U.S. DEPARTMENT OF
ENERGY

Transmission Innovation Symposium

Modernizing the U.S. Electrical Grid

Sandra Jenkins
U.S. Department
of Energy

Joseph H. Eto
Lawrence Berkeley
National Laboratory

Jeff Dagle
Pacific Northwest
National Laboratory

Symposium Proceedings

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Symposium Chairs

Sandra Jenkins
U.S. Department of Energy

Joseph H. Eto
Lawrence Berkeley National Laboratory

Jeff Dagle
Pacific Northwest National Laboratory

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1. Acronyms and Abbreviations

AC	alternating current
AI	artificial intelligence
CERTS	Consortium for Electric Reliability Technology Solutions
DC	direct current
DER	distributed energy resources
DOE	United States Department of Energy
EMS	energy management system
EPRI	Electric Power Research Institute
EV	electric vehicle
FACTS	flexible alternating current transmission systems
FERC	Federal Energy Regulatory Commission
GW	gigawatt(s)
HVDC	high-voltage direct current
ICS	industrial control systems
ISO	independent system operator
MISO	Midcontinent Independent System Operator
ML	machine learning
MW	megawatt(s)
NERC	North American Electric Power Corporation
RAS	remedial action scheme
R&D	research and development
RTO	regional transmission organization
SPS	special protection scheme
T&D	transmission and distribution
SCADA	supervisory control and data acquisition
VSC	voltage source converter

1. Introduction

The foundation of the United States Department of Energy (DOE) Transmission Reliability research program was established 20 years ago by a series of commissioned white papers. Those white papers described the dramatic institutional and regulatory changes that the U.S. electricity transmission grid was undergoing at the time and articulated the technical challenges that these changes created. The challenges outlined in the white papers were the basis for the initial research goals of the DOE Transmission Reliability program. To a large extent, the reliability research needs outlined in the original white papers have now been met. As a result, now is an appropriate time to step back and review the technical challenges that the industry currently faces and to use those challenges as the basis for identifying the next set of targets for DOE's transmission-related research and development (R&D) programs.

To support this process, DOE, supported by Lawrence Berkeley National Laboratory and Pacific Northwest National Laboratory, formed small teams of experts drawn from the national laboratories and academia to prepare a new set of foundational white papers. These white papers review and assess the challenges now facing the U.S. transmission system and focus on the technologies that will be required to address the challenges. The white papers define the technical issues that must be addressed now to prepare the industry for the transmission system that will be required 10-20 years in the future. One key purpose of the papers is to identify technical areas where DOE can take a leadership role in catalyzing an orderly transition to the future transmission grid. This includes DOE's roles as a visionary articulating and defending what is needed, as a facilitator bringing together the parties that must work effectively together to achieve the goals, and as an investor to spark and guide needed R&D investments.

Each of the white papers was peer reviewed by up to five experts from academia and industry. The papers were then vetted and discussed formally with a broad, diverse audience of stakeholders at a DOE-sponsored Transmission Innovation Symposium entitled "Modernizing the U.S. Power Grid" that was held virtually on May 19-21, 2021. More than 450 individuals registered to participate in the symposium. This volume is a summary of the presentations and discussions that took place during the Transmission Innovation Symposium. This summary volume is accompanied by the white papers, each presented in a separate volume. Together, the white papers and the discussions from the symposium will anchor the next generation of DOE's Transmission Reliability R&D programs.

1.1 Background

In 1999, DOE restarted its Transmission Reliability research program in response to the Secretary of Energy Advisory Board's finding that DOE should address "emerging gaps in public interest R&D created by the transition to competitive markets."[1] As a first step, DOE commissioned the newly formed

[1] Secretary of Energy Advisory Board. 1998. *Maintaining Reliability in a Competitive U.S. Electricity System, Final Report of the Task Force on Electric System Reliability*. Sep. 28. U.S. Department of Energy.

Consortium for Electric Reliability Technology Solutions (CERTS)[2] the first generation of white papers to assess industry trends, technical challenges, and needs for public interest R&D.[3]

The 20 years of DOE-sponsored transmission reliability R&D initiated by those first white papers have led, or contributed, directly to the following major technical accomplishments:

1. Creation of software tools now in routine use by the North American Electric Reliability Corporation (NERC) to monitor compliance with mandatory reliability rules and to support the development and testing of new reliability metrics;
2. Creation of new, interconnection-wide grid monitoring systems consisting of thousands of high-speed, time-synchronized measurement devices that provide unprecedented visibility into the operation of the grid, supported by significant industry-cost-sharing funding and the American Reinvestment and Recovery Act;
3. Adoption by all regional transmission organizations/independent system operators (RTOs/ISOs) of advanced software for real-time co-optimization of energy and reserves to improve both system reliability and the wholesale-market efficiency;
4. Implementation of customer demand-response programs in all RTO/ISO wholesale ancillary services markets, on a footing equal to supply-side resources; and
5. Industry-wide adoption of DOE-led microgrid concepts and first-ever field demonstration of grid-forming microgrids, at scale, using commercial hardware.

1.2 The Need for, and Role of, a New Generation of White Papers on Electricity Transmission System Research & Development

As noted above, the reliability research needs outlined in the original Transmission Reliability white papers have now largely been met. In addition, the Transmission Reliability research program is now a part of a standing DOE Office of Electricity (which did not exist in 1998). Equally important is that significant, complementary DOE programs, including Advanced Grid Modeling, Energy Storage, Advanced Power Grid Components, Advanced Sensors, and Resilient Distribution Systems, are now also conducting research in technical challenges facing the transmission grid.

In view of past Transmission Reliability program accomplishments and the now greatly expanded portfolio of grid-related research managed by the Office of Electricity, it is time to revisit and re-assess transmission grid research priorities and establish new technical objectives for the office’s transmission-

[2] The Consortium for Electric Reliability Technology Solutions (CERTS) was formed in 1999 to research, develop, and disseminate new methods, tools, and technologies to protect and enhance the reliability of the U.S. electric power system and the efficiency of competitive electricity markets. The founding members of CERTS include Lawrence Berkeley National Laboratory; Oak Ridge National Laboratory; Pacific Northwest National Laboratory; Sandia National Laboratories; the National Science Foundation Power Systems Engineering Research Center; and the Electric Power Group.

[3] https://certs.lbl.gov/project/certs-grid-future

related research, as well as to identify the connections among and between this research and other related research activities within the Office of Electricity and DOE as a whole.

White Papers: Scope and Lead Authors

1. Electricity Transmission Systems R&D: Grid Operations
   Thomas Overbye, Texas A&M, and Anjan Bose, Washington State University

2. Electricity Transmission Systems R&D: Distribution Integrated with Transmission Operations
   Emma Stewart, Lawrence Livermore National Laboratory (at time white paper was written; now with National Rural Electrification Cooperative Association), and Chen-Ching Liu, Virginia Polytechnic and State University

3. Electricity Transmission Systems R&D: Automatic Control Systems
   Jeff Dagle, Pacific Northwest National Laboratory, and Dave Schoenwald, Sandia National Laboratories

4. Electricity Transmission Systems R&D: Hardware and Components
   Chris O'Reilley and Tom King with support from Oak Ridge National Laboratory staff

5. Electricity Transmission Systems R&D: Economic Analysis and Planning Tools
   Jessica Lau, National Renewable Energy Laboratory, and Ben Hobbs, Johns Hopkins University

A list of the peer reviewers for each white paper appears in Appendix A.

Transmission Innovation Symposium: Modernizing the U.S. Power Grid

The final white papers were vetted publicly at the DOE Transmission Innovation Symposium: Modernizing the U.S. Power Grid that was held virtually on May 19-20, 2021. The final agenda of symposium appears in Appendix B.

Of the more 450 symposium participants, roughly 45% were from industry or industry organizations, 30% from the national labs, 15% from academia, and 10% from DOE offices.

The symposium keynote speakers were Pat Hoffman, Acting Assistant Secretary of the DOE Office of Electricity and Wanda Reeder, CEO of Grid-X, LLC as well as chair of DOE's Electricity Advisory Committee. Following the keynote talks and a detailed question-and-answer session, the symposium consisted of five sessions organized around the white papers:

1. Grid-operations
2. Distribution integrated with Transmission Operations
3. Automatic Control Systems

4. Hardware and Components
5. Economic Planning and Analysis Tools

After the authors' presentations on the white papers, an invited panel of leading industry practitioners commented on the papers' recommendations for future DOE R&D. The panelists' remarks were followed by an open question-and-answer period, and DOE invited additional written comments to be submitted following the symposium.

Organization of this Volume

This volume is a summary of the white paper presentations and discussions that took place at the symposium. It is accompanied by stand-alone volumes for each of the five white papers.

This volume is organized as follows:

In Section 2*,* we summarize the symposium keynote presentations by Pat Hoffman, Acting Assistant Secretary of the Office of Electricity, and Wanda Reeder, CEO of Grid-X, LLC, and chair of DOE's Electricity Advisory Committee. The presentation slides appear in Appendix C.

Sections 3-7 summarize each of the white paper sessions. Each summary begins with a synopsis of the white paper that draws from the executive summary written by the authors. Next, we summarize the prepared remarks offered by the two invited expert panelists on each topic. We conclude with a summary of the question-and-answer session that followed the presentation. The presentation slides used by the white paper authors appear in Appendix D.

Written comments on the symposium that were submitted to DOE by May 27, 2021 are included in Appendix E.

2. Opening Session

2.1 DOE Keynote

Patricia Hoffman, Acting Assistant Secretary, U.S. DOE Office of Electricity

- The Biden administration has laid out an aggressive strategy for combatting climate change, including 100% renewable energy by 2035 and a net-zero-energy economy by 2050. To meet these goals, we will need significant investment in electricity infrastructure.
- The Energy Secretary also announced goals for:
    - 30 gigawatts of off-shore wind by 2030
    - Cutting the cost of solar by 60% in the next 10 years
    - Increasing electrification of transportation, buildings, and industrial sectors to meet environmental targets
- Highlights from the white papers:
    - If we are going to meet renewables targets, we will need an expanded—perhaps substantially—transmission grid to deliver the increased volume of renewable energy
    - We will need to be flexible about how we build out the transmission system so that it can be reconfigurable to be broken into smaller systems through a process known as intentional islanding (from the Grid Operations paper, p. 14)
    - We are going to have to continue to invest in observability and flexible controls through sensors and advanced data analytics (machine learning, artificial intelligence [ML/AI])
    - Regarding cyber security, we need to get into the physics of the system in conjunction with the cyber/communications aspects of the system. We need to be able to identify the difference between events caused by physical versus cybersecurity issues, as described well in the white paper on Distribution Integrated with Transmission Operations
    - Transmission planning is important because we are introducing significant change to the system. We are talking to ISOs and independent transmission operators about where the most important lines for the system are located. This discussion is going to intensify during the next couple months. The concept of multi-value planning is incredibly important as we go making investments in the next few years.
    - Markets are going to have to evolve. We need to rethink the energy and ancillary services markets (described on p. 25 of the Economic Planning and Analysis white paper)
    - At the end of the day, ramping services, essential reliability services, and capacity are going to have more value, and the value of energy services will not be as dominant as it is today.
- I challenge you all to set a stake in the ground regarding what some of the investment priorities for industry should be; we need to think about how to time investments, and how to execute on some of our targets and objectives as an industry.
- How do we set goals to phase investment strategies?
    - R&D technology and cost targets
    - Energy storage technology and cost targets
- At the same time, how does the DOE define investment priorities from a transmission planning

point of view to set the stage for driving additional investment going forward?

  - It is important for industry to have a prominent seat at the table as we look at investments and the jobs plan and determine how we collectively drive the investments that are critical to our future.

2.2 Industry Keynote

Wanda Reder, President and Chief Executive Officer, Grid-X Partners, LLC and Chair, DOE Electricity Advisory Committee. See slides in Appendix C.

- We need to step back and think about how to connect the details and recommendations in the white papers to trends, drivers, goals and objectives, so we have a cohesive plan that is outcome based.
- We need to remember how connected electricity infrastructure is to other critical infrastructures.
- The five white papers are a foundation for transformational change. The white papers discuss emerging transmission characteristics and how important they are to planning R&D.
- The current transmission infrastructure is aging—much of it was built over a half century ago—and this is stressing the system. We have a long way to go to update the system. The system is very human dependent, and there are opportunities for assisting operators with more automation.
- In regard to future transmission, the industry is going through change that is orders of magnitude greater than ever before. We need to innovate to meet the needs of a future system that will require more automation, data, modeling, and investment.
- We need to look at what we can do with ancillary services at the distribution level to buy time to build things on the bulk transmission system.
- We need to continue industry engagement for strategic planning and execution so we can advance together.
- Transformations needed:
  - We need to cross the barriers posed by institutional siloes and foster communication, promote imagination, and anticipate uncertainty. We cannot shy away from addressing elephant-in-the-room type concerns. We need to make sure we don’t miss anything.
  - Value increases when there is interoperability with other devices and systems in use. This is where grid architecture comes in.
  - If we are to succeed in achieving goals, the work force cannot be an afterthought; it needs to be at the forefront and considered throughout strategies for transformational change.
- We cannot kick the can down the road. We are asking for transformational change, which requires cultivation of imagination.

2.3 Discussion

- What are some of the challenges with simulations in training?
  - Patricia Hoffman: There is value in simulations in training, especially when using good sources of data. We can’t only rely on historical data going forward as the system is

changing. We need to incorporate cyber security training as well. Need to use real system data in order to make realistic training situations and develop simulations that help explore how to optimize the restoration process in different situations. All of these can help our workforce and develop future operators, as well as even help educate consumers.

  - Wanda Reder: There are so many facets in the workforce beyond just the operational workforce. The types of skills will need to evolve so that we will be able to understand and set up automation, data flows, and cyber-security aspects. Using real systems is important, but we need to think broader.

- What are the challenges for industrial control systems and supervisory control and data acquisition (SCADA) – challenges and possible markets? Where is the technology evolving?
  - Wanda Reder: Lots of opportunity for innovation in this space, and we are moving into an era where we are going to need faster communications that are also safe and resilient. SCADA is slow, at least compared to some of the new sensors coming on the system. Need to make sure new capabilities are integrated effectively. This is particularly true for the area of transmission and distribution interface.
  - Patricia Hoffman: Need more tools for operators that include automation. Need to be able to segment the system for resilience as well as cyber security. Explore how to structure and design control systems that include segmentation for security of these critical systems.
- What solutions do you see for cyber physical training and tools? How do we secure information exchange - maybe bringing together cyber security and telecommunication folks?
  - Wanda Reder: I do think we are going to need to bring together these two groups, thanks for bringing the idea forward. We need to be deliberate in putting plans around this area since it is one that needs further development.
- What can DOE do to foster the development of data sets for use in both industry and academics for ML and AI innovation?
  - Patricia Hoffman: We do have to help develop data sets. We need to have them available for researchers and technology development, but we need to be careful about the sharing parameters. Need to allow for sharing, to develop research around evaluation of the system, especially when you look at planning infrastructure investments. With cyber-security and vulnerability concerns, we need to think about access carefully, and this certainly will not be easy, but there does need to be a certain level of information sharing moving forward.
- With all the things that need to be done to modernize the grid, is the workforce up to the task, and what do we need to improve?
  - Wanda Reder: We need to keep in mind both new employees and existing and how they each require different strategies for how to evolve skills, such as different training or curriculum. Even in the design of the product, we need to design better screens and systems that are easier to use so that we are not relying on as much "tribal knowledge" as we have in the past. That said, I am very pleased with the workforce that we have; they have been showing their ability to make more out of less, bring in distributed energy resources, incorporate new markets. The workforce has shown their ability to be flexible and forward leaning these past 10 or so years with the dramatic rate of change we've seen

on the system. We need to be able to give them the tools they need to continue and make the next quantum leap.

- With distributed energy resources (DER) and goals to increase the ability to segment the electricity system with intentional islanding, how can we include distribution technologies in addition to transmission-level research?
    - Patricia Hoffman: We are going to have look at transmission and distribution because in many ways they are already blended. We need to look at the system holistically and think about microgrids and distributed load and what can be automated at the distribution level. There are going to be values from DER and customer and local services. How do we think about load profiles and load management going forward? There is an opportunity to take advantage of tools and resource efficiency as well as automation here.
    - Wanda Reder: Well said.
- How do we build new transmission lines? They currently take a long time, so how are we going to meet the aggressive administration goals?
    - Patricia Hoffman: First, maximize existing capacity through dynamic line rating and power-flow control, re-conductoring, etc. That's the low-hanging fruit. Second, use every tool in the toolbox for new transmission: how can we use existing rights-of-way from highways or rail, or other routes for energy corridors. Bottom line is we need to recognize that more transmission is necessary to meet renewable energy targets. We need to think early about where to place this transmission, working at the local and state level, and engage the community early and often. We need to engage the community to think about where to place transmission and where there are opportunities going forward. Third, how can we develop tools to think innovatively about transmission siting and permitting, for example, thinking creatively about how to address environmental issues around certain land areas ahead of project development?
    - Wanda Reder: Historically, we have looked at siting and permitting of transmission and distribution separate. Going forward we are going to need to look across these areas holistically. For example, what can we do behind the meter and on the distribution level? How can we use power electronics on the distribution system for ancillary services? We need to look across multiple regions and scales to plan effectively and efficiently for new lines.
- How do we get end uses more engaged (e.g., grid response of buildings, flexible electric vehicle [EV] charging, etc.)?
    - Patricia Hoffman: Huge opportunity in the space of electrification of industrial heating loads as well. The challenge is with the strain this might put on existing distribution systems and required upgrades. Customer awareness of what technologies are out there for existing buildings, as well as incorporating advanced technologies into the new building fleet. There is momentum building with consumers wanting to get engaged. Consumers are getting smarter and are looking for more ways to manage their energy consumption. Starting with the education side, to making sure that the buildings are smart to allow automation, and then things can become more balanced within the distribution level.
    - Wanda Reder: The electricity industry at large has not done a very good job of engaging

customers at large. Need to try and learn from other industries how to engage and get at the interests of customers.. I would also say the incentive base needs to be questioned. Just time-of-use rates alone are not going to get us there.
    - Patricia Hoffman: Wanda brings up a good point. We don't want to leave any customers behind. We have to think about how to invest in this in a way where everyone can benefit, and no one is harmed by changes in rate design. Lots of lessons learned from time-of-use block rates and how do we get into dynamic rate designs. This will be an interesting discussion, and challenge, going forward.
- There is a perception that the United States is falling behind on high-power technologies such as high-voltage direct current (HVDC) and dynamic line rating, power-flow control, etc. Is there anything that we need to be doing to get the United States back into a leadership position in high-power electronics?
    - Wanda Reder: As a part of this R&D effort we need to look at prioritization of investment and how do you map it back to objectives. We can come out of this with strong recommendations on where the investment and research need to be to either stay in the lead or get back in the lead. We know power electronics are going to be a part of the solution. The U.S. has been in the lead and we have done a lot, and there is no reason the U.S. can't invest in these solutions. I expect this will be a big part of the R&D portfolio.
    - Patricia Hoffman: Wanda said exactly what I was going to say. I am hoping that this forum will highlight what we need to do with power electronics going forward.
- What can we do to incentivize these technologies? Are some of these problems more regulatory and policy based?
    - Wanda Reder: Technology is one leg of the stool. We need a technology vision that brings together these elements. The regulatory and policy side are important. Fortunately, DOE is in a good position to convene these areas, with its connections to [the Federal Energy Regulatory Commission] FERC and NERC and the states. We as an industry have done a lot as well.
    - Patricia Hoffman: There is probably going to be a need with some of these new technologies for DOE to buy down some of the risk from consumers and utilities. We can look at it from an R&D role and how to do demonstrations and pilots to help buy down some of the risk associated with new technologies to help accelerate deployment. As we move forward, we are going to need to have conversations with regulators for incentives and rate mechanisms that allow for the transformation with, and installation of, new technologies.
- What are some things to define the necessary level of reliability and resilience given the trends and changes on the system while keeping in consideration different consumer classes and social justice?
    - Patricia Hoffman: The conversation around reliability and resilience is an important one. This goes back to the white papers: we need to look at probability analysis and scenario analysis to better define boundaries on the system around resilience across different risks. We have a lot of lessons learned from events this past year, from cold weather events. We as a community must be able to do that analysis around these boundary conditions to drive investments to mitigate events. This needs to include climate change considerations with

drought, flood, and fire conditions. It is important to engage stakeholders to get the biggest "bang for the buck" from a capital investment point of view.

  - Wanda Reder: We need to do "what if" rather than "what now." Without imagination of scenarios and what can happen, it is hard to anticipate challenges and manage uncertainty. This is important to consider when we plan the R&D portfolio.

- Patricia Hoffman: To close out, we are coming out of a time where we had lots of excess capacity on the system, which provided flexibility to mitigate uncertainty. The system is tighter and more stiff when we look at operations, and we need to take these challenges into consideration as we go forward.

3. Session 1: Grid Operations

Authors

Anjan Bose, Washington State University, and Thomas Overbye, Texas A&M University (presenter)

Abstract

This white paper addresses transmission grid operations, which are coordinated through SCADA - energy management systems (EMSs). The white paper makes recommendations for R&D in the following areas: technologies for support of real-time operations; engineering tools to support real-time operations; technologies to enhance the use of historical real-time data; engineering tools to support transmission planning; training simulators; high-impact, low-frequency events; restoration, and coupling with other infrastructure; and research infrastructure.

Synopsis

This white paper addresses transmission grid operations, how they are evolving especially as more renewable and distributed resources are being added to the grid, and what R&D are needed to continue operating the power grid in a reliable, economic manner during the coming decades.

The paper starts with a brief history of the evolution of transmission operations from the early digital control centers to the present day, including some predictions about expected future evolution. Transmission grid operations are coordinated through SCADA-EMSs that are usually housed at the overall reliability coordination level of the ISO/RTO, with several underlying control centers operating smaller regions of transmission. Tools that support real-time decision making collect measurements, process them, and display the results to the operator. As the number and rate of measurements increases, these tools need to be enhanced to improve operator situational awareness. Another set of engineering tools, such as state estimators and contingency analysis, provides the operator with suggestions based on real-time data. These tools need to be expanded to take advantage of the increase in available measurement data, such as from synchrophasors.

Control centers are the repositories of streaming real-time data and thus are valuable libraries of information for off-line analysis that can be the basis for forecasts, studies of new evolving grid behaviors, and updates of the models used in analysis. These repositories can also be the training libraries for ML and AI. This kind of analysis is closely related to transmission planning, which has become more difficult over time because of the uncertain nature of generation growth. Thus, this paper discusses transmission planning in some detail as well as the need for planning tools to deal with uncertainties regarding generation. Although construction of generation will remain deregulated, transmission planners will still have to calculate and track generation adequacy, which will also require new tools.

With increasing grid complexity, the skill set needed to operate the transmission system is expanding, and operator training is becoming more important. Improvements are needed in training simulators, which tend to be quite rudimentary compared to, for example, flight simulators. Recent weather incidents that have affected the grid—storms, cold snaps, fires—are pointing toward the need for greater focus on grid resilience. These kinds of high-impact, infrequent events need much more study with improved tools to understand preparedness as well as the costs of decisions about grid-hardening efforts.

The paper concludes with a discussion of the infrastructure needed for the types of research and development mentioned above. There is only one grid, which operates 24/7. Research on improved operational tools requires realistic simulation of transmission operations. We underscore the need for real, synthetic data sets and models of every grid component along with compatibility of tools based on standardized data format and management.

First Invited Panelist

Ken McIntyre, Executive Director, System and Operations Integration, Midcontinent Independent System Operator (MISO)

The perspectives articulated in the white paper are well aligned with the changes that grid operators continue to witness and also plan for. We must be deliberate and take new and different approaches to address the problems facing our industry because "business as usual" is not an option when moving forward. The balancing equation that underpins all grid operations has become exponentially more complicated with greater uncertainty both on the supply and the demand sides.

The author used four key words to describe the grid: "impressive," "diverse," [potentially] "opaque," and "vital." While these descriptions are generally accepted, opaqueness, in particular is most recognizable by potential partners (regulators, vendors, researchers and manufacturers) who are working together, with sufficient but limited RTO/ISO insight, to address key challenges.

In addition to these characteristics, the 2019 MISO Forward report highlighted the following three areas for consideration:

- Availability – refers to the need for resources (including knowing where they are) to address uncertainty
- Flexibility – refers to the need to recognize that traditional assumptions about the grid (e.g., inertia) and how to operate it (e.g., with fully dispatchable resources) no longer hold
- Visibility – which is always a priority for operations but now must also account for what's taking place within distribution systems, which (by design) may never be fully visible to transmission operators

Three areas of recommendations from this white paper are singled out for special attention:

1. Operations Real-Time and Engineering Support (People, Processes, and Technology)

The industry must begin furthering technology and intelligence in the area of state estimation and forecasting (advanced tools such as linear state estimation), along with the more granular visibility across the grid. Because of the nature of renewables, geographic information system modeling becomes a must (geography matters) along with shared data/information/modeling and more common tools across grid operators. We also must:

- Optimize and provide solutions, both corrective and preventative actions, for predicted conditions, including load profiles and capacity location to maintain flexibility.
- Develop visualization with underlying AI, ML, and automation. Think Autopilot!
- Focus on restoration and black start, managing into and out of emergencies by leveraging all resources, including renewables and demand-side resources.
- Optimize forecasting during normal and emergency conditions, including forecasting and predicting uncertainty and grid performance risk factors, anticipating market behavior, and forecasting unplanned outage alerts.

Other areas may need to be discussed that may be inherent in some of the other tools already listed, such as outage coordination. Transmission owners/operators also need to maintain their equipment and have a good understanding of the history of components, how often their maintenance cycles are performed, and how often they experience break/fix cycles.

    - With less flexibility in the system and as we continue to maximize and optimize existing transmission assets, transmission outages will become increasingly more difficult to manage and pose greater risk (given the increased uncertainty about availability and flexibility in the grid).
    - Another aspect to underscore is the time it will take to understand the impact of planned and unplanned behaviors of the new technology and how we assess that risk when operating the grid.

- For planning next-day operations as well as up to a year into the future, we need to think about how we assess risk and approve maintenance outages. The approach today is mainly reactive or "as needed," based on operator experience because of a lack of information and tools.
- In the future, we will need to leverage AI, ML, and automated studies to continually analyze the planned future system topology, resources, and load profiles in order to identify potential risks and offer solutions.
- System operators will need to work closely together, providing windows of opportunity to support reliability, and meet transmission owner/operator maintenance requirements.

2. Transmission Planning

- Integrated planning must support availability and flexibility on the grid.
- Dynamic representation must be modeled as new technologies are integrated into the grid, load characteristics change (responding to frequency perturbations on the grid), and automated actions are incorporated in the field and at control centers (think overseeing

Autopilot function). We need to study and plan for availability but also flexibility. We must mitigate transmission limits so ancillary or responsive reserves are not stranded between areas of the grid. This supports the need to look into flexible alternating current transmission systems (FACTS), static volt-ampere-reactive compensators, and synchronous condensers, to improve flexibility as the grid decentralizes.

- Long-term forecasting is imperative as we move from peak studies to every-hour studies and can incorporate variables such as human behavior (full electrification) and social impacts (for example, a post from Twitter can impact bitcoin mining behavior!).
- To design and build a resilient and reliable grid, we need to look at extreme events and understand the limitations and characteristics of the grid during normal and emergency conditions.

3. Training Simulators

- Digital twin simulators are needed for testing of applications and systems; think Pilot Simulation and Autopilot.
- Operators of the future will be monitoring more automated systems but will still need to understand grid characteristics and dynamics and expected outcomes.
- Simulation needs to advance to more scenarios and extreme conditions and allow for testing of automated processes to ensure that desired outcomes are achieved under certain scenarios. Operators cannot only be focused on following procedures, logging, and meeting compliance requirements.
- Training needs to extend beyond operators if this is not already being done. This is imperative as support roles and planning tools become critical for planning the grid and preventative actions.
- Let's change the mindset from "playback" to "play-forward."

Second Invited Panelist

Sandra Ellis, Interim Director, Transmission Grid Operations, Pacific Gas and Electric Company

Essential takeaways:

- The authors provided thoughtful and insightful observations.
- The assessments of the current state of transmission grid operations – engineering tools and situational awareness – are accurate.
- The proposed future research recommendations align with the increased complexity of transmission grid operations.
- Improved collaboration among industry (utilities, EMS & operational technology vendors) /academia/government is critical.

Perspectives on recommendations:

All recommendations are noteworthy for ensuring reliable and safe future grid operations.

My relative ranking of the recommendation areas based on immediate concerns for the present and future state of the transmission grid are as follows:

1. Engineering Tools to Support Transmission Planning
2. Operator Support of Real-Time Operations, in a tie for second place with Engineering Tools to Support Real-Time Operations
3. High-impact low-frequency events; restoration; coupling with other infrastructure
4. Research Infrastructure consideration
5. Training simulators

Final thoughts:

Next-level research that is essential to address challenges in grid operations includes: probabilistic transmission planning, dynamic models, synthetic models, and operational procedures based on risk assessments.

Improving cross-collaboration among academic/industry/ government is critical. e.g., data exchange and realistic test environments.

There is a need to ensure research areas/recommendations will support the educational pipeline for future engineers/operators.

Discussion

- Opaqueness and information sharing, information sharing between organizations or even between different departments within the same organization:
    - Operations information doesn't flow well to planning. The concept is to ensure it is available to those who have legitimate needs for it, but operations information is sensitive and should be restricted. This is an area for DOE to address. There are differences in different regions.
    - Visibility of operations is a question as the system becomes a lot more complex: How much visibility do we need to share between the different regions? Especially at high speed, this is a technical question.
    - There needs to be a value proposition for why people will share information between organizations. With a value proposition, the data will flow more easily. Need to look at regulatory requirements, ownership issues.
    - Building confidence across different teams is necessary to break down silos.

Additional Questions and Comments Received through the Chat that were not Discussed by the Panel

- With decreasing number of large synchronous generators, how do you propose to keep the remaining synchronous generators from falling out of synchronism?
- How about more interactive information exchange between non-utility-owned stakeholders in operations and the system operators? Who needs to know what? Some info will not be known;

what is the protocol for minimal information exchange instead of the transmission operator asking for very high-granularity models?

- Must focus on bridge building between academia/research/national Labs. Clarification: bridge between those entities and industry (manufacturers, software developers, utilities, etc.).
- There are silos between system planners and system operators in utility industry. Any thoughts on how to improve the communications between planners and operators. Is DOE's research addressing these issues as [they are] critical for future grid planning and operations?
- Do you expect to see future grid operation planning tools/software [that] will have analytical capability on probability-based system operation assessment in the next 1-2 decades? To get there, what are the key R&D areas industry and academia should focus on?
- Policy changes are driving operations of the grid into a space where operators and planners generally react to changes in the grid. In the past changes to the grid were very much proactive and seemingly well studied well in advance. The recent close calls in [Western Electricity Coordinating Council] WECC and elsewhere are surely signs of the reactive (i.e., non-proactive) nature of studies and analysis.

4. Session 2: Distribution Integrated into Transmission Operations

Authors

Chen-Ching Liu, Virginia Polytechnic and State University
Emma M. Stewart, National Rural Electric Cooperative Association (formerly of Lawrence Livermore National Laboratory) (presenter)

Abstract

This white paper presents a vision of a future grid in which distribution systems are integrated with, and play a supporting role in, transmission grid operation. In our vision of a future integrated transmission and distribution (T&D) system, DER provide collaborative, coordinated operational support for both transmission and distribution operations. The white paper makes recommendations for R&D in the following areas: enhanced data/information; data analytics and protection/control technologies; grid decision-support environment, tools, and communications; operators and control centers; and cyber security and privacy.

Synopsis

This white paper presents a vision of a future grid in which distribution systems are integrated with, and play a supporting role in, transmission grid operation. In our vision of a future integrated T&D system, DER provide collaborative, coordinated operational support for both transmission and distribution operations. An increase in renewable electricity and energy storage will facilitate reduction in climate impacts through retirement of major greenhouse-gas-producing assets. In the grid of the future, non-wire alternatives will be commonplace. Large-scale trading in electrical energy and ancillary services will be carried out in an integrated T&D environment where distribution system operators will also serve as distribution system reliability coordinators. DER and data on demand will be widely available through a networked information environment that will enable operation, control, and trading. Computational tools, including optimization and AI/ML, will be available to support this integration. A hybrid, intelligent decision-support environment will combine human operators and AI tools. Cyber and physical system security and privacy will be ensured by comprehensive procedures and advanced monitoring, detection, and mitigation technology. The integrated T&D system will have the capability to recognize and mitigate threats from extreme events such as major hurricanes, earthquakes, wildfires, and cyber intrusions. Training and development will be in place to prepare a workforce well versed in advanced optimization and AI/ML tools and able to function effectively in the future integrated T&D environment.

We present our R&D recommendations in the form of themes organized around five layers of the operation and control architecture envisioned for the integrated T&D grid of the future:

1. **Enhanced Data/Information**

R&D themes: DER/load information such as energy and control capacities, availability for scheduled trading, operational or control actions, location of connection with the distribution grid, protection design, status/analog data, and measurements from meters and sensors

2. **Data Analytics and Protection/Control Technologies**

R&D themes: (1) Control devices and systems installed on the grid and at DER and locations with significant load (2) Computational tools to be used by DER owners and loads in an electricity market environment

3. **Grid Decision-Support Environment, Tools, and Communications**

R&D themes: (1) Decision-support and analytical tools used by distribution operators to schedule operations and support reliable, resilient, cyber-secure transmission grid operation (2) Computational tools to determine the ancillary services necessary to maintain system reliability and resilience, including advanced distribution management systems, outage management, and service restoration

4. **Operators and Control Centers**

R&D themes: (1) Means for distribution grid operating centers and DER/microgrid operating centers to coordinate with energy control centers in the transmission system, including data sharing; field-crew dispatch; and planning, operational, control, and restoration tasks (2) Workforce development

5. **Cyber Security and Privacy**

R&D themes: A holistic strategy for cyber-physical system security and stakeholder data privacy

First Invited Panelist

Leonard Kula, Chief Operating Officer and Vice-President, Planning, Acquisition and Operations, Independent Electricity System Operator

Three foundational premises underlie my remarks on this white paper:

First, DER penetration will grow significantly, but it will not, and likely will never, be the dominant source of generation on the grid. DER will provide capacity, but it must be supplemented by transmission-level resources for energy.

Second, not all DER will participate in providing resources to the grid. [DER that does not provide resources to the grid] will operate autonomously behind the customer's meter and act as a negative load when seen from the grid's perspective.

Third, growth in the measurements required to provide observability of DER will be difficult to maintain as DER increase in number. Complete observability of DER should not be expected.

From these premises, the following observations are made on this white paper:

The white paper does a good job describing the evolution of distribution system operations, but it does not describe the parallel evolution of transmission system operations as completely. For example, outage management and reliability coordination by transmission system operators are not discussed, yet they will also need to evolve to recognize and account for growth in DER.

The white paper does not adequately describe what and how responsibilities can, should, or will be divided between the transmission system operator and the distribution system operator. For example, how would operational actions that improve transmission system reliability yet also create distribution system reliability problems be resolved/harmonized?

Second Invited Panelist

Matthew Gardner, Director – System Protection, Power Delivery Group, Dominion Energy

There is a danger in relying on the "old" ways that transmission thought of distribution (distribution is just passive load) and that distribution thought of transmission (transmission is simply an infinite bus). The danger lies in thinking of distribution as a monolith. There are a number of distribution-specific considerations that need to be accounted for in planning R&D that addresses distribution operations integrated into transmission. These considerations include:

- Scale – The circuit miles of distribution are an order of magnitude greater than the circuit miles of transmission. The number of monitoring points within distribution are two orders of magnitude greater.
- Regulation – Transmission is regulated by a single federal agency. Distribution is regulated separately by each state or oversight board.
- Pace – It has taken 25 years for microprocessors to become ubiquitous in transmission equipment; it will take even longer for them to become ubiquitous in distribution equipment. Bolt-on solutions and backward compatibility with existing distribution technologies should be recognized as a more practical approach for introducing new technology into distribution operations.
- Modeling – Development and maintenance of a complete or perfect model of distribution systems is an illusory goal. Instead, data-driven, scenario clouds are the only feasible approach.
- Communications – Communication technologies will play an essential role. The focus should be on incremental improvements to existing approaches, for example, moving away from low-cost but stand-alone sensors to focus instead on integrated sensors.
- Market Size – The market size for distribution technologies is much larger than it is for transmission technologies. This is an advantage for introducing new technology into distribution. For example, there are greater opportunities for open-source approaches.
- Work Force – New entrants are drenched in technology in ways that the old guard may not fully appreciate. We should work with gamers to design control interfaces and to develop training simulators.
- Pilots – Fail-fast pilots are desirable.

- Data – We should bring researchers to the sources of the data, not provide data sets (or synthetic data) for them to work on.

Discussion

- HELICS and NAERM: please expand on what these are because not everyone on the call is familiar with these DOE projects and elaborate on how you envision that they may help address the issues raised in your paper.
    - HELICS stands for Hierarchical Engine for Large-scale Infrastructure Co-Simulation, a DOE Grid Modernization co-simulation project to bring transmission and distribution together, including buildings, DER, and other analysis.
    - NAERM is the North American Energy Resilience Model, bringing transmission-level models together with information from different regions for a heads-up view of how the whole country is operating and how interfaces are working together.
    - The future vision isn't necessarily that DER does everything. We need to enable the various levels of renewable resource penetration that may occur at different locations.

Additional Questions and Comments Received through the Chat that were not Discussed by the Panel

- The authors should be aware that IEEE Standard 2030.11™ IEEE Draft Guide for Distributed Energy Resources Management Systems Functional Specification was approved as a new standard by the IEEE Standards Association Board on 9 May 2021. A copy of the document was forwarded to the Standards Publications Department. In the meantime, the approved standard in draft form is available from the IEEE Standards Association now. That guideline is highly pertinent to the idea of distribution/transmission interfaces.
- Is there an official DOE definition of "non-wire alternatives"? In some forums seems like these exclude traditional FACTS devices. Shouldn't these also be considered as non-wire alternatives?
- With increased direct current (DC) loads and DC generation with photovoltaics, the need for DC distribution makes sense in the future distribution grid. Is DOE's research considering DC distribution as an option for future?
- Is transmission-distribution integration potentially making systems more vulnerable to cyber attacks?
- Who can be some early adopters for an integrated T&D paradigm? Will the vertically integrated utilities take a key role first? Also, what role will the National Rural Electric Cooperative Association and electric co-ops take?
- All DER must be dispatched through a security-constrained dispatch method.
- Do you have examples (models? institutional processes?) of how you are starting to consider distribution-side resources in transmission planning and operations? Do you have any DER in your resource adequacy (even small overall)?
- Do we have an estimate for the infrastructure investment in the distribution system that will support a full transition to a transactive energy paradigm with multi-directional flows, peer-to-peer market etc., and how do you envision the changes in the structure and business models of the distribution companies in such a future scenario?

- If we can envision a faster distribution system evolution, would there be any “leapfrog” technologies that would help leap over the need for slow evolution of 50-year-old technology? Much as African countries leaped over the need to install telephone infrastructure in the ground to widespread use of cellphones? If we are going to integrate intermittent renewables into the system writ large, it seems that demand response will need to be embraced throughout the industry and customer base. Communications technologies perhaps? Home automation?
- Biden administration announced on April 22, 2021 a pledge to reduce U.S. economy-wide carbon emissions to around 50% of 2005 levels by 2030. Do you see any changes in the DOE’s white papers in terms of prioritizing / reprioritizing the R&D topics to meet the clean energy goals?
- At the current time, we do acquire DER in our capacity auction and then dispatch them in our real-time energy markets. We have about 1,000 megawatts (MW), on a 25,000-MW system. At this time, the 1,000 MW is small enough that we're not materially impacting the distribution system. There are more DER installed in Ontario that are not participating in market and system operations: missed opportunity. We are grappling with the way forward. Do we (1) understand the location, quantity, and characteristics of all DER and model/forecast/dispatch them like transmission-connected resources, or (2) specify the performance requirements for DER (capacity, energy, ramp etc.) and require aggregators to meet those requirements, putting the onus on the DER aggregator/virtual power plant to support reliability?
- DER aggregation must be within a single balancing authority. You cannot aggregate rooftop solar in Florida with those in Iowa and sell the package to Ontario. Remember the power-flow equation.
- I would offer that DER aggregation might need to be on a single node within the power system, or maybe within the same small electrical region where power flow is understood and similarly impacted by dispatch of the aggregated DER resource.
- Another aspect of the greater integration between T&D is the effect of customer/end-user preferences; load flexibility from loads (especially EV and heating, ventilation, and air conditioning would invariably depend on customer choices, etc. Do the panelists see value for integrating customer behavior for next-gen transmission operations?
- Considering transmission system operators and distribution system operators are busy with their own problems on a daily operation basis and may not have bandwidth or incentives, coordinating transmission system operators and distribution system operators may need a federal or FERC-level organization (or alliance) with some well-agreed regulation/standards in place. What is your perspective on such regulatory effort to expedite this T&D coordination progress?

5. Session 3: Automatic Controls

Authors

Jeff Dagle, Pacific Northwest National Laboratory
Dave Schoenwald, Sandia National Laboratories (presenter)

Abstract

This white paper describes technologies that can be deployed to improve real-time control of the U.S. electricity grid during both normal and off-normal conditions and to improve the grid's operational efficiency and resilience. The white paper makes recommendations for R&D in the following areas: remedial action schemes (RASs); power electronic devices for control; simulation tools; grid architecture; DER for control; adaptive islanding; grid hardening against threats; and grid restoration (black start).

Synopsis

This white paper describes technologies that can, with prioritized R&D investment by DOE, be deployed to improve real-time control of the U.S. electricity grid during both normal and off-normal conditions and to improve the grid's operational efficiency and resilience. In addition to describing these technologies, we provide a list of recommendations for DOE research and development investment, prioritized by timeliness and focused on the grid of the next 20 years.

This paper addresses the following topics:

- The evolution of digital controls
- Coordination among RASs and special protection schemes, including adaptive islanding, an advanced system integrity protection scheme that reduces the impact of an uncontrolled cascading failure during an emergency by deliberately breaking an interconnection into smaller segments
- Planning for and managing frequency response, voltage stability, small signal stability, and transient stability on a grid that has a significant penetration of inverter-based generation
- New requirements for generator (and load) capabilities to support the grid, including leveraging the faster capabilities that are enabled by power electronics

Other emerging technologies that are discussed include wide-area, real-time control involving high-speed time-synchronized measurements; and expanding control actuation capabilities to include inverter-based generation, energy storage, and other power electronics-enabled resources. We focus on how these technologies will enable enhanced system-wide control.

We also address supporting technologies, such as the need for creating advanced simulation tools to design and deploy the capabilities listed above, and discuss considerations for developing controls and protection schemes that are robust to natural or man-made threats. This includes threats that may be directed at the control systems themselves, especially cyber threats. We examine the opportunity for increased automation, or alarming/cuing and intelligent analytics, to improve operator performance during emergencies or times when staffing is short.

First Invited Panelist

Ryan D. Quint, Senior Manager, BPS Security and Grid Transformation, North American Electric Reliability Corporation

There is a need to more clearly articulate the value proposition for, or business needs served by, automatic controls. Today, the grid needs flexibility while ensuring reliability and security more than anything else. How do automatic controls address this need?

Response-based RAS is a sensitive issue. The San Diego blackout was caused (in part) by automatic controls (i.e., a response-based RAS). Design and deployment of automatic controls requires accurate models, precise measurements, and lots of studies. There is great promise, yet it is difficult to anticipate every possible means by which something could go wrong. Should we find ourselves operating in an unstudied state, having an automatic control unexpectedly operate is a great risk to reliable operations.

Modeling is one of the biggest challenges. All of our planning (including that for automatic controls) depends on the accuracy of the modeling studies. Yet the accuracy of modeling is currently limited. For example, studies following the Blue Cut Fire event illustrated that we did not have adequate information on how inverters perform and still do not have accurate models to for many bulk power system-connected resources in the interconnection-wide base cases.

The white paper does not fully discuss the operational coordination issues that arise when generation is dominated by inverter-based sources. We know that inverters can be programmed to provide voltage control, and primary and fast frequency response. But we have not thought through how, specifically, we want them to participate in control of the grid particularly under low-short-circuit-strength conditions or extremely high penetration levels (as seen in present operating conditions such as the 90+% renewables penetration levels that the California Independent System Operator is experiencing today).

We should especially think about leveraging capabilities of DER. For example, EVs could provide frequency response to grid-level events; however, we need to ensure those resources are providing grid-friendly behavior before even considering them for grid services. We need to communicate grid-level issues/needs to the end-use communities. There is a need for R&D to bring these parties together to discuss needed reliability technology developments.

Second Invited Panelist

Greg Zweigle, R&D Fellow Engineer, Schweitzer Engineering Laboratories

The paper is well-written and does a nice job of outlining research needs and goals in this area.
The goal of research should be to make operation of the power system simpler, not more complex. It is easy to make things more complex; it is much harder to make them simpler. "Simpler" means more understandable, easier to de-bug, and more reliable to operate. "Complex" means harder to understand, harder to de-bug, and more likely to be unreliable in ways we cannot anticipate.

There are already many factors introducing new complexities into power system operations, such as gas-electric interdependencies, distributed resources, and software interdependences. Layering complexity upon complexity introduces new risks. We therefore should avoid introducing further complexities.

In this regard, we must always ask ourselves whether automatic controls are a step in the right direction. As the authors state, new controls "must not introduce unnecessary complexity."
We should move away from a stance from which we develop complex control schemes for which we conclude that there are no obvious deficiencies to instead develop (and embrace) simpler (inherently stable) control schemes with obviously no deficiencies.

This simplest way means the most cyber secure, most reliable, safest, and best return on investment.

Discussion

- Primary control was never designed or tuned for stabilizing the wide-area system; how do we better understand the fundamental design challenges of fast-acting controls for solving wide-area problems?
    - Control design challenges: using storage, or the Pacific HVDC Intertie, to dampen oscillations. The control design needs to incorporate simplicity. Start with a proportional control, then add a supervisor for situational awareness, to gracefully disarm the control if necessary.
    - Using different kinds of sensors and actuators to modularize the control design: Flexible and portable to address issues of damping, small signal stability, and transient stability without impacting the function of primary control. Making the grid more stable.

  There is still a long way to go, but this is not currently changing rapidly. There are cyber-security concerns.
- RASs: a lot of different scenarios; how do we vet those, keep them up to date, document, ensure that human operators understand the schemes? Will adaptive RASs help some of the challenges with traditional RASs?
    - Adaptation abilities will be important because it is difficult to have a specific response to an event when there is uncertainty about the nature of the event as it is occurring.

RASs have been well studied and well documented, but as they proliferate there is a risk that they may interact with each other in unanticipated ways.
    - Industry has good experience with other types of emergency controls (e.g., under-frequency load shedding), that are coordinated with other controls but automatically take action during specified conditions without needing to enumerate every possibility in a complex decision tree. Our concept of adaptive RAS is similar; it is programmed to take action, based on an observed response, which is determined to be the right action regardless of the specific events leading up to that condition.
- Modeling, and bringing in human behavior: what is the role of digital twins for modeling these responses?
    - The challenge of the model. There are pros and cons. It has a lot of potential. The challenge is having the humans keep up with the transfer of information, making sure the model is updated; compiling models is challenging. Basic database management problem is keeping models updated. We have a long way to go.
- Proprietary nature of inverter-based resources and manufacturers not wishing to disclose details of how their controls work. How do we increase transparency for system operators?
    - There is a big push for generic electromagnetic transients program models. There is a need for higher-resolution models. The details of the controller implementation are important. We need help from the vendors to provide the details. The responses from original equipment manufacturers are mixed. Our message is consistent: transmission planners should be asking for a positive sequence model, a detailed electromagnetic transients program model, and assurance that the models accurately depict how the controller will operate. We need to rethink what it means to have model verification.
    - After the models are documented, don't update the firmware.

Additional Questions and Comments Received through the Chat that were not Discussed by the Panel

- Increased computational capabilities enable the use of more granular models that can accommodate dynamic operating strategies such as topology control through transmission switching, dynamic line rating that enables higher rating for limited durations, etc. Such strategies will enable more efficient use of the transmission infrastructure and increased use of computational power to replace transmission investment. Should system operators be equipped with supercomputers to enable such development?
- Application of digital twin simulation technologies to simulating power systems including human behavior may be needed to study the power system behavior with increased renewables.
- There are two ways of making sure feedback works: millions of scenarios, or a fundamental approach to having provable stable response in closed loop.
- The Electric Power Research Institute has pioneered the increased transmission capacity of the existing infrastructure using dynamic ratings, FACTS, and converting alternating current (AC) lines for DC operation. These options will certainly meet the short-term needs for increasing

transmission capacity; however, DOE should be considering a long-term outlook in their R&D efforts where there is a need for new transmission and distribution to meet the future low-carbon clean energy goals.

- How many universities teach courses on automatic controls for changing industry?
- On the emphasis of "do no harm," like the quote "all models are wrong; some are good," in control, we say "all controls do harm; good controls do more good than harm." Is "do NO harm" realistic in control designs?
- Making regulatory pushes for technology adoption vs. doing commercial deployment first and then developing standards: how do you strike the balance between keeping adopters happy to use good technology without making them feel like they're being dragged into the future?

6. Session 4: Hardware and Components

Authors

Chris O'Reilley, Oak Ridge National Laboratory
Tom King, Oak Ridge National Laboratory (presenter)
Edgar Lara-Curzio, Oak Ridge National Laboratory
Zhi Li, Oak Ridge National Laboratory
Madhu Chinthavali, Oak Ridge National Laboratory
Lingwei Zhan, Oak Ridge National Laboratory
Travis Smith, Oak Ridge National Laboratory
Mike Marshall, Oak Ridge National Laboratory

Abstract

This white paper focuses on transmission technology hardware and components, not including energy storage, and makes recommendations for R&D in the following areas: power-flow control devices; high-power delivery systems to transmit over long distances; advanced sensors; and advanced protection systems.

Synopsis

This white paper focuses on transmission technology hardware and components to help ensure the reliability and resiliency of the future grid. To prioritize transmission technologies for public-private partnerships and federal investment, our team analyzed multiple potential pathways that the future grid could take. We grouped those pathways into four scenarios and identified technology solutions that could address the challenges outlined in each scenario. The technology solutions that rose to the top in the largest number of scenarios were evaluated in this white paper.

The four future scenarios, which were defined to capture major trends that would have significant implications for future grid infrastructure and operations, are:

1. A more distributed grid
2. Increased clean energy with high penetration of variable renewable energy
3. Increased load growth with re-establishment of manufacturing base
4. Cyber and physical vulnerabilities and threats to the nation's grid

Several key technologies consistently emerged from our analysis that addressed the conditions of these extreme scenarios. Our recommendations for future R&D investment are centered around these key technologies:

Power-flow control devices: Transmission-scale reactive power devices, low-cost hybrid systems and energy storage, power electronic building blocks for multiple applications such as FACTS devices and solid-state transformers

High-power delivery systems to transmit over long distances: Ultra-conductive systems, smart materials (constructed using advanced manufacturing techniques), transformers, wireless power transfer, superconductivity

Advanced sensors: High-fidelity sensors, asset monitoring (non-destructive evaluation, drone survey of lines), and alternative timing

Advanced protection systems: Model-driven adaptive protection systems, negative sequence source and alignment to advanced sensor and communication technologies

First Invited Panelist

Andrew Phillips, Vice President, T&D Infrastructure, Electric Power Research Institute

Achieving a 100% carbon-free economy will require significant and rapid investment in new transmission. These transmission assets must be both reliable and resilient. Hardware is hard because all hardware has to work all the time.

This perspective has direct implications for R&D on transmission hardware. The R&D timelines in the paper focus only on developments up to the point of creating prototypes. To this, we must add the time required to full adoption. These additional steps, which include accelerated aging tests and extended field demonstrations, should be recognized.

In fact, many promising technologies won't be able to make a significant contribution to the expected rapid build-out of transmission because it takes 7-15 years to build new transmission lines.

A portfolio approach to R&D should be pursued that balances short, medium, and long term; and low risk vs. high risk. In the short run, develop test beds and run pilots to lower their costs. In the medium term, vet prototypes with manufacturers so that technologies can be tested in final configuration in pilots. In the long term, focus on game-changers; recognize that only one out of 10 will work.

Increasing the capacity of existing rights-of-way is an important focus. In addition to the areas identified in the white paper, there is also a need to look at a broader range of technologies. These technologies include voltage upgrades, AC-to-DC conversion, multi-circuit conversion, and adding conductors. These are not yet considered mainstream because there is significant utility uncertainty (or unfamiliarity) regarding their performance.

Finally, we need to address concerns about whether vendors will have access to needed raw materials and will we have the right workforce? Can we upgrade it or add robotics?

Second Invited Panelist

Jeffrey G. Hildreth, Electrical Engineer, Diagnostics, Metrology and Laboratories, Bonneville Power Administration

Coordination among researchers is important. There are many research providers in this space (the Electric Power Research Institute, Advanced Research Projects Agency-Energy, utilities, etc.). The Office of Electricity's programs should proceed with a good understanding of what these other providers are doing.

The white paper emphasizes technology "push." There is a need to also focus on market "pull." That is, we should consider how markets and policies influence utility technology decisions. In other words, we should evaluate R&D based on how well it incentivizes and de-risks market adoption by utilities.

Decarbonization is going to be a big driver. Maximizing use of existing assets is the low-hanging fruit. Power-flow control and HVDC technology, therefore, should be emphasized.

There are big advances in power electronics. We are not building HVDC, but we are pursuing the underlying research.

We should explore how market designs can incentivize adoption of new technology.

Electrification of transportation needs to be recognized. There will soon be lots of storage on the grid. We need to explore how to incentivize EV charging to minimize strain on the grid. We need to determine how to design/control charging so that it is grid friendly.

Finally, there is a critical need for high-power, in-grid test beds at the transmission level, especially for power-flow control devices. There is no substitute for real-world demonstration as a principal means of "de-risking" a technology. All utilities want to be first to be second. This is an expensive undertaking. It requires utility partnerships. DOE should encourage development of test beds as national resources.

Discussion

- Are the scenarios mutually exclusive, independent, or can you get combinations of these scenarios?
    - The idea of combining the scenarios was discussed, but for the purposes of the paper they were considered separately.
- Converting existing AC lines to DC
    - Already discussed during the panel session.
- Wireless transmission
    - The recommendation is to monitor for any advancements (this idea has been around for a long time). There remain feasibility challenges. There are niche applications, but bulk power transmission is likely not feasible for the foreseeable future.

- Technical or logistical barriers to adopting sensor technologies
    - Installation is a challenge. If an outage is required, there are additional installation challenges. Ease of use is a key consideration. It is not just developing the transducer but need to consider as a system. The complete installation is typically 2x the sensor cost. Also, accuracy of the information.
    - It is not just about making a sensor easy to install. It is still expensive. Labor costs can be significant. Should multiply sensor cost by π, or maybe even π^2.
    - More sensor data are not necessarily a good thing from a utility perspective. The data need to be reliable, and the analytics need to provide actionable information. That is the real challenge.
    - There is a good role for DOE: multiple utilities sharing their experiences. Because failures are rare, they are good opportunities to exchange information.
- Sensitivity and precision, or specifically quantum sensors
    - As engineers, we like to measure with a vernier, mark with a chalk, and cut with a chainsaw. We need to understand what actionable information is needed, then take measurements accordingly.
    - Quantum sensors were not specifically covered in the white paper.
- Superconductors, specific use case offshore wind
    - DOE has been investing in this for decades. The challenge is reliability/resilience. Dependent on refrigeration system. Redundant refrigeration adds significantly to the cost. A lot of the technology has migrated offshore. Can we conduct longer-term R&D? Can we achieve room-temperature superconductivity? Scientific barriers. Maybe other parts of DOE can investigate this.
    - Transmission lines already have good efficiency. There is a relatively small benefit for bringing on a highly complex technology. Maybe there are niche applications.
- Hardware for power-flow control vs. smarter dispatch with power injections (generation and load control at the nodes)
    - There would need to be comparisons between what you can do from operations vs. what you can do with advanced hardware. Test beds allow better understanding of the benefits and value proposition.
    - Look at where DOE is best able to add value. Hardware is hard; there is unique role for DOE. On the operations side, academia is contributing a lot (papers addressing these issues). The challenge there is data sharing.
- Power electronics, other applications beyond solid-state transformers (e.g., solid-state breakers)
    - Yes, the white paper addresses these applications. Also, power electronics can be hybrid with transformers.
- The role of 5G associated with sensor communications
    - There is a communications section, but it did not specifically address 5G. There are R&D challenges related to security and reliability that are associated with integrating wireless data.
- What are sensor deployment weakest links?

    - We have long battery life and power harvesting, and other challenges have been overcome. We are expecting long-lived assets. We are monitoring assets that are expected to operate for many decades. We need to be confident of multi-decade life of these sensors. Communications remains a challenge, understanding the protocols and the medium. We need to understand obsolescence time frames, be immune to wireless jamming.
    - New components need to integrate with legacy systems.
    - Data need to be available and sure.
- Low-frequency AC?
    - Not included in the white paper.
    - It relates to the maturity of power electronics.
    - There is a significant barrier to utilities implementing new technology that requires training and poses other workforce issues.
    - Would be converted with power electronics, not transformers.
- What DOE effort would be most useful to industry?
    - Test beds – not just HVDC, but anything that needs to be tested on the grid. Need utilities that will make their grid available for field testing. Need the infrastructure available for the testing, but also protection and redundancy available so that customers are not impacted as a result of the testing.
    - Portfolio approach – increased power in rights-of-way (existing or new), including current upgrade, voltage upgrade, HVDC, new compact transmission line design, low-frequency AC. That will be the bottleneck in reaching the low-carbon future.

Additional Questions and Comments Received through the Chat that were not Discussed by the Panel

- Can DOE labs provide a national grid digital twin? Instances of this environment could be used for planning, testing, implementing, and operations training for the future grid while providing an avenue for stakeholder and regulatory input.
- Given that the U.S. is not utilizing the higher-voltage AC or DC transmission available commercially, why are we recommending doing R&D in superconductivity, wireless, etc.?
- Can the panelists comment on the importance, if any, of edge processing of sensor data to extract actionable information to drive the selection of the communication infrastructure?
- Could you comment on the technical readiness of voltage-source converters (VSCs) for multi-terminal HVDC in the U.S.? Is there any reason to build new line-commutated converters, or should we go all in on VSC?
- VSC HVDC is technically ready to implement in multi-terminal HVDC environments. Multi-terminal DC grid with VSCs was implemented in China already. It can be done in the U.S. as proposed in macro grid concepts by MISO and others. There is still a need for line-commutated converters for ultra-HVDC (800 kilovolts and above with 8,000 to 12,000 MW power levels) as VSCs have not been demonstrated at ultra-HVDC levels.

7. Session 5: Economic Analysis and Planning Tools

Authors

Jessica Lau, National Renewable Energy Laboratory (presenter)
Benjamin F. Hobbs, Johns Hopkins University (presenter)

Abstract

This paper describes ongoing and future needs for concepts, methods, data, processes, and technologies to support comprehensive planning for the U.S. electricity transmission system. The white paper makes recommendations for R&D in the following areas: multi-value planning; workforce development; behavioral underpinnings of economic valuation and market designs; market simulation and planning models with flexibility and scalability; and adaptive transmission resource planning under profound uncertainty.

Synopsis

This paper describes ongoing and future needs for concepts, methods, data, processes, and technologies to support comprehensive planning for the U.S. electricity transmission to meet reliability, economic, sustainability, and other policy goals.

The paper first identifies universal themes that transmission tools and concepts will need to account for. These include facilitation of reliable, economic operations and resource investment, as well as support of social and environmental goals such as addressing greenhouse gas and air pollution reduction and landscape preservation. There is also a need for more data and greatly enhanced computational abilities to simulate operations and evaluate resource and grid investments. This need is driven by the explosion of new devices and assets on the grid, by rapidly improving optimization methods, and by greater recognition of the profound uncertainties involved in long-run planning. Additionally, new research should be founded on social-science-based understanding of market responses to network enhancements, transmission investment impacts on resource investments, and facilitation of inter-regional cooperation to make trade more efficient. Finally, to effectively harness this understanding and use those tools to design a grid that effectively addresses multiple goals, there is a need for an appropriately trained planning and engineering workforce.

The white paper elaborates on these themes by outlining specific requirements for transmission tools. For instance, future tools will need to recognize that grid reinforcements can both substitute for and enhance the value of supply, storage, and demand-management investments. Thus, an anticipative transmission planning paradigm should be more widely used than is the case day. In this paradigm, grid planners consider the ways in which grid investments would affect not only how resource investments are operated, but also what technologies are built and where. In addition, a comprehensive view of grid, supply, demand, and distribution-transmission relationships is necessary to correctly value and appropriately plan grid reinforcements. Correct valuation and appropriate planning will also require advances in technology modeling, economic theory, numerical optimization methods, and the design of institutions to align private incentives with overall market and social benefits and costs. Besides these complementary and substitutive relationships among bulk and distributed resources, storage, and grid reinforcements, future planning methodologies must account for several other analytical and practical challenges, including, among others:

- compensation for the value that grid reinforcements provide not just to energy markets but also capacity and ancillary services
- recognition that this value depends strongly on market designs and efficiency of trade and coordination among balancing authorities
- decision making in the face of increasing short-term variability and long-run uncertainty
- coordination of markets and infrastructure planning, as well as the increasing roles for assets, such as storage, that can receive both regulated and market revenues
- the need to provide incentives for participation in inter-balancing authority projects so that all participants benefit

The white paper outlines five research areas and 23 specific topic areas that the authors recommend that DOE consider as responses to the above challenges, to be pursued over the next 10 to 20 years. The five research areas are:

1. **Multi-value planning**: enabling assessment and planning of a variety of concurrent power system goals
2. **Workforce development**: training and empowering workers to support electricity consumers through education, learning, and experiences
3. **Behavioral underpinnings of economic valuation and market designs**: deepening of social science research to understand consumers, markets, operations, and non-techno-economic drivers
4. **Market simulation and planning models with flexibility and scalability**: expanding realism, flexibility, and scalability to appropriately model and plan for the grid of the future, including developing models with greater fidelity to actual physical and market systems as well as simplified models that are accessible to regulators and stakeholders who can use them for education and insight into the tradeoffs inherent in transmission planning
5. **Adaptive transmission resource planning under profound uncertainty**: advancing robust planning through risk assessments and scenario planning, considering the full range possible futures

These research efforts should involve not only power engineers, but also computer scientists, empirical economists, and human factors specialists.

First Invited Panelist

John Buechler, Executive Director, Eastern Interconnection Planning Collaborative

Comprehensiveness vs. Complexity

- The report is comprehensive and has a broad-ranging scope.
- System reliability is recognized as the core principle (page 1).
- The basic transmission planning needs are recognized: input data, fidelity, flexible modeling tools, computational improvements, better forecasting methods The challenges to meet these technical requirements are significant in themselves.
- The addition of externalities will add uncertainty and complexity, not necessarily improving the accuracy of results and possibly resulting in increased risks to system reliability.
- As noted, "…simpler models ...can produce very important insights for regulators and stakeholders" (pages 3 & 12).

"Transmission Resource Planning"

- Proposed definition (page 1): *"Transmission Resource Planning" = transmission planners will anticipate how supply, storage, load, and distribution are intertwined and can provide grid reinforcements and respond to pricing."*
- While somewhat modified, this definition implies that transmission planners must "anticipate" the factors that drive supply resources, market prices, and consumer response in order to plan a reliable grid.
- This is contrary to traditional transmission planning practice and historical experience.
- Resource expansion is driven by technology, public policies, and regulatory requirements (page 2).
- Transmission planners then respond by providing a reliable and economic delivery system to meet these needs (page 23).

Technical vs. Non-Technical Aspects

- Government policies and regulations as well as consumer behavior pose significant risks and uncertainties for energy planning.
- Workforce development and education are also important.
- R&D on socio-economic issues can aid in understanding these factors.
- However, the R&D recommendations for these topics have little to do with the core aspects of transmission or resource planning.
- Attempting to force these non-technical considerations directly into the transmission planning models will add needless complexity to already daunting technical and data challenges.
- Such R&D can and should be conducted separately, and DOE has the expertise to perform and/or coordinate such efforts.
    - Please clarify if this was, in fact, the authors' intent

Focus on Markets & Economic Planning

- The Eastern Interconnection Planning Collaborative's membership is composed of entities with ISO/RTO structures as well as vertically integrated private utilities, the Tennessee Valley Authority, and several municipal/cooperative members.
- Maintaining and improving bulk system reliability is the universal objective of the Eastern Interconnection Planning Collaborative's members, and many of the analytical tools used are the same, other aspects of planning may differ, but some of the collaborative's members believe that market-faced methods may have less significance in systems where the majority of generation and transmission is owned in common.
- These diverse views should be recognized by DOE when conducting market-based R&D.

Linkage to Other DOE Initiatives

- Although there are many linkages proposed among the various R&D initiatives recommended in the white paper, other existing or ongoing DOE initiatives are not mentioned, e.g.:
    - *DOE Grid Valuation Project* – This project provides a good foundation for integrating various technical and non-technical perspectives into the planning process.
    - *North American Energy Resilience Model Project* – Our understanding is that this multi-Lab Project is also investigating multi-sector interdependencies in planning of the electric system (e.g. natural gas, water, & communications).
    - *DOE "Near Term Reliability & Resilience Analysis"* – This project will study the implications of the changing resource mix in various regions of the country in relation toextreme weather events.
- It is recommended that DOE incorporate these initiatives into consideration of the recommended R&D.

Authors' Recommendations

In the context of the above comments, the authors' recommendations have appropriately prioritized the subject matter, for example:

- High-Priority Topics
    - Multi-value planning
    - Multi-sector interdependencies
    - Larger-scale production cost models
    - Fidelity improvements
    - Extreme events modeling
    - Improved forecasting methods & data needs

Second Invited Panelist

Tim Heidel, Chief Technology Officer, VEIR, Inc.

It is essential that transmission planning processes work effectively and that new transmission is built in order to meet the challenge of decarbonizing the power system. Yet transmission planning is only going to get harder because it must now also take into account of delivery of ancillary services, energy storage, aesthetics/visual impacts, equity considerations, and other political factors.

Aspects of the white paper that are notable/laudable:

- Anticipative transmission planning – Not only must building of transmission anticipate what will happen in the future, but building of transmission also changes or influences what will happen in the future.
- Recognition of value/role of grid flexibility in grid operations – This is important for example with respect to the deliverability of ancillary services.
- T&D interface – This interface is critical. There could be more emphasis placed on how the growth in DER will create more needs for coordination for distribution network expansion to enable delivery into the transmission network.
- Recognition of the significance of inter-regional trade and the price and non-price barriers to trade and of the importance of empirical research to better understand these barriers.
- Emphasis on importance of social science expertise more generally, e.g., market response to network enhancement, the effects of investments in network upgrades on market behaviors, and the opportunities for inter-regional coordination.
- Emphasis on the importance of research on forecasting, not just applied to natural events and load, but also applied to changes in policy and technology. How do we assign probabilities to these events/scenarios?
- Cross-cutting issues including the need for interdisciplinary teams, the importance of diversity in complexity of modeling approaches/fidelity, and the value of transparency in models and data, recognizing need for security of sensitive information.

Areas on which more emphasis/focus is suggested:

- Recognizing and taking more explicit account of R&D needs of the many stakeholders who now participate in the transmission planning process, not just the “traditional” entities we think of as the transmission planners. Relationships among parties and institutional design are aspects of these processes that are worthy of study. Social science methods will be required.
- More emphasis on metrics, decision criteria, treatment of aspects that can be quantified as well as those that are also important but difficult to quantify. How do we justify investments? How do we avoid litigation?
- The focus on tools should be balanced by a focus on analysis of institutional designs/the processes by which transmission planning decisions are made and the role of tools in informing these processes and decisions.

Discussion

- Given that transmission has substitutes, what are the implications for regulating and pricing transmission? Also, what mechanisms are available to shift, long term, some stranded cost risk

from rate-makers to investors? In other quasi-monopoly markets, principles from the theory of contestable markets have been used to at least partially supplant rate-of-return-based pricing. What theories and incentive mechanisms can be used to price transmission efficiently and more equitably to share downside risks between ratepayers and investors or provide ratepayers (who are de facto investors) a share of the up side?
  - When these are our societal objectives, we start moving in these directions. Grid planning can self-regulate. Look at the possibilities of doing something different.
  - FERC, the ISOs, and others recognize that transmission has roles to play in markets, as a regulated resource subject to cost recovery and as a resource that also competes with others. For example, think of storage: is it a regulated asset, or should it be incentivized to operate efficiently? This is a key issue. We will be grappling with this issue for years.
- What types of studies should DOE be investing in relating to these institutional design and decision-making process and the roles of various stakeholders?
  - Understanding what the national strategy looks like, understanding jurisdictional boundaries. Near-term strategies, e.g., transmission for integrating offshore wind. Early-stage theoretical studies. We have seen many instances of things that we thought were unlikely have unexpectedly occurred.
  - Looking carefully at what happened to the power system over the past several decades. For example, deregulation turned out differently than expected. Other positive lessons from things like regional interconnections, energy imbalance markets can serve as inspirations for future reforms. Understanding how transmission infrastructure investment can facilitate cooperation and positive development.

Additional Questions and Comments Received through the Chat that were not Discussed by the Panel

- Decomposition vs. aggregation models? The decomposition is top-down, aggregation is bottom-up clustering. The two must interact.
- Stochastic dynamic programming has hit its limits for several reasons (pricing allocation, computational jamming). We need to embed much more ML/AI when bidding.
- What tools are available/recommended today or efforts under way to achieve co-simulation of transmission/distribution/resources?
- How do innovators with technologies for the "future grid" get access to this process? It seems like there is some difficulty. For example, secure communications for both sensors and end-to-end nodes would have prevented the recent oil pipeline hack, but they can't seem to get an audience because they are thinking "too far" outside the box.
- Are the workforce shortages described in this paper aimed just at transmission planning engineers or utility workers, in the office and the field? Do you have recommendations for development of the field workforce?
- Any thoughts on how to utilize retired professionals (e.g., planners) in the future with the assumption they are interested in the industry?

- How about valuing non-transmission solutions and comparing relative to cost/value brought about by new transmission investments? Need a study to introduce interactive transmission planning that evaluates these tradeoffs.
- Today transmission is viewed as a constraint. It should become an enabler.
- The UK introduced performance-based regulation. How about this?
- Transmission Resource Planning: An all-inclusive tool & process to conduct holistic planning is not literal co-optimization but supporting investment decisions that coordinate interactions among resource and transmission, economics, and how the market will respond.
- Technical & non-technical aspects: The technical and non-technical R&D are more appropriately conducted separately to avoid overloading the technical planning models that already face numerous challenges in response to needs of the future resource mix.

APPENDIX A. Peer Reviewers

Grid Operations

- John Adams, Electric Reliability Council of Texas
- Emanuel Bernabau, PJM
- Marija Ilic, Massachusetts Institute of Technology/Carnegie Mellon University
- David Roop, Dominion Energy
- Anonymous

Distribution Integrated with Transmission Operations

- Judith Cardell, Smith College
- Evangelos Farantatos, Electric Power Research Institute
- Matthew Gardner, Dominion Energy
- David Pinney, National Rural Electrification Cooperative Association
- Sila Kilicote, eIQ Mobility

Automatic Control Systems

- Dmitry Kosterev, , Bonneville Power Administration
- Sakis Meliopoulus, Georgia Tech
- Alison Silverstein, Alison Silverstein Consulting
- Hongming Zhang, National Renewable Energy Laboratory
- Greg Zweigle, Schweitzer Engineering Laboratories

Hardware and Components

- Ram Adapa, Electric Power Research Institute
- Fabio Bologna, Electric Power Research Institute
- Mariesa Crow, Missouri University of Science and Technology
- Jeff Hildreth, Bonneville Power Administration
- John Paserba Mitsubishi Electric Power Products

Economics Analysis and Planning Tools

- John Buechler, Eastern Interconnection Planning Collaborative
- Jay Caspary, Grid Strategies
- Tim Heidel, VEIR
- Richard O'Neill, Federal Energy Regulatory Commission/Department of Energy
- Ramteen Sioshansi, Ohio State University

APPENDIX B. Symposium Agenda

Transmission Innovation Symposium:

Modernizing the U.S. Electrical Grid

May 19 (12:00 - 4:30 Eastern) and May 20, (12:00 - 2:30 Eastern)

Agenda

Wednesday, May 19

12:00 PM - 12:10 PM	**Welcome and Logistics** —Sandra Jenkins, US DOE Office of Electricity
12:10 PM - 12:30 PM	**DOE Keynote** —Patricia Hoffman, Acting Assistant Secretary, US DOE Office of Electricity
12:30 PM - 1:00 PM	**Invited Keynote** —Wanda Reder, President and Chief Executive Officer, Grid-X Partners, LLC and Chair DOE Electricity Advisory Committee
1:00 PM - 2:00 PM	**Grid Operations** —Anjan Bose, Washington State University —Tom Overbye, Texas A&M University (presenter) Panelists: —Ken McIntyre, Executive Director, System and Operations Integration, Midcontinent Independent System Operator —Sandra Ellis, Interim Director, Transmission Grid Operations, Pacific Gas and Electric
2:00 PM - 2:15 PM	**Break**
2:15 PM - 3:15 PM	**Distribution Integrated with Transmission Operations** —Chen-Ching Liu, Virginia Polytechnic and State University —Emma M. Stewart, National Rural Electric Cooperative Association (formerly of Lawrence Livermore National Laboratory) (presenter) Panelists: —Leonard Kula, Chief Operating Officer and Vice-President, Planning, Acquisition and Operations, Independent Electricity System Operator —Matthew Gardner, Director – System Protection, Power Delivery Group, Dominion Energy
3:15 PM - 3:30 PM	Break

3:30 PM - 4:30 PM **Automatic Control Systems**
—Jeff Dagle, Pacific Northwest National Laboratory
—Dave Schoenwald, Sandia National Laboratories (presenter)

Panelists:
—Ryan D Quint, Senior Manager, BPS Security and Grid Transformation, North American Electric Reliability Corporation
—Greg Zweigle, R&D Fellow Engineer, Schweitzer Engineering Laboratories

Thursday, May 20

12:00 PM - 12:15 PM **Welcome and Logistics**
—Sandra Jenkins, US DOE/OE

12:15 PM - 1:15 PM **Hardware and Components**
—Chris O'Reilley, Oak Ridge National Laboratory
—Tom King, Oak Ridge National Laboratory (presenter)
—Edgar Lara-Curzio, Oak Ridge National Laboratory
—Zhi Li, Oak Ridge National Laboratory
—Madhu Chinthavali, Oak Ridge National Laboratory
—Lingwei Zhan, Oak Ridge National Laboratory
—Travis Smith, Oak Ridge National Laboratory
—Mike Marshall, Oak Ridge National Laboratory

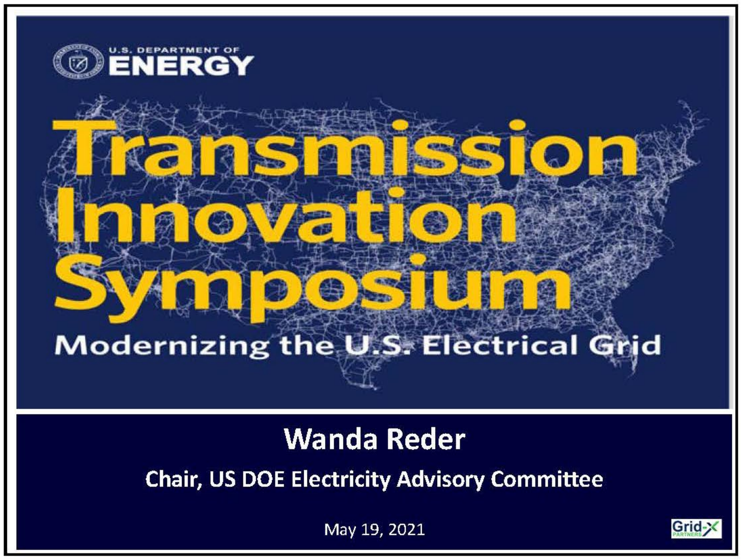
Panelists:
—Andrew Phillips, Vice President, T&D Infrastructure, Electric Power Research Institute
—Jeffrey G. Hildreth, Electrical Engineer, Diagnostics, Metrology and Laboratories, Bonneville Power Administration

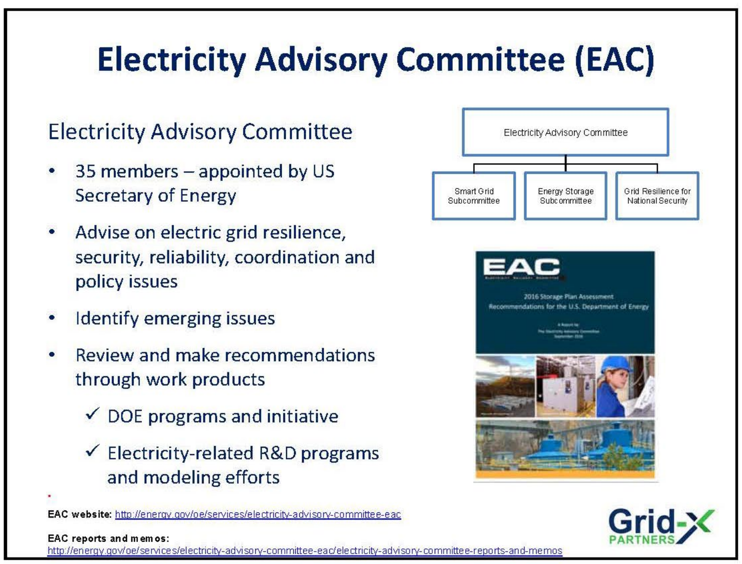
1:15 PM - 1:30 PM **Break**

1:30 PM - 2:30 PM **Economic Analysis and Planning Tools**
—Jessica Lau, National Renewable Energy Laboratory (presenter)
—Benjamin F. Hobbs, Johns Hopkins University (presenter)

Panelists:
—John Buechler, Executive Director, Eastern Interconnection Planning Collaborative
—Tim Heidel, Chief Technology Officer, VEIR, Inc.

APPENDIX C. Keynote Presentation Slides





Trends and Drivers

- More Distributed Energy Resources

- More Weather Dependent

- Electrified Transportation

- Growing Customer Expectations

- Escalating Security Concerns

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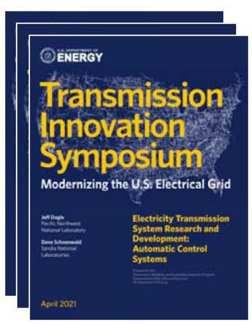
Five White Papers

U.S. Electricity Transmission System Research & Development

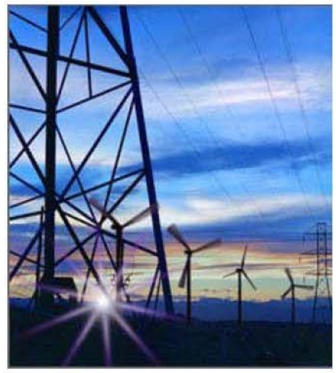


- Grid Operations
- Distribution Integrated with Transmission Operations
- Automatic Control Systems
- Hardware and Components
- Economic Analysis and Planning Tools

White papers: https://www.energy.gov/oe/transmission-innovation-symposium

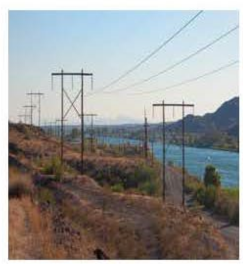
Emerging Transmission Characteristics

- Reduced reactive power, short-circuit current, and frequency stability
- Increased consumer expectation and societal dependency
- Greater uncertainty ie power flows, voltage fluxuation, backfeed
- Greater infrastructure interdependence (ie electric + transportation)
- More data, measurements, sensors, software, modeling tools...
- Increased system complexity and coordination
- Increased cyber and physical attacks
- Increased siting scrutiny



Current Transmission

- Much transmission was designed and built over a ½ century ago for different resources
- Where are we?
  - Rebuilt & strengthened
  - Primitive "smart" devices: partially upgraded with microprocessors
  - DER <u>un</u>aware
  - Isolated voltage control
  - People-dependent



Compliments of David Quier, PPL VP Transmission

Future Transmission

- The great enabler: DER aware and fully integrated
- Predictive, preventative controls that are faster than real time
- Increased visualization, data driven
- Predictive capabilities and forecasting
- Automatic management with self-healing features

Source: Electricity Transmission System Research and Development: Distribution Integrated with Transmission Operations Section 3 Future Vision for Independent System Operators and Distribution System Operators

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Typical R&D Portfolio Opportunities

- Strategic Planning
  - Context, strategic framework
  - Metrics, success factors
  - Outcomes connected to drivers and objectives
  - Relevancy with industry input
  - Milestones, road-mapping, marketplace alignment
- Execution
  - Coordination and interoperability
  - Grid-scale testing and demonstrations
  - Technology transfer, adoption

Transformation Needed

- Eliminate the silos!
- Promote imagination, which is the number one tool for creativity and innovation.
  - ✓ 9/11 attacks revealed four kinds of failures: in imagination, policy, capabilities and management.
  - ✓ "It is therefore critical to find a way of routinizing, even bureaucratizing the exercise of imagination."
- Anticipate uncertainty: envision alternative futures to better sense, shape and adapt
- Link action to broader goals

Source: Washington Post March 18, 2021 "We can't prevent tomorrow's catastrophes unless we imagine them today"
https://www.washingtonpost.com/outlook/2021/03/18/future-forecasting-strategic-planning/

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What Is Missing …

- Quantifiable linkage to economic growth and affordable energy
- Managing with closer tolerances
- Transmission development with multi-regional planning
- Energy storage advancements
- Energy efficiency
- Cyber and physical security
- A vision for improved load factor
- Comprehensive optimization

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“Use It” + Interoperability = More Value

The function and value of a water heater changes as it interoperates with other devices and participates in markets

Technology needed to enable and unleash value

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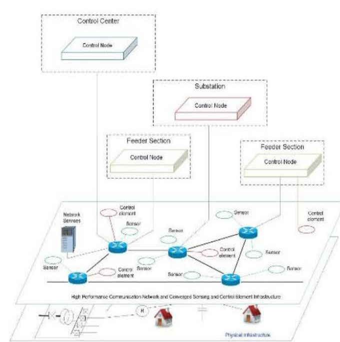
Architectural Considerations

Grid architecture is a systems analysis discipline that begins with objectives and determines how structures integrate and coordinate

- Coordinate to solve problems
- Recognize constraints and optimization objectives
- Examine relationships and interfaces so coordination frameworks can be develop
- Sensing, communication and control infrastructure is a foundational



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Source: US Department of Energy, Office of Electricity, July 2018 EAC Briefing

Workforce Advancements

- Often workforce development is an afterthought
- Critical for transformational change
  - ✓ Automation and artificial intelligence will change the skills that are needed
  - ✓ Multi-disciplinary awareness is essential
- Requires cross training, drills, curriculum, demonstrations and more…
- Capability development needs to be integrated throughout

"Cross training is essential so cyber defenders understand criticality of power system equipment and system operators can determine when to shut down equipment being damaged by a cyber attack."

Robin Podmore - IncSys

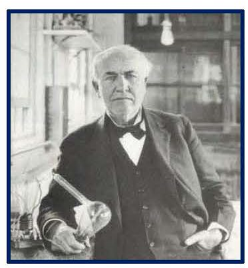
Grid-X PARTNERS

Summary: Transmission Innovation

- White papers are an excellent foundation
- Strategic context is important: the EAC can help
- Recognize the trends and drivers
- Transformation is needed
- Cultivate and use imagination!

Thank you!

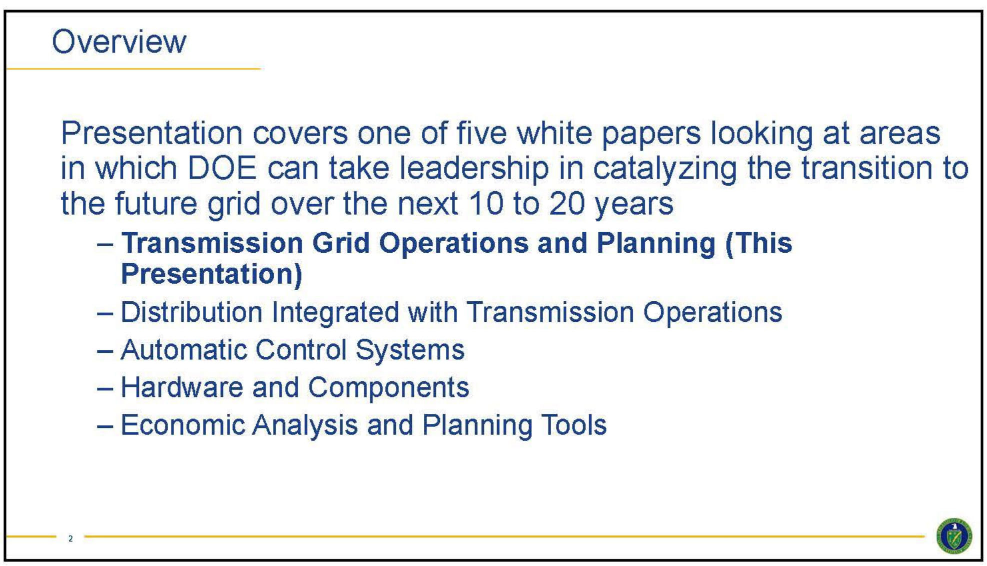
Wanda.reder@gridxpartners.com



"If we did all the things we are really capable of doing, we would literally astound ourselves" – Thomas Edison

Grid-X PARTNERS

APPENDIX D. White Paper Presentation Slides



Grid Operations and Planning Paper Overall Structure

The paper has eleven chapters

- Introduction
- Electricity Transmission Grid Operations: Past and Present
- Likely Future Scenarios
- Technologies to Support Operators' Management of Real-Time Operations
- Engineering Tools to Support Real-Time Operations
- Technologies to Enhance the Use of Historical Real-Time Data
- Technologies for Engineering Tools to Support Transmission Planning
- Training Simulators
- High-Impact, Low-Frequency Events; Restoration; Other Infrastructures
- Research Infrastructure
- Recommendations

3

A Few Starting Quotes

"For at least the next two decades, most customers will continue to depend on the functioning of the large-scale, interconnected, tightly organized, and hierarchically structured electric grid for resilient electric service."

- *Enhancing the Resilience of the Nation's Electricity System*, The National Academies Press (NAP), Washington, DC, 2017)

"All models are wrong but some are useful"

- George Box, *Empirical Model-Building and Response Surfaces*, (1987, p. 424)
- The math itself is correct

"If I have seen further it is by standing on the shoulders of Giants"

- Isaac Newton (1675 in letter to Robert Hooke)

"It is always wise to look ahead, but difficult to look further than you can see"

- Winston Churchill

"It is a mistake to think that the future is just some extrapolated view of the present"

- *Analytic Research Foundations for the Next-Generation Electric Grid*, NAP, 2016

4

Where We've Been Over the Last 140 Years

Chapter 2 covers the history of electric grid operations

- The grid has been in a continual state of change and electric utilities have often been leaders in new technology and analytics
- Many of the grid changes have been driven by rare events
  - 1965 blackout, WECC 1996 blackout, Sept 11, 8/14/03 blackout, others
- The operation of the grid has gotten much more complex over the last several decades, and one size definitely does not fit all!
- Concepts can take decades to fully develop
  - EMSs, state estimation, optimal power flow, simulators
- Understanding the different operating modes is crucial
  - normal, alert, emergency, in extremis, restoration

5

Transmission Operations and Planning in Four Words

Impressive

- Electrification including operations is an engineering marvel!!

Diverse or **Complex**

- Recent changes have made the US grid much more diverse

Vital

- We're more dependent than ever, and blackouts can rapidly move from annoying to catastrophic

Opaque (at least some)

- While information is shared within the operations community, much of this information is not shared outside of this community; often this opaqueness is required, but it can hinder research

6

Where We're Going During the Next Decade or Two

Chapter 3 presents our thoughts on future directions

- We're optimistic for the future! This is an exciting time to be in the power field, with rapid changes occurring in all areas of the grid.
  - These rapid changes mean that we're sailing into uncharted waters with lots of opportunities but also potential perils
- A key take away is since the future is inherently uncertain, research needs to prepare for a range of scenarios
  - A goal should be to future-proof the grid so regardless of how the grid evolves the US is prepared [a]

7

[a] *Analytic Research Foundations for the Next-Generation Electric Grid*, The National Academies Press (NAP), Washington, DC, 2016

Where We're Going During the Next Decade or Two, cont.

- There is likely to be a continued growth in wind and solar generation with much more storage and perhaps a large increase in load with electrified transportation
  - Some of these changes will be at the transmission level (our scope) and some in the distribution system (out of our direct scope yet certainly impacting the transmission grid)
- The essence of the transmission grid is unlikely to change
  - Most electricity will flow through the transmission system and most customers will depend upon it for at least part of their electricity needs
- Large increase in observability and controllability of the grid
- Rare events are likely and are likely to have a paramount impact

8

Background on Recommended Research Focus Areas

- The next sections present some specifics, but it is important to understand the scope of this paper
  - This is one of five papers focused on the research and development targets for DOE's Office of Electricity
  - Hence paper does not present an overall research agenda for the electric power industry
  - Many of the research needs are better handled be others: NSF, EPRI, vendors, utilities, other parts of DOE, other agencies
- Overall research focus should be on the complexities of large-scale grids, with a focus on better mitigating high impact events

9

Operators' Management of Real-Time Operations

- Two types of control centers (ISOs/RTOs/RCs and TOPs) and two types of technical staff (operators and engineers)
  - Humans will be very much in the loop next two decades
- Top research focus areas include
  - Data management
    - There will be much more data including from PMUs and other sources
  - User interface (including visualizations) especially for rare events
    - Displays tend to work well in normal operations; focus on emergencies
  - Intelligent applications
    - This will become more crucial as the grid becomes more automated
  - Transmission-distribution data exchange

10

Engineering Tools to Support Real-Time Operations

Enhanced engineering support tools are needed, driven both by more data and the need for better decisions

- State estimator (SE) including linear state estimators
  - The SE should be more robust, particularly for stressed system conditions
- Contingency analysis including dynamics
  - Faster algorithms and more complete system representation
- Power flow and optimal power flow, SCOPF
  - There are still convergence issues, and a need for faster algorithms
- Corrective/preventative actions
  - Better decisions support for humans, and automated control support

11

Technologies for The Use of Historical Real-Time Data

Transmission operations generate and consume vast amounts of data; there is a need to better utilize this data for future decision making and for planning

- Forecasting
  - Focus on electrical applications, with weather forecasting out of scope
- Machine learning
  - Research is needed to develop the knowledge required for operators to take action. Deep learning from long periods of historical data can predict what actions are needed
- Model tuning
  - More effective and automated use of historical data is needed to create better models

12

Engineering Tools to Support Transmission Planning

The goal of planning is to ensure that the transmission system is adequate during normal and likely contingent situations, and that it is resilient to high impact events

- Transmission planning is more difficult in the absence of integrated generation planning; lack of generation adequacy in the future is a major threat to grid reliability/resiliency
- Better stochastic methods for planning and long-term forecasting
- Better representation of grid dynamic behavior including more representation of the protection system and RASs
- Machine learning applications including the use of historical data
- Improved situational awareness with planning models, which are ever growing in complexity

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Training Simulators

Training simulators are widely used in operations, but they can also be used for broader training and education; newer ones now incorporate faster dynamics

- Power system module
  - Improved integration of faster dynamics
- Control center module
  - There is a need for broader access and for incorporation of coupled infrastructures
- Instruction module
  - Primitive compared to other industries, needs much development
- Power system simulation access
  - For people other than operators

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High-Impact, Low-Frequency Events; Restoration, Infrastructure

Blackouts cannot be totally eliminated, but their frequency and duration can be decreased.

The societal impact of blackouts is not a linear function of their size or duration

– The industry also has a long and mostly successful track record of quickly restoring service following many disruptions

However, there are some events are of such magnitude that their impact on the electricity grid and on society as a whole could be catastrophic

– "High-Impact, Low-Frequency" (HILF) or "Black Sky" events

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High-Impact, Low-Frequency Events; Restoration, Infrastructure

Mitigating the impact of HILF events needs to be a high (or highest) priority

– A broad portfolio of research is needed to understand, simulate and develop mitigation strategies for HILF events. Recent events have demonstrated that such events could be devastating

– Researching these issues can help with normal operations as well

HILF Simulation

– Currently there is a lack of HILF event simulations. Many people working in the electric power industry (not just operators) could benefit from participating in HILF event simulations

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Research Infrastructure (From a Transmissions Perspective)

Research is not done in a vacuum and a complete discussion of priorities needs to consider the capabilities of researchers to provide useful results. The three main research providers are

- Industry, universities, national labs

According a recent Power-Globe email by Bikash Pal (IEEE PES VP for Publications)

- Nine of ten top publications in the 20th century came from industry
- Now a comparatively insignificant portion of papers is contributed by industry or people conducting practice oriented research

There is a desperate need for more practice oriented research!

- Much information about current industry practice is not published

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Research Infrastructure

Recalling "all models are wrong but some are useful" a common research practice is to

- Simplify the problem to make it relative easy to express mathematically (putting all the "wrongness" here)
- Provide an elegant mathematical solution, which impresses paper and proposal reviewers; scalability is often ignored
- Real complexities are left to "future work" that never gets done!

A key issue in transmission operations and planning is actual electric grids are quite complex and don't fit this paradigm

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Research Infrastructure

At least some research (and subsequent publications) should be structured to “Develop and publicly release large-scale, complex electric grid test systems that demonstrate current electric grid research challenges”

- Many published papers in 2021 show results on grids smaller than the 949 bus system Tinney used in 1967 for the power flow (with 32K memory) or the 96 generator transient stability from 1960!

Follow up research could then focus on the development of solution methodologies, including a focus on engineering situational awareness, utilizing these test cases

- Require the solution fit the problem, not the problem the solution

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Research Infrastructure: Some Recommendations

- Improved access to large-scale, complete electric grid models and data sets; due to CEII issues some of this would be synthetic
  - ARPAE has done a lot to help make available high quality, public synthetic grids
  - Certainly some non-public research should be done on CEII electric grids
  - The ability to conduct large-scale (continent wide) studies to research changes in transmission architecture is hampered by balkanization of data and tools
- In at least some calls for proposals
  - In merit review criteria have a high weight for “Technical experience and expertise of staff in performing work similar to the topic area of the proposal applied to large-scale, complex electric grid models”
  - In the “Applications Specifically Not of Interest” include “Submissions that have not demonstrated the ability to solve large-scale, complex electric grid models”
  - Obviously there would not apply to all FOAs, but given the current situation a major change is needed; others (NSF) can fund more fundamental work

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ENERGY
Questions?
Anjan Bose and Thomas J. Overbye
Electricity Transmission System Research and Development: Grid Operations and Planning
bose@wsu.edu, overbye@tamu.edu

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Transmission Innovation Symposium

Modernizing the U.S. Electric Grid

Distribution Integrated With Transmission Operations

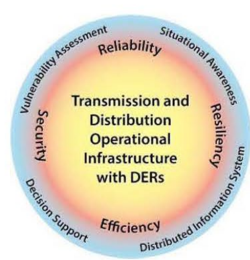
Emma M. Stewart
Chief Scientist
NRECA (formerly LLNL)

Chen-Ching Liu
American Electric Power Professor
Virginia Tech

May 19 2021

Outline

- Vision
- State of the Art
- Energy Delivery System Transformation
- Drivers and Vision
- Architecture
- Research Directions
- Federal Justification



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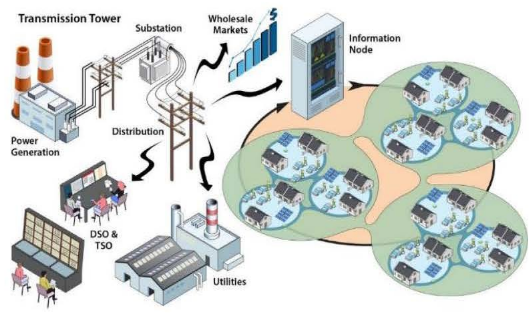
Vision of Integrated DSO & TSO Environments

- Transformation of distribution from being viewed as a ***load***, to active ***subsystems*** of the transmission grid
- Interdependent, integrated and bidirectionally supportive in markets, operations, and control
- Subsystems incorporate generation, storage, EVs, active loads, with a mix of configurations and capabilities



Operation that is safe and secure with mixed levels of technology adoption, with equal opportunities for advancement

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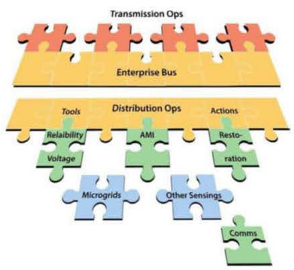
Present State, Drivers and Vision

Where we are…T & D Boundaries



T & D – operated to manage outages within standards, rapidly recover and maintain remote capability for safety reliability and restoration

Significant advancements in distribution operations, integration of DER – but not everywhere

Diverse topologies, decentralized operations, limited sensing and communications disparities

Interconnected infrastructure – gas, water, communications, transport, but events highlight weakness (and opportunities)

New markets to support transmission from new technologies, but limited to simply "do no harm" to distribution

Edge cases driving innovation

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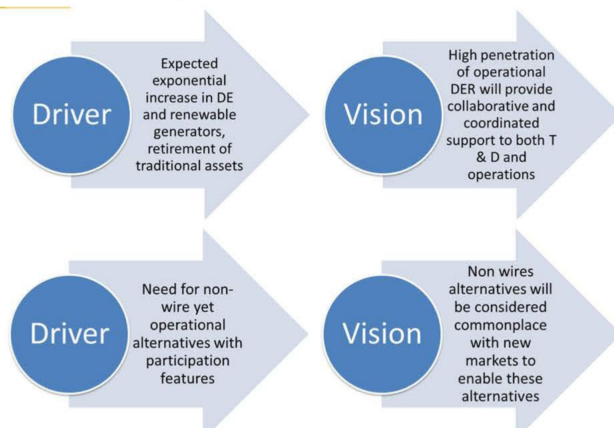
Drivers and Visions (1)



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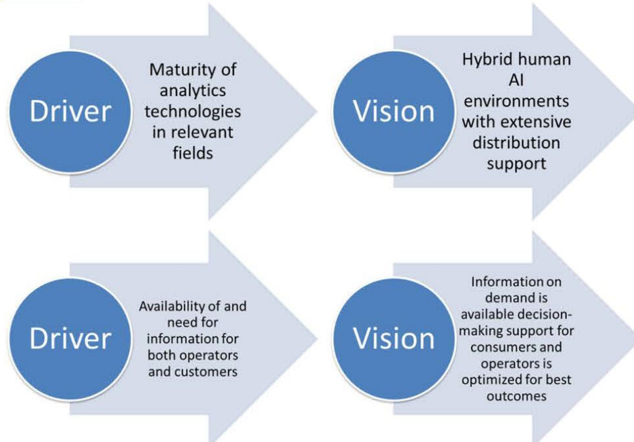
Drivers and Visions (2)



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Data, Analytics, Machine Learning and Artificial Intelligence

- Data and Information at the heart of the future vision
- Data Utility, Distributed Information System Layer, Integrated & Hybrid ML
- Why: Central + Decentralized + Distributed is a multi objective problem beyond human cognitive capabilities
  - Too much data, not enough timely actionable information
  - Prediction and prevention key to solving some of the growing resilience and reliability issues
- Application of other industries – medical, defense and finance – learn and grow from those infrastructures
- ML does not address all issues – but a multi-objective future needs to advance in this field

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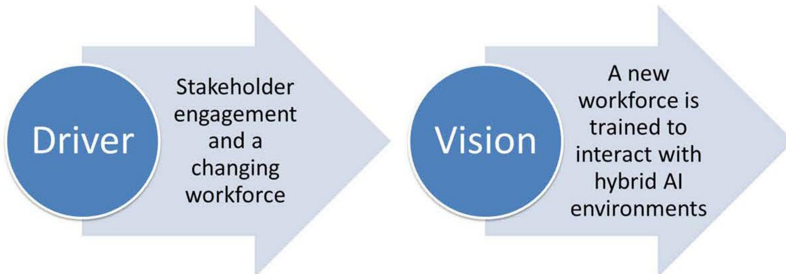
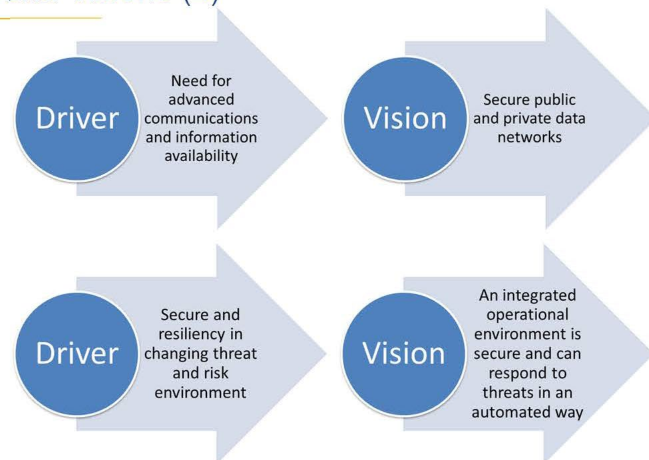
Drivers and Visions (3)



Stakeholders

- Consumers transitioning to prosumers
- Utilities and their operators
- DER owners and operators
- ISO, DSO, TSO
- Workforce, communities, and education system

Drivers and Visions (4)



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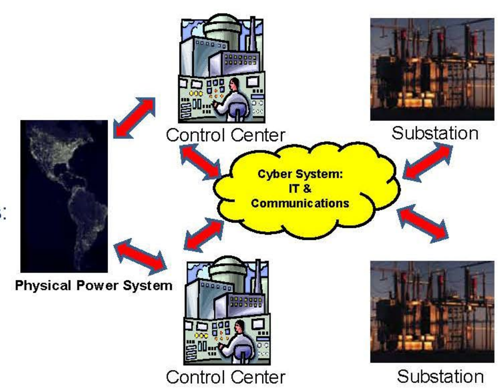
Cyber, Resilience and Electric Grid Infrastructure

- High tier adversaries capable, determined, active and advancing
- Catastrophic weather events increasing in frequency and severity
- Cyber and physical events public, interconnected information structures growing
- Response, challenges and capabilities: uniquely spread across public and private infrastructure
- Future vision must have security and resilience at its core, built in from the ground, not bolted on



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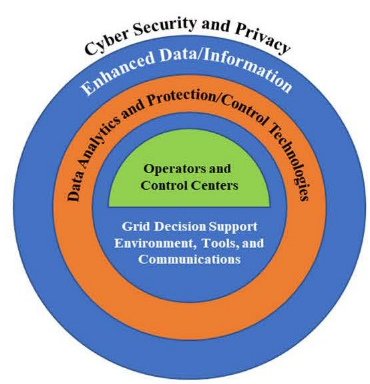
Architecture For the Future Integration

Architecture of Solutions

- Enhanced Data/Information
  Information Availability, Communications
- Data Analytics and Protection/Control Technologies
  High Penetration DERs, Non-wire Alternatives
- Grid Decision Support Environment, Tools, and Communications
  Hybrid Human-AI Environment
- Operators and Control Centers
  Changing Workforce
- Cyber Security and Privacy
  Secure Integrated Environment



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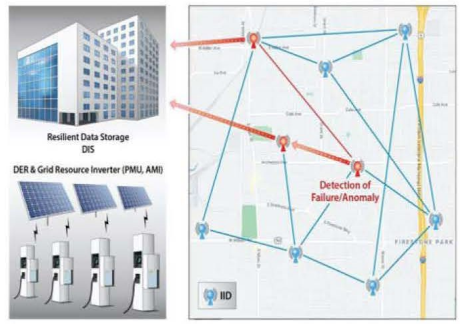
Distributed Information System (DIS) – Core of the Architecture

- **DIS:** Networking of Integrated Information Devices (IIDs) - substations, feeder/laterals, DERs, significant loads, etc.
- **Measurements/Status** – voltages/currents, normal/faulted conditions, synchronized time stamps.
- **IIDs** share measurements, status, fault indicators with other IIDs and SCADA nodes.
- **Optimized deployment** around an operational communications and security framework.
- Major step forward from existing SCADA or smart grid functions.



Grid Decision Support Environment, Tools, and Communications

Situational Awareness (SA):

Status under fast variations and intermittency of DERs, contingencies/failures.

Target: On-line tool for validation incorporating DER uncertainties and T&D scenarios.

Vulnerability Assessment (VA):

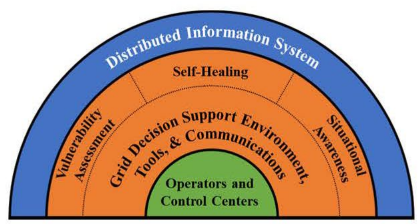
Impact of contingencies, cascading, threats.

Target: Damage assessment, forecasting resources, critical load, reconfiguration, optimizing control/recovery. VA metrics and defense. Blackstart/resiliency resources. ML and optimization.

Self-Healing:

Logic reasoning/judgement under incomplete information and uncertainties. Data-driven decision support through ML and data analytics. Integration of decentralized operations.

Target: Self-healing, safe reconfigurable with reduced field crew deployment. Distributed decision making.



Distributed Information System (DIS)
Providing data/measurements for decision support. Networking with SCADA and AMI for operation, control, and market.

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Research Themes & Recommendations

Overcoming Barriers - Stepping Stones & Research Directions

- Cost of sensing and measurement and deployment of the sensor/measurement infrastructure
- Lack of standards, real-world (>1) pilots, and transitional tools for integrating AI and enhanced data streams
- Need for workforce development and workforce education pathways
- Need for boundaries and regulations for T&D Integration
- Challenges related to vendors, interoperability, and the supply chain
- Need for modeling and simulation tools and research data sets that accurately represent operational conditions

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Research Organization and Targets

- **Enhanced Data/Information**
  - *R1: Cohesive Sensing, Measurement, Communications, and Advanced Analytics Plan for Integrated Transmission & Distribution Operations & Sensors*
  - *R2: Design, Development, and Testing of Information and Communications Technology for Distributed Information Systems (DIS)*
  - *R3: Test Systems, Models and Tools for Validation of T&D Methods*
- **Data Analytics and Protection/Control Technologies**
  - *R4: Development and Demonstration of Operations Use Cases for Artificial-Intelligence-Enabled Decision Support in a Decentralized Environment with High Penetration of Distributed Energy Resources*
  - *R5: Situational Awareness of Distribution Systems*
  - *R6: Transmission, Distribution, and Communications Tools for an Integrated Transmission and Distribution System*
- **Grid Decision-Support Environment, Tools, and Communications**
  - *R7: Artificial Intelligence and Machine Learning Tools for Distributed Decision Support*
- **Operators and Control Centers**
  - *R8: Communications, Visualization Tools, and their Incorporation into an Integrated Transmission and Distribution Environment*
  - *R9: Workforce Development*
- **Cyber Security and Privacy**
  - *R10: Cyber-Physical System Security Tools for Transmission and Distribution Systems*

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Foundational Activities - Near Term Needs

a) Development of an integrated T&D data, sensing, and communications plan, with benchmarking and operational use cases

b) Design and testing of a new DIS that is secure, reliable, and integrates data elements

c) Development of a hybrid AI and ML roadmap and use cases as well as a benefits assessment for a test system environment and for new operational elements, considering the current state of the art in parallel fields and critical environments

d) Development of a comprehensive, high-volume, modernized set of validated, representative operational test models and data sets for the future integrated T&D system and its associated communications

e) Development of a targeted, expanded pilot and demonstration transition scheme for rapid bridging of the research - commercialization gap

f) Pre-emptive development of diverse K-12, higher-education, and industry apprenticeship pipelines for the future engineering, security, and science workforce for the energy delivery industry

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Federal Role

- To establish the infrastructure for integrated T&D, DOE leadership with private partnership is critical
- DOE can play a valuable role by uniting what is now separate research in transmission and distribution and shifting to R&D that considers a single, integrated, cohesive energy delivery system
- Technology demonstration programs in which transmission and distribution entities work together, devising programs to provide T&D integration opportunities for utilities
- Some additional roles:
  - Drive product, tool, or algorithm scalability metrics
  - Documentation of success (and failure) stories from demonstration projects
- Pilot program guidelines and technology-pitching assistance for pilots and joint working groups
- Innovation versus demonstration – split cycles
- Supporting workforce development partnerships integrated with innovation

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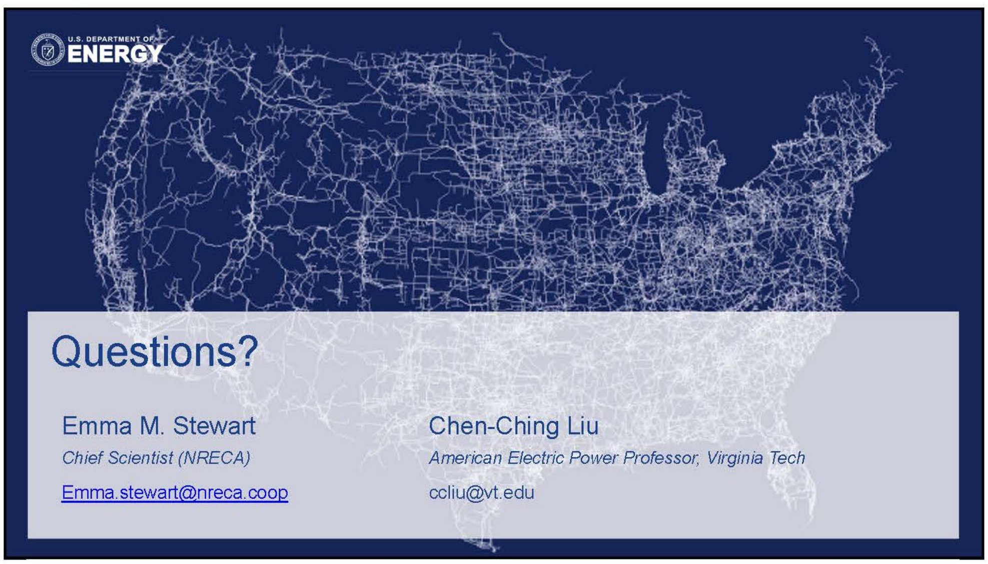

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2

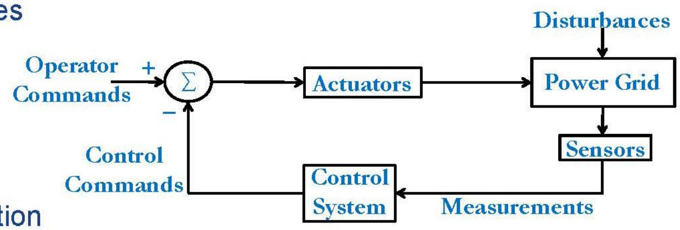
Introduction

Why automatic control systems matter to the grid:

- Improved operational efficiency
- Improved reliability during normal conditions
- Improved resilience to adverse conditions

Cross-cutting nature of controls – Depends on:

- Architectures
- Sensors
- Actuators
- Modeling
- Simulation
- Demonstration



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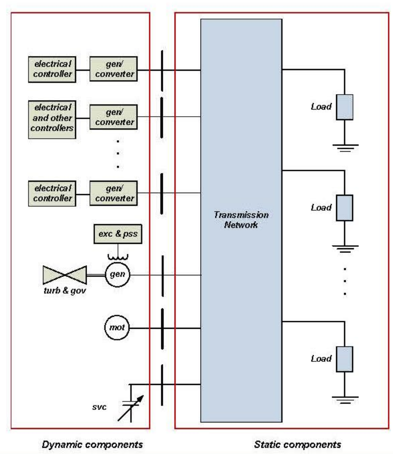
Today's Grid: How We Got Here

- Traditional synchronous generation ➔ system inertia to maintain stability
- Mostly centralized, dispatchable generation
- Regulated markets
- Transmission and distribution generally considered separately
- Available grid measurements typically not fast nor widely available



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The Grid of 20 Years from Now: Key Drivers for Controls

1. Economic – Renewables more cost-competitive, storage will follow, market incentives/risks, advanced technology more cost-competitive
2. Legal – Market structures, States' RPS mandates
3. Societal – Decarbonization, more microgrids
4. Technical – Network-enabled, more power electronics driven, inverter-induced issues, wider availability of advanced measurements
5. Threats – Climate, unintentional, intentional

1 – 5 ➔ Controls need to be:

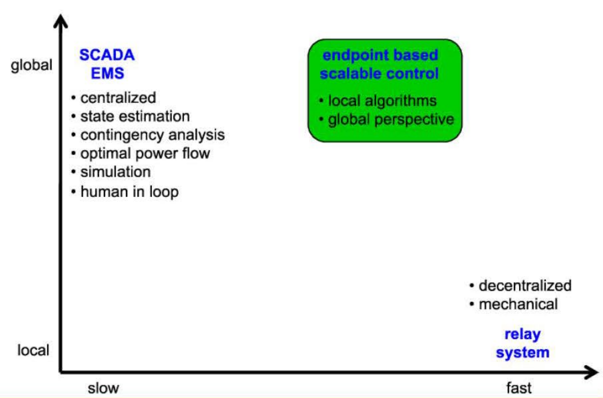
Fast – Real-time response and feedback-driven

Distributed – Can harness widely dispersed resources

Resilient – Hardened against threats & enable faster recovery to events

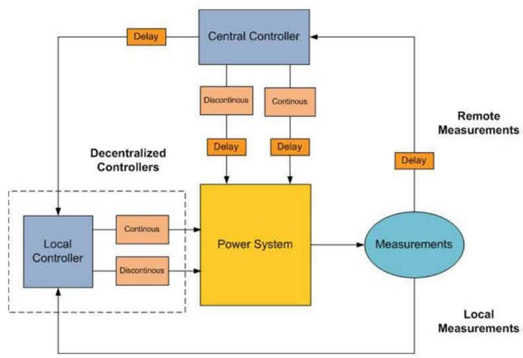
The Grid of 20 Years from Now: Fast

- Power electronics driven
- Network-enabled resources
- Availability of advanced measurements



The Grid of 20 Years from Now: Distributed

- Renewables
- Energy storage
- Microgrids
- Architectures that will leverage new technologies



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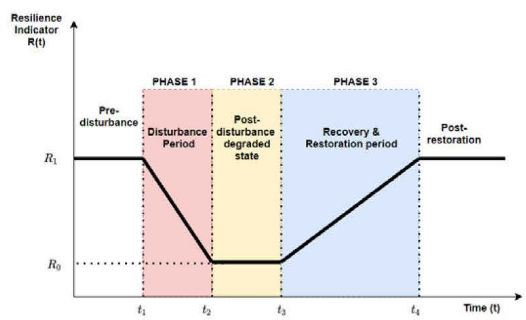
The Grid of 20 Years from Now: Resilient

- Prevention: Grid must be hardened against threats
- Damage Control: Adaptive islanding as a tool to mitigate damage
- Recovery: Grid restoration (black start)



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Summary of R&D Recommendations for Automatic Controls

Recommendations by category: Fast

- Remedial Action Schemes (RAS)
  - Develop, simulate, and demonstrate **new RAS designs**
  - RAS designs should be **response-based** (vs. traditional event-based)
  - RAS designs should provide more **flexibility and robustness**
- Power Electronics (PE) Devices for Control
  - Study potential for **phase & frequency decoupling** using PE devices
  - Design algorithms to **mitigate cascading grid failures** using PE devices
- Improved Simulation Tools
  - Develop new solvers to enable **extended-term simulations**
  - Improve error analysis to study **uncertainty propagation**
  - Implement **advanced simulation frameworks**

Summary of R&D Recommendations for Automatic Controls

Recommendations by category: Distributed

- Architectures
  - Develop new control **architectures that combine engineering and economics**, incorporate optimization, and address robustness of **massively networked large-scale systems**
  - Develop distributed, real-time, **scalable architectures that accommodate uncertainties in renewable generation** and match supply to demand by making use of wide-area real-time information, and that **decompose global objectives into coordinated local algorithms**

Summary of R&D Recommendations for Automatic Controls

Recommendations by category: Distributed (cont.)

- Distributed Energy Resources (DERs) for Control
  - Assess **feasibility and risks in deploying large numbers of DERs** in meeting grid control objectives
  - Design **coordinated control algorithms to harness** the wide availability and power injection capabilities of **DERs** to improve grid reliability & resilience
- Adaptive Islanding
  - Develop pre-planned automatic controls to **isolate portions of the grid to prevent an uncontrolled cascading failure**
  - Ensure **frequency & voltage control occurs seamlessly** during islanding

11

Summary of R&D Recommendations for Automatic Controls

Recommendations by category: Resilient

- Grid Hardening to Threats
  - Develop dynamic models and control strategies that combine game theory, machine learning, and adaptation to **improve grid resilience to unknown, irrational, and adversarial** market players and external **threats**
- Grid Restoration (Black Start)
  - Devise techniques for **sequencing of IBRs** for use in black start
  - Develop strategies to **mitigate risks from using IBRs** in black start
  - Apply machine learning and AI techniques to **better assess threats and model operator behavior** during black start

12

Next Steps

R&D recommendations will require:

- Address basic research/theory to identify potential solutions
- Create tools to implement proposed solutions
- Demonstrate feasibility of developed solutions through testbeds, hardware-in-loop, grid demonstrations
- Engagement and cooperation of:
  - Electric utility industry (power providers, suppliers, ISOs)
  - Research community (DOE, labs, academia, utilities, suppliers, ISOs)
  - Regulators (FERC, NERC, WECC, States)
  - Consumers, etc.

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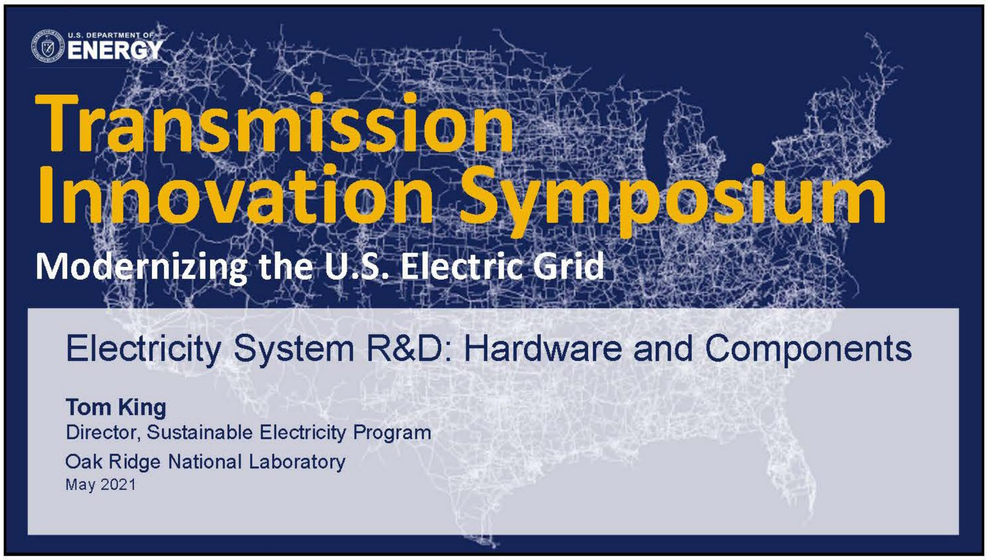
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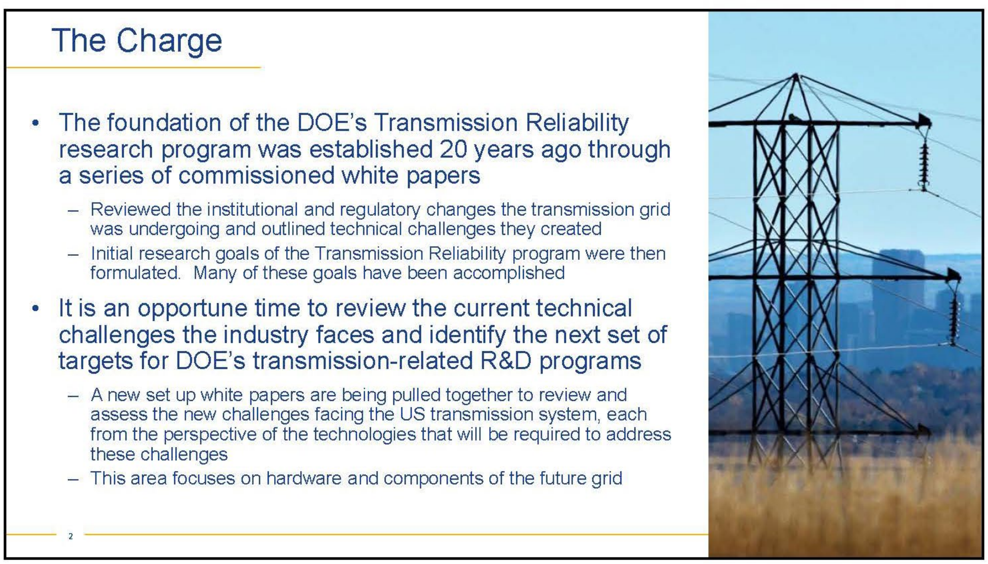
Transmission Innovation Symposium
Modernizing the U.S. Electric Grid
Electricity System R&D: Hardware and Components
Tom King
Director, Sustainable Electricity Program
Oak Ridge National Laboratory
May 2021


The Charge
• The foundation of the DOE's Transmission Reliability research program was established 20 years ago through a series of commissioned white papers
– Reviewed the institutional and regulatory changes the transmission grid was undergoing and outlined technical challenges they created
– Initial research goals of the Transmission Reliability program were then formulated. Many of these goals have been accomplished
• It is an opportune time to review the current technical challenges the industry faces and identify the next set of targets for DOE's transmission-related R&D programs
– A new set up white papers are being pulled together to review and assess the new challenges facing the US transmission system, each from the perspective of the technologies that will be required to address these challenges
– This area focuses on hardware and components of the future grid
2

Approach

- Scenario analysis used to identify key transmission technologies
- Four scenarios:
  - A more distributed grid
  - Increased clean energy with high penetration of variable renewable energy
  - Increased load growth with re-establishment of manufacturing base and the electrification of transportation
  - Cyber and physical vulnerabilities and threats to the nation's grid
- This white paper **did not** cover energy storage, cybersecurity, advanced controls and software
  - All are important areas for consideration
  - Either being addressed in other white papers or through DOE programs, such as ESGC
  - Technologies, markets and policies are all necessary elements to consider in the future grid. This white paper highlights technology components.

Scenarios	Description	Challenges	Solutions
Distributed	Numerous drivers are pushing toward a more distributed grid. As intermittent resources such as wind and solar become more common, traditional base-load plants such as coal and nuclear become less economically attractive.	• Integration of distributed generation • Decreased revenue for transmission system owners/decreased need for new transmission lines (i.e., change in business model) • Operating under reduced base-load conditions	• Improved transmission/ distribution simulation • Advanced adaptive protection schemes • Networked microgrid control schemes • Distributed power-flow devices • Advanced dynamic reactive power sources
Clean Energy	Utilities embrace decarbonization along with unprecedented policy changes that dramatically alter the generation mix.	• Generation location and alignment with load centers • Changes in power flow across the country • Localized reactive power issues • Grid flexibility response (inertia, voltage, frequency, and load/generation response)	• Power electronic technologies for power-flow control • Advanced conductor and underground systems • Long-distance energy transfer

Representative examples of scenario analysis

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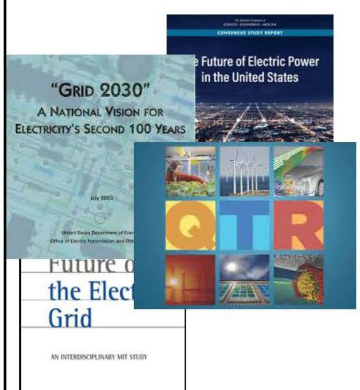
Recommendations for future R&D investment are centered around these key technologies:



Technical areas are consistent with other reports

- **Power-flow control devices**: Flexible alternating current transmission system (FACTS) based power flow control devices, embedded high voltage direct current systems, power electronics building blocks for multiple applications such as FACTS, multi-terminal DC (MTDC) systems, and solid-state transformers"
- **High-power delivery systems to transmit over long distances**: Ultra-conductive systems, smart materials (constructed using advanced manufacturing techniques), transformers, superconductivity
- **Advanced sensors**: High-fidelity sensors, asset monitoring (non-destructive evaluation, drone survey of lines), and alternative timing
- **Advanced protection systems**: Model-driven adaptive protection systems, negative sequence source and alignment to advanced sensor and communication technologies

4

Power Flow Control Devices

- Overview
  - Maintain operations, improve infrastructure utilization, ensure power quality, relieve power congestion, increase stability margin, and avoid power outages.
  - Challenging due to complex grid topologies, continuously varying loads, renewables integration, and difficulty of cost-effective energy storage.
- Benefits
  - Improved power grid efficiency, reliability, and resiliency
  - Improved AC power grid stability performance and resiliency
  - Improvements in modularity, maintainability, scalability for future expansion, and standardization
  - Enhancement of microgrid resiliency of transmission level interconnection and optimal power flow control
- Advancements are needed in:
  - FACTS-based power flow control
  - Embedded HVDC systems
  - Power Electronics Building Blocks

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Power Flow Control Devices - recommendations

R&D Technology Area	Recommended R&D	R&D timeline
FACTS-based power flow control devices	• Accelerate maturation of advanced FACTS-based devices and emerging low-cost devices. • Field condition testing / testbeds for emerging power-flow control technologies • Integrated FCL use with power-flow control devices - lower costs and improve reliability.	Near term (1-5 years)
Embedded HVDC systems	• Field demonstrations for multi-terminal voltage source converter-HVDC systems. • Enable hybrid DC circuit breakers. Mechanical circuit breakers with current injection are a mature, cost-efficient technology. Pure solid-state breakers operate rapidly but limitations include cost and interruption capabilities.	Near term (1-5 years) field demonstrations and commercial applications of embedded
Power electronic building blocks for multiple applications	• Power stage subsystem: o Modular multi-level converter-based voltage-source converters o Materials advances and manufacturing into components o High-voltage (20+ kilovolt) WBG semiconductor devices for thermal management • Control and protection subsystem: o Develop system protection for WBG semiconductor devices and higher-voltage (e.g., >1 kilovolt) DC systems o Develop controllers, sensors, and auxiliary power supplies • Thermal management: o New materials, more compact mechanical components, tighter integration with passives and packaging, and understanding of broader system interactions o Develop packaging for WBG semiconductor devices	Near term (1-5 years) continue to improve state-of-the art with next generation systems

6

High Power Delivery for Improved Reliability

Sumitomo Electric

- Overview
  - Increase in power demand: economic growth, demographic changes, and the Transportation and industrial electrification
  - "Re-conductoring" has emerged as a practical solution in which old cables are replaced with newer cables having greater capacity and lower losses
- Benefits
  - Interconnecting regions with HVDC lines could balance the expected power supply-demand imbalance between regions in the U.S
  - Better electrical conductors and insulators could reduce transmission losses by as much as 10–20%
  - RD&D to reduce the cost of such advanced technologies would be beneficial to promote their more rapid deployment
- HVDC will potentially play significant role
- Advancements are needed in
  - Electrical conductors
  - Electrical insulators
  - Manufacturing processes
  - Transformers

7

High Power Delivery for Improved Reliability- recommendations

R&D Technology Area	Recommended R&D	R&D timeline
Electrical conductors	• Accelerate alloy development with improved electrical and mechanical properties. • Modify metallic conductors to improve oxidation / corrosion resistance while preserving low interfacial electrical resistance • Carbon-based conductors - meso-scale structures exhibiting physical and mechanical properties of nano-phased materials • Manufacturing processes for connectors	Near term (1-5 years), number of miles of high-voltage transmission lines that will reach end of useful life in the next 10 to 20 years
Electrical insulators	• Polymeric materials that exhibit high dielectric breakdown strength and high environmental durability. focus on investigating the effect of adding nanoparticles to polymer matrix composites. • Multi-physics simulations to determine the response of HVDC cables to the simultaneous application of thermal and electromagnetic fields, structural loads, and environmental effects	Near term (1-5 years), - number of miles of high-voltage transmission lines that will reach end of useful life in the next 10 to 20 years
Manufacturing processes	• Use of metals and other materials to manufacture grid components and study of soft magnetic materials for advanced manufacturing • Develop lightweight, high-strength, and failure-proof structural composites • Develop methods for cost-effective large-scale manufacturing of conductors and connectors • Cost-effective large-scale conductors and connectors manufacturing using metallic matrix composite materials with improved electrical and mechanical properties • Manufacturing processes for carbon nanotubes and carbon nanotube-based conductors using low-cost abundant precursors for a novel class of cables.	Near term (1-5 years) - materials and manufacturing methods may address the end of useful life of existing infrastructure
Transformers	• Standardize modular transformers – no need for redesign • Customizable components allow the transformer's performance characteristics to meet specific needs	Near term (1-5 years) enable rapid deployment transformers in response to an event

8

Advanced Sensors

- Overview
  - Visibility into the operation is vital to system reliability, resiliency, and security.
  - System monitoring and access to system data are foundational for situational awareness, operations decision making, and long-term planning.
- Benefits
  - Enhanced grid situational awareness
  - Enhancement of grid asset management
  - Optimized grid operation and cost reduction through advanced DLR
  - Secure and accurate time synchronization in nationwide by advanced timing
- Advancements are needed in:
  - High-fidelity sensors
  - Asset monitoring
  - Advanced timing

9

Advanced Sensors- recommendations

R&D Technology Area	Recommended R&D	R&D timeline

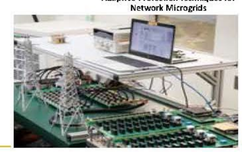
High-fidelity sensors	• Synchronized measurements
	  o Timing technologies that do not rely on the GPS
	  o Measurement intelligence and algorithms, enhancing measurement accuracy, reliability, availability, security, and versatility
	  o Multiple measurement functions in one device,
	  o Extremely low-computational-cost measurement methods to enable ubiquitous measurements
	• Optical monitoring systems
	  o Cost reduction.
	  o Optical sensor characterization platform to evaluate the performance under various grid conditions;
	  o Long-term field testing to justify performance
		Synchronized Measurements: Near term (1-5 years) overcome challenges preventing synchronized measurement application in control rooms
		
		Optical monitoring systems: Near term (1-5 years). Cost to benefit ratio

Asset monitoring	• Embedded sensing for asset monitoring - co-design and integration of sensing method and asset structure into manufacturing • System-level design and interfaces for autonomous initiation, data processing, self-calibration, and energy management for self-sustained operation; • Next-generation multi-functional sensor platforms and wireless protocols; • DLR technology with prediction capability for a wide range of time frames;	Near term (1-5 years) embedded sensing asset monitoring with advanced manufacturing - improve penetration of asset monitoring in energy systems
Advanced timing	• Alternative timing approaches - pulsar-based timing, instrument / pulsar-based timing • Hybrid timing system(s) coordinated when GPS signal is unsatisfactory - • Timing system spoof detection and protection.	Near term (1-5 years). Timing is a fundamental component for data synchronization for grid monitoring.

Advanced Protection Systems

- Overview
  - Power system evolution = devices, methods, and schemes evolution
  - Fundamental characteristics no longer hold, and operational expectations, system-wide interoperability, and complexity are increasing.
- Benefits
  - Accommodate microgrids, islanding and switching between utility and DER sources
  - Increased ability to handle complex topologies and operational requirements
  - less dependent on traditional protection concepts
  - Sensitive enough to detect faults and reliable enough to avoid mis-operations
  - Can do more with existing or smaller protection engineering workforce
- Advancements are needed in:
  - Model-driven adaptive relaying
  - Artificial intelligence/machine learning
  - Setting-less (coordination-less) relay
  - Integration with sensors (traditional and non-traditional)

Adaptive Protection techniques for Network Microgrids



11

Advanced protection- recommendations

R&D Technology Area	Recommended R&D	R&D timeline
Model-driven adaptive relaying	• Approach to incorporate internal power system simulator within local relays, – Automatically calculate protection settings and adjust coordination with local and remote terminals – Protective relays: adaptively coordinate for multiple power system contingencies and configurations	• Near term (1-5 years) to allow time for development, commercialization, and adoption
Artificial intelligence/machine learning	• Algorithm for auto-tuning models or learning expected load level, to characterize and provide accurate parameters • Mitigations techniques for system configuration when position navigation and timing series are not available,	• Near term (1-5 years) to allow time for development, commercialization, and adoption
Setting-less (coordination-less) relay	• Develop protection based on dynamic state estimation • Avoid complex settings and coordination tasks, • reduce errors, and continuously monitor protection zone measurements;	• Mid term (10-15 years)
Integration with sensors (traditional and non-traditional)	• Sensors that measure quantities other than voltage and current, e.g., acoustic, vibration, and thermal sensors	• Mid term (10-15 years)

12

Role of the Department of Energy

- DOE can address immediate and long-term challenges to America's energy security while supporting applied research on advanced technologies.
- Plays an instrumental role in bridging the innovation gap (a.k.a. the “valley of death”) by means of public -private partnerships among industry, utilities, and research organizations such as national laboratories.
- Additionally, DOE can use its convening power to bring together stakeholders and further refine the areas addressed in this report, federal investments that can have the most significant impact

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Summary

- Future grid facing many challenges and “quickly evolving”. Transmission technologies that will enable a reliable, resilient grid include
  - Power-flow control devices
  - High-power delivery systems to transmit over long distances
  - Advanced sensors
  - Advanced protection systems
- DOE role through public private partnership can accelerate the advancement of transmission technologies


U.S. DEPARTMENT OF ENERGY
Questions?
Tom King
Sustainable Electricity Program
Director
kingtjjr@ornl.gov
Chris O'Reilley
Thomas King
Edgar Lara-Curzio
Zhi Li
Madhu Chinthavali
Lingwei Zhan
Travis Smith
Mike Marshall
We would like to recognize Ryan Dehoff, Christopher Fancher, Peter Fuhr, Joshua Hambrick, Pooran Joshi, Yilu Liu, Benjamin McConnell, Srijib Mukherjee, Alex Plotkowski, Yarom Polsky, and Nils Stenvig of Oak Ridge National Laboratory for their technical expertise contributions to the development of the recommended research and development technologies.

U.S. DEPARTMENT OF ENERGY

Transmission Innovation Symposium

Modernizing the U.S. Electric Grid

Economic Analysis and Planning Tools

Jessica Lau
National Renewable Energy Laboratory

Benjamin Hobbs
O'Connor Sustainable Energy Institute, Johns Hopkins University
CAISO Market Surveillance Committee

May 20, 2021

All views shared are the authors' and do not represent the position of any affiliated organizations or sponsors

Outline

- Our Vision of the Future Grid
- Recommendations
  - Multi-Value Planning
  - Workforce Development
  - Behavioral Underpinnings of Economic Valuation and Market Designs
  - Market Simulation and Planning Models with Flexibility and Scalability
  - Adaptive TRP Under Profound Uncertainty
- Summary

2

Our Vision of the Future Grid

3

R&D Recommendations

- DOE supports a national strategy for reliable, affordable, & resilient energy systems to promote the welfare of citizens and maintain the United States as a leading world economy
- We developed recommendations for the next two decades
- **Transmission Resource Planning (TRP)**: Our description for all-inclusive tool & process to conduct holistic planning
  - Not literal co-optimization, but supporting investment decisions that coordinate interactions between resource and transmission, economics, & how the market will respond
  - May include expansion, production cost, power flow, & other models and analyses

Table 1. Authors' R&D recommendations for the U.S. Department of Energy

Research Areas & Topics	Immediate Priority	Short-Term Focused Support	Long-Term Sustained Support
3.1 Multi-Value Planning			
· *Planning with multi-value objectives*	■	■	
· *Creating advanced scenarios & performing sensitivity analyses*		■	
· *Bridging and bonding transmission and distribution planning*			■
· *Investigating multi-sector interdependencies & planning*	■		■
3.2 Workforce Development			
· *Providing students & professionals with experience-building opportunities*	■		■
· *Supporting educational & outreach tool development*			■
· *Increasing accessibility to all*	■		■
3.3 Behavioral Underpinnings of Economic Valuation & Market Designs			
· *Researching how trading institutions have evolved*		■	
· *Researching market & non-market drivers of resource investment*		■	
· *Conducting on consumer & distributed resource decisions*			■
· *Researching market designs & software on deliverability of ancillary services*	■	■	
3.4 Market Simulation & Planning Models with Flexibility & Scalability			
· *Devising frameworks & practical tools for developing reliability/security requirements, & their integration into economic planning models*			■
· *Developing more realistic & larger-scale production-cost models*	■	■	
· *Identifying fidelity improvements that would most improve plans*	■	■	
· *Incorporating enhanced flexibility in models & tools*			■
· *Representing market inefficiencies & effects on transmission benefits*		■	
· *Researching decomposition for solving large-scale TRP models.*		■	
· *Modeling extreme events & resilience in TRP*	■	■	
3.5 Adaptive TRP under Profound Uncertainty			
· *Developing multi-stage risk-based TRP models*		■	
· *Developing computational advances*			■
· *Defining imaginative scenarios*		■	
· *Improving forecasting methods & data*	■		■
· *Developing robust cost allocation to promote cooperation*	■	■	

4

1. Multi-Value Planning

➢ **Drivers**:
- Numerous, diverse, complex, and rapidly evolving goals for the grid, energy, and environment
- Expand transmission and grid planning to consider objectives and values important to all stakeholders

➢ **Recommend** tools, processes and structures to consider:
- Planning flexibly for multi-value objectives with data and models
- Advanced scenario and sensitivity creation
- Bridging and bonding transmission and distribution planning
- Multi-sector interdependencies and planning

➢ **Outcomes:**
- Drive innovation in addressing and balancing stakeholder objectives and facilitate public partnership
- Create data, tools and processes appropriate for different users (i.e., complex and realistic, simple and useful)

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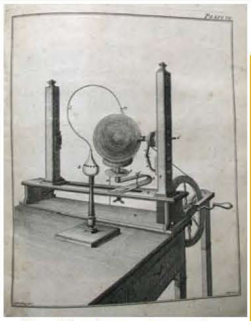
2. Workforce Development

➢ **Drivers**:
- Shortage and aging workforce in transmission and grid planning
- Evolution of skillsets necessary to support grid planning objectives
- Engaging society to improve relationship and interactions with electric industry

➢ **Recommend** technical, social, and hands-on R&D to support:
- Providing students and professionals with experience-building opportunities
- Developing educational and outreach tools
- Increasing accessibility to all in workforce and electric consumers

➢ **Outcomes:**
- Adequate number of qualified professionals in the industry
- Foster broad set of skills in engineering, economics, regulatory law, and social science
- Broad understanding and public partnership in the development electric infrastructure

6



3. Behavioral Underpinnings of Economic Valuation & Market Designs

➢**Drivers**:
- Benefit estimates must reflect how TRP might change operations & trade in an imperfect world
- Poor market design→decreased econ & reliability benefits of TRP

➢**Recommend** social science research to understand:
- Evolution of institutions that affect transmission & trade economics
- Effects of inefficient market design & participant behavior on use of grids, & economic outcomes
- Market & non-market drivers of resource investment (especially consumers & DERs) for use in "co-optimized" TRP
- Market designs & software to manage A/S deliverability

➢**Outcomes:**
- Market designs to fully realize benefits of TRP
- Realistic co-optimized TRP models to avoid mischaracterizing response of resource investments
- Defensible estimates of benefits of grid reinforcements

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4. Market Simulation & Planning Models with Flexibility & Scalability

➢**Drivers**:
- TRP model complexity grows because of technology diversity & complexity, and expanded geographic & time horizons
- Yet also need transparent & easy-to-use models that address basic drivers & tradeoffs to engage stakeholders & regulators

➢**Recommend** TRP model improvements:
- Frameworks, tools, & data to integrate reliability & security requirements into economic planning--especially extreme events
- Large-scale computation & decomposition to coordinate more realistic production-cost models with TRP
- Assess flexible tools: how effective is open-source release of data & models, how useful are simpler, easy-to-run tools?
- Represent effects of market inefficiencies (e.g., trade barriers) on transmission benefits & optimal plans, especially in co-optimization

➢**Outcomes:** Enhance planner & stakeholder confidence by:
- Exploring more options & assumptions under uncertainty
- Improving benefit estimates in the face of technological complexity & market inefficiencies

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5. Adaptive TRP Under Profound Uncertainty

➢**Drivers**:
- Capital intensity of the power sector → long-run uncertainties mean stranded assets & missed opportunities
- Need to quantify uncertainties, integrating past data & expert judgment

➢**Recommend** method improvements
- Practical consideration of resilience & multiple scenarios when evaluating near-term decisions & later adaptability
- Imaginative definition of operating & planning scenarios, exploiting research on human-factors & experimental design
- Improved forecasting methods & data, including:
  - ✓ multiple energy sectors (buildings, transportation, fuels)
  - ✓ integrated T&D
  - ✓ drivers of load consumption changes
  - ✓ industry partnerships
- Robust cost allocation to promote planning cooperation among regions, by mitigating financial risks from uncertain trade patterns & costs

➢**Outcomes:** Assurance that:
- Society benefits from grid infrastructure investments
- These benefits are robust to alternative futures

9

Our Vision of the Future Grid → *Recommended Research*

- "The way it has been doesn't mean it's the way it will be"
  - →*Change is accelerating, and we need to do things differently*
  - →*Methods to plan under profound near- and long-term uncertainty*

- "Transmission and supply can be interchangeable"
  - →*Benefit quantification methods that recognize how transmission can substitute for and complement resources*

- "Incentives show up in many ways (markets, tariffs, taxes, alignment)"
  - →*Co-optimize, recognizing how grid reinforcements, allocation, & pricing affect drivers of market reform and resource investment & operations*

- "Human resources are critical"
  - →*Involve industry in training, and data & methods development*

DOE's role is crucial!

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U.S. DEPARTMENT OF ENERGY
Questions?
Jessica Lau
Sr. Technical Manager
Jessica.Lau@nrel.gov
Ben Hobbs
Theodore & Kay Schad Professor of Environmental Management
bhobbs@jhu.edu

APPENDIX E. Written Comments Received

Transmission Innovation Symposium: Modernizing the U.S. Electric Grid

Comments on Protective Relaying Coverage by the White Papers

M. Kezunovic
Texas A&M University
June 4, 2021

Preamble

The white papers were quite thoughtful, the symposium discussions were enlightening, and the exchanged information was indeed educational and revealing. Collectively, the experts that contributed to the white papers have offered unique insights that are rather impressive and long lasting, the panelists have nicely complemented the points in the white papers with their comments, and the white paper coordinators have done an excellent job in recruiting highly respected and knowledgeable experts.

The comments below focus on expanding some of the issue in protection, substation automation, and outage and asset management. Hopefully, the points discussed below will shed additional light on the white paper recommendations that mention protection explicitly, which is mostly done in the white papers on "Hardware and Components" and "Automatic Control Systems" (see APPENDIX).

1. Introduction

The core objective of protection systems is to maintain safe power grid operation under adverse power system conditions, often caused by environmental impacts. This is done through fast and reliable operation of protective relays, which are set to operate locally for faults, and related solutions across the power system through remedial actions or special protection schemes for system-wide extreme disturbances. The result of protection scheme operation is characterized as an outage, which may be related to a single component of the power system (line, transformer, generator) or can affect larger grid areas. Whatever causes the outages, their economic impact in the United States is estimated to average over $100 billion annually. In extreme events of large brownouts or blackouts, a single event such as the recent February 14, 2021, outage in Texas due to cold front Uri caused 4.5 million consumers to be left without electricity and over 7 million without drinking water for several days. The devastating impacts resulted in over 120 human fatalities and several hundred billion dollars in financial loses. Beside the financial loses, the human and social impacts are quite devastating, too.

The statistics show that over 50% of outages are caused by inclement (but not necessarily catastrophic) weather and equipment failure caused by tear and wear. Other evidence shows that power systems outages may occur due to an extreme imbalance between generation and load. Cascading events (system faults followed by equipment failures) and low-probability, high-impact events can also contribute to the outages. The introduction of distributed energy resources (DERs) can contribute to the deterioration of safety issues stemming from their interaction with the grid and can endanger DER owner/user if the DER protection is not properly designed. Last but not least, cyberphysical attacks can target protection and cause outages through impact on grid controls.

The following are research focus areas intended to complement the recommendations in the white papers.

2. Research Areas and Recommendations

2.1. Protection Requirements

The operational principles and requirements of the legacy protection system were established almost 150 years ago when the power systems were commissioned for the first time. It is becoming evident that such principles and requirements are not sufficient to protect future power systems. This section mentions a few research topics that will need to be pursued expand protection system principles and requirements needed in the future grid development.

Dependability vs Security. The traditional definitions of dependability and security have been established long time ago as an essential reliability requirement of protection systems [1]. The dependability relates to the requirement of a local protection relay to operate when a fault on equipment occurs. The security relates to the requirement for a relay not to operate when the fault is not inflicted. With heavy loading of the existing system, and under the interaction of the distribution system with the transmission system and DERs, several new research areas have emerged:

- The impact of DERs operation on the transmission and distribution relays [2]
- The impact of low frequency oscillations on the transmission protection [3]
- Anti-islanding protection of DERs [4]
- Protection of AC and DC microgrids [5]

It is recommended that emerging areas of research be pursued to cope with the new challenges of grid development affecting protective relay dependability and security in the future.

Reliability vs Resilience. Despite many great discussions introduced by the DOE, NAE, IEEE, NERC, FERC, CIGRE and professionals in different reports and papers, the rigorous and all-encompassing definition of resilience is still missing [6,7]. Here are a few research issues that may be beneficial to pursue regarding this topic:

- Which resilience metrics can help the regulatory, legislative, and even political decisions to address the cost and impact of protective relaying improvements [8]?
- What evaluation framework should be used to define the impact of protective relaying actions on the system resilience [9]?
- What is the relationship between system reliability and system resilience, and how is one affected by the other when outages occur [10]?
- How often do cascading events that occur as local faults propagate to system-wide disturbances and how may they be detected and arrested to avoid major blackouts [11]?

It is recommended that research be initiated into the further conceptualization, quantification, and evaluation of the resilience relationship to protective relaying performance as a logical extension of the well-established reliability framework for protective relay operation.

2.2. Technological Solutions

Over the years, a major development that has enabled innovation in protective relaying is further digitalization of substation equipment. The development of all-digital substation with precise time-synchronized measurements and optical sensors supplemented with IEC61850 communication standardization has paved the way for fundamentally new approaches to future monitoring, control, and protection technological solutions. The discussion in this section highlights two profoundly impactful developments that have not yet delivered their full potential and hence need further research.

Substation Automation. The all-digital integrated substation concept was invented and implemented in the 1970s [12,13]. Microprocessor technology maturity proliferated the development of a digital relay as a standalone device in the mid-eighties, and the concept of substation Intelligent Electronic Devices (IEDs) prevailed for many years. The industry has come a full circle where today the IEEE and other professional organizations are promoting the concept of all-digital integrated substations again [14]. The role of intelligent substations in hosting the protection functions in the next 10–20 years needs to be examined by researching the following issues:

- How to fully integrate all-digital substation concept in the next generation of the energy management systems at the T&D level [15]
- How to fully automate the analysis of protective relaying operation so otherwise off-line function is incorporated in on-line action to mitigate relay mis-operations [16,17]
- How to enhance local substation functionalities to support distributed processing for more cost effective, environmentally friendly, and reliable solutions [18].
- How to enhance fault-locating principles to allow precise identification, timely repair, and speedy restoration of faulted equipment [19, 20]

It is recommended that future substation developments be viewed in the context of the overall grid control system that may be hierarchically implemented where local protection functions are automatically executed in substations but fully coordinated with the centralized functionalities that may involve operators in the control loop.

Synchronized Measurements. The history of time-synchronized measurements dates back to the eighties, and the benefits for different protective relaying and control applications were recognized in the early nineties [21]. In the meantime, many protection and control applications were developed and deployed, and many more are in various research and development phases [22]. While this area initially resulted in the applications that used phasor estimates, further work is needed to explore application using point-on wave samples. Several research areas are recommended for further understanding and leveraging of time-precise measurements in protective relaying:

- What are the new opportunities for innovative substation-wide relaying using intra-station communications for the utilization of synchronized samples and artificial intelligence methods [23]?
- How does the inter-station communication exchange of synchronized samples improve unit protection of the power apparatus [24]?
- How can merging the time-precise measurements with spatial information improve transmission system protective relaying and control applications [25]?
- What are the next generation protection applications of time-synchronized measurements in distribution systems integrated with DERs [26]?

It is recommended that research initiatives are lunched into investigation of full benefits of time-synchronized measurements across the spectrum of protection applications in generation, transmission, distribution, and DERs.

2.3. Predictive Outage and Asset Management

The main reason for occurrence of outages is the breakdown of equipment electrical insulation, which can happen due to the assets aging, or may be inflicted when the assets are exposed to strong electrical stresses such as lightning, interference of wildlife, or contacts with vegetation. With many utilities keeping record of the causes of outages and equipment failure statistics, new opportunities to deploy machine learning and artificial intelligence aimed at predicting the risk of failure are worth exploring. The following research recommendations are pointing at some innovative approaches that offer strong promise based on the initial research.

Hierarchically Coordinated Protection. The shortcoming of the legacy protection was recognized 35 years ago when adaptive relaying was introduced to make protective relaying more attunable to changing power system operating conditions [27, 28]. The most recent opportunities to enhance protective relaying have been created as the proliferation of Big Data analytics combined with machine learning, and artificial intelligence has started to attract attention in power system applications [29, 30]. As a result, several research areas have emerged:

- How to formulate predictive protection and how to integrated it with the traditional corrective and adaptive protection [31]
- Protection issues that span new DER deployments, including microgrid protection and protection of distributed generation resources [32]
- How weather impacts may affect outage management in the future grid to mitigate and even avoid major outages caused by regular storms [33]
- Protection issues that affect long-term planning of power systems for resilient solution [34]

It is recommended that predictive methods be investigated to anticipate system faults and risk analysis be used accordingly to define mitigation strategies for avoiding (minimizing) risk of outage impacts.

Predictive Asset Management. The cost of the legacy system assets in the United States are estimated at close to one trillion dollars. Most equipment is rather old, and serious concerns were expressed recently about the inadequacy of such assets to support future grid expansion with the plans for wide transportation electrification [35-36]. The traditional asset management analysis has spanned across different concepts such as reliability centered maintenance and just-in-time maintenance, but new approaches are needed to avoid major asset failures that may lead to system-wide outages. Several research areas need to be explored to account for the new challenges:

- How the weather-inflicted causes of power apparatus deterioration can be predicted and mitigated [37]
- Which opportunities use Big Data to account for variety of environmental impacts on asset aging and failure [38]
- How transportation electrification may stress the utility assets, and how such stresses may be avoided or mitigated [39]
- How the grid operating conditions may be predicted to allow for timely reconfiguration of protective relaying to avoid relay mis-operation [40]

It is recommended that future research focuses on asset management since the asset failure or reconfiguration if not properly anticipated and mitigated may cause major outages in the future.

2.4. Research Infrastructure

The research related to protective relaying requires adequate research infrastructure for modeling, simulation and testing of new solutions, and engineering tools to support design and setting of the relays and relaying systems. The research infrastructure may range from field installations in the utility system for testing complete relaying solutions to the use of real-time simulators for hardware-in-the-loop or system-in-the-loop testing of control devices and systems. The legacy engineering tools are mostly focused on relay modeling, and system simulation studies are needed to properly set the relays. We discuss several research topics that need to be pursued to define new research infrastructure as an extension of existing practices to evaluate emerging protective relaying concepts and solutions.

Large Scale System-in-the-Loop Test Beds. The introduction of real-time simulators for relay testing in the early nineties has enabled the evaluation of new protective relaying solutions for complex applications such as series compensated transmission lines [41]. Since then, the state-of-the-art in real time simulators have focused on expanding the simulator capabilities by increasing the computational speed and allowing modeling and simulation of fast phenomena associated with power electronic operations [42]. Future research about the modeling, simulation, and testing infrastructure is needed to allow for evaluation of more complex protective relaying solutions for local and system-wide relaying:

- What are the most appropriate designs of federated testbeds capable of modeling, simulating and testing large-scale, system-wide protective relaying solutions [43]?
- How can system-in-the-loop testbeds be developed for comprehensive evaluation of solutions associated with mitigation of impacts in the accurate timing uses in protection and control [44]?
- What are the future needs for testbeds and cyberphysical digital twins that can be used to model and detect cybersecurity attacks on local and system wide protection systems [45]?
- How should a testbed for Big data analytics for study of weather impacts on assets and protection systems look like [46]?

It is recommended that the infrastructure of large-scale testbeds become a focus of future research efforts as an essential requirement to properly test and evaluate future protection solutions.

Protection Engineering Tools and Methodologies. The need for new engineering tools and methodologies for design of protection relays was recognized a long time ago [47]. While relay modeling and simulation has contributed to the understanding of protective relay operation [48], further development of such models is needed to fully understand the impacts of protective relaying on system operation [49]. Going forward, the following research areas need to be pursued to develop adequate engineering tools for power system protective relaying studies:

- How to integrate protection system models and power system models and related controls to assess the interaction between the cyberphysical components [50]
- How to model the interaction between different critical infrastructures to better understand their interdependencies that may lead to system outages [51]
- How to model protection systems to better assess impacts of hidden failures that may contribute to the protection system mis-operation [52]
- How to test complex protection systems to assure that their life cycle management is properly handled to avoid their failure or mis-operation [53]

It is recommended that the research focus on engineering tools and methodologies for design and testing of protection relays and systems be emphasized due to the need for more advanced solutions.

2.5. Workforce development

The workforce development issue has been widely recognized across all five white papers. The following comments are related to the workforce development in the are of power system protection. This specialized area requires knowledge from many other areas, so by its nature, it is highly multidisciplinary. The set of research recommendations is focused on training curriculum development for the education of future protection professionals and the public, including legislators and regulators, that is needed to better appreciate the reasons for outage occurrences and the role the public can play in mitigating the outage impacts.

Professional Training Curriculum. Many surveys and curriculum developments have focused on academic professional training at the university level [54]. They are supplemented with surveys about the need for continuing education of protection professionals [55]. They point to many unresolved research topics associated with professional training curriculum development:

- What academic curriculum should be used at universities to advance knowledge in the protective relaying area [56]?
- What instructional materials and laboratory infrastructure should be used to support the academic education [57]?
- What should be the short course curriculum, supplemented with webinars and hands-on experiences that are aimed at life-long learning for professional development [58]?
- How can students be attracted to the profession as they enter the educational system in grades K-12 [59]?

Education of the Public. In the past, the education of the public regarding outages and power restoration was focused on the general notion that outages may occur due to weather impact caused by climate change [60]. This educational approach has not been considered worth particular research efforts since it was considered that the public has passive role when it comes to any particular impact on outage mitigation. With the changing paradigm, where outages may be predicted, the role of public in avoiding or mitigating the impacts does require further research to better understand associated questions:

- What are the mitigation measures that the general public can undertake to avoid impacts of lasting outages [61]?
- What is the educational means to alert the most vulnerable societal groups of safety issues associated with outages [62]?
- How can legislators be best educated about the need for emergency alerts and mitigation measures before and during electricity outages [63]?
- How can regulators and legislators be engaged in the discussion about equity issues related to outage impacts on the most vulnerable populations [64]?

Conclusions

The key conclusion is that power system protection is a crucial component of future grid development and should have been treated (in the opinion of this reviewer) as a stand-alone white paper. While the protection-related research issues have been mentioned extensively in the two white papers (APPENDIX), the protection importance, the challenges and opportunities, and profoundly different future requirements and implementation concepts need to stand out as the key research issue to be fully appreciated and understood.

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APPENDIX

White paper recommendations related to protection

The following are the white paper recommendations that related either directly or indirectly to protection:

Hardware and components:

- *Model-driven adaptive relaying*. Incorporate an internal power system simulator within local relays to automatically calculate protection settings and adjust coordination with both local and remote terminals and adaptively coordinate for multiple contingencies and configurations of the power system they are protecting
- *AI/ML*. Develop algorithm to auto-tune models or learn expected load levels in order to characterize and provide accurate parameters by learning normal system behavior as well as system response during system breaker operations, fault events, and normal operations. Incorporate mitigation techniques for system configuration when position navigation and timing series are not available
- *Setting-less (coordination-less) relays*. Develop protection based on dynamic state estimation ("setting-less protection") which aims to avoid complex settings and coordination tasks and thereby reduce errors, and continuously monitors protection zone measurements, with mismatches between measured data and the dynamic model indicating that something is wrong inside the protection zone.
- *Integration with sensors (traditional and non-traditional)*. Develop sensors that measure physical quantities other than voltage and current, such as acoustic, vibration, and thermal sensors
- *Optical monitoring systems*. Accelerate applications of optical PTs/CTs in power systems through collaborative efforts among national laboratories, industry, and DOE
- *Synchronized Measurements*. Support deployment of timing technologies, including long-term performance demonstration, system-level integration of multiple time sources, and benefit-cost analysis.
- *Advanced Protection Systems*. Promote and coordinate government, research organization, industry, and utility collaboration on defining the needs and requirements for advanced protection systems. Promote and coordinate, across DOE, co-simulation and model integration to ensure that system dynamics are accounted for in model results. Promote and coordinate industry collaboration on backward compatibility of equipment and ensuring that newly developed equipment is backward compatible; collaborate with research entities and industry to define compatibility requirements for the equipment

Automatic Control Systems

- *Response-Based Remedial Action Schemes*. Rigorously develop, and validate with comprehensive engineering simulation and field demonstration projects, entirely new remedial action scheme designs that are response-based (vs. traditional event-based schemes) and provide flexibility and robustness to a wider range of off-normal conditions.
- *Adaptive Islanding Schemes*. Develop pre-planned automatic controls to isolate portions of the grid to prevent an uncontrolled cascading failure, thereby limiting the extent of a disruption to

the smallest possible area during system emergencies or incipient cascading failure conditions; although impossible to fully test in the field prior to implementation, evaluate for efficacy through comprehensive modeling and simulation. Ensure frequency and voltage control occurs seamlessly during the transition. Maintain optimal management of load and generation resources during both grid-connected and islanded modes.

- *Control Architectures*. Develop distributed, real-time, closed-loop architectures that accommodate uncertainties in renewable generation and match supply to demand by making use of wide-area real-time information, and that decompose global objectives into coordinated local algorithms. Research distributed architectures that ensure safety and stability of the grid in the presence of incomplete and intermittent information. Develop scalable algorithms that are deployable at a huge distributed scale, supported by local decisions and global coordination
- *Inverter-Based Resources for Control Actuation*. Assess feasibility of, and develop, control designs for, inverter-based resources in applications including voltage stability, transient stability (transient power-quality control), damping of small signal oscillations and/or forced oscillations, power quality (e.g., harmonics), and negative sequence current supply (for unbalanced faults and/or unbalanced load).
- *Improved Dynamics Simulation*. Improve error analysis and study of uncertainty propagation in Improve error analysis and study of uncertainty propagation in numerical solvers to improve simulation accuracy and speed. Investigate advanced simulation frameworks, including parallel computing and adaptive modeling
- *Controls for Grid Restoration*. Define roles for grid-following and grid-forming inverters that can be used with black-start restoration. Devise techniques for sequencing of inverters with other power generation resources in black start. Develop strategies to mitigate risks to the grid from using inverter-based generation for black start. Model operator behavior during black start. Apply machine learning and artificial intelligence techniques to black-start process

Wed, May 19

Are you considering the gas grid as a “supplementary electricity” network by turning wind power into green hydrogen and sending “electricity” to load centers via the gas grid?

Can you point me to any papers if this has been investigated/researched?

Thank you,

Anja Limperis
New York, NY

Wed, May 19

Dear Panelists,

Thank you very much for the interesting talks.

I have one question regarding the research opportunities for future electric grids.

I would like to hear your opinions about different computing architectures for the simulation, control, and optimization of power system networks. Such different computing architectures would include high-performance computing, cloud computing, quantum computing, and etc. Also how likely would power industries be interested in such techniques and develop tools by utilizing them for future grids?

Byungkwon Park, Ph.D.
Advanced Computing Methods for Engineered Systems
Computational Sciences and Engineering Division
Oak Ridge National Laboratory (ORNL)

Comments on the DOE White Paper

"Electricity Transmission System Research and Development: Hardware and Components"

Submitted by

Line Roald lroald@wisc.edu, Assistant Professor
Giri Venkataramanan giri@engr.wisc.edu, Professor
University of Wisconsin-Madison
1415 Engineering Dr
Madison, WI 53706

As identified by the authors of white paper on "Electricity Transmission System Research and Development: Hardware and Components", it is imperative that our future transmission infrastructure is able to support the integration of clean, renewable energy generation at scale, as well as increases in the demand for electricity due to increases in manufacturing (and electrification of transportation, heating and other sectors). The authors of the white paper suggest that power-flow control and high-power delivery systems to transmit power over long distances are core components of realizing this vision.

We agree with the authors that one important focus of DOE should be on research to enable a transmission infrastructure that has *sufficient capacity* to support high power flows across large geographical distances, and is *flexible enough* to accommodate flows that vary with weather conditions, time of the day and season. However, we find that the white paper is too narrow in identifying the technologies that can be used to achieve these goals. While HVDC and FACTS devices are important technologies that deserve continued support, there are also other alternatives that deserve consideration.

One example of an alternative technology that is promising, though still in its infancy, is low frequency AC (LFAC) transmission. Recent research [citations] has investigated the benefits of upgrading *existing* backbone transmission corridors to a **low frequency AC (LFAC)** system that promises the needed capacity and flexibility at lower cost compared to other alternatives including HVDC systems. With frequency converters on each side of an LFAC line, it is possible to (1) reduce the line reactance and thus *increase the power transfer capacity*, particularly on long, stability-constrained lines, and (2) use the frequency converters to directly control power flows, which enables *improved utilization and flexibility from existing transmission assets* across a range of operational scenarios. Fig. 1 shows an LFAC upgrade to a transmission line embedded in an AC system, and illustrates how the frequency and power flow control can improve transfer capacity and utilization[1].

Relative to other technologies such as HVDC, a key benefit to LFAC is that the technology can *utilize existing conductors and tower configurations* (since there is still three phases and three conductors) and can build upon existing protection system technology (since there is still a zero-crossing of the current) to enable *multi-terminal systems* or an *LFAC supergrid.*

[1] T. Ngo, M. Lwin and S. Santoso, *Steady-State Analysis and Performance of Low Frequency AC Transmission Lines*, IEEE Transactions on Power Systems, vol. 31, no. 5, pp. 3873-3880, Sept. 2016

Furthermore, initial comparisons of LFAC and HVDC indicate that the system level benefits (in terms of reduced congestion and operational cost) are comparable, or even better with LFAC[2]. In contrast to the HVDC system, where voltage is the only degree of freedom available to determine the amount and direction of power flow in a multiterminal network, the availability of the phase angle as a degree of freedom to determine the magnitude and direction of power flow in a network is **retained** in an LFAC system. This provides the flexibility and capability to operate the LFAC system with ease leading to performance that is superior to the HVDC system or the conventional 60Hz system.

We believe that DOE should play an important role in funding the research that will bring this technology to fruition, by supporting the development of the required hardware (i.e., converter topology, converter control and protection systems) as well as the necessary software analysis tools to assess system-wide operational benefits (reduced cost, improved congestion management) through steady-state optimal power flow analysis and dynamic contingency analysis. We are currently completing a project funded by the New York Power Authority to explore this emerging technology, indicating promising potential for this approach. Successful development and deployment of this technology can be a cost-effective pathway of increasing transmission capacity for integrating sustainable power into our transmission system and pave the way for meeting the challenges of securing our energy future. Any questions regarding these comments can be addressed to the authors be e-mail.

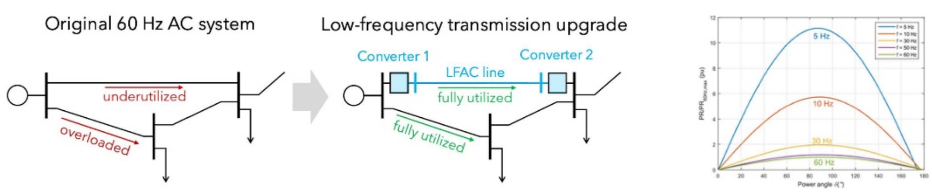

Figure 1: Upgrade in power control and transfer capabilities of an underutilized line to LFAC.

Links to selected publications related to these topics are provided in the table below, along with a short summary of the document. These documents provide a broader background to the technology along with access to other pertaining literature.

No.	Publication name (click to access full document)	Description
1	Low Frequency AC Transmission Upgrades with Optimal Frequency Selection	This paper investigates the use of LFAC as a transmission upgrade using existing lines and proposes models and analysis methods to determine the optimal choice of frequency. It presents an optimal power flow model with frequency as a variable, quantifies the system-wide advantages and finds that an LFAC upgrade achieves similar and

[2] D. Sehloff and L. Roald, *Low Frequency AC Transmission Upgrades with Optimal Frequency Selection*, online.

		sometimes better results compared with HVDC upgrades.
2	Steady State Modeling for Variable Frequency AC Power Flow	This paper introduces and validates models for steady state calculations with frequency as a variable. It then introduces an analytical quantification of the power flow capacity of a transmission branch as a function of frequency. These models and analysis provide a foundation for system level studies.
3	Steady State Modeling and Optimization for Variable Frequency AC Transmission Systems	This document first provides a review of LFAC literature, including topics of feasibility, analysis methods, hardware, and existing applications. Next it discusses details of modeling for LFAC and presents an optimal power flow model, software implementation, and case studies with extensions for series compensation and N-1 analysis.
4	A Comparative Evaluation of Power Converter Circuits to Increase the Power Transfer Capability of High Voltage Transmission Lines	This paper compares two topologies of power converters that can be used in low frequency power transmission. The two topologies compared are the Modular Multilevel Matrix Converter (MMMC) and the Back-to-Back Modular Multilevel Converter (BTB-MMMC). For these two topologies, design equations have been proposed that size the main components and operational variables. Among the aspects to be compared are: (i) the size of the reactive components, (ii) the requirements in semiconductors, (iii) operating losses and (iv) fault tolerance.

Thu, May 20

Great symposium with excellent information and discussion by panelists. Some additional thoughts that you may want to consider for the future.

- As the transmission grid changes, the ability of planners to deal with the rapid addition of renewable resources is making the grid more fragile due to the timeline to build the systems to support dispersed generation and add necessary redundancy. In the immediate future, grid devices that can accommodate inverter based generation until the grid is enhanced is needed and are being deployed but their large footprint is sometimes a constraint. There is a need for smaller footprint devices such as Statcoms or mobile Statcoms, synchronous machines and battery storage systems. DOE engagement in research to reduce the footprint size of these devices would be beneficial.
- The need to develop new transmission lines will require a different type of line designs that can be maintained, but will be more acceptable to the general public if we are to ease development and acceptance. DOE should research new designs such as advanced Gas Insulated Line designs (to reduce capacitance impact) and the use of MVDC or HVDC designs to aid the expansion of the grid in ROW constrained areas.
- The deployment of smart devices that can quickly assess failing equipment but this will require a different response of personnel or else personnel may be responding and arrive at the moment of catastrophic failure. Several utilities have had a near miss with arriving personnel using advanced transformer on-line DGA monitors. Automatic response mechanisms should consider this in their designs.
- The area of Human Machine Interfaces must be improved for the workforce of the future. Most advanced devices in use in the substation environment use HMI devices that were developed prior to today's technology. As a result, the workforce that is now trained to work with iPhone devices no longer are comfortable with using screens that were based on a hierarchical approach with layered screens - some using early Windows or DOS type formats. DOE should advance HMI development by vendors of complex systems like HVDC or Statcoms.
- Power engineers in the future will need a knowledge of power electronic devices due to the significant penetration of silicon based devices on the future power system. Education in the future must ensure curriculum which allows for this understanding for future power engineers.
- Policy should encourage designs that are more robust and resilient for extreme events based on our understanding of the expected future risk of weather or manmade risk such as EMP / cyber risk. DOE guidance and research that can support these improved designs should be simple and easily understood if it is to be implemented.

- Blackstart in a grid that has a large penetration of inverter based generation is concerning due to loss of short circuit strength on restart and the placement of remaining blackstart generation. Utility understanding of the challenges that must be faced is critically important so we can address before this becomes an issue.
- The loss of short circuit strength is an issue for microgrids that may be developed and will translate to an issue for commercial and residential customers if their protective equipment are to function. A simplified approach on how utilities should consider an acceptable short circuit strength for their customer's equipment is needed unless we transfer the burden of this issue to individual businesses or homeowners. More research is needed in this area on how to address.

I appreciate the opportunity to be part of this Symposium and hope some of these thoughts are beneficial.

David W. Roop
DWR Associates, LLC

AC Link Power Flow Control in Transmission Systems

Comments submitted to DOE's 2021 Transmission Innovation Symposium

Dr. Giri Venkataramanan
Professor, Department of Electrical & Computer Engineering
University of Wisconsin–Madison
1415 Engineering Drive
Madison, WI 53706
giri@engr.wisc.edu

Dr. Fernando Mancilla–David
Professor, Department of Electrical Engineering
University of Colorado Denver
Campus Box 110, P.O. Box 173364
Denver, CO 80217-3364
fernando.mancilla-david@ucdenver.edu

May 2021

Comments about white paper "Electricity Transmission System Research and Development: Hardware and Components"

The authors of white paper on "Electricity Transmission System Research and Development: Hardware and Components", observe that it is imperative that our future transmission infrastructure is able to support the integration of clean, renewable energy generation at scale, and the growing demand for electricity due to increases in manufacturing (and electrification of transportation, heating and other sectors). The authors of the white paper suggest that power-flow control and high-power delivery systems to transmit power over long distances are core components of realizing this vision.

We agree with the authors that one important focus of DOE should be on research to enable a transmission infrastructure that has sufficient capacity to support high power flows across large geographical distances, and is flexible enough to accommodate flows that vary with weather conditions, time of the day and season.

We observe the references to various classes of FACTS devices that can be used to improve the utilization of the transmission infrastructure. We are writing to bring to the attention of DOE Transmission Reliability and Renewables Integration Program regarding a class of FACTS devices that based on pulse width modulated AC power flow controllers that do not incorporate a DC link in the power conversion architecture.

The origins of this technology date back to some of the investigations supported by the Electric Power Research Institute in the later years of the last century. The attached list of references available in the technical literature from the recent past decade have established their feasibility in steady state and dynamic performance in realistic power systems. Detailed evaluations of selected devices also indicate that their performance is comparable or superior to more common FACTS devices that have been reported in the literature.

We believe that DOE should play an important role in funding the research that will bring this technology to to maturity, by supporting the development of the required hardware (i.e., converters, control and protection systems) as well as the necessary analysis tools to assess system-wide operational benefits (reduced cost, improved congestion management) through steady-state optimal power flow analysis and dynamic operational management. Investments in this technology can be a cost-effective pathway of increasing transmission capacity for integrating sustainable power into our transmission system and pave the way for meeting the challenges of securing our energy future.

Any questions regarding these comments can be addressed to the authors by e-mail.

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