Vision for a self-healing power grid

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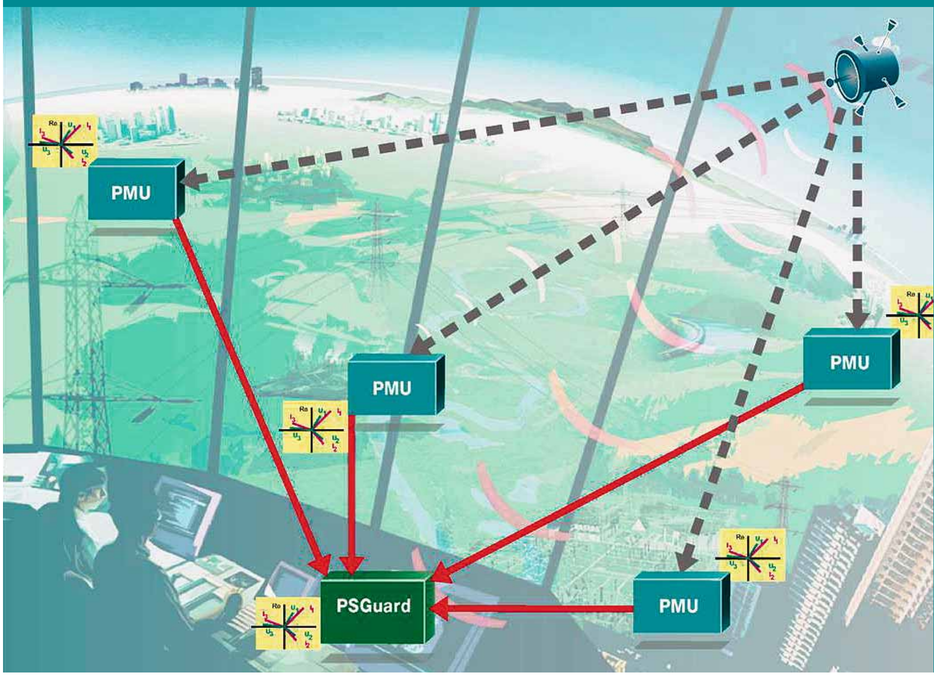


Power system reliability has been thrust into the limelight by recent blackouts around the world. The social and economic costs of these failures can add up to billions of dollars every year. As the digital age prevails, more efficient manufacturing processes, based on computers and power electronics, have come to dominate industry. As the portion of electricity in the total energy consumption continues to grow, the value of power system reliability increases. This article discusses a vision for state-of-the-art solutions to improve power system reliability through improved monitoring and control.

The likelihood of blackouts has been increasing because of various physical and economic factors. These include (1) the demand for larger power transfers over longer distances, (2) insufficient investment in the transmission system, exacerbated by continued load growth, (3) huge swings in power flow patterns from one day to the next that render classic off-line planning studies ineffective, and (4) the consolidation of operating entities. These factors result in larger operational footprints and greater demands on the operator to deal with smaller error margins and shorter decision times. These circumstances have created a less reliable operating environment by pushing power systems close to their physical limits. Such an environment requires more intensive on-line analyses to better coordinate controls across the entire grid. Wide-area monitoring and control tools, eg, Phasor Measurement Units (PMU) and Flexible AC Transmission System (FACTS) devices, and distributed generation and storage devices are the primary technologies used to address such problems. The role of FACTS devices in measures to counter blackouts is described in [1].

ABB is a leading provider of such innovative and field-proven products and services to the utility industry. This article presents the results of an investigation by the authors (supported by the EPRI IntelliGrid consortium) into the requirements for the next generation of power system monitoring and control technologies. The evolution of these technologies is envisioned to lead to the realization of self-healing power grids. A self-healing grid is expected to respond to threats, material failures, and other destabilizing influences by preventing or containing the spread of disturbances [2]. This requires the following capabilities:

- Timely recognition of impending problems
- Redeployment of resources to minimize adverse impacts
- A fast and coordinated response to evolving disturbances
- Minimization of loss of service under any circumstances
- Minimization of time to reconfigure and restore service

In order to realize a self-healing grid, a high performance IT infrastructure will be needed to address gaps in the geographical and temporal coordination of power system monitoring and control. Current practices require considerable improvements at various hierarchical levels, including substations, control areas, regions and the grid. Temporal coordination will require improvements in adapting the faster and often local controls to the slower global controls.

ABB has developed the functional and architectural specifications of the IT infrastructure necessary for supporting a self-healing grid. This work included an assessment of its technical and financial feasibility [3, 4]. The remainder of this article comprises a brief overview of the results of the work.

Infrastructure for a self-healing grid

To attain a self-healing grid, it is essential to address a comprehensive set of operating concerns (in normal and abnormal conditions) that are associated with performance enhancement, adequacy of resources (market procurements, etc), and equipment and system operating limits (stability, sustained oscillations etc), as well as primary and back-up protection of systems and components.

ABB has developed the functional and architectural specifications of the IT infrastructure necessary for supporting a self-healing grid.

Existing on-line analytical capabilities are envisioned to continue playing their respective parts in the proposed infrastructure to address operating concerns. In addition, current off-line capabilities (eg, forecasting, dynamic analysis, transmission capability analysis) will migrate into the on-line environment. The details of their implementation will differ, as will the interdependencies in each of the functional areas of data acquisition and maintenance, monitoring, performance enhancement, and control actions. These functional areas have to provide non-stop service in terms of

- Providing situational awareness throughout the grid
- Predicting, preventing and containing problems
- Enforcing operational plans and required margins
- Supporting system restoration

These capabilities require the use of on-line decision support tools with intensive computational and communication requirements. The envisioned infrastructure calls for a distributed system in which the locations of hardware, software and data are transparent to the user. This enables autonomous intelligent agents distributed throughout the system to realize the required functions and to support local, global and/or cooperative processes through timely and effective information access throughout the system.

Architecture

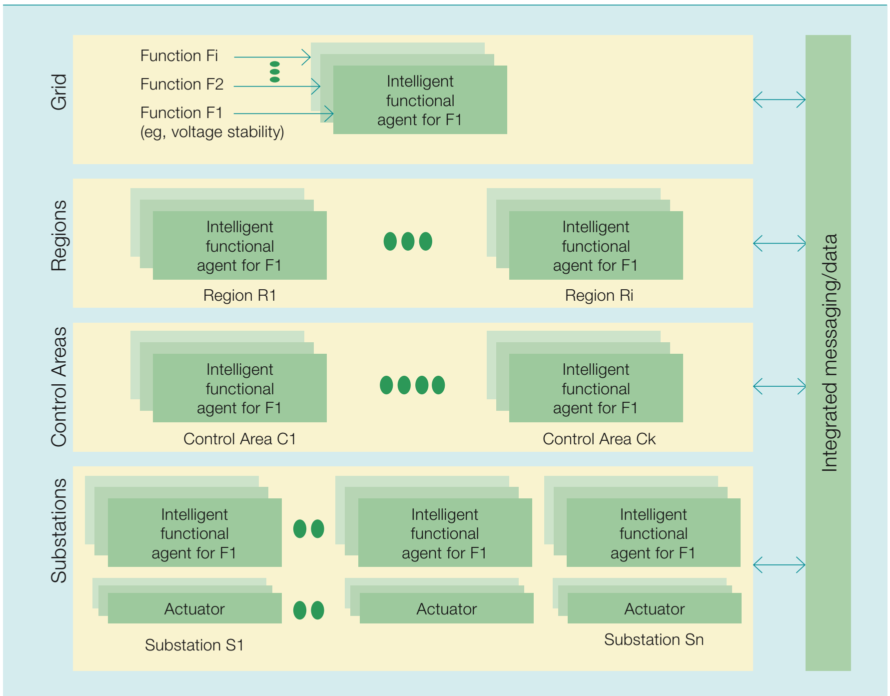
The IT infrastructure 1 must be modular, flexible, and scalable to meet global operational needs and to allow for evolutionary implementation on a continental scale.

The computing and communication systems of the infrastructure support a large number of computers and embedded processors scattered throughout the system. These must communicate with each other through networks with standardized interfaces that use message-oriented middleware and web services. The network would be dedicated to local and global data exchanges and decision processes using distributed databases that are integrated through open interfaces. The system would be constructed of plug-and-play hardware and software components.

The infrastructure supports a complex of software applications, including autonomous intelligent agents distributed throughout the system in a virtual hierarchy. They adapt to events and environments, and act both competitively and cooperatively for the good of the entire system. They can improve control performance by responding to problems faster than a human operator [5]. Thus the system supports more intelligence at all levels, especially at lower levels such as substations, to provide timely and accurate control responses.

The agents are distributed in a three-dimensional system to take into ac-

1 Infrastructure for distributed autonomous intelligent agents



count the geographical distribution and control hierarchy of the power system, as well as the diversity of functional areas. Various users and software components at different locations access and maintain the data (static and dynamic) that is distributed across the system in virtual relational databases.

Determining the degree of autonomy at each level, and the protocols for resolving conflicts between the levels, can be a major design challenge. Generally, the software at the higher-level needs to consider data for a larger portion of the power system. The software at the lower level can provide timely feedback and quick responses to local information, according to the most recent directives from the higher levels.

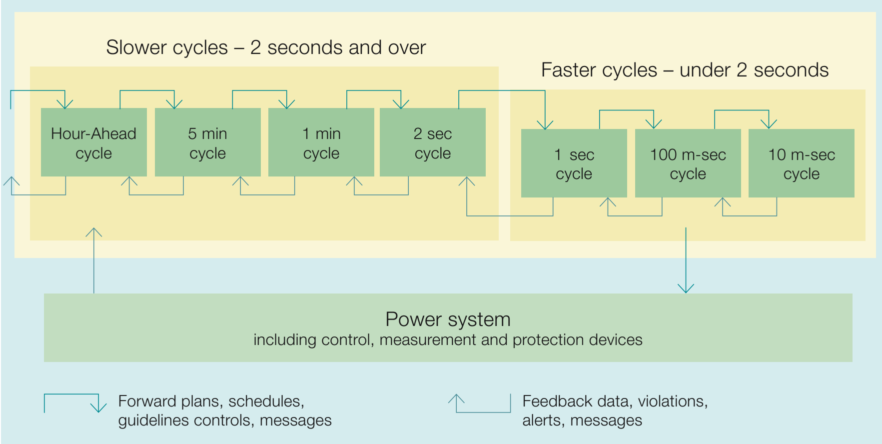
Each cycle can be tailored to the required control response times, computational burden, and historical practices.

Some existing Special Protection Systems and Remedial Action Schemes (SPS/RAS) may be seen as precursors of intelligent agents. Their effectiveness is expected to be improved by frequent tuning from a higher-level, as well as through better local analyses.

Coordination of tasks via execution cycles

There is also a temporal dimension in which the various agent tasks can be distributed, based on the time-scales of the relevant physical phenomena in the power system. This temporal coordination can be accomplished via several execution cycles. (An execution cycle refers to a set of related tasks executed in a temporally coordinated manner.) The execution cycles and their periods are defined according to operating needs and engineering judgment. Each cycle can be tailored to the required control response times, computational burden, and historical practices. The specific periods

2 Organization and interactions of execution cycles



Factbox Execution cycles for temporal coordination

Cycle	Purpose
1-hour-ahead	■ Assure adequacy of resources ■ Identify system bottlenecks
5-minute	■ Assure reliability, efficiency ■ Update control parameters and limits ■ Look-ahead (about 10 to 20 minutes) ■ Alert system operator and/or hour-ahead cycle
1-minute	■ Maintain efficiency and reliability, as per the 5-minute cycle. ■ Adapt the more recent models
2-second	■ Collect/validate data for use by control area or interconnection including data acquired in the 10-millisecond cycle (PMUs). ■ Perform closed loop controls (Area Generation Control, etc.) ■ Adapt control parameters and limits for faster cycles
1-second	■ Control extended transients (secondary voltage control, etc.). ■ Adapt control parameters and limits for faster cycles
100-millisecond	■ Control imminent system instabilities including execution of intelligent Special Protection Schemes (iSPS) based on adaptive models or criteria identified by slower cycles.
10-millisecond	■ Perform faster intelligent protection actions (load shedding, generation rejection, system separation)

Autonomous intelligent agents

In computer science, a software agent acts “on behalf of” a user or a program in a relationship of agency with the authority to decide when (and if) action is appropriate. The idea is that agents are not strictly invoked for a task, but are persistent so as to activate themselves, depending on the perceived context.

Agents can be intelligent, ie, possess learning and reasoning skills, and autonomous with the capability to adapt the way in which they achieve their objectives without human intervention. They can be distributed on physically distinct machines, as necessary, and could be mobile so that their execution would be transferability to different processors. Multi-agent systems consist of distributed agents that achieve an objective cooperatively. They can execute their tasks synchronously or asynchronously, and access decentralized databases as needed.

The design of agent-based systems should consider means to provide the capability to a) prioritize, schedule and/or synchronize tasks, b) facilitate communication and collaboration using appropriate ontology for representing knowledge and metadata in a hierarchical organization, and c) detect and respond to all possible changes in the environment.

and activities of the execution cycles can be configured according to the relevant operating concerns. These cycles cover time-scales ranging from 10 milliseconds to an hour. The exact periods of the cycles may be different in each implementation. A representative set of execution cycles is presented in the Factbox on page 23.

Based on the latency of real-time data acquisition, the cycles can be categorized as slow or fast. In the foreseeable future, the communications technology will impose a qualitative dichotomy at about 2 seconds 2.

Each functional agent is composed of plug-and-play building blocks.

The slower cycles perform the intensive computations required for system-wide coordinated controls, performance optimization, and control strategies. The faster cycles address local (substation and vicinity) analytical needs to respond to rapid events using the control strategies developed by the slower cycles. Higher-level intelligence is more prominent in the slower cycles, while the lower level intelligence is dominant in the faster cycles. The execution cycles interact with each other through exchange of event triggers, control parameters, problem indicators, contingency alerts, etc.

Each execution cycle includes a number of functional agents. Each functional agent is composed of plug-and-play building blocks called components, which may be reused in other contexts.

State estimation: a pre-requisite for self-healing capabilities

In contemporary control centers, most analytical functions are limited to slow cycles. For example, the state estimator (SE) is a key function that provides a refined snapshot of the steady state operating condition by minimizing the effects of errors in available data. The results of a state estimator are used not only by the operator, but also by various analytical functions in the slower cycles. These analytical functions need solutions for ever-larger networks with little time skew to support the emerging needs in market operations, in addition to meeting traditional reliability requirements. Similar needs arise in faster cycles to provide self-healing capabilities.

In order to meet these emerging needs, SE should be implemented as a cooperative solution by distributed agents. Each agent can inform other agents of the state of its own portion of the power system at any specified time, with an accuracy of a few milliseconds.

An SE agent at a substation retrieves data from the substation and other substations within an "electrical" vicinity, defined in real-time by an agent at a higher level.

An SE agent at a control-area receives data for a prescribed time from all substation agents in the area and assembles a solution for that area. This requires dealing with issues of geographical and temporal coordination at boarders of the different areas. Similarly, SE Agents at regional and higher levels have to coordinate solutions from the various control areas.

Such implementation of the SE function as a cooperative solution limits the time-skews to a few milliseconds, regardless of the size of the system (assuming PMUs are utilized for all measurements). The sub-second SE capability is essential to support the required faster local (ie, substation, etc) control. Local SE validation improves quality of the SE solutions at the higher levels.

Enhanced graphics should seamlessly combine navigation and presentation of information using animation and three-dimensional capabilities.

Effective visualization of information should allow the operator to understand the state of the system at a glance, and respond in a timely manner. Such situational awareness is an integral part of analysis and control. In addition to the current status, projection of trends, forecasted changes and look-ahead scenarios should be presented. Various views of the same object may be needed to present different aspects of the system to numerous users with diverse needs.

Enhanced graphics should seamlessly combine navigation and presentation

Prevailing viewpoints on the prevention of blackouts

The essence of a self-healing grid is its ability to prevent or contain major disturbances in power supply and to recover from problems in a timely manner. There are three prevailing philosophical viewpoints on major disturbances and the efforts to mitigate them [6].

Disasters are bound to happen: Power system disturbances are just random events that cannot be controlled by human intervention.

Strengthen the weakest point: Each disturbance exposes the "weakest link" in the system at the time it occurs. With the subsequent reinforcements, the next disturbance would have to be greater in scope to expose the next "weakest link" in the reinforced system. Thus, the cycle repeats.

Contain problems via better engineering: Proponents of this viewpoint believe that the complexity of the power system can be managed so as to predict and prevent (or contain) the problems before they become too large.

of information using animation and three-dimensional capabilities. Over time, such features may evolve to create a "virtual reality" environment.

In conclusion

In accordance with the approach of containing problems via better engineering, the envisioned framework requires deployment of autonomous intelligent functional agents across an interconnection-wide system to support a self-healing power grid. This would enable the system to adapt to the varying operating conditions of the system for analyzing and maintaining its reliability in real-time and in the near future. The interactions between the intelligent components of the infrastructure would be orchestrated through a set of execution cycles, tailored to the physical phenomena and operating concerns in the power system.

> The immediate benefits are improved economics through lower congestion and unserved energy resulting from relieving operational limits and reducing interruptions.

More robust monitoring and control capabilities, realized through coordinated local and global controls, provide the resilience needed to deliver non-stop service and a greater degree of automation. The split-second local control decisions made under extreme emergency conditions would be faster and more robust than would be possible using only the operators or higher level controls.

This new infrastructure can be realized using existing technologies. All enabling technologies called for are either in use or proven in concept. Most of the necessary analytical techniques are already being used in various off-line and on-line design processes, eg, protection systems, generator controls, and system operating limits, though some improvement in speed, degree of automation, and level of distribution and coordination will be required.

The proposed system could be implemented in an evolutionary manner, starting with the realization of self-healing capabilities for the "backbone" of the grid. These capabilities could then be extended to additional portions of the transmission system as business needs and budgetary constraints allow. The development of the state estimation function discussed above would serve as a foundation for the overall realization of the required infrastructure.

Our work in this area has analyzed the functional, architectural, and financial feasibility of the proposed infrastructure. The authors have developed a methodology for evaluating the return on investment for this infrastructure, considering the costs related to hardware and software. The immediate benefits are improved economics through lower congestion and unserved energy resulting from relieving operational limits and reducing interruptions. ABB's efforts to enhance products and technologies for improving the reliability of power systems will continue to advance the industry towards the realization of a self-healing power grid.

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ABB Network Management products

ABB is a leading provider of state-of-the-art power equipment, systems and services to improve power system reliability. Advanced monitoring and control is an essential part of efforts to improve power system reliability and cost effectiveness.

ABB business units for Network Management and Substation Automation.

These business units provide devices and turn-key systems for monitoring and control. They have been at the forefront of IT system development to facilitate seamless integration of transmission and distribution (T&D) operations. The resulting integrated platform supports systems for distribution and outage management, Supervisory Control and Data Acquisition (SCADA), energy management, and energy market operations. This includes a group of advanced technologies for Wide Area Monitoring Systems (WAMS). WAMS utilize phasor measurement readings of grid conditions at strategic points across a very large area. With precise time-stamps at their points of origin, the readings can be used to provide an accurate picture of the grid, far beyond any single control area, and to support faster coordinated control actions.

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