Appendix B2:
A Systems View of the Modern Grid

SENSING AND MEASUREMENT

Conducted by the National Energy Technology Laboratory
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EXECUTIVE SUMMARY

The urgent need for major changes to our power delivery system requires that key technologies be developed and implemented in our nation's power grid. A wide range of technologies are needed and can generally be grouped into five key technology areas.

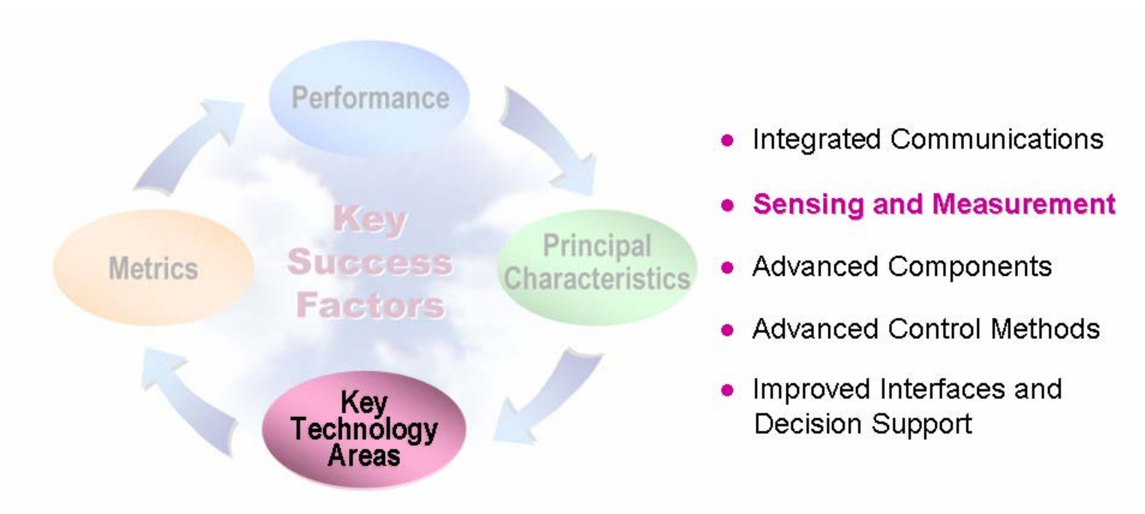


Figure 1: The Modern Grid Systems View provides an "ecosystem" perspective of modern grid development.

Sensing and Measurement, the key technology area discussed in this paper, is an essential component of a fully modern power grid. Advanced sensing and measurement technologies will acquire and transform data into information and enhance multiple aspects of power system management.

These technologies will evaluate equipment health and the integrity of the grid. They will support frequent meter readings, eliminate billing estimations, and prevent energy theft. They will also help relieve congestion and reduce emissions by enabling consumer choice and demand response and by supporting new control strategies.

In the future, new digital communication technologies, combined with advanced digital meters and sensors, will support more complex measurements and more frequent meter reading. They also will facilitate direct interaction between the service provider and the consumer. Broadband over Power Line (BPL) and digital wireless communications are examples of technologies that can accomplish this interaction.

The core impacts of the sensing and measurement transformation further strengthen the case for their implementation. These technologies will fully empower the electric power market, allowing customer choice and input and resulting in savings in capital and operating costs, benefits to the environment through improved efficiency, and benefits to the economy and the public from enhanced safety, reliability, and power quality.

In this paper, we will look at the following important features:

- The current state of sensing and measurement
- The future state of sensing and measurement
- Benefits of implementation
- Barriers to deployment

Although it can be read on its own, this paper supports and supplements “A Systems View of the Modern Grid,” an overview prepared by the Modern Grid Initiative team.

Current State

The transformation of grid sensing and measurement technologies is happening today. In this section, we review how far industry and other investors have moved toward the realization of truly advanced capabilities.

In recent decades, the power industry has begun a move toward modernization by employing digital electronics in metering, typically with large customers whose usage and interval measurement requirements justify the added expense. In addition, a number of utilities have deployed automatic meter reading via a variety of communication channels. However, meter-reading intervals have not been shortened.

At the customer level, the transformation of the electric meter is still in its infancy. There have been a number of pilot projects and a few commercial installations using advanced meters to enable demand response (DR). However, the utility industry as a whole has not yet begun to deploy this strategy on a large scale. In addition, technology suppliers have been reluctant to invest in research and development before the market's scope and size is fully understood. Unless they can be retrofitted later, technologies invested in today may ultimately be "thrown away" if different technologies become the standard.

At the utility grid level, advancements are occurring more extensively on transmission than on distribution. Wide-area monitoring systems and dynamic line rating are helping achieve real transmission progress, while technologies such as electromagnetic signature measurement/analysis have only begun to be used to identify distribution equipment problems.

Today's challenge is to accurately envision the modern grid and successfully design the advanced sensing and measurement infrastructure that can enable it.

The technologies, processes, and research described here will contribute to the realization of a modern grid. Deployment times will vary, given differing states of development and their relative impacts on grid modernization.

Advances focused on both the customer and on the utility grid, including the related area of protection systems, are covered next in greater detail.

Customer-Focused Advances

Utilities can employ various pricing tools to shape customer usage patterns, resulting in benefits for electric energy users and providers alike. For example, some utilities have already implemented unique DR programs that combine conventional time-of-use pricing, real-time super-peak pricing, advanced metering, and appliance control. With such programs, the energy company controls the price signal while its customers decide how and when they will modify their usage patterns.

Table 1 and the figures that follow provide more detail on a number of customer-focused applications that are either currently available or under development.

Table 1: Customer-Focused Applications

Customer-Focused Applications	
Application	**Description**
Consumer gateway	• Bi-directional communications between service organizations and equipment on customer premises. • Advanced meter reading. • Time-of-use and real-time pricing (RTP). • Load control. • Metering information and energy analysis via website. • Outage detection and notification. • Metering aggregation for multiple sites or facilities. • Integration of customer-owned generation. • Remote power-quality monitoring and services. • Remote equipment performance diagnostics. • Theft control. • Building energy management systems. • Automatic load controls integrated with RTP. • Monitoring of electrical consumption of total load and, in some cases, various load components. • Functions embodied in meters, cable modems, set-top boxes, thermostats, etc. • The Electric Power Research Institute (EPRI) has performed substantial conceptual work in this area.

Customer-Focused Applications	
Application	**Description**
Residential consumer network See Figure 2 for a representative home network.	• Subset of the consumer gateway concept. • Reads the meter, connects controllable loads, and communicates with service providers. • End-users and suppliers monitor and control the use and cost of various resources (e.g., electricity, gas, water, temperature, air quality, secure access, and remote diagnostics). • Consumers monitor energy use and determine control strategies in response to price signals. • Products are available to a limited extent today. • Pacific Northwest National Laboratory, together with the Bonneville Power Administration, has piloted a comprehensive residential consumer network.
Advanced meter See Figure 3 for a representative advanced meter system	• Employs digital technology to measure and record electrical parameters (e.g., watts, volts, and kilowatt hours). • Communication ports link to central control and distributed loads. • Provides consumption data to both consumer and supplier. • In some cases, switches loads on and off. • Products are available from commercial vendors today.

Table 1: Customer-focused applications

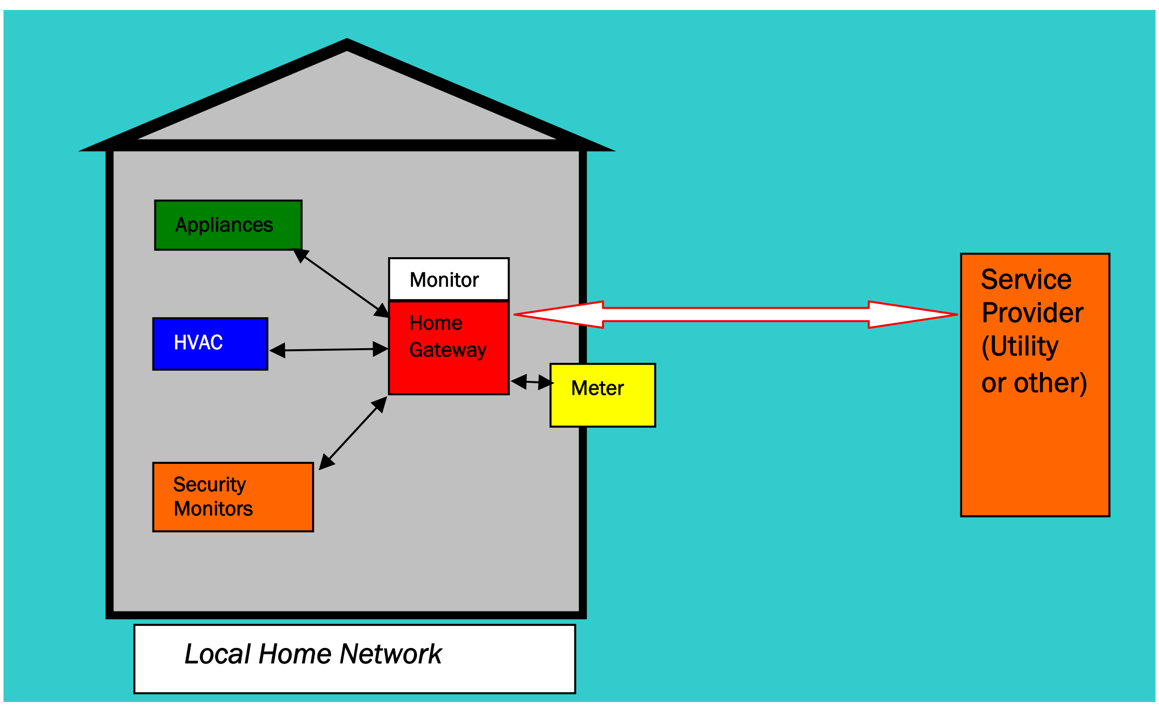


Figure 2: Example of a residential consumer network. Home gateway reads the meter, is tied to various end-use devices, and communicates with a service provider.

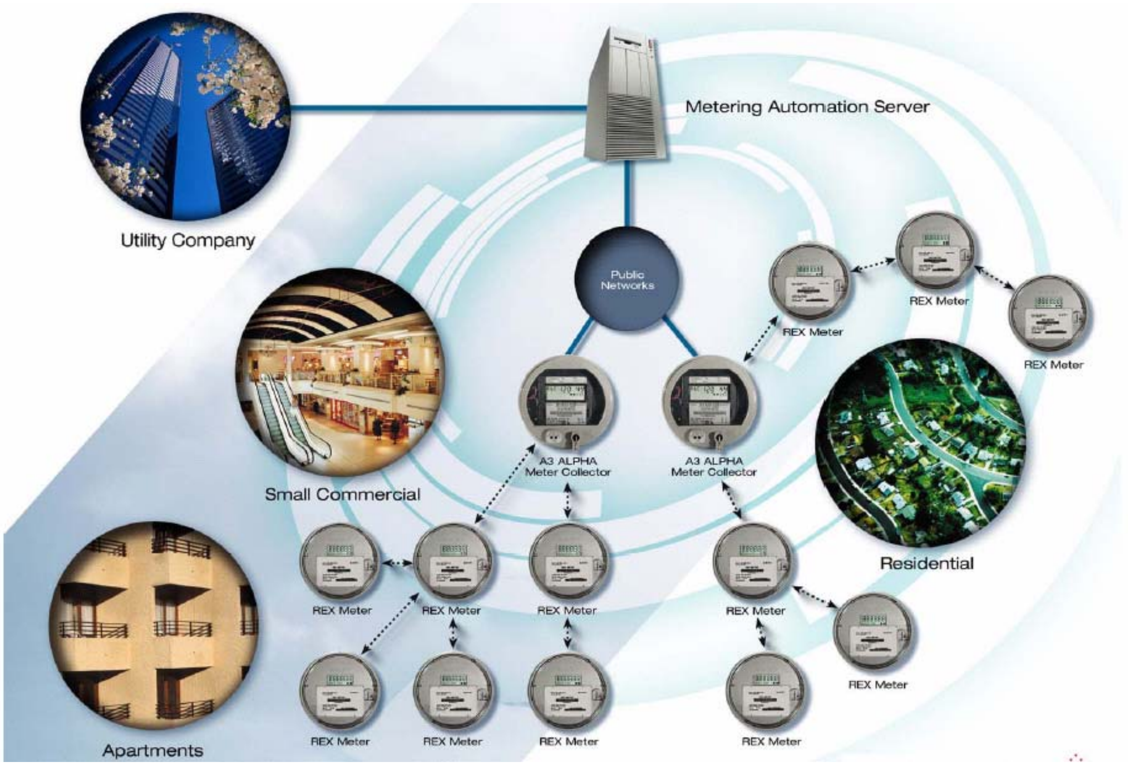


Figure 3: An example of meter-reading architecture. The electric meter measures a variety of electrical parameters and may also control metered load. Image courtesy of Elster Metering.

What is the Consumer Portal?

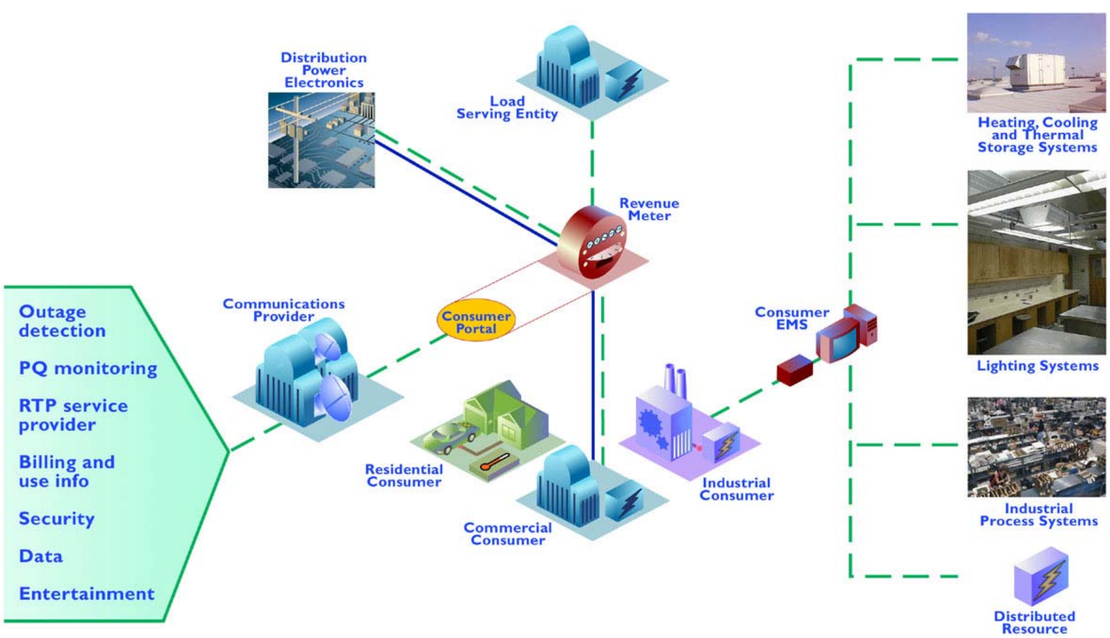


Figure 4: EPRI's Consumer Portal architecture. Image courtesy of EPRI.

UTILITY-FOCUSED ADVANCES

Utility Monitoring Systems

For most utilities, real-time monitoring systems provide up-to-date information on major substation equipment and some transmission line conditions. However, this is not true for most distribution facilities.

EPRI and the Tennessee Valley Authority have identified several requirements for advanced condition sensors, such as devices that determine the instantaneous condition of switches, cables, and other grid components.

They have found that first of all, costs must be low for the sensors, including their installation and maintenance. Second, inspections must be easily implemented, with special attention to hard-to-access locations, such as energized conductors on structures and inside cabinets. Third, the sensors must be small in size and secure from damage. Finally, they must not create problems related to electromagnetic compatibility (EMC).

Table 2 describes some advanced utility monitoring systems that are either commercially available or are currently under development.

Table 2: Advanced Utility Monitoring System

Advanced Utility Monitoring System	
System	**Description**
Wide-area monitoring system (WAMS) See Figure 5	• GPS-based phasor monitoring unit (PMU). • Measures the instantaneous magnitude of voltage or current at a selected grid location. • Provides a global and dynamic view of the power system, automatically checks if predefined operating limits are violated, and alerts operators. • Provides a global view of disturbances, as shown in Figure 5. • Compares generator operation points to allowable limits to keep generators in a safe state. • Tracks inter-area, low-frequency power oscillations and presents results to system operators; also used to tune damping controllers. • Combines phasor data with conventional SCADA (supervisory control and data acquisition) data for enhanced state estimation. • The Consortium for Electric Reliability Technology Solutions is one of several groups striving to develop WAMS technology for North America. • Of the many sensing and measurement technologies currently under development, WAMS may have the greatest potential for enabling grid reliability improvement.
Dynamic line rating technology See Figure 6 for an example	• Measures the ampacity of a line in real time. • The Power Systems Engineering Research Center has sponsored development of a computer program that calculates line sag and current-carrying capacity in real time using inputs from both direct and indirect measurements. • One university, with support from the National Science Foundation and a local utility, plans to develop a wireless network for dynamic thermal rating of a line at a target cost of $200 per sensor; this would allow the determination of dynamic thermal line rating for all spans, eliminating the need to identify a critical span.
Conductor/ compression connector sensor  Image courtesy of EPRI.	• Measures conductor temperature to allow accurate dynamic rating of overhead lines and line sag, thus determining line rating. • Measures temperature difference between conductors and conductor splices. • Interrogation via helicopter, ground, BPL, or wireless. • Battery-free. • Unique serial number tied to asset GPS location.
Insulation contamination leakage current sensor  Image courtesy of EPRI.	• Continually monitors leakage current and extracts key parameters. • Critical to determining when an insulator flashover is imminent due to contamination. • Clip-on, wireless, battery-free. • Unique identification number. • On-board storage of key parameters. • On-board storage of solar power. • Ability for interrogator to reset data.

Advanced Utility Monitoring System	
System	**Description**
Backscatter radio technology  Image courtesy of EPRI.	• Provides improved data and warning of transmission and distribution component failure. • Communicates data back to a substation or other data collection point. • Small, low cost, reliable. • Battery-free, with minimal electronics and long service life. • Radiation-free for reduced EMC concerns. • Uses inexpensive, off-the-shelf components. • Always "awake," enabling fast inspection speeds.
Electronic instrument transformer	• Replaces precise electromagnetic devices (such as current transformers and potential transformers) that convert high voltages and currents to manageable, measurable levels. • Fiber-optic-based current and potential sensors, available from several venders, accurately measure voltage and current to revenue standards over the entire range of the device.
Other monitoring systems	• Fiber-optic, temperature-monitoring system: Provides direct, real-time measurement of hot spots in small and medium transformers, thus addressing utility concerns about the safety and reliable operation of high-voltage equipment. • Circuit breaker real-time monitoring system: Measures the number of operations since the last time maintenance was performed, as well as operation times, oil or gas insulation levels, breaker mechanism signatures, etc. • Cable monitor: Determines changes in buried cable health by trending partial discharges or through periodic impulse testing of lines. • Battery monitor: Minimizes battery failure by assessing cell health, specific gravity liquid level, cell voltage, and charge/discharge characteristics. • Sophisticated monitoring tool: Combines several different temperature and current measurements to dynamically determine temperature hot spots; measure dissolved gases in oil; evaluate the high-frequency patterns and signatures associated with faulty components and report the health of transformers and load tap changers in real time. • Many of these systems are commercially available.

Table 2: Advanced Utility Monitoring System

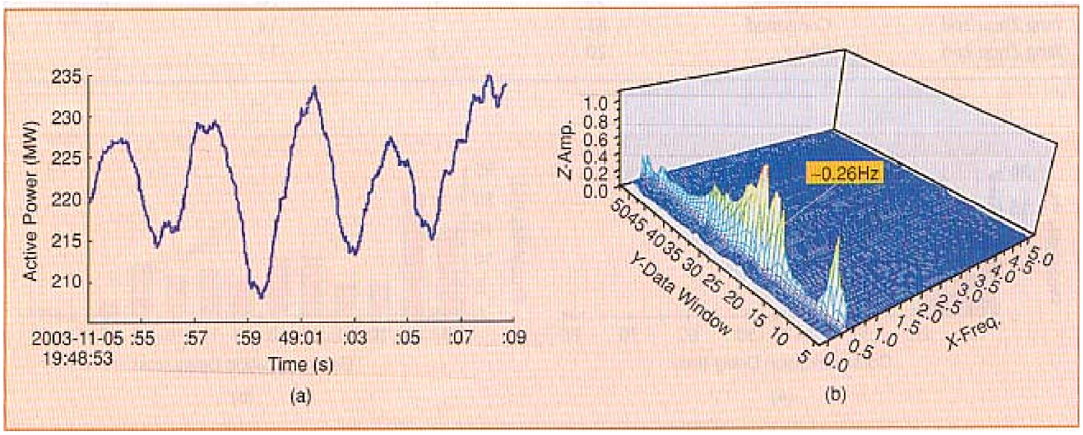


Figure 5: This sample image of a WAMS record-and-replay function display provides a global view of disturbances. Graphic under IEEE copyright. It appeared in the article, "WAMS Applications in Chinese Power Systems" in the *IEEE Power & Energy Magazine*, V4:1 (Jan/Feb 2006). Image courtesy of *IEEE Power and Energy Magazine*.

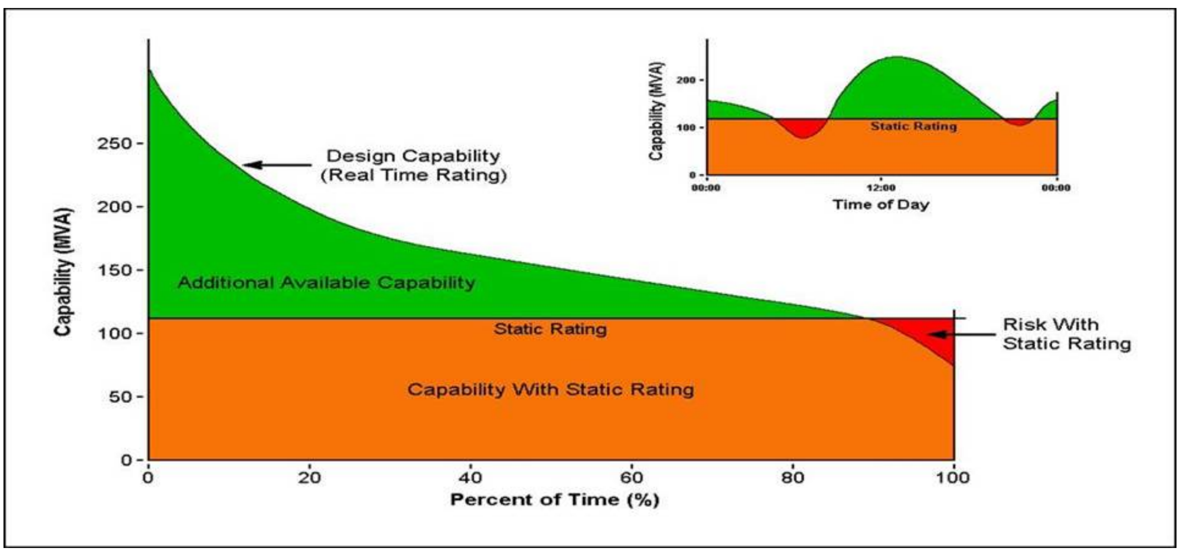


Figure 6: A real-time rating characteristic. Historically, line ratings have been based on assumed static conditions, but in-service conditions can differ substantially from those assumptions. This figure illustrates the dynamically increased power rating achievable with actual conditions provided by tower-mounted weather stations, line tension monitors, and/or visual cameras. Image courtesy of EPRI.

Advanced Protection Systems

In the past, more than 70 percent of major system disturbances have involved protective relaying systems, not necessarily as the initiating event but as a contributor to the cascading nature of the event. Today, products to reduce this problem are increasingly available. Compared to the electromechanical and analog relays of the past, new digital relays include many value-adding functions, such as fault location, high-impedance distribution fault detection, more sophisticated transformer and bus fault detection, self checking diagnostics, adaptive relaying and greater use of networked digital communications. As these new digital devices continue to be deployed throughout the grid, reliability will be significantly enhanced.

Table 3 describes two advanced protection technologies.

Advanced Protection System	
System	**Description**
Fault-testing recloser	• Applies a very fast, low-energy pulse to the line to determine if a fault is still present. • Minimizes damage caused by reclosing into faulted lines. • Significantly reduces damaging fault-current and voltage sags on the faulted line and adjacent feeders. • Substation transformers experience fewer through-faults, thus extending service life. • Cables, overhead conductors, splices, and terminations experience less thermal and mechanical stress from through-fault currents.
Special protection system	• Real-time monitoring of key generation assets or transmission lines and their associated power flows. • Upon a change of status (like loss of generation and/or loss of transmission), a pre-programmed set of actions takes place (e.g., wide-area load shed, generator redispatch, separation of interties). • Allows power transfers across the grid that would not comply with single or multiple contingencies under normal criteria. • Allows operators to load transmission lines closer to thermal limits or beyond normal voltage or system stability limits.

Table 3: Advanced protection systems

Related Research and Development

Research and development will support the integration of the sensing and measurement capabilities discussed previously as they come to market. In addition to utilities, EPRI and various equipment vendors are actively engaged in important R&D efforts.

Table 4: Research and Development Related to Sensing and Measurement.

Research and Development Related to Sensing and Measurement	
Name	**Description**
The Consortium for Electric Reliability Technology Solutions (CERTS)	• Is working to accelerate meaningful opportunities for customers to participate voluntarily in competitive electricity markets. • Studies focus on determining the effect of demand response on market efficiency and on demonstrating advanced demand-response technologies and strategies that will improve the reliability of the grid. • Work on WAMS contributes to this key technology area.

Research and Development Related to Sensing and Measurement	
Name	**Description**
The Power Systems Engineering Research Center (PSERC): Transmission and Distribution Technologies stem	• Reliability-based vegetation management through intelligent system monitoring. • Digital protection systems using optical instrument transformers and digital relays interconnected by an IEC 61850-9.2 digital process bus. • Optimal placement of PMUs for state estimation.
The California Energy Commission	• Advanced metering design, costs, and benefits. • Tariff design. • The evaluation of dynamic rates and programs for small customers. • The evaluation of DR programs for large customers.

Table 4: Research and Development Related to Sensing and Measurement

Requirements and Regulations

Customer metering has always fallen within the purview of state regulatory bodies. So, too, have the tariffs that determine how and what a customer will pay. Hence, a metering transformation cannot occur without the support and encouragement of these regulators.

The Energy Policy Act of 2005 (EPAct) is very clear in this regard. The following sums up the spirit of this new law:

> It is the policy of the United States that time-based pricing and other forms of demand response, whereby electricity customers are provided with price signals and the ability to benefit by responding to them, shall be encouraged, and the deployment of such technology and devices that enable electricity customers to participate in such pricing and demand response systems shall be facilitated, and unnecessary barriers to demand response participation in energy, capacity, and ancillary service markets shall be eliminated.

The law is also very proactive in requiring electric suppliers to employ advanced metering and communications technology. It will certainly motivate regulators to more seriously address the need for these technologies.

FUTURE STATE

We have examined the current state of the sensing and measurement technologies. Now, we will look at how this key technology area will develop in the future.

At the customer level, the modern grid will have no electromechanical customer meters or meter readers. Instead, modern solid-state meters will communicate with both the customer and the service provider.

Microprocessors in these advanced meters will offer a wide range of functions. At a minimum, they will record usage associated with different times of day and costs of production. Most will also be able to register a critical peak-pricing signal sent by the service provider, charging at that critical rate while it is in effect. At the same time, the meter will notify the customer that the critical rate has been implemented.

A still more sophisticated version will adhere to a desired-usage profile preprogrammed by the customer. In response to fluctuating electricity prices, the unit will automatically control the customer's loads in accordance with that schedule.

The most sophisticated versions will even provide non-utility services, such as fire and burglar alarms.

This new metering approach will be built on the digital communications capabilities of the Internet, will employ standard Internet protocols, and will use reliable, ubiquitous communications media, such as wireless, BPL, or even fiber to the home. The customer interface will be user friendly, with increasing levels of sophistication as product features are added. Security will be designed to prevent tampering or disruption.

At the utility level, advanced sensing and measurement tools will supply expanded data to power-system operators and planners. This will include information about the following:

- Power factor
- Power quality throughout the grid
- Phasor relationships (WAMS)
- Equipment health and capacity
- Meter tampering
- Vegetation intrusion
- Fault location
- Transformer and line loading

- Circuit voltage profiles
- Temperature of critical elements
- Outage identification
- Power consumption profiles and forecasting
- Curtailable load levels

New host software systems will collect, store, analyze, and process the abundance of data that flows from these modern tools. The processed data will then be passed to the existing and new utility information systems that carry out the many core functions of the business (e.g., billing, planning, operations, maintenance, customer service, forecasting, statistical studies, etc.).

As the requirements for a modern grid crystallize, additional parameters will need to be calculated in the meters, and other measurement and sensing points will be desired. The architecture of a modern grid must allow retrofitting of advancements without the need for massive infrastructure change-out.

Future digital relays that employ computer agents will further enhance reliability. A computer agent is a self-contained software module that has properties of autonomy and interaction. Wide-area monitoring, protection and control schemes will integrate digital relays, advanced communications and computer agents. In such an integrated distributed protection system, the relays will be capable of autonomously interacting with each other. This flexibility and autonomy adds reliability because even with failures in parts of the system, the remaining agent-based relays continue to protect the grid.

The primary assumption underlying the realization of sensing and measurement is that the benefits of developing and implementing these technologies will exceed the cost. Hence, an important variable is the value assigned to those benefits, some of which reach beyond the utility function to impact society as a whole.

There is little doubt that modern digital technology can produce low-cost, highly effective solutions, with all such technological developments depending on two major factors:

- Scale of deployments
- The continued reduction in the price of digital integrated circuits

The projected scale of various deployments is enormous. A global metering transformation would employ hundreds of millions of intelligent, communicating meters. But, as Moore's Law consistently shows, the price of chips will continue to drop even as their processing power grows.

Also, as history has shown us, the associated requirement of ubiquitous, reliable, inexpensive communications will become increasingly available as the revolution in digital communications continues to play out (see “Appendix B1: Integrated Communications”).

Benefits of Implementation

The benefits of realizing the sensing and measurement key technologies are many. Some of the most important are listed below.

Meter Transformation

The "transformed meter," in the form of the consumer portal and other gateway technologies, will provide a wealth of information to customers and utilities alike.

Resulting benefits to consumers:

- The ability to make informed usage decisions
- A direct, real-time connection to the electricity market
- The motivation to participate in that market
- Reduced energy costs

Benefits to utilities:

- Greater load control
- Reduced operational costs
- Congestion relief
- Reduced energy theft

Data Collection

Advanced sensors and new measurement techniques will collect valuable information about electrical conditions throughout the grid. Advanced tools will then analyze system conditions, perform real-time contingency analyses, and initiate a necessary course of action, as needed.

Benefits of improved data collection:

- More effective asset utilization and maintenance
- Constant awareness of in-service equipment health and capacity
- Identification and prevention of potential failures and the rapid assessment of emergent problems
- Safer operation with alerts to operators when devices are about to fail

Control Instrumentation

Advanced monitoring, control, and protection systems, as well as DR tools, are integral to a reliable, self-healing grid. Below are some benefits that will be realized:

- Reduction of cascading outages
- Prevention of rapidly developing instability situations

- Control of slowly developing instability situations
- Deterrence of organized attacks on the grid
- Full utilization of existing assets
- Reduced congestion
- More targeted and efficient maintenance programs
- Fewer equipment failures and thus reduced costs from catastrophic equipment failures
- Minimization of environmental impact
- Maximum use of the most efficient generators and reduced emissions associated with power generation
- Reduced power-delivery energy losses

BARRIERS TO DEPLOYMENT

Considerable research, development, and deployment are needed to fully realize the sensing and measurement key technologies. Unfortunately, an unintended consequence of restructuring in the electric power industry has been reduced research and development.

Engineering-oriented power industry managers, having a long term view, created a U.S. grid that was world-class for most of the twentieth century. But today's business-oriented managers, operating in a restructured utility environment, have adopted a shorter term perspective. Incremental improvements are still sought, but the break-through technologies (such as advanced monitoring systems) that are frequently more costly have lost their appeal.

The cost to create and deploy many of the sensing and measurements technologies discussed in this paper is high, and private industry has been reluctant to invest in costly, long-term developments. The federal and state funds needed to augment private investment have been very limited.

A lack of understanding of the fundamental value of a modern grid, and of the societal costs associated with an antiquated one, has created the misperception that today's grid is "good enough."

Meanwhile, the technical experience base is graying, so there are fewer and fewer advocates for the modern grid technology.

POSSIBLE SOLUTIONS

Fortunately, the core measurement (communication and information) technologies are within practical reach, and economic projections are favorable. In addition, the regulatory impetus provided by the 2005 EPAct can be expected to drive this area so that, a decade from now, extensive advanced sensing and measurement technologies could be commonplace.

Regulators can be the change-agent to lead the way in grid modernization. They must act now to correct the unintended drawback that deregulation has caused. R&D must be significantly encouraged, supported, and increased in the utility sector.

Successfully realizing sensing and measurement technologies requires progress in the following areas:

- The broad development and deployment of supporting communication technologies, such as wireless and BPL

- User-friendly customer interfaces and agents
- Tariffs that are effective from both the consumer and the utility perspective
- New, low-cost sensing and measurement techniques and central information technology systems to process, analyze, and take action on the large volume of collected data
- Additional proof-of-concept demonstrations to explore and illustrate the benefits to consumers and energy companies

A number of advanced sensing and measurement technologies that could have a major impact on grid modernization are available today. However, the current high production, installation, and maintenance costs, along with limited market exposure, have hindered their adoption. These technologies include the following:

- Advanced communicating revenue meters
- Consumer portals and agents
- Major equipment health monitors
- Electronic instrument transformers
- PMUs
- Line sag monitors

Broader deployment will take place as technical performance is proven, costs drop, and as societal value is recognized. It is the role of government to ensure that the proper value is placed on these extended societal benefits.

Several other components that could have a major impact remain in research and development. With the proper incentives, they could ready for deployment in two to four years. These are some examples:

- WAMS analysis systems
- Advanced low-cost communicating transmission and distribution sensors
- Electromagnetic interference detectors
- Sag monitors that utilize a global position system or other advanced, low-cost technology

The full integration of multiple key technologies must occur before the complete modern grid vision can be realized, and this could take ten to fifteen years or more. As these technologies are being incorporated into the power grid, many other synergies among the five key technology areas will surface. For example, the implementation of integrated communications, advanced control methods, sensing and measurements, and advanced components will allow a new series of special protective systems that can be customized to a region's unique characteristics.

The U.S. economy will suffer in many ways if we cannot develop and employ the technologies needed for a world-class power grid. Without the development and deployment of key technologies like sensing and measurements, our power grid will remain at high risk for widespread blackouts, such as the one that occurred in 2003 affecting 40 million people in the United States and 10 million in Canada.

SUMMARY

Advanced sensing and measurement technologies are essential components of a modern power grid.

When deployed, they will perform crucial functions that will transform both the customer and utility levels of the electric power industry. For instance, they will enable consumer choice and demand response, eliminate billing estimations, transform data into information, help relieve grid congestion, and support advanced protective relaying.

The consumer interface will be user-friendly, with increasing levels of sophistication as product features are added. New digital metering systems will be built on the communications capabilities of the Internet and will employ standard Internet protocols. They will use reliable and ubiquitous communications media, such as wireless, BPL, or even fiber to the home.

At the utility level, new sensing and measurement tools will supply expanded data to power system operators. This data will include voltage, power factor, phasor relationships (WAMS), power quality, equipment health and capacity, as well as timely information about meter tampering, vegetation intrusion, fault location, and outage occurrences.

Development in this key technology area is projected to bring savings in capital and operating costs throughout the grid. Another benefit is a reduction in environmental impact, realized due to the improved efficiency and asset utilization brought by sensing and measurement. Additionally, the economy and the public will benefit from enhanced safety, reliability, and power quality. These, as well as other advantages all give weight to the need to develop this key technology area.

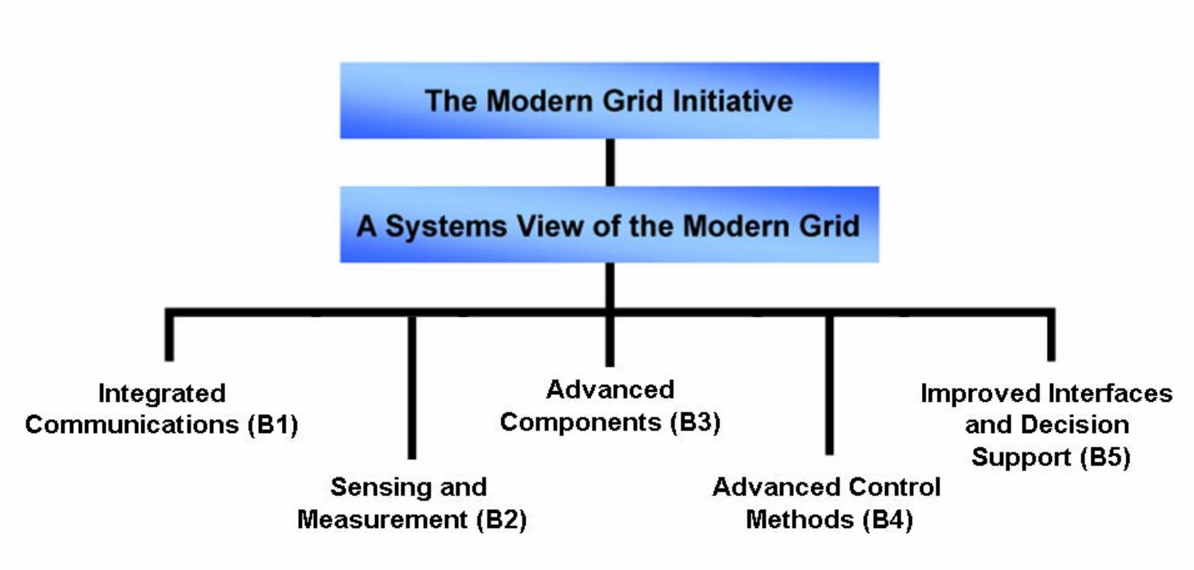
Our ability to implement other key elements of the modern grid will be significantly limited without the successful realization of sensing and measurement.

Today's challenge is to accurately envision the grid of the future and successfully design the advanced sensing and metering infrastructure that will enable it.

For More Information

This document is part of a collection of documents prepared by the Modern Grid Initiative (MGI) team. For a high-level overview of the modern grid, see "A Systems View of the Modern Grid." For additional background on the motivating factors for the modern grid, see "The Modern Grid Initiative."

MGI has also prepared five papers that support and supplement these overviews by detailing more specifics on each of the modern grid key technology areas. This paper has described "Sensing and Measurement."



These documents are available for free download from the Modern Grid Web site.

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ACRONYMS

BPL	Broadband over Power Line
CERTS	The Consortium for Electric Reliability Technology Solutions
DR	demand response
EMC	electromagnetic compatibility
EPAct	Energy Policy Act of 2005
EPRI	Electric Power Research Institute
GPS	Global Positioning System
MGI	Modern Grid Initiative
PMU	phasor measurement unit
PSERC	Power Systems Engineering Research Center
R&D	Research and Development
RTP	real-time pricing
SCADA	Supervisory Control and Data Acquisition
WAMS	wide-area monitoring system