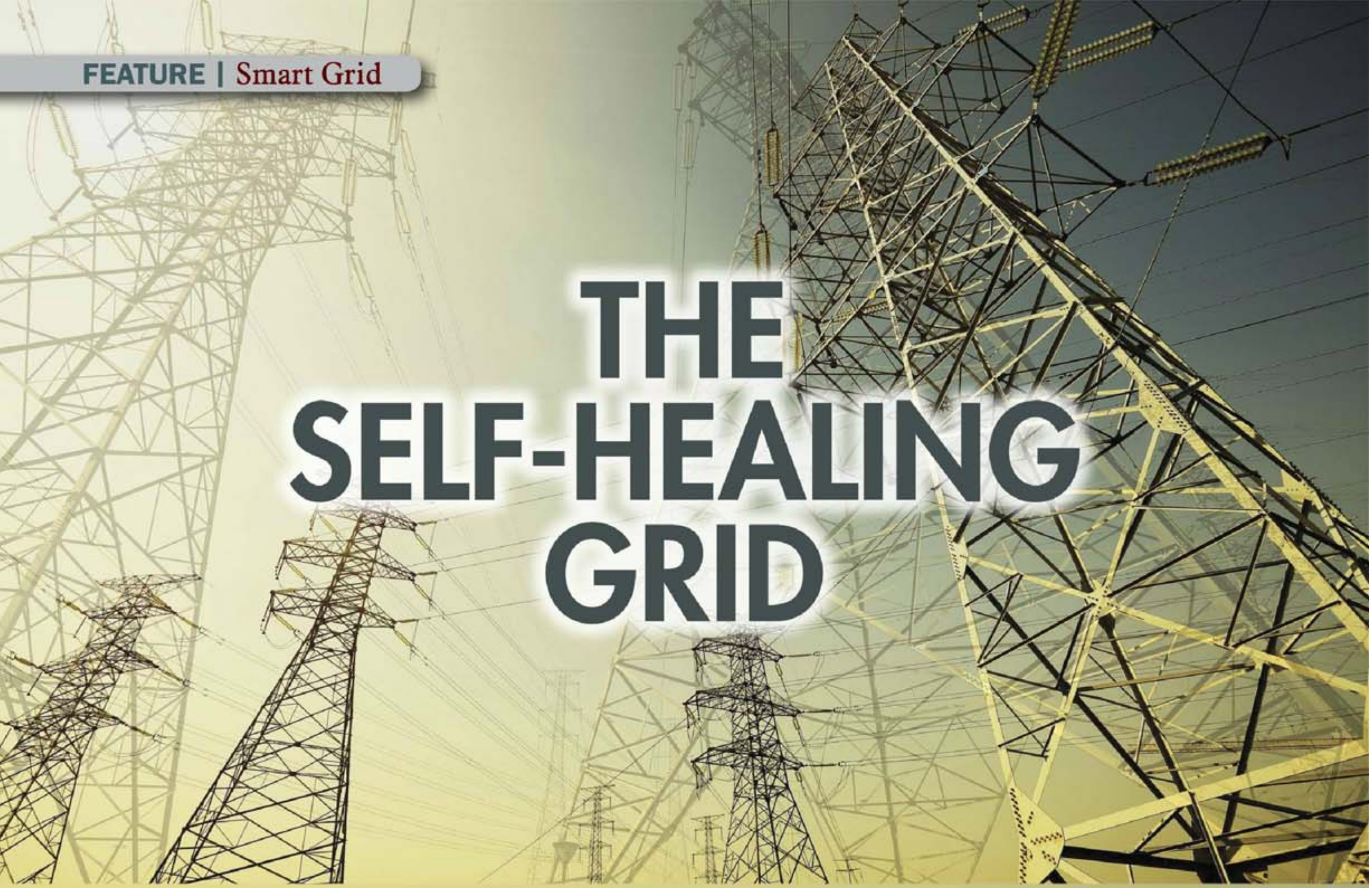


THE SELF-HEALING GRID

What's needed to speed restoration "next time"?

BY MASSOUD AMIN, IEEE Senior Member

In the months since Hurricane Sandy struck the East Coast with unprecedented fury, much discussion has focused on two questions about power restoration in the Northeast: Did the Smart Grid provide assistance or would a Smart Grid solution have helped?

The questions are valid, if vague. And the short answer is unsatisfying: it depends. A longer answer is more helpful because it allows us to consider the drivers of power grid modernization, the concepts governing a "self-healing" grid and what we need to do to maximize the benefits of future investments.

Detailed, post-event analysis will be needed to ascertain whether Smart Grid technology did, in fact, soften Sandy's impact or speed up power restoration. Meanwhile, let's place the storm and its impacts in context.

First, it needs to be understood that a massive, physical assault on the scale of last October's superstorm is bound to overwhelm the power infrastructure, at least temporarily. No amount of money or technology can guarantee uninterrupted electric service under such circumstances.

Second, the power industry in the United States is just beginning to adapt to a wider spectrum of risk. It is noteworthy that both the number and frequency of annual, weather-caused, major outages have increased since the 1950s. Between the 1950s and 1980s, those outages increased from two to five each year. In the period between 2008 and 2012, those outages increased to between 70 and 130 per year. According to a 2011 white paper entitled, *"U.S. Electrical Grid Gets Less Reliable"*, I authored, published by the Institute of Electrical and Electronics Engineers (IEEE), weather-related outages accounted for 66 percent of power disruptions, which affected up to 178 million customers' meters in that five-year period.

178 million

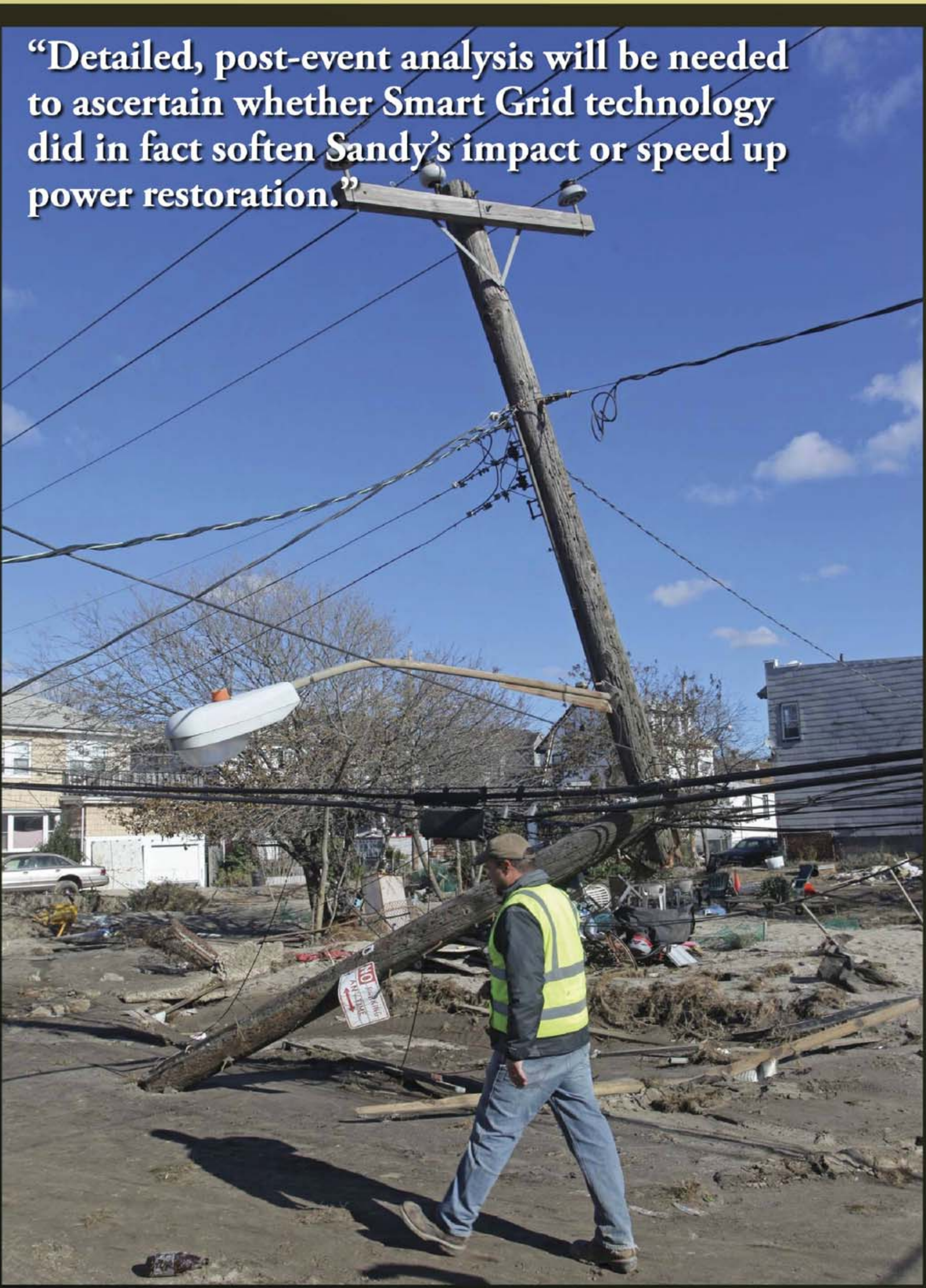
Number of U.S. customers affected by weather-related outages in a five-year period

Source: IEEE white paper, *"U.S. Electrical Grid Gets Less Reliable"*

This adaptation process continues as we implement strategies, technologies and practices that will harden the grid and improve restoration performance after a physical disturbance. The investments so far in advanced metering infrastructure (AMI) and the coming wave of investment in distribution automation are but the beginning of a multi-decade, multi-billion-dollar effort to achieve an end-to-end, intelligent, secure and resilient self-healing system.

Third, cost-effective investments to harden the grid and support resilience will vary by region, by utility, by the legacy equipment involved and even by the function and location of equipment within a utility's service territory.

"Detailed, post-event analysis will be needed to ascertain whether Smart Grid technology did in fact soften Sandy's impact or speed up power restoration."



In Hurricane Sandy's case, coastal areas were subject to storm surges and flooding, while inland, high winds and lashing rain produced the most damage. Improved hardening and resilience for distribution systems in those different environments would take different forms. Underground substations along the coasts may have to be rebuilt on the surface while it might be cost-effective to perform "selective undergrounding" for some overhead lines further inland.

The one generalization we can make, however, is that the pursuit of an intelligent, self-healing grid has some common characteristics that will make the power grid highly reliable in most circumstances—certainly in cases where disruptions are less catastrophic than Hurricane Sandy. Additional, location-specific steps based on rational risk assessment can also be taken by utilities and customers.

The economic benefits of a modernized power grid will accrue as investments are made. Indeed, in my view, our 21st century digital economy depends on us making these investments—regardless of the prognosis for more extreme weather to come as our climate changes.

> **“ If the U.S. is to remain economically competitive on a global scale, it must modernize its power grid. ”**

WHAT'S THE PROBLEM?

It's fair to ask: why should we make significant, ongoing investments in upgrading the electric grid?

Hurricane Sandy's widespread damage and the resulting, extended outages certainly put a fine point on the answer, but the context is much broader than investing to withstand the occasional, if horrific, superstorm. Simply put, the U.S. must modernize its power grid just as other nations are doing in order to remain economically competitive on a global scale.

Currently, outages from all sources cost the U.S. economy somewhere between $80 billion to $188 billion annually, according to the Electric Power Research Institute and the Lawrence Berkeley National Laboratory. A 2011 competitiveness report by the World Economic Forum ranked U.S. infrastructure below 20th among the world's nations in most of nine categories and below 30th for the quality of our air transport and electric power sectors. Clearly, the U.S. needs to invest in grid modernization simply to catch-up with its global rivals.

> **“ This smarter grid would increase the system's efficiency by about 4.5 percent which is worth another $20.4 billion. ”**

THE VALUE PROPOSITION

Because of the fundamental importance of the mission and the costs involved, we have to take a critical approach to the enormous investments needed to improve reliability and resiliency and enable economic competitiveness. One metric is "payback", or return on investment (ROI).

Having studied this in-depth, I and others who work at EPRI have calculated that each one dollar invested garners a return of $2.80 to six dollars to the broader economy. Some of our findings were published in the article *"EPRI Ups Estimates of Smart Grid's Investment Benefits"* in the IEEE Smart Grid Newsletter. The return on investment begins immediately with job creation and economic stimulus. To reach these numbers we used a very narrow definition of "Smart Grid". If the definition is broadened, the benefits increase.

A smarter, stronger grid would reduce the low-end estimate of current outage costs—$80 billion annually—by $49 billion, in my estimates. This smarter grid would increase the system's efficiency by about 4.5 percent which is worth another $20.4 billion, annually. Together, improving just those two aspects—reducing outages, improving efficiency—brings about $70 billion in annual benefits. According to a 2011 report published by the Pacific Northwest National Laboratory, a smarter grid would also reduce carbon dioxide (CO2) emissions by 12 to 18 percent.

To accomplish this, cost estimates for the U.S. as a whole range somewhere between $338 billion and $476 billion for a smarter grid and about $82 billion in hardening costs for a stronger grid. So when you recast it as a 20-year project, it's going to cost the U.S. somewhere between $25 billion to $30 billion a year for 20 years.

Much of the early work has been done in the past few years as federal stimulus funding encouraged advanced metering infrastructure (AMI). AMI has introduced end-of-line sensors (also known as smart meters) that can communicate price signals and demand response actions that can serve to balance supply and demand and provide "last gasps" that automatically indicate when power has failed at the customer's premise.

The coming wave of distribution automation is adding distributed intelligence, intelligent electronic devices and enabling improved fault detection, isolation and restoration as distribution management systems and outage management systems are integrated. But we need to follow this initial effort with serious levels of annual investment for decades to meet 21st century economic and environmental challenges.

> **“ A stronger grid would reduce the low-end estimate of current outage costs—$80 billion annually—by $49 billion. ”**

THE 'SELF-HEALING' POWER GRID

The term "Smart Grid" isn't very precise. I prefer smart "self-healing" grid, because it more precisely describes the desired outcome of the investments I advocate for grid modernization. The pursuit of a self-healing grid brings a number of benefits through stability and adaptation.

Three elements come into play here. First, real-time monitoring can alert grid operators to the precursors or signatures of impending faults based on probabilistic analysis. Real-time monitoring has been enabled by a leap from traditional SCADA (supervisory control and data acquisition) systems to phasor measurement units (PMUs), also known as synchrophasors. This technology improves the resolution of data polled from field devices from two to four times per second with SCADA to 20 to 50 times per second with PMUs. PMUs also provide precise, GPS-based time stamping so that events on the system can be analyzed accurately and chronologically in a wide-area management system, or WAMS. This allows operators to see "how the dominoes fell in the dark".

Second, real-time monitoring enables operators to react swiftly to restore balance to the system or to program field devices to respond automatically. This allows constant tuning of the grid's many components to achieve an optimal, highly efficient state.

The third functionality of the self-healing grid is rapid isolation. This allows the system to automatically isolate parts of the system that are failing or about to fail from the rest of the system to avoid

“Extreme events, like Hurricane Sandy, will occur with greater frequency so new tools and approaches to system upgrades are required.”

the spread of disruption and to enable more rapid restoration. See "*Rapid Isolation, By the Millisecond*" on page 46.

As a result of these three functions, the self-healing Smart Grid is able to reduce the number of outages and their duration. And because all three functions are self-healing in nature, they add an end-to-end resilience to the grid that can detect and override human errors that can result in power outages.

END-TO-END TECHNOLOGIES

An end-to-end system that anticipates problems, supports operator decisions or reacts automatically has a few elements worthy of emphasis.

At the customer end are the interval meters that provide usage data, serve as end-of-line sensors for voltage conservation and emit "last gasps" as they—and the customer—lose power. Upstream of the meters, but downstream of the operators, we'll see a proliferation of advanced sensors (intelligent electronic devices, or IEDs) that facilitate real-time monitoring and control of critical assets. Advanced protective relays, for instance, provide improved isolation of faults. All of the technologies discussed in this feature are supported by two-way communication networks that bring the real-time monitoring data back to operators and allow the latter to send commands back to assets in the field. Finally, visualization tools such as dashboards convert data into color-coded graphics and automated alerts that provide decision support.

THREE-TIERED INTELLIGENCE

The self-healing grid can be thought of as having three tiers of intelligence. The bottom layer, closest to devices in the field, is distributed intelligence. It is akin to the reptilian brain with simple responses to environmental stimuli. At a substation, for instance, an intelligent device monitors the health of the asset and communicates that to the middle layer where the validation of incoming data and coordination of various functions takes place in milliseconds. This is somewhat akin to a mammalian neocortex that can strategize, act and be upgraded through experience to higher functionality. The top layer contains the centralized command-and-control functions directed by human operators.

RISK ASSESSMENT

The initial step, before implementing these strategies and technologies, is a risk assessment. Risk is dynamic, local and specific. National policies will help, but achieving hardening and resiliency on the ground will be specific to a utility's customers' needs, its legacy systems, location and technology roadmap.

A dynamic risk landscape requires annual updating to ensure protection of the right assets. How has the risk portfolio or the spectrum of risk changed? With climate change, the variability of weather events has increased. We are going to see more and more extreme events that have never happened before and we'll see them with greater frequency. Hurricane Sandy appears to be an example of this challenge.

So a clear sense of dynamic risk should guide our investments in hardening and resilience based on evidence and data. We need a new set of tools and a fresh set of approaches to system upgrades in order to be more dynamic and more adaptive to achieve resiliency and security.

BACK TO THE 'BIG PICTURE'

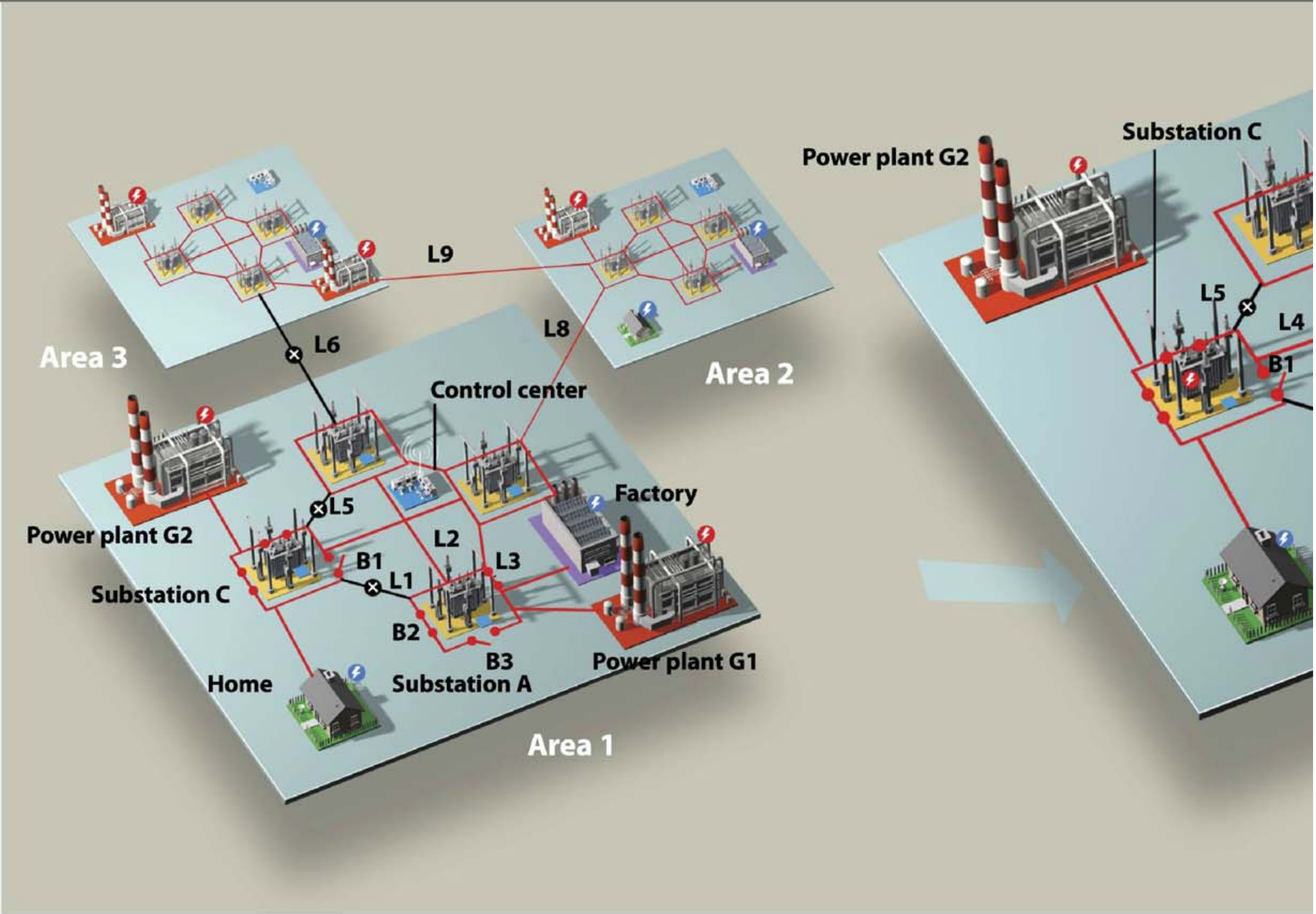
When the U.S. has made such strategic commitments in the past, the payoffs have been huge. Think of the interstate highway system, the lunar landing project and the internet. Meeting each of those challenges has produced world-leading economic growth by enabling commerce, technology development and a mix of the two. In the process, we developed a highly trained, adaptive workforce.

Similarly, given the economic, societal and quality-of-life challenges and the ever-increasing interdependencies among infrastructures we have today, we must decide whether to build electric power and energy infrastructures that support a 21st century's digital society or be left behind as a 20th century industrial relic. ET

Massoud Amin is an IEEE senior member, an ASME fellow, director of the University of Minnesota's Technological Leadership Institute and a professor of electrical and computer engineering.

Rapid isolation is a functionality of the self-healing grid. This allows the system to automatically isolate parts of the system that are failing or about to fail from the rest of the system to avoid the spread of disruption and to enable more rapid restoration. The schematic on page 46 illustrates the moment-by-moment sequence of events in a hypothetical scenario in which rapid isolation takes place.

RAPID ISOLATION, BY THE MILLISECOND



Three functionalities of a self-healing grid will be effective in anticipating, recognizing and limiting damage to the system. Real-time monitoring, enabled by synchrophasors, provides two of those functionalities, in that it can recognize the signature of disturbances and allow operators to take steps in real-time to balance the system. The third and, arguably, the most important functionality is rapid isolation, which enables the system to automatically isolate impending or actual failures from the rest of the grid to limit disruption and speed restoration.

This schematic illustrates the moment-by-moment sequence of events in a hypothetical scenario in which rapid isolation takes place. Note that the term "rapid isolation" covers a number of seemingly disparate actions. As circuit breakers isolate the fault, a number of possible, unintended consequences can nudge the system off balance via voltage oscillation. The response may require actions by both the intelligent, self-healing grid and human operators, as one or the other throttles generation slightly up or down as well as curtailing load on the affected lines. The result, in this hypothetical scenario, is the identification and isolation of the fault, which under traditional conditions, would have cascaded, taken down power to a larger swath of customers and, possibly, damaged substation equipment.

– Massoud Amin, IEEE

RAPID RESPONSE

0.04 second later

A loss of power in L5 and L6 leads to a fault in line L1. Computers signal to circuit breakers B1 and B2 to open, isolating the fault, but B2 fails, remaining closed.

0.1 second

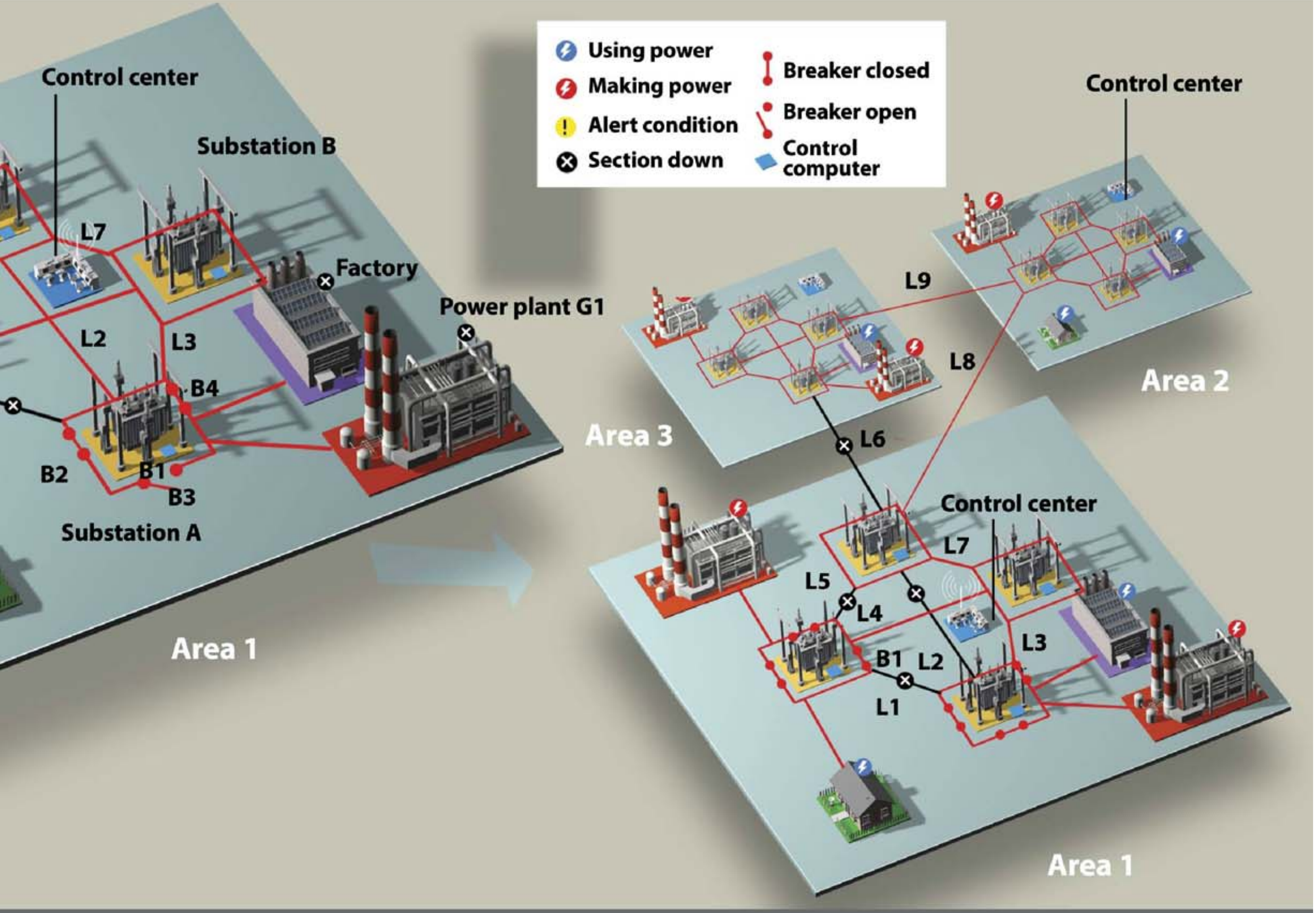
Power generation at G1 automatically responds, ramping up to compensate for the loss of G2, in turn caused by trouble on lines L5 and L1. G1 also ramps to balance line voltage throughout Area 1 at 60 hertz (cycles per second).

0.4 second

A computer simulator at substation A signals breaker B3 to open to protect the substation from a surge of current. B3 successfully opens; line L2 shuts down. G1 compensates by further ramping.

0.5 second

Generator G1 is shut off by the control center to prevent excess ramping and resulting damage.



RAPID DECISIONS

0.6 second

Substation B's computer ordinarily would shut down line L3 to shed load if generator G1 went offline. Instead, because shutting down G1 was the result of deliberate action, Area 1's computers communicate with each other and then drop the load of a large factory, balancing supply and load and maintaining more critical loads including hospitals and streetlights.

10 seconds

In a matter of seconds, the computer in substation B senses significant voltage oscillations that are great enough to cause damage to equipment on lines L3, L4 and L7. Traditional protocols would suggest shutting down lines L3, L4 and L7. In the new paradigm, however, area computers switch generator G2 to manual control and operators at the Area 1 control center are advised to ramp generation and/or cut load to achieve balance.

RETURN TO TYPICAL OPERATIONS

60 seconds

Lines L3, L4 and L7 remain in service. L4, however, is overloaded. Operators at the control center use satellite-based communications to reach Area 2 control center operators for assistance. Area 2 operators route power over line L8. And they command their sector's control computers to incrementally modify power flows to compensate for the power exported suddenly over L8. Meanwhile, field crews repair damage to lines L5 and L6, allowing computers to bring L1 and power plant G1 back online. Power flows in all three areas return to normal.

Photo credit (self healing grid): Don Foley

SUPPORTING LOCAL DISTRIBUTION SYSTEMS

Resiliency aided by distributed generation, energy storage and microgrids

In the short run, for support of local distribution systems—such as a priori preventive preparations for a disaster or during an *in situ* emergency response and recovery from natural disasters like Hurricane Sandy—technologies at the distribution system's "edge", under end-users' control, may provide uninterrupted power to utility customers when the grid itself is down thus technologies such as distributed generation, energy storage and microgrids shift the centralized power paradigm by providing a level of increased self-sufficiency among end-users.

In the longer run, fluctuations in electricity demand itself—perhaps at times of peak load, but also in a grid-based system with a dynamic interplay of supply-and-demand—may be met by "edge" technologies such as distributed generation, energy storage and microgrids. For these technologies to provide benefits, utilities will need to provide a flexible, digital architecture and infrastructure that enables such a dynamically smart, adaptive and resilient system with two-way power flows.

CUSTOMER DEMAND

Customer demand—not further regulation, policies or subsidies—must drive the market for distributed generation, energy storage and microgrids. Consumer demand, in turn, will be driven by heightened interest in energy efficiency, greater electricity demand for a digital economy and increased awareness of the cost of service interruptions.

Indeed, according to a November 2012 global survey of power executives (sponsored by the IEEE Smart Grid, conducted by Zpryme Research and Consulting, LLC), power utilities around the world expect consumer demand to rise for technologies that aid efficiency, meet demand and lower the frequency and duration of outages, leading utilities and grid operators to incorporate or, at least, enable the aforementioned three technologies.

GROWTH AND SUCCESS

The cited study found that consumer market-driven innovation will lead to a high-growth phase for these three technologies. Thus, according to the study, manufacturers must, in turn, "closely integrate customer feedback into their R&D (research and development) roadmaps". The overall success of the market for these technologies will require improved coordination of stakeholder efforts on standards, R&D and funding to drive down costs and broaden the market.

Related, enabling technologies for distributed generation, energy storage and microgrids include energy management systems, distributed energy management systems and communication technologies. Future distributed energy systems must be able to interact across both centralized and decentralized electrical networks supporting advanced grid services (net metering, load aggregation and real-time energy monitoring, for example) that often will be delivered in the cloud.

CHANGING NETWORK LAYERS

Utilities should be aware that network-layer change underscores the wisdom of investment in a future-proof architecture and communications network that can handle not only the defined goals of the present and near-term future, but also the undefined but evolving needs of a dynamic digital future.

A well-informed design and resilient, integrated IP-based secure network foundation will enable utilities to choose from best-of-breed solutions as they emerge thus adapting the network to new purposes and functionality and consistently driving costs down by leveraging information in new ways for increased customer-centered services. ET

- *Massoud Amin, IEEE Senior Member*

This article is based on a survey sponsored by the IEEE Smart Grid and conducted by Zpryme Research and Consulting, LLC entitled, "Power Systems Of The Future: The Case For Energy Storage, Distributed Generation, and Microgrids" which can be downloaded for free.