CHANGING WHAT'S POSSIBLE

GENI Program Overview

There is growing evidence that the U.S. transmission system is in urgent need of modernization. The system has become congested because growth in electricity demand and investment in new generation facilities have not been matched by investment in new transmission facilities[1]. Because power purchasers typically try to buy the least expensive energy available, transmission constraints impose real economic costs upon energy consumers. In the instances where transmission constraints are so severe that they limit energy deliverability relative to consumers' electricity demand, such constraints can compromise grid reliability[2]. There has been a steady increase in the number of service interruptions on the electricity grid; blackouts resulted in an estimated $79 Billion (approximately 22% of the total revenue for electricity sales) economic losses annually[3].

Confounding the challenge of cost-effective and reliable transmission are two emerging trends:

- The aging of the electricity infrastructure in the United States, and
- The increasing deployment of non-dispatchable generation.

1. BACKGROUND

Nearly one-third of the electricity infrastructure in the United States – from generation, to distribution, to transmission, and controls – is approaching end-of-life or is already past end-of-life[4]. Today, the average age of a substation transformer is 42 - two years more than their expected life span - and the average generating station was built in the 1960s using even older technology[5]. This "asset wall" represents both a significant driver for change and an opportunity for investment.

Today, electricity generation in the United States includes baseload power from coal, gas, hydroelectric and nuclear power plants. For much of the country, generation is scheduled in response to market transactions that occur over a range of timescales. Coal-fired power plants and nuclear power plants are not designed to respond to short term changes in demand. Managing generation to respond to short timescale fluctuations in demand is achieved primarily by gas-fired plants (so-called spinning reserve). Managing congestion, ensuring reliability and economically delivering power for variable demand is achieved primarily by dispatching and curtailing generation[6] [7].

The second major trend for the electricity grid is the deployment of non-dispatchable generation. Much of this is driven by Renewable Portfolio Standards that have stimulated the growth of wind and solar generation. The penetration of both forms of generation is expected to increase as grid-parity is realized across broader markets. However, neither source of generation can be scheduled and dispatched with the reliability of today's baseload and peaking sources. Furthermore, the intermittency of both wind and solar stresses existing transmission resources and is a significant obstacle to continued integration of alternative generation[8]. The short-timescale variability of wind and solar coupled with the absence of dispatchable, fast-ramping coal-fired power and nuclear power concentrates the problems of managing the grid to deploying significantly more gas-fired balancing reserve.

During the last decade the available tools for managing the delivery of electricity have improved. In addition to controlling generation, scheduling and dispatching demand – so-called "demand response" – may be an effective approach to

[1] Department of Energy, National Transmission Grid Study, (Washington, D.C., 2002).
[2] Department of Energy, National Transmission Congestion Study, (Washington, D.C., December 2009).
[3] Kristina Hamachi LaCommare and Joseph H. Eto**,** Cost of Power Interruptions to Electricity Consumers in the United States, Lawrence Berkeley National Laboratory, 2006.
[4] Black & Veatch, Fourth Annual Strategic Directions in the Electric Utility Industry Survey, 2010.
[5] Department of Energy, The Smart Grid; An Introduction, (Washington D.C., 2008).
[6] PJM Tutorial, "Energy Markets and Congestion Hedging", <**http://pjm.acrobat.com/p46628810/**>
[7] PJM, "How RTOs Establish Spot Market Prices", http://www.pjm.com/~/media/documents/reports/spot-market-prices-j-chandley.ashx].
[8] Debra Lew, "Western Wind and Solar Integration Study," Prepared for National Renewable Energy Laboratory, September 2010.

compensate for the proliferation of non-dispatchable generation. Lower cost, rampable, dispatchable storage can relieve the stress on available transmission due to intermittent generation sources. Additionally, the transmission infrastructure itself is becoming more controllable. Power electronics – both in the form of flexible alternating current transmission system (FACTS) devices and HVDC terminals – allow for the control of both real and reactive power flows. The coordination and control of these widely distributed resources (spinning reserve, demand response, large-scale storage, FACTs, HVDC terminals) throughout the grid requires sensing and monitoring of the power flows, low-latency communication to collect the sensor data and transmit control actions, computational resources to dynamically model and calculate the control actions, and power electronics to implement the control at these widely distributed locations. Historically, none of these technologies were sufficiently powerful, cost-effective, or reliable for wide-scale deployment of such distributed controls. This is no longer true:

- Over 1,000 Phasor Measurement Units (PMU) will be deployed nation-wide by 2013 and will provide measurement data for both voltage and current waveforms at 30 ms intervals[9],
- Low-latency internet protocols over high-speed network have enabled total latencies <100ms[10],
- The cost per FLoating point OPeration (FLOP) has recently dropped below $2 per GigaFLOP[11] and
- Lower-cost, higher voltage power electronics[12].

2. PROGRAM OBJECTIVES

To address the evolving infrastructure needs discussed above, ARPA-E is interested in advanced architectures for the transmission and distribution of electricity. Specifically ARPA-E seeks innovation in the area of (1) control architectures that are resilient, reliable, cost-optimizing and are capable of managing distributed resources in response to 40% intermittent, non-dispatchable generation and (2) hardware demonstration of resilient, reliable power flow control.

ARPA-E will fund high risk, high reward research efforts that, if successful, will have a transformational impact on the resilience, cost, and control of electricity transmission.

3. AREAS OF INTEREST

Particular Areas of Interest include but are not limited to Control Architecture and Transmission Controller technologies:

Control Architecture: Recent advances in PMU technology for monitoring the state of the grid, IP protocols for grid-connected communications, distributed computing for secure transactions and distributed optimization, and power electronics for controlling real and reactive power flows have the potential to transform the business of delivering electrical power. Despite the dramatic advances that can be leveraged in each of these fields, the challenge of controlling the electricity grid is daunting.

ARPA-E is interested in control architectures that are capable of robust, reliable control of the electricity grid *despite*:

- The limits of state estimation (because of the finite number of PMUs deployed);
- Incomplete and imperfect information flow (because of the inherent latency of even the best communications relative to controlling the continuous, speed of light flow of electrical power);

[9] North American SynchroPhasor Initiative, < http://www.naspi.org/resources/2009_march/phasorfactsheet.pdf>.
[10] Ibid.
[11] Adam Stevenson. "High-Performance Computing On Gamer PCs, Part 1: Hardware," < http://arstechnica.com/science/news/2011/03/high-performance-computing-on-gamer-pcs-part-1-hardware.ars> (31 March 2011).
[12] Department of Energy, Advanced Research Projects Agency- Energy, Agile Delivery of Electrical Power Technology (ADEPT), < http://arpa-e.energy.gov/ProgramsProjects/ADEPT.aspx>

- Constrained computational resources for dynamic decision support (because power flow optimization is mathematically (NP) hard);
- Inherent uncertainties in market mediated transactions; and
- Physical constraints to control (set by the cost, performance, and reliability of power electronics).

Examples of topics sought include, but are not limited to:
- Distributed, dynamic control for achieving globally optimized, wide-area control of power flow;
- Optimal use of possible new market mechanisms for control (e.g. reliability differentiated delivery); and
- Automated, real-time dispatch of spinning reserve, demand response, grid storage, and/or FACTS devices.

Transmission Controller: This FOA recognizes that control architectures and algorithms are only one component of program success. Resolving congestion with emerging generation and demand profiles will likely require better utilization of transmission assets. Power flow control can be achieved with advanced FACTS devices such as Unified Power Flow Controller (UPFC) and multi-terminal HVDC. In both cases power electronic interfaces within either an HVAC or HVDC/AC grid enable dynamic routing of electrical power. The deployment of FACTS devices has been limited by both the cost and reliability of these systems. For example, the UPFC installed in 2003 at the New York Power Authority cost $52M (including the cost of series and shunt transformers) and is used to route real (and reactive) power flows of typically 40MW (and 40MVAr)[13]. Typical costs for FACTS power electronics range from $0.12-0.3/W [or $0.12-0.3/VAr]. Today, multi-terminal, voltage-source controlled HVDC systems are also capable of rapidly shuttling power between terminals but are expensive. New overhead HVDC lines are typically $1M/GW/mile and terminal cost of $160,000-250,000/MW. HVDC line costs are exacerbated by the absence of HVDC fault protection which requires the installation of redundant transmission. Detail cost information can be found in Appendix F of the reference below[14].

ARPA-E is interested in Transmission Controller technologies including, but not limited to:

i. *Mesh AC networks* with power flow controllers for resilient network operation. The controllers should be capable of routing real and reactive power flows within the mesh network. Robust and stable operation of the network with respect to line congestion, intermittent generation, and equipment failure should be demonstrated. These can include (but are not limited to):

    - Employing controller architectures that do not require the active electronic elements to carry the full power throughput of the node.

    - Employing controller architectures that can be retrofit into existing assets (such as conventional transformers and transmission lines).

    - High-voltage, high-frequency electronics for reduced component and packaging costs.

ii. Resilient multi-terminal HVDC mesh and branch networks. Applications that can realize sufficient cost reductions in the HVDC terminals to be cost-competitive relative to overhead HVAC for relatively short spans (100km, 2000MW) and/or cost reductions in the HVDC lines to support higher power flows and lower total cost relative to overhead HVAC in underground installations are especially encouraged. These can include (but are not limited to):

    - Architectures for fault tolerant HVDC converters/terminals;

    - HVDC breakers and fault current limiters (>100kV, MJ);

    - Low-cost cabling for either overhead retrofit or underground; and

[13] Transmission and Distribution World, "Reinforcing the T&D Infrastructure", 2002; <http://tdworld.com/mag/power_reinforcing_td_infrastructure/>
[14] National Grid, "2009 Offshore Development Information Statement Appendices", < http://www.nationalgrid.com/NR/rdonlyres/62196427-C4E4-483E-A43E-85ED4E9C0F65/39230/ODISAppendicesFinal_0110.pdf>

- High-voltage, high-frequency electronics for reduced component and packaging costs.

Areas Specifically Not of Interest:

- Incremental improvements to, or combinations of, existing products and technologies, wherein no significant advances in understanding or reductions in technical uncertainty are achieved;
- Demonstration projects that do not involve a significant degree of technical risk;
- New transmission technologies that have virtually no 'backward compatibility' and hence no path to incremental deployment – eg. nation-wide HVDC grid, a new wireline communication network for transmission of sensor and control data, and economic dispatch algorithms that are incompatible with evolving electricity markets or industry structure;
- Technologies that optimize the operation of the distribution grid without improving the reliability, resilience, and efficiency of the transmission grid; and
- Technologies that are solely directed to the control and optimization of in-building electricity distribution.

Any Concept Papers or Full Applications that focus on "Areas Specifically Not of Interest" will be rejected as nonresponsive and will not be reviewed or considered.

4. TECHNICAL PERFORMANCE TARGETS

Applications will not be considered for funding unless they have a well-justified, realistic potential to meet or exceed all of the Primary Technical Targets by the end of the period of performance for the proposed project.

Applications will receive favorable consideration if they meet or exceed at least one of the Secondary Technical Targets. Preference will be given to applications that have a well-justified, realistic potential to meet or exceed most, if not all, of the Secondary Technical Targets.

In the Concept Paper phase, applicants should ideally present data to describe (1) the anticipated performance metrics of the proposed technology concept; (2) the performance metrics of current state-of-the-art and why the proposed metrics are a significant advance; and (3) the applications that are enabled and likely to result in significant market penetration if the proposed metrics are met. The Concept Paper should acknowledge the general requirements for the Area of Interest as outlined in this Section. The Concept Paper should distinguish the proposed work from other R&D in substantively similar areas, especially if DOE is funding efforts that appear to be similar.

In the Full Application phase, applicants must present data to quantitatively describe (1) the anticipated performance metrics of the proposed technology concept; (2) the performance metrics of current state-of-the-art and why the proposed metrics are a significant advance; and (3) the applications that are enabled and likely to result in significant market penetration if the proposed metrics are met. Performance metrics must be identified, and the applicants shall propose final deliverables and target final values for performance metrics. For example, a proposal for an advanced control architecture must provide specific details regarding the relevant algorithms and techniques that will be explored – simply suggesting that one is using stochastic optimization or robust control is not sufficient. A discussion of specific algorithmic approaches - with their inherent limitations and advantages – should be presented. Similarly, a proposal for an advanced transmission controller should present details regarding circuit architecture and the component technology required for implementation. Improvements to energy efficiency and cost need to be supported by an energy and cost model with explicitly stated assumptions and variables. The Full Application will acknowledge the primary and secondary technical targets outlined in this Section.

The Primary Technical Targets and Secondary Technical Targets for this FOA are stated below.

A. PRIMARY TECHNICAL TARGETS

Control Architecture: The application must clearly address the following program elements and Secondary Technical Targets:

- The proposed solution should be able to manage large dynamical systems with greater than 10,000 nodes representing a multiplicity of connected balancing areas. Scalability of the architecture and underlying subsystems (algorithms, computation, etc.) should be established.
- A simulation platform should be used for control validation – the simulation must be benchmarked against real-world datasets supplied by transmission operators or utilities. The performer should clearly state the source as well as the spatial and temporal scale of the validation data set. The dataset should include normal operating conditions as well as relevant fault conditions.
- The integration and management of intermittent, non-dispatchable generation with penetration as high as 40% (kW-hrs of total); Estimation of avoided cost relative to adding additional balancing reserves for managing intermittency that would be necessary without the technologies involved in the project;
- The application should address or *resolve* the sensing, communications, computational, and actuation (ramp and dispatch) challenges for implementation in "real-time" markets;
- Failsafe designs where a safe, "dumb" operation occurs in the event of local or wide-area failure or attack. Formal resiliency criteria such as Byzantine fault tolerance should be employed where possible for sub-systems.

The underlying models should be benchmarked against real-world temporal and spatial variations of locational marginal prices (LMP) with a particular control area. The models should be capable of estimating the economic benefits of the new control architectures, both through better utilization of existing grid assets and through the avoided costs from removing or mitigating the need for new transmission and generation investments. Useful resources for exploring the in-service state-of-the-art computational are included below[15].

Transmission Controller: The application for an advanced transmission controller must clearly address the following program elements and Secondary Technical Targets:

- The proposed solution should be demonstrated with a minimum of 3-controllers/terminals connected on a small-scale mesh with a minimum of 5 nodes. Each terminal should be configured for operation at a minimum of 10kV. Individual elements of the transmission controller should be tested at relevant transmission level voltages (>100kV).
- A protocol for testing the resiliency and stability of the interconnected controllers should be established.
- Software controls with simulated latency should be used to demonstrate full bi-directional control of real and reactive power flows.
- The conversion efficiency of controllers/terminals must be greater than 99%.

[15] Evolution of Computing Requirements in the PJM Market: Past and Future Ott, A.L. (PJM Interconnection llc, Norristown, PA, United States) Source: *2010 IEEE Power & Energy Society General Meeting*, p 4 pp., 2010], [The evolvingdesignofRTOancillaryservicemarkets Alan G.Isemonger Energy Policy 37 (2009) 150–157],

- Commercial feasibility and a plausible incremental deployment plan should be developed; A cost-benefit analysis for a single controlled link using the proposed technology on the transmission grid is required.

- *For Mesh AC networks:*

  - The individual controllers should operate in a fail-normal mode where failure in the electronics results in a graceful loss of control but not of power flow through the node.

  - *Strategies for achieving >10x reductions in cost (target cost < $0.04/W) should be considered.*

- For resilient multi-terminal HVDC mesh and branch networks:

  - *Strategies for >4x reductions in terminal and line cost relative to existing state-of-the-art should be considered*. Proposals that can realize sufficient cost reductions in the HVDC terminals to be cost-competitive relative to overhead HVAC for relatively short spans (100km, 2000MW) and/or cost reductions in the HVDC lines to support higher power flows and lower total cost relative to overhead HVAC in underground installations are especially encouraged.

B. SECONDARY TECHNICAL TARGETS

Control Architecture: The application should clearly address the following Secondary Technical Targets:

- Commercial feasibility and a plausible incremental deployment plan; who will deploy this control? How will it integrate into today's electricity management systems?

- The integration of the proposed control architecture into electricity markets (e.g. dynamic unit commitment calculation for bid evaluation in the spot market, pricing for reliability differentiated service, the plausible implementation of reactive power flow markets);

Transmission Controller: The proposal for an advanced transmission controller should address the following Secondary Technical Targets:

- The new capabilities enabled by the proposed technology that will support the integration and management of intermittent, non-dispatchable generation with penetration as high as 40% (kW-hrs of total); Estimation of avoided cost relative to adding additional balancing reserves for managing intermittency that would be necessary without the technologies involved in the project;

- The design of complementary system elements to manage the sensing, communications, and computational challenges for dynamic control of power flow;

- The integration of the proposed control architecture into electricity markets (e.g. dynamic unit commitment calculation for bid evaluation in the spot market, pricing for reliability differentiated service, the plausible implementation of reactive power flow markets);

Project Teams should consist of technical experts in the areas of dynamical controls, control engineering of electricity grid, high-voltage power management hardware, and electricity markets as well as domain experts from transmission operators or utilities.