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THE PRIMARY OBJECTIVE OF A POWER SYSTEM IS TO safely provide reliable energy services to society at an affordable cost. In many countries, this objective has been supplemented by another: meeting the energy demand with sustainable resources, which has culminated in the energy transition to low-carbon and zero-carbon energy systems. This transition, occurring rapidly around the world, is characterized by the increasing penetration of variable renewable energy (VRE), inverter-based resources (IBRs), and distributed energy resources (DERs).

Enabling Power System Transformation Globally

A System Operator Research Agenda for Bulk Power System Issues

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While contributing toward sustainability goals, these trends can potentially compromise the primary objective of a power system given existing planning and operational paradigms. To continue to meet the primary objective as power systems transition, advances in the operation and planning of the power system are required. To meet this need, several system operators on the cutting edge of this transition have collaborated with technical institutions around the world to create the Global Power System Transformation (G-PST) Consortium. The consortium aims to support advanced system operator research, development activities, and all system operators globally with knowledge and training as they transform their power systems.

Following an extensive and rigorous process, the G-PST Consortium defined a common research agenda to advance the operations and planning of power systems for the transition. The agenda seeks to include all possible advancements, from fundamental to applied research, driving solutions that are expected (but not assumed) to be globally applicable to all system operators. The advancements will vary by system and range from simple modifications of existing technologies and practices to fundamentally new and better ways to plan and/or operate the power systems of the future.

The initial research agenda focuses on near-term issues (i.e., over the next decade) and includes technical aspects of operational and planning activities within the bulk power system. While other issues like planning and operating DERs, sector coupling (including power-to-X), electricity market design, and regulatory and policy topics are respectfully acknowledged, they have been set aside to varying extents as "out of scope" for this initial phase of the G-PST research agenda. Note, "out of scope" does not imply that these issues will be ignored. These interface issues must be represented in a meaningful and appropriate manner and are presently treated tangentially in the research agenda.

Fifty-nine research questions were organized according to their primary membership among six groupings that represent themed "research programs," as depicted in Table 1. The questions have varying degrees of overlap and possible redundancy, and they are tightly coupled with many dependencies. The questions could easily be replaced with a smaller or larger number that covers the research landscape equally well.

Inverters, Inverters, and More Inverters

The displacement of synchronous generation with IBRs, the addition of loads connected via inverters, and the increasing prominence of energy-storage devices in IBR form are changing the fundamental synchronous nature of the bulk power system. To maintain high levels of reliability in the system, the designs of both the bulk power system and IBRs have to change, and existing operating and planning practices will need to adapt. This is not a case of an IBR-dominated system being less or more reliable than a synchronous system. It is a case that they are in many ways different, and the differences must be reflected in the design, analysis, operations, planning, forecasting, and risk management of power systems.

Incremental tweaking and artificially forcing IBRs to look like synchronous machines is a limited short-term strategy that does not leverage the true potential of IBRs. IBRs can be highly flexible and controllable. Because of this, there may be opportunities to make IBRs behave better than synchronous machines in some respects. However, the control algorithms that dictate the response of IBRs to grid conditions vary across inverter designs and manufacturers. Furthermore, the algorithms can interact at both local and system-wide levels and with other elements in the power system, such as high-voltage dc transmission terminals. This dramatically complicates the analysis of IBRs in the power system and may lead to stability challenges.

table 1. Summary of the research agenda.

Research Program	Description	Number of Questions
Inverter Design	Development of capabilities, services, design methodologies, and standards for IBRs	11
Stability Tools and Methods	Development of new tools and methods as well as modifications or supplements to existing tools and methods, required to ensure reliability, security, and stability in power systems	8
Control Room of the Future	Development of new technologies and approaches for enhanced real-time visibility and analysis in power system operator control rooms	17
Planning	New planning metrics, methods, and tools to capture the characteristics and influence of a changing resource mix	15
Restoration and Black Start	Creating new procedures for black-starting and restoring a power system with high or 100% IBR penetrations	1
Services	Quantifying the technical service requirements of future power systems to maintain the supply–demand balance reliably and at least cost	7

The control algorithms that dictate the response of IBRs to grid conditions vary across inverter designs and manufacturers.

The challenges are compounded as most inverters currently do not provide certain services like inertia response and high-fault current, both of which contribute to maintaining stability. This system/device interaction demands a co-design approach with a simultaneous focus on both the system and the inverter to reach a low-cost and effective overall solution. Finding a solution requires close working relationships and collaboration with industry solution providers such as inverter manufacturers. Therefore, the Inverter Design Research Program focuses on capabilities, services, design methodologies, and standards for IBRs (Table 2). It also examines the cost implications of these designs in terms of additional hardware and tradeoffs with other performance measures like efficiency or load factor.

Figure 1 highlights the impacts of photovoltaic (PV) inverter-level voltage control on a test system with no synchronous generation. The test system is an adapted portion of the North American Eastern Interconnection, with 165 buses, 112 branches, and 1.1 GW of load represented as constant-current active power and constant-impedance reactive power. The loads are supplied by 17 inverter-based devices, including seven type IV wind plants, eight PV plants, and two static synchronous compensators. The total generation capacity is 2.2 GW. The wind plants have local voltage control on the grid-side converter, and they have no plant controller or frequency-response capability. There is a 480-km, 1-GW, uncompensated 345-kV transmission corridor comprising three parallel conductors to a compact load center located at the far end of the transmission corridor with static synchronous compensators at either end. A solid six-cycle, three-phase fault to ground at the sending end of the 480-km transmission corridor is simulated for the following scenarios:

1) *Scenario 1*: Of the eight PV plants, only one has inverter-level voltage control. The remaining seven plants are set to operate on inverter-level reactive power control.
2) *Scenario 2*: Of the eight PV plants, four (including the plant from Scenario 1) have inverter-level voltage control. The remaining four are set to operate on inverter-level reactive power control.
3) *Scenario 3*: All eight PV plants operate on inverter-level voltage control.

In Scenario 1, with a minimal number of devices on inverter-level voltage control, the system is unable to achieve a postdisturbance steady state and results in a complete system collapse. However, with the increased number of plants on inverter-level voltage control, not only does the system stabilize quickly, but increasing the number (i.e., Scenario 3 compared with Scenario 2) has a pronounced benefit on voltage recovery.

These simulation results illustrate many aspects of the Inverter Design Research Program (e.g., research question

table 2. Inverter Design Research Program questions.

1) What are the needs of a power system (to achieve security and good regulation) expressed in technology-neutral form, and how do these needs map to services that any resource, including an IBR or a synchronous machine, can provide?
2) For each service defined in question 1, how feasible is it to provide from IBRs, what "cost" does it add, and what limitations exist on its magnitude and duration of service? What implications do these have for system operations?
3) What are the limitations of each IBR technology option to provide frequency-control services, and how do the various frequency services overlap and compete?
4) What design standards or dispatch guidance should be introduced to avoid instability (e.g., caused by phase-locked loops or other elements) in weak grids? This is a more widely drawn version of the question on minimum ratios of grid-forming to grid-following inverters.
5) What are the appropriate inverter capabilities and, consequently, control design methods for operation in grids with a high percentage of IBRs? Are standard configurations and combinations of services helpful in simplifying operational decision making?
6) Are the black-box models (impedance spectrum and binary code) favored by manufacturers for disclosure sufficient for stability assurance and system design across all problem types?
7) What recommendations should be made for standard behaviors of IBRs in certain frequency ranges for different power system conditions to aid system design? For example, should a contribution to damping be mandatory at certain frequencies?
8) What impedance requirements should be placed on IBRs to suppress negative-sequence and low-order harmonic currents?
9) How will protection systems need to change to accommodate high penetrations of IBRs, and what possible actions might an inverter take during a fault that would aid fault detection and location?
10) What is the future of frequency control as the synchronous generation fraction reduces? Might tightened or loosened frequency limits lead to a more reliable, secure, lower-cost IBR-based power system?
11) At what point is it better to break from trying to replicate synchronous machine features and exploit the wider flexibility of inverters?

5 in Table 2), but they apply to a single simulated example. Generalizable design methods and standards are required to guarantee stability across all credible events and systems. This global applicability is at the core of the G-PST research agenda, although local adaptation will almost always be required.

To Be Synchronous or Nonsynchronous: That Is the Question

With increasing IBR penetrations, the underlying nature of the power system is changing from one based largely on a synchronous paradigm to one based on a nonsynchronous one. These changes will limit the applicability of some existing tools and

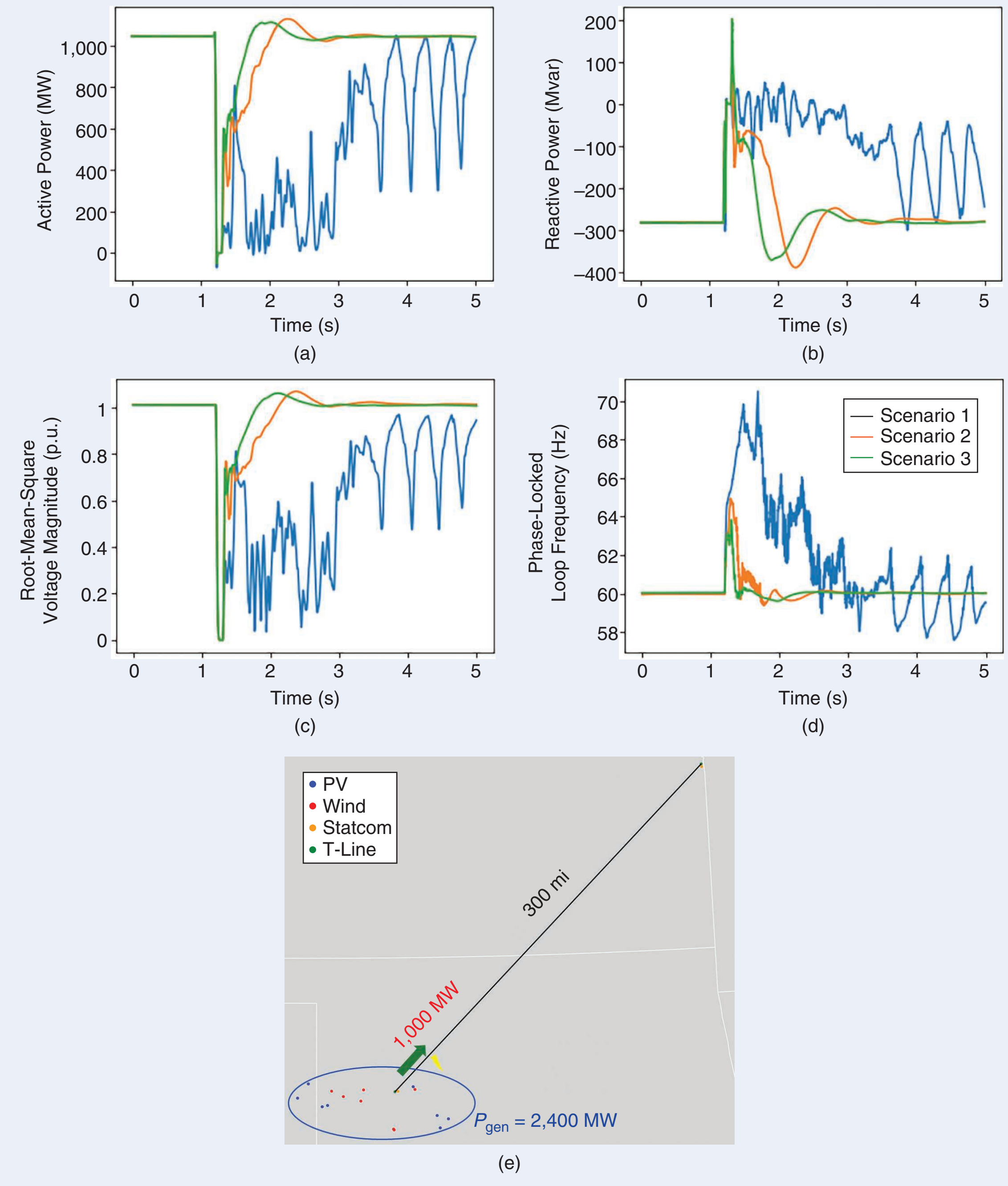

figure 1. A 100%-IBR test system response to a fault with varying PV-plant inverter-level voltage control. (a) and (b) represent active and reactive power, respectively, on the transmission line, (c) the sending end voltage magnitude, (d) the phase locked loop frequency, and (e) a schematic of the test system. p.u.: per unit.

> At what point is it better to break from trying to replicate synchronous machine features and exploit the wider flexibility of inverters?

methods that underpin their power system planning and operating decisions. They also will dictate the development of new tools and methods to ensure the system's reliability, security, and stability. Therefore, analytical tools must be developed to help evaluate the operation of a power system with a large number of IBRs.

IBR models pose a challenge in that there are various proprietary control schemes across manufacturers. Depending on the type of stability modeling conducted, existing generic models may not be adequately detailed to capture their behavior under a variety of grid conditions. As IBR penetrations increase, the converging issues of appropriately designing and modeling IBR responses and integrating these tools into planning and operation practices will become increasingly pressing.

Even in high-IBR scenarios with no fossil-fueled generation, many power systems will still operate with synchronous machines at least part of the time (e.g., with nuclear, hydropower, geothermal, or hydrogen-fired plants). New stability tools and methods will need to be fully integrated into existing ones, which are part of the system operator "toolbox," to conduct analyses in planning and operating time frames. Such stability tools must be configured to allow system operators to switch seamlessly from synchronous to asynchronous analyses as generation shifts over time.

The use of these tools in long-term planning and online applications may face computational limitations that require additional hardware, software, refinements, and approximations to make them tractable while maintaining accuracy. Ensuring that proposed solutions are scalable and that they adequately cover the diversity of power system contexts and IBR designs are two of the main issues to be solved as new methods and tools are developed.

The Stability Tools and Methods Research Program (Table 3) focuses on understanding the limitations of existing tools and methods. It also deals with developing new and/or improved tools and methods to identify potential reliability, security, and stability issues and the associated least-cost solutions in future power systems. These tool sets will focus on core stability issues with the ability to evaluate small- and large-signal stability. Ultimately, they would have to cover an entire suite of prospective issues, including frequency stability, frequency-domain profile (eigenvalue analysis), protection equipment performance in reduced short circuit power systems, network reduction, power quality assessment, and other dimensions.

The research program attempts to yield both 1) new methods that can be implemented as new capabilities within existing tools for detecting incipient instabilities and 2) new analytical tools for detecting instabilities and other foreseen power system issues, using both legacy and new methods for assessment. New tools would need to take traditional concepts, related to dynamic stability, plus newer concepts, related to IBR control interactions and system strength, and merge them with concepts of economic dispatch and unit commitment.

A Much More Complex System to Control

The increasing roles of inverters, highly distributed VRE generation, storage, and DERs bring a complex control challenge unlike anything seen before in the bulk power system. Many variables need to be observed at faster rates and controlled in a much more dynamic and stochastic environment, including the potential for large-scale common-mode failures. The control room of the future thus must be able to manage significantly higher volumes of data to be quickly converted into actionable information (via novel tools and methods). Furthermore,

table 3. Stability Tools and Methods Research Program questions.

12) What approaches can be taken to near real-time system modeling with large quantities of IBR that make design for system stability sufficiently accurate and still tractable?
13) What methods can be used for offline and online monitoring tools for detecting incipient instabilities? What new capabilities are needed to address these limitations?
14) What type of online contingency and stability analyses should be conducted at changing levels of IBRs?
15) What analytical tools and models should be provided to planners and operators for robust assessment of system performance?
16) What tools are needed for operational analysis of higher-impedance grids?
17) What analytical methods and tools should be used to determine the appropriate mix and capabilities of grid-forming and grid-following inverters to mitigate low-inertia conditions for a given power system?
18) What are the appropriate analytical methods and tools to determine—for a given power system—the extent to which very fast frequency response can substitute for inertia. Relatedly, what tools and methods are needed to effectively compose a mix of Δf and df/dt responses?
19) What tools and methods are needed to identify the best mitigation strategies for voltage-collapse problems under high-IBR conditions? And how effective is the IBR in recovering from deep voltage dips (bearing in mind lack of short-term overload current)?

The control room is at the core of all efforts to monitor and maintain reliability in the face of shifting power system conditions.

human operators need to effectively interface with this information and take well-informed actions.

Alternatively, information on power system conditions and potential risks must lead to automated actions if humans cannot reasonably respond in time to avoid reliability issues. The control room is at the core of all efforts to monitor and maintain reliability in the face of shifting power system conditions. As the grid becomes more dynamic and stochastic, the control room must be equipped to collect, process, and react to more information than ever before. Failure to keep pace with these challenges can result in additional costs, increased emissions, and/or reduced reliability and performance. For example, if system operators are forced to reduce clean IBR generation or turn on more expensive fossil-fueled generation to maintain stability, then both costs and emissions rise.

Wind and solar PV renewable energy variability and uncertainty combine with the fundamental, almost instantaneous, supply–demand balance requirement of the power system. This means that wind and solar PV energy should be forecasted in advance as accurately as possible to dispatch all flexibility resources to maintain the balance. Resources need to be scheduled accordingly across multiple time horizons while also accounting for the inevitability of inaccurate forecasts.

System operators are also tasked with managing numerous natural and man-made disasters that may impact the power system, even as the frequency and severity of natural disasters continue to increase. Though these may be noncredible events, system operators are increasingly driven to ensure some residual level of supply–demand balance, even as both supply-side and demand-side resources are impacted by conditions such as severe hot- or cold-weather events, fires, and storms. Preparing and responding to such events will require significant visibility into real-time system operations and the ability to dispatch resources at nearly every level of the power system.

figure 2. The control room of the future and that of the past (inset). (Source: National Renewable Energy Laboratory; used with permission.)

Given the speed at which many of these factors can change because of changes in the distribution system impacting DERs, sudden changes in resource availability (e.g., cloud cover), or interactions between IBRs, power system operators will have to process information and reach decisions significantly faster than they did in the past. With an increase in change sources, not only must the information be processed more quickly, but also, significant events will become more common. Addressing these issues may require a combination of telemetry and communication infrastructure to collect data, novel visualizations, and tools (e.g., machine learning or artificial intelligence) to help system operators interpret the data and potentially automate responses.

Figure 2 is one possible vision for the control room of the future; the operators are immersed in a 3D visual environment with the most important information being displayed intuitively. This is in contrast to the current situation (see inset), where the operator has a multitude of visual displays, all of which may be important. The assumption here is that many of the operator actions have been automated and the control room is adaptively presenting the most important information requiring real-time decisions.

As the power system evolves, system operators will need new tools and operating paradigms to deal with a more inverter-based, variable, and distributed grid. Here, for instance, operators may need to monitor inertia in real time to ensure that adequate frequency control is available or may require better tools to track the impact of DERs on the demand they are serving. Rapid and diverse changes also present opportunities. For example, a growing communications and telemetry infrastructure can provide planners with the data and control to develop cost-optimal reliable power systems and give them increased access to distribution-sited assets to more efficiently operate those systems.

The Control Room of the Future Research Program (Table 4) focuses on the development of new technologies and approaches for enhanced real-time visibility and analysis in power system operators' control rooms. Topics include the accuracy of wind/solar forecasts, ramping forecasts, and forecasts of net load that properly account for DERs (distributed solar, electric vehicles, demand response, distributed storage, and so on). Other topics are operational strategies to increase the efficiency of network capacity, such as dynamic line rating, the coordination of critical maintenance outages, and the management of environmental threats (e.g., fires, floods, and hurricanes).

> The range and diversity of changes happening on the power system are challenging our ability to make it all work together seamlessly.

Data needs may include phasor measurements and real-time state estimation to allow the system operator to monitor real-time risks. Computational and telemetry limitations in collecting and processing data to conduct real-time analyses are also important topics within this research program. Finally, the program also addresses the potential applicability of machine learning and artificial intelligence technologies and visualizations that provide necessary information for operators to make decisions (manual or automated) to mitigate reliability risks.

Making It All Work Together

The range and diversity of changes happening on the power system are challenging our ability to make it all work together

table 4. Control Room of the Future Research Program questions.

20) How can operators identify critical stability situations in real time and optimize system security?
21) How can system operators get relevant real-time visibility and situational awareness of the state of the power system with increasing penetrations of IBRs and DERs?
22) How can the system strength, inertia, and limits of stable frequency range be monitored in real time in high-IBR systems?
23) What are the appropriate methodologies to visualize and interpret relevant information for improved decision support for fast real-time control actions?
24) What quantities must be monitored, screened, and validated in real time to ensure that there will be adequate flexibility availability from uncertain system resources in the near term?
25) How can control capabilities for IBR-based system assets (flexible alternating current transmission systems, line impedance adjusters, and so on) and network flexibility more generally be maximized to enhance reliability and/or reduce costs?
26) Are there sufficient flexibilities available in the near term to compensate variations in load and generation (fast changes as well as long-lasting extreme situations such as prolonged periods of no solar and wind)?
27) How do control rooms address uncertainties in weather conditions that impact loads and renewable energy output and rate of change (ramps)? How can probabilistic forecasting techniques be better incorporated into real-time operations?
28) How can data best be utilized to ensure that system operations include the ability to detect and mitigate a range of uncertain disturbances?
29) What quantities must be monitored, screened, and validated to ensure reliable service provision from aggregated flexibility resources in distribution systems, supporting stable system operation?
30) What type of digital architecture is necessary to enable the variety of software required to operate a control room in real time, near real time, and in autopilot mode?
31) How can grid topology be flexibly adapted at various operating conditions?
32) What is a suitable data architecture for DER monitoring and modeling? Once DER resources have been aggregated spatially and temporally, how should this information be provided to the control room? Can DER categories be developed that allow groupings based on their ensemble response to system-level events? What is the appropriate data architecture required to monitor/predict and control DERs in real time?
33) What is the communication capability needed to support monitoring and control of DERs? What is the suitability of the existing communications infrastructure—in terms of reliability, latency, bandwidth, and (cyber)security—relative to investing in a bespoke system? For DER control purposes, what two-way communication protocols are necessary?
34) What are the relative merits of different control architectures for DERs? What might an efficient distributed control architecture be for DERs that 1) makes use of appropriate device characterizations and real-time monitoring data, 2) accounts for practical constraints around device-level communication, and 3) accounts for heterogeneous subgroup controls of DERs and various existing distribution system operator/transmission system operator control schemes?
35) What is the best way to integrate large data sets, streaming information, and historical system performance to create actionable operational insights?
36) How can the status (generation output, state of charge, and so on) of each key category of DER be monitored/estimated in real time? What are appropriate DER categories and the appropriate spatial and temporal resolution to monitor DERs effectively? What are the appropriate technical means of achieving this level of aggregation?

> As the fossil resources that have traditionally provided the backbone of restoration are displaced, IBRs will need to fill this gap.

seamlessly. Planning for all of these changes is critical. As the primary energy resources change from fossil/nuclear fuel to more VRE resources, and as more of these resources become inverter based and distributed, the planning paradigm must account for their different characteristics. As other technologies (e.g., batteries) become more pervasive, they also increase the need to update power system planning. Electrification and integration of the other parts of the energy system (e.g., transport and heat) can dramatically alter demand patterns, which will also impact the planning paradigm.

To keep up with the trends, the metrics and methodologies to plan reliable and resilient power systems must be continuously updated to ensure that they are "fit for purpose" and deliver the required levels of reliability in the future. System operators all have their unique variation on long-term planning, driven in part by their regulatory, policy, and market environments.

Despite these variations, one area of clear consensus is a need to focus on network infrastructure planning as many system operators have relatively limited responsibility for generation investments. Instead, they are tasked with planning transmission investments to accommodate a range of future generation portfolios while maintaining the robust and reliable operation of the power system. Thus, the processes and tools required to plan the future bulk power system in a liberalized market setting, where the generation side of the equation is market and/or policy driven, should focus on the transmission system and ensure that there are enough services to maintain reliability and resilience.

Driven in part by climate change, the events on power systems are becoming more extreme and highlight some common-mode failures; it is important to account for them in planning activities. As the consumer becomes more active in the power system, possibly creating a more heterogeneous demand side, the whole concept of planning standards may need to be adapted to enable a more optimal system. DERs in particular can influence traditional reliability control services like underfrequency load shedding, impacting operating practices in important ways that must be accurately accounted for at the planning stage.

Finally, the more dynamic a power system is, the more complex its operations become (see Table 4), and the more important it is that the planning process accounts for the operational details. This poses a computational burden that can be addressed with advanced computational methods, using both hardware and software, and/or methods for representing power system operations accurately in a reduced form. In sum, defining the network infrastructure of least regret is growing more complex. Operators must establish the necessary tools and processes to plan and build (and eventually operate) a future power system that is dominated by VRE, IBRs, and DERs while accounting for risk and uncertainty holistically.

Developing new planning metrics, methods, and tools to capture the characteristics and influence of a changing resource mix, including new flexibilities from demand-side resources and storage, is the focus of the Planning Research Program (Table 5). This program does not consider distribution network planning or include detailed considerations of electrification, sector-coupling impacts, or DERs. Nevertheless, these will need to be represented in planning exercises or, in the case of sector coupling, by quantifying demand response or long-duration storage assets.

Sometimes It Will All Go Wrong

In common with all systems, there are times when the lights go out. These failures are unavoidable but can be minimized in a cost-effective manner, which is the main driver of all 59 research questions.

When the power system does go black, it must be restored quickly and efficiently. Traditionally, flexible hydropower or fossil-fueled power plants, such as simple cycle gas turbines or diesel generators, have provided the first step of a black start. Inverter-based resources such as wind generators and solar PVs cannot currently provide a black start, and their participation in the subsequent steps of system restoration is generally avoided. However, IBRs generally have the potential for fast and customized behavior; they offer the potential to provide valuable contributions to restoration efforts, such as fast frequency-containment reserves and tailored inertia response.

As the fossil resources that have traditionally provided the backbone of restoration are displaced, IBRs will need to fill this gap. Additionally, high penetrations of DERs complicate traditional "cold load pickup" practices as blocks of load that have embedded distributed PVs or distributed storage may result in complex behavior that must be considered in the restoration process. The sheer number of distributed generators requires new forms of awareness and automation to make their inclusion feasible for operators.

There are several unique problems associated with "bootstrapping" the system with solar and wind IBRs from a black condition back to normal operation. This is addressed in question 52: "How do system operators black-start a system with very few (or no) synchronous machines?" The first challenge is to ensure that, in planning and operational time frames, the IBRs have a sufficient energy source available to enable the black start (i.e., sufficient wind speeds, solar irradiation, or

> This entire process is further complicated by the fact that restoration is often done under difficult conditions with uncertain and imperfect information.

charged storage energy). The second challenge is to extend the capability of IBRs to allow the creation and control of stable voltage waveforms (grid-forming inverters).

Solutions exist for these challenges but have not yet been integrated into the power system at a relevant scale. Each subsequent step in the restoration process represents a complex data-acquisition and decision-making process to ensure that each stage is safe and viable. The physical capability of the "pieces" (substations, lines, distribution feeders, and more generators) as they are being reassembled must be respected, and there must be sufficient control range in the controllable elements to maintain an acceptable voltage, frequency, and power balance.

This entire process is further complicated by the fact that restoration is often done under difficult conditions with uncertain and imperfect information. For example, following a blackout due to destructive weather, system elements may be damaged and unavailable, and information about the state and availability of components may be imperfect. Therefore, restoration plans and training must consider impaired system states, and the design of generators must include reasonable fallback settings in the event of communication failure.

How to Organize It?

Making the power system work physically is only half the challenge. It must also be organized commercially and institutionally

table 5. Planning Research Program questions.
37) What additional probabilistic planning methods and tools are necessary for planning a power system with a high share of IBRs and, in particular, VRE resources?
38) What studies and metrics are required to identify long-term scarcity of capacity to maintain reliability?
39) What additional methods and tools are necessary to incorporate resilience concepts and the ability to recover from adverse conditions considering uncertain future states into planning a power system with a high share of renewables?
40) What additional planning models and methods are needed to plan for various levels of uncertainty and no-regrets investments in a paradigm of increasing electrification and growing IBR and DER penetrations?
41) How should sufficient black-start capability and the performance and integrity of the protection system be modeled in long-term reliability studies?
42) What features need to be added to long-term planning methods and studies to consider other reliability services in addition to traditional resource adequacy and deliverability?
43) How can system security be balanced against lower costs for operation and investment?
44) What studies and metrics are required to evaluate resource adequacy with hybrid plants (e.g., PV-plus-storage systems) and virtual power plants?
45) How do system operators adequately account for extreme events in planning studies, particularly those that impact the resources used in a high-renewable-energy future (wind, solar, demand-side flexibility)?
46) What mechanisms are necessary to accurately model and account for DERs in planning exercises to ensure a reliable power system is being planned? What data are necessary to accurately model various levels/paradigms of DER control, including influence on underfrequency load-shedding schemes?
47) What additional load- and resource-forecasting models are necessary to account for electrification of the transportation and building sectors?
48) What changes can be incorporated into the transmission planning process to accommodate new drivers of uncertainty in electricity demand (e.g., large growth due to electrification or low growth due to increased use of DERs)?
49) What additional planning models and methods are needed to plan for a system that can withstand expected or unexpected lulls in the weather driving much of the resource mix, e.g. an extended wind drought?
50) What are appropriate aggregate DER models and methods for inclusion in transmission-level modeling?
51) What models and methods are necessary to quantify the need and requirements for long-duration energy storage?

> Current state-of-the-art services (e.g., capacity, ancillary services, and so on) fall far short of future service requirements.

to ensure cost-effective and reliable operations and investment decisions. At the heart of organizing the power system are defining "services" that need to evolve with the changing characteristics of the power system. They are fundamental to supporting the sociotechnical objective of reliably maintaining supply–demand balance at all points in time, at all locations, at least cost, equitably, and with minimum impact on the environment.

These services determine the operation and planning of the electricity grid across all time scales; the required characteristics of the technologies connected to the power system; and, through commercial mechanisms, the incentives to innovate and invest and to do so equitably. Current state-of-the-art services (e.g., capacity, ancillary services, and so on) fall far short of future service requirements. There is a danger of developing electricity grids that are costly, unreliable, inequitable, and inflexible and will therefore not deliver the step change needed for the energy transition.

For example, with increasing penetrations of variable renewables, there is a decline in "inertial response" and a corresponding deterioration in frequency control. There are also several compounding factors. For instance, distributed solar PV systems are reducing the efficacy of the existing emergency frequency controls in place in many jurisdictions to arrest frequency decline (e.g., underfrequency load shedding).

Inertia has not been in short supply historically as it comes inherently with synchronous generation and therefore was not deemed to be a service. There are several candidate solutions to declining inertial response, starting with focusing directly on supply–demand balance and ignoring frequency control, which is only an indicator of this balance. Maintaining frequency as the indicator of a supply–demand imbalance and deploying fast-frequency-response and grid-forming converters as substitutes for physical synchronous inertia constitute another approach. Interestingly, some of the energy sources for these substitutes can be the VRE sources themselves.

There are many other examples, including a possible change in the most fundamental of all services: energy. With increasing penetrations of variable renewables, there may well be a point where the energy service, because of oversupply, is replaced in the hierarchy by capacity. Because of the way in which rules for participation have developed, many services today may be biased toward provision by more established technologies, in particular synchronous machines, as other technologies (e.g., IBRs and storage) were not previously in existence.

Developing system services in technology-agnostic ways such that the full capabilities of all eligible technologies are utilized, including those on the distribution grid and in customer premises, can help system operators meet reliability in a cost-optimal fashion. However, what is missing is a unifying framework for defining and procuring services so that the "best" combination of services is found, recognizing that system characteristics, both technical and societal, vary by location.

The Services Research Program questions (Table 6) aim to quantify the technical requirements of a future power system to maintain the supply–demand balance reliably and at the least cost. A set of new services and/or a reordering of the services hierarchy is needed to guide the transition toward higher penetrations of variable renewables in electricity grids. This reordering should be based on their importance as determined by fundamental electrical engineering, economics, and social factors. The new services hierarchy may be fundamentally different than those in the past. For instance, under high penetrations of variable, zero-marginal-cost

table 6. Services Research Program questions.
53) How should the definitions of services for IBR-dominated grids be structured? Can standard services and standard characteristics be defined that are reasonable for large and small IBRs and across VRE, storage, and demand response interfaces?
54) What methodologies can be employed to determine if strong/stiff voltage-control services can be reliably provided through reactive power droop or active regulation?
55) What models and methods are necessary to quantify the ability of VRE to provide essential reliability services to the grid, and how do system operators quantify the value of these reliability services (for example, as an input to system-specific market/incentive design questions)?
56) What roles can offshore wind and high-voltage dc clusters play in providing energy system flexibility?
57) How can system performance requirements be translated into reliable new technology solutions?
58) How can system operators quantify the transmission-level service opportunities from DERs? What are the practical and technical limitations to the reliable provision of various DER services?
59) How can transmission-level services provided by DERs be valued? What DER transmission-level service valuation methodologies are best suited as a compromise between simplicity and full cost-reflectiveness?

generators, capacity services may become more critical than energy services. The Services Research Program also aims to characterize the ability of power system-connected technologies (e.g., generation and demand) to meet these requirements cost-effectively. Put differently, this program is "where the markets meet the physics"—it is an important bridge to detailed electricity market design, which is out of scope for the G-PST Consortium.

Finally

The research questions described here are not entirely new, and activity already is taking place to solve many of them. Some of the research questions (or parts thereof) are, by their nature, transitory and near term; i.e., they will no longer be relevant when power systems reach a certain stage in the transition. Research efforts solving "transition" issues must be considered as a cost of the changeover, and their application needs to be considered in light of their transitory nature.

While many system operators are facing similar research challenges, each power system is different when considered technically, institutionally, and geographically. This leads to potentially different detailed solutions in applications and different levels of urgency and pathways to solutions. Great care will be taken to ensure that the solutions being developed under the G-PST Consortium are not skewed toward a particular system operator's needs. They must be "generic" and capable of being applied more broadly to all of the system (and future system) operators globally.

This research agenda has been informed by a select group of system operators on the cutting edge of the transition and is limited to an initial scope, a 10-year horizon, and a focus on the bulk power system. In time, the ambition of the G-PST Consortium is to expand the involvement of others, including distribution system operators and actors in the broader integrated energy system. Therefore, a fuller research agenda with a wider scope will expand into adjacent areas (e.g., planning and operating DERs, power-to-X, and so on) and to a longer time horizon (e.g., 20–30 years).

Conclusion

The G-PST Consortium's Research Agenda Group has produced a research agenda consisting of 59 research questions organized into six research programs. It is focused on the near-term (10 years) core bulk power system issues. The questions are overlapping, dependent, and interacting. A holistic and/or coordinated global effort is required to solve these questions quickly so the transition to future power systems is not hampered or delayed.

For Further Reading

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