission Planning Perspectives: Interconnection, Modeling, and Studies	Brad Marszalkowski, ISO-NE Songzhe Zhu, CAISO
Advanced Modeling and Studies Perspectives	Andrew Isaacs, Electranix
Research and Development Perspectives	Deepak Ramasubramanian, EPRI Aboutaleb Haddadi, EPRI
Q&A	Rich Bauer, NERC

NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

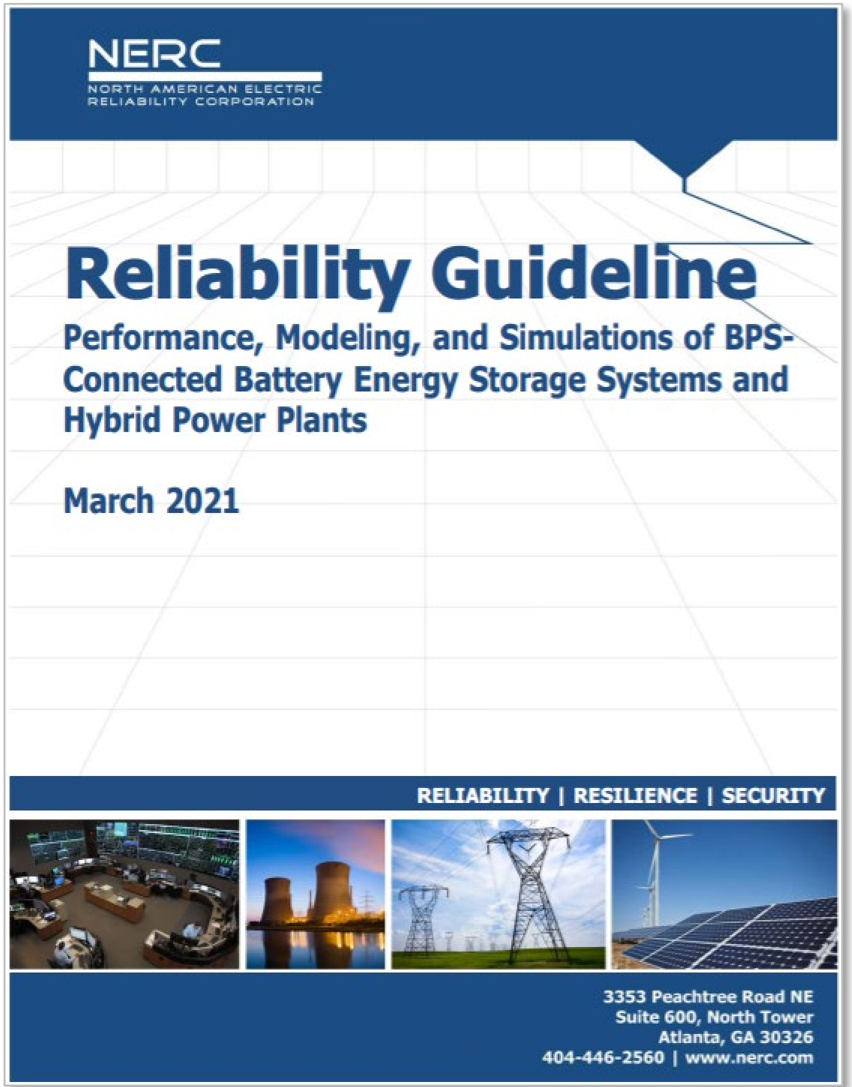
IRPWG Welcome Remarks

Allen Schriver, NextEra, IRPWG Chair
Julia Matevosyan, ERCOT, IRPWG Vice Chair

Reliability Guideline: Performance, Modeling, and Simulation of BPS-Connected BESS and Hybrid Power Plants

Ryan Quint, NERC, IRPWG Coordinator

Guideline Overview



- Fundamentals
- Definitions
- Performance Recommendations
- Modeling Recommendations
  - Power Flow Modeling
  - Dynamics Modeling
  - Short Circuit Modeling
- Transmission Planning Studies
  - Interconnections
  - Hybrid Additions
  - Planning Assessments
  - Blackstart Considerations

NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Recommendation A1: Applicability

- Recommendations in guideline should be applied to all BPS-connected BESS and hybrid plants
  - Should not be limited to only BES facilities
  - Newly interconnecting BESS and hybrid power plants may not meet BES definition; however, ***unified performance and behavior from all BPS-connected inverter-based resources is important for reliable operation of the North American BPS***

Applicability: TOs, TPs, PCs, BAs, RCs, GOs, GOPs, project developers, equipment manufacturers

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Recommendation P1: BESS and Hybrid Plant Performance

- BESS and hybrid plant ***owners*** should closely review the recommended performance characteristics in the reliability guideline and adopt recommendations into existing and new facilities to the extent possible
  - Work closely with TOs, BAs, RCs, TPs, and PCs
  - Ensure all entities have understanding of operational capabilities and limitations of the facilities being interconnected
- BESS and hybrid plant ***developers*** should also adopt the recommendations when designing new facilities
  - Coordinate with equipment manufacturers, and entities listed above

Applicability: GOs, GOPs, project developers, equipment manufacturers

Recommendation P2: Interconnection Req’s and Processes

- TOs should update or improve their interconnection requirements to ensure they are clear and consistent for BESS and hybrid power plants.
- TPs and PCs should ensure that their modeling requirements include clear specifications for BESS and hybrid power plants.
- TPs and PCs should also ensure that their study processes and practices are updated and improved to consider the unique operational capabilities of those facilities.

Applicability: TOs, TPs, PCs

Recommendation P3: Unique Operational Capabilities

- All applicable entities should consider the detailed guidance contained in this guideline and fully utilize the operational capabilities of these new technologies to support reliable operation of the BPS. Capabilities like grid forming technology, operation in low short-circuit networks, the ability to provide primary and fast frequency response (FFR), and other functions more readily available in these new technologies should be fully utilized (as needed) and are essential reliability services (ERSs) for the BPS.

Applicability: TOs, TPs, PCs, BAs, RCs, GOs, GOPs, project developers, equipment manufacturers

Recommendation M1: Models Matching As-Built Facilities

- All BESS and hybrid plant GOs (in coordination with the developer and equipment manufacturers) should ensure that the models used to represent BESS and hybrid power plants accurately represent the controls, settings, and performance of the equipment installed in the field.
  - Requires concerted focus by GO, developer, and equipment manufacturer during the study and commissioning process as well as more rigorous verification and testing by the TP and PC throughout.
- GOs should also provide updated models to the TP and PC that reflect as-built settings and controls after plant commissioning.

Applicability: TPs, PCs, GOs, GOPs, project developers, equipment manufacturers

Recommendation M1: Models Matching (cont.)

- TPs and PCs should study any modifications to equipment settings that have an impact on the electrical performance of the equipment prior to changes being made
  - Per NERC FAC-002
- TPs and PCs should ensure clear modeling requirements and processes
  - Types of models, level of detail, benchmarking between models, etc.
- GOs, GOPs, and developers should verify that dynamic models fully represent the expected behavior of the as-built facility
  - In coordination with their TP, PC, and equipment manufacturers

Applicability: TPs, PCs, GOs, GOPs, project developers, equipment manufacturers

Recommendation M2: Software Enhancements

- Technological advancement of controls outpacing capabilities available in standardized library models
- Simulation software vendors should:
  - Work with BESS and hybrid plant inverter and plant-level controller manufacturers to develop more flexible dynamic models
  - Be proactive in addressing modeling challenges faced by TPs and PCs, particularly as number of these resources increases in studies
  - Support advancement of “real-code” models or user-defined models in a manner that does not degrade or limit the quality and fidelity of the interconnection-wide base case
  - Add model validation, verification, quality review, and other screening tools to support TP and PC review of model quality
  - Improve steady-state modeling of hybrid plants – avoid workarounds

Applicability: Simulation software vendors, equipment manufacturers

Recommendation S1: Study Process Enhancements

- TPs and PCs should improve study processes for interconnection studies and annual planning studies
  - Ensure they are appropriate for a BPS with significantly more BESS and hybrid power plants
  - Close attention needed by TPs and PCs to ensure study approaches align with new technologies
- Stressed operating conditions
- Selection of study assumptions
- Inclusion of various modeling practices
- Determination of appropriate dispatch conditions

Applicability: TPs, PCs

Recommendation S2: Expansion of Study Conditions

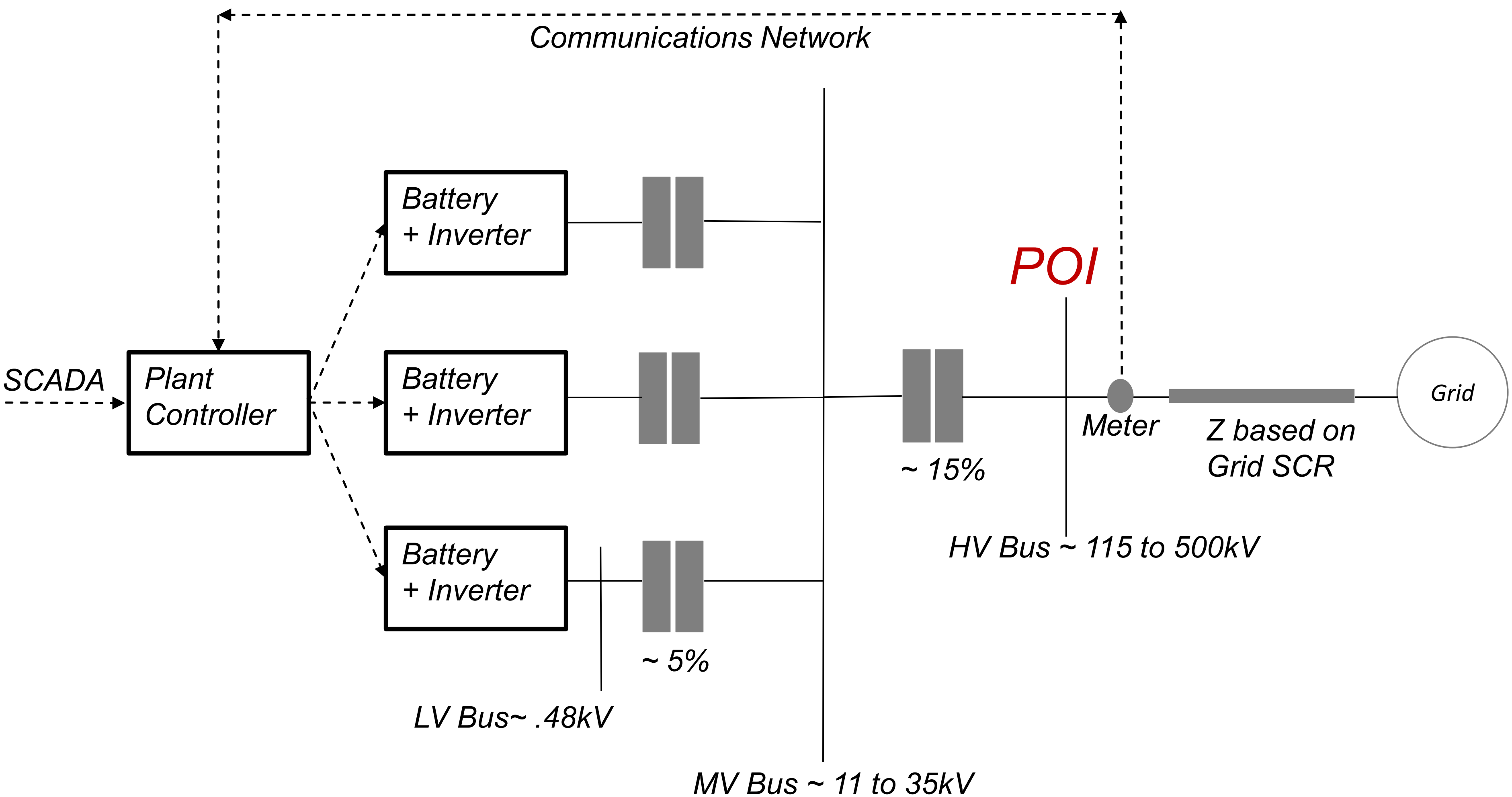
- TPs and PCs studying different expected operating conditions than previously used for planning assessments
  - Variability and uncertainty of renewable energy resources
- BESS and hybrid plants may help address some operational variability
- Developing suitable and reasonable study assumptions will become a significant challenge for future planning studies
- TPs and PCs may need to expand the set of study conditions used for future planning assessments as the most severe operating conditions may change over time

Applicability: TPs, PCs

Equipment Manufacturer Perspectives

Prashant Kansal, Tesla
Siddharth Pant, General Electric

BESS Overview

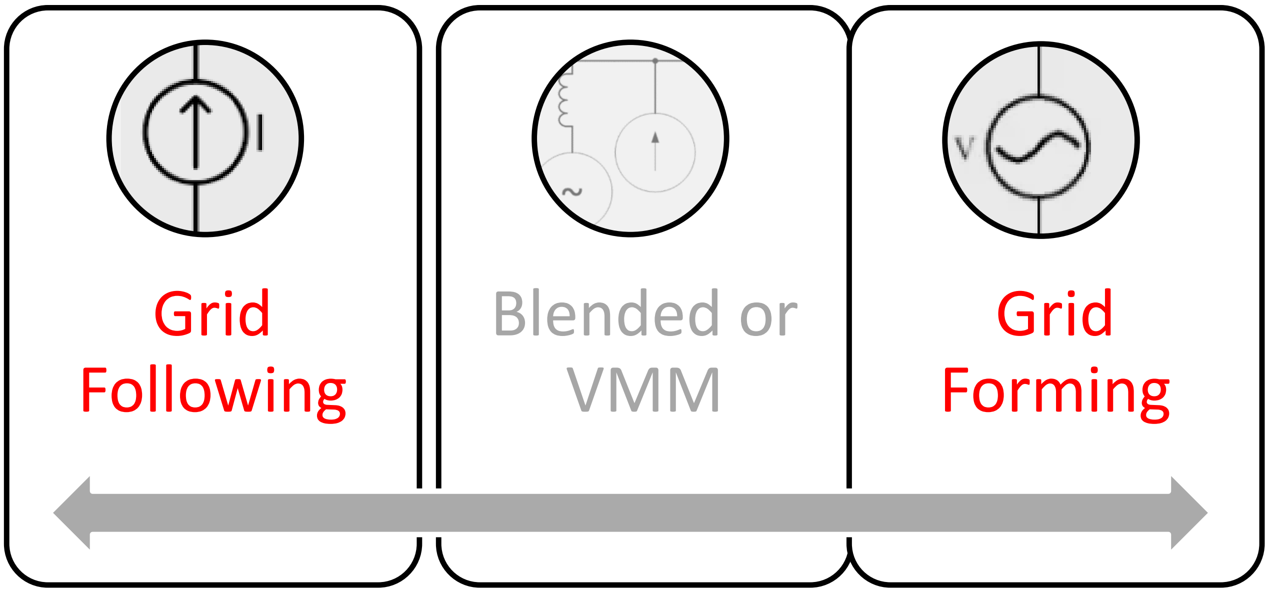


Plant Controller- BESS Only

- Typical control functions targeted to meet command at POI:
  - Real Power
    - Direct power command based on the grid operator dispatch signal
  - Reactive Power
    - Direct reactive power command
    - Site voltage reference control based on POI voltage and Vref target
    - Power factor control based on real power command and targeted power factor
  - Site Compensation
    - Both real and reactive commands have the compensation added to meet the site real and reactive losses in balance of plant
- Additional control functions that can be enabled:
  - Real Power: Freq/watt function, Ramp limits, Operator power limits
  - Reactive Power: Volt-Var, Ramp limits, Operator power limit

BESS Inverter Control Functions

- Three main controls modes at the inverter level:



VMM (Virtual Machine Mode): Dispatch ability of current source & instantaneous response of voltage source

BESS Inverter Control Functions

- Grid Following:
  - Receives real and reactive power commands from the plant controller
  - Smart inverter functions like Freq/watt, volt/var, volt/watt
  - Positive and negative sequence reactive current injection
  - Ride through trip settings

- Grid Forming:
  - Receives voltage and frequency set points from the plant controller
  - Machine model to emulate machine
  - Ride through trip settings

- Virtual Machine Mode:
  - Blend of the above two controls

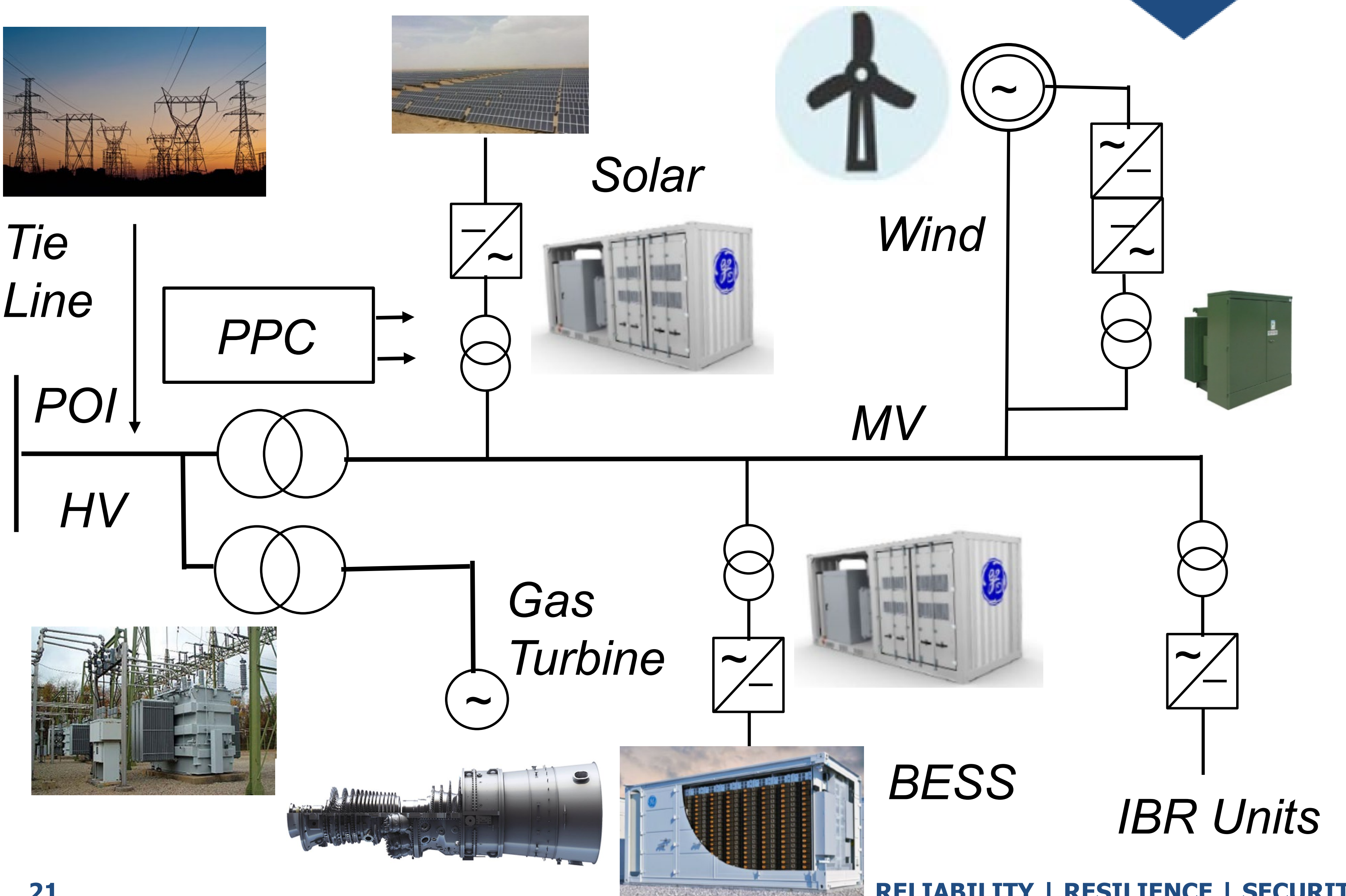
BESS-Only Use Cases

- Grid Following:
  - Energy shifting
  - Renewables power smoothing
  - Ancillary services: providing grid stability with sub second smart inverter responses

- Grid Forming:
  - Load following - Microgrids
  - Black start – Microgrids and Transmission

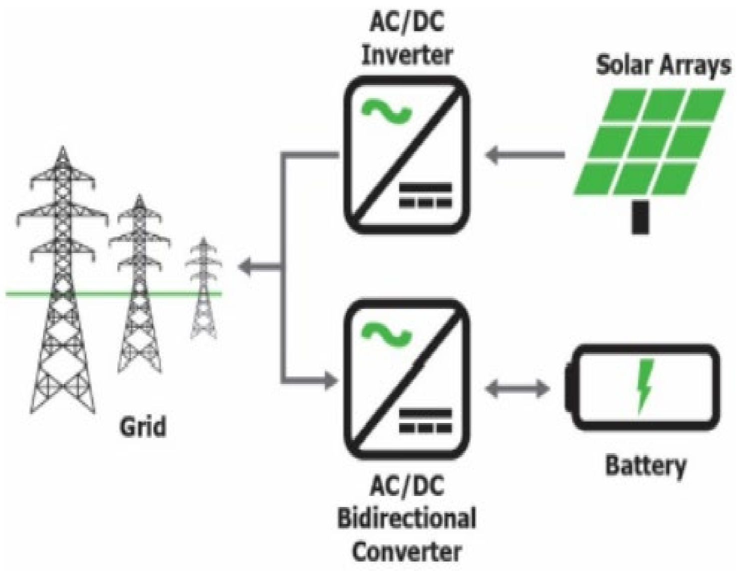
- Virtual Machine Mode:
  - Sub cycle frequency/inertial response helps to arrest frequency nadir
  - Interconnection in weaker grids (SCR <1.5)
  - Improves SCR for the grid and can be an alternative to synchronous condensers

Hybrid Resource

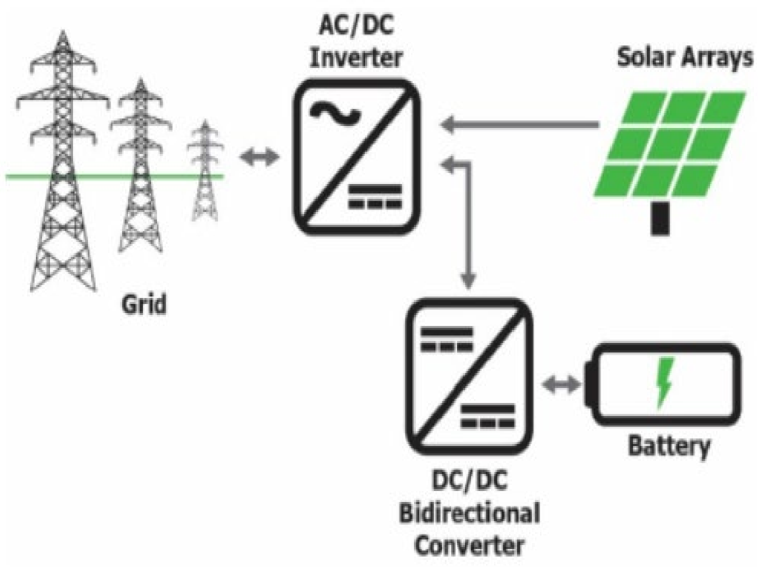


Solar + BESS Hybrid Resource

AC coupled hybrid resource

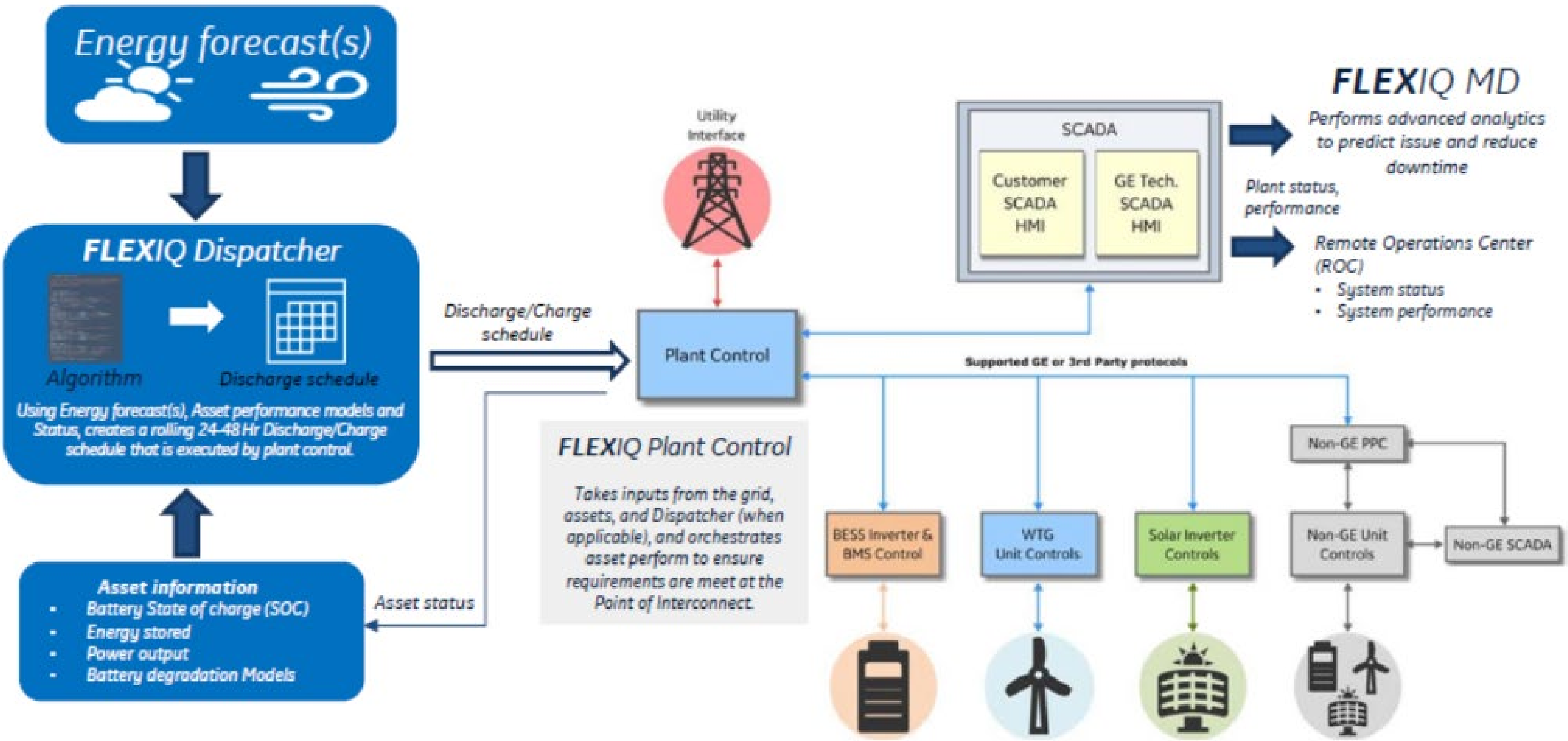


DC coupled hybrid resource



Plant Control

FLEXIQ Control System (Plant Control, Dispatcher, and MD)



Source: GE

Grid Forming (GFM) Resource

- GFM: Current limited voltage source behind an impedance
- Key Functions Enabled:
  - Operation at very low system short circuit ratios
  - Black start capability
  - Provide fast frequency response
- Grid Forming is not new. Examples of BESS for standalone and industrial applications:
  - 1MW/1.4MWh - 1995
  - 30MW x 20 MWh BESS - 2017
  - 13 MW x 13 MWh BESS - 2020
- Same controls are applicable to utility-scale BESS, solar PV, and hybrid systems

Some Parting Remarks

- Combining BESS and solar PV, wind, and other technology (hybrid plants) enables many desirable grid services
- Different resource types within a plant are likely to require greater attention to plant-level and inverter-level control coordination to achieve desired performance at POI, compared to that usually required in a solar PV or wind plant
- Definition of plant performance requirements and identification of economic considerations are ***key*** to optimal choice of resource types, technologies, and plant design
- Grid forming control for hybrid resources is available and may be the right choice for some applications.

Source: Adapted from Sebastian Achilles, GE, IEEE PES 2020 General Meeting Presentation

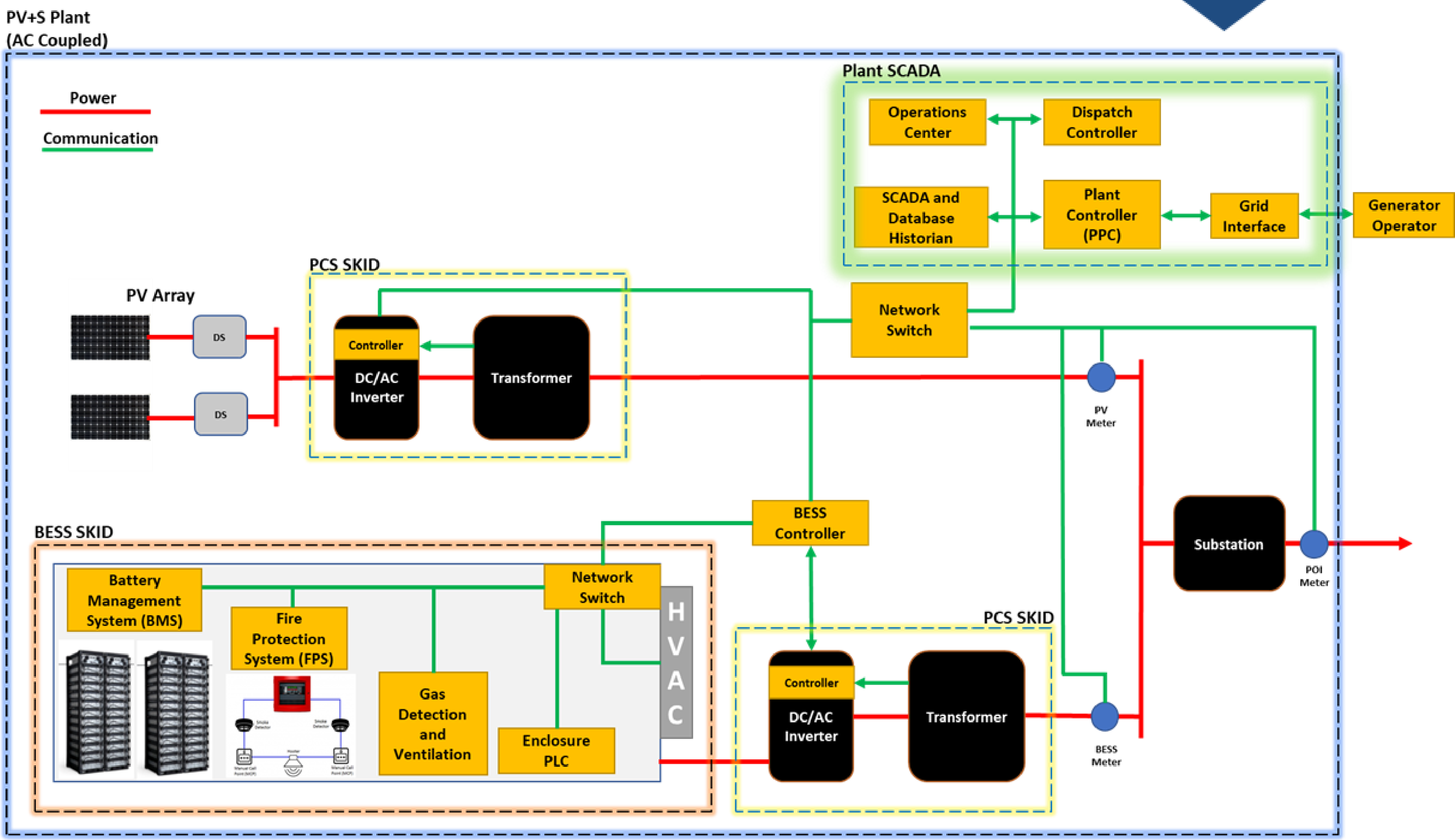
BESS and Hybrid Plant Developer, Owner, and Operator Perspectives

Venkat Konala, Urban Grid
Rachana Vidhi, NextEra Energy

Solar PV + Storage (PVS) Plant Services

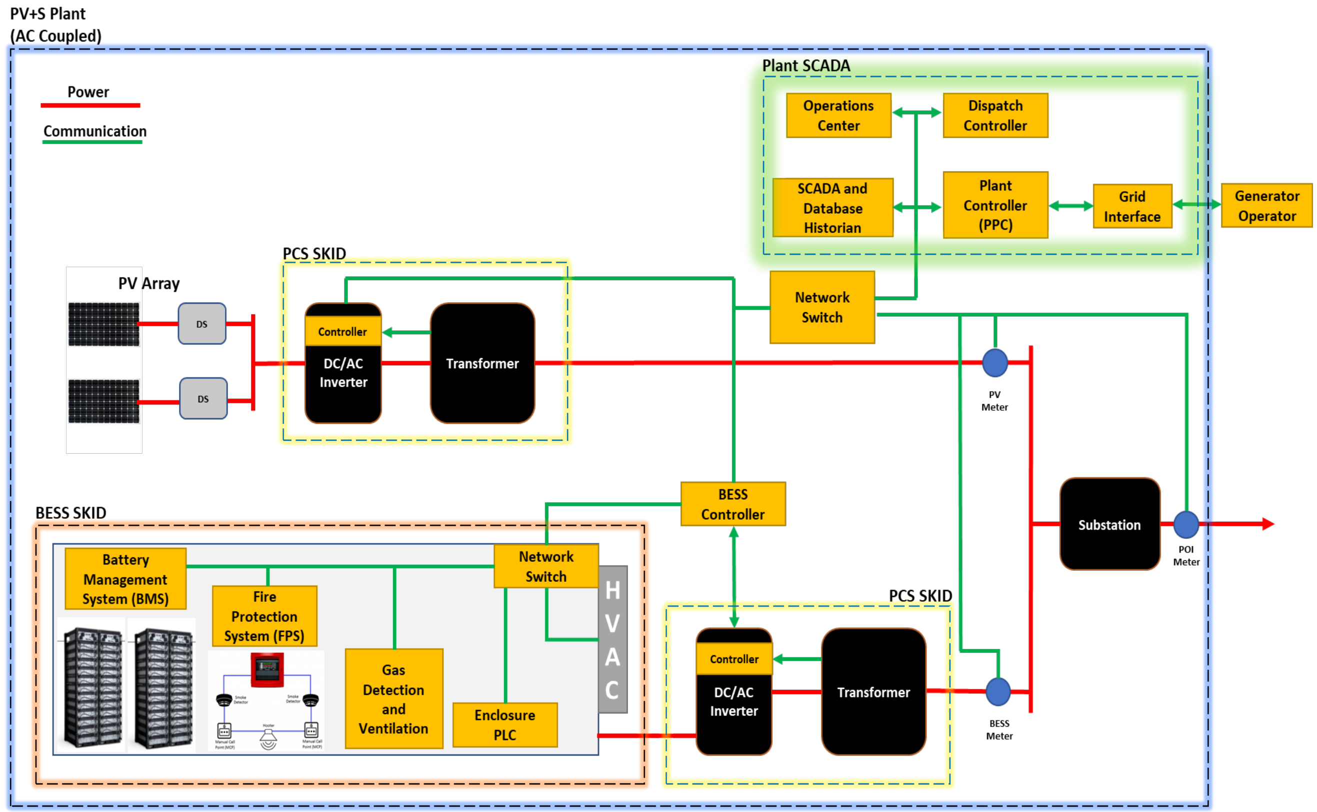
- Services are stacked to provide multiple value streams
  - Energy shifting
  - Capacity firming
  - PV smoothing
  - Frequency regulation
  - Ramp rates
  - Blackstart

PVS Architecture and Data Flow



Integration

- Plant Scada and Controls
  - Dispatch System
  - Plant Controller
  - Data Historian
  - BESS Controller
- Coordination
  - Controls
  - Equipment Interlocks
  - Fault Ride Through
- Data
  - Control
  - Monitoring
  - Performance
  - Warranty
- Power Quality
  - Harmonics



Plant Scada

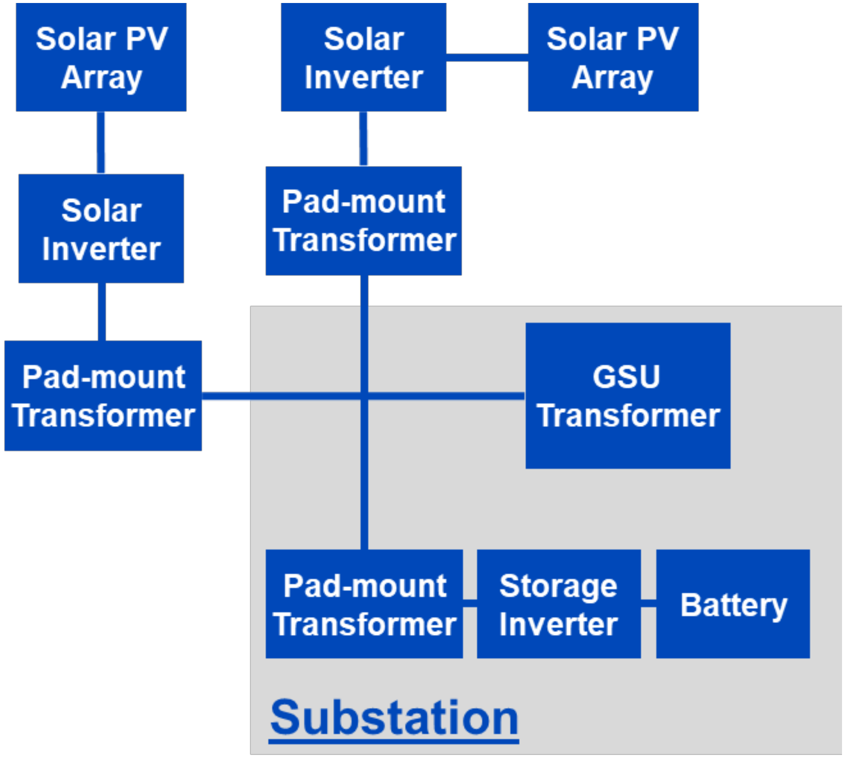
- Dispatch System
  - This is where the third-party dispatch optimization algorithm runs and outputs a dispatch schedule
- Power Plant Controller
  - Based on the dispatch schedule as determined by the Dispatch System, the PPC is intended to regulate the POI by regulating the P and Q commands to PV and BESS systems
- BESS Controller
  - Based on the operational state of the BESS, the BESS controller regulates the P and Q commands to BESS inverters
- Data Historian
  - Configured to store data for plant performance, monitoring and to support battery warranty requirements

Storage Integration with Renewables

- Construction of new storage can typically be done with little to no impact to existing wind or solar asset operation
  - Short duration outages may be needed for initial tie connection (safety)
  - Most of the controls and related integration testing can be done with existing asset online and generating
- Utilizing in-house plant-level control software allows for more flexibility and at a lower cost
  - NextEra has utilized in house controls on all storage projects since 2016, and has successfully integrated our controls in several ISOs
- NextEra has integrated new battery storage into existing wind or solar facilities at several different sites since 2014

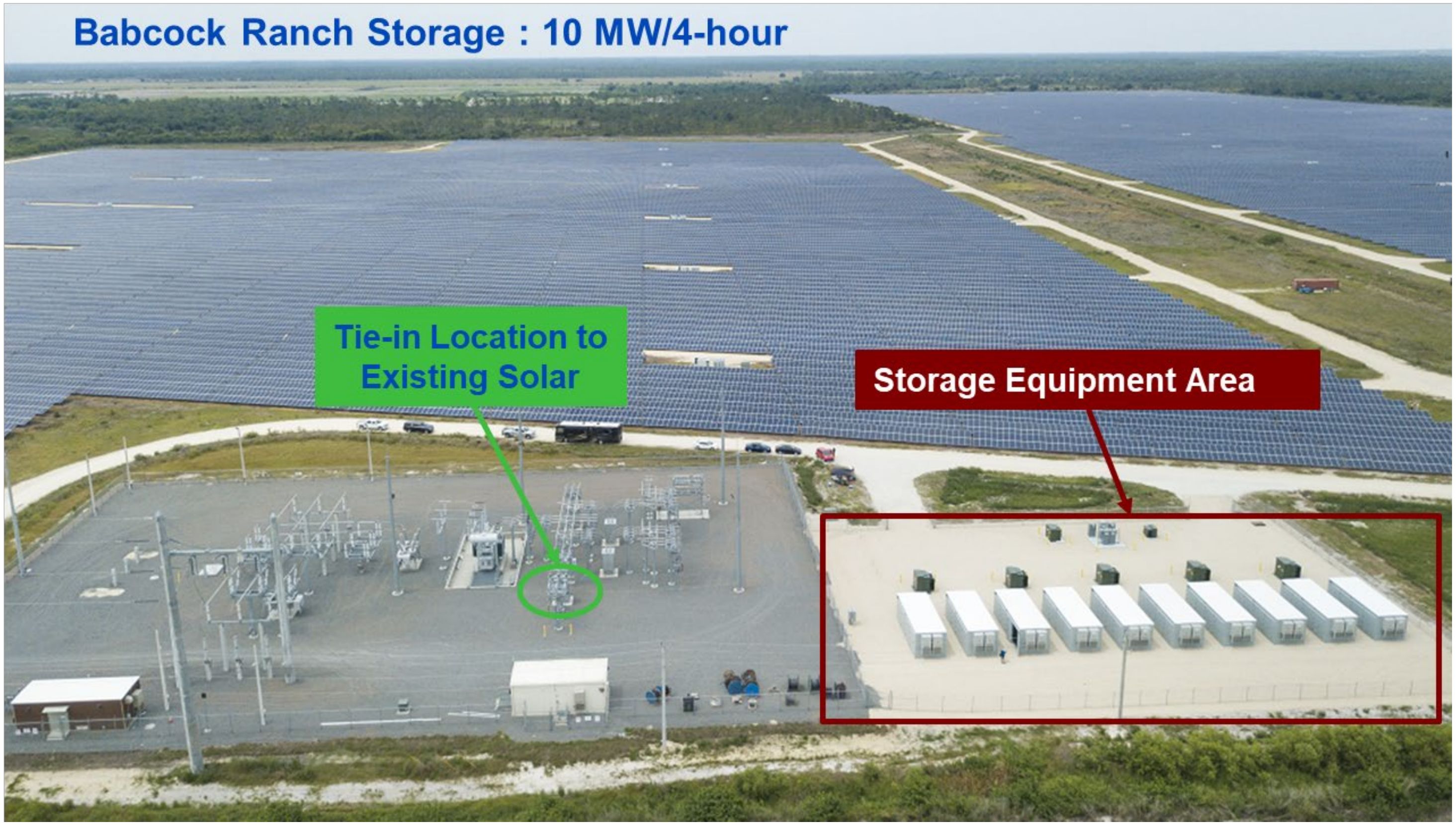
Solar + Storage Integration: AC-Connected

- Advantages
  - Easy retrofit to existing solar plants
  - Can easily participate as separate resource in the market
  - Can capture AC solar clipping and ISO driven curtailments
- Disadvantages
  - Cannot capture DC solar clipping
  - Effectively operates as two independent plants



- AC integration of the solar array and the battery storage facility can be done at the substation; location allows for charging from the entire solar array and preserves ITC

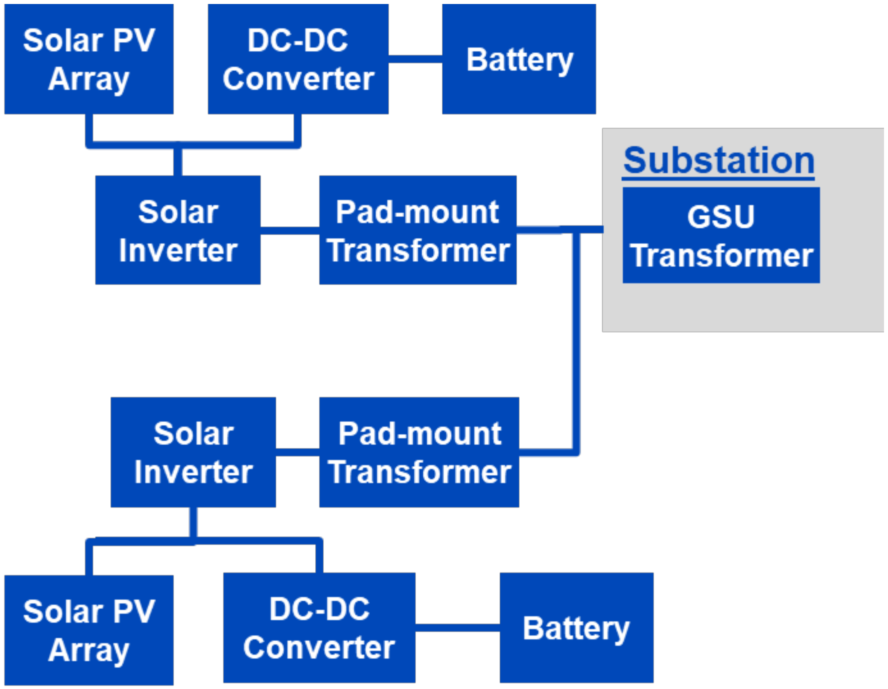
Solar + Storage Integration: AC-Connected (continued)



- AC coupled integration of storage into solar is relatively simple as the storage equipment can be placed adjacent to the solar collection sub, with little impact to solar operations

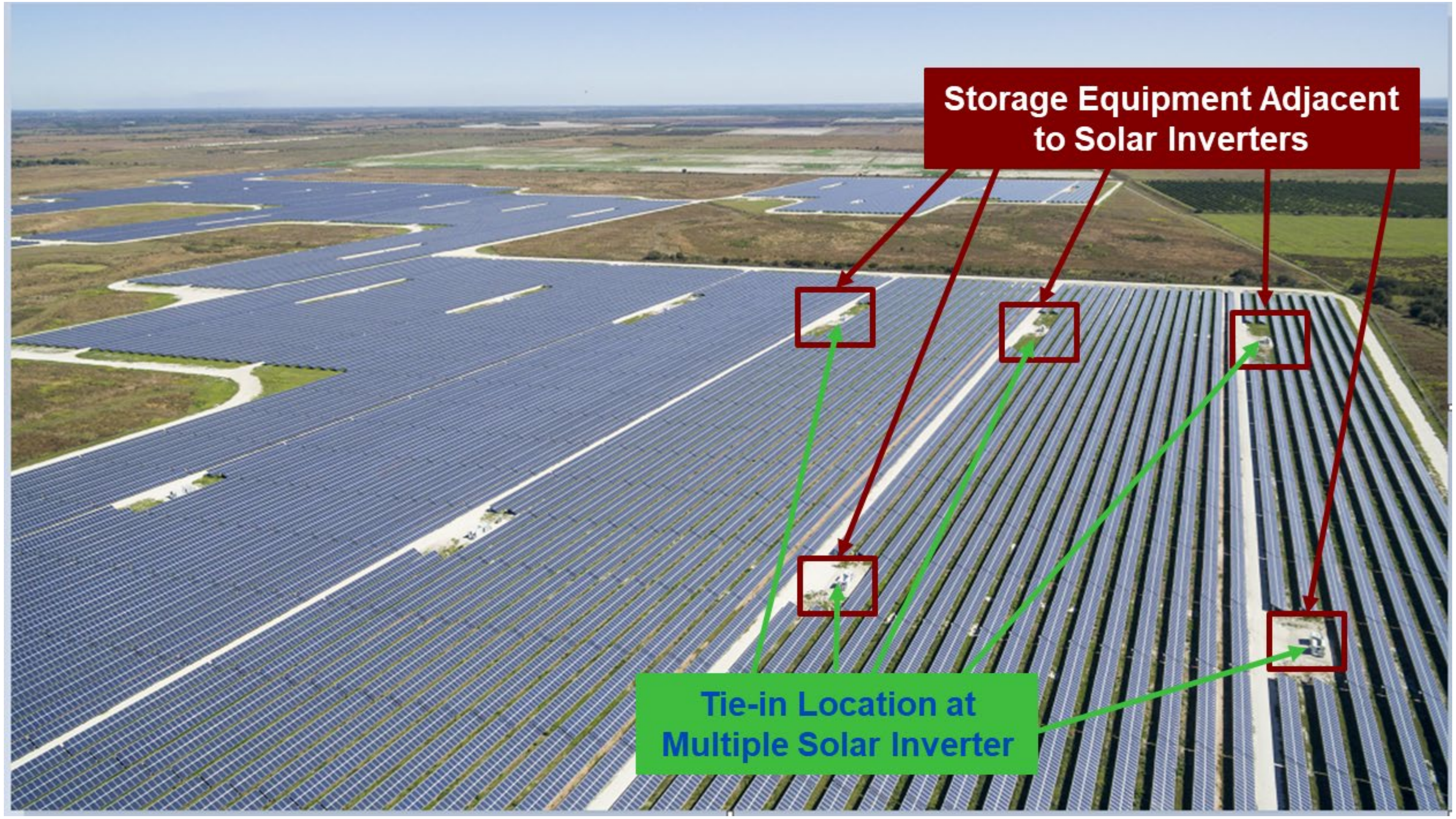
Solar + Storage Integration: DC-Connected

- Advantages
  - Access to all clipped energy
  - Savings on pad-mount and collection system costs
  - Higher round trip efficiency
- Disadvantages
  - Requires batteries located in the solar array, not at the substation
  - Difficult to retrofit on existing solar
  - Augmentation could be challenging



- Solar array and battery storage system are connected at the DC side of the inverter, which can capture the DC clipped energy

Solar + Storage Integration: DC-Connected (continued)



- DC coupled integration of storage into existing solar is more complex, as room must be available adjacent to each solar inverter to place the battery equipment

Solar + Storage Integration: DC-Connected (continued)

- Illustrative Layout for DC Coupled Solar + Storage

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Integrating Storage: Additional Considerations

- Some ISOs may have some flexibility in how a storage + wind/solar is registered and participates in the energy market
  - Co-located but separate resource model vs. Hybrid participation
  - Utilities in non-ISO regions may have differing approaches as well
- Revenue metering designs to capture generation (and charging) between co-located renewable and storage; also includes gen-tie losses and station service load allocations
  - Requirements vary by ISO/RTO, PPA off-taker and contract language
  - Developing a metering strategy early on is important

Integrating Storage: Additional Considerations

- Separate agreements are often used to address shared facilities use, O&M responsibilities, cost sharing, etc.
  - Typically will be applicable only when storage is added to an existing operational facility and under a separate legal entity

- In addition to electrical integration, market participation models, revenue metering designs and affiliate agreements may also need to be considered

Transmission Planning Perspectives: Interconnection, Modeling, and Studies

Songzhe Zhu, California ISO
Brad Marszalkowski, ISO New England

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Interconnection Considerations

- Size the interconnection request: installed MW capacity, contractual MW limit and MWh
  - Installed MW capacity typically doubles the contractual MW limit in a hybrid IBR plant
  - Duration of sustained MW injection matters; not only for operational flexibility but also for resource adequacy credits
- If hybrid, choose between ac-coupled or dc-coupled
  - Cost, flexibility, RA credits, etc.
- Choose the source of charging and maximum charging power
  - Source of charging has financial impacts on the IBR, such as tax credits

Modification Considerations

- Change ac or dc-coupled, MWh, source of charging down the road
  - Understand utility's policy and process for making modification and the impacts on the IBR
- Add BESS to an existing plant
  - Adding BESS behind-the-meter, i.e. without increasing MW at point of interconnection, could be done expeditiously (surplus interconnection service in FERC Order 845)
- Replace batteries as performance degrades
  - Understand utility's retention policy for interconnection and resource adequacy counting

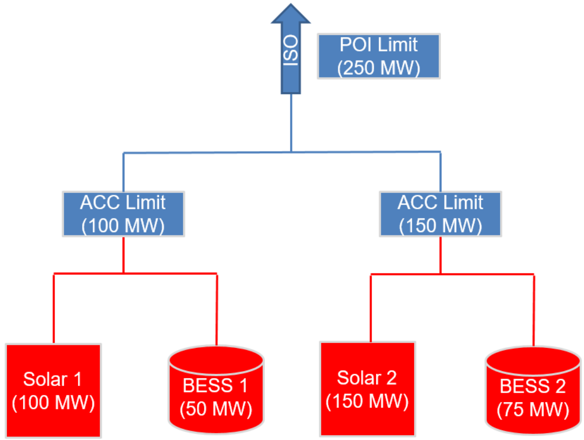
Interconnection Requirements

- Generally follow the same technical requirement for asynchronous generators (and synchronous generators if applicable)
  - Voltage ride-through capability
  - Frequency ride-through capability
  - Power factor design criteria
  - SCADA capability
  - Transient data recording equipment for facilities above 20 MW
  - Automatic voltage regulation
  - Primary frequency response capability
- The requirement applies to both charging and discharging mode

Meeting the Interconnection Requirements

- Control the active power not exceeding the contractual limits
  - Technically, this can be achieved easily with one power plant controller
  - Actual implementation could be more complicated, e.g. different owners for different portions of the IBR in one plant

- Different components of an ac-coupled hybrid plant could supplement each other to meet the power factor requirement on the high side of substation transformer
  - Power plant controller coordinates reactive control
  - Solar PV inverters may need to have “night-var” capability



Source: CAISO Proposal for Hybrid Resources – Aggregate Capability Constraint for Co-Located Resources

Modeling Requirement

- Positive sequence model
  - Generic model or user-written model
  - Generic RES model capability is being enhanced; industry education is still needed, especially for hybrid IBR plants
  - Model is required upon submission of interconnection request, updated whenever there is a change before commercial operation
  - As-built model and test reports are required after commercial operation; periodic updates or updates upon changes
- EMT model
  - Many utilities now require EMT model for IBR plants due to SSCI and weak grid issues
  - Similar technical requirement has been implemented cross the country; however, when the model is required varies
  - EMT model is often used to benchmark the positive sequence model

Modeling Considerations

- Properly model both physical limits and contractual limits
  - Power plant controller model reflects contractual limits
  - Inverter model reflects physical limits
- Power plant controller power flow model is being implemented in all major software platforms
  - Monitor total plant output against the plant Pmax/Pmin, which are contractual limits
  - Coordinate voltage droop control among all generators in the plant
- Power plant controller dynamic model is repc_a or repc_b*
  - Use repc_b if multiple generators in the plant are represented in the power flow model
  - Repc_b is the most “confusing” and misused model

**Model name varies for different software platform. Refer to the reliability guideline.*

Notes on REPC_B Model

- In GE PSLF, repc_b always on system MVA base (i.e., 100 MVA)
- Reactive power command (Wext) and active power reference (Pext) always initialize to zero
  - PMAX/PMIN and QMAX/QMIN are relative limits instead of absolute limits
- QMAX/QMIN should be voltage limits if Wext signal is voltage
  - determined by the down-stream reec model
  - All downstream reec models should take the same type of signal

EMT Model Requirement

- EMT models are usually black-box. It is important to provide documentation with setup instructions, control functions, protections, etc.
- Provide model test reports
- Full representation of the plant from generators to the point of interconnection
- Include the full detailed inner control loops of the power electronics
- Represent all plant level controllers
- Represent all protections
- **Be configured to match expected site-specific equipment settings**

Model Validation

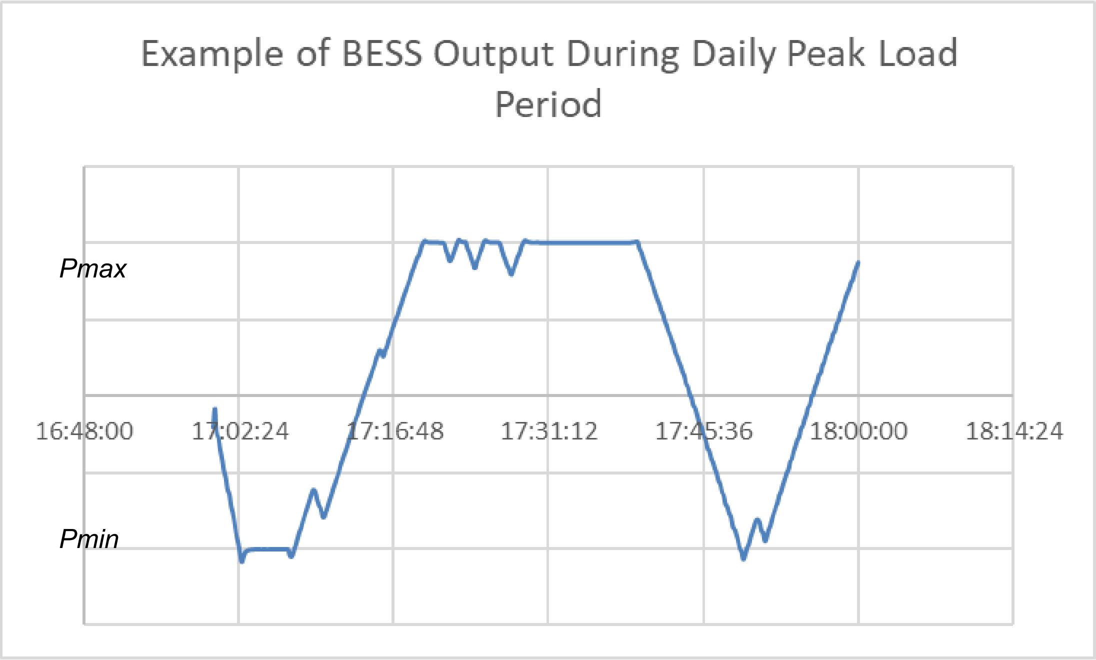
- During the interconnection studies
  - Validation focuses on the performance, i.e. meeting all interconnection requirements and perform well at the specified system strength
  - The generic model may be benchmarked with the user-written model
- After commissioning
  - Perform MOD-026 and MOD-027 tests to verify small disturbance performance for both positive sequence model and EMT model
  - Benchmark between positive sequence model and EMT model under large disturbance at the specified system strength
  - Models are further validated using actual system event data

Interconnection Studies

- Interconnection studies (same for all generator types):
  - Power flow contingency analysis
  - Voltage stability analysis
  - Transient stability analysis
  - Short circuit analysis
- Different dispatch of BESS and hybrid are studied under various peak conditions, such as summer peak, spring off-peak, e.g.
  - At maximum discharging output: peak and off-peak
  - At maximum charging output: peak and off-peak
  - At capacity counted for resource adequacy: peak

Interconnection Studies (Cont'd)

- All dispatch scenarios plausible (as shown by operational data)
- Studies establish operating boundaries
  - More often, operational measures used instead of transmission upgrades



Transmission Expansion Studies

- BESS and hybrid generation is often used as transmission alternative to relieve transmission constraints.
  - Proper placement of future BESS and hybrid generation is the key – siting and sizing
  - Availability of the BESS and hybrid generation in desired operating mode (charging/discharging) is crucial
- Hourly production cost simulation is commonly used to establish dispatch snapshots for power flow and stability analysis

Performance

- BESS/Hybrid plants have unique operating characteristics and so need to be studied and perform, regardless of dispatch

- BESS/Hybrid plants, while either charging or discharging should have capability to:
  - Support system events
  - Have full four quadrant operation
  - Regulate high and low voltage excursions
  - Provide dynamic voltage control
  - Inject reactive power at zero active power
  - Have active power/Frequency regulation

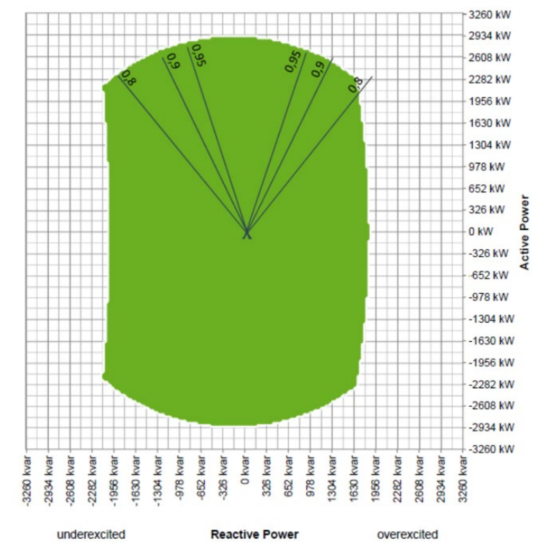


Figure 1.1: Example of 2.7 MVA BESS Capability Curve [Source: SMA America]

Performance (Cont.)

- BESS/Hybrid plants, while either charging or discharging, should:
  - Avoid use of momentary cessation to greatest extent possible
  - Have ride through capability in compliance with PRC-024
  - Ride through phase jumps
  - Operate under low short-circuit strength conditions

AC vs DC-Coupled considerations

- Some small differences in study dispatch and modeling.
  - Active/Reactive power capability is an aggregation of the generating resources, BESS, and any reactive devices.
  - Generating resources comprising the hybrid plant may respond differently to faults than the BESS portion.
  - BESS may or may not charge from the grid
  - More dispatch permutations for AC-coupled than DC-coupled

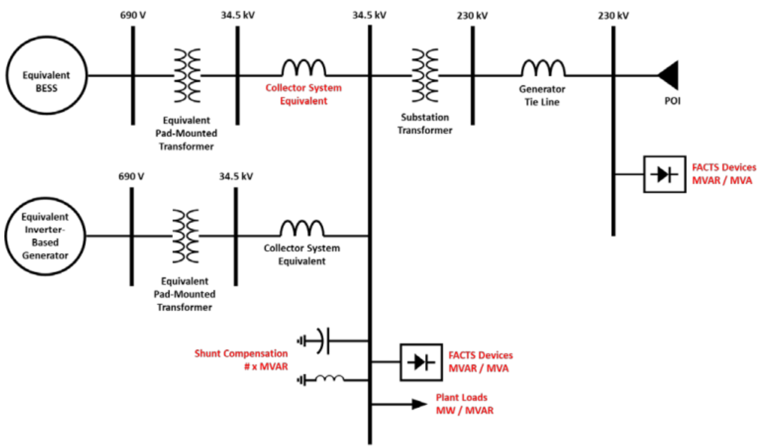


Figure 2.2: Generic Power Flow Model Example for AC-Coupled Hybrid Power Plants

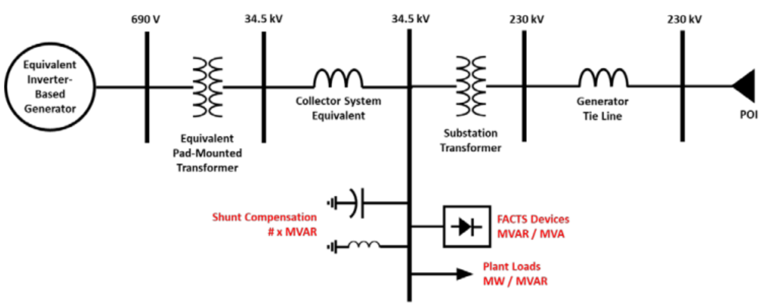


Figure 2.3: Generic Power Flow Model for DC-Coupled Hybrid Power Plants

AC vs DC-Coupled considerations

- Dynamic modeling differs between AC and DC Coupled hybrid plants
  - DC Coupled requires models for only the inverter/grid facing portion of the plant, so different units (BESS, Solar, etc) behind that interface are abstracted away
  - AC Coupled requires models for all different generating resources and the BESS, so it generally requires more models.

Table 3.6: Models for DC-Coupled Hybrid in PSLF and PSS®E

Component		PSLF Module	PSS®E Modules
Grid Interface		regc_*	REGC*
Electrical Controls	May Charge from Grid	reec_c or reec_d	REECC1 or REECD1
	DC-Side Charging Only	reec_a or reec_d	REECA1 or REECD1
Plant Controller		repc_*	REPC*/PLNTBU1
Voltage/Frequency Protection		lhvrt/lhfrt	VRGTPA/FRQTPA

Table 3.4: Models for AC-Coupled Hybrid Plants (in PSLF and PSSE)

Functionality	GE PSLF Module	Siemens PTI Module
BESS Grid Interface	regc_*	REGC*
BESS Electrical Controller	reec_c or reec_d	REECC1 or REECD1
Plant-Level Controller	repc_b[79]	PLNTBU1
Auxiliary Controller		REAX4BU1 or REAX3BU1
Voltage/Frequency Protection	lhvrt/lhfrt	VRGTPA/FRQTPA
Non-BESS Generation Component of Hybrid Facility	Use appropriate modules for the generation type (i.e., applicable models for wind, solar, synchronous generation, etc.)	

Advanced Modeling and Studies Perspectives

Andrew Isaacs, Electranix

Acknowledgements:

- *Study Team: Anuradha Kariyawasam, Lukas Unruh, Andrew Isaacs*
- *ATC Team: Planning and Operations Groups*
- *OEMs: Tesla and SMA*

The Problems

- N-1-1 Wind SCR < 1.5… Wind unstable
- Too much excess power through 138 kV
- Voltage low or collapsing

The Solution

- BESS is grid-forming to strengthen wind interconnection
- BESS provides dynamic VAR support to regulate voltage
- BESS automatically absorbs excess power to prevent overload and collapse

NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

The Model

- Both SMA and Tesla provided detailed PSCAD models of grid-forming BESS for demonstration of proof-of-concept
- Detailed PSCAD model of wind farm
- Extensive system/network model
- Various dispatches and faults

Did it work?

- Both Tesla and SMA solutions provided sufficient stability through GFM controls to allow the wind plant to operate stably and ride-through faults.

- Both devices provided dynamic voltage control as expected

Active Power Issue

- GFM inherently provides the correct response in transient timeframe, *but as long as frequency* is nominal, it will return to pre-fault dispatch!
- We wanted this:
- But got this:

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Active Power Issue

- This was solvable either using a new dispatch between the N-1 and the N-1-1, or…
- An external controller that measured power flow on the outlet line and adjusted the active power order of the BESS, like this…

- This required no change to BESS controls, but did require a new controller

Active Power Issue

- Alternate solution proposed to BESS manufacturers (who are now thinking about it! ☺): Revisit ATC's "AC Line Emulation" currently implemented in Makinac HVDC controls.
- This scheme looks for a significant angle change across a line (in this case, across the BESS transformer), and automatically adjusts power order to accommodate the change, which mimics an AC line. Like this:

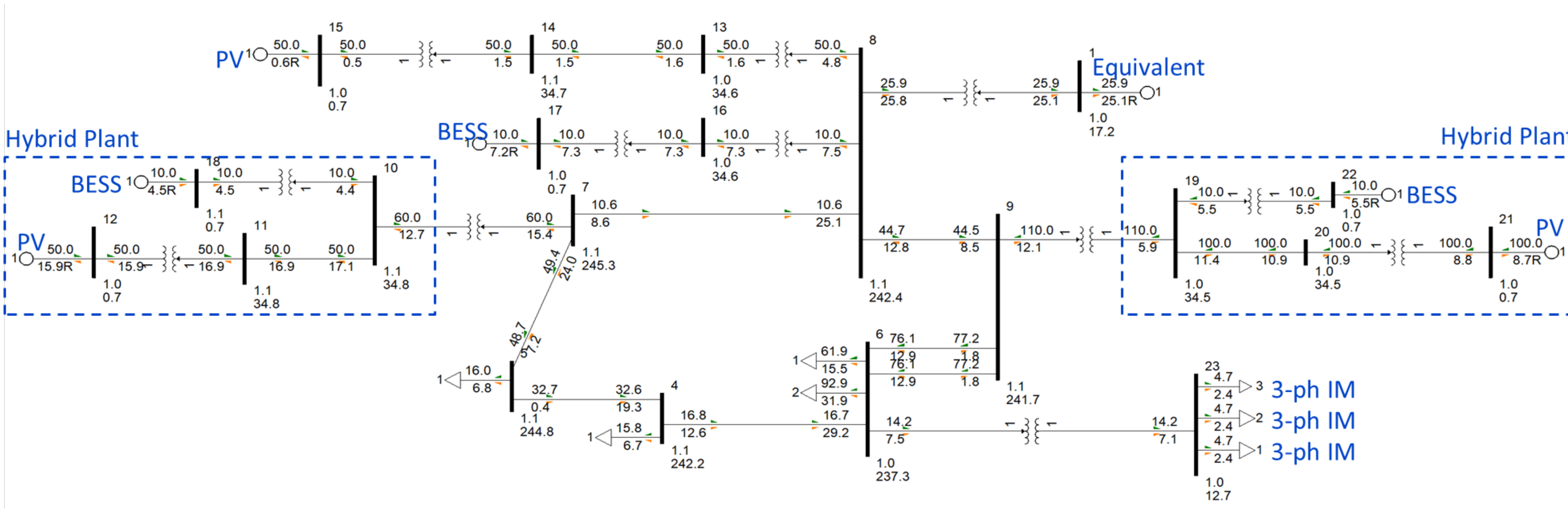
Take-Away!

- Smartly controlled batteries are highly capable to solve multiple real-world problems simultaneously
- Utilities should be establishing clear interconnection requirements (i.e., FAC-001) for these capabilities ***(!)***
  - Clear reliability needs to solve complex problems, based on experience

Research and Development Perspectives

Deepak Ramasubramanian, EPRI
Aboutaleb Haddadi, EPRI

Frequency Control from Hybrid Plants



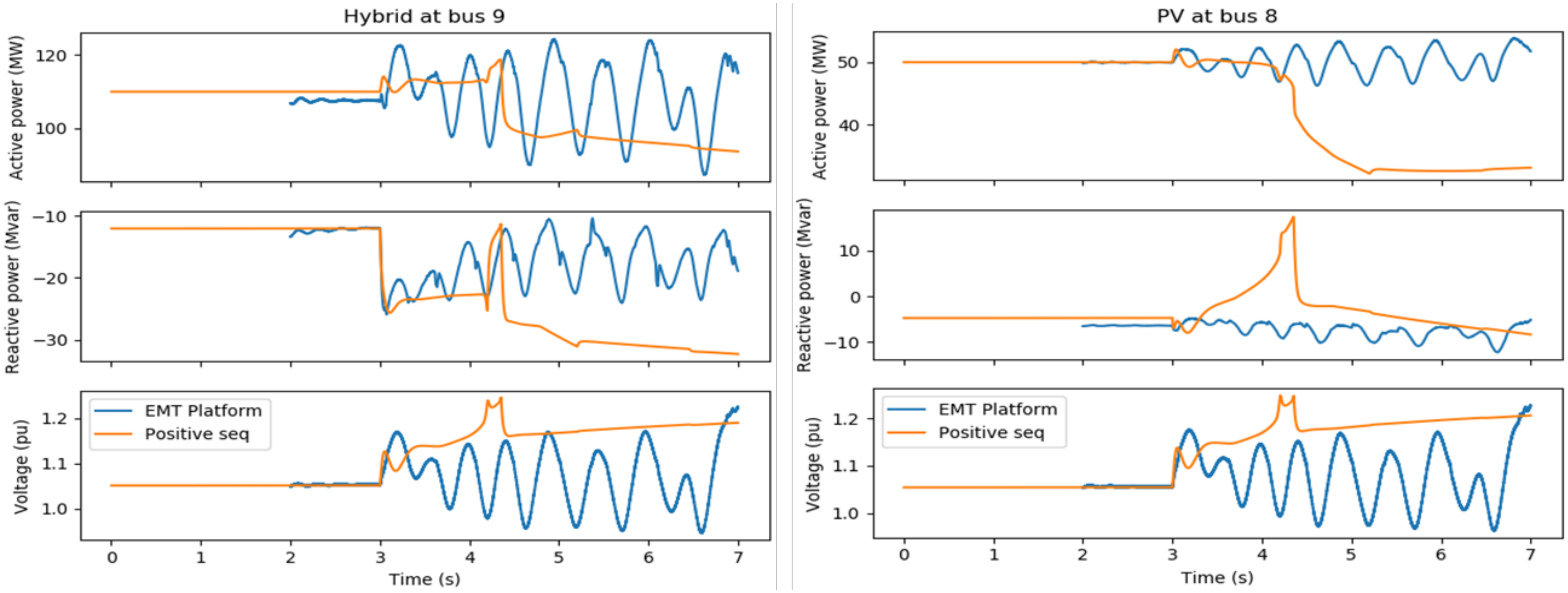
- All BESS are in grid forming mode
- All PV plants are in grid following mode

» Will GFM BESS be sufficient for islanding of system?

» Can positive sequence simulation platforms provide adequate insight?

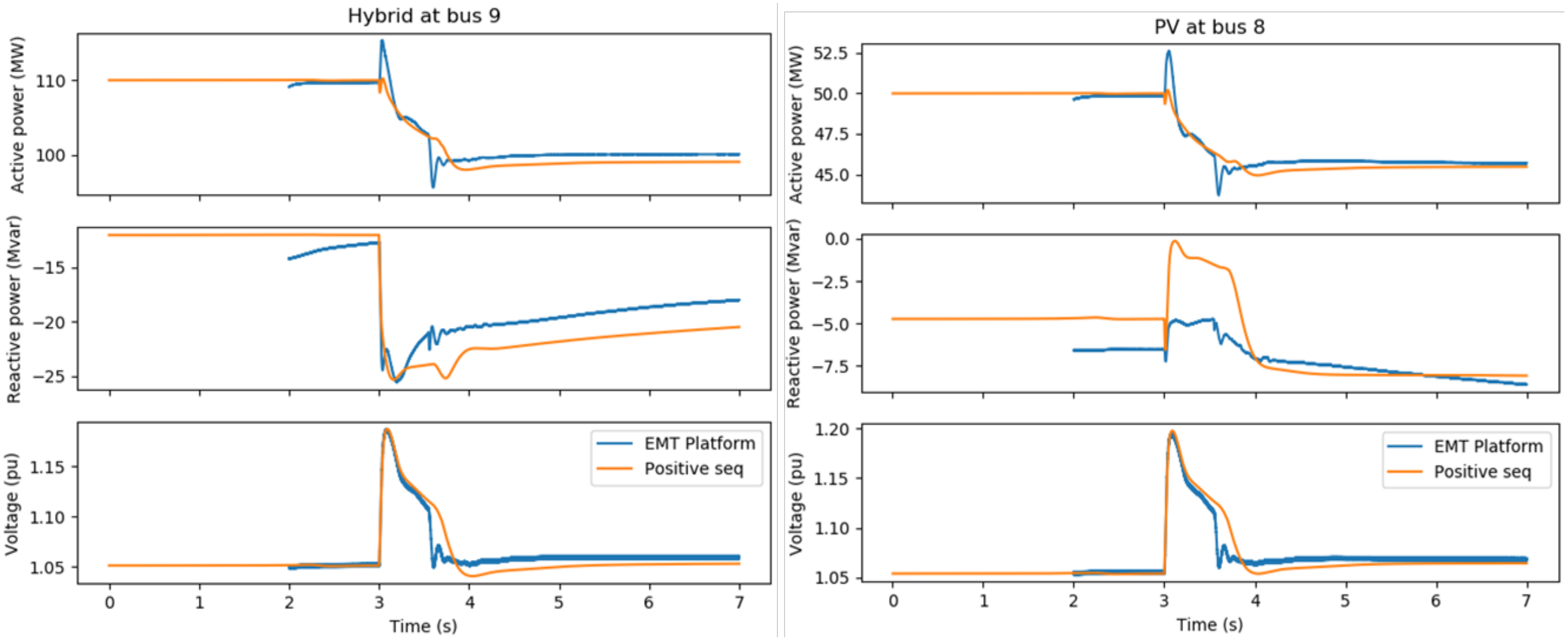
- *[GFM model]: EMT and Positive Sequence Domain Model of Grid Forming PV Plant (GFM-PV), EPRI, Palo Alto, CA, 2021, 3002021787 (link)*
- *[Positive sequence model]: REGC_C Implementation in PSS/E (REGC_C (PSS®E)), EPRI, Palo Alto, CA, 2021, 3002020781 (link)*

Trip of Equivalent with All Solar PV as Grid Following



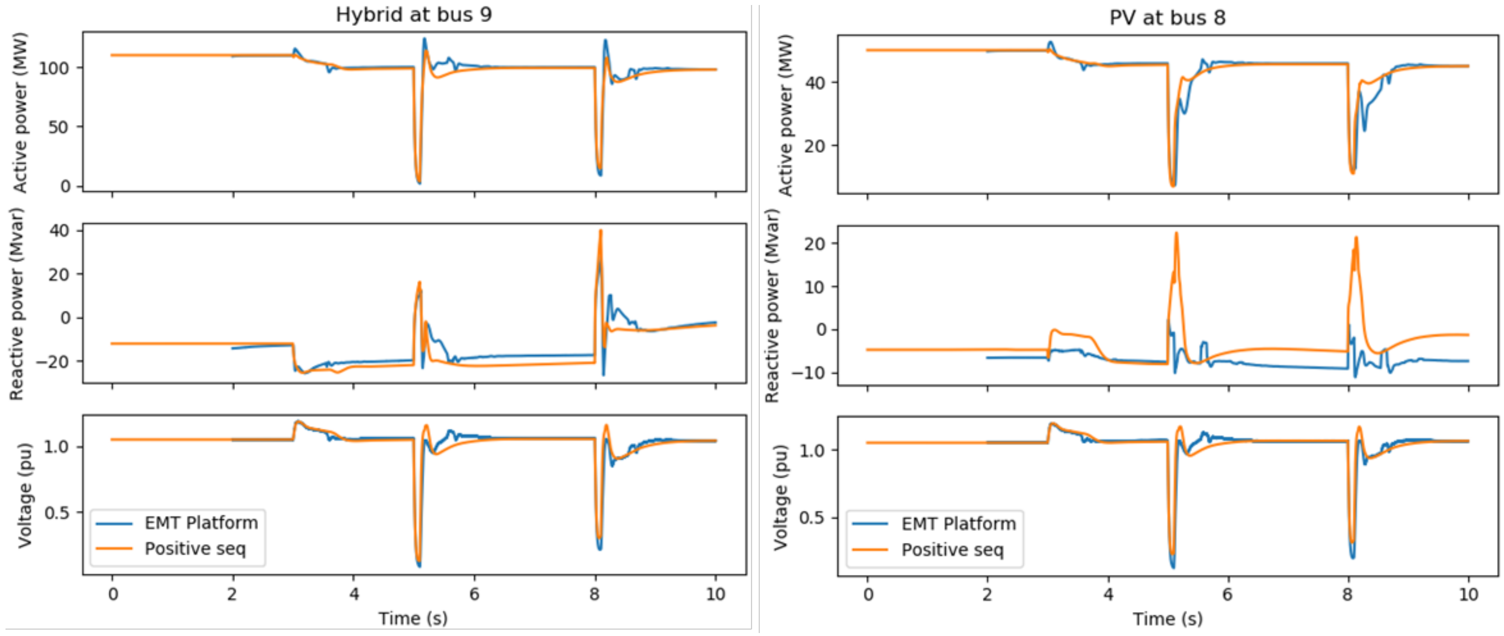
- EMT domain and positive sequence domain provide different type of response, but both provide the same picture:
  - With only BESS as grid forming, it is not possible to bring about a reliable system response
  - Rating and number BESS can play a role
- More work needed to reconcile oscillatory behavior across simulation platforms
  - Load dynamic behavior plays a role here, which implies need for accurate induction motor models

Trip equivalent with all PV as Grid Following but providing frequency response at 10pu/s



- With BESS as grid forming, and solar PV providing frequency support, it is possible to bring about a reliable system response
- **Same response trend** observed across both simulation platforms

Trip equivalent with all PV as Grid Following but providing frequency response at 10pu/s, and two subsequence faults



- EMT domain and positive sequence domain provide similar response
- **Same response trend** observed across both simulation platforms
  - More room for improvement in model development and parametrization

Key Takeaways

- Inclusion of only BESS in grid forming mode may not be sufficient for a system unless:
  - Large number of BESS in grid forming mode
  - Large rating of BESS in grid forming mode
- Important to consider response from other resources too
  - Ramp rate limits of devices can play a role
- Characterization of load dynamics is extremely crucial
  - Induction motor load vs static load can provide different response
- Continuous improvement of models across software platforms

Short Circuit Studies

Background

- *Renewable energy resources exhibit different fault current characteristics compared to traditional generators.*
- *There is an anticipated impact on the performance of traditional system protection.*

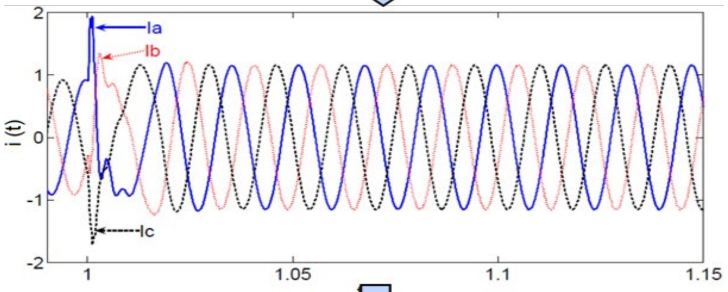
Industry Gap

- *Need for development of accurate models of inverter-based resources (IBRs) for short circuit studies.*
- *Need for evaluation of the performance of legacy protection functions.*

Challenge

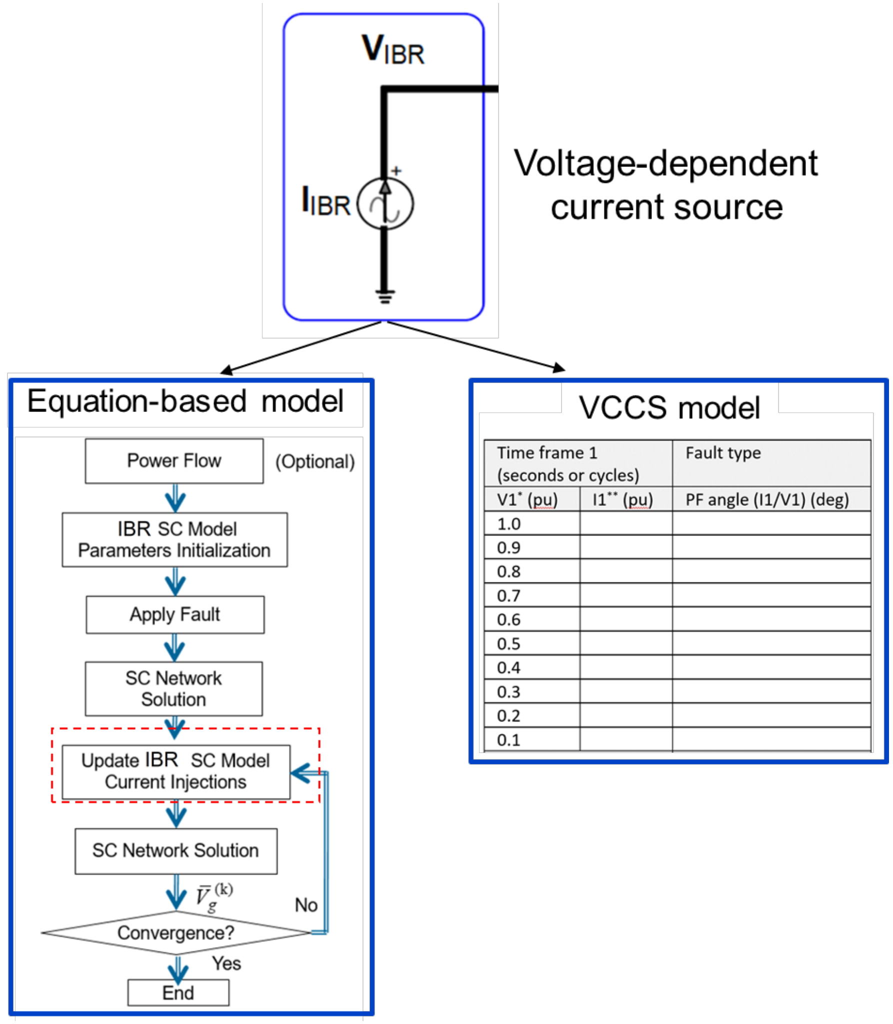
- *Gap between what data an IBR manufacturer can release and what model an SC program can use to represent the data*

Inverter Based Resource



IBR Short Circuit Model

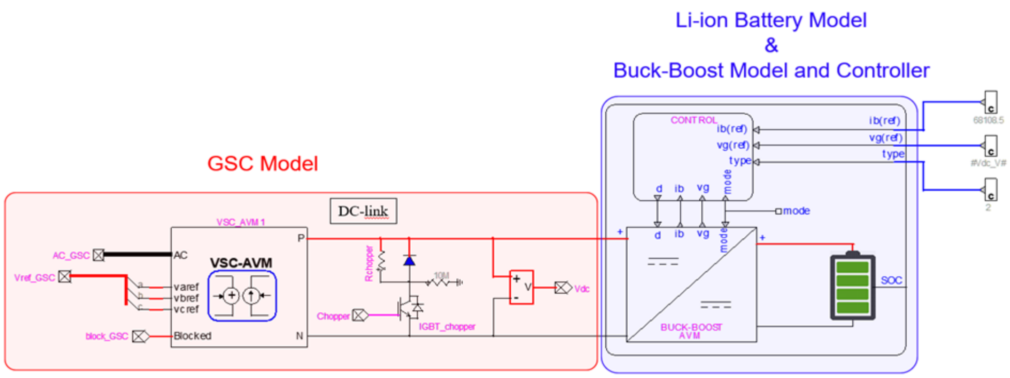
- IEEE PSRC C24 Recommendation (link)
  - Voltage-dependent current source representation;
  - Non-linear solution, requires iteration with network solver
- Implementations:
  1. Equation-based model
  2. Tabular model (Voltage-Controlled Current Source (VCCS))



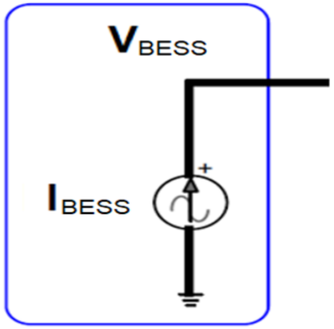
Time frame 1 (seconds or cycles)		Fault type
V1* (pu)	I1** (pu)	PF angle (I1/V1) (deg)
1.0		
0.9		
0.8		
0.7		
0.6		
0.5		
0.4		
0.3		
0.2		
0.1		

Battery Energy Storage System Short Circuit Model

EMT Model



SC phasor model

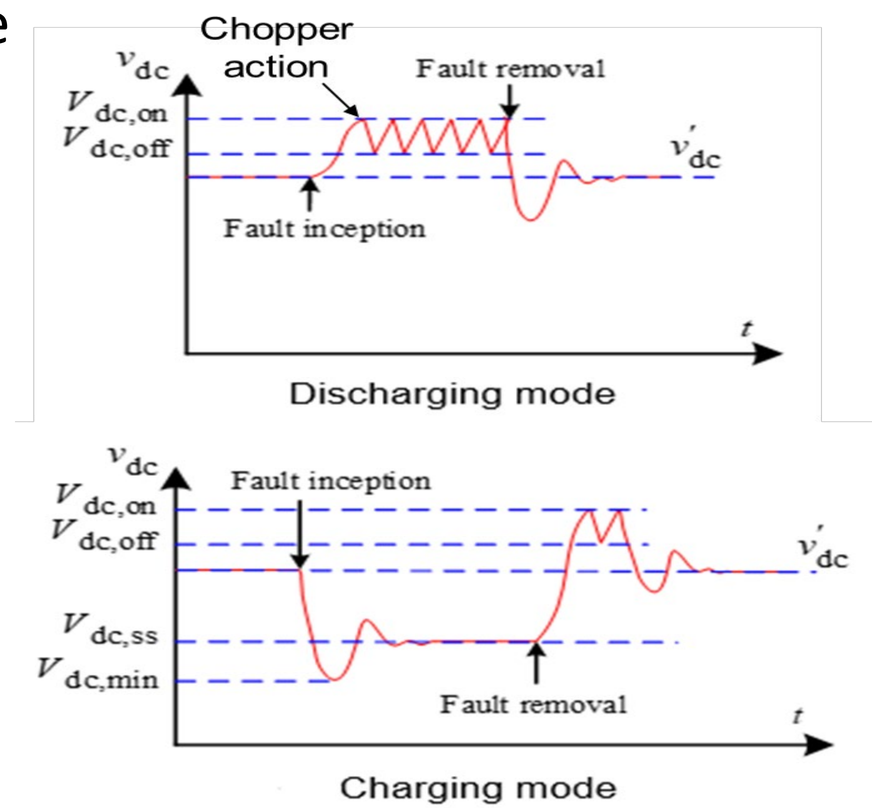


- Dynamic reactive fault current injection (FRT)
- Negative sequence fault current contribution
- Current limiter logic and P/Q priority
- Bidirectional dc-dc converter (BDC)
- Operating mode (charging vs discharging)
- DC link control

- *[EMT model]: Battery Energy Storage Systems Modeling for Short-Circuit Studies, EPRI, Palo Alto, CA, 2020, 3002018696 (link)*
- *[SC phasor model]: To be released in Q4 2021.*

BESS Fault Response

- **Discharging mode:** Fault response similar to PV and Type IV WTG
- **Charging mode:** Constant battery charging current control can prevent a BESS from complying with FRT grid code requirements due to inadequate dc-link management.



- *[EMT model]: Battery Energy Storage Systems Modeling for Short-Circuit Studies, EPRI, Palo Alto, CA, 2020, 3002018696 (link)*
- *[SC phasor model]: To be released in Q4 2021.*

Questions and Answers