The Modern Grid Strategy

THE TRANSMISSION SMART GRID IMPERATIVE

Developed for the U.S. Department of Energy
Office of Electricity Delivery and Energy Reliability
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Office of Electricity
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DISCLAIMER

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EXECUTIVE SUMMARY

The concept of a smart grid encompasses the entire electric power delivery system, beginning at the output of all generation sources and extending to the final use of the delivered energy. PJM RTO, the administrator of the world's largest competitive wholesale electricity market, offers this view of the smart grid:

> The U.S. electrical infrastructure will evolve as a highly automated and interconnected network much in the fashion of the Internet; one where information and knowledge will flow through intelligent systems to serve the entire grid community; one where a dynamic network of smart devices enables the real-time balance of generation and delivery of electricity with the highest reliability and lowest cost. This will be accomplished while stewarding the environment in a responsible manner and enabling growth of the national economy.

Most of the initial smart grid focus has been limited to making the distribution system smarter and to installing the advanced metering that can make the consumer an active participant in the grid's operation. With 21st-century technological advances paving the way, many regulators have stressed this initial focus on advanced metering infrastructure (AMI) and demand response (DR). Unlike other markets, electric customers have typically been charged a flat rate for their kilowatt hours, without regard to production costs that vary over time. Economists argue that providing variable price signals, based on cost of service that varies over the course of a day, results in more efficient resource allocation, and engineers point out that the technical limitations requiring a flat pricing model no longer exist.

The fact is, while the entire distribution system has seen very little technological change over most of its existence, there is now a huge need and opportunity for improvement, made possible by today's digital communications and control tools.

The transmission situation is somewhat different. Technical advances have occurred throughout transmission's history, with advances in monitoring, protection, analysis and control, accompanied by periodic breakthroughs in transmission capacity. Power electronics has also played an important role, by enabling DC transmission and a variety of Flexible AC Transmission Systems (FACTS) enhancements. It is this continuous technical progress that has perhaps placed transmission on the smart grid backburner; it is already pretty smart.

THE TRANSMISSION CHALLENGE

The time has come to increase the smart grid's focus on transmission. Both need and opportunity argue as much. An efficient, reliable transmission system has had, and will continue to have, an essential role in satisfying the nation's growing thirst for electricity, the most flexible and useable form of energy. Advanced digital technology, as well as power electronics, can raise transmission to a new level of performance, even as the emergence of remote renewable energy farms and increasing electricity market applications create new challenges.

Growth of large central station wind and solar farms, a national priority, will be stymied until existing transmission capacity is increased using new technology (FACTS, optimized transmission dispatch, high capacity conductors, advanced storage, etc.) along with the addition of new high capacity high voltage direct current (HVDC)—800 kV—and high voltage alternating current (HVAC)—765 kV lines. Bottom line: while it is true that today's transmission is more advanced than distribution, the transition to a smart grid requires much more transmission capability and now is the time to make the required investment.

To place this in context, we should first understand the historic role of transmission, which was to connect remote generation to load areas and to interconnect isolated power systems. Interconnection provides multiple benefits by exploiting the diversity that can exist between differing systems:

- Diversity between the times that peak loads occur, allowing the same generation equipment to supply more than one system's load.
- Diversity of outages, allowing spare equipment to support more than one system.
- Diversity of fuel sources, allowing the most economical fuel choice for any given situation.

However, new and emerging requirements find transmission in roles it was not designed to perform. One example is the role of market channel, connecting buyers and sellers across very large geographic regions. Excessive transmission-use variability and far less predictability are the result. Further complicating factors come with the penetration of renewable generation such as wind and solar. In 2008, the North American Electric Reliability Corporation reported proposals to connect 145,000 MW of new wind capacity to the transmission grid by 2017. And the emergence of the plug-in electric hybrid vehicle (PHEV), while initially an increased demand consideration, could one day play a significant role as a system energy storage resource. The PHEV could be used for storage and demand side management (an asset) in a smart grid environment, or it could create significant new uncontrolled demand (a liability) during peak load periods in the absence of a smart grid's control characteristic. Coordinated operation of storage, demand response, and distribution-level generation will all be needed to address these and other 21st-century issues.

While recognizing that transmission challenges are large, the first requirement for any transmission system remains the same—it must be extremely reliable. The importance of this tenet is perhaps best illustrated by the events of the 2003 Northeast blackout. That blackout was not so much the result of an inadequate or failing transmission infrastructure; it was faulty computer and monitoring systems, human errors, and lack of proper maintenance that were mostly to blame. One analysis of the event concluded "…that much can be solved by updating technology and by changing procedures followed within the operating companies. This fix is cheaper and much more immediate than huge investment in new power lines" (Loretta and Anderson 2003).

And perhaps the most important aspect of any such upgrade is integration. It would be entirely possible to have very advanced systems in place in each individual Regional Transmission Organizations (RTO)/Independent System Operators (ISO) or Investor Owned Utilities (IOU), but if there is no integration between these entities on a national or at least an interconnection level, then there is still the potential for another blackout like the last one.

The same holds true for planning and markets. There is no way to optimize the planning of the interconnected power system if each entity does its own planning studies and makes its own recommendations for upgrades. This should be done on an interconnection-wide basis to maximize reliability and minimize cost. All solutions (FACTS, DR, distributed generation, etc) should be considered along with new transmission lines, but this should be done in a coordinated fashion. For wholesale power markets, the efficiency will only increase if there are more participants. The ideal power market would be a single market that spans the entire interconnection, where all loads and all generators have equal access. This would create a more efficient market, better identify needed areas of investment, allow the maximum opportunities to manage or eliminate congestion, and create opportunities for remote generation (like many renewables) to have the highest level of access to end users.

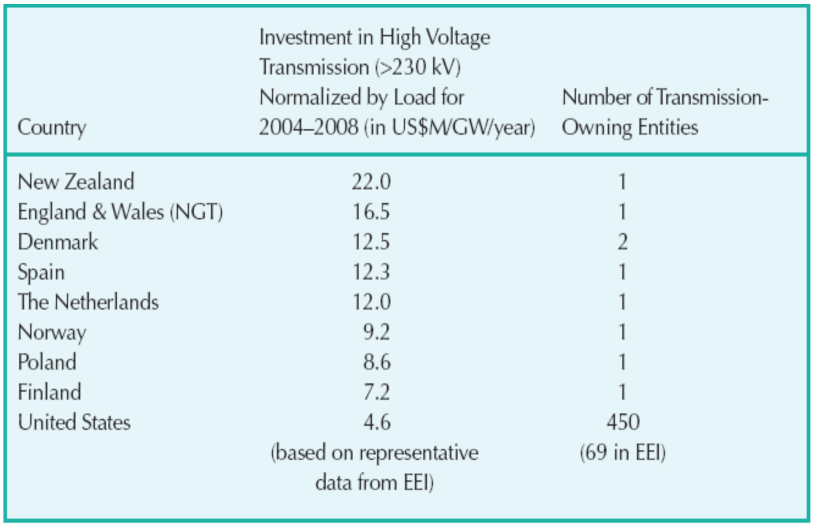
In the final analysis, the right combination of new power lines and new technologies will be needed to meet the transmission mission, such as that stated by American Electric Power:

> Reliable and efficient, integrated operation requires that the resources of all power plants be available, without transmission constraints, to all parts of the system under a wide range of operating conditions and possible future scenarios…in a broad variety of operating and market conditions.

Given that transmission will need to become both smarter and bigger, the ability to build new transmission in a timely manner remains a key strategic issue, especially if large quantities of renewable energy will need to be transported over large distances. Transmission projects require permits from their states, any one of which can delay or stop a project, with the Federal Energy Regulatory Commission's right of eminent domain as a yet untested backstop if a project is delayed up to a year. In some instances, the multi-state siting process has been known to take much longer than the time it takes to actually build the line. Further compounding the problem is the question of cost allocation. DOE's Electricity Advisory Committee has stated that "cost allocation is the single largest impediment to any transmission development."

While federal backstop rules have been enacted to reduce these delays, the issue of state versus federal authority casts a huge shadow on the possible outcomes. The net result is continued uncertainty about the cost and timing of transmission expansion. This may explain the fact that between 2000 and mid-2007 only 14 interstate high voltage (HV) transmission lines, with a total length of 668 miles, have been built.

The impact of America's multiple and overlapping responsibilities is perhaps best reflected in the following table.



Country	Investment in High Voltage Transmission (>230 kV) Normalized by Load for 2004–2008 (in US$M/GW/year)	Number of Transmission-Owning Entities
New Zealand	22.0	1
England & Wales (NGT)	16.5	1
Denmark	12.5	2
Spain	12.3	1
The Netherlands	12.0	1
Norway	9.2	1
Poland	8.6	1
Finland	7.2	1
United States	4.6 (based on representative data from EEI)	450 (69 in EEI)

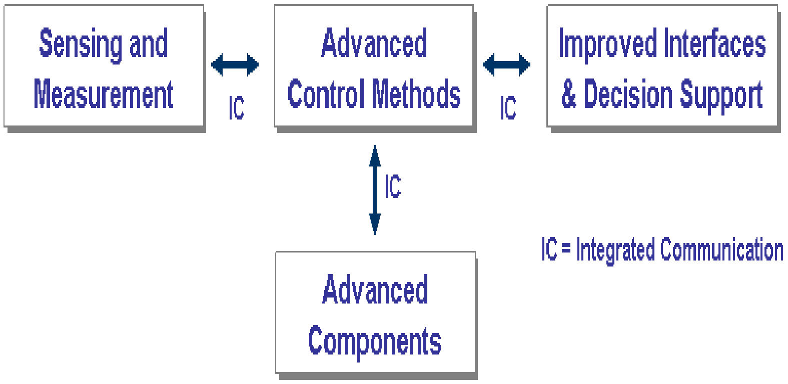
(**Source**: **Massoud Amin, "Our Nation's Energy Infrastructure: Toward Stronger, More Secure, and Smarter Grid" 2009 webinar.**)

Note that the United States, with by far the largest number of Transmission-Owning Entities, has had the lowest investment in HV transmission for the period shown. This would seem to indicate there is truth to the adage that the difficulty of reaching a good decision is proportional to the number of decision makers and to the variety of their objectives.

MAKING TRANSMISSION BIGGER AND SMARTER

Transmission expansion is clearly an important aspect of grid modernization, but this path includes all the challenges described above. Hence, applying advanced technology to enhance the existing grid is the appropriate parallel path, one that deploys the concepts of a smart grid.

There are five key technology areas (KTAs), as shown in the following diagram, which serve as smart grid enablers. These KTAs apply to every level of the grid and represent an important opportunity to address most transmission concerns.



INTEGRATED COMMUNICATIONS

The key to a smarter transmission system, as with the distribution system, is a reliable, high-speed integrated communications (IC) platform. The ability to rapidly move information between transmission stations, and from these stations to system control centers, provides the basis for virtually all advanced applications. As PJM says:

“It’s an instantaneous, seamless, accurate flow of information and energy that transcends many of the barriers in today’s grid operations.”

And when IC blankets both transmission and distribution, new opportunities are created for each to support the other. For example, demand response, distributed generation, distributed storage, and voltage dispatch can all help an RTO ensure a reliable transmission grid, but this IC must be designed with the future in mind. Capacity, security, and performance must be sufficient to accommodate not only the applications of today, but also those that will be conceived tomorrow. All our experience with similar digital evolutions has taught us this lesson.

While IC is the glue that ties everything together, each of the other four KTAs has an important role in the transmission smart grid.

SENSING AND MEASUREMENTS

Recognizing that you can only manage what you measure, there is a clear need for more and better measurement tools.

DYNAMIC LINE AND EQUIPMENT RATING

This need includes measurement of temperature, wind speed, and incident sunlight. The real-time data can also be used to forecast load as well as the potential output of renewable generation. New applications could correlate wind speed with wind turbine output and transmission line capacity, for example. Sensors that measure transmission line and substation health parameters (such as high frequency emissions of corona or partial discharges) of transmission facilities also fall in this category.

SYNCHOPHASOR MONITORING

Most monitoring of the grid is based on non-simultaneous average values of measurements taken over a period of many seconds. This is valuable in assessing the steady-state condition of the grid, but is not very useful in understanding fast-moving transient phenomena that can be associated with a system collapse. Monitoring of line voltage phase angles (phasors) can fill that gap, providing the instantaneous measurement of electrical magnitudes and angles that can reveal emerging instability. Deployment of phasor measurement units (PMUs) is growing, along with the development of predictive algorithms that can assess system risk. For example, the Center for Energy Advancement through Technology Innovation (CEATI) has initiated a project to directly input phasor data into an ultra-fast load flow to identify thermal overloads, voltage constraints, and voltage instabilities. Reliable broadband communications channels are needed to accommodate the system-wide deployment of this tool.

RELIABILITY ASSESSMENT

The complexity of operating a power grid has grown in recent years and will become even more challenging in the years ahead. Today, operators are asked to make critical decisions within seconds, as opposed to minutes or hours in years past. Operators are destined to eventually fail if they are not armed with sophisticated tools that reveal issues and offer mitigating solutions.

AMI

Advanced metering need not be limited to a billing role. Voltage and power quality measurements at customer sites and back at the substation can provide valuable information to the RTO about system problems as well.

ADVANCED CONTROL METHODS

A more complex transmission system will require more sophisticated controls.

ADVANCED PROTECTION

Protection falls within this KTA. Historically, protection of the transmission system has consisted of removing faulted elements (e.g., lines, busses, transformers) from service as quickly as possible. Instantaneous measurements, frequently combined with communications between the ends of the protected element, have been applied to this task. Often a delicate balance had to be struck to distinguish between a heavily loaded line and one that is short-circuited. And relay settings based on assumed system conditions and configurations are often not revisited for long periods, casting doubt on their continued validity. Today's digital computing and communications tools open the door to more advanced approaches to protection. Consider the possibilities that are created if every transmission node is able to communicate with every other node reliably, securely and at very high speeds. Relay setting could then be adapted to reflect real-time system conditions. Even better, simple and secure differential line protection could be employed, even allowing increased power flows in some cases.

SPECIAL PROTECTIVE SYSTEMS

Beyond advanced line protection, system integrity protection systems (SIPS) and remedial action schemes (RAS) could protect large regions rather than individual elements. As described at the 2007 iREP Symposium:

> A SIPS is applied to the overall power system or a strategic part of it in order to preserve system stability, maintain overall system connectivity, and/or to avoid serious equipment damage during major events… There are several steps involved in the SIPS corrective action. For example, local measurement, or a series of predetermined parameters at several locations are transmitted to multiple control locations. Depending on the intent of the scheme, immediate action can be taken and further analysis performed.

COORDINATION OF RENEWABLE GENERATION AND STORAGE

Given the variability of renewable generation, greater real time control will be needed to balance supply and demand. Storage can provide a useful, and in some cases critical, buffer by absorbing renewable generation when load is low and supplementing it when load is high. But storage can take many forms and be spread across a large geographic area. And it can be located at any voltage level, even including the distribution secondary. The emergence of PHEV and Community Energy Storage (CES) could result in literally millions of small controllable storage devices on the distribution system that could complement large storage devices located throughout the transmission system. The control system required to optimize these various elements will utilize the IC and advanced sensing technologies described above. Additional features could include the application of demand response and distributed generation to provide still more control flexibility.

CENTRALIZED FLOW CONTROL

With the emergence of a variety of devices that can direct real and reactive flow on the transmission system, operators' ability to influence grid conditions can be significantly enhanced. Increased system stability, controlled flow over specified paths, damping of active power oscillations, and steady state and dynamic voltage control are all benefits that result when the operation of these devices is coordinated.

DOE has recognized the growing need to operate transmission networks as efficiently as possible and to assure maximum utilization of transmission assets. For example, a recently awarded project, Improving Reliability of Transmission Grid to Facilitate Integration of Wind Energy in Tri-State G&T and AECI, will develop and demonstrate new tools to ensure successful integration of wind generation, addressing such issues as:

- The relative impact of local transmission additions versus regional EHV transmission additions.
- A comparison of balancing generation near wind generation facilities versus having long-distances between the intermittent wind resources and balancing generation.
- The cost impacts of additional switching, generation ramping, and other wind integration strategies.

ADVANCED COMPONENTS

These components provide tools that help shape the character of tomorrow's grid.

ADVANCED FLOW CONTROL DEVICES

A variety of new components, many based on power electronic advances, enable greater control of flow, voltage, and power quality. The list includes various FACTS devices, Variable Frequency Transformers (VFTs), solid state transformers, superconducting condensers, and HVDC. With further advances in the capability and cost of power electronics, these devices will find increased application at the transmission level. For example, the Intelligent Power Infrastructure Consortium at the Georgia Institute of Technology is developing distributed power electronic devices that can act as current limiters. A controllable, active version could respond to commands to instantly increase or decrease the line impedance, significantly increasing asset utilization in a network.

Another advanced component under development, the Thin AC Converter (TACC), could allow extended dynamic voltage and power flow control. A TACC located between the station bus and an existing conventional asset such as a transformer or capacitor bank could provide dynamic reactive power insertion and controlled flow of real power.

FAULT CURRENT LIMITERS

Devices that can limit fault magnitude offer huge economic benefits. As transmission system fault capacity increases with each added source, existing equipments' short circuit ratings are eventually exceeded. Replacement is then necessary even though the equipment is satisfactory in all other respects. An electronic dynamic Short Circuit Current Limiter is today available at 500 kV; it has near zero impedance at steady state, and during a fault it electronically switches in milliseconds to a current limiting reactor. Other approaches to fault current limiters can employ the inherent characteristics of superconductivity.

HIGH TEMPERATURE SUPERCONDUCTING (HTS) CABLE AND HIGH CAPACITY (HIGH TEMPERATURE) CONDUCTORS

High temperature, low sag cables employed today will allow increased power transfer by limiting the sag that occurs as higher currents produce hotter wires. While increased transfer capability is a good thing, it comes at the price of increased losses and associated emissions. Clearly the better solution would be a superconducting line that is virtually loss free. Advances in superconducting wire are making this goal increasingly feasible. With several superconducting cables operating reliably, the technical hurdles are falling away and the economics are improving.

ADVANCED STORAGE

Storage is perhaps the most important advanced component today because of its key role in complementing renewable generation. With the proper amount and type of storage broadly deployed and controlled, renewable generation can be transformed from just an energy source to a provider of dispatchable generation capacity as well. The tables below summarize the attributes of different advanced battery energy storage technologies. Meanwhile, R&D continues to search for the ideal storage device. A better transportation battery—for example, one that has high energy density, portability, and can accommodate many thousands of charge/discharge cycles—could be all that is needed to break America’s addiction to oil and to allow a new fleet of millions of PHEVs that can also serve as energy sources to the grid.

Large advanced battery energy storage systems for stationary applications in substations can also be a key enabler of the smart grid. Recent breakthroughs in advanced battery energy storage systems have shown the ability to deliver 5,000–10,000 charge/discharge cycles or more. Advanced battery systems used to trim daily peaks could last more than 10 years and perhaps up to 30 years. The need to store and shift wind and solar generation produced during off-peak periods, for subsequent dispatch during peak periods, will require 200–300 cycles per year. Recent developments show that there are three types of advanced batteries that have the required minimum cycle life: Vanadium Redox Battery or VRB, Sodium Sulfur or NAS, and Zinc Bromide or ZnBr.

The economics of energy storage are also improving as shown in Tables 1 and 2 below. The cost for certain advanced battery technologies has decreased by more than 50 percent, down to $2000/kW for a 7-hour battery, making it possible for these systems to provide an attractive return on investment when multiple value streams are monetized (e.g., shifting renewables from off-peak to on-peak, peak shaving arbitrage by buying cheap energy at night and selling it during high-cost daily peaks, etc.). Environmentally benign battery systems are also now available, making permitting easier. The efficiency of some advanced batteries is now over 70 percent, which is sufficient to be economical.

As the penetration of wind and solar generation increases, the need to store low-marginal-cost, intermittent, non-dispatchable renewables will increase. And as the cost for natural gas used during peak generation by combustion turbine peakers or combined cycle units increases, the value proposition for energy storage can only improve.

Table 1– Advanced Battery Technology Characteristics

Advanced Battery Type	Capital Costs $kW-hr	Life Cycle Number of charge/discharge cycled to 80% DOD	% Round Trip Efficiency AC to AC
Li - ion	Very High ($600 – $1,200/kW-hr)	Medium (2,000–5,000)	Very High (85% to 95%)
VRB	Medium ($350 – $500/kW-hr)	High (up to 10,000)	Medium (70-75%)
NAS	Medium ($350-- $500/kW-hr)	Medium (3,000–5,000)	High (85% to 90%)
ZnBr	Low ($150-- $250/kW-hr)	High (>10,000)	Medium (70-75%)
Comments	Note that costs do not include cost of installation which adds about 20% to 30% to the cost depending on size of installation	For storing wind or solar, cycle lives of 10,000 or greater will be needed (300 to 500 cycles a year times 30 years)	Efficiency is important for arbitrage but less so for peak shaving, frequency regulation, etc.

Table 2 – Additional Advanced Battery Technology Characteristics

Advanced Battery Type	Environmental impact (ease of permitting)	Energy to size Energy Density Wh/L	Other Issues or disadvantages
Li - ion	Low	Medium (80–200 Wh/L)	High self-discharge rate and requires special charging circuit
VRB	High	Low (15–25 Wh/L)	Potential environmental concern and permitting difficulties
NAS	Medium	High (145–150 Wh/L)	Safety concerns addressed by design; backup generator required
ZnBr	Low	High (130–150 Wh/L)	Energy density is a big issue for transportation
Comments		Energy density is not an issue unless the cost of land is high, as in urban locations	

DECISION SUPPORT

The complex world of transmission has made the operator's job extremely challenging, but new tools can make it a bit easier.

- **Data Mining**—Some data that is available from devices currently deployed across the transmission system is not being collected, or does not have adequate communications to be transmitted, or is not used because it cannot be processed efficiently. It is important to take advantage of data and technology that is already available as part of the transformation to a smarter grid.

- **Fast Simulation**—Fast Simulation & Modeling (FSM) is designed to provide the mathematical underpinning and look-ahead capability for a self-healing grid—one capable of automatically anticipating and responding to power system disturbances, while continually optimizing its own performance. It will provide a tool to aid in decision-making by permitting an operator to get an accurate estimation of the state of the grid in real time. This will allow the operator to optimize grid operations as well as predict grid behavior based upon historical and real time data.

- **Advanced Visualization**—Advanced system analysis and visualization are essential technologies that must be implemented if grid operators and managers are to have the tools and training they will need to operate tomorrow's more complex grid. These technologies convert masses of power-system data into information that can be understood by human operators at a glance. Animation, color contouring, virtual reality, and other data display techniques will prevent "data overload" and help operators identify, analyze, and act on emerging problems in a timely manner. In many situations, the time available for operators to make decisions has now shortened from hours to minutes, sometimes even seconds.

These are the five KTAs that will be needed to make the transmission smart grid a reality. Other elements will surely emerge, but they will likely fall into one of these fundamental areas.

SUMMARY

The transmission system of the future is the logical extension of today's electric grid. Transmission has a long history of deploying new technologies that continuously improve performance in response to the changing needs of society. This strategy of innovation is needed today, more than ever before, to maximize electric energy's ability to meet the nation's goal of a sustainable future—one that is not dependent on external sources of supply. Doing so requires a transmission system that is both bigger and smarter than today's system.

The technologies are ready to be deployed. Digital computing and communications are the primary tools needed to make the grid smarter. Power electronics and super conductivity provide additional value. And material science is likely to deliver the very important storage element.

Expanding the size of the transmission grid is a different matter. The need for, and complexities of, building consensus for new transmission construction is an obstacle that has been more difficult to overcome. This is a political problem, not a technical one. Solving it will require a uniform understanding of the stakes involved and the will to make the fundamental societal changes required to accommodate the transition to a transmission smart grid.

For more information

This document is part of a collection of documents prepared by the Modern Grid Strategy team. Documents are available for free download from the Modern Grid website.

The Modern Grid Strategy

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