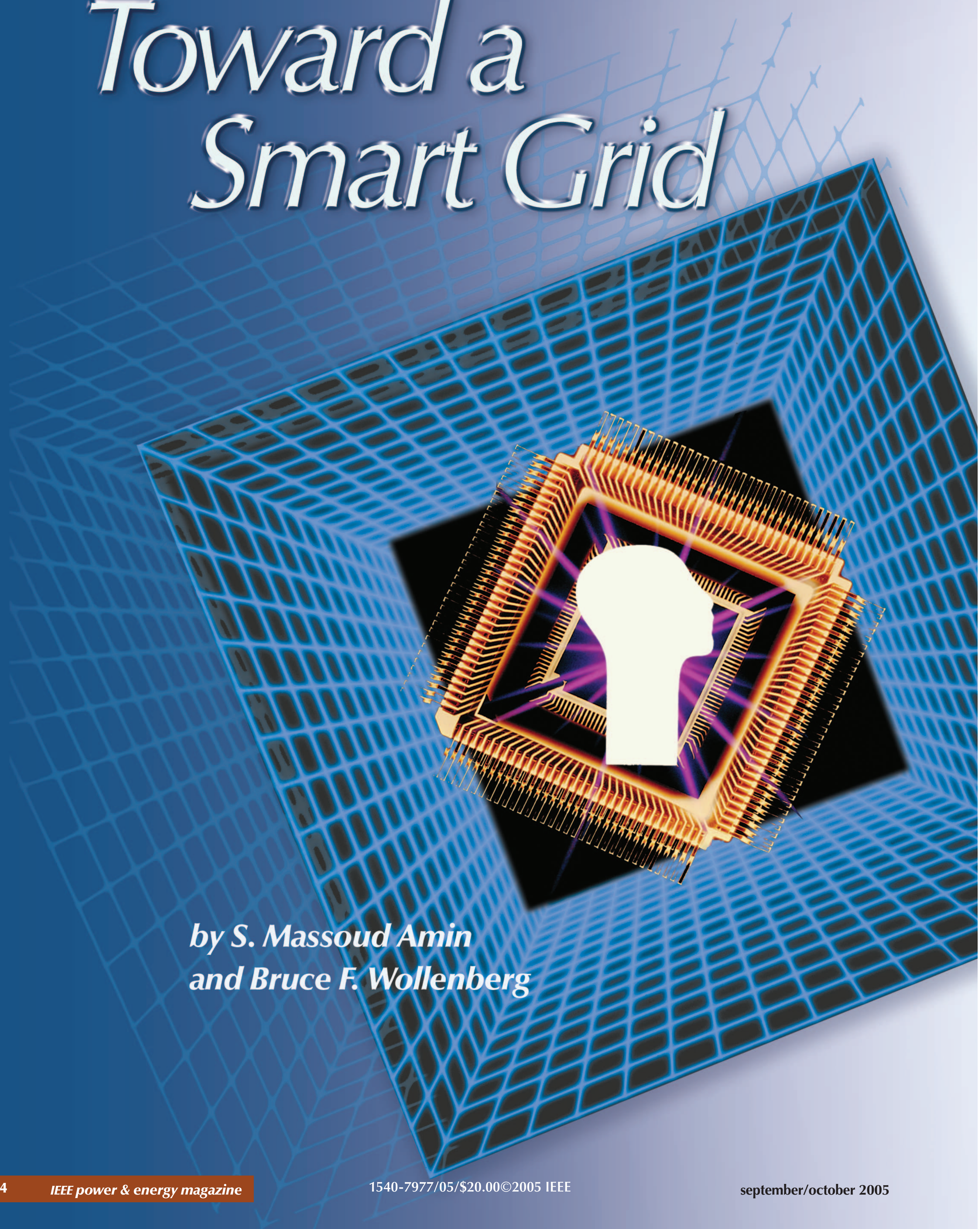
Toward a Smart Grid

by S. Massoud Amin
and Bruce F. Wollenberg



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Power Delivery for the 21st Century

THE NORTH AMERICAN POWER GRID FACES MANY CHALLENGES THAT IT WAS NOT designed and engineered to handle. Congestion and atypical power flows threaten to overwhelm the system while demand increases for higher reliability and better security and protection. The potential ramifications of grid failures have never been greater as transport, communications, finance, and other critical infrastructures depend on secure, reliable electricity supplies for energy and control.

Because modern infrastructure systems are so highly interconnected, a change in conditions at any one location can have immediate impacts over a wide area, and the effect of a local disturbance even can be magnified as it propagates through a network. Large-scale cascade failures can occur almost instantaneously and with consequences in remote regions or seemingly unrelated businesses. On the North American power grid, for example, transmission lines link all electricity generation and distribution on the continent. Wide-area outages in the late 1990s and summer 2003 underscore the grid's vulnerability to cascading effects.

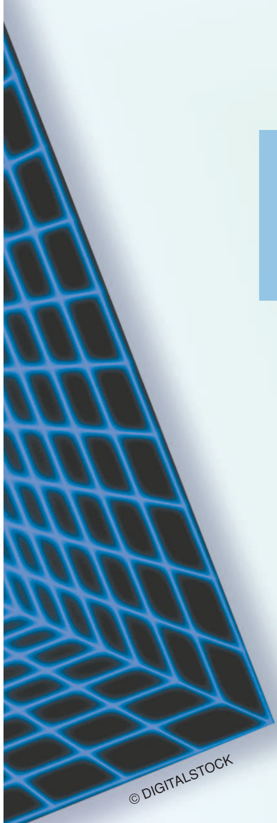
Increased risks due to interdependencies among the critical infrastructures, combined with a purely business focus for service providers, have been recognized, as indicated by Dr. John Marburger, director of the White House Office of Science and Technology Policy, before the House Committee on Science on 24 June 2002.

- ✔ The economy and national security of the United States are becoming increasingly dependent on U.S. and international infrastructures, which themselves are becoming increasingly interdependent.
- ✔ Deregulation and the growth of competition in key infrastructures have eroded spare infrastructure capacity that served as a useful shock absorber.
- ✔ Mergers among infrastructure providers have led to further pressures to reduce spare capacity as management has sought to wring out excess costs.
- ✔ The issue of interdependent and cascading effects among infrastructures has received almost no attention.

Practical methods, tools, and technologies based on advances in the fields of computation, control, and communications are allowing power grids and other infrastructures to locally self-regulate, including automatic reconfiguration in the event of failures, threats, or disturbances.

It is important to note that the key elements and principles of operation for interconnected power systems were established before the 1960s, before the emergence of extensive computer and communication networks. Computation is now heavily used in all levels of the power network: for planning and optimization, fast local control of equipment, and processing of field data. But coordination across the network happens on a slower timescale. Some coordination occurs under computer control, but much of it is still based on telephone calls between system operators at the utility control centers, even—or especially—during emergencies.

In this article, we present the security, agility, and robustness/survivability of a large-scale power delivery infrastructure that faces new threats and unanticipated conditions. By way of background, we present a brief overview of the past work on the challenges faced in online parameter estimation and real-time adaptive control of a damaged F-15 aircraft. This work, in part, provided the inspiration and laid the foundation in the 1990s for the flight testing of a fast parameter estimation/modeling and reconfigurable aircraft control system that allowed the F-15 to become self-healing in the face of damaged equipment.



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Background: The Case of the Missing Wing

In the late 1980s, an Israeli pilot of an F-15 aircraft had a midair collision with his wingman. As a result, the F-15 aircraft lost over 90% of the right wing, losing not only control surfaces but also symmetry, which would typically cause the plane to flip over and crash. Fortunately, in this case, the F-15 pilot managed to successfully land the aircraft using the remaining control surfaces combined with a judicious use of engine thrust.

In the aftermath of this event, the aircraft was put through extensive wind-tunnel flight dynamics and control tests at McDonnell Douglas (now Boeing) in St. Louis, Missouri. Not only was luck on the pilot's side, but he was also an outstandingly capable pilot who accurately sensed the stability manifolds of the aircraft and continually steered the plane back into the stability region quickly and repeatedly via the effective use of the remaining control surfaces and the engine thrust.

During 1985–1998, a research team at Washington University was involved with several pertinent optimization and control projects. This team contributed to the development of a damage-adaptive intelligent flight control system (IFCS) led by NASA and Boeing. The work utilized neural network technology to predict the aircraft parameters and to continuously optimize the control system response. The IFCS was designed to provide consistent handling response to the pilot under normal conditions and during unforeseen damage or failure conditions to the aircraft (Figure 1).

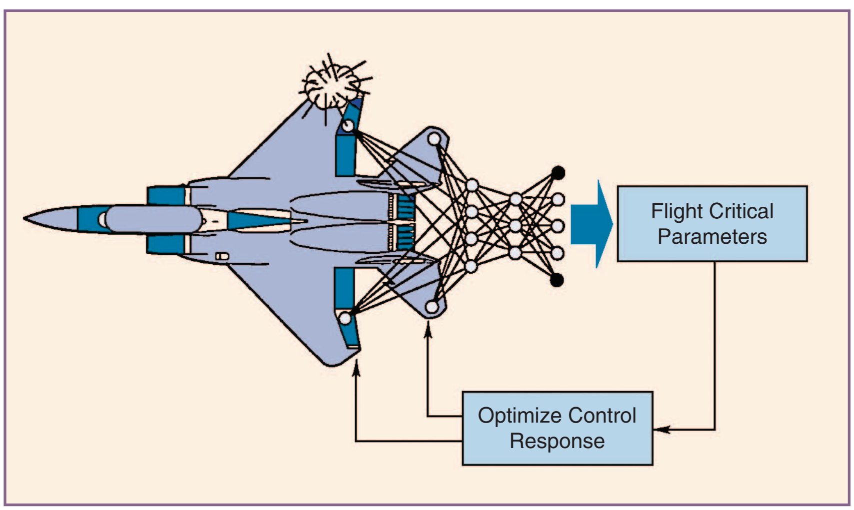

figure 1. The IFCS design goal is to optimize controls to compensate for damage or failure conditions of the aircraft. (Picture courtesy of Boeing and NASA.)

In addition, concepts and simulations for reconfigurable networks were extended to land and air transportation networks, thus enabling more adaptive and resilient operations for the U.S. Department of Defense (DoD). In particular, during 1993–1998, analyses and simulations were developed for the U.S. Transportation Command and Air Force's Air Mobility Command to make their operations more resilient to a broad array of destabilizers. For example, the loss of an airbase, dimished mobility, or fueling/transport capabilities in multiple areas could be sustained without loss or long delays of shipments of critical components.

The IFCS laid the conceptual foundation of a self-healing power system, where analogously a squadron of aircraft can be viewed in the same manner as components of a larger interconnected power delivery infrastructure, a system in which system stability and reliability must be maintained under all conditions, even when one (N–1 contingency) or more (N–k contingencies) components are disabled.

Industry and Government Programs

The work on the F-15 in part provided background for the creation, successful launch, and management of research programs for the electric power industry, including the Electric Power Research Institute (EPRI)/DoD Complex Interactive Networks/Systems Initiative (CIN/SI).

The CIN/SI aimed to develop modeling, simulation, analysis, and synthesis tools for the robust, adaptive, and reconfigurable control of the electric power grid and infrastructures connected to it. In part, this work showed that the grid can be operated close to the limit of stability given adequate situational awareness combined with better communication and controls. A grid operator is similar to a pilot flying the aircraft, monitoring how the system is being affected and how the "environment" is affecting it and having a solid sense of how to steer it in a stable fashion. Given that in recent decades we have reduced the generation and transmission capacity, we are indeed flying closer to the edge of the stability envelope. As a very brief testimonial, the July 2001 issue of *Wired* magazine (http://www.wired.com/

wired/archive/9.07/juice.html) summarized this work as

> The best minds in electricity [research and development] have a plan: Every node in the power network of the future will be awake, responsive, adaptive, price-smart, eco-sensitive, real-time, flexible, humming—and interconnected with everything else.

Further extensions and novel applications of the EPRI/DoD CIN/SI are being pursued by several key organizations, including

- ✔ EPRI's IntelliGrid program (http://www.epri-intelligrid.com/intelligrid/home.jsp)
- ✔ EPRI's Fast Simulation and Modeling (FSM) program
- ✔ the U.S. Department of Energy's GridWise program (http://www.gridwise.org).

In addition, the area of self-healing infrastructure is being considered by the White House's Office of Science and Technology Policy and the U.S. Department of Homeland Security (DHS) as one of three thrust areas for the National Plan for Resesarch and Development in Support of Critical Infrastructure Protection (http://www.dhs.gov./interweb/assetlibrary/ST_2004_NCIP_RD_PlanFINALApr05.pdf). There is even a recently created commercial newsletter on the "smart grid" subject (http://www.smartgridnews.com).

In what follows, we provide our vision and approach to enable a smart, self-healing electric power system that can respond to a broad array of destabilizers.

table 1. A comparison of the protection systems, smart grid, and central control system.

Protection Systems	Smart Grid	SCADA/EMS Central control systems
Local	Fast	SCADA system gathers system status and analog measurements information
Very fast	Distributed	Topology of the power system to determine islands and locate split buses
Few connections to other protection systems	Accurate	Alarms
	Secure	State estimation
	Intelligent	Contingency analysis Security dispatch using optimal power flow (OPF)

How to Make an Electric Power Transmission System Smart

Power transmission systems also suffer from the fact that intelligence is only applied locally by protection systems and by central control through the supervisory control and data acquisition (SCADA) system. In some cases, the central control system is too slow, and the protection systems (by design) are limited to protection of specific components only.

To add intelligence to an electric power transmission system, we need to have independent processors in each component and at each substation and power plant. These processors must have a robust operating system and be able to act as independent agents that can communicate and cooperate with others, forming a large distributed computing platform. Each agent must be connected to sensors associated with its own component or its own substation so that it can assess its own operating conditions and report them to its neighboring agents via the communications paths. Thus, for example, a processor associated with a circuit breaker would have the ability to communicate with sensors built into the breaker and communicate those sensor values using high-bandwidth fiber communications connected to other such processor agents.

We shall use a circuit breaker as an example. We will assume that the circuit breaker has a processor built into it with connections to sensors within the circuit breaker (Figure 2). We also provide communication ports for the processor where the communication paths follow the electrical connection paths. This processor agent now forms the backbone of the smart grid as will be discussed later.

Table 1 compares the smart grid to protection systems and SCADA/energy management system (EMS) central systems. We propose a system that acts very fast (although not always as fast as the protections system), and like the protection system, its agents act independently while communicating with each other. As such, the smart grid is not responsible for removing faulted components, that is still the job of the protection system, but acts to protect the system in times of emergencies in a much faster and more intelligent manner than the central control system.

The Advantages of an Intelligent Processor in Each Component, Substation, and Power Plant

We presently have two kinds of intelligent systems used to protect and operate transmission systems: the protection systems and the SCADA/EMS/independent system operator (ISO) systems. We shall assume for the sake of this article that the protection systems are all digital. Of course, modern SCADA/EMS/ISO systems are all digital systems as well. Again for the sake of this article, we shall use the term *central control* instead of SCADA/EMS/ISO for reasons that will become apparent later.

Modern computer and communications technologies now allow us to think beyond existing protection systems and the central control systems to a fully distributed system that places intelligent devices at each component, substation, and power plant. This distributed system will enable us to build a truly smart grid.

> To add intelligence to an electric power transmission system, we need to have independent processors in each component and at each substation and power plant.

The advantage of this becomes apparent when we see that each component's processor agent has inputs from sensors in the component, thus allowing the agent to be aware of its own state and to communicate it to the other agents within the substation. On a system level, each agent in a substation or power plant knows its own state and can communicate with its neighboring agents in other parts of the power system. Having such independent agents, which know about their own component or substation states through sensor connections, allows the agents to take command of various functions that are not performed by either the protection systems or the central control systems.

Making Power Systems Components Act as Plug-and-Play Interconnects

One of the problems common to the management of central control facilities is the fact that any equipment changes to a substation or power plant must be described and entered manually into the central computer system's database and electrical one-line diagrams. Often, this work is done some time after the equipment is installed, resulting in a permanent set of incorrect data and diagrams in use by the operators. What is needed is the ability to have this information entered automatically when the component is connected to the substation—much as a computer operating system automatically updates itself when a new disk drive or other device is connected.

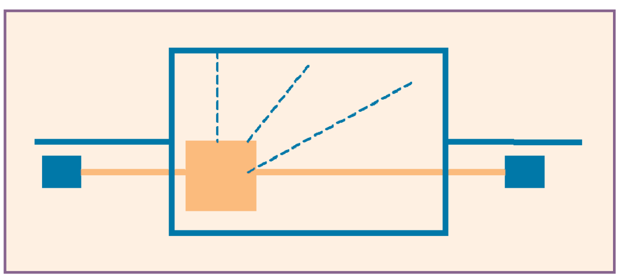

figure 2. Circuit breaker with an internal processor and communication links.

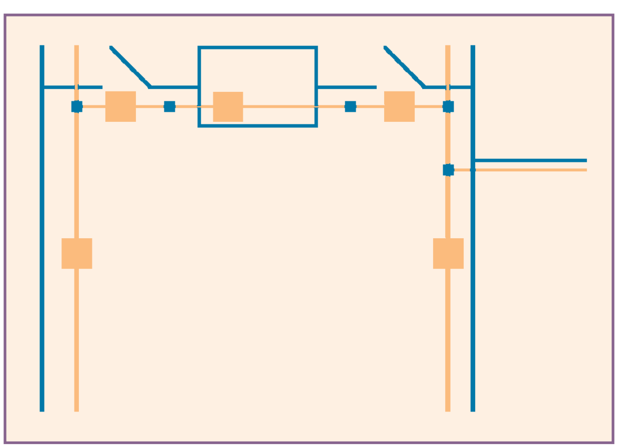

figure 3. Processors are connected by a fiber link.

When a new device is added to a substation, the new device automatically reports data such as device parameters and device interconnects to the central control computers. Therefore, the central control computers get updated data as soon as the component is connected; they do not have to wait until the database is updated by central control personnel.

Figure 3 shows a substation bus-bar pair connected by a set of disconnect switches and a circuit breaker (the component processors are shown in orange). Each processor has communication paths connecting it with processors of the substation component in the same pattern as the electrical connections in the substation.

When a new component is added to the substation it also has a built-in processor. When the new device is connected, the communication path (Figure 4) is connected to the processor of the device it connects to electrically. When the new component's processor and communication path are activated, it can report its parameters and interconnects to the central control system, which can use the information to update its own database.

Diagnostic Monitoring of all Transmission Equipment

Placing the processing of sensor data in a local agent avoids the problem of sending that data to the central computer via the limited-capacity SCADA communications. The means for processing the local sensor data can be designed by the component manufacturer, and the agent then only needs to send appropriate alarms to the central computers. If the component is under such stress that the local agent determines it is in danger of being damaged, it can initiate shutdown through appropriate interconnects to the protections systems associated with the component.

The Electric Power System as a Complex Adaptive System

When the EPRI/DoD CIN/SI was planned in 1997–1998, complex adaptive system (CAS) research was beginning to produce an understanding of the complex overall behavior of natural and human systems.

The electric power grid, made up of many geographically dispersed components, is itself a CAS that can exhibit global change almost instantaneously as a result of local actions. EPRI utilized CAS to develop modeling, simulation, and analysis tools for adaptive and reconfigurable control of the electric power grid.

The underlying concept for the self-healing, distributed control of an electric power system involves treating the individual components as independent intelligent agents, competing and cooperating to achieve global optimization in the context of the whole system's environment. The design includes modeling, computation, sensing, and control. Modeling began with the bulk power market in which artificial agents represent the buyers and sellers of bulk power. Based on this and other projects using evolutionary algorithms, EPRI developed a multiple adaptive agent model of the grid and of the industrial organizations that own parts of it or are connected to it.

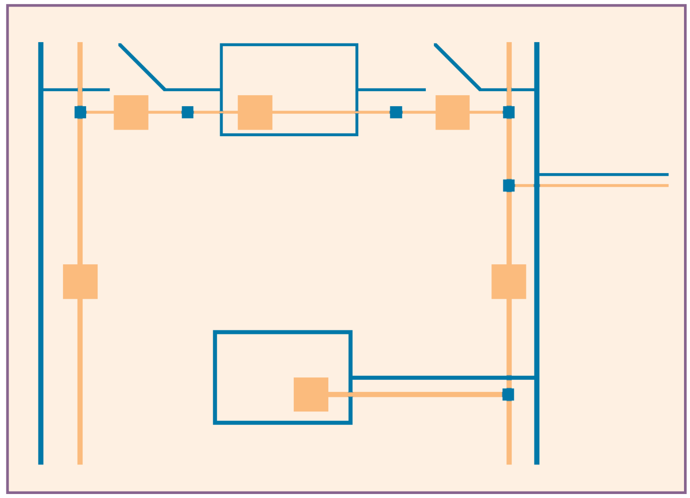

figure 4. The new device is also connected to the information layer.

As presently configured, the Simulator for Electric Power Industry Agents (SEPIA) was a comprehensive, high-fidelity, scenario-free modeling and optimization tool for use by EPRI members to conduct computational experiments in order to gain strategic insights into the electricity marketplace. However, as new sensors and activators become available, this simulation will be expanded to provide the mathematical models and computational methods for real-time, distributed, intelligent control capable of responding locally to disturbances before they affect the global performance of the network. Several pertinent questions arise.

1) *What is an agent?* Agents have evolved in a variety of disciplines, artificial intelligence, robotics, information retrieval, and so on, making it hard to get consensus on what they are.
2) *What types of agents are there?* There are probably as many ways to classify intelligent agents as there are researchers in the field. Some classify agents according to the services they perform. System agents run as parts of operating systems or networks. They do not interact with end users but instead help manage complex distributed computing environments, interpret network events, manage backup and storage devices, detect viruses, and so on.
3) *How do adaptive agents work?* An adaptive agent has a range of reasoning capabilities. It is capable of innovation (developing patterns that are new to it) as opposed to learning from experience (sorting through a set of predetermined patterns to find an optimal response). Adaptive agents can be passive (responding to environmental changes without attempting to change the environment) or active (exerting some influence on its environment to improve its ability to adapt).

Despite the many advances of CIN/SI, the theoretical foundation remains incomplete for full modeling, measurement, and management of the power system and other complex networks. Two pertinent issues for future investigations are

- ✔ why and how to develop controllers for centralized versus decentralized control
- ✔ issues involving adaptive operation and robustness to disturbances that include various types of failures.

A key unresolved issue for complex interactive systems is understanding what control strategy (centralized, decentralized, or hybrid distributed) provides optimum performance, robustness, and security and for what types of systems and under what circumstances.

If distributed sensing and control is organized in coordination with the internal structure existing in a complex infrastructure and the physics specific to the components they control, these agents promise to provide effective local oversight and control without excessive communications, supervision, or initial programming. These agents exist in every local subsystem and perform preprogrammed self-healing

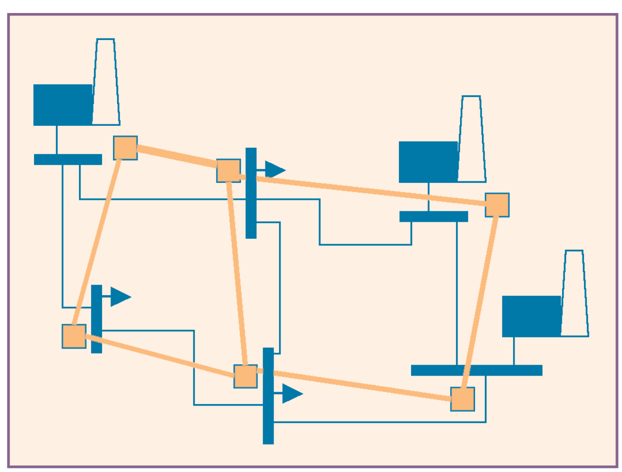

figure 5. A sample system with processors connected by communication links.

On a system level, each agent in a substation or power plant knows its own state and can communicate with its neighboring agents in other parts of the power system.

actions that require an immediate response. Such simple agents already are embedded in many systems today, such as circuit breakers and fuses as well as diagnostic routines.

We are using extensions of this work to develop modeling, simulation, and analysis tools that may eventually make the power grid self-healing; the grid components could actually reconfigure to respond to material failures, threats, or other destabilizers. The first step is to build a multiple adaptive agent model of the grid and of the industrial organizations that own parts of it or are connected to it.

Grid Computing

Grid computing can be described as a world in which computational power is as readily available as electric power and other utilities. According to Irving et al. in "Plug into Grid Computing,"

> Grid computing could offer an inexpensive and efficient means for participants to compete (but also cooperate) in providing reliable, cheap, and sustainable electrical energy supply.

In addition, potential applications for the future power systems include all aspects that involve computation and are connected, such as monitoring and control, market entry and participation, regulation, and planning. Grid computing holds the promise for addressing the design, control, and protection of electric power infrastructure as a CAS.

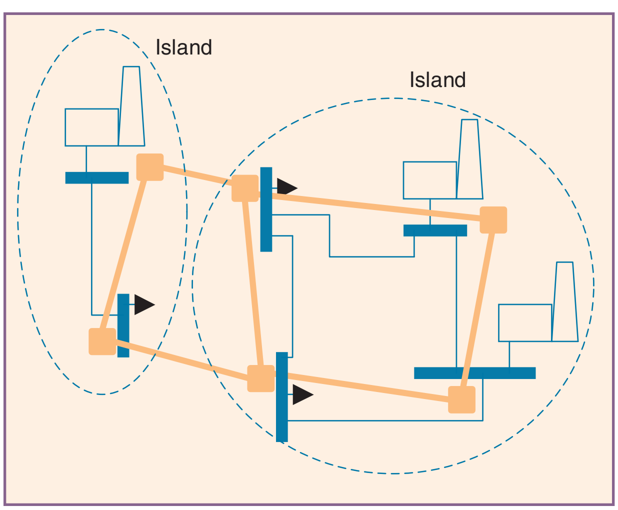

Figure 6. An emergency condition with two islands created by transmission outages.

Making the Power System a Self-Healing Network Using Distributed Computer Agents

A typical sequence seen in large power system blackouts follows these steps:

1) a transmission problem, such as a sudden outage of major lines, occurs
2) further outages of transmission lines due to overloads leave the system islanded
3) frequency declines in an island with a large generation load imbalance
4) generation is taken off line due to frequency error
5) the island blacks out
6) the blackout lasts a long time due to the time needed to get generation back online.

A self-healing grid can arrest this sequence.

In Figure 5 we show three power plants connected to load substations through a set of looped transmission lines. Each plant and each substation will have its own processor (designated by a small red box in the figure). Each plant and substation processor is now interconnected in the same manner as the transmission system itself.

In Figure 6 we impose an emergency on the system; it has lost two transmission connections and is broken into two electrical islands. The processors in each island measure their own frequency and determine that there are load/generation imbalances in each island that must be corrected to prevent being shut down. The processors would have to determine the following:

- ✔ the frequency in each island
- ✔ what constitutes each island
- ✔ what loads and what power plants are connected to each island
- ✔ what is the load versus generation balance in each island
- ✔ what control actions can be made to restore the load/generation balance.

The substation and power plant processors form a distributed computer network that operates independently of the central control system and can analyze the power system state and take emergency control actions in a time frame that cannot be done by central computer systems.

How to effectively sense and control a widely dispersed, globally interconnected system is a serious technological problem. It is even more complex and difficult to control this sort of system for optimal efficiency and maximum benefit to the consumers while still allowing all its business components to compete fairly and freely. A similar need exists for other infrastructures, where future advanced systems are predicated on the near-perfect functioning of today's electricity, communications, transportation, and financial services.

Next Steps

In the coming decades, electricity's share of total energy is expected to continue growing, and more intelligent processes will be introduced into this network. For example, controllers based on power electronics combined with wide-area sensing and management systems have the potential to improve the situational awareness, precision, reliability, and robustness of power systems. It is envisioned that the electric power grid will move from an electromechanically controlled system to an electronically controlled network in the next two decades. However, the electric power infrastructure, faced with deregulation (and interdependencies with other critical infrastructures) and an increased demand for high-quality and reliable electricity, is becoming more and more stressed.

Several specific pertinent "grand challenges" to our power systems, economics, and control community persist, including:

- ✔ the lack of transmission capability (transmission load is projected to grow in the next ten years by 22–25%; the grid, however, is expected to grow less than 4%)
- ✔ grid operation in a competitive market environment (open access created new and heavy, long-distance power transfers for which the grid was not designed)
- ✔ the redefinition of power system planning and operation in the competitive era
- ✔ the determination of the optimum type, mix, and placement of sensing, communication, and control hardware
- ✔ the coordination of centralized and decentralized control.

For Further Reading

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Biographies

S. Massoud Amin is a professor of electrical and computer engineering, directs the Center for the Development of Technological Leadership (CDTL), and holds the H.W. Sweatt Chair in Technological Leadership at the University of Minnesota, Minneapolis. Before joining the University of Minnesota in March 2003, he was with the Electric Power Research Institute (EPRI), where he held positions of increased responsibility (including area manager of infrastructure security, grid operations/planning, markets, risk and policy assessment), developed the foundations of and coined the term *self-healing grid*, and led the development of more than 19 technologies being transferred to industry. After the events of 11 September 2001, he directed all security-related research and development. Before October 2001, he served as manager of mathematics and information science at EPRI, where he led strategic research and development in modeling, simulation, optimization, and adaptive control of national infrastructures for energy, telecommunication, transportation, and finance. Massoud has twice received Chauncey Awards at EPRI, the institute's highest honor. He is a member of the Board on Infrastructure and the Constructed Environment (BICE) at the U.S. National Academy of Engineering. For additional publications, see http://umn.edu/~amin.

Bruce F. Wollenberg is a professor of electrical and computer engineering and the director of graduate studies at the University of Minnesota. He also serves as director for the electrical engineering program of the University of Minnesota Center for Electric Energy. His research has focused on power system engineering and applications of control and optimization techniques to the design of power systems and power system control. His contributions include the development of special computer algorithms to solve and to optimize the operation of power system networks. His recent work is in the development of smart-grid technologies and in the investigation of new deregulated electric power market configurations using mechanism design, of new algorithms to accurately allocate losses and other ancillary service-related quantities to transactions made on a transmission system, and of control systems that use small-area transmission models and network communications to solve large transmission system problems. Bruce is a Fellow of the IEEE, and in 2005, he was elected to the U.S. National Academy of Engineering. For additional information, visit http://www.ece.umn.edu/faculty/wollenberg.html.