Appendix B4:
A Systems View of the Modern Grid

ADVANCED CONTROL METHODS

Conducted by the National Energy Technology Laboratory
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EXECUTIVE SUMMARY

It is becoming increasingly difficult today to meet our nation's 21st century power demands with an electric grid built on yesterday's technologies.

A fully modernized grid is essential to provide service that is reliable, secure, cost-effective, efficient, safe, and environmentally responsible. To achieve the modern grid, a wide range of technologies must be developed and implemented. These technologies can be grouped into five key technology areas as shown in Figure 1 below.

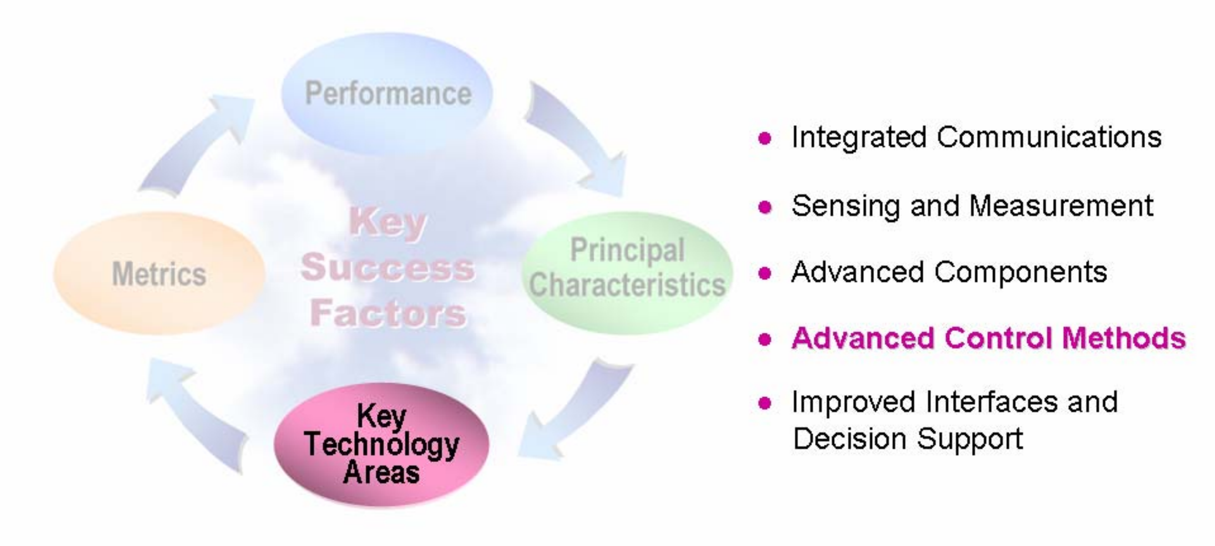


Figure 1: The Modern Grid Systems View provides an "ecosystem" perspective that considers all aspects and all stakeholders.

The advanced control methods (ACM) featured in this paper comprise one of the five key technology areas that must be developed if we are to have a truly safe, reliable, and environmentally friendly modern grid.

ACM technologies are the devices and algorithms that will analyze, diagnose, and predict conditions in the modern grid and determine and take appropriate corrective actions to eliminate, mitigate, and prevent outages and power quality disturbances. These methods will provide control at the transmission, distribution, and consumer levels and will manage both real and reactive power across state boundaries.

To a large degree, ACM technologies rely on and contribute to each of the other four key technology areas. For instance, ACM will monitor essential components (Sensing and Measurements), provide timely and appropriate response (Integrated Communications; Advanced Components), and enable rapid diagnosis (Improved Interfaces and

Decision Support) of any event. Additionally, ACM will also support market pricing and enhance asset management.

The analysis and diagnostic functions of future ACM will incorporate predetermined expert logic and templates that give "permission" to the grid's software to take corrective action autonomously when these actions fall within allowable permission sets.

As a result, actions that must execute in seconds or less will not be delayed by the time required for human analysis, decision-making, and action. Significant improvement in grid reliability will result due to this self-healing feature of the modern grid.

ACM will require an integrated, high-speed communication infrastructure and corresponding communication standards to process the vast amount of data needed for these kinds of system analyses. ACM will be utilized to support distributed intelligent agents, analytical tools, and operational software applications.

This paper covers the following four important topics:

- Current state of ACM
- Future state of ACM
- 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 communication infrastructure supporting today's control systems consists of a wide spectrum of technologies patched together. The required information is transmitted from the sensor to the control systems, processed by the control systems, and then transmitted to the controlling devices.

This current communication infrastructure is too limited to support the high-speed requirements and broad coverage needed by ACM, and it does not provide the networked, open architecture format necessary for the continued enhancement and growth of the modern grid. Additionally, today's grid lacks many of the smart sensors and control devices including consumer portal devices that need to be deployed to measure the required data and provide the control mechanisms to manage the electric system.

Some progress is being made. For instance, distribution automation (DA) technologies are presently being integrated with supervisory control and data acquisition (SCADA) systems to provide rapid reconfiguration of specific sections of the distribution system. This will minimize the impact of system faults and power quality disturbances on customers. DA provides the ability to monitor and operate devices that are installed throughout the distribution system, thereby optimizing station loadings and reactive supply, monitoring equipment health, identifying outages, and providing more rapid system restoration. However, this integration needs to happen more quickly and on a much wider scale.

Some of today's ACM technologies are locally based, such as at a substation, where the necessary data can be collected in near real time without the need for a system-wide communication infrastructure. But these control algorithms act autonomously at a local substation level and hence do not benefit from a system-wide perspective. Often, these algorithms are integrated with centralized systems to enable others not located at the substation to have access to the data. Substation automation technologies provide this functionality and are in their early phases of implementation at most utilities. Numerous vendors provide modern substation automation technologies today using architectures similar to that shown in Figure 2.

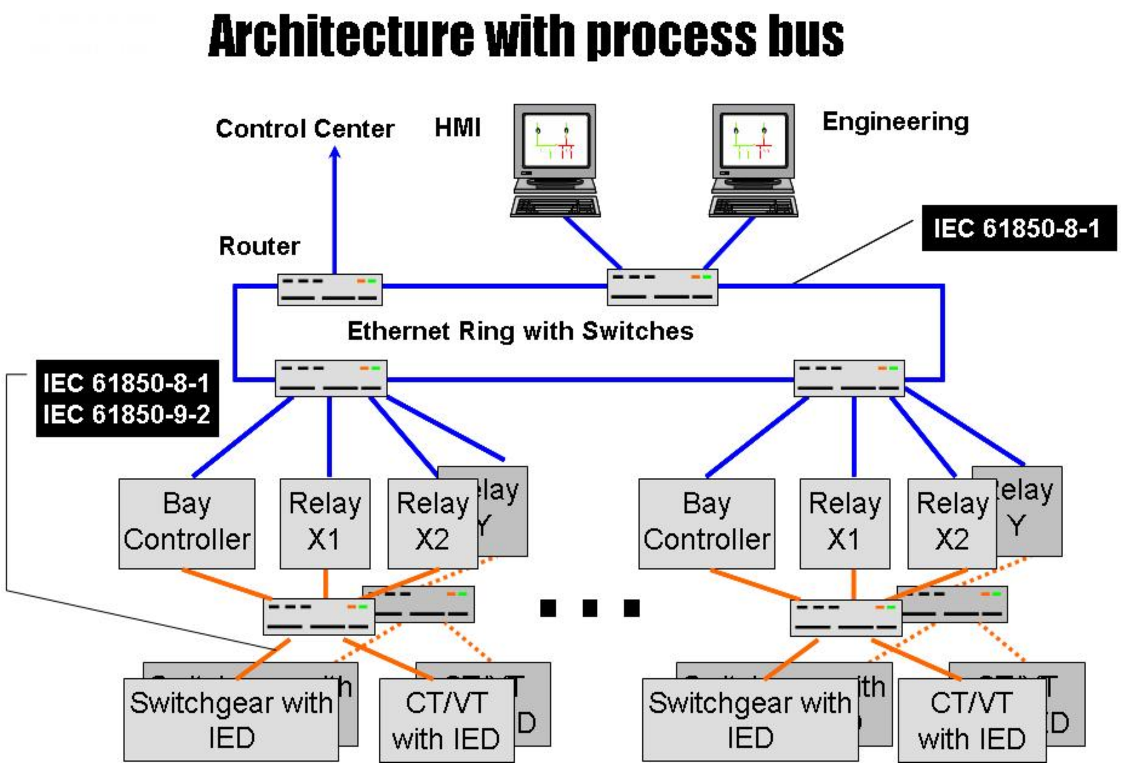


Figure 2: Example schematic of substation data architecture. Image courtesy of the International Electrotechnical Commission.

ACM technologies depend heavily on data sensing and some form of data transmission (See "Appendix B2: Sensing and Measurement" and "Appendix B1: Integrated Communications"). Today's sensors that measure system parameters (e.g.., watts and watt-hours, VArs and VAr-hours, volts, amperes, power factor, phase angles, harmonics, etc.) are only beginning to evolve from the traditional electric/electromechanical design to a solid-state, electronic-based technology of higher accuracy, more intelligence, and with the capability to interface with digital communication systems. The widespread deployment of intelligent electronic devices (IEDs) at the system, equipment, and consumer levels must occur to support ACM in the future.

Significant advances have been made in software-based control algorithms in nearly every industry and much has been done in the area of ACM. Some of the ACM technologies needed for the modern grid are currently available or are in research and development. These technologies are slowly being integrated into three important areas: distributed intelligent agents, analytical tools, and operational applications. Some of the technologies in these areas are described in the three tables which follow.

DISTRIBUTED INTELLIGENT AGENTS

Distributed Intelligent Agents are adaptive, self-aware, self-healing, and semi-autonomous control systems that respond rapidly at the local level to unburden centralized control systems and human operators. Several of these agents are often combined to form a multi-agent system with peer-to-peer communication. These multi-agent systems are capable of reaching goals difficult to achieve by an individual system. Some of these technologies are described in Table 1 below.

Distributed Intelligent Agents	
Agent	**Description**
Digital protective relay	• Senses electric system parameters, analyzes data, and initiates control actions autonomously to protect system assets • Communication-enhanced coordination ensures only last device feeding a faulted section clears the fault • Protection coordination can be automatically updated as circuits are reconfigured • Provides post-disturbance data for analysis of event • New design not yet universally deployed across the grid
Intelligent tap changer	• Senses both high- and low-side voltages to perform advanced control • Minimizes draw of reactive power from transmission system
Dynamic circuit rating tool	• Determines the safe and accurate dynamic rating of lines • Interfaces with advanced sensors that monitor weather parameters, line sag, and conductor temperature to obtain the required inputs • Normally provides additional line capacity except during times when weather conditions and line loadings are not favorable
Energy management system	• Monitors electric system parameters and marketing information; considers consumer preset settings and acts on the behalf of the consumer to manage energy costs, comfort, and health • Supports demand-response (DR) programs based on real-time pricing
Grid-friendly appliance controller	• Senses grid conditions by monitoring the frequency or voltage of the system and provides automatic DR in times of system distress • Can be installed in household appliances such as refrigerators, washers, dryers, stoves, etc., to turn them off or on as required to allow the grid to stabilize
Dynamic distributed power control devices	• Increases or decreases line impedance • Improves utilization of under-utilized lines • Can manage flexible alternating current transmission system (FACTS) devices installed at substations to provide instantaneous and autonomous control of line flow and voltage • Low-cost, mass-produced, distributed power-flow devices can be installed on each phase of a line to provide 10% or more instantaneous control of power flow

Table 1: Distributed intelligent agents

ANALYTICAL TOOLS

The heart of the ACM analytical tools are the software algorithms and the high-speed computers needed to process and analyze the information. This feature is a key part of the overall ACM control loop. Some of these tools are described in Table 2 below.

Table 2: Analytical Tools

Analytical Tools	
Tool	**Description**
System performance monitoring, simulation, and prediction	• Monitors frequency, voltage, congestion, and market power to detect abnormal operating patterns • Predicts how system will respond if critical equipment is forced out of service • Validates quality of real-time data and off-line system models • Optimizes plans for system stabilization and restoration based on real-time or simulated disturbances
Phasor measurement analysis	• Monitors the instantaneous value of voltage or current • Determines whether a transient swing in the power system is stable or unstable • Detects imminent grid emergencies • Supports more rapid state estimation • Improves dynamic modeling and analysis • Online model with better visualization still needs to be developed so that control room operators can effectively interpret phasor measurement unit (PMU) phasor data.
Weather prediction and integration	• Improved accuracy of weather forecasts leading to improved load forecasts • Better at detecting the possibility of extreme events at long range • Various methodologies available, including artificial intelligence, neural networks, fuzzy logic, etc.
Ultra-fast load flow analysis	• Provides visualization tools showing regions of secure operations limited by voltage constraints, voltage instability, thermal limits, and flow gate constraints • Optimal mitigation measures can be applied online to expand the boundary of the operating region, reduce transmission congestion, optimize outage management, and support improved system planning analyses • Ultra-fast load flows that solve a 40,000-bus system in less than a second are available

Analytical Tools	
Tool	**Description**
Market system simulation	• Analyzes engineering and market aspects of the grid – links physical performance and control with economics • Provides open-source environment where independently developed software components can be shared by other people and organizations • Spans energy systems currently analyzed in isolation (e.g., transmission grid, distribution systems, and customer systems) • Under development at PNNL
Distribution fault location	• Will use data from digital relays or other monitoring systems along with circuit databases to determine the location of a fault on the distribution circuit • A new traveling wave system is being developed that is expected to be cost-effective for distribution systems. • Technologies have not yet been adopted due to complexity and high cost.
High-speed computing	• Essential because of the vast amount of data and the complexity of the analyses performed by ACM • Takes advantage of multiple networked computers to create a virtual computer architecture capable of distributing process execution across a parallel infrastructure • Work is being done to create a universal medium for information exchange. • New technologies are under development

Table 2: Analytical tools

OPERATIONAL APPLICATIONS

The modern grid will rely on local intelligence, automation, and decentralized control for selected applications, particularly those with primarily local impact. Centralized ACM will be utilized in other applications that provide a broader and more integrated perspective, such as the prediction of overall system capability and health. Some of these applications are described in Table 3 below.

Table 3: Operational Applications

Operational Applications	
Application	**Description**
SCADA	- Supports energy management systems (EMS) and transmission operations but has limited deployment at the distribution level - Today's SCADA systems are too slow and do not acquire data at the speed needed for ACM technologies. - More recently, Regional Transmission Organizations and Independent System Operators have expanded SCADA capabilities.
Substation automation	- Provides local control, remote control, and monitoring at the substation level - IEDs utilized for protection and control are normally integrated with a station computer, providing human-machine interface for local control, monitoring, and system configuration. - Makes the substation information available for retrieval by substation planners, protection engineers, maintenance personnel, and others as needed - The IEDs and the local network are linked to various other users to lay the foundation for higher-level remote functions such as advanced power system management and equipment condition monitoring while it is in service.
Transmission operations, energy management systems, and market operations	- Transmission SCADA systems provide system data to advanced state estimators, which solve large networks to determine system conditions every five minutes - Determines needed changes in system generation and, based on economic factors, provides EMS signals to participating units - Optimizes the economic dispatch of energy and at the same time mitigates the congestion on transmission lines - Location-dependent, real-time prices are calculated based on the re-dispatch of generation every five minutes to provide a price signal to generators, transmission owners and operators, and consumers. - Control methods currently in use by some of the Regional Transmission Organizations have advanced substantially over the past few years. - Need to incorporate advanced flow control, distributed energy resources (DER), and demand response (DR) options
Distribution automation	- IEDs have been integrated with distribution SCADA systems on a limited basis to provide rapid reconfiguration to minimize system impacts from faults and other power-quality disturbances - Currently, cost of DA technology has limited its widespread deployment. - New low-cost, high-speed, and reliable digital communications systems will eliminate many of the economic hurdles faced by DA deployment.

Operational Applications	
Application	Description
Demand response	• Used by system operators as a tool for mitigating congestion and peak-loading issues • Consumers give permission to system operators to interrupt loads under specific conditions • Consumers interact with system operators using the consumer's energy management system • Load can be interrupted autonomously using technologies embedded in grid-friendly appliances (GFAs) when specific conditions are detected.
Condition-based maintenance (CBM)	• Monitors and trends key asset characteristics, analyzes the information, and predicts when maintenance or replacement should be performed to prevent failure • Enables more effective and efficient maintenance practices, reducing occurrences of unexpected component failures as well as consumer and system outages • Becoming an accepted practice for managing health and maintenance of system assets
Outage management	• Integrates customer outage information with the up-to-date status of the distribution network • Helps operators rapidly determine causes of distribution outages • Enables more rapid restoration, including remote reconfiguration • Gives accurate information to customers regarding the status of power interruptions
Asset optimization	• Integrates plant operations, fuel management, and maintenance processes • Collects, verifies, and analyzes operational data using facility-specific parameters, and informs operators in real-time when a system is malfunctioning or running below expectations • Identifies conditions that could lead to a problem, determines the root cause, and prioritizes recommended solutions • Provides actual and what-if load data for devices, feeders, and substation transformers at the system level • Reconciles hourly SCADA data to provide an accurate view of asset loading system-wide and hourly-load profiles for each device • Assists operators in understanding which assets are over- or under-utilized and performs a risk analysis for each asset • Various technologies currently exist

Table 3: Operational applications

FUTURE STATE

The advanced control methods of the future require an advanced and integrated communication system to operate effectively (see "Appendix B1: Integrated Communications").

Many control functions are performed today to some degree and in limited locations. In the future, however, ACM will become significantly more sophisticated, will consider regional and national perspectives in addition to local ones, and will be fully deployed throughout the national grid. Where appropriate ACM will be distributed and where necessary, it will be centralized.

FUNCTIONS ACM WILL PERFORM

Collect data and monitor grid components – In the future, low-cost, smart instrument transformers, IEDs, and analytical tools will measure system and consumer parameters for every significant data point needed by ACM. New, low-cost devices will provide the condition of grid components and will be deployed and integrated with ACM to provide an overall assessment of the system's condition. These data will be presented to ACM for analysis on a near real-time basis by an integrated communication system. In addition, phasor measurement units (PMU), integrated with global positioning system (GPS) time signals will be deployed nationwide to provide a perspective of grid status and an early warning of developing instabilities.

Analyze data – The availability of near real-time data for all needed data points, and more powerful processors to analyze this data, will make possible rapid expansion and advancement in the capability of software-based analytical tools. Here are some specific examples:

- State estimators and contingency analyses will be performed in seconds rather than minutes, giving ACM and human operators additional time to react to emerging problems. This will also support the use of real-time transmission system optimization tools.
- Expert systems will convert the data to information that can be used for decision making. This information can then be input into probabilistic risk analyses.
- Load forecasting will take advantage of the system-wide distribution of near real-time data as well as improved weather forecasting technologies to produce highly accurate load forecasts at the system, component, and consumer levels.
- Probabilistic risk analyses will be performed routinely to determine the level of risk when taking equipment out of service for repair, during periods of high system stress, and following unexpected

outages. Indicators that present real time operating risk will be in place at regional and local operations centers to assist operators with the decision-making process.

- Grid modeling and simulations will enable operators to perform accurate "what-if" scenarios from a deterministic as well as probabilistic perspective.

Diagnose and solve – The availability of near real-time data processed by powerful high-speed computers will enable expert diagnostics to identify solutions for existing, emerging, and potential problems at the system, subsystem, and component levels. The probability of success for each solution will also be identified and the results made available to the human operator. This function of ACM will be carried out at local, regional, and system-wide levels based on the perspective needed or desired.

Take autonomous action when appropriate – Protective relaying schemes have acted autonomously in response to system faults for many years and will continue to do so in the future. The modern grid, however, will make significant advances by incorporating real-time communication systems with advanced analytical technologies. These advances will make possible autonomous action for problem detection and response. They also will mitigate the spread of existing problems, prevent emergent problems, and modify system configurations, conditions, and flows to prevent predicted problems.

Autonomous action will continue to be performed at the local level but will also be expanded to the regional and national level as control methods become more integrated with local control systems and centralized in the overall structure. Protective relay settings will be adapted to meet actual system conditions in real time.

Provide information and options for human operators – In addition to providing actuating signals to the control devices, ACM will provide information to the human operator. This information will be useful in two different ways.

First, the vast amount of data collected by the control system for its own use is of great value to the human operator. This data will be filtered and presented to sophisticated visualization programs to create an effective man-machine interface. (See "Appendix B5: Improved Interfaces and Decision Support"). These visualization programs will reduce the large amount of data to a format that allows the human operator to understand system conditions at a glance.

Second, the data will provide decision assistance. When the control algorithms determine a corrective action needs to be taken by a human operator (i.e., an action not appropriate for autonomous control), it will provide options to the human operator, giving probabilities for success for each option. In addition, when the controls take autonomous actions, those actions and their results will be reported to the operator.

Integrate with other enterprise-wide processes and technologies – Much of the data collected by ACM and the results obtained through the analyses they perform are of significant value to numerous other enterprise-wide processes and technologies. Equipped with this new data, these other processes and technologies can be significantly enhanced. Feedback from these secondary results will enable the advanced control methodologies to gain additional intelligence that will further refine the self-healing nature of the modern grid. The following are some examples where ACM can enhance existing processes and technologies.

- **Load forecasting and system planning** – Having extensive near real-time load data will eliminate the need to estimate past load and will provide accurate coincident load data from which more accurate forecasting will result. More accurate load forecasting will optimize the decision-making process concerning when and where new capacity additions are needed.
- **Maintenance** – Near real-time component condition and loading information will make possible a significant reduction in the number of equipment failures and the cost of reactive maintenance. The results of the maintenance process (including condition-based maintenance) will be fed back to the ACM technologies to improve their probabilistic risk analysis capabilities.
- **Market operations with RTOs** – ACM at the control area level will improve the interface with advanced control algorithms at the RTO level, resulting in the improvement of economic dispatch, the mitigation of transmission congestion, and the enhancement of system reliability.
- **Work management** – Near real-time consumer and system component data will enable work management and scheduling processes to determine the most effective timing for performing scheduled work. For example, "what if" scenarios will be performed to determine the risk in taking equipment out of service for performing work.
- **Outage management** – ACM will assist operators and storm-response personnel by sectionalizing, isolating, and providing recovery status on a near real-time basis. The outage management system will take advantage of the status information of all consumers and system components (integrated and analyzed by ACM) to precisely locate the outage and its cause. This information will also allow more accurate prediction of return-to-service times.
- **Simulation and training** – The increased level of sophistication that ACM technologies bring to the modern grid requires a corresponding increase in sophistication in the training for the human operator. The online controls and data will be interfaced to the training simulator to provide realistic system conditions and responses for various training scenarios.
- **Geographic information systems (GIS) for Spatial Analysis** – Near real-time data will be imported into GIS technologies to enable spatial analyses of various types to be performed. Locations of movable assets such as trucks, equipment, and personnel will be provided to the ACM to give the operators a better understanding of where these

assets are located and to incorporate the personnel safety component into the self-healing feature of the modern grid.

- **Automatic meter reading** – Manual meter reading will be eliminated as meter reading and billing will be performed using accurate near real-time data collected by modern grid technologies.

BENEFITS OF IMPLEMENTATION

The wide acceptance and implementation of the modern grid's advance control methods will benefit all involved – the power industry, businesses, and industry as well as consumers and society in general.

Here are some of the many advantages to be realized:

- **The overall reliability** of the distribution and transmission systems will be generally improved, leading to decreased costs and increased revenues.
- **The self-healing vision** for the Modern Grid will be achieved. Appropriate actions will be taken to prevent or minimize adverse consequences. The scope of cascading events will be limited to prevent wide-area outages.
- **Sophisticated analytical capabilities** will prevent, detect, and mitigate the consequences of security attacks.
- **Integration with consumers and their loads** will provide energy price signals to encourage them to participate in the electricity market based on real supply-and-demand influences. The markets will then be more efficient and the result will be the lowest possible price for electricity.
- **Restoration times** following major grid events will be reduced by the provision of key and timely information and strategies needed by emergency response organizations.
- **Transmission congestion** will be minimized, contributing to further reductions in energy prices and more robust energy markets.
- **Supply-side and demand-side conditions will be monitored** to identify both emerging and actual power quality issues. Appropriate corrective actions will be taken to address power quality challenges before they become significant or lead to loss of reliability.
- **Utilization of DER and DR** to displace spinning reserve and increase system efficiency will reduce environmental impacts.
- **Integration of asset utilization data** into transmission and delivery (T&D) planning models will aid the planning of major long-term investments needed to increase system capacity.
- **Providing the material-condition data** for assets to condition-based maintenance (CBM) programs will improve the overall health and reliability of assets, reduce their out-of-service times, reduce the cost of maintenance, and improve the repair vs. replace decision-making process.
- **Integration of ACM** with work management and outage management systems will improve the efficiency in performing system and trouble work and will reduce the outage time and cost to consumers.

BARRIERS TO DEPLOYMENT

Significant barriers exist that impede the development and implementation of advanced control methods, but deployment of ACM is necessary to ensure safe, reliable, clean, economic, and environmentally responsible power in the future.

The move forward will remain limited until system data are available from a much wider area in near real time and a high-speed communication system is in place so that these ACM technologies can act. In addition, faster and more powerful computers are required so that ACM can respond immediately to rapidly forming power system events.

Another barrier is the lack of broad consensus for the modern grid vision among stakeholders. A greater understanding of the advantages of the modern grid – especially its self-healing function and its huge environmental benefits – is lacking. Conflicting objectives among stakeholders impede the full implementation of these control methods and their integration with other important processes and technologies. For example, the possibility of reduced revenues to suppliers of electricity impedes the full utilization and dispatch of consumer DER, much of which is far cleaner than central fossil-based generation. New regulatory models may be a solution to this conflict.

State regulatory bodies and current regulations do not fully support the vision for the modern grid. Increased cooperation between state and federal regulators is also necessary. New regulations that stir and motivate the vision for a modern grid must be created and existing regulations that impede progress must be modified. Regulated utilities need incentives for investing in ACM that provide societal benefits.

The perspective for ACM lacks breadth. Existing control methods are primarily focused at the local level. A greater deployment of local controls is needed and must be encouraged in the future; however, a wider, more centralized perspective is also needed. Effective integration of distributed controls to support a regional and even national monitoring and control perspective is lacking. An integrated, system-wide (region-wide or greater) control perspective needs to be formulated.

The cost of sensors is too high. The widespread deployment of IEDs is currently limited because of cost. In addition, a method to retrofit existing components to make them IED-ready is needed to keep implementation costs down. Otherwise, the placement of IEDs into the current electric system could take decades since components are not replaced today until they fail. Economies of scale and design innovation are needed to drive costs down.

The data today are incomplete and not available fast enough. As long as only limited data are available, many needed features of the modern grid, like the self-healing characteristic, are not possible.

The infrastructure for integrated communication is missing. Deployment of the needed communication systems, including supercomputers, is needed to support the processing and analysis of the large data volumes that will be supplied by advanced technologies of the modern grid.

SUMMARY

Advanced control methods are technically achievable.

The needed software and hardware systems can be developed relatively easily following the development of a comprehensive set of control-system specifications.

But first the lack of a clear vision, the problem of insufficient data, the absence of a comprehensive communications infrastructure, and the inadequacy of IED deployment must be addressed for ACM to be universally accepted and implemented.

In addition, conflicting objectives among stakeholders must be addressed and answers found to benefit all involved.

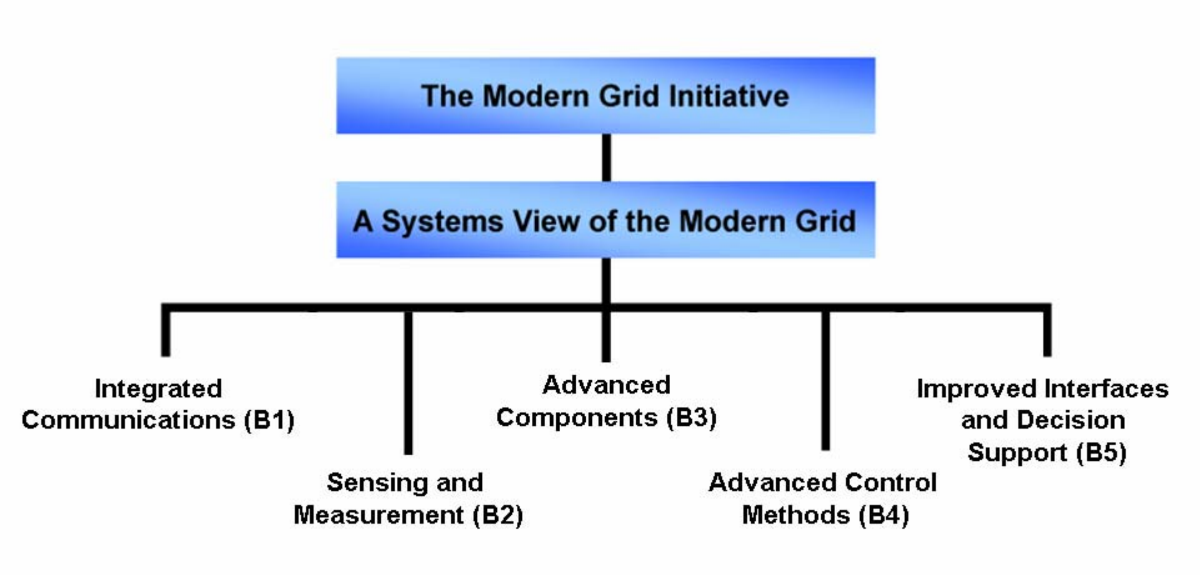
Development of clear specifications for ACM and other key technologies is an important step in advancing the modern grid. Specifications for data acquisition, communication standards, and retrofits of existing components to convert them to IED functionality, all in support of these ACM technologies, will provide the basis for rapid progress.

But the most important step is the development of a national vision for the modern grid, endorsed by the great majority of stakeholders.

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 key technologies of the modern grid. This paper has described the fourth key technology area, “Advanced Control Methods.”



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

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ACRONYMS

ACM	Advanced Control Methods
CBM	Condition Based Maintenance
DA	Distribution Automation
DER	Distributed Energy Resources
DR	Demand Response
EMS	Energy Management System
FACTS	Flexible Alternating Current Transmission System
GFA	Grid-Friendly Appliance
GIS	Geographic Information System
GPS	Global Positioning System
IED	Intelligent Electronic Device
MGI	Modern Grid Initiative
PMU	Phasor Measurement Units
PNNL	Pacific Northwest National Laboratory
SCADA	Supervisory Control and Data Acquisition
T&D	Transmission and Distribution
VAr	Volt-amperes reactive