INTEGRATED PLANNING VIRTUAL WORKSHOP

Ensuring Stability in Modern Power Systems

Workshop Organizers

Energy Systems Integration Group and Breakthrough Energy

Presenters

Nicholas Miller, HickoryLedge
Sam Maleki, Electromentors
Alex Shattuck, Energy Systems Integration Group
Carlo Brancucci, encoord Inc.
Wallace Kenyon, encoord Inc.

September 15–16, 2025

ESIG
ENERGY SYSTEMS
INTEGRATION GROUP

About the Energy Systems Integration Group

The Energy Systems Integration Group is a nonprofit organization that marshals the expertise of the electricity industry's technical community to support grid transformation and energy systems integration and operation. More information is available at https://www.esig.energy or info@esig.energy.

ESIG Publications Available Online

This workshop summary is available at https://www.esig.energy/reports-briefs/workshop-summary-integrated-planning. All ESIG publications can be found at https://www.esig.energy/resources/reports-and-briefs.

Disclaimer

The meeting organizers made every effort to accurately convey the points made by the participants. Any incorrect or misheard statements are the responsibility of the organizing team.

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Workshop Overview

This virtual workshop was held on September 15 and 16, 2025, with 230 participants from 21 countries and regions including Africa, South America, Australia/New Zealand, East and South Asia, Europe, and the Caribbean.

The September 2025 workshop is the fourth in the series, following three Integrated System Planning Workshops that took place between October 2024 and April 2025. The three previous workshops focused on key concepts for successful integrated planning from the perspective of different industry stakeholders including capacity expansion and the emerging arsenal of tools and techniques that support the necessary spectrum of analyses.

The September workshop expanded on these topics by providing technical details on planning power systems with high levels of inverter-based resources (IBRs) including fundamentals for power system dynamics, power system voltage and frequency stability, modeling and studying in the new paradigm, and what system conditions can be studied and with which tools. Recordings and workshop materials for the September workshop as well as the previous workshops can be found on the ESIG Integrated Planning Forum web page.[1]

The presenters were:

Nicholas Miller, HickoryLedge
Sam Maleki, Electromentors
Alex Shattuck, Energy Systems Integration Group
Carlo Brancucci, encoord Inc.
Wallace Kenyon, encoord Inc.

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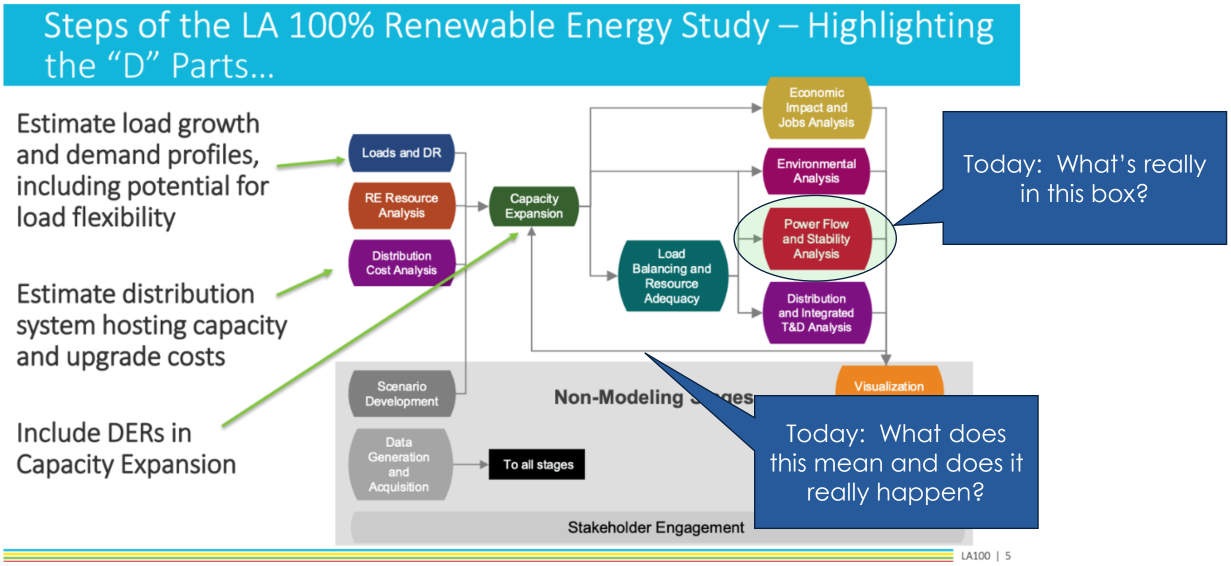
[1] https://www.esig.energy/working-groups/system-planning/integrated-system-planning/

Introduction

Nick Miller introduced the workshop and described how the focus was to emphasize power system stability and its relationship to the integrated planning processes examined in the preceding integrated planning workshops. The intent was to illuminate the often highly specialized issues associated with ensuring system stability, and to examine how they impact broader integrated planning decisions.

Nick started with discussion of the central focus of resource planning, in which processes (as described in the earlier workshops) determine the adequacy of energy and power supply over relatively long time periods, ranging from individual hours to seasons, years and even longer. He reused one of the process charts from the LA100 study[2] presented in November 2024 to draw attention to the present practice wherein stability issues, as they affect system reliability, and therefore the viability of any integrated plan, are normally toward the end of a long, laborious process. Nick's annotations to the National Renewable Energy Laboratory's (now the National Laboratory of the Rockies) figure point to the focus of the webinar (Figure 1).

FIGURE 1



Steps of the LA 100% Renewable Energy Study – Highlighting the "D" Parts…

Estimate load growth and demand profiles, including potential for load flexibility

Estimate distribution system hosting capacity and upgrade costs

Include DERs in Capacity Expansion

Today: What's really in this box?

Today: What does this mean and does it really happen?

Source: Paul Denholm, "Overview of NREL's Approach to Integrating Distribution-Sited Resources in the LA100 Study," https://www.esig.energy/presentation/ip-workshop-overview-of-nrels-approach-to-integrating-distribution-sited-resources-in-the-la100-study-paul-denholm/?wpdmdl=12195&refresh=671fa490f02c01730126992

He described how the complex and often arcane analyses that take place at this stage can be quite opaque to practitioners focused on big-picture policy and resource mix issues. The reality is that stability analysis is normally something of an afterthought.

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[2] National Laboratory of the Rockies, n.d., "LA100: the Los Angeles 100% Renewable Energy Study and Equity Strategies," https://maps.nlr.gov/la100/#home-1.

This introduction set the stage for the balance of the webinar where speakers explored why ensuring stability is essential; how workshop information should be aimed at helping non-specialists better understand the basics of system stability; why the challenges of ensuring system stability have changed—especially through the filter of greatly increased IBRs such as wind, solar, and batteries; and how a more holistic, inclusive process can result in better decisions and outcomes.

Spain/Iberia Blackout of April 28, 2025

Nick continued, speaking about how a severe failure to maintain system stability resulted in the blackout of the entire Iberian Peninsula earlier in 2025. There were high human and economic costs associated with this widely publicized event. Nick presented a high-level synopsis of the incident, viewed through the filter of its implications for policy and integrated planning here. In short, this event has cautionary lessons that can be applied to all large interconnections and provides a highly tangible example of why we, as an industry, must care about stability (Figure 2).

The blackout occurred on a day when about 75% of the power needs of Spain were being provided by renewable generation—mostly solar. Spain was exporting power to its neighbors. The operating condition, while having quite high levels of renewables, was representative of most days in April, with only minor obvious differences from many previous days. But at midday, system operators in Spain and across western Europe observed oscillations in frequency and voltage. Some aspects of the oscillations were familiar, others less so. As is often the case with these phenomena, they start and stop without obvious cause, but tend to be associated with certain stress conditions. In this case, experience (operational and analytical) suggested that reducing exports from Spain would mitigate this intermittent problem. Operational actions were taken to do so. Shortly thereafter, about 12 minutes after the last oscillations observed had self-extinguished, a sequence of generator trips in Spain caused acute imbalance between Iberia and the neighboring system, and consequent separation from the rest of continental Europe. The generator trips cascaded into broad system failure and collapse.[3]

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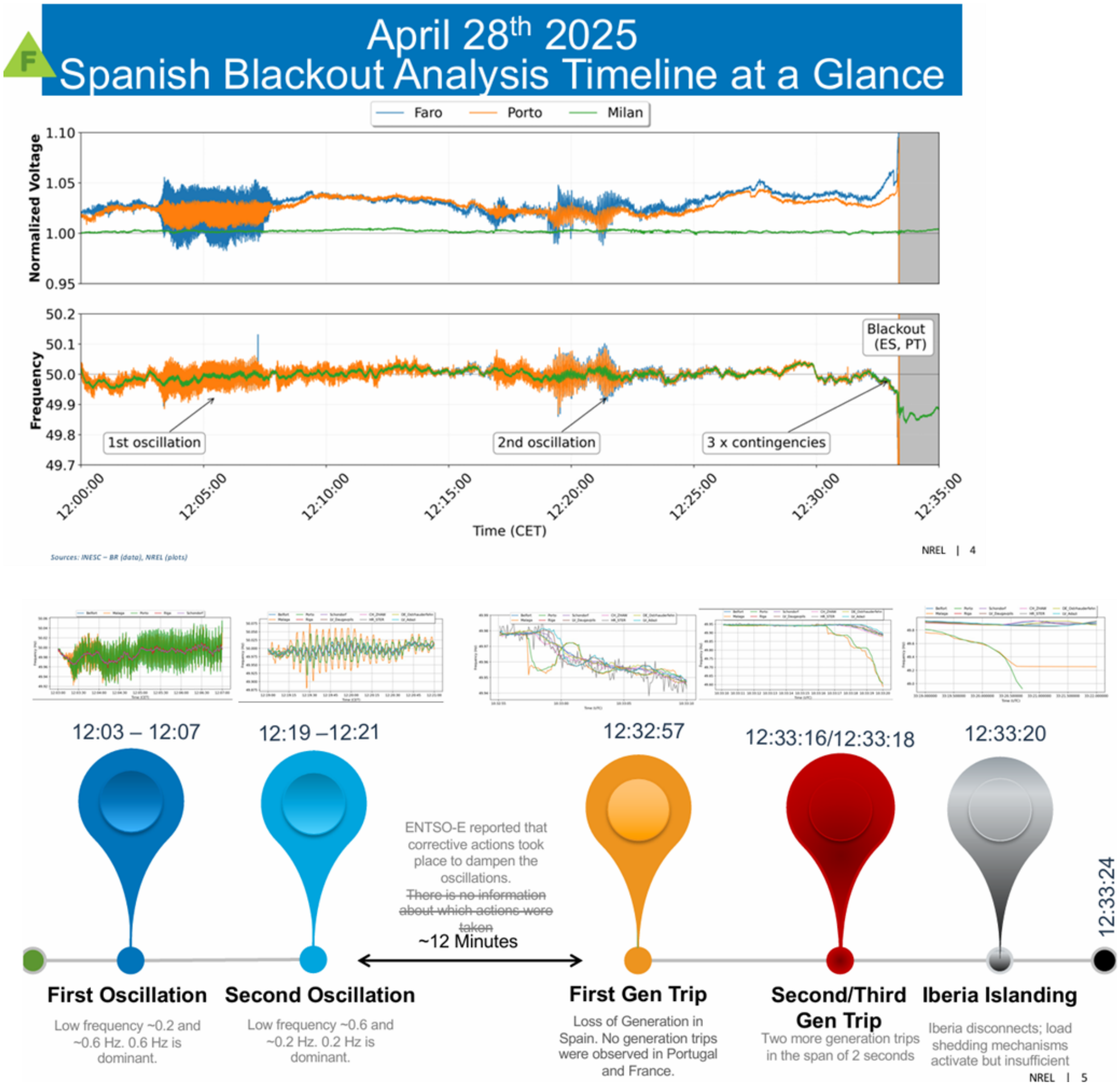
[3] The workshop presentation is a highly simplified synopsis; more detailed information was consulted in the formulation of this talk, including an excellent NREL presentation which included this figure (https://docs.nlr.gov/docs/fy25osti/95103.pdf) and official reporting from Europe (https://www.entsoe.eu/news/2025/05/09/entso-e-expert-panel-initiates-the-investigation-into-the-causes-of-iberian-blackout/).

FIGURE 2



April 28th 2025
Spanish Blackout Analysis Timeline at a Glance

Sources: INESC – BR (data), NREL (plots)

NREL | 4

12:03 – 12:07

First Oscillation

Low frequency ~0.2 and ~0.6 Hz. 0.6 Hz is dominant.

12:19 –12:21

Second Oscillation

Low frequency ~0.6 and ~0.2 Hz. 0.2 Hz is dominant.

ENTSO-E reported that corrective actions took place to dampen the oscillations.
~~There is no information about which actions were taken~~

~12 Minutes

12:32:57

First Gen Trip

Loss of Generation in Spain. No generation trips were observed in Portugal and France.

12:33:16/12:33:18

Second/Third Gen Trip

Two more generation trips in the span of 2 seconds

12:33:20

Iberia Islanding

Iberia disconnects; load shedding mechanisms activate but insufficient

12:33:24

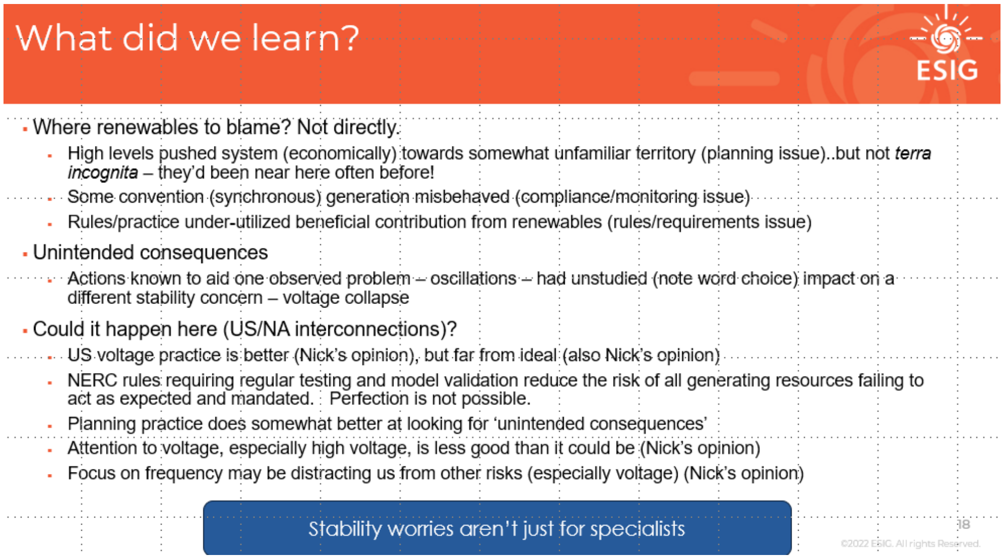
NREL | 5

Source: https://docs.nlr.gov/docs/fy25osti/95103.pdf

The presentation examined the public response to the event, noting that long before any credible forensics had been performed to determine the actual cause of the blackout, sweeping judgments about renewable energy policy were being made. The absence of facts did little to restrain some voices declaring renewables and “lack of inertia” to be the root cause.

Subsequent forensics (which are still continuing) indicate that loss of voltage control and resultant high voltages on the bulk power system were at the core. A combination of somewhat unusual operating condition, misbehavior of some conventional synchronous generation, and reactive power management practice in Spain all contributed. Lack of inertia did not. As always, the issues are complex and somewhat nuanced. Nick's closing slide captured his key takeaways (Figure 3).

FIGURE 3



What did we learn?

- Where renewables to blame? Not directly.
  - High levels pushed system (economically) towards somewhat unfamiliar territory (planning issue)..but not *terra incognita* – they'd been near here often before!
  - Some convention (synchronous) generation misbehaved (compliance/monitoring issue)
  - Rules/practice under-utilized beneficial contribution from renewables (rules/requirements issue)
- Unintended consequences
  - Actions known to aid one observed problem – oscillations – had unstudied (note word choice) impact on a different stability concern – voltage collapse
- Could it happen here (US/NA interconnections)?
  - US voltage practice is better (Nick's opinion), but far from ideal (also Nick's opinion)
  - NERC rules requiring regular testing and model validation reduce the risk of all generating resources failing to act as expected and mandated. Perfection is not possible.
  - Planning practice does somewhat better at looking for 'unintended consequences'
  - Attention to voltage, especially high voltage, is less good than it could be (Nick's opinion)
  - Focus on frequency may be distracting us from other risks (especially voltage) (Nick's opinion)

Stability worries aren't just for specialists

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Source: Nicholas Miller.

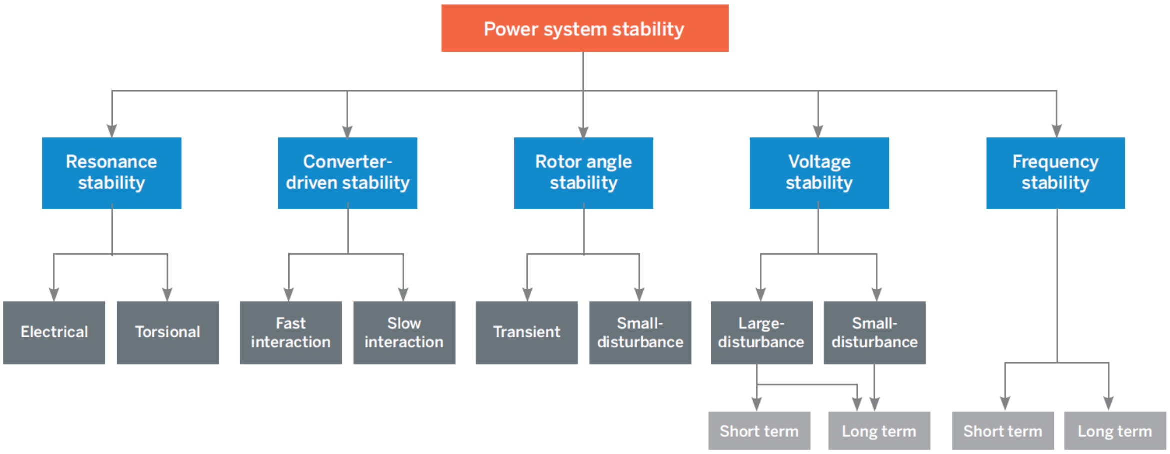
Introduction to Fundamentals of Stability and Power System Dynamics

With the Iberian Blackout example, Nick introduced some of basic concepts that guide practice for ensuring stability. Importantly (and stripped of all nuance), the basic tenet of stability planning can be summarized as "We live in an N-1 world." There are North American Electric Reliability Corporation (NERC) rules (and a world of detail), but simply put, "N-1" means the system must tolerate the loss (trip, failure, removal, etc.) of *any* single element, and exhibit acceptable behavior without human intervention.

The art and science of power system stability is complex. Figure 4 from IEEE reflects an industry view of technical constituents of power system stability. Each of the boxes has a vast set of issues and supporting practice, many of which are evolving as technology changes. Further, the parsing of system dynamics into these boxes is actually very messy: practical issues cut across several boxes and often defy simple characterization. Nevertheless, a power system that isn't stable isn't viable, regardless of how good the integrated plan is in other aspects.

FIGURE 4

IEEE Stability Classification Hierarchy



Source: N. Hatziargyriou et al. "Definition and Classification of Power System Stability—Revisited and Extended," *IEEE Transactions on Power Systems* 36(4)(2021): 3271–3281 (https://doi.org/10.1109/tpwrs.2020.3041774); reproduced in https://www.esig.energy/reports-briefs/oscillations-guide/.

Of particular importance today is the fundamental truth that IBRs (wind, solar, batteries, data centers, etc.) behave differently, and consequently introduce new stability issues and change existing ones (often beneficially). Interaction between many inverters adds huge complexity. Big rating devices (huge solar and wind farms, HVDC, and now, mega data centers) are of particular concern. Possible grid topologies are more complex and varied.

While all the issues in the figure must be satisfactorily addressed, it is voltage and frequency stability (on the RH side of the figure) that tend to be central when really big, societally disruptive, stability failures occur—as we saw in Iberia.

Fundamentals of Voltage Stability

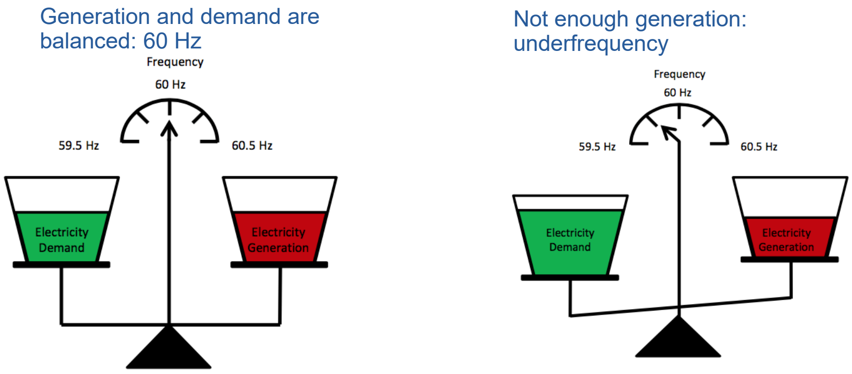
Sam Maleki began with a discussion of voltage and reactive power. He noted that "'normal' people do not like to think about 'imaginary' power, i.e., 'reactive' power (a.k.a. 'Q,' a.k.a. 'VARs')." But it is easy to understand that keeping the voltage everywhere within acceptable bounds is important. He discussed how "acceptable" is complicated, but most of the time it means keeping the voltage to within about +/-5% of "nominal." Maintaining voltage stability is a subset of that practice where we make sure that departures from normal do not progress toward higher or lower values in an uncontrolled and unbounded fashion.

The tools and practice to achieve that end-all depend on successful management of reactive power. There are limits beyond which maintaining voltage becomes impossible. Sam presented a classic illustration of voltage stability as a function of power transfer level. This “nose curve” shows how, for a given topology, voltage (y axis) drops with increasing power (x axis), reaching a maximum—the “nose” beyond which it is impossible to push power. The talk examined ways to determine these limits, increase the limits, and detect when the system is approaching the limits, and how various resources—both generation and grid assets—affect them.

Fundamentals of Frequency Stability and Dynamics

Maintaining system frequency is as important as maintaining acceptable voltage. Sam started with the well-known balance beam analogy of system frequency, showing how load and generation must be kept in balance at all times (Figure 5).

FIGURE 5



Generation and demand are balanced: 60 Hz

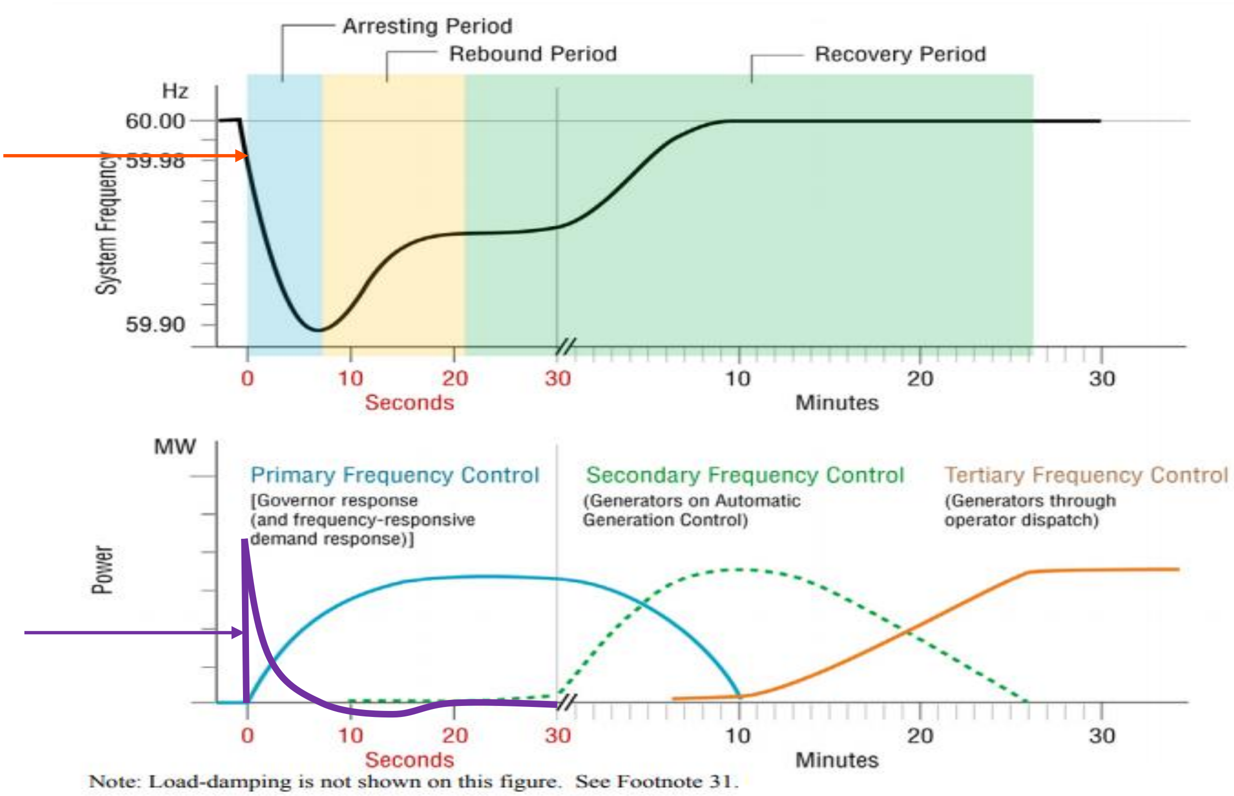
Not enough generation: underfrequency

Source: N.W. Miller et al., *Western Wind and Solar Integration Study Phase 3—Frequency Response and Transient Stability: Executive Summary*, National Renewable Energy Laboratory (2014), https://docs.nrel.gov/docs/fy15osti/62906-ES.pdf.

The imagery is useful, but does not reflect the physical reality that maintaining this balance covers a time scale ranging from cycles to minutes, with different physical behaviors of system assets changing character and importance over those time frames.

Sam presented a widely used LBNL figure (with some annotations) that captures the important time scales for maintaining frequency (Figure 6). The original LBNL figure focused on the provision of frequency services used to maintain frequency. The original figure lacked the annotation for system inertia (shown in purple). This has important practical implications. Historically, inertia was an uncontrolled consequence of system operation—varying with the commitment of synchronous generation dispatched to meet load demand. Inertia has never been a “service” as such, but rather another parameter of system operation, like transformer or line impedance. Inertia (purple arrow) is one factor that affects how quickly frequency changes (red arrow) following a disturbance that removes generation (or load).

FIGURE 6



Source: Adapted from Joseph Eto et al., *Use of Frequency Response Metrics to Assess the Planning and Operating Requirements for Reliable Integration of Variable Renewable Generation* (2010), https://eta-publications.lbl.gov/publications/use-frequency-response-metrics-assess.

Lower inertia means, all other things being equal, that frequency drops faster, requiring faster actions to arrest the fall of frequency and keep the frequency swing within acceptable bounds. But things are never equal Sam presented an exercise showing that the *size* of a disturbance, for example, may have a much bigger impact on frequency change. The balance of the illustration showed that controlled response to the frequency change, especially primary frequency response, is critical to success. In short, inertia is a factor, but only one. He closed with the admonition that using “inertia” as shorthand for all the issues associated with maintaining frequency is misleading and ill-advised.

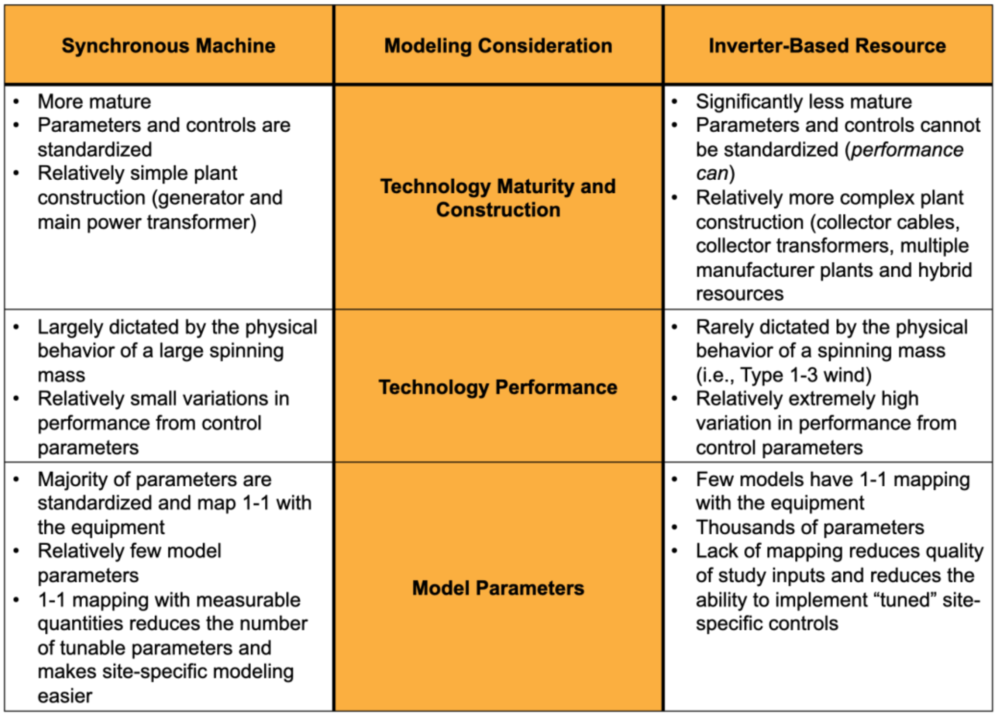
Planning (and Modeling) of IBR-Dominant Systems: What Is Different?

Alex Shattuck delved into important and specialized considerations for IBR-dominant systems, building on the fundamentals presented the previous day. Inverter-based resources, including solar photovoltaics, wind generation, battery energy storage, HVDC, and variety of transmission enhancing technologies, as noted on the first day, all exhibit quite different behaviors in the time frames of interest for system stability.

Alex showed a synopsis of 10 major disturbance reports published by NERC since 2016. In each event, IBRs failed to continue delivering power to the grid in response to normal design-basis grid disturbances. NERC forensics showed that none of the affected facilities in any of these published reports had models that accurately reflected actual performance. The present reality is that the motivations for IBR interconnection are not aligned with grid reliability. Current regulatory structure promotes disparate, misaligned, and sometimes confusing requirements, and stakeholder-driven processes have failed to produce sufficient technical minimum performance requirements. After many reports in 2023, NERC produced the following declaration: “This report shows that the voluntary recommendations set forth in NERC guidelines and other publications are not being implemented.”[4]

Alex discussed a dozen different dynamic performance issues and the alignment of IBR performance within the various simulation tools needed to produce meaningful results—i.e., results that will guide good decisions on infrastructure and system limitations. In each case, the differences between existing synchronous resources and IBRs can be substantial (Figure 7).

FIGURE 7



Synchronous Machine	Modeling Consideration	Inverter-Based Resource
• More mature • Parameters and controls are standardized • Relatively simple plant construction (generator and main power transformer)	**Technology Maturity and Construction**	• Significantly less mature • Parameters and controls cannot be standardized (*performance can*) • Relatively more complex plant construction (collector cables, collector transformers, multiple manufacturer plants and hybrid resources
• Largely dictated by the physical behavior of a large spinning mass • Relatively small variations in performance from control parameters	**Technology Performance**	• Rarely dictated by the physical behavior of a spinning mass (i.e., Type 1-3 wind) • Relatively extremely high variation in performance from control parameters
• Majority of parameters are standardized and map 1-1 with the equipment • Relatively few model parameters • 1-1 mapping with measurable quantities reduces the number of tunable parameters and makes site-specific modeling easier	**Model Parameters**	• Few models have 1-1 mapping with the equipment • Thousands of parameters • Lack of mapping reduces quality of study inputs and reduces the ability to implement “tuned” site-specific controls

Source: Energy Systems Integration Group.

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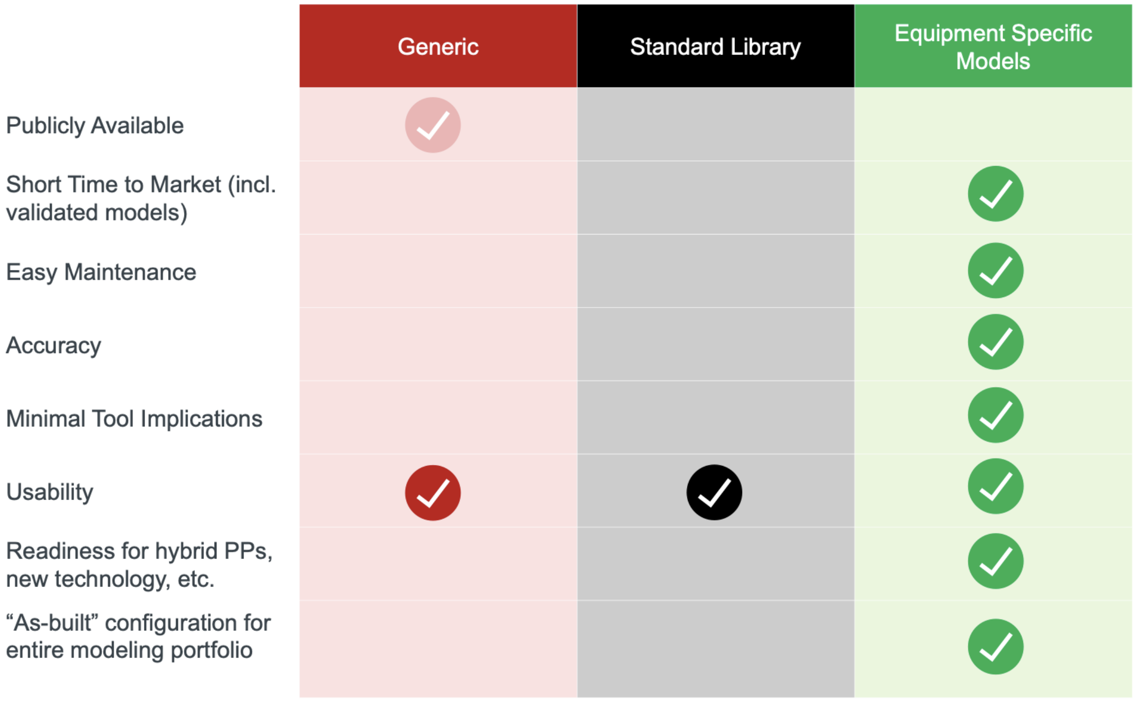
[4] NERC, 2023, *Inverter-Based Resource Performance Issues Report: Findings from the Level 2 Alert*, https://www.nerc.com/globalassets/our-work/reports/white-papers/nerc_inverter-based_resource_performance_issues_public_report_2023.pdf.

The overarching theme is that behavior of IBRs is dominated by inverter controls rather than the underlying physics that govern much of the behavior of synchronous machines. The result is a much wider range of possible behaviors and the possibility that behaviors can be substantially altered by small (i.e., software or parameter) changes. Alex went on to explore why getting good models of IBRs is so challenging, enumerating technical, economic, commercial and regulatory hurdles that need better resolution. The primary challenge, and root cause to modeling deficiencies in North America, is the requirement or strong incentivization for the usage of standard library models in lieu of detailed vendor-specific models. Only a very small number of transmission system operators in North America allow the submission and usage of vendor-specific models. This creates both mandatory and perceived requirements that only standard library models may be used to represent IBR plants. Standard library models are not recommended by any of the major renewable energy original equipment manufacturers and these manufacturers have made statements to this effect in public and on the federal record.

Failure to allow and utilize vendor-specific models when representing IBR plants creates an inability to represent the actual performance of the IBR plant or any of the manufacturer-specific advanced controls. This lack of accuracy and inability to represent actual equipment capabilities and advanced controls can lead to both false-positive and false-negative study results. This means that the studies will just plainly be wrong, with no way to determine whether the error is conservative or not. In other words, modeling without vendor-specific models and site-specific parameters (which can only be accurately mapped in vendor-specific models) can both lead to erroneous transmission upgrades or mask real and installed problems; the latter is evidenced by the numerous NERC major disturbance reports and three IBR-related NERC alerts (Figure 8).

FIGURE 8



	Generic	Standard Library	Equipment Specific Models
Publicly Available	✓		
Short Time to Market (incl. validated models)			✓
Easy Maintenance			✓
Accuracy			✓
Minimal Tool Implications			✓
Usability	✓	✓	✓
Readiness for hybrid PPs, new technology, etc.			✓
“As-built” configuration for entire modeling portfolio			✓

Source: Vestas. Presented by Vestas at the NERC IRPS Meeting, February 15, 2024.

One aspect of the regulatory and practice challenges that are particularly germane to system reliability, and which entered into the Iberian Blackout example, is that a range of functional capabilities that are enabled by the extreme agility and flexibility of IBRs are often underutilized. Alex showed capability for primary frequency response and advanced frequency controls, reactive power supply capability and accompanying advanced voltage controls, and weak grid support features—all of which are commercially available today and each of which face hurdles to be fully used and integrated into today’s systems.

What Condition Is Being Studied and with What Tools? Toward More Holistic Planning

The final content of the webinar was presented by Carlo Brancucci and Wallace Kenyon of encoord Inc., where they brought together the challenges previously presented with a view toward improving the linkage and feedback between economic and reliability planning as well as the imperative of testing if economic solutions are operationally stable. They started with discussion of the institutional reality that resource planners and transmission planners tend to inhabit separate organizational and technical worlds. As a result, practice and language are often disconnected or even at cross purposes. The natural first step, then, taken by Carlo and Wallace, was describing the motivating factors and technical landscape.

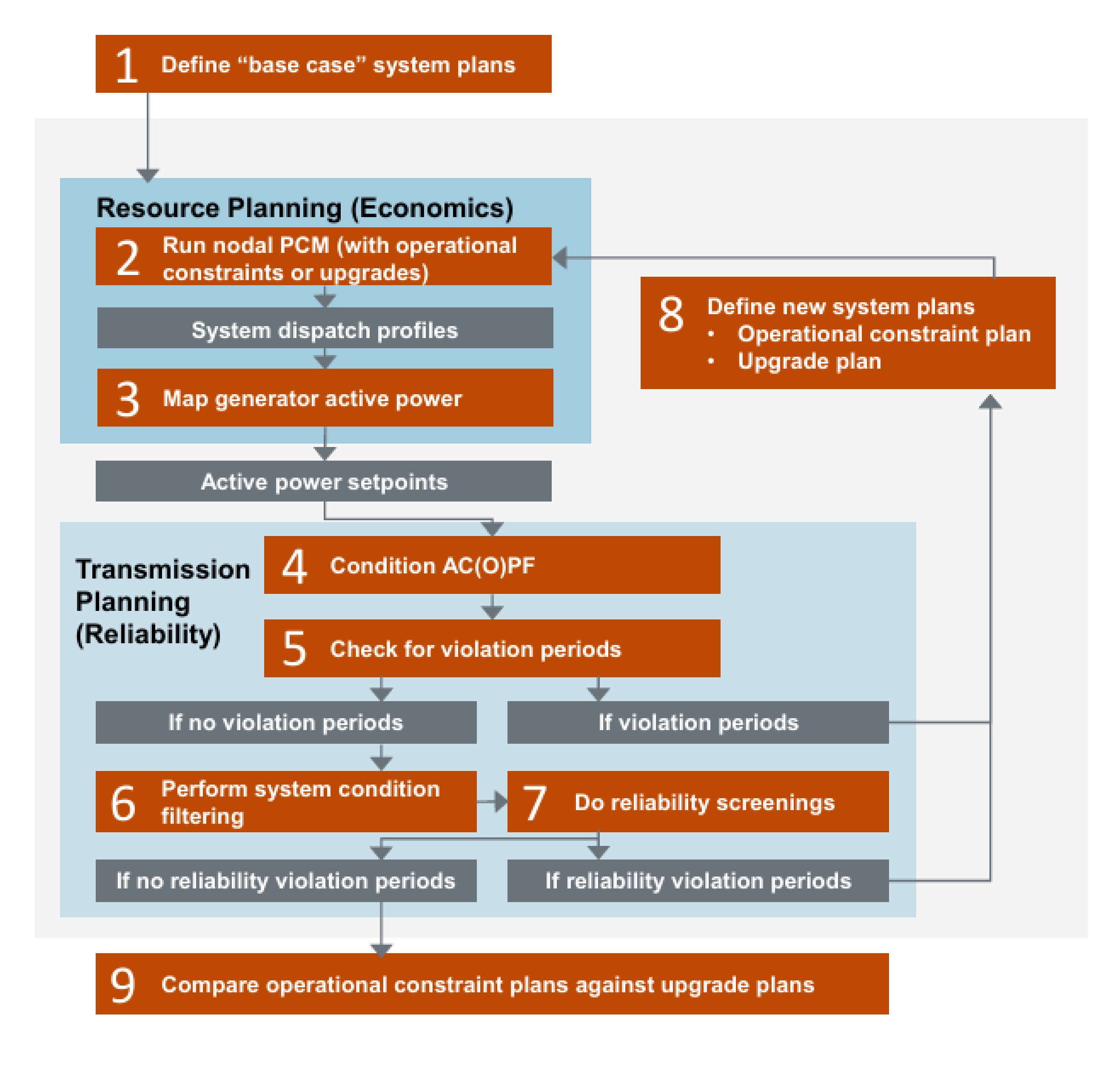
Resource planning, especially generation planning, faces development of generation and storage assets to ensure an adequate, reliable, and least-cost electricity supply. Good practice develops multi-year scenarios with a variety of projections for demand growth, technology and fuel costs, policy drivers, and weather variability. A range of capacity expansion tools (as presented in earlier Breakthrough IP lectures) typically use hourly resolution (8760/year) simulations with probabilistic and production cost tools applied to quantify risks of unserved demand and system costs considering a range of portfolios and scenarios.

Transmission planning, on the other hand, is intended to ensure the reliability and stability of the high-voltage bulk power system through current, and future, and infrastructure assessments. Once again, scenarios are used, but they focus on operational and future scenario snapshots of a very small subset of the hours considered in resource planning. Focus is typically aimed at coincident loading, such as peak, shoulder, and at-risk operational periods, to name a few. For each, a range of static and dynamic tools are applied with strict methodologies to judge the operational security of the system in each respective period.

Practice today extracts constraints, such as interarea power exchange limits, from analysis of these snapshots and applies them to full (8,760/hour) years for analysis by resource planners. Historically, this sequential approach has worked reasonably well. But with the growth of more complex systems, including multidirectional flows, weather-dependent variable resources, highly distributed resources, and a broader range of transmission technologies, the cost of this sequential, siloed approach applying non-varying limits for annual analyses becomes significant. Major unforeseen reliability risks may exist in selected futures if there is a limited consideration for a wider range of operational snapshots. Furthermore, addressing these transmission constraints in a near-term, reactive fashion may have a significant impact on the economics of renewable generation and storage.

As the grid transforms, integrated planning is key to delivering reliable, affordable power under increasingly complex conditions. Carlo and Wallace presented an approach that more tightly and recursively connects these pieces of analysis between the resource and transmission planning activities. The individual steps, presented in detail in the webinar and extensively described in the *Integrated Planning Guidebook*, employ the traditional planning tools and approaches but position them within a framework that is more amenable to feedback between the planning domains (Figure 9). As a result, a more meaningful economic evaluation of identified technical constraints can be exercised, which permits a more rigorous analysis of the value in relieving them.

FIGURE 9



Source: Energy Systems Integration Group, *Integrated Planning Guidebook: A Practical Coordination Framework for Electricity Planners* (2025), https://www.esig.energy/reports-briefs/integrated-planning/

In summary of the two days, it was shown that new frameworks can lay the foundation for meaningful and fruitful coordination and iteration between historically disparate silos. The emphasis was producing benefits, in terms of quantified economic and reliability tradeoffs, with the potential to optimize investments across generation and transmission, and to identify most reliable, cost-effective solutions. The process can uncover new stress periods and expose hidden reliability risks or constraints.

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Ensuring Stability in Modern Power Systems

This workshop summary is available at https://www.esig.energy/reports-briefs/workshop-summary-integrated-planning

To learn more about work being done in this area, please send an email to info@esig.energy.