# A Perspective on the Research and Development of Applications of Artificial Intelligence in the Electric Power Industry."

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**Abstract**

Viewed as manufacturing, the electric power industry is more similar to process industries such as petroleum, chemicals and pharmaceuticals than to the manufacture of automobiles, electronic devices and clothing by discrete, assembly-line operations. However, it has most of the same challenges as these other industries, often carried to their extremes. For instance, while electricity has essentially zero shelf life and it's transportation is effectively instantaneous, a local fault in that transportation/transmission system can instantly halt deliveries everywhere. With the advent of deregulation, competition and unbundling, the business aspects of electric power are becoming virtually indistinguishable from most other manufacturing industries. Issues of maintenance scheduling and product mix are becoming far more important than ever before. In the future, various unbundled areas of the industry will have strong similarities, as well as some significant differences, to other industries as varied as telecommunications and retail sales. The purpose of this "Perspective" is to outline some of these similarities and differences, and to describe some of ways in which artificial intelligence is being used to address these challenges in the context of the electric power industry.

## The Electric Power Research Institute

The Electric Power Research Institute (EPRI) was formed in 1973 to apply advanced science and technology for the benefit of its member utilities and their customers. Funded through voluntary contributions by over 600 member utilities, EPRI's work covers a wide range of technologies related to the generation, delivery, and use of electricity, with special attention paid to cost-effectiveness and environmental concerns. By far the majority of EPRI research is devoted to the development of products and procedures which are application-specific and are destined for the immediate use of its members. However, a portion of its effort, managed within the Strategic Research and Development Office, is directed toward exploring new technological ideas, pursuing advanced concepts, and fostering areas of science with potential for breakthroughs. Many of the EPRI's product developments and research projects involve artificial intelligence.

## Background On The Electric Power Industry

The North American power network may realistically be considered to be the largest machine in the world since its transmission lines connect all the electric generation and distribution on the continent. Computer simulations support all the planning and most of the operational control that goes into assuring the success of its primary function: to deliver bulk electric power from generation sources to load areas reliably and economically. Because the assurance of reliability has been the overwhelming goal in performing this function, artificial intelligence has had relatively little employment. However, power sector deregulation and privatization are now taking place worldwide, and with the advent of free competition in the electric power industry, new ways are being sought to improve efficiency without seriously diminishing reliability.

Deregulation and the introduction of competition is being achieved through the unbundling of electrical services: converting the historic, vertical integration of generation, transmission and distribution into separate companies, or at least separate services, each optimizing its performance based on different criteria and all operating at arms length. Common wisdom, based on the experience of other industries and other nations, expects that in five years there will be only about fifty companies. The generation companies will be completely deregulated, except for some lingering environmental constraints. The distribution companies will still be regulated, along the lines of today's local telephone companies, but major industrial/commercial customers, and cooperatives of individual residential customers, may generate their own power or buy it from the lowest bidder. The transmission companies will be partly regulated in an attempt to ensure open access and non-discriminatory pricing for "wheeling" power between any generator and any user or distributor, while maintaining some level of system security despite their lack of control of either generation or load.

On a limited basis, several utilities are beginning to employ remote control, distributed sensing, and communications methods to improve network performance. High-speed electronic power controllers such as FACTS (flexible AC transmission system) devices represent an especially promising technology. By replacing the slow mechanical switches now used to manage system operations, these controllers offer for the first time the potential to dynamically fine-tune transmission so that power delivery can respond instantly to changes in demand without the burden of maintaining large amounts of "spinning reserve" generation. However, these devices represent a two-edged sword. On the one hand, they are capable of controlling the system's inherent modal behavior and directing the flow of active power to where it is wanted by accepting changes in reactive power elsewhere. But, on the other hand, increased use of high-speed electronic controllers like FACTS presents more opportunities for large disturbances to occur. In addition, the use of economically beneficial, high voltage direct current (HVDC) interconnections also encourages dependence on geographically remote power sources, making the new controls associated with them essential for secure & stable operation.

It is ironic that, just as system-wide control and information exchange is becoming possible through technology, political considerations are preventing it from taking place. However, this provides both an opportunity and a challenge for the use of artificial intelligence to aid each separately controlled part of the system in the optimization of its own profitability by adapting rapidly to changes in the other parts. Forecasting, producing estimates based on limited information, and calculating the cost/benefit of additional information will be essential to success in a market that will include complex "derivatives" based on future options to power production, transmission capacity and segmented delivery services.

The electric power industry is similar in many ways to the telecommunications and transportation industries, but it has important differences which cannot be ignored in its practical operations, whether regulated or market driven, integrated or unbundled. While electricity also "flows" (from high voltage to low voltage locations), its transmission is inherently different from that of gas or water:

- Power flows through the grid in inverse relation to the impedance on each line.
- Electric power systems use phase shifters rather than valves.
- Providing the required flow on one line often results in "loop flows" on several other lines.
- Despite batteries and capacitors, and in contrast to "line packing" of gas or the use of reservoirs for water, there is no practical way to store large amounts of electricity for any significant length of time.
- Reliable electric service is critically dependent on the whole grid's ability to respond to changed conditions instantaneously.
- Global stability is essential for local efficiency, but every local change has some effect on global stability.

For an electric power network, there are three basic operating requirements:

- all components within their thermal ratings
- all voltages within upper and lower limits
- all generators synchronized

Electricity has the shortest shelf-life of any product that we manufacture. Its perishability is partly compensated by the ability to transport it at almost the speed of light. But the infrastructure required for that transportation is made up of local parts that have limited capacities, and the viability of the whole system depends in an extremely complex way on the performance of each of those parts.

## Knowledge-Based Operation & Maintenance Of Power Plants

Power plants, especially the large, coal-fired steam plants that are typically over twenty years old, have the most need for artificial intelligence applications in the traditional form of expert systems. There are many reasons for this. Backfitting automated control is impractical and/or too expensive. The useful life of the plant is being extended, while, at the same time, experienced operators are retiring. Plants that were designed for base load operation (full power all the time) are now being maneuvered to handle varying loads and to produce a variety of ancillary services (viz.: VARs, reserves, emission credits). Competition puts a high premium on efficient operation and reduced maintenance costs. EPRI has produced a variety of workstations, advisory systems, performance aids, procedural guides and other products to support plant operation and maintenance. Many of these employ symbolic AI techniques such as production rules or inference diagrams, while others are model-based or data-driven with an intelligent user-interface. Neural networks and other computational AI methods are also beginning to be used.

Most of these performance aids are highly specific, both as to the particular plant in which they are installed and the aspect of the plant that they address (viz.: soot-blowing, turbine diagnostics). This situation has two significant disadvantages:

1. The individual performance and decision aids do not obtain maximum benefit from the knowledge generated by the other systems. Often, they are not even aware of each others presence.
2. The customization and re-validation of these tools for each different plant is a significant engineering task -- sometimes approaching the cost of the original development and validation.

Two recently completed EPRI projects addressed these problems.

## The Integrated Knowledge Framework

The primary objective of this project (EPRI 1996b) was to describe the functional knowledge required for integrated management, operation, and maintenance of plants and all their components, in the context of the other components within each plant and of the other plants within the power system control area. Plant Information Management Systems and Digital Control Systems, available from commercial vendors, address very well the "how" of automation, computerization and interprocess communication, but not the "what." To answer that question, and to supply adequate direction to the concepts of proactive maintenance and integrated control, it was necessary to deal with a higher level of abstraction: the meaning in context of data and information. This, in turn, required developing an integrated view of a power plant as an entity in itself and in the context of its role in the power system, with emphasis on defining the knowledge (not just data or information) that is needed, or at least useful, for each subsystem, component and hierarchical level of organization within the plant.

This project, conducted by a team of utility, EPRI, and contract personnel, produced an Integrated Knowledge Framework (IKF) that uses an object-oriented structure to describe and document the management and operational functions at a generic, coal-fired power plant. It describes these functions in such a way that they can be performed by any combination of people and/or computers. The IKF identifies the data, information and knowledge required for the important functions typically performed at a fossil power plant, as well as the flow of that data, information and knowledge between the function that generates it and those that use it. The IKF provides a guide (or benchmark) for comparison with existing specific plant practices and implementing improvements to those practices. The IKF also provides a guide for the order and combination of implementing improvements, so that the improvements complement each other to yield the maximum mutual benefit. Finally, it can serve as a template, devoid of history or personal bias, for the complete re-engineering of the plant organization in, for instance, a new context as part of a non-regulated generation company.

## Automating the Validation of an Expert System

The most promising approach to automating the validation, and possibly the customization, of a rule-based expert system seems to lie in the design of a genetic algorithm (GA) to serve as a form of "devil's advocate" and attempt to make the control system fail. (Grefenstette 1987, 1988) This approach is applicable in principle to any system employing artificial intelligence, but is best described in terms of the validation of an intelligent control system. It requires a validated simulation of the "plant" (the underlying system to be controlled) as well as the intelligent controller designed to manage that plant. The individual population members of the GA represent possible operating conditions for the plant and its environment as well as possible plant failure modes (if the controller is expected to overcome these also). The fitness function for the GA is designed to encourage the evolution of population members that cause unsatisfactory performance by the control system. The successful evolution of one or more such individuals demonstrates that the control system is inadequate in its handling of the particular situation represented by each such individual. Either the control system must be improved or that particular combination of circumstances must be prevented from occurring by a separate safety device or other defensive mechanism.

Clearly, this approach can uncover all the modes of failure in the intelligent control system, but does not provide absolute assurance if, after many generations of evolution, no instances of unsatisfactory control occur. However, the most successful individuals in each successive generation represent bounds within which the controller performs satisfactorily. The convex hull of these bounds provides a well-defined hyperspace within which the system can be guaranteed to perform satisfactorily. If guaranteed performance is required to an infinite extent in at least one non-trivial dimension, then it would be necessary to invent or discover formal logical methods to prove the intelligent control system's unbounded correctness.

A recent EPRI project has tested the use of genetic algorithms to validate a rule-based expert system. (Roache *et al.*.1994) In any practical application, validation is critical to expert system success. Most fielded expert systems are validated by testing whether the expert system provides appropriate conclusions for specific (positive) cases. Since exhaustive testing of all rule combinations is not computationally feasible in any real-world expert system, cases where the system provides inappropriate conclusions (negative cases) are easily missed.

This project (EPRI 1996a) used the Fossil Thermal Performance Advisor (FTPA), an expert system developed for New York Electric & Gas (NYSEG). The FTPA provides the operator of a coal-fired, steam power plant with recommendations for improving the performance of the plant. For this cooperative project, the Naval Research Laboratory provided the GA software, NYSEG contributed the FTPA, and EPRI contracted with DHR Technologies, the original developer of the FTPA, for a neural network model of a power plant and additional bridging software. The individual population members of the GA were designed to represent possible operating conditions for the plant and its environment. Its fitness function encouraged the evolution of population members that produced unsatisfactory performance by the plant but were either inadequately diagnosed by the expert system or caused the expert system to recommend actions which actually decreased plant performance. Besides errors purposely inserted for test purposes, the GA successfully exposed an error in the expert system which had not previously been detected by designers or users over more than three years of actual use.

## Intelligent Control Systems (Ics) Joint Initiative

In 1992, the National Science Foundation (NSF), in collaboration with EPRI, initiated 21 projects in intelligent controls aimed at developing adaptive automation for complex, nonlinear, or poorly understood systems. Most of these projects are essentially over, and all will be complete by the end of 1996. All the researchers are publishing their results in the open literature, but consideration is also being given to publishing a joint NSF/EPRI compendium of all the projects in 1997. Among the research goals of these projects have been:

- methods for learning and adaptation in heterogeneous systems
- methods for reasoning and planning
- analysis of interaction of multiple agents, both human and machine
- techniques for transformation of data into knowledge
- methods for rule generation and modification
- automatic knowledge interpretation
- techniques for development of qualitative and quantitative models
- methods for autonomous process operation
- intelligent sensors and actuators
- tools and techniques for ICS verification and validation

A few of the 21 projects of the Intelligent Control Systems (ICS) initiative have been investigating the use of discrete control methods in the context of the inherently continuous operation of power plants and power networks. The most practical approaches seem to include aspects of both discrete and continuous methods. (Clymer 1993) One such project, at the University of Notre Dame, is investigating methods for obtaining effective DES (discrete event systems) plant models from sequences of observed events. This approach uses optimal designs of state space partitions to define the observed events and uses query-based inductive inference procedures to identify the plant's effective DES dynamics. The emphasis in this project is on methods exhibiting relatively low computational and sample complexity.

## Intelligent Automation For Future Power Systems

Both the geographically distributed nature of the electric power system and its anticipated unbundling into separate competing companies suggest that its operation and control be modeled using multiple, independent, intelligent agents. Besides being needed for global optimization in the context of all these conflicting goals, regulations and physical constraints, such a model structure could, by operating in a parallel and distributed manner, produce an information and control structure that was robust in the face of local disturbances and fast enough to limit their effect on the global network.

Research is now underway for the future development of a completely automated electric power network: (Wildberger 1994)

- measured by locally autonomous intelligent sensors,
- modeled as a hierarchy of cooperating adaptive agents,
- computing in parallel, distributed in space,
- automatically controlling local operations, guided by global criteria and centralized supervisory control,
- communicating only essential information, possibly over the power lines themselves, and
- robust enough to operate sub-optimally either individually or in groups when separated by disturbances.

## Measurement By Intelligent Sensors

Plans for advanced instrumentation development are based on the requirement for timely knowledge of a range of electrical, environmental, and structural parameters that currently cannot be monitored with requisite accuracy, but are necessary to efficiently coordinate system operations. The huge number of sensors and the distributed nature of the instrumentation network will necessitate self-calibration and self-diagnosis capabilities, low installed costs, and highly efficient communications facilities. At least enough embedded intelligence will be required to allow communication only by exception, founded on a context derived from similar exception-based communications from the other intelligent sensors. Ultimately, these sensors must be integrated with locally-positioned intelligent controllers because the time between identification of a potential failure or problem and its occurrence can be too short for effective intervention from a centralized control room. Necessary attributes for advanced sensors include a span of observability sufficiently large to manage local operations over all possible conditions, abilities to monitor and account for power quality and other burdens introduced to the system by customers, and functions for monitoring the integrity of components while protecting them from excessive stress so as to allow operation closer to design performance.

In 1995, EPRI and NSF began a joint exploratory research initiative intended to improve electric utility sensing capabilities along with other aspects of the national infrastructure. This effort, and other ongoing work to combine artificial intelligence technology with innovative sensing methods such as fiber optics, micromechanical devices, and acoustical techniques, should lead, in a few years, to improvements such as in-service self-calibration, direct measurement of presently derived quantities such as power and imbalance, and predictive functions at the bulk system level for problems such as instability and voltage collapse. By the next century, an integrated suite of selfadjusting instruments may be available for continuous measurement of all system parameters and monitoring of component status.

## Distributed Control by Multiple Intelligent Agents

Beginning in 1995, the possibility of distributed control of an electric power system by intelligent agents operating locally with minimal supervisory control is being explored at Iowa State University based on a more general approach developed at the Santa Fe Institute. The project began by modeling the bulk power market with the artificial agents representing the buyers and sellers of bulk power. As agents evolve in a series of experiments, the simulation would expose the various possible configurations that the market could take, subject to different degrees and kinds of cooperation, competition and regulation. If successful, this model and its realization as an interactive simulation will be gradually extended in future years to include: first, the effectsof futures trading; second, retail as well as wholesale wheeling, and then the implication for each transaction of the resulting power flow on the existing network. As agents evolve, their responses to changing conditions may provide dispatchers with a means for identifying optimal power flow solutions and control actions, some of which may be unexpected or counterintuitive.

Another project, started in 1994 at San Jose State University, is exploring techniques for using complex cellular automata (CA) (EPRI 1994) to model certain aspects of the power grid. The long term goal is to perfect a distributed-computation simulation of the global behavior of a circuit (viz.: stability) based on the local behavior of the individual components and to test this approach by examining possible CA representations of power quality (harmonics, load induced transients, etc.) where cells might represent individual loads (viz.: appliances) within a building.

A cellular-automaton implementation of partial differential equations has been developed, including: the heat equation, the wave equation (or telegrapher's equation), the damped driven oscillator, the damped driven oscillator coupled with the wave equation, and the Fermi-Pasta-Ulam non-linear soliton wave. These simulations have never before been implemented as pure cellular automata (CAs). The CA implementation makes it possible to rapidly explore alternate parameter settings, to breed and mutate those settings, and to view space-time diagrams of the simulation in real time. The user can guide the evolution of a set of cellular automata simulations intended to represent linked ensembles of several hundred electrical devices (as in an office-building). CAPOW2 (the second version of the Cellular Automata Power Simulator) runs under Windows 3.1 and is available as shareware on the Internet. (Rucker 1996)

Work is continuing on how best to use this modeling tool for real world problems, as well as on extending these techniques to branching networks and continuous-valued two-dimensional CAs with arbitrarily complicated internal structure. Rules that include a list of active cell sites will permit the user to draw the circuit on the screen with the mouse, adding circuit elements with mouse clicks. Once the circuit simulation is running, the user will be able to "zap" the circuit with mouse clicks to observe transient responses to outages and surges. Rules which update every single cell in the 2D array will also be tried as a method for modeling the electromagnetic fields near wires. This full 2D model could also provide a large-scale qualitative "satellite-camera view" of patterns of power reaction and diffusionand across a continent-sized grid.

## Summary

The electric power industry has certain basic similarities to any other manufacturing industry that converts raw materials into wholesale and retail products. With deregulation, competition and unbundling of its hitherto integrated structure, these similarities are becoming more apparent. This paper outlined some of the diverse ways in which AI is being applied in the electric power industry and some of the current research being sponsored by EPRI that is directed toward the use of AI to better meet the industry's new challenges.

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