GLOBAL PST CONSORTIUM

IBR Research Team Stability Tools Inventory: Status and Needs

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Tools: Introduction

Introduction

This presentation is intended to create a foundation on which we can constructively communicate about the tools needed to address the most pressing concerns of the Founding System Operators (FSOs).

It deliberately has the dynamic behavior of IBRs at the center of the discussion, with context to all the tools' needs associated with the transformation.

The presentation is study- or simulation-centric: tools for planning are particularly emphasized, with less emphasis on situational awareness and related operations tools.

The presentation is interactive, and mostly non-sequential: Follow links to explore your interests, or proceed sequentially through these 1st 7 core slides, then explore.

Outline:

- Today's pressing concerns, from a tool's perspective
- Stability centric view of the operations and planning analysis world: Inventory of tools and needs
- Topical discussions

Note: A glossary of acronyms is provided, which is accessed by clicking on this icon wherever you see it:

Summary what we’re hearing from the FSOs: our perceptions of what they are worrying about.

Tools: FSO's Pressing Concerns

- Are present tools giving answers that can be trusted? There is incomplete confidence that new mechanisms of failure are fully understood.
- Are present (simulation) tools being used properly, i.e., at the right time?, for the right problem?, do they link together well?
- Are the current processes adequate for the future?; how can we help the processes evolve faster, better than their natural or organic evolution?
  - How can the inputs to the simulation tools be improved? i.e., higher fidelity model data; more meaningful cases
  - How can the results of simulation work be better used? i.e., post-processing tools to turn results into insights; to aid in decision making based on simulation results
- The degree of uncertainty (in future scenarios) and variability (of new resources) is making standard (study) practice unwieldy, unsustainable:
  - How can the tools be used (and do they need to be modified) to allow better decision making in this increasingly uncertain and stochastic future?
  - How can screening processes (e.g., case selection, risk survey, data handling) be improved?

Summary what we're hearing from the FSOs: our perceptions of what they are worrying about.

Tools: FSO's Pressing Concerns

- How do off-line tools, developed for the immediate future, become (or advise) on-line tools of the near-future?
- Are new tools needed to help leadership decisions, especially related to timing? For example, are widespread systemic upgrades needed in specific areas, like (a) massive retirement and replacement of protective relays, (b) overhaul of blackstart and system restoration practice, (c) major new transmission, (d) revision of ERS procurement mechanisms, ...
- Help is needed with learning curves & human development: What can tools do to improve/speed the learning curve; speed the dissemination of knowledge more widely within organizations?
- Is the linkage between observed, measured, "real" phenomena adequate? What is the role and opportunity for improvement of measurement-based tools/simulations? Validating the "truth" and making better predictions of what to be studied.

Overview: Establishing a common baseline and identifying gaps in the Tools arsenal

Classes of Study Activities

- Planning
- Operations planning
- Operations guidance
- Interconnection studies:
  - Equipment design
  - Facility design
- Financial, economic
- Environmental
- etc.

Tools for these types of studies are the focus of this effort; which are aimed at addressing issues where the differences between IBRs and synchronous resource behaviors are most important

In the balance of this presentation, we attempt to present a view of the simulation environment used presently by the FSO organizations, and to identify where there are unmet needs for new or improved tools, as they relate to increased and new inverter-based resources

Stability Centric View:

- Phasor-based (positive sequence, fundamental frequency) time simulations, i.e., "stability" tools will continue to be the workhorse of the industry for a long time. The industry needs, with significant urgency, to:
  - Develop better models (and possibly other improvements to solution algorithms, data handling, etc.) for available equipment.
  - Develop supporting tools/linkages between tools that advise and improve the use of the phasor-tools and the decisions that result from simulations.
  - Establish better understanding and guidelines for where the presently available tools/models are legitimate, when they fail, where they can be trusted, and where not.
  - Develop 1st generation GFM models, with our present best guesses incorporated, with the full knowledge that they are imperfect. The journey followed by WECC/IEEE with the generic WTG models comes to mind.
  - Consider long-term development of tools that might replace, partially or completely, phasor-based stability tools; or interact with them in radically different ways.

All 5 of these are critically important steps to be pursued on the way to an "end point"

"we need a tool(s) that can be run quickly so that one can examine many scenarios and conditions, but that is accurate when there is little synchronous generation online; a tool that has the ability of EMT for weak grid situations but that can be run like a full-scale stability program many times over."

Glossary:

Stability Centric Environment

Follow (click) each tool for more detailed discussion

"Economics" tools
- Production Simulations
- Reliability (ELCC, LOLE, ...)
- Capacity Expansion

Initial conditions

Boundary conditions

Model

Positive Sequence Phasor analysis
- Stability
- Loadflow

Meta-tools

Validation, refinement, model data

Conditions for study, Boundary conditions

"Physics" tools
- EMT
- Protection design
- State-space, SSS
- Impedance based techniques
- Voltage stability, static tools,
- Measurement based tools
- RTDS, HIL tools
- Harmonics, PQ
- Aggregation & Equivalencing
- Hybrids (e.g. Phasor + EMT)

How these tools are used depends on the problem/activity:
See application matrix.

Tools: Topical discussions

This section provides links to discussions that can guide tool development. IBR related gaps are noted where appropriate.

Follow links to explore the following topics (and return here).

- Meta-tools
  - Example meta-tool: Simulation confidence
  - Example meta-tool: What tool to use? tool selection assist
  - Example meta-tool: Contingency analysis
- Stages of tool development
- Attributes of good tools
- Who uses what tools?
- What's a model?
- Humans and tools
- Stochastics & Probability

IBR gaps:

- Throughout the detailed slides in the balance of this presentation, there are orange boxes like this.
- In general, the content of boxes present R&D needs (covering a spectrum from "pure" Research to "just do it" Development)
- R&D projects that help resolve these gaps (singly or in groups) appear to be needed.
- Priorities for these are open to discussion

Thanks

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Appendix 1

Section break

To the reader:

- from here on, slides and discussions that are linked to the main presentation, particularly the environment slide, are presented.
- You can access them by continuing, or you can access them from the main body of the presentation.

Meta-tools (general attributes)

Return to Topical Discussions

There are several classes of tools that are not simulations, but which provide valuable or essential assistance to the analytical process. These tools may facilitate data handling, help assure that simulation work is correct and meaningful, help extract, explain or present results. With rapidly changing requirements, processes that were once manual and required domain expertise will need help. Here are 4 general categories of these "meta" tools:

Pre-processing

- Data screening, data preparation
- Case design and preparation. (e.g. contingency analysis)
- What additional initial analysis is needed?

Linkage tools

- Output from one tool (simulation platform) processed for input to another tool
- Round-trip tools (back and forth between two simulation platforms)
- Multi platform tools (complexity grows exponentially...)

Post-processing

- Are results correct/meaningful?
- What has been learned? What tool to use?
- Visualizations. Summaries.
- What additional follow-on analysis is needed (or not)?

Decision Support

- What is the right tool for the problem at hand?
- Triggering decisions: do results/evidence indicate a specific (large?) decision is required (e.g. Time to build a new T line?)

Stages of Tool Development

Software tools are not useful to FSO end users unless all stages of its life cycle are addressed. Research community often fails at taking software concepts and getting them to FSOs in a usable form.

Return to Topical Discussions

Stage	What?	Who?	Comments
Specify	RFP; clear functional requirements; clear conceptual objectives	Funding entities, GPST, gov't, end users	Ownership; initiative; prioritization can all be challenges
Develop/Prove	Test concepts; write proof-of-concept codes/tools; exercise, demonstrate	Researchers, universities, and/or commercial software vendors	Researchers tend to do this well, if the idea has merit and the spec is well thought out.
Scale Commercialize	Implement in (or "next to") the commercial tools. Make it "work" with real IT systems, real data sets, with acceptable computer burden	Needs to be cooperative effort between researchers and commercial software entities. Today it's "somebody else's problem"	This is a step that researchers, software businesses & industry are failing on repeatedly. Needs viable business models.
Maintain Train Evolve	Keep it working; provide training; fix bugs; answer the phone; make upgrades; make it "talk" to other software tools.	Combination of commercial software companies and end-user organizations.	This is often a failure point. Insufficient funding, institutional memory, glamor, ownership

Attributes of Good Simulation Tools

Return to Topical Discussions

- Meaningful
  - Simulation results are of sufficient fidelity (accurate, close to reality in aspects that matter to decision making) to allow for good decisions – this is problem dependent
- Scalable
  - Tools that can handle problems of size/dimensionality necessary for the specifics of the system and studies/problems. Computational burden must be acceptable. Must work in FSO-like computing environment
- Robust & User-Friendly
  - Can be used by "end" users (not just researchers, developers) and requires data that is obtainable and maintainable
  - Can be relied upon to (a) give reproducible results, (b) not crash, (c) be numerically stable, (d) etc., ...
  - The simulation environment is intuitive, so the user can gain insights and be able to make informed decisions; has some safeguards to reduce user errors, filter bad data, digest and present results
  - Has regular maintenance; provides user-support. Has good documentation.

These attributes are related to the stages of the previous slide: All 3 attributes need to be considered from the start. They can't be "added in" any more than "quality" can be added at the end of development process.

Organization: who uses what tools?

Return to Topical Discussions

- How do the tools talk?
- What does that mean organizationally?
- Who knows what? Who owns the data?
- What tools (practices) can moderate the GIGO risk
- How do the "old" silos (organizational divisions) fail now?
  - More than just tools, but related.
  - What might the tools do to improve the permeability of the silos? To make the whole organization more effective?
- Keeping tool related skills up to date, and properly shared
- Identifying the new skills that are needed.

Different functions within the FSO organizations may not communicate, share, and coordinate in a fashion consistent with the needs of the transformed power system. We ask "what can tools do to help, not hurt?"

Much of this is vastly broader than just IBRs, although these questions apply to the tools discussed here.

Glossary:

Tools usage matrix (as related to IBR integration)

Return to Topical Discussions

Application/problem	Stability (Phasor)	Physics (time domain)	Physics (non time domain)	Economics	Comments
BPS Transmission Expansion Planning	1	2	3	1	
BPS IRP/Resource Planning	2	3	3	1	all these are secondary to energy and economic tools
IBR Interconnection	2	1	1	3	
Reactive Compensation	1	2	2	1	
Transfer/path limit analysis	1	3	2	3	
Operations security	1	3	3	2	
Protection	2	3	1		Specialty tools for protection
Harmonics, PQ		2	1		Specialty tools for harmonics
Forensics/RCA	2	1	1		Broad topic; depends on failure

This slide is in contrast to the idea that there is a need for meta-tools to decide which tool to use in a particular circumstance. Similar, but not the same problem. Needs more thinking. This may be inadequate, in that the reader needs the process and which tool for which conditions guidance. Can't all fit here!

Key

Score	Description
1	Primary Tool
2	Supporting tool: regularly used to guide/bound primary tool work
3	Appropriate in special circumstances

Humans and tools

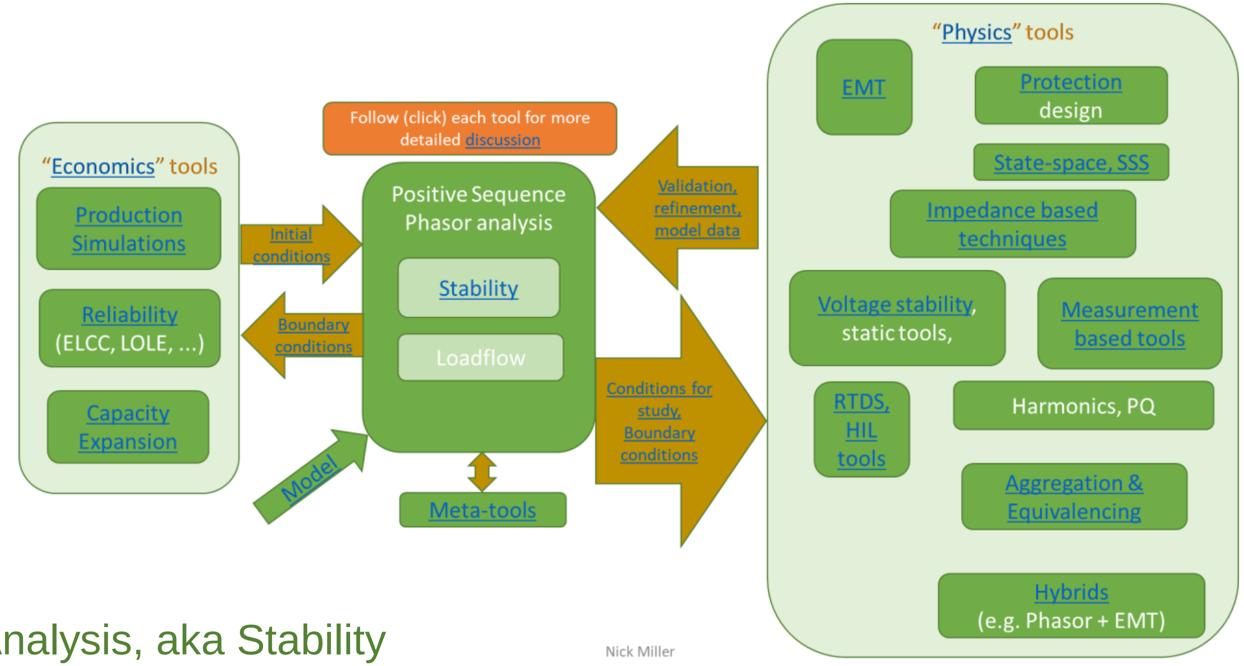
Return to Topical Discussions

- There are varying levels of skill and experience in those doing the heavy simulation lifting at FSOs
- Tools should capture the cutting-edge institutional learning in a fashion that can be immediately useful. Not everyone doing the "real" work is immersed or a researcher!
  - There are intricacies and nuances involved when solving mathematical equations that are to be respected. Expectation of robustness needs to be tempered with reality, and expectation of a minimum degree of skill from users.
- Tools that will raise confidence in the simulations, and the resulting decisions, are needed.
- This is a moving target: understanding, simulation tools (algorithms and models) will change and improve, equipment is evolving rapidly.
- We need mechanisms so that "we" can all share learning and experience; the dimensionality is daunting.
- Anything created must be structured so that it can be "kept up to date" (whatever that means)
- The human expert is going to be the decision maker on whether a result is useful/useless/in between - their knowledge and understanding is critical – education must be apart of this.
  - At the research level: are some of these issues suitable for various AI? Certainly, post-processing seems like it could benefit from expert systems
- Standards. At what point and where are data standards (e.g., standard exchange formats) needed and appropriate?
- There is a commercial angle that must be respected: providing most of these core tools is a commercial, competitive business for profitable companies.

Glossary:

Tools Inventory

- The following section provides a more detailed examination of each of the cells in the "stability centric" tools environment
- Each slide attempts to capture:
  - Language (what are the names by which the process & the tools are known in the industry)
  - Key attributes/usage
  - Relationship of the tool to Positive Sequence Phasor Analysis, aka Stability simulations
  - Gaps in the tool capability with respect to IBRs
  - Maturity of the tools (slider) - identifies:
    - Mainstay, commercial offerings, especially in wide utility usage
    - Commercial specialty tools, in selected utility usage
    - Available research grade tools; in use beyond the originating entity
    - Narrow tools; developed or continuously "work in progress", but only used by the creators of the tool
    - Still at proof of concept, or proposal stage



Tools Inventory

Stability: Positive Sequence Phasor Analysis

Language:

- AKA (generically):
  - Positive sequence fundamental frequency dynamics (PSFF)
  - Stability, transient stability
  - Phasor dynamics
- AKA (brand names):
  - PSS/e,
  - PSLF,
  - DSAtools TSAT,
  - DigSilent PowerFactory
  - PowerGEM – TARA,
  - Others...

Key Attributes:

- System planning and operations planning workhorse; commercial software with license fees
- Phasor based
- Mixed DAE; network algebraic; time frame ~1 cycle to 10s of seconds
- Meaningful for changes in fundamental (power) frequency quantities;
- Not for analysis of non-fundamental frequency behavior
- Well suited to very large systems; many cases
- Being continuously improved.

IBR gaps:

- Available IBR models mainly GFL.
- Fidelity & numerical stability concerns, especially for weak systems. problems
- GFM models nascent; unproven
- Meaningful initialization; GIGO risks substantial

Glossary:

“Physics” tools

- Physics tools have detailed or specialized representations of specific system elements, with (usually) simpler (than stability program) equivalent representation of the entire power system.
- They are used to design and refine elements (including rating and controls) and validate models for specific applications, perform diagnostics and forensics on elements.
- Physics tools often have full 3 phase, or 3 sequence, representations of system elements
- Some have narrow, highly specific functions (e.g. setting protective relays, or designing harmonic filters)
- They generally require a degree of specialized engineering expertise to use well

EMT: Electro-Magnetic Transient tools

Language:

- AKA, (generically):
  - EMTP (used generically)
  - Point-on-wave
  - Three-phase transient model
- AKA (brand names):
  - EMTP (the original)
  - ATP
  - PSCAD
  - Simulink
  - Others..

Key Attributes:

- Detailed design and research workhorse
- Multiphase; detailed representation of physics;
- Primarily DEs, including network. Time frame ~0.1ms cycle to 1s of seconds
- Well suited to difficult specific equipment issues;
- Large systems difficult; very large systems extremely difficult
- High user skill requirements; High GIGO risks

Relationship to Stability:

- For validation of PSFF
- For design of controls; input to PSFF
- For dealing with multi-frequency (i.e. not just fundamental frequency) phenomena
- For analysis, including large scale, of Weak Grids
- Some systems trying to substitute EMT for PSFF at analytical center.

IBR gaps:

- Available IBR models often proprietary
- Generic IBR models of debatable utility
- SOA GFM models scarce
- Access to controls
- Ability to quickly, successfully run large systems...

Glossary:

Real-Time Simulation (RTS) Platforms

Language:

- AKA, (generically):
  - SIL (software –in-the-loop)
  - HIL (hardware-in-the-loop)
  - Point-on-wave
  - Three-phase transient model
- AKA (brand names):
  - RTDS
  - Other commercial??
  - Other research grade platforms...

Key Attributes:

- Simulation environment where execution matches actual clock-time (1 second of simulation = 1 second of elapsed time)
- Allows "real" elements to be interfaced with simulated "boundary conditions"
- Evolved from old analogue simulation world (TNA, etc.)
- Both software and hardware can (in theory) go directly from test to field
- Well suited to small, detailed representation. Scalability can be a challenge.
- Skill and labor intensive

Relationship to Stability:

- For validation of PSFF
- For forensics
- For qualification (of controls, devices)

IBR gaps:

- Available IBR models often proprietary
- Standard practice (for modeling, testing, transfer,...)
- Equivalents for RTS models
- Linkages to measurement-based tools and field measurements

RTDS

Various "Lab" RTS

Commercial, in wide use

Specialty but established

Proof-of-concept stage

Glossary:

State-space Tools

Language:

- AKA, (generically/subsets):
  - Small signal stability
  - Eigenvalue analysis
  - Damping calculations
  - FFA (fast fourier analysis)
  - Prony Analysis
- AKA (brand names):
  - SSAT (part of DSAtools)
  - PSS/e (python scripts)
  - PowerFactory (supporting functions)
  - Other commercial?
  - Other research grade platforms...

Key Attributes:

- Primarily based on frequency domain description of dynamics
- Explicit or implicit use of eigenvalues, to describe frequency and damping of oscillations
- Mature math; foundations assume linearity of systems.
- Small systems allow for "full" state-space representations (A matrices)
- Several tools extract state-space information by post-processing time simulations

Relationship to Stability:

- For validation of stability models and results
- For establishing gain limits/control settings
- For forensics. These tools are important for determining causality and mitigation for control interaction and similar problems. In planning and after the fact.
- For facility/interconnection design

IBR gaps:

- Some large-scale tools assume dynamics of synchronous machines dominate
- "Tricks" emerging for handling some non-linearities; need work
- IBR models highly non-linear; building true state matrices still deeply imperfect
- Bandwidth of IBR challenges is wide; difficult to get all relevant differential equations in a single tool.
- Standard practice limited, at best...

Support functions of std stability tools

Various "Lab" SS tools

Commercial, in wide use

Specialty but established

Proof-of-concept stage

Hybrids (Phasor + EMT Tools)

Language:

- AKA, (generically/subsets):
  - POW+Phasor
  - ...
- AKA (brand names):
  - PowerFactory
  - PSCAD + PSS/e (V5)
  - Electranix PSCAD hybrids
  - Matlab/Simulink
  - Others under development

Key Attributes:

- Detailed, EMT type representation of a (usually) small specific part of the system, numerically "spliced" to a large phasor representation of the system
- Historically tools have been used for single, large devices being integrated to AC grids: e.g. HVDC terminals
- Mostly highly specialized, often proprietary software. High setup and skills requirements

Relationship to Stability :

- A possible route forward to solve the scalability plus fidelity problem
- Could share majority of representations, with higher fidelity IBR models used (sometimes?)

IBR gaps:

- Implementation for many IBRs at multiple locations is challenging.
- Evolution to "plug & play" modules in phasor framework
- IBR models for EMT (which have their own gaps) need to be adapted to algorithmic requirements of hybrid
- Determining phasor/EMT model boundaries
- Rare, highly specialized today
- Standard practice non-existent

Specialty commercial tools

Selected OEM proprietary tools

Various "Lab" tools

Commercial, in wide use

Specialty but established

Proof-of-concept stage

Glossary:

Protection Tools

Language:

- AKA, (generically/subsets):
  - Relay setting programs
  - ...
- AKA (brand names):
  - ASPEN
  - CAPE
  - ETAP

  Functionality for testing and validation of settings:
  - Matlab/Simulink
  - PSCAD.

Key Attributes:

- Detailed representation of line and other protection characteristics. Used for calculating settings, coordination between multiple protective devices.
- Historically based on assumption that fault current delivery is from (synchronous) machines.
- Network representation sequency based; some simplifications.

Relationship to Stability:

- Network data can have the same source as stability program (often separate in organization)
- Some relays with settings modeled may be modeled in stability programs.

IBR gaps:

- IBR models for delivery of fault current are recent additions to (some programs).
- Significant fidelity concerns with IBR models for both fault current and impedance for protection setting.
- Significant concern of systemic relay vulnerability to unexpected behavior (in models and in field)
- Tools to help determine when existing protection (i.e. specific types of relays) are no longer suitable, and must be replaced with higher functionality relays suited to IBRs

Widely used commercial tools

Various experimental tools for IBR and new protection concepts

Commercial, in wide use

Specialty but established

Proof-of-concept stage

Voltage Stability Tools

Language:

- AKA, (generically/subsets):
  - Nose Curve
  - Continuation loadflow
  - PV curves, VQ curves
- AKA (brand names):
  - VSAT
  - PSS/e modules...
  - PowerWorld
  - PowerGEM

Key Attributes:

- Generally static (algebraic) modeling, that determine point of, and margin from, voltage collapse
- Used to set power and loading limits; to establish reactive power adequacy and Q reserve margins
- Historically a support function in operations, and used for reactive power planning and design
- Low computing burden; well suited to big systems and many cases

Relationship to Stability:

- Network data usually same (or high overlap) with loadflow.
- Potential guide or give indicative of stability limits for more detailed analysis (which conditions and events are most important)

IBR gaps:

- IBR models with specificity for voltage and reactive power controls absent
- Understanding of character of voltage collapse with high IBR is insufficient. Especially true for GFM.
- Bridging static concepts to dynamics shows promise

Impedance based Tools

Language:

- AKA, (generically/subsets):
  - Impedance spectrum analysis
  - Black/grey-box analysis
  - Measurement-based analysis
- AKA (brand names):
  - Matlab/Simulink
  - PSCAD
  - EMTP
  - Others

Key Attributes:

- Impedance transfer function and/or spectrum identified or measured at certain point of a power system.
- Poles/zeros of transfer functions; peaks/valleys and phase angles seen from frequency spectrum.
- Impedance return ratio, Bode stability criterion, and Nyquist stability criterion.
- Measurement-based analysis, black-box analysis, online analysis, real-time analysis.
- Modular modeling and analysis.

Relationship to Stability:

- The transfer function representation of state space model.
- By ignoring certain dynamics (passive components) can lead to a steady impedance model, which has parallel equivalence to the model used in other analysis, like phasor-based tools.

IBR gaps:

- Impedance models of IBRs highly depend on their flexible control parameters and algorithms.
- The impedance representation of synchronization and/or frame dynamics is still under research.

Tools used in experimental tests and simulations.

Commercial, in wide use | Specialty but established | Proof-of-concept stage

Measurement based Tools

Language:

- AKA, (generically/subsets):
  - Phasor-measurement – PMU
  - DFR – digital fault recorder
  - NERC MOD – model validation testing s/w
- AKA (brand names):
  - Others

Key Attributes:

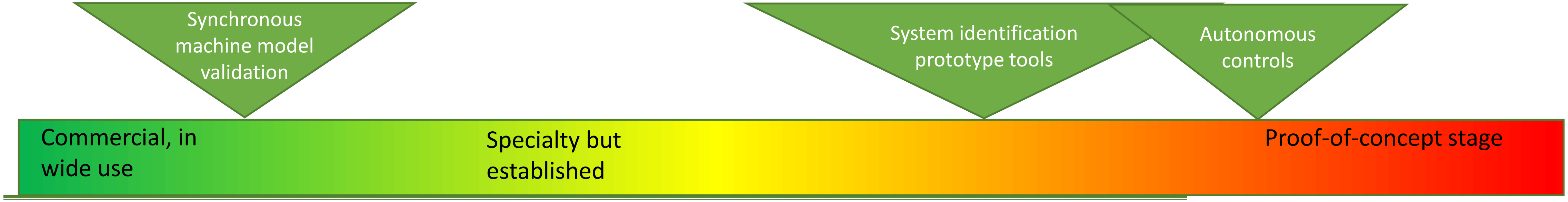
- Measurement-based tools capture actual physically observable phenomena, and then
  - Advise simulations
  - Advise operators
  - Initiate actions
  - Identify systems and risks

Relationship to Stability:

- Today, NERC mandates that power plant stability models be validated with measurements.
- Other components and entire system or subsystem models could be validated.

IBR gaps:

- Techniques for using IBRs to “probe” the system for the purpose of system identification
- Techniques for model validation of “as built” IBR equipment
- Techniques for using measurements to identify high risk conditions that need to be studied
- Techniques for improving performance of specific assets.



Glossary:

Aggregation & Equivalencing Tools

Language:

- AKA, (generically/subsets):
  - Distribution aggregation
  - Wind/solar plant equivalencing...
  - EMT equivalents
- AKA (brand names):
  - NERC/WECC/EPRI have prototype tools for development/population of composite load model
  - Most commercial stability programs have ability to create short-circuit impedance (Z) models

Key Attributes:

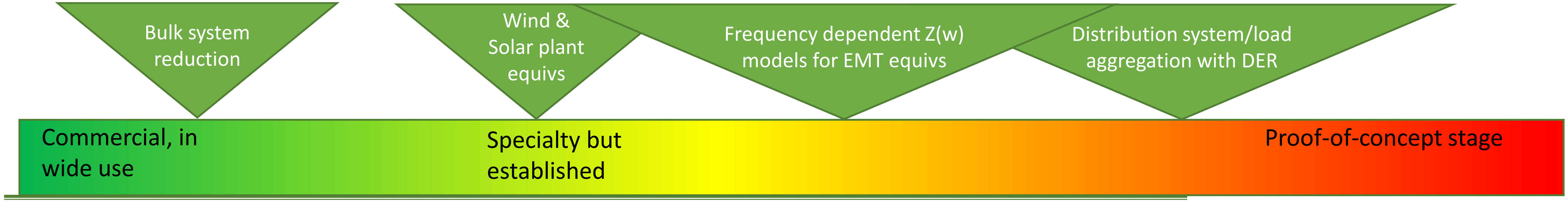
- Generally, these tools reduce complex portions of the power system to more manageable size "equivalents" for use in other simulation tools. Includes:
  - Cut points (bulk power system behind a cut plane
  - Low voltage; distribution/"load" equivalents
- Static fundamental frequency Z models are used for stability and protection programs

Relationship to Stability:

- Equivalents of distribution systems, wind and solar plants, are inputs to stability programs
- Network data from stability data sets is used to create EMT equivalents

IBR gaps:

- 1st gen tools that populate composite load models based on geography and other factors need further development and validation.
- Equivalents for EMT may be overly simple. Research needed on what is important (e.g. Z(w)? To what f?) how to develop, create realizable (e.g. RLC) models? How to create? Sequence representation?
- Are active models needed? Synergy with Impedance-based tools?
- Mature tools for wind & solar plant equivalences



Glossary:

“Economics” tools

- These tools tend to cover much longer time frames, and are used to investigate “big” questions: What will run? When? What will it cost? What should be built? How often with there be shortages? Etc.
- They use some of the same data as stability programs, and a great deal of specialized cost and economic data.
- These tools rely on input data, derived from stability tools, to establish boundary conditions that must be respected for *secure* least-cost operation. Whether resources are IBRs or synchronous is (only) of importance in this regard.
- The separation between the various tools in this group is becoming less viable, with practice emerging that melds the distinct functionalities

Production Simulations

Language:

- AKA, (generically):
  - Market Simulations
  - Production Cost Simulations
  - Production Cost Models - PCM
- AKA (brand names):
  - Plexos
  - MAPS
  - Polaris PSO
  - VCE WISDOM
  - PowerGEM Probe
  - Aurora
  - UPLAN
  - PROMOD
  - GridView
  - Other commercial??
  - Other research grade platforms...

Key Attributes:

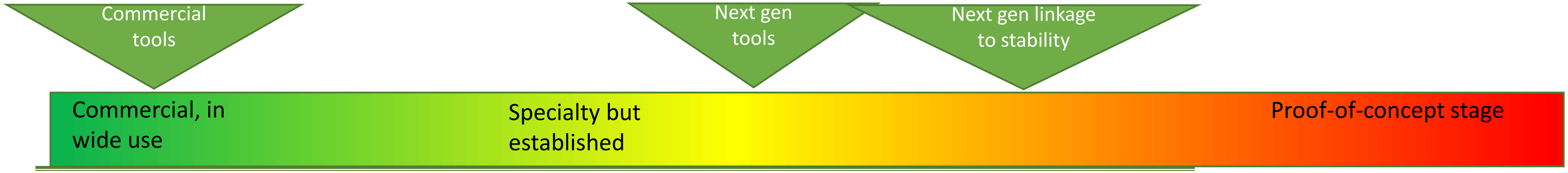
- Simulation of large systems for extended time periods (often 1 year)
- Focus on least cost operation: what generation runs, when, at what cost.
- Captures many variable costs; does not capture fixed costs.
- Representation of IBR resources extensive, BUT does not care specifically that resources are IBR.
- Execution time-steps usually between 5 minutes and 1 hour)

Relationship to Stability:

- For initial condition “snapshots) for Stability
- Accept limits, e.g. transfer ratings and reserve requirements, determined by Stability
- Shared (nominally) data

IBR gaps:

- Boundary conditions/limits related to IBR dynamic performance mostly ad hoc
- Seamless “round-trip” between stability and production simulations.
  - Data usually poorly aligned with stability
- PCM varied in abilities. Some do poorly reproducing extreme (shortage) conditions. Representation of DER and active load patchy.
- Big gaps between best-in-class modeling, and actual use in important institutional decision making.



Tools Inventory

Reliability Tools

Language:

- AKA, (generically/subsets):
    - LOLE, LOLP (lose-of-load expectation, probability)
    - ELCC (equivalent load carrying capability)
    - PRM (reserve planning margin) tools
        - ...
- AKA (brand names):
    - GE MARS
    - E3 RESOLVE
    - SERVM
    - Polaris PSO
    - Others...

Key Attributes:

- Statistical/probabilistic tools, that produce probability of failure of energy supply (i.e. variations 1 day – in – 10 years reliability metrics
- Usually Monte Carlo or similar method, checks if available supply can meet expected demand. Many dice rolls.
- Traditionally take inputs like plant outage rates and load requirements.
- Present practice includes statistical representation of weather dependent generation
- Maybe used to set PRM targets
- Not economic; costs not included.
- Weather dependence aspect highly important; reliance on inverters not important at all

Relationship to Stability:

- Network data may be simplified (to areas)
- Will influence available fleet
- Stability tools may feed transmission limits to multi-area reliability tools

IBR gaps:

- Dynamics, like ramping needs, poorly represented, if at all
- Lack of chronology makes energy limited (i.e. storage, demand response) difficult to model; misses correlated outages resulting in poor capture of extremes
- Lack of forecast error considerations
- Improved metrics (e.g. beyond 1 day in 10 years) are needed.
- Economic terms increasingly necessary. New efforts linking to Resource Adequacy and Capacity Expansion are emerging.

Widely used commercial tools

Various experimental tools for new reliability concepts

Commercial, in wide use | Specialty but established | Proof-of-concept stage

Glossary:

Capacity Expansion Tools

Language:

- AKA, (generically/subsets):
  - Capacity Addition tools
  - Resource planning tools
  - Long-term tools
  - Resource Adequacy tools...
- AKA (brand names):
  - ReEDS
  - PLEXOS
  - Strategist
  - Aurora
  - ABB tool
  - Wisdom
  - Others.

Key Attributes:

- Economic tools that look across multiple year planning horizon, with the intent of identifying what type and amount of resources need be added, when, in order to meet economic, environmental and reliability goals.
- Typically do not look at all hours of the year, and use sample time slices

Relationship to Stability:

- Typically well upstream from stability analysis
- Will provide resource portfolio that production simulation tools will commit and dispatch.

IBR gaps:

- IBR behaviors that affect the economics & efficacy of new resources can be difficult to represent and may be poorly captured in these tools
- Potential for missing constraints, or under valuing performance attributes of IBRs
- With more weather dependent IBRs, use of samples rather than full and multiple years increasingly inaccurate

Linkage Tools

- These tools connect various specific simulation tools and platforms
- At their simplest, they provide data bridges between different formats
- More sophisticated linkage tools aid the user in selecting, mapping or otherwise modifying data exchanged between tools.
- They can be critical, and are often neglected, parts of the tool arsenal

Linkage: Economic tools to Stability tools

Overview & Language:

- Stability simulations normally start from a single snapshot: i.e. a specific operating condition
- Production Simulations produce thousands (hourly or faster) of these snapshots, with (hopefully) real(istic) commitment, dispatch, loads, etc.
- Most *nodal* production simulation tools (i.e. ones that include explicit representation of the grid) can, in theory, export loadflows

IBR gaps:

- Today, linkage is minimal. "planning cases" are set (e.g. summer peak, etc.). Accompanying commitment and dispatch usually loosely based on experience and production runs. Data sets often "align" poorly. (often owned by different parts of organizations).
- Tools to select "hours" that are most meaningful for stability analysis need improvement.
  - This is fertile ground for research; and links to other stability research
- Tools that make it easy and efficient to "export" cases to stability tools are needed.
  - This is a task for standards creation; standardized, non-proprietary data exchange formats are needed
  - Also, for the software vendors, as mechanics of data exchange can be poor.
- Tools that make it easy for the data sets (stability and production) to be compatible are needed.
  - This is an institutional challenge/task for owners of the databases.

Simple case export

Screening tools to select "best" hours for export to stability

Having this separate from the stability to economics tools hides the need for there to be iterative exchange between the two platform to get good results today.

Commercial, in wide use

Specialty but established

Proof-of-concept stage

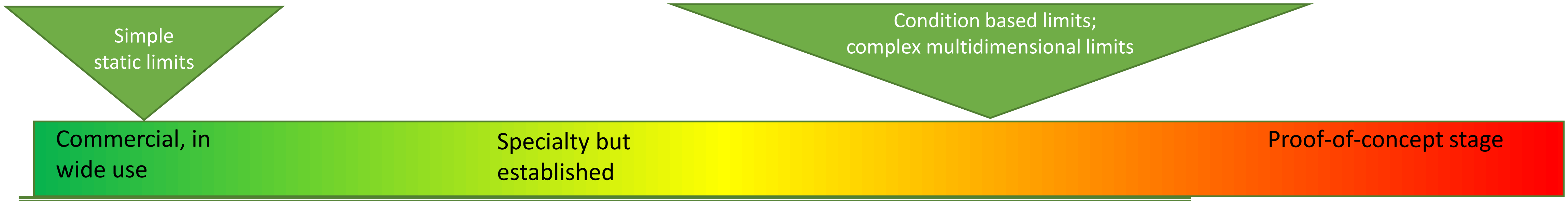
Linkage: Stability tools to Economic tools

Overview & Language:

- Production Simulations need input data to bound cases, some of which can only be created by stability analysis.
- Boundary conditions include: Stability constrained transfer (path) limits, reliability-must-run constraints, location-based reserve requirements, to name a few.
- With IBRs, constraints may be different in character as well as magnitude

IBR gaps:

- Today, linkage may be crude. Limit models are static, and not highly differentiated.
- “New” types of constraints (related to IBRs) that are determined by stability analysis that should be accommodated by production simulations include:
  - Weather or IBR power level dependent transfer limits and ERS capability
  - Short circuit constrained unit commitment
  - Storage SOC based ERS capability
  - Heterogeneous performance for ERS (e.g. higher FR contribution from high gain IBRs)
- Tools and practice to establish these constraints
- Tools to translate stability results to forms usable by production simulations



Linkage: Stability tools to Physics tools

Overview & Language:

- Stability models represent system elements, including IBR resources, with relatively simple individual models in large, complex representations of the entire power system
- Physics tools have detailed or specialized representations of specific system elements, usually with simpler equivalent representation of the entire power system.
- Physics tools are used to design and refine elements (including rating and controls) and validate models for specific applications, perform diagnostics on elements.

IBR gaps:

- Methods to use stability tools to trigger detailed physics investigation of IBR behavior
- Methods to give better fidelity power system equivalents based on large-scale stability system models; methods to allow larger physics-based models (including, up to entire systems)
- Seamless transfer of network data (and other relevant data) from stability databases to physics tools;

Mixed. Some good tools for data transfer

Commercial, in wide use

Specialty but established

Proof-of-concept stage

Linkage: Physics tools to Stability tools

Overview & Language:

- Physics tools often are used to produce specific details of design or limitations that are necessary for stability modeling
- Parameters of specific equipment, including rating and performance, are determined in physics tools that are "mapped" to stability models.

IBR gaps:

- Methods to "map" detailed physics representations of IBRs to available stability device models.
- Methods to communicate (or enforce) important behavior of IBRs that would normally be "invisible" to stability simulations.
- Methods to focus stability simulations (e.g. select initial conditions, disturbances, pick "cases") that will produce the most useful and meaningful results.
- Methods to correlate and align simulations between tools.

Highly varied;
Essentially all manual expertise

Commercial, in wide use

Specialty but established

Proof-of-concept stage

Pre- and Post-Processing Tools

- These tools are used before, after or around core analysis tools.
- At their simplest, they organize multiple cases – e.g. setting up fault or contingency cases, or sifting results for violations.
- More sophisticated tools address the high, and growing, dimensionality of the problems at hand. They substitute brute force for more deliberate choices in
  - what to run,
  - what to look at,
  - what might be learned from simulation results.

Stability Meta-tools: Contingency Analysis

Language:

- AKA (generically):
  - Contingency analysis
  - Case setup/selection
- AKA (brand names):
  - EPRI "Advanced Contingency Analysis"
  - Assistance modules for this function in most commercial loadflow and stability programs

Key Attributes:

- Automation tools that "wrap" around stability (and loadflow) tools, running many cases.
- Include aspects to create input files to stability programs, and ways to "sift" through output files, looking for example, for violations of planning criteria. Basic tools are mature, and are often highly customized to specific systems/users.

IBR gaps:

- Available tools tend to be "brawn" – testing huge number of contingencies. Smarter selection of contingencies to be analyzed is needed.
- Tools that are IBR centric, selecting contingencies based on limitations of IBRs and high IBRs systems

Std stability contingency tools

IBR centric tools

Commercial, in wide use

Specialty but established

Proof-of-concept stage

Software & Model discussion: topical details

- The next several slides look a little deeper into explanations, considerations and objectives that drive successful tool development

What is a stability “model”?

This seemingly simple question causes a lot of confusion

- Utilities represent their entire system in a simulation model (using software such as GE PSLF, or Siemens PSS/E ®, PowerFactory, or TSAT, or ....).
- This model is a mathematical representation of all components in the network, such as:
  - Generation (Thermal, Renewables, etc…)
  - Transmission (Lines, Transformers, FACTS, etc…)
  - Loads

For illustration, we’ll compare a “stability” ‘model’ to an EXCEL spreadsheet ‘model’

What is a ‘model’? continued

EXCEL: To solve problems in EXCEL , one needs:

1) A license to the software, sold by Microsoft (or ?)
2) A workbook file for the problem at hand, normally full of relevant data.
3) A library of built-in functions (e.g. SQRT, NPV, etc..). Users can’t change the function, but must give it input data to produce output.
4) Possibly some special MACROs, written to provide non-standard functions (e.g. tax depreciation on capital equipment in Elbonia). Users need the structure (code) of the macro AND input data.
5) Data to drive calculations, functions and MACROs

Stability Program: To solve problems in a “stability program”, one needs:

1) A license to the software, sold by commercial software vendor
2) A data set for the problem at hand (this is the grid “model”. The ‘workbook’)
3) A library of built-in functions (called “standard library models”), e.g. GENROU (for synchronous generators), IEEEST1 (for one standard type of excitation system), REGC_B (generic grid-following inverter for wind turbines)…. There may be thousands of these models in the grid model.
4) Possibly some special MACROs, written to provide non-standard functions (called “user-written models”), e.g. HVDC, special relays, and some wind turbine generators, battery energy storage systems, specialty relays,…)
5) Data to drive calculations, standard models, user-written models and ‘events’. Without data, the functions and MACROs don’t work. Thus, the data is part of the ‘model’.

So... Asking for “the” model isn’t sufficiently precise

Meaningful

Issues/Language:

- Are simulation tools producing results that sufficiently capture the important aspects of subject phenomena? i.e., are they “accurate”?
- Are the results misleading or incorrect, in that they could cause poor decisions?
- Are the tools looking at the “right” conditions? e.g, the limiting conditions that drive equipment specifications or investments?

IBR gaps:

- What is “sufficient” is poorly understood in many regards. i.e. “how accurate is good enough” is itself a research question. This issue applies to individual elements, and to aggregations and equivalents
- Requirements for “excessive” accuracy have caused their own pathologies
- IBR models are evolving. Differences between implementations (age, vendor, design) are bigger than with synchronous machines
- Modeling of distribution, especially with high IBR DER, is rudimentary at best. This is a major gap.
- Probability or stochastic capacity, i.e. the ability to move away from deterministic analysis, are increasing necessary to get meaningful answers

One reviewer observed: sufficiency of accuracy is related to the planning/operation decision to be made. If use of a more accurate model does not change the ultimate decision, then the more accurate model is not needed. The research aspect here is determining the level of accuracy that is needed. The same concept applies for aggregated models of distribution system and loads for transmission analysis.

Scalability

Issues/Language:

- Are simulation tools capable of handling the size model (e.g. number nodes, elements, participants,...)?
- Are the computer resources (e.g. simulation times) acceptable for practical problems?
- Are the datasets (and database structure) necessary manageable?
- Can the tools be adapted to the IT environment of the end user without undue misery?

IBR gaps:

- Evidence that computing times are unacceptably slow with
  - Complex loads models
  - Some specialty IBR models
  - Required short time steps (e.g. <5ms integration steps for phasor-tools)
  - With unduly complex IBR plant models (e.g. w/o equivalencing)
- Movement to more complex and complete modeling of distribution hugely increases dimensionality. Problems include:
  - Data handling; validation
  - Institutional interface (between T and D, for example)
- Some approaches today are so computation/data/user intensive, that too few “cases” are examined to make good decisions.
- Computational burden, usability with large EMT models extreme, unsustainable

Robust & User-Friendly

Issues/Language:

- Are simulation tools capable of handling the variety of inputs necessary for practical problems?
- Are the limits of the tools understood?
- Do the simulations run (i.e. not crash? ..)
- Are the tools intuitive?
- How onerous is the learning curve?
- Are there reasonable safeguards against poor data inputs?

IBR gaps:

- Stability models with composite loads are difficult to populate; to debug.
- Multiple IBR models, especially user-written models, are difficult to exchange, to debug, and tend to be poorly documented.
- Testing procedures for software and specific component models are inconsistent (even *ad hoc*)

These attributes are difficult to quantify and measure. But they are highly important according to the FSOs.

Discussion: Replacing Phasor-analysis with EMT

Discussion highly welcome here

There is broad consensus that EMT tools are a critical element in the tool arsenal for addressing IBR integration, especially in systems with high levels of IBRs (including approaching 100% instantaneous operation).

One approach being pursued by a few entities is to move from the "stability centric" environment around which this document is built, to an EMT centric model. i.e. one in which the core (majority?) of analysis is performed on EMT tools.

This is radical/fundamental paradigm shift, and carries a wide spectrum of issues and implications. Many of the challenges identified throughout this presentation apply here:

- Computational burden
- GIGO risk; data checking; human skills building
- Case paralysis (too few cases possible)
- Numerical stability
- Component model fidelity (esp. IBRs); model validation
- Component model transparency (access to innards)
- Case selection
- Result post-processing; what is learned? Are the results meaningful?
- Model reduction/equivalencing (with high IBRs)
- Time-scale (very small time step required; simulation duration – this is part of the computation burden issue)
- *And foundationally: "Even if we CAN move to an EMT centric environment, should we?"*

Glossary:

Discussion: Stochastics & Probability EMT

Discussion highly welcome here

- The industry has a long history of discomfort with deterministic analysis, in which a few individual snapshots of conditions are used as the basis for important planning decisions. With the grow of high variable and fundamentally stochastic resources (wind & solar), the angst has risen. This issue is much broader than IBRs, but some *inverter specific* aspects that (may) drive towards tools with more probabilistic capability include:

- Device performance differences for
  - Different point-on-wave inception of external event (e.g. fault timing)
  - When the resource is in (for example) current or voltage limits
  - Count and temporal separation of disturbance events (multiple fault ride-thru behavior)
- Systemic performance differences
  - Differences in multiple electrically proximate IBRs at/out of limits
  - Statistical expectations of protection performance (another point-on-wave issue)

IBR gaps/research topics:

- Which statistically variable considerations are important?
- For those, how to model them meaningfully, and in what tools?
- How to link this aspect of stochastic nature of the resources with broader planning considerations?

Appendix 2: Functional Specifications

Section break

This section contains a few deep dives into selected concept for addressing gaps that align with most the pressing concerns:

The detailed explorations give more context on the problem, and start to layout concepts for specific targeted tool research and development.

- Simulation confidence Meta-tool
- Stability models for GFM inverters

These examples are conceptual, and would/might be representative of follow-on from the inventory discussions

Simulation Confidence:

- This section is a deep dive into one concept for addressing one of the pressing concerns:

  How confident can we be in the stability simulations at the core of our studies?

- There is a need for meta-tools that help make sure that the tools (esp. the stability tools) are being used properly...
  Including:
  - When can you “trust” the tool(s)?
  - Help with both pre- and post- processing
  - Help with the GIGO problem.

- What limitations are “inherent” to the method vs. GIGO/bad driver problem?

Ideas on screening (for simulation fidelity)

(“Confidence in Stability* simulation”)

The idea is to provide guidance, in the form of rating for stability simulations. This concept recognizes that there are not crisp delineations, but rather a continuum of fidelities.

A framework - generic slider:

“my case”

High Confidence Simulations | Meaningful/Indicative Simulations | Misleading/Meaningless Simulations

Quantitatively meaningful results

- Results can be used with confidence to make operating and planning decisions
- Quantitative measures of behaviors, like swing amplitudes, damping, rates of change are within normally acceptable ranges of accuracy/confidence

Useful, but exercise caution

- Results will probably give meaningful indication of stable vs unstable.
- Exact behaviors, e.g. swings, amplitudes are approximate.
- Results probably not meaningful for specification of equipment, settings, protection
- This metric alone probably insufficient to determine usefulness of simulations

Highly suspect

- Results, if meaningful at all, are limited to qualitative insight.
- Relative behaviors may provide some useful guidance on necessary cases/investigations that use other (“physics”) tools

* See earlier discussion on the nomenclature of “stability” simulations

Input model/data attribute screening: before simulation evaluation

This is a conceptual illustration, showing how various physical attributes of the study system affect the expected fidelity of the stability simulations. A research project might include identification of key screening attributes

"my case"

eSCR: 5 | 2 | 1 | 0.5

"my case"

Compensation level:
- Minimal; shunt only
- Considerable static shut; dynamic shunt; distant series
- Heavily compensated; critical voltage approaching nominal; series nearby
- Radial through series; critical voltage at or greater than nominal

"my case"

Transfer stress:
- Relatively short; transfers near SIL;
- Moderate distances; transfers less than ~2 SIL
- Long-distances; transfers above 2 SIL

Quantitatively meaningful results | Useful, but exercise caution | Highly suspect

Glossary:

Simulation output screening: post-simulation evaluation

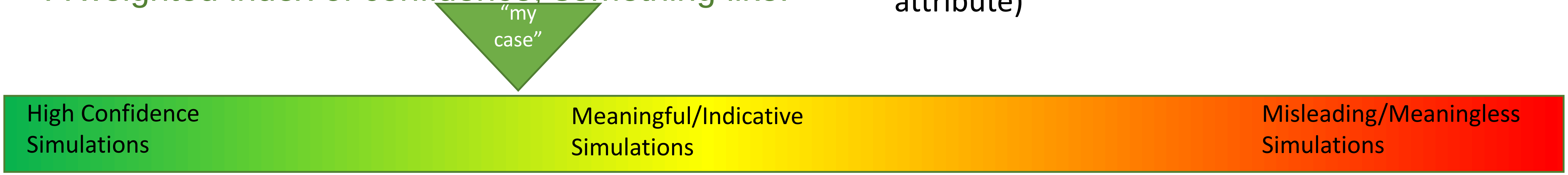
- How might someone using stability simulations determine how confident they are in the results, after fact?
- For example: What behaviors in simulations are (might be?) indicative of “good” runs, bad runs...
- Maybe a “key” (of the variety used for species identification), or similar “wishbone” FMEA techniques could be used:
  - Qualitative behaviors to look for (these are examples that push results into the “red”):
    - Crashes on fault application: result probably meaningless; possibly indicative of high stress
    - Oscillations > ~4 Hz: frequency: frequency meaningless; possibly indicative of converter control stability
    - Voltage swings > ~1.6pu: quantitatively meaningless; possibly indicative of control or compensation problem.
    - Etc... (this could and should go on for a while!)

Glossary:

How might one use multiple indices?

- A weighted index of confidence, something like:

Score = $\Sigma A_i * W_i$ (weighted score for each attribute)



- Additional rules:
- Presumably, if any attribute is in the red; forget it. could be built into the weighting function. Go to other tools (e.g. EMT)
- If everything is green; proceed with gusto.
- If there’s a mix, or significantly in the yellow. Proceed cautiously, get some calibration runs made with EMT or other physics tools; be more skeptical of results (see next page).
- This could be something like a fancy spreadsheet. Don't want to create a monster. Would also need to have the weights be easily adjusted by user.
- Would anybody really use it?
- A well-designed R&D project could address these concerns

How might such a tool be calibrated/validated?

This is illustrative; would require considerable refinement to be useful.

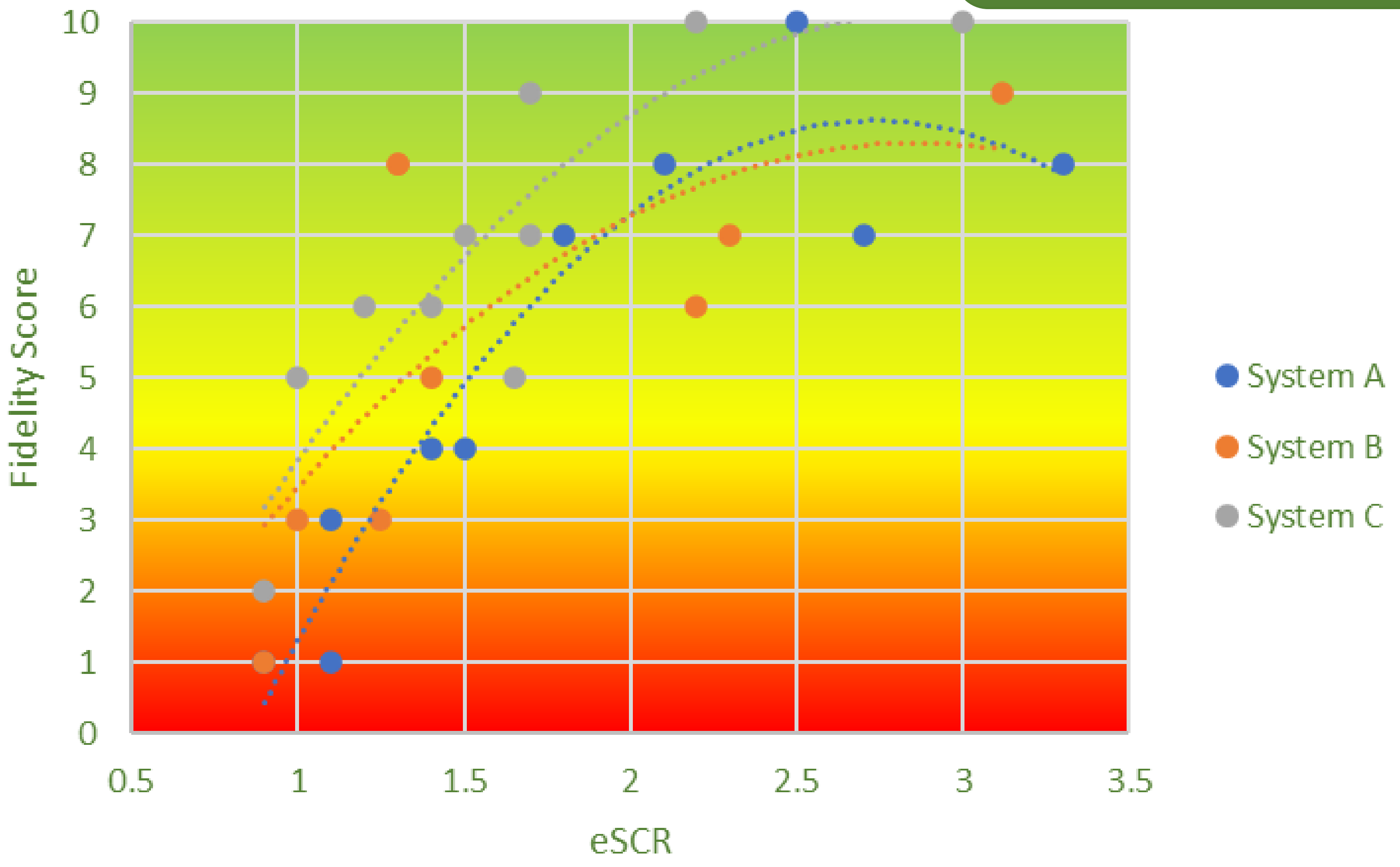
- The idea would be to do EMT, HIL or other high fidelity case work on a variety of systems with different attributes.
- Run comparison cases over a spectrum of those attributes within the study system (I've used eSCR to illustrate)
- Evaluate the fidelity of each case, using a weighted score based on something like this spread sheet
- Look for confidence rules to be extracted. See next page.

Simulation Attribute		Score Meaning			
Stability Prediction		10	7	4	1
	Stable/Not	Correctly Predicts		correct, but poor correlation	incorrect
	Time of Instability		within a second, within a swing cycle	substantively different timing	
	Cause of Instability		correct mechanism, but poor quantitative match	grossly indicative	wrong or missed mechanism
Post-fault swings		Correct within tight tolerance	Directionally correct; adequate for evaluation	Grossly correct, but misleading	Garbage
	Frequency				
	Amplitude				
	Phase				
Post-fault recovery		Correct within tight tolerance	Directionally correct; adequate for evaluation	Grossly correct, but misleading	Garbage
	P recovery time				
	Q recovery time				
	V recovery/overshoot				
During Fault		Correct within tight tolerance	Directionally correct; adequate for evaluation	Grossly correct, but misleading	Garbage
	Current delivery magnitude				
	Voltage level				

Last slide (for now) of “Simulation Confidence” concept presentation

Return to simulations environment

Return to Functional Specifications



Rank & Weight Specific simulation performance attributes

Do something like this for each major screening attribute

Use results to calibrate sliders and help new user to figure where their system falls in each attribute

(I suspect that some of this has been done. By whom?)

Stability models for GFM inverters

Background

- Stability models for GFM are essential and are presently in the early stages of development.
- FSOs need models that have good attributes.

SOA/Status:

- Who is working on this now?
  - EPRI/PEACE/WECC (?)
  - NREL (?)
  - S/W+OEMs:
    - Siemens-PTI, Siemens-Gamesa?
    - GE ?
  - Other OEMs
  - Other S/W vendors
    - DigSilent?
    - PowerTech?
    - PowerGEM?
  - EirGrid?
  - AEMO?
  - ENTSO-E, Migrate, ... ???

R&D needs:

- Model structure that can adapt (GFM is far from settled art)
- Validation (against EMT? HIL? Field measurements? Staged, actual events? Other)
- Standardized input data
- Methods to obtain input data
- Reconciliation of different nascent concepts/model designs

This is a rough draft

In the follow-on work, I envision several individual "packages" of slides that pick up on a gap from the tools inventory, and describe the need, application and outline of the research needs. Maybe 3-5 slides per "project"

Return to simulations environment

Return to Functional Specifications

Stability models for GFM inverters

Closure...

Placeholder:
I envision a slide with the outline of a “project” to address the needs and status provided in the preceding slide.

Return to simulations environment

Return

Chronology Concepts for Reliability Programs

Notes:

Reliability tools that a built around statistical expectation of coincident stresses; i.e. high demand and high forced outages (to greatly simplify), tend to use random draws and other techniques that fail to capture sequential or time dependence of resource availability (and load for that matter). There is some consensus that this approach is increasingly unacceptable, and a variety of work is being done to add temporal or sequential considerations. This needs to be documented, and inspected with a view towards identifying development and conceptual gaps.

Placeholder:
This is important.
Whether it is an IBR centric topic is debatable.

Supporting Materials

Section break

This section contains various support information that is accessed by hyperlinks.

The reader is welcome to look, but the individual slides generally lack context

Acronyms

- AI: Artificial intelligence
- BPS: Bulk power system. The "grid", usually all major generation, EHV transmission and infrastructure.
- DAE: differential algebraic equations. In context where DEs then AEs are usually solved in some iterative and sequential fashion, as is the case with stability programs
- DER: Distributed energy resources
- EMT: electro-magnetic transient. A class of simulation with individual phases and explicit representation of AC waveforms
- EPRI: Electric Power Research Institute
- ERS: Essential reliability services (aka "ancillary services")
- FMEA: Failure Mode and Effects Analysis
- FSO: Founding system operators.
- GFL: grid following (as opposed to grid forming) inverters
- GFM: grid forming inverters
- GIGO: "garbage in, garbage out". Use of bad input data will result in poor outputs from simulation tools
- GPST: Global Power System Transformation
- IEEE: Institute of Electrical and Electronic Engineers
- IRP: Integrated resource plan
- NERC: North American Reliability Corporation. The reliability entity for North America
- POW: Point-on-wave
- PQ: Power Quality
- PU: per unit
- PRM: Planning reserve margin
- RCA: Root cause analysis
- RFP: Request for proposal
- RTS: Real time simulator
- SIL: Surge impedance loading. The "natural" power carrying ability of an AC line.
- SOA: "state-of-the-art"
- TNA: transient network analyzer. Analog predecessor of EMT simulation tools
- WECC/IEEE: US Western energy Coordination Council. Has lead US activities in development of generic phasor-based stability models for GFL IBR, including wind and PV.
- WTG: wind turbine generator

Glossary:
Definitions and other language clarifications

Much terminology in this field is non-standard. Definitions may not exist, and in many cases, descriptions have different regional meanings. Some relevant items are addressed here:

- **Interconnection study**. This language usually applies to the connection of a single resource (e.g., one VER plant) to a grid, and covers the specialized analysis for that purpose. This is distinct from **"Integration study"** which usually means a systemic investigation with many resources (e.g., an X% wind & solar future...)
- **ERS procurement**. Essential Reliability Services, aka "Ancillary Services" are in some cases procured through market mechanisms. Others are procured through mandated behaviors or by imposing operating constraints that "cause" the service to be provided when necessary (often without compensation to the provider)