ENERGY
Technologies to Enable a Smart Grid

Technology Innovation Program
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The Technology Innovation Program (TIP) at the National Institute of Standards and Technology (NIST) was established for the purpose of assisting United States businesses and institutions of higher education or other organizations, such as national laboratories and nonprofit research institutions, to support, promote, and accelerate innovation in the United States through high-risk, high-reward research in areas of critical national need.

TIP seeks to support accelerating high-risk, transformative research targeted to address key societal challenges. Funding selections will be merit-based and may be provided to industry (small and medium-sized businesses), universities, and consortia. The primary mechanism for this support is cost-shared cooperative agreements awarded on the basis of merit competitions.

AN AREA OF CRITICAL NATIONAL NEED

The proposed topic “Technologies to Enable a Smart Grid” is within the critical national need area of Energy. This includes the technologies that will be required to enable a reliable Smart Grid approach to electric power distribution, demand, and response control, grid connectivity, and the integration of renewable energy sources into the grid. TIP specifically aims to fund research in energy storage systems and the integration of stored energy into the grid system, advanced sensors and their energy sources to be deployed along the grid, and communication and control technologies (high voltage power electronics).

The proposed topic area, “Technologies to Enable a Smart Grid” was selected from a larger field of challenges where transformative research could be expected to have a large societal impact. Input regarding potential challenges was obtained from government agencies (such as the Department of Energy and the National Science Foundation), industry (electric utilities), companies, universities, industry organizations (such as American Council on Renewable Energy, American Wind Energy Association, Edison Electric Institute, Electricity Storage Association, Energy Storage Council, American Public Power Association, and Public Utility Commissions) and national laboratories.

The United States Department of Energy (DOE) defines the Smart Grid as “an automated widely distributed energy delivery network characterized by a two-way flow of electricity and information and will be capable of monitoring everything from power plants to customer preferences to individual appliances. It incorporates into the grid the benefits of distributed computing and communications to deliver real-time information and enable the near-instantaneous balance of supply and demand at the device level.”[1] The vision of a successful Smart Grid includes:

- Intelligent, real-time control, monitoring, and efficient distribution of power from traditional and renewable sources of energy;
- Bi-directional energy flow management by supplying energy from the electric grid to the users and taking excess energy from the users to the electric grid;
- Peak energy management of demands at different locations and different times by optimizing energy generation, storage and distribution.

Currently, the United States electric grid is an electricity delivery network that provides power to consumers via transmission systems that carry electricity load from generation sources to distribution substations, and distribution systems that deliver electricity from distribution substations to customers. The electrical grid is a "network of networks," comprised of over 3,100 separate electric utilities that distribute energy to end-user consumers.[2] Additionally, DOE characterizes the Smart Grid[3] as an electricity delivery network modernized using the latest digital/information technologies to meet key defining functions:

- Enabling active participation by consumers,
- Accommodating all generation and storage options,
- Enabling new products, services, and markets,
- Optimizing assets and operating efficiently,
- Operating resiliently against physical and cyber attack as well as natural disasters,
- Anticipating and responding to system disturbances in a self-healing manner, and
- Providing the power quality for the range of needs in a digital economy.

The desired goal of a prospective competition is to develop a portfolio of technologies that will enable the development of a nationwide Smart Grid and benefit one or more areas originally developed by the DOE's Modern Grid Team:[4]

- Optimizing the grid's utilization and efficiency,
- Providing greater power quality,
- Enhancing resiliency against attack and natural disaster, and
- Anticipating and responding to system disturbances.

Analysis of current Smart Grid technologies that aim to address the four priority areas above reveals various stages of research and development and varying levels of Federal, academic, and industrial support. Some technologies are in fact nearing deployment while other areas of predicted breakthroughs are in the most basic stages of fundamental research. While there is a general understanding of what components are required to achieve an active Smart Grid, there are a number of key challenges that are essential to its full operation and would benefit from accelerated support: **system-level stochastic modeling, energy storage and the integration of stored energy into the grid system, advanced sensors with independent energy sources, system and control technologies, and devices and methodologies for the widespread integration of grid-tied renewable energy sources. Underlying all of the above is high voltage power electronics**.

An operationally effective and efficient Smart Grid requires transformative research in a wide variety of technologies rather than incremental advances of the current state-of-the-art. TIP will support the need for transformative research through proposals for high-risk, high-reward research in these underexplored challenge areas. Given the advancing age of sections of our nation's electrical grid infrastructure, the accelerated research of enabling Smart Grid technologies across the grid with real-time communication and load control capabilities from the point of generation to the point of end-use consumption is critical.

The need for advanced technologies for Smart Grid deployment and development is *national* because every community in the nation is dependent on the constant, uninterrupted flow of electricity for residential, industrial, and commercial use, as well as the proper functioning of essential services and infrastructure. The need is *critical* because major portions of the current United States grid architecture are inadequate to handle increased electricity load to accommodate projected increases in demand. Failure to adequately address the challenges of developing an advanced Smart Grid could lead to severe economic disturbance due to increasing interruption of electricity distribution to end users and increased vulnerability to attack and natural disasters.

Much of the transformative research required is either underfunded or not funded at all by the private sector. Supplier companies generally do not fund high-risk R&D without demonstrated interest of the over 3,100 utilities that operate the various grid subsystems and serve as the customer base for much of this technology. However, these utilities often tread cautiously when contemplating technology development because they must be responsive to both ratepayers and shareholders who are concerned primarily with electricity cost and local reliable service. Therefore, it is unlikely that utilities will purchase and incorporate any Smart Grid technology that is not thoroughly researched, developed, and demonstrated. This means the research undertaken in this area is usually evolutionary, rather than revolutionary.

The challenges facing the U.S. electric grid require accelerated investment in high-risk Smart Grid technology research to prevent deterioration of this vital infrastructure that will result in costly service interruptions. Furthermore, the Smart Grid will enable the efficient integration of intermittent renewable energy sources into the nation's power system decreasing dependence on carbon-fueled power plants to meet projected increased demand and maintain peak capacity. The Smart Grid will also enable the end-user to efficiently manage local power usage and will lead to a reduction in aggregate energy demand.

Magnitude of the Problem

In 2008, the United States was the largest energy consumer[5] in the world. According to DOE's Energy Information Administration (EIA), the United States consumed 102 quadrillion Btu (quads) with a projected growth to 131 quads by 2030. Of the 102 quads consumed in 2008, electrical energy accounted for 14 quads[6] and is projected to grow to 16 quads in 2030[7]. Adding this additional electrical energy to the existing electrical grid distribution system will prove extremely challenging both technically and economically:

- *Load.* The system currently operates around 90 percent of its designed capacity with very little excess capacity to distribute additional or new generating capacity (the projected increase referenced above would exceed the total capacity of the system).
- *Reliability and Integration.* The grid does not employ a reliable two-way communication system, distributed sensors, or adequate storage to allow responses to intermittency for renewable and other energy sources or to allow bi-directional communication between end user and distributed generation source.

- *Age.* Many components of the system are more than 50 years old and are incapable of handling the additional load demands predicted by the EIA or supporting the advanced devices necessary to increase the intelligence of the electrical grid.
- *Benefit/Cost Ratio.* Improvements must be demonstrated in terms of benefit/cost and performance/cost ratios and they must be able to be clearly articulated to the utility stakeholders.

The bulk electric grid in the United States consists of five independent systems: three on the mainland (Eastern Interconnect, Western Interconnect and the Texas Interconnect) plus Alaska and Hawaii. There are also many thousands of public and private utilities operating within the bulk system.[8] The grid was developed when electricity was cheap. The grid has insufficient ability to balance loads or control power flows. The grid systems are expected to work reliably (e.g., 99.97 percent of the time[9]) and they do. It is the 0.03 percent unreliability that costs the American consumers in excess of $150 billion annually. Economic losses from power outages can be significant.

The drivers of the modern grid are digitization (the process of converting information into a digital format), growth in consumption and the environmental impact.[10] Interruptions and disturbances measuring less than one cycle are enough to crash computer servers, microprocessor based devices, life support machines and other automated machines. The economic consequences of these occurrences can be enormous. In the last 40 years there have been five massive blackouts in the United States, three of which have occurred in the last eleven years.[11] While massive blackouts currently are few and far between, there have been numerous small blackouts and brownouts due to slow response times for mechanical switches, lack of automated analytic controls, and lack of awareness on the part of operators who lacked the necessary tools to be able to react quickly or to anticipate an outage. The 2000 blackout lasting only one hour resulted in trading delays valued at $20 trillion at the Chicago Board of Trade. The 2003 Northeast blackout caused losses in excess of $6 billion. An EPRI Report[12] states that $1.8 trillion in annual additive revenue could be had by 2020 with a substantially more efficient and reliable grid. The Galvin Electricity Initiative reported in “The Case for Transformation” that reducing power disturbances would save $49 billion annually, reduce the need for massive infrastructure investments by between $46 billion and $117 billion over the next 20 years, and would allow consumers to easily control their power consumption while adding $5 billion to $7 billion back into the economy when widely deployed.[13]

Under the current grid system, the amount of electricity generated must be balanced by the load, i.e., it must be used immediately when generated. It cannot be easily stored. One consequence of this is that systems must be kept available to accommodate peak demand even though peak demand occurs infrequently. Peaking combustion turbines (which are typically fueled by natural gas) run for only a few hours per year but at a high generating cost of $1,000 per megawatt-hour. The California Independent System Operator (CAISO) cites California peak usage in 2005-2006 of 50,085 megawatts (5,000 megawatts or roughly 10 percent above regular usage). This demand occurred only 0.65 percent of the time, i.e., a total of 57 hours.[14] What is needed to meet increasing demand is to create a system where added energy capacity can be derived from new, distributed sources at all hours, stored and utilized when needed without the need for constructing additional generating plants, especially traditional coal-fired plants.[15]

Large energy losses also occur on the grid when energy production from conventional power plants and renewable sources do not match the load demand. This happens when demand spikes, or when generation from renewable sources or equipment failure suddenly decreases supply. Improved control of energy sources, efficient control of renewable systems together with new storage capability (generation plus storage) can also be a consideration in decreasing the need for additional centralized power plants.

In recent years, the growth of renewable power sources, in particular, photovoltaics (PV) and wind, has been remarkable. These technologies are becoming fairly mature. Less mature technologies, e.g., tidal power, are also under development. In the nine years from 2000 to 2009, worldwide annual production of PV modules increased from 288 megawatts (MW) to 7861 MW, an average annual increase of 44 percent[16]. The rapid growth of grid-tied deployment of PV and wind systems has been mostly in industrialized countries. Wind turbines tend to be deployed in large utility-scale multi-megawatt arrays. Photovoltaic deployments usually take the form of distributed rooftop systems — two to six kilowatts (kW) for systems deployed on residential rooftops, and greater than 10 kW for systems on commercial rooftops — tied to the electric power grid. Utility-scale PV (greater than 10^3 kW) is also seen, but distributed deployment of small roof-top mounted systems is the dominant trend. Renewable power sources tied into the grid can also include fuel cell systems. In 2010, fuel cell deployments are still rare. However, they might well become quite common in a hybrid scenario that uses hydrogen generated by photovoltaics to allow electric power generation during periods of darkness and/or inclement weather.

The distributed approach seen in modern photovoltaic deployments presents several special challenges to the national grid infrastructure. These challenges include

(i) Development of distribution topology suitable for large-scale bi-directional power flow;
(ii) Power quality degradation due to harmonic distortion introduced by the many inverters in a high-density deployment;
(iii) Safety issues related to the “islanding” effect of distributed PV systems; and
(iv) The need for near-real time measurement of renewable resources, viz., solar power density and wind speed, with approximately 100-meter grid resolution to allow effective power management.

As of 2010, the density of distributed photovoltaics in residential neighborhoods in the United States has been relatively small. This environment has maintained a net power flow from conventional central station power plants into neighborhoods. However, as the density of renewable deployments increases, it is likely that some neighborhoods will generate more power than they consume — a scenario that cannot be adequately handled by utility power conditioning equipment (including transformers) in the present grid topology. *Present topology has always assumed one-way flow of net power.* The reversal of net power flow can interfere with network protection mechanisms and result in network failure. In the present topology, reverse power flow is interpreted as a fault in an upstream supply feeder. Network protectors quickly sense the reverse current, and physically disconnect the feeder. The present protection scheme is designed to isolate faults, thereby protecting equipment and personnel.

Photovoltaic modules generate direct current (dc) power. For grid-tied systems, the power must be changed to alternating current (ac) power using inverters, with the output voltage and frequency suitable for upload to the grid. The voltage waveform is synchronized to the phase of the grid. The presence of inverters tends to introduce distortion to the waveform. For a waveform, the percentage of net power in the harmonics (other than the fundamental) is referred to as the harmonic distortion.

Harmonic distortion introduced by PV inverters can damage devices that receive power from the grid. The likelihood of damage is increased with the number of inverters. The presence of many PV systems feeding power into the grid has the potential to introduce an unacceptable level of harmonic distortion, particularly with respect to higher harmonics introduced by inverters that use pulse-width modulation to synthesize a true sine wave.

The need for inverters to change dc power to ac power, and the potentially deleterious effect introduced by many inverters simultaneously uploading power into the grid, is not limited to the presence of wide-spread distributed photovoltaics. The direct current power provided by storage batteries and fuel cells will also require inversion. Thus, the issue of inverter integration will be pervasive in the smart grid environment.

Loss of power line continuity, i.e., a utility fault, frequently happens during ice storms and other natural events. However, photovoltaic systems, unless they are discontinued from the grid, will continue to maintain a voltage on utility lines in these situations. This is an attribute of distributed generation, referred to as “islanding”. The introduction of many inverters by a dense deployment of PV systems increases the likelihood of PV islanding. Islanding has the potential for injury to technicians responding to utility faults on power lines. Consequently, PV systems must be designed so that they are immediately discontinued from the grid when voltage on the grid suddenly falls. Article 690 of the National Electric Code (NEC) addresses islanding.

Finally, highly distributed PV systems will require near-real time measurement of renewable resources, so that the smart grid can seamlessly bring power sources on-line or off-line. This will be accomplished by a measurement system that provides near-real time data on solar power density and wind speed, with a grid spacing small enough to isolate small clusters of generators. Grid resolution as fine as 100 meters is required for densely deployed PV systems.

Mapping to National Objectives

Energy is a concern of the new Administration (American Recovery and Reinvestment Act of 2009) as well as former Administrations. On January 21, 2009, the White House issued its *New Energy for America Plan* listing five areas for priority attention:

- 10 percent electricity from renewable sources by 2012 and 25 percent by 2025 (up from 2 percent in 2008),
- Within 10 years to save more oil than currently imported from Venezuela and Saudi Arabia (*currently 2.5 million barrels per day*),
- Reduce greenhouse gas emissions by 80 percent by 2050,
- One million hybrid cars by 2015, and
- Create new jobs based on a clean energy future.

Congress issued the *2007 Energy Independence and Security Act* (follow-on to the *Energy Policy Act of 2005*) which called attention to the problems associated with the grid. The Act establishes through the DOE an Electricity Advisory Committee (EAC) to make recommendations on the different aspects of energy independence and security including the electric grid.[17] To implement the energy agendas set forth by the new Administration will require substantial development of the electric grid.

In December 2008 the EAC released a report entitled *Smart Grid: Enabler of the New Energy Economy* that states that a "Smart Grid is … foundational for a sustainable energy future; and if there is a growing consensus within the United States that clean energy is a platform for rebuilding the American economy, then it follows that the realization of a Smart Grid is also critical to economic growth."[18]

Thus the development of a Smart Grid is clearly a key enabler to achieve the national energy objectives of the Federal government and is seen as a critical endeavor to ensure the economic prosperity of the United States as well as an integral component in addressing the energy security, environmental health and economic concerns facing the nation.

NIST Laboratory Activities

NIST has a vital role in enabling the Smart Grid. Section 1305 of the *Energy Independence and Security Act of 2007* tasks NIST with coordinating and developing a standards-based interoperability framework for the Smart Grid. The Act directs NIST to coordinate the development of protocols and model standards to allow the interoperability of the various components of the Smart Grid by working collaboratively with both private and public entities. NIST has begun the coordination of the interoperability framework by creating Domain Expert Working Groups (DEWGs), hosting a workshop, and writing a progress report on the framework development. The DEWGs comprise industry experts from electric utilities, manufacturers, industry organizations and users groups, consultants, standards development organizations (SDOs), and academia. They are working in several Smart Grid domain areas (commercial buildings, industrial plants and centralized generation, residences, transmission and distribution grid) to identify the key interfaces, interoperability barriers and standards necessary to overcome them, and to enable the rapid development of the smart grid. They are providing power grid stakeholder input to the development of the interoperability framework. Section 1305 also directs the Federal Energy Regulatory Commission (FERC) to begin the adoption process of the recommended standards when sufficient industry consensus has been achieved for use in bulk electric power transmission systems. [19]

The United States, in recognizing the need for a reduced reliance on fossil fuels, has initiated many programs to generate energy using sustainable sources such as solar, wind, and hydro, among others. The success of the integration of renewable energy sources rests on the development of a Smart Grid. Both government and industry have begun limited development efforts on various aspects to improve the grid. Major corporations have spent considerable resources on developing and testing one or more aspects related to the Smart Grid, for example, smart metering (GE's 2009 Super Bowl commercial) as one step in implementing the Advanced Metering Initiative (AMI).[20] There are also many small- and medium-sized businesses as well as university research programs that are developing energy technologies that relate to the implementation of the Smart Grid.

Challenge Areas for Accelerated Funding

There are significant technology challenges that need to be addressed if the Smart Grid is to become a reality. By 2025, the United States is projected to obtain 25 percent of its electric power from renewable sources distributed throughout the nation.[21] Distributed power of that magnitude cannot be connected to the grid at this time because grid control was not designed for such widely varying and distributed sources. The grid instead was designed for a limited number of large centralized sources with a one-way flow of power to users. Since distributed renewable sources are by nature intermittent, users will at one moment supply net power to the grid and at another receive net power from the grid when a renewable source is not sufficient to meet their needs.

To address the system control requirements associated with these distributed sources, the Smart Grid will rely on a number of technologies for which funding is not expected to be available in a timely fashion. TIP thus has an opportunity to accelerate support to these technologies and to assist with the development of the Smart Grid. These technologies can be grouped broadly as:

- System-level stochastic modeling,
- Energy storage systems,
- Advanced sensors and sensing systems with independent power sources,
- System measurement challenges,
- Devices and methodologies for the wide-spread integration of grid-tied renewable energy sources, and
- Advanced high voltage (greater than 10 kilovolts) power electronics.

System-level stochastic modeling

Modeling efforts for the grid have been deterministic in nature, and usually with the assumption that at most one major grid element will fail at any given time. However, the introduction of distributed energy storage and distributed renewable resources affects grid behavior in a complex manner best characterized by stochastic models. The development of stochastic models for the smart grid environment is considered an urgent need by the National Coordinator for Smart Grid Interoperability.[22]

Advances in system-level stochastic modeling funded by TIP would need to address several of the following characteristics:

- Stochastic system-level models for systems of systems (i.e., systems of grids) with variable energy sources and loads,
- Modeling of n=2 reliability environments, i.e., system reliability with the simultaneous failure of two major system elements,
- Modeling based on system elements that include advanced automated grid-control equipment,
- Modeling that includes energy storage for homes in a renewable grid-tied environment, and
- Modeling that is particularly amenable to data from utilities with stochastic processes in mind.

Energy storage systems

Electrical storage for the Smart Grid integrates and addresses three requirements that involve very different operational time scales.

- *Power quality* – response times of seconds or less assuring continuity of quality power,

- *Bridging power* – response times of seconds to minutes assuring continuity of service when switching from one source to another, and
- *Energy management* – response times of hours for decoupling the timing of generation and consumption.

There are a variety of energy storage systems today, including batteries, flywheels, superconducting magnetic energy storage (SMES), compressed air, pumped hydro, and ultra-capacitors to name a few. Each of the storage forms can be applied to one or more of the three categories listed above. However, new, advanced storage technology is clearly needed.

Current storage technologies have limited application to grid system storage because of their low power limitations, low energy density, and high cost. Only one battery today has high power with adequate energy density and efficiency; it is now being tested under real power loads in both the United States and Japan – the sodium-sulfur battery. However, it is still very expensive (about $3,000 per kilowatt installed), and has a very large footprint (e.g., a 34 megawatt storage farm in Japan, enough to power a small town, required one acre of batteries). For California to successfully implement its Renewable Portfolio Standards reduction target of 33 percent by 2020, it would require four gigawatts of stored electricity requiring over 117 acres (and potentially more than $10 billion).

Lead acid batteries, though one of the oldest and most developed technologies (predominantly for automotive use), is still evolving. It has been used in a number of storage projects in the United States. While this technology has many advantages, its energy management capabilities are very limited due to its short cycle life, inconsistent energy delivery, and high maintenance cost. DOE has major efforts in trying to improve lead-acid batteries. Efforts are being made by both industry and government using materials such as silicon carbide and graphene.

Devices with substantially higher energy and power densities, faster recharge rates, and longer charge-discharge cycle lifetimes are needed to meet the requirements of the Smart Grid. There are also safety issues that must be addressed to prevent premature and at times catastrophic failures as well as significant cost factors. Flow batteries such as Vanadium Redox, Poly-Sulfide (PSB) and Zinc-Bromide have good energy and acceptable power but are expensive. Flywheels have high power but low energy density and are used today for frequency regulation. They are also very expensive. Superconductor Magnetic Energy Storage (SMES) has high power, low density, very high production and installation costs, and currently is only used for niche operations such as paper mills. Electrochemical capacitors have long cycle life, high power and acceptable energy density but their cycle times are very short. Even something that appears to be relatively simple such as using Plug-in Hybrid Electric Vehicles (PHEV) as a resource for grid storage will require efficient and flexible power-electronics based conditioning systems and metering infrastructure to reliably integrate with the grid.

Currently available storage technologies are lacking the substantially higher energy and power densities, faster charging rates, and longer charge-discharge cycle lifetimes needed to meet the requirements of the Smart Grid. Advances in storage technologies funded by TIP would need to address several of the following characteristics:

- Fast response time,
- High reliability and long lived,

- Improved benefit/cost ratio,
- Capacity from 10 to 10,000 kilowatt-hours,
- Hybrid storage systems,
- New battery / capacitor chemistries, and
- Integrate with high voltage power electronics (greater than10 kilovolts).

Advanced sensors and sensing systems with independent power sources

Grid security and monitoring systems will require:

- Stand-alone sensor units on all major grid components and
- Grid-independent power sources for the sensors.

These sensors will be distributed along transmission lines (so they must be light weight and low cost) and on all significant grid components such as transformers, capacitors, switches and breakers with data processing and communications capability which can operate independently of the grid power and monitor and report on the state of the grid in real time.

These sensors must be powered independently of grid power and maintain operation during disturbances and outages, with minimal maintenance. Power with a capacity approaching 10 watts will be needed. There are numerous devices well along in development that scavenge energy from the conversion of vibration via the piezoelectric effects, receive and convert radio frequency energy, and other systems that capture very low levels of electric power in the range from micro-watts to tenths of a watt. None of these scavenging devices has the capability to store energy. How much energy a sensor needs will depend on the location and task assigned to that sensor on the grid. For example, some sensors may require as much as 65 watt-hours while others may only need 5 watt-hours. Energy storage is important because conditions under which energy can be scavenged are intermittent and the sensors must operate continuously and under upset conditions such as short power transitions or outages.

Advances in sensors and sensing systems for critical grid components funded by TIP would need to address several of the following characteristics:

- Self-powered,
- Intelligent,
- Low maintenance,
- Improved benefit to cost ratio,
- Real time (sense, process, transmit data),
- Packaging that is compatible with high voltage, high temperature, and that is environmentally sound.

System measurement challenges

Measurement needs for the Smart Grid fall into two categories: measurement of performance and efficiency on a large scale and measurement of power consistency over the grid on a fine scale. In fact, measurement technology of a more global nature is needed and presents unique challenges.

First, in the area of performance and efficiency, new measurements will be needed to evaluate the state, or condition, of the grid. For example, for a given set of users, new measurements could aid in determining the most efficient configuration of the grid, and, once implemented, whether the grid has achieved that performance level. New, cheaper and more robust dynamic measurement technology capabilities are needed to:

- Ascertain the effectiveness of the systems and devices that may result from new and/or substantially improved technologies for the Smart Grid such as power grid and source conditions in real time,
- Determine what kind and how much increased efficiency actually occurred, and
- Determine under what standards various systems platforms may be integrated or replaced.

Measurements will need to be done in high voltage environments and will need to be reliable and secure. Measurement systems will need to be integrated effortlessly into the bi-directional communications of the Smart Grid.

Advances in measuring the performance and efficiency of the grid funded by TIP would need to address the ability to assess whether system changes met all of the following characteristics:

- What they were supposed to deliver,
- Improved performance and efficiency, and
- Enabled continued grid security (bi-directional).

In addition, the area of fine scale measurements addresses the need for phase angle and frequency of the power on the grid through widely separated points. Subtle shifts in phase angle or frequency of power on the grid can lead to serious stresses and damage to major grid components. A difference of a few hundredths of a hertz in frequency between points on the grid contributed to the failure of the power grid around Lake Erie. High accuracy measurements of phase angle between distant points on the grid require that sensors be precisely synchronized. How to make these fine scale measurements and how to interpret the data is a serious challenge. Some variations in phase angle might be localized and long in duration. These should be addressed by hardware that provides power factor corrections. Some variations in phase angle may be dynamic and must be corrected by the grid dynamic control software and hardware.

Advances in fine scale measurements funded by TIP would need to address both of the following characteristics:

- Relative phase angles between geographically distant points on the grid, and
- High accuracy frequency measurements over a large number of measurement points on the grid.

Devices and methodologies for the wide-spread integration of grid-tied renewable energy sources

Wide-spread integration of renewables requires fundamental changes in the electrical systems design of the power grid. These changes will allow a highly interactive character to the generation and flow of power from thousands of relatively small sources, and will be implemented by both new device designs and novel system topologies and algorithms. Some devices, e.g., inverters, might be integrated into individual photovoltaic modules.

Advances in wide-spread integration of grid-tied renewables funded by TIP would need to address several of the following characteristics:

- Distribution topologies suitable for large-scale bi-directional power flow,
- System approaches for minimization of harmonic distortion in high-density renewable deployments,
- Safety improvements related to “islanding” in high-density renewable deployments, and
- Integration of near-real time measurements for determination of solar power density and wind speed with 100-meter grid resolution.

Advanced high voltage (greater than 10 kilovolts) power electronics

Underpinning the above technologies and the electric grid as a whole are power electronics. Power electronic devices are “a key technology for controlling the grid and connecting renewable energy generation to the grid…and can provide ancillary services such as reactive power compensation and voltage and frequency regulation…and in general improve the power quality and reliability of the electric grid.”[23]

High voltage power electronics can be defined as the use of switching devices to control and convert electrical power from one form to another to meet a user’s need. Convert is a general term used in power electronics to describe the process of changing power from one form to another requiring control systems, semiconductor switches, thermal management and protection devices, magnetics, such as transformers and filters, and control software among others. These devices are responsible for control of the grid and transfer of electricity to and from the grid.

Advances in high voltage power electronics funded by TIP will need to address one or more of the following:

- Materials with suitable properties (i.e., functioning at high temperatures and high voltage),
- Semiconductor devices,
- Modularized circuit designs that can be mass produced, combined and stacked to meet a broad range of requirements,
- High temperature and standardized packaging,
- Control systems (hardware and software issues), and
- Maintenance of power quality in an environment populated by many inverters simultaneously uploading distributed power to the grid..

While lowering cost and improving efficiency and reliability will always be a consideration, attention will need to be given to the ability to operate above 10 kilovolts. And new challenges in grid control will need to be addressed that arise from transients such as clouds passing over photovoltaic arrays introducing changes to the grid state that occur on the order of seconds. Problems such as this latter one will most likely need the integration of hardware and software solutions.

Summary

In today's, grid the electricity generated must be balanced in real time with the load demand. A fundamental component of the Smart Grid is energy storage, that is, excess energy will be stored when available and used on an as-needed basis. Energy storage has the potential to provide a seamless continuity through brief outages, helps to smooth renewable energy's entry into the grid, and allows better asset allocation for generation, transmission and distribution.

Grid security and monitoring systems will require multiple stand-alone sensor units along transmission lines and on all significant grid components with data processing and communications capability which can operate independently of the grid power and monitor and report on the state of the grid in real time.

To successfully address these technical challenges, TIP will support high-risk, high-reward research that could enhance and accelerate the development of:

- System-level stochastic modeling,
- Technologies for storage of electrical energy applicable to grid support,
- New self-powered sensing technologies,
- New system measurements and instrumentation to enable a more reliable, robust, efficient, and secure grid,
- Wide-spread integration of grid-tied renewables, and
- High voltage power technologies.

Technologies that will allow automated responses to power demands and problems with the least disruption of reliable power flow are needed. These technologies will address infrastructural problems associated with grid performance and the measurement of that performance, grid real time controls, bi-directional communication, incorporation of sustainable energy sources, and interaction with distributed energy resources. New devices and algorithms are needed for high efficiency conversions from solar DC to AC synchronized with grid power, wind conversions from variable to regulated power, energy storage to support reliable grid operation during power interruptions and disturbances and meet increasing peak demand, and energy scavenging for power sensing devices to monitor the behavior of the grid.

The challenges facing the current United States electrical grid are myriad: from aging infrastructure that contributes to increased power interruptions to the lack of bi-directional communications and controls to enable automated load management and switching. Therefore, the Federal government has made the development of a Smart Grid a national priority to ensure the nation's prosperity and security. However, there are a number of challenges that need to be met and overcome. While many of these are already adequately funded by Federal and industry funds, there are challenges appropriate for TIP support.

References

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[4] American Superconductor. “Smart Grid: It’s More than you Think.” http://www.amsc.com/products/applications/utilities/smartgrid.html.

[5] The United States used 102 quads of energy in 2007, representing 22 percent of world total energy – EIA Energy Monthly Reports.

[6] EIA Primary Energy Consumption by Sources and Sector 2007 – Coal 23%; petroleum 40%;natural gas 24%; renewable 7% nuclear 8% (percentages rounded off).

[7] EIA – *Annual Energy Outlook 2009*.

[8] The DOE reports 3,100 electric utilities in the United States. Of these, 213 are stockholder owned, providing power to 73% of customers, 2000 are publicly owned utilities run by state and local government agencies providing power to 15% of customers, and 930 are electric cooperatives providing power to 12% of customers. Additionally, there are approximately 2100 non-utility power producers.

[9] Galvin Electricity Initiative. “Fact Sheet: The Electric Power System is Unreliable.” Found at www.galvinpower.org/resources/galvin.php?id=26.

[10] Imre Gyuk, “Energy Storage for a Greener Grid,” DOE Energy Storage Research White Paper and personal discussions.

[11] *Smart Grid: Enabler of the New Energy Econom.* A Report by the Electricity Advisory Committee. December 2008.

[12] *Electricity Sector Framework for the Future Volume I: Achieving the 21st Century Transformation* (quoted in the EAC Smart Grid Report referenced above).

[13] http://www.galvinpower.org/resources/galvin.php?id=27

[14] Jim Detmers. “CAISO Operational Needs from Demand Response Resources.” November 2006. Included in the Electricity Advisory Committee December 2008 Report on the Smart Grid referenced above.

[15] The effect of greenhouse gas emissions, particularly carbon dioxide, on the climate is one of the five priority areas in the new Administration’s energy agenda. Energy-related carbon dioxide emissions in the U.S. are projected to grow from 5.89 billion metric tons in 2006 to 7.37 billion metric tons in 2030. The predominant drivers for these emissions are transportation and electricity generation. Coal-fired power plants alone released

more than 1.9 billion tons of carbon dioxide. NETL's *Tracking New Coal Fired Power Plants* Report of June 30, 2008 reported 52 power plants either under construction, near construction or permitted for a total of 26,911 MW capacity.

[16] Navigant Consulting Inc., *Annual Report on Photovoltaic Manufacturer Shipments, Capacity & Competitive Analysis 2009/2010*, April 20, 2010.

[17] Reports on the grid were issued in December 2008: *The Smart Grid: Enabler of the New Energy Economy* and *Bottling of Electricity: Storage as a Strategic Tool for Managing Variability and Capacity Concerns in the Modern Grid*.

[18] U.S. Department of Energy. *Smart Grid: Enabler of the New energy Economy*. A Report by the Electricity Advisory Committee. December 2008.

[19] Section 1305 (d): "At any time after the Institute's work has led to sufficient consensus in the Commission's judgment, the Commission shall institute proceedings to adopt such standards and protocols as may be necessary to insure smart grid functionality and interoperability in interstate transmission of electric power, and regional and wholesale electricity markets."

[20] Examples include IBM, EPRI, and GridWise on smart metering (IBM Press Release. September 24, 2008), and PG&E, GE, and Silver Spring on smart metering in the California market (*SmartGridNews*. February 2, 2009).

[21] 25x'25 America's Energy Future (www.25x25.org).

[22] Private communication between Dr. George W. Arnold and the TIP Energy Team on July 13, 2010.

[23] Office of Electricity Delivery and Energy Reliability. Power Electronics Research and Development Program Planning Document Draft. 2008.

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