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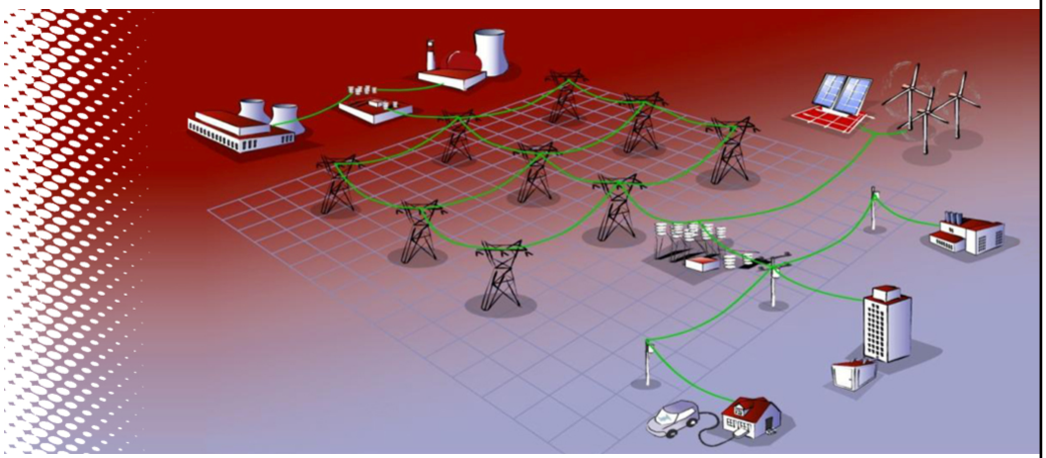

Anticipates and Responds to System Disturbances (Self-Heals)

September 2, 2010

DOE/NETL-2010/1421

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NETL Contact: Keith Dodrill

Integrated Electric Power Systems Division

Office of Systems, Analyses and Planning

National Energy Technology Laboratory

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Prepared by:

Booz Allen Hamilton (BAH)

Bruce Renz

Renz Consulting, LLC

Joe Miller and Jess Harmon

Horizon Energy Group

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LIST OF ACRONYMS, ABBREVIATIONS, AND DEFINITIONS

AMI	Advanced metering infrastructure
ARRA	American Recovery and Reinvestment Act of 2009
CIM	Common information model
DA	Distribution automation
DER	Distributed energy resources
DMS	Distribution management systems
DOE	Department of Energy
DR	Demand response
HV	High voltage
IC	Integrated communications
KTA	Key technology areas
NERC	North American Electric Reliability Corp.
NETL	National Energy Technology Laboratory
O&M	Operations and maintenance
PC	Principal characteristic
RAS	Remedial action systems
RTO	Regional transmission organizations
SA	Substation automation
SIPS	System integrity protection systems
T&D	Transmission and distribution
WAPC	Wide area Protection and control

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Executive Summary

The white paper titled, *A Systems View of the Modern Grid*, defines the seven principal characteristics of the smart grid. One of those characteristics is *Self Heals*. This main objective of this paper is to clearly define the *Self Heals* principal characteristic and present the distinction of the current state from a possible future state.

In the context of the smart grid, “self-healing” refers to a design concept that enables problematic elements of an electrical system to be identified, isolated, and restored, with little or no manual intervention, so as to minimize interruptions of service. Self-healing is, in essence, the smart grid’s immune system. A strong immune system enables the grid to perform continuous, online self-assessment to detect existing or emerging problems, predict future potential problems, and initiate immediate corrective responses. The self-healing concept is a natural extension of traditional power system monitoring, control, and protection philosophies—but taken to the next level with automation through advanced theory and technology. For example, a self-healing grid will frequently utilize a network design that links multiple loads and energy sources. Sensors and analytic programs will detect patterns that are precursors to faults, providing the ability to correct conditions before disturbances actually occur. The self-healing objective is to limit event impact to the smallest load area possible. This approach can also mitigate power quality issues, taking such corrective steps as instantly transferring a customer from a disturbed source to a “clean” one. Fault location, voltage and power-quality problems, emerging dynamic instabilities, and other grid abnormalities will be quickly discovered and corrected. Advanced simulation models combined with new visualization tools will reveal congestion issues, overlays of failure probabilities, and resulting threat levels. In addition, the self-healing grid will also have an improved ability to recognize high-risk situations. When forecasted adverse weather and/or real-time contingency analyses are incorporated into a probabilistic model, grid operators will better understand the risks of each decision, as well as ways to minimize those risks.

From a self-healing perspective, the current distribution system is limited where substation automation (SA) systems are applied at a local level, using local information for decision-making. While the basic design of the integrated transmission grid—many geographically diverse generation sources feeding a high-voltage, switchable, networked transmission system—is conducive to self-healing, the fundamental design of today’s distribution systems does not accommodate a comparable depth of self-healing.

In order to achieve a “self-healing” grid, some barriers will need addressed. For example, financial Resources will need to be made available potentially through government support. Additionally, a new regulatory model should be considered that decouples delivery company profits from sales volume. Instead, a model that rewards achievement of the seven principal characteristics would accelerate smart grid progress, particularly in the area of self-healing. Compatible and interoperable equipment will need to be developed in a manner and speed to serve the industry through these changes.

Of course, modernizing the grid infrastructure to support self-healing will require significant utility investment. But the resultant benefits—to consumers, utilities, employers, government, and society—will return that investment many fold including improvements to reliability, security, safety, power quality and the environment.

INTRODUCTION

The health of an electric system, like that of the human body, is determined in large part by the strength of its immune system—by its ability to heal itself. In that context, the North American grid's immune system is not especially strong. This was clear during the Northeast power blackout of 2003, which left tens of millions of Americans and Canadians without electricity for days during the sweltering heat of mid-August.

The United States' century-old power grid is notable for being both massively complex and inextricably linked to nearly every human activity and achievement. To sustain human progress, society must modernize the grid for the twenty-first century. With current and emerging technology—combined with wise policy, adequate funding, and comprehensive implementation—the grid can become smart enough to be essentially self-healing.

In the context of the smart grid, "self-healing" refers to a design concept that enables problematic elements of an electrical system to be identified, isolated, and restored, with little or no manual intervention, so as to minimize interruptions of service. Self-healing is, in essence, the smart grid's immune system.

The smart, self-healing grid will perform continuous, online self-assessment to predict future potential problems, detect existing or emerging problems, and initiate immediate corrective responses. The self-healing concept is a natural extension of traditional power system monitoring, control, and protection philosophies—but taken to the next level with more advanced theory and technology. The required smart infrastructure will utilize autonomous intelligent agents throughout the power system to achieve both local and global objectives.

A self-healing grid will frequently utilize a networked design that links multiple loads and energy sources. Sensors and analytic programs will detect patterns that are precursors to faults, providing the ability to correct conditions before disturbances actually occur. The self-healing objective is to limit event impact to the smallest load area possible. This approach can also mitigate power quality issues, taking such corrective steps as instantly transferring a customer from a disturbed source to a "clean" one.

Figure 1, which illustrates a project sponsored by the Department of Energy's (DOE) National Energy Technology Laboratory (NETL), provides a real-life example of the self-healing concept. In this deployment, two distribution primary circuits, having multiple points of interconnection, support each other by matching, in real time, available backup capacity and lost (outaged) load. The core of this design is a dynamic feeder reconfiguration system, which finds distribution system faults, isolates them, and restores service within seconds.

A unique aspect of this installation is its ability to determine, in real time, available backup capacity and to match that capacity to lost load in the zones being backed up.

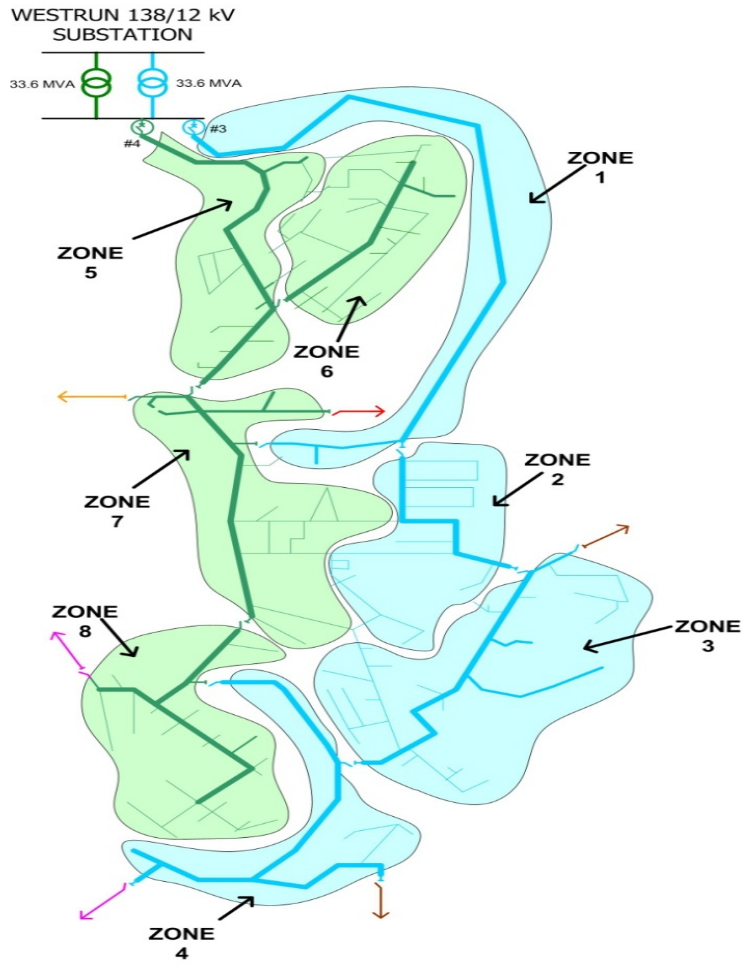

Figure 1: DOE/NETL-Sponsored Self-Healing Deployment

In general, self-healing's intelligent switching feature maintains power to a maximum number of customers by instantaneously transferring them to an alternate energy source when their primary source has been lost. Alternate energy sources may include circuit ties to other feeders, as in Figure 1, or to distributed energy resources such as energy storage devices and distributed electrical generators (powered by both renewable and non-renewable fuels). Demand response (DR) can also be a tool to quickly shape the load to meet available supply during the self-healing process.

One key aspect of a smart, self-healing electrical grid is that it will know a great deal about problems affecting its operation. Fault location, voltage and power-quality problems, emerging dynamic instabilities, and other grid abnormalities will be quickly discovered and corrected. Advanced simulation models combined with new visualization tools will reveal congestion issues, overlays of failure probabilities, and resulting threat levels. In addition, the self-healing grid will also have an improved ability to recognize high-risk situations. When forecasted atmospheric extremes and/or real-time contingency analyses are incorporated into a probabilistic model, grid operators will better understand the risks of each decision, as well as ways to minimize those risks.

Figure 2 below illustrates one way to convey broad information at a glance. In this hypothetical example, the top map uses colors to identify the geographic distribution of voltage phase angles (a given color represents a specific phase angle), while the bottom map shows the loci of similar angles (a steep gradient here, shown as lines clustered next to each other, would indicate heavy loading in the region). As reported in the reference article by Horowitz, Phadke and Renz:

> "Since the positive sequence voltage phase-angle profile of a network conveys a great deal of information regarding its power flow and loading conditions, such visualizations can instantly show the quality of the prevailing system state and its distance from a normal state. High-speed dynamic phenomena can be represented by animations of such visualizations."

As further suggested by author Phadke, the operator could be trained to recognize the 'normal appearance' of the system (e.g. color, pattern, etc.), and hence to quickly understand a 'stressed appearance' when it develops.

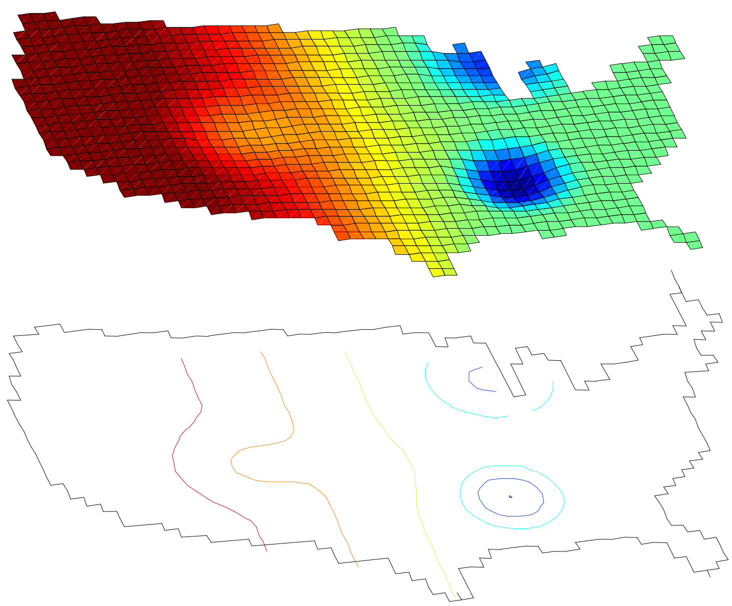

Figure 2: Geographic plot of voltage phase angle at a specific moment in time

Effective presentations and related decision support tools will help operators quickly grasp system conditions, and enhance the situational awareness that is the key to safe and secure grid management While advanced sensing, analysis, protection, and control are important elements of a self-healing grid, so too is a robust transmission and distribution (T&D) infrastructure. High-capacity interconnections, joining major regional transmission organizations (RTOs), allow for inter-regional power flows during an emergency. But if this power transfer capability is not adequate, then upgrades to higher capacity or the construction of new tie lines is required. This infrastructure improvement also results in more robust energy markets, allowing less expensive remote generation to flow to areas of high-cost local supplies. The smart grid will act to reduce the number and duration of outages, minimize restoration times, and reconfigure the grid to produce optimum reliability and quality of service. All these features are rolled up under a common term—the "self-healing" characteristic—of the smart grid.

Of course, modernizing the grid infrastructure to support self-healing will require significant utility investment. But the resultant benefits—to consumers, utilities, employers, government, and society in general—will return that investment many fold. These benefits include:

- **Improved Reliability**—Self-healing will produce a substantial improvement in grid reliability. The annual cost of power disturbances to the U.S. economy is significant—on the order of $100 billion. The savings from a single massive blackout is estimated to be on the order of $10 billion per event, as described in "Final Report on the Aug.14, 2003, Blackout in the United States and Canada."
- **Improved Security**—A self-healing grid is, almost by definition, the most secure grid. Self-healing decreases the threat of a security attack because energy sources are distributed and self-healing technologies can maintain or restore service during and after attack.
- **Safety**—Increased public safety will be a benefit of the smart grid. The smart grid will quickly locate and de-energize downed wires. Restoring power faster to more people will reduce the impact to "life-support" customers, as well as maintaining HVAC to elder care facilities. Additionally, fewer outages mean fewer opportunities for criminal acts.
- **Quality**—The self-healing grid will detect and correct power quality issues. Power quality issues represent another large annual cost to society, estimated to be in the tens of billions of dollars.
- **Environmental**—The self-healing grid will accommodate multiple green resources, both distributed and centralized, resulting in substantial reductions in emissions. In addition, the environmental impact associated with outages and major equipment failures will be dramatically reduced—and a more efficient grid means lower electrical losses (hence lower emissions).

There is little doubt that a prosperous society is built upon a healthy electric power infrastructure. This is most apparent when that infrastructure is weakened or disabled, for example, during a major blackout. In fact, an extended blackout would have a crippling effect on the fundamental structure of society. But today, there are ways to strengthen this system and to improve its ability to detect and fight off stress. Modern technology can make it more resistant to the challenges of a twenty-first century society. Today's advances in computers, communications, materials, and chemistry have yet to be applied in an integrated way to this task. As they become integrated, all of society will benefit.

CURRENT AND FUTURE STATES

CURRENT STATE

Transmission

Today's transmission grid was designed with many self-healing features. Auto-reclosing and auto-sectionalizing are common techniques employed to maintain service under adverse conditions. The mesh network design of the transmission system is inherently self-healing due to its built-in redundancy and such protective relaying features as high-speed reclosing and single-phase tripping.

System planners have historically modeled the transmission system to verify that, under a normal system configuration, assumed loads could be met even during expected peak conditions. In addition, planners ensured that these same loads could be met even with the failure of single, and in some cases, multiple lines or components.

Sophisticated protective relaying schemes are in place to monitor system conditions and take corrective action should specific parameters exceed limits. Transmission lines and equipment are relayed out (opened) when conditions require. Most loads normally are not impacted by a single transmission line fault because the system can tolerate such a contingency. Substation automation and new intelligent electronic devices have taken transmission protection to the next level. Some of today's special protection systems and remedial action schemes (SPS/RAS) are obvious precursors of the intelligent agents that will be deployed throughout the grid. Their effectiveness is expected to be improved by frequent tuning from a higher level, as well as through better local analyses.

The design of the current transmission system has actually incorporated the notion of self-healing for many years by implementing new technologies, processes, and techniques as they became available. Significant advances in digital control, protection, and communications technologies, correctly applied, will continue to improve this self-healing capability.

Distribution

At the distribution level, new distribution automation (DA) technologies are being deployed to increase reliability and efficiency. DA applications improve the efficiency of system operations, reconfigure the system after disturbances, improve reliability and power quality, and identify and resolve system problems. Many DA applications can also be extended to coordinate with new customer applications, such as demand response (DR), and distributed energy resources (DER). In addition, distribution systems that include feeder-to-feeder backup allow enhanced DA functionality. These new approaches are directionally consistent with the vision of the self-healing characteristic of the smart grid.

However, from a self-healing perspective, the current distribution system has been limited by a significant lack of distributed resources and intelligent networking capabilities. Today most DA and substation automation (SA) systems are applied at a local level, using local information for decision-making. While the basic design of the integrated transmission grid—many geographically diverse generation sources feeding a high-voltage, switchable, networked transmission system—is conducive to self-healing, the fundamental design of today's distribution systems does not accommodate a comparable depth of self-healing**.**

FUTURE STATE

The self-healing characteristic of the smart grid, at both the transmission and distribution level, will move beyond its current state by integrating enhanced capabilities that include the following features:

Look-Ahead Features

- Analytical computer programs, using many new and timelier system measurements, will identify challenges to the system, both actual and predicted, and take immediate automatic action to prevent or mitigate problems. Where appropriate, and when time allows, these algorithms will also provide options for the system operator to manually address such challenges.
- Probabilistic risk analysis will identify threats to the system under projected normal operating conditions, single failures, double failures, and out-of-service maintenance periods.
- Load forecasting will be greatly improved. These models will cover various time horizons—minutes, hours, and days in support of operations; monthly, quarterly, and annually to support operations and maintenance (O&M) planning activities; and longer range to support investment decisions.
- Fast simulation & modeling (FSM) will enable look-ahead capabilities to anticipate power system disturbances, while continually optimizing grid performance. FSM will:
    - Provide faster-than-real-time simulations to avert previously unforeseen disturbances
    - Perform what-if analysis for large-region power systems
    - Integrate market, policy, and risk analysis into system models, and quantify their effects on system security and reliability.

Monitoring Features

- Numerous intelligent sensors and communication devices will be integrated with power system control. Real-time data acquisition, employing advances in communication technology and new, lower-cost smart sensors, will provide a significantly larger volume and new categories of data, such as wide-area phasor measurement information. This dramatic increase in the volume of real-time data, combined with advanced data processing and visualization techniques, will give system operators a rapid grasp of the power delivery system's health. Advanced metering infrastructure (AMI) systems will provide an additional new source of relevant distribution status information, including loadings, voltage profiles, harmonics, and outage conditions.

- By analyzing equipment condition data, such as high-frequency emission signatures, condition-monitoring technologies will provide additional perspectives on the probability and consequences of potential equipment failures.
- System state estimators will take advantage of advanced measurement and data acquisition technologies and powerful computers will enable them to solve problems in seconds or less. The availability of phasor information will make state estimators faster and more accurate.
- Command and control centers at the regional level for transmission operations, and at more local levels for distribution operations, will serve as hubs for many new self-healing features.

Protection and Control Features

- Advanced relaying will be employed to communicate with central systems and adapt to real-time conditions. Line current differential relaying, enabled by high speed communications between high voltage (HV) stations, will increasingly replace older impedance schemes, providing more secure and reliable protection of transmission lines
- Due to their "uncontrolled" nature, real and reactive power flows are often smaller than can be thermally accommodated, reflecting an underutilization of some transmission paths. Power transfer is governed by line impedance, voltage magnitude, and phase angle difference across a transmission corridor. Improved utilization of transmission lines will be realized through the broad deployment and dispatching of flexible AC transmission systems (FACTS) devices that can control each of these steady state flow parameters.
- High-speed switching, throttling, modulating, and fault-limiting devices will dynamically reconfigure the grid. This will include faster isolation and sectionalization, as well as rapid control of power flows in response to dynamic system challenges.
- Intelligent control devices, such as grid-friendly appliances, will modulate load requirements in response to changing grid conditions.
- Broadband communications between stations and from stations to control centers will allow wider areas to be protected as an integral unit. System integrity protection systems (SIPS), remedial action systems (RAS), and other wide area protection and control (WAPC) concepts will be more widely deployed as integral features of the new transmission smart grid. In particular, extensive phasor monitoring will provide cycle by cycle assessment of the grid's dynamic performance.
- The computing and communication systems of the self-healing grid will employ a multitude of embedded processors scattered throughout the system that will communicate via standardized interfaces. They will employ control cycles that match relevant power system time constants, such as:

- 1-hour cycles that assure adequacy of resources and reveal system bottlenecks;
- 5-minute cycles that manage reliability and efficiency;
- 2-second cycles that implement steady state area controls;
- 100-millisecond cycles that address developing system instabilities; and
- 10-millisecond cycles that trigger intelligent protection actions (load-shedding, generation rejection, system separation).

Distribution Technology Features

- Two-way power flow at the distribution level will be made possible by new communications, protection, and control technology. Two-way power flow is an essential feature of the distributed energy resource applications that help make a distribution circuit more robust.
- Distribution management systems (DMS) having the following features will help operators process and analyze extensive new data streams and develop/implement optimal distribution control strategies:
  - Common enterprise network electrical connectivity model– configuration controlled by the engineering design process and integrated with all other enterprise applications that require an up-to-date model to operate
  - Geographic information system (GIS) – provides the locational dimension of assets and land base information for all users.
  - Supervisory control and data acquisition (SCADA) – provides primary monitoring of distribution assets and associated control infrastructure
  - Outage management system (OMS) – primary application for understanding the extent of outages and supporting the stabilization and recovery of the system from an outage
  - Distribution automation (DA) – analysis and control application that monitors grid operational issues and dispatches controls to operate line sectionalizing equipment to minimize impact of degraded conditions or actual outages.
  - Maintenance applications and programs such as condition based maintenance, asset health monitoring, and maintenance data and records
  - Customer information system (CIS) – application that contains customer specific information
  - Advanced metering infrastructure (AMI) – provides consumer usage information, power detection and remote switching capability
  - Engineering information system (EIS) – contains engineering data, drawings, records
  - Workforce management system – provides work status, location of field personnel, and work related information
  - Distribution planning tools – analysis applications that perform load flow analysis to identify strengths and weaknesses in the distribution system (e.g., predicted future low voltage and overload conditions)
  - Conservation voltage reduction (CVR) – monitors and maintains feeder voltages closer to minimum levels by dynamically adjusting regulators and capacitor banks thereby reducing losses and reducing consumption
  - Advanced network applications - provides functions that achieve optimum network utilization

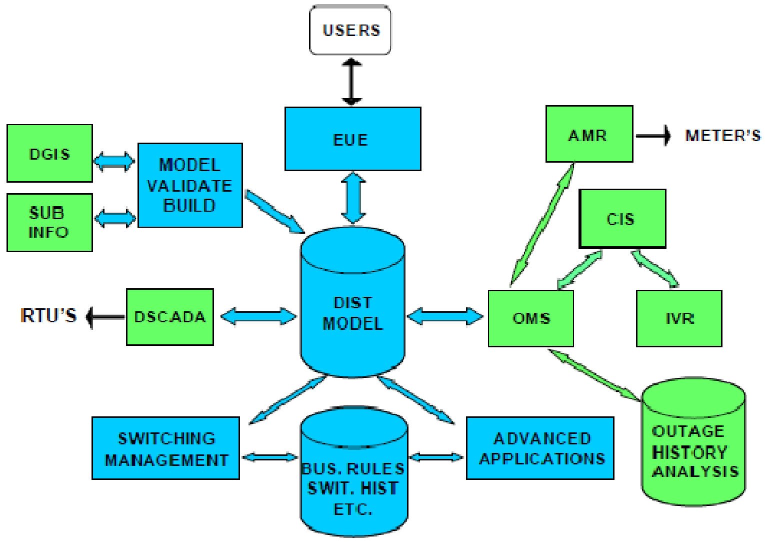

Figure 3: Example of an Integrated Distribution Management System (Source: Southern Company*)*

- The great value of DMS is its capability to integrate and display multiple applications (as in Figure 3) to give operators and other users a complete context of various functions that have been historically separated by utility department processes and technologies (silos).
- Distribution networks will become increasingly dynamic and complex, driven by requirements to integrate renewable energy and stored energy sources, as well as the need to address peak loading issues and the demands of plug-in electric vehicles. A mix of centralized and decentralized intelligence and peer-to-peer networking will be employed to manage this complexity.
- Distributed generation and energy-storage technologies will be widely deployed, particularly at the distribution level, and dispatched as system resources in response to self-healing and other needs. Distributed energy resources (DER) will also support local circuit needs. There exists a large fleet of DER and the smart grid is expected to encourage the deployment of a much greater number in the future. DER provides a significant opportunity for optimizing assets as they are called upon to contribute to the generation mix, support demand response to reduce peak load and improve reliability when the grid needs their support. The microgrid, a local energy network, offers integration of DER with local electric loads. It can operate in parallel with the grid or in an intentional island mode to provide a customized level of high reliability and resilience to grid disturbances. This advanced, integrated distribution system addresses the need for application in locations with electric supply and/or delivery constraints, in remote sites, and for protection of critical loads and economically sensitive developments.
- Transformation of the distribution system from a radial design to an intelligent network design, through the addition of circuit-to-circuit ties, the integration of DER and DR, and the application of advanced communication technology, will create a self-healing infrastructure.

- DR programs will be widely expanded and utilized as system resources to assist in the management of system overloads, voltage issues, and stability issues. DR will also be used to support local circuit needs and to flatten system load curves.
- DA will be further expanded and integrated with widespread DER and DR and, in conjunction with new operating and visualization tools, will enable successful dynamic islanding.
- Critical system components will be “hardened” where appropriate, including redundant designs and in-place spares.

These advances together will create a sophisticated self-healing capability that will dramatically improve overall reliability, efficiency, and safety and will also enhance resistance to a security attack.

REQUIREMENTS

KEY SUCCESS FACTORS

The self-healing principal supports the following key success factors:

Reliability

The predictive nature of the smart grid, coupled with its ability to implement corrective actions in real time, will provide a major improvement in reliability at the transmission, distribution, and consumer levels. The self-healing feature of the smart grid will go beyond the prevention and mitigation of outages. It will also include monitoring of system equipment and consumer portals to identify both unhealthy equipment that requires immediate repair and emerging or actual power quality issues.

Security

The same features of the self-healing grid that enable it to improve reliability also enable it to better resist terrorist attacks and natural disasters.

- Probabilistic analytical tools will identify weaknesses in the smart grid that can then be integrated into an overall security plan.
- Self-healing's intelligent networking, advanced monitoring, DR, and DER features will make the grid far more robust and hence more difficult to attack.
    - The real-time data acquisition capability of the smart grid will immediately detect challenges to its security.
    - The real-time response of high-speed control devices will provide rapid response to attacks.
    - Following security challenges, real-time data acquisition and control will greatly enhance the damage assessment process and significantly reduce restoration times.
- Combined, these smart grid features make the power system a far less attractive target and more resilient in the face of natural disasters.

Economics

The self-healing feature of the smart grid will optimize the economics of all stakeholders:

- System reliability (and power quality) will improve, leading to a substantial reduction in economic losses incurred by businesses and individual consumers when power is lost.
- Generators, transmission owners and operators, and distribution companies will benefit from a reduction in lost revenues that now occurs when the grid experiences high congestion or unplanned outages. Greatly improved restoration times will also provide these stakeholders with economic benefits.

- Consumers will benefit from more efficient energy markets.
- More efficient operation will reduce electrical losses and maintenance costs.

Efficiency and Environmental Friendliness

Much of the same data acquired to support the self-healing feature of the smart grid will also provide valuable information for asset management programs. In addition, the self-healing characteristic supports a range of environmental benefits.

- Equipment failure prediction and prevention will reduce the environmental impact associated with such events as transformer fires and oil spills.
- The self-healing grid will accommodate all forms of generation, including many green technologies that produce zero emissions.
- Electrical losses associated with the generation and transfer of power will be significantly reduced.
- Self-healing will help enable deep penetration of electric vehicles (EV) by providing control and protection capabilities that match EV charging rates to available circuit capacity and by accommodating vehicle to grid supply modes.

Safety

The self-healing feature of the smart grid includes the capability and intelligence that promotes the safety of workers, consumers, and other stakeholders.

- By reducing outages and area blackouts, the associated safety issues are mitigated. Both health and environmental stresses are diminished as emissions are reduced.
- By providing complete status information, unsafe conditions are quickly identified
- By monitoring equipment health, utility personnel will avoid working on energized equipment that is at a high risk of failure.

OBSERVED GAPS

The gap between the current and future states of the self-healing smart grid can be summarized as follows:

- Self-healing in the current transmission system is more advanced than in the distribution system, but opportunities exist to significantly improve both. While individual vendor applications exist for certain self-healing features, no previous initiative has integrated a full complement of T&D technologies to create a fully self-healing power delivery system.

- The cost to develop and implement the needed changes is high. Addressing this cost will require the alignment of all stakeholders, including the federal government, as many benefits of a self-healing grid are societal in nature. Utility savings alone may not justify the investment needed to realize all the societal benefits.

Advances are needed in many technical areas, including:

- Development and deployment of low-cost intelligent electronic devices, including advanced sensors;
- Development and deployment of DER and DR, as well as their integration and use by reliability coordinators;
- Deployment of DA managed by local distribution reliability centers;
- Installation of circuit-to-circuit ties to move the distribution system toward a networked topology;
- Deployment of a ubiquitous communication infrastructure that can support the self-healing feature, as well as the other principal characteristics of a smart grid.
- Development and deployment of new visualization techniques to help operators quickly grasp system risk levels; and
- Development and deployment of new control algorithms and new control devices, particularly those that are based on power electronics, to execute self-healing actions.

Design Concept

The self-healing grid will be based on an advanced communications platform and will employ multiple grid technologies to identify challenges and immediately respond to maintain or restore service.

Probabilistic risk assessments, based on real-time data and contingency analysis tools, will identify equipment and systems that are most at risk. New operator visualization displays will then create a clear understanding of grid capability and levels of risk.

The self-healing grid will employ voltage and flow control; fault current limiting; coordinated distributed generation, storage, and DR; and advanced protection capabilities. Appropriate local and remote devices, running real-time analyses of electrical events, will issue protection and control signals that address emerging problems. Frequently, the short-time interval of such events will require all this to happen without manual intervention.

Design Features and Functions

The features and functions of the self-healing grid, as described in the following section, will be present at all levels of the power system, from generating source to load, including RTOs and distribution utilities.

Probabilistic Risk Assessment

Estimation of system state and real-time contingency analysis results will be available within seconds, producing easily interpreted descriptions of impending risks at the interconnect level, RTO level, and control area level.

Power Stabilization Techniques

New power stabilization software and hardware will be developed to look for the early signs of, and then prevent, a spreading blackout. Phasor monitoring will provide new insight into rapidly emerging instabilities. While alarms will be initiated for human intervention, automation may take mitigating actions as determined by control algorithms. Split-second decisions, such as opening tie lines, changing flow patterns, releasing or absorbing energy or reactive power, or shedding load will be taken before an unstable situation becomes a blackout. New advanced-protection systems based on advanced digital computing and communications will produce improved stability margins.

Additional inter-RTO tie line capacity will maximize needed power transfer capability during emergency conditions. While many tie lines exist today, some require upgrades to higher capacities with the need for more to be built.

Distribution System Self-healing Processes

Distribution circuits will have many isolating elements that communicate with each other and with centralized DMS. By sensing circuit parameters and sharing internal logic, these elements will determine when and where to isolate a fault and restore service to others. This can be done through the closing of optimally selected switches, the injection of distributed generation and energy storage devices, and the management of load levels using DR tools. Further, these same isolating elements will monitor and control voltage and power quality.

User Interface

The self-healing grid comprises many subsystems. Those features and functions dealing with state estimation, probabilistic risk assessment, and major equipment reliability will be accessible to North American Electric Reliability Corp. (NERC), RTO, and control area operators. Distribution centers will have access to distribution information and relevant transmission information. They will also aggregate energy storage, distributed generation, and curtailable load information, and pass these along to the relevant RTO and control areas for bulk power supply applications.

FUNCTIONAL ARCHITECTURE STANDARDIZATION

Standardization of the many functions of the smart grid is essential to allow the benefits of multi-sourcing and interoperability. Figure 4 shows how data can be collected at the substation and used to deliver new self-healing applications involving cascading blackout protection, fast state estimation, real-time problem identification, and power quality analysis.

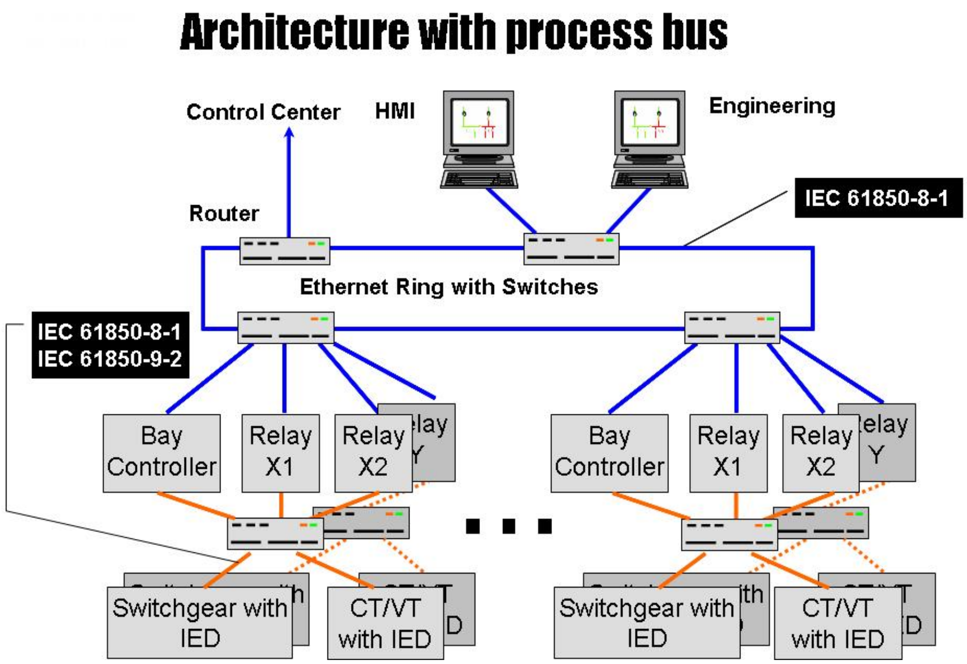

Figure 4: Example Schematic of Substation Data Architecture (printed with permission, C. Brunner, UTINNOVATION LLC)

This collection of smart grid data should satisfy a common information model (CIM) format to absolutely correlate parameters with the equipment they represent. Standardization in use of CIM architecture will enable wide transportability, as well as fast and easy access to results.

Figure 4, shown previously, describes a representative DMS architecture, which is another area in which standardization will be valuable. Other related areas for standardization include microgrids and various forms of distributed energy resources. In addition, standardization of the communications infrastructure and protocols is needed to ensure interchangeability between devices of diverse suppliers. The applicable communication technology can be cost- and location-specific, but each communications channel must satisfy required security, latency, interface and quality criteria.

Reclosers and sectionalizers presently exist on the distribution system to isolate faults. These switching devices can often be retrofitted with standardized communications, data processing, and actuating devices to make them compatible with the smart grid's self-healing requirements.

BARRIERS

Major change usually faces substantial barriers. The smart grid is no exception. This section discusses the barriers to achieving a self-healing grid.

- **Financial Resources**—The business case for a self-healing grid is good, particularly if it includes societal benefits. But regulators will require extensive proof before authorizing major investments based heavily on societal benefits. Also, concerns about rapidly changing technology that may become obsolete within a few years can cause some regulators to hesitate to approve such investments.
- **Government Support**—The industry may not have the financial capacity to fund new technologies without the aid of government programs to provide incentives. Current smart grid funding from the American Recovery and Reinvestment Act of 2009 (ARRA) is a step in a supportive direction.
- **Compatible Equipment**—Some older equipment must be replaced as it cannot be retrofitted to be compatible with the requirements of the self-healing characteristic. This may present a problem for utilities and regulators, since keeping equipment beyond its depreciated life minimizes the capital cost to consumers. Early retirement of equipment may become an issue.
- **Speed of Technology Development**—Specific areas that will need to be accelerated include the following:
    - An integrated, secure, reliable high-speed communications platform;
    - Intelligent electronic devices (both front-end sensors and back-end control devices);
    - Distribution automation schemes to provide distribution-level self-healing capabilities that will accommodate all forms of DER and act as an asset to the transmission system;
    - Cost-effective, environmentally-acceptable DER, including micro grids and energy storage devices capable of existing among residential populations;
    - DR systems using real-time pricing;
    - Advanced transmission protection schemes that provide rapid area-wide response to system threats;
    - Tools to accommodate two-way flow on existing distribution circuits; and
    - Advanced analytical tools.
- **Policy and Regulation**—A new regulatory model should be considered that decouples delivery company profits from sales volume. Instead, a model that rewards achievement of the seven principal characteristics would accelerate smart grid progress, particularly in the area of self-healing.

BENEFITS

A self-healing grid provides benefits to consumers, utilities, employers, government, and society in general.

The following list is representative of the types of gains that can be expected.

- **Improved Reliability**—Self-healing will produce a substantial improvement in grid reliability. The annual cost of power disturbances to the U.S. economy is significant—on the order of $100 billion. The savings from a single massive blackout is estimated to be on the order of $10 billion per event, as described in "Final Report on the Aug.14, 2003, Blackout in the United States and Canada."
- **Improved Security**—A self-healing grid is, almost by definition, the most secure grid. Self-healing decreases the threat of a security attack because energy sources are distributed and self-healing technologies can maintain or restore service during and after attack.
- **Safety**—Increased public safety will be a benefit of the smart grid. The smart grid will quickly locate and de-energize downed wires. Restoring power faster to more people will reduce the impact to "life-support" customers, as well as maintaining HVAC to elder care facilities. Additionally, fewer outages mean fewer opportunities for criminal acts.
- **Quality**—The self-healing grid will detect and correct power quality issues. Power quality issues represent another large annual cost to society, estimated to be in the tens of billions of dollars.
- **Environmental**—The self-healing grid will accommodate multiple green resources, both distributed and centralized, resulting in substantial reductions in emissions. In addition, the environmental impact associated with outages and major equipment failures will be dramatically reduced—and a more efficient grid means lower electrical losses (hence lower emissions).

RECOMMENDATIONS

This section outlines recommendations to help achieve the self-healing characteristic.

- Some of the individual components, hardware, and software already exist for self-healing features to become a reality. The integration of these elements is needed to form a set of true smart grid applications
- Although the self-healing concept could be installed piecemeal, an integration plan is needed to ensure that many of the benefits of a complete system are not lost.
- The self-healing characteristic is enabled by each of the five smart grid key technology areas (KTA), as shown below. Hence, progress must be encouraged in all five. Most essential is the integrated communications (IC) key technology area, which provides the foundation for all self-healing features.

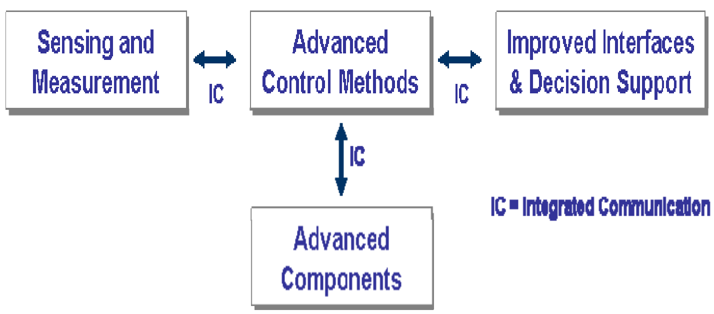

Figure 5: IC (Integrated Communications) Links the KTAs

- Demonstration projects of untested and never-before-integrated technologies are necessary to provide a platform for broader deployment. Currently, a number of such studies are being funded through the AARA. Several DOE-sponsored projects are currently demonstrating self-healing at the distribution level. Additional support at the state and local levels would be valuable.
- Many benefits of a self-healing grid accrue to society in general. The public is the beneficiary whether the benefits are for the environment, national security, safety, or the economy. Legislators and regulators must recognize these public goods so that the utility industry has the incentive and wherewithal to move forward.

SUMMARY

The health of an electric system, like that of the human body, is determined in large part by the strength of its immune system—by its ability to heal itself. In that context, the North American grid's immune system is not especially strong.

Today, there are ways to strengthen this system and to improve its ability to detect and fight off stress. Modern technology can make it more resistant to the challenges of a twenty-first century society. Today's advances in computers, communications, materials, and chemistry have yet to be applied in a meaningful way to this task. That is what can and must be done.

There can be no doubt that a prosperous society is built upon a healthy electric power infrastructure. This is most apparent when that infrastructure is weakened or disabled, as it is during a major blackout. In fact, an extended blackout would have a crippling effect on the fundamental structure of society.

Of course, modernizing the grid infrastructure requires a utility investment of considerable magnitude. But the resultant benefits, when viewed from a societal perspective, will return that investment many fold.

The quest for a self-healing grid will require a coalition of dedicated, knowledgeable people determined to make a difference.

For more information

This document is part of a collection of documents prepared by the Smart Grid Implementation Strategy (SGIS) team. Documents are available for free download from the SGIS website.

http://www.netl.doe.gov/smartgrid/

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