DDAS for Autonomic Interconnected Systems: The National Energy Infrastructure

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Abstract. The most critical element of the nation's energy infrastructure is our electricity generation, transmission, and distribution system known as the "power grid." Computer simulation is an effective tool that can be used to identify vulnerabilities and predict the system response for various contingencies. However, because the power grid is a very large-scale nonlinear system, such studies are presently conducted "open loop" using predicted loading conditions months in advance and, due to uncertainties in model parameters, the results do not provide grid operators with accurate "real time" information that can be used to avoid major blackouts such as were experienced on the East Coast in August of 2003. However, the paradigm of Dynamic Data-Driven Applications Systems (DDDAS) provides a fundamentally new framework to rethink the problem of power grid simulation. In DDDAS, simulations and field data become a symbiotic feedback control system and this is refreshingly different from conventional power grid simulation approaches in which data inputs are generally fixed when the simulation is launched. The objective of the research described herein was to utilize the paradigm of DDDAS to develop a marriage between sensing, visualization, and modelling for large-scale simulation with an immediate impact on the power grid. Our research has focused on methodological innovations and advances in sensor systems, mathematical algorithms, and power grid simulation, security, and visualization approaches necessary to achieve a meaningful large-scale real-time simulation that can have a significant impact on reducing the likelihood of major blackouts.

1 Introduction

The August 2003 blackout cascaded throughout a multi-state area of the U.S. and parts of Canada within a few minutes. Hindsight reveals the blackout was the result of the system operating too close to the point where synchronous

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operation of the generators could be lost (transient stability limit). In this situation, the inability of operators and system controllers to quickly respond to unexpected anomalies in the system resulting in the blackout. An August, 2004 IEEE Spectrum article entitled "The Unruly Power Grid" [1] emphasizes the need for accurate system modelling and fast computation in order to provide operators and system controllers with timely on-line information regarding the dynamic security of the entire electric grid, thereby reducing the likelihood of future cascading system failures.

One of the main difficulties in controlling complex, distributed systems such as the electric power grid is its enormous scale and complexity. Presently, transient stability studies are conducted open loop based upon predicted load profiles months in advance. As such, the results are only approximations of what might happen based upon the assumptions, load estimates, and parameters assumed in the computer studies. Distributed dynamic estimation based on dynamic GPS-synchronized data has the potential of alleviating the shortcomings of the present state of the art. The simulation of the evolution of the system state forward in time using dynamic and synchronized measurements of key system parameters appears to be within reach. Fast, accurate, data-driven computation can revolutionize operating procedures and open the door to new and challenging research in the operation and control of the electric power grid.

There are several key areas that must be addressed to achieve the overall research objective: faster-than-real-time simulation, distributed dynamic sensing, the development of behavioral models for situations where physics-based models are impracticable, and visualization. Faster-than-real-time simulation alone is insufficient – the simulation must be accurate and track the true operating conditions (topology, parameters, and state) of the actual system. An integrated sensing network is essential to ensure that the initial state of the simulated system matches the present state of the actual system, and to continually monitor and, if necessary, adjust the parameters of the system model. Moreover, it has been recognized that the dynamic characteristic of loads can influence the voltage stability of the system. Due to their sheer number and the uncertainties involved, it does not appear possible to model distributed loads and generators, such as wind turbines and photovoltaic sources, using deterministic physics-based models. Neural networks may be used in cases where physics-based models do not exist or are too complex to participate in a faster-than-real-time simulation. Finally, even if the goal of an accurate faster-than-real time predictive simulation is achieved, the number of potential contingencies to be evaluated at any instant of time will be intractable. Therefore, methods of identifying vulnerabilities using visualization and the development of suitable stability metrics including heuristic approaches are sought.

The research performed at Purdue University, the Georgia Institute of Technology, and PC Krause and Associates has addressed each of these critical areas. The purpose of this paper is to describe the research conducted heretofore and key results obtained to date.

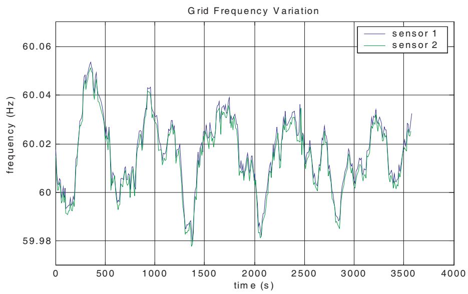

Fig. 1. Grid frequency variations at two locations in the power grid separated by 650 mi. NTP and post-processing techniques were used to synchronize time stamps of the data to within 10 μs.

2 Distributed Dynamic Sensing

Presently, sufficient measurements are taken so that, with the aid of a state estimator, the voltage magnitudes, phase angles, and real and reactive power flows can be monitored and updated throughout the grid on a 30-90 second cycle. A current project, supported by the Department of Energy (DOE), has as its goal to instrument every major bus with a GPS-synchronized phasor measurement unit. While this would provide system operators with more up-to-date top-level information, a concurrent bottom-up approach can provide even more information, reduce uncertainty, and provide operators and researchers alike with more accurate models, an assessment of the true state of the system, and diagnostic information in the event of a major event such as a blackout. The large scale of the power grid means that many sensors in various locations will be required for monitoring purposes. The number of sensors required for effective monitoring means they must be inexpensive, while maintaining the required accuracy in measurements. A custom designed sensor board including data acquisition hardware and a time stamping system has been developed. This sensor uses the Network Time Protocol (NTP) and WWVB, a US-based time signal that, because of its long wavelength, propagates far into buildings (unlike GPS). This new board will provide the required accuracy in measurement and time stamping at a very reasonable cost. The goal is synchronization of sensors deployed throughout the grid to within 10 μs or better because a one degree error in a phase estimate corresponds to a 46-μs delay.

Since November 2004, six proof-of-concept sensors were deployed in various locations in the U.S. These sensors have been in operation and have been collecting data since that time. The sensors communicate through the Internet, and regularly send the collected data to a central server. A significant amount of effort has gone into developing an automated system wherein the sensor data is automatically processed and archived in a manner that can be easily retrieved via a web interface. In the future, this will allow additional sensors to be added with only minimal effort. A typical example is shown in Fig. 1, which depicts

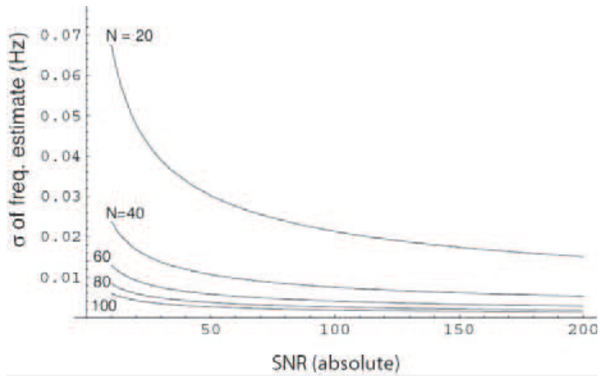

Fig. 2. Cramer–Rao lower bounds on the variance of the error for estimates of the signal frequency based on 1200 samples per second (20 per period) of the 60 Hz power signal with additive white Gaussian noise

frequency estimates from two proof-of-concept sensors (one in West Lafayette, Indiana, and the other in Maurice, Iowa) over the period of an hour. The data shows the synchronization of the relative frequency changes in the electric grid even in geographically distant sensor locations. The technique used to estimate the frequency of the power signal is equivalent to the maximum likelihood estimate for large SNR's, which is typically the case with our measurements. We have derived the Cramer–Rao lower bounds on the variance of the error of this (unbiased) estimator. The results are shown in Fig. 2.

3 Distributed Heterogeneous Simulation

Recent advancements in Distributed Heterogeneous Simulation (DHS) have enabled the simulation of the transient performance of power systems at a scope, level-of-detail, and speed that has been heretofore unachievable. DHS is a technology of interconnecting personal computers, workstations, and/or mainframes to simulate large-scale dynamic systems. This technology provides an increase in simulation speed that approaches the cube of the number of interconnected computers rather than the traditional linear increase. Moreover, with DHS, different simulation languages may be interconnected locally or remotely, translation to a common language is unnecessary, legacy code can be used directly, and intellectual property rights and proprietary designs are completely protected. DHS has been successfully applied to the analysis, design, and optimization of energy systems of ships and submarines [2], aircraft [3], land-based vehicles [4], the terrestrial power grid [5], and was recently featured in an article entitled "Distributed Simulation" in the November 2004 issue of Aerospace Engineering [6]. DHS appears to be an enabling technology for providing faster-than-real-time detailed simulations for automated on-line control to enhance survivability of large-scale systems during emergencies and to provide guidance to ensure safe and stable system reconfiguration. A DHS of the Indiana/Ohio terrestrial electric grid has been developed by PC Krause and Associates with cooperation from the Midwest Independent System Operator (MISO), which may be used as a real-life test bed for DDDAS research.

4 Visualization

The computational and sensory tasks generate data that must be scrutinized to assess the quality of simulation, of the models used to predict state, and to assess implications for the power grid going forward. We envision accurate visual representations of extrapolations of state evolution, damage assessment, and control action consequences to guide designers and operators to make timely and well-informed decisions. The overriding concern is to ensure a smooth functioning of the power grid, thus it is critical to provide operators with situation awareness that lets them monitor the state of the grid rapidly and develop contingency plans if necessary. An easily understood visual presentation of state variables, line outages, transients, phase angles and more, is a key element for designers and operators to be in a position to perform optimally.

The Final Report on the August 14th Blackout in the United States and Canada by the U.S.–Canada Power System Outage Task Force [7] states clearly that the absence of accurate real-time visualization of the state of the electric grid at FirstEnergy (FE) was an important shortcoming that led to the blackout of August 2003. FE was simply in the dark and could not recognize the deterioration leading to the wide-spread power failure. Our mission, therefore, is to assist grid system operators to monitor, predict, and take corrective action.

The most common representation of the transmission grid is the one-line diagram, with power flow indicated by a digital label for each arc of the graph. Recently, the diagrams have been animated [8], allowing insight into power flow. Flow has also been visualized using dynamically sized pie charts that grow superlinearly as a line approaches overload. The one-line diagram is impractical for visualizing complex power systems: buses overlap with each other and with lines to which they are not connected, and lines intersect. Although considerable research in information visualization has been devoted to graph drawing [9], contouring is a simpler and more effective method for power grids. Contouring is a classic visualization technique for continuous data, which can be applied to discrete data by interpolation. Techniques have been developed for contouring bus data (voltage, frequency, phase, local marginal prices), and of line data (load, power transfer distribution factors) [8, 10, 11]. Phase-angle data as measured directly via GPS-based sensors or semi-measured/calculated from existing sensors/state estimators may be used as an indicator of transient stability margin or via "energy" functions.

We have developed tools for visualizing phase angle data that allow the operators to detect early and correct quickly conditions that can lead to outages [12]. To provide real-time assessment of power grid vulnerability, large amounts of measured data must be analysed rapidly and presented timely for corrective response. Prior work in visualization of power grid vulnerability handles only

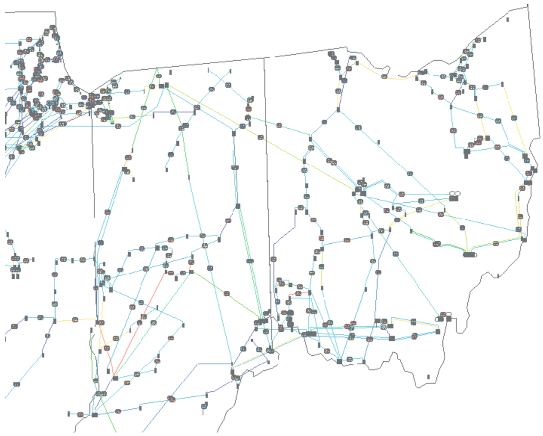

Fig. 3. Visualization of Midwestern power grid

the case of static security assessment; a power flow is run on all contingencies in a set and the numerical data is visualized with decorated one-line diagrams [13]. Strategically, it is an advantage to use preventative techniques that lead to fast apprehension of the visually presented data and thus to situation awareness. Displays created based on the theory of preattentive processing (from the scientific field of human cognitive psychology) can provide such a visualization environment [14]. These displays would use a combination of colors and glyphs to provide underlying information, as depicted in Fig. 3.

5 Neural Distributed Agents

Neural networks (NNs) provide a powerful means of simplifying simulations of subsystems that are difficult or impossible to simulate using deterministic physics-based models, such as the composite loads in the power grid. The ability of a neural distributed agent [15] to reduce the computational burden and to help achieve real-time performance has been demonstrated. Instead of directly computing the state of the coupled systems, the states of each subsystem are pre-computed and functionalized to the state variables using NN methods. The state of the coupled system for any given condition is then constructed by interpolating the pre-calculated data. The approach used involved decomposition of the system into several subsystems and utilizing a NN to simulate the most computationally intensive subsystems. The NN produces pre-computed outcomes based on inputs to respective subsystems. The trained NN then interpolates to obtain a solution for each iteration step. Periodic updates of the NN subsystem solution will ensure that the overall solution remains consistent with the physics-based DHS. NN-based models further facilitate real-time simulation by reducing computational complexity of subsystem models. Similar concepts have been used for real-time simulation of the dispersion model of chemical/biological agents in a 3-D environment [16].

This concept was demonstrated using a small closed electrical system consisting of a generator connected to transmission lines. The generator subsystem was created in Simulink [17] and provided the template for training the NN. The generator subsystem was then replaced by a NN configuration with the goal of reducing by at least two orders of magnitude the time required to simulate the computationally intensive physics-based generator equations used in the Simulink subsystem. The current phase of the project restricts the NN to simulating only steady-state electrical generator response. The generator subsystem physics model provided corresponding I/O pairs by varying parameters in the transmission lines. These pairs were then used to train the NN such that the subsystem output would be pre-computed prior to any simulations using the subsystem. More than 160 system variations were obtained that produced a stable steady-state system. To accurately train the network, the generator subsystem data obtained from the original model was split into a training data set and a testing data set. The training data set was used to create a feed-forward back propagation NN. The output of the NN consisted of six electrical current values. The electrical current consisted of the magnitude and phase angle for each of the three phases of the system. The NN input consisted of six components of the electrical voltage, similar to the components of the current. The trained networks were tested using the testing data set consisting of 20 data points that were used to compare the results of the completed NN with the results produced by the original generator subsystem model. The mean square error between the outputs of the physics and NN models were used to measure the validity of the NN training.

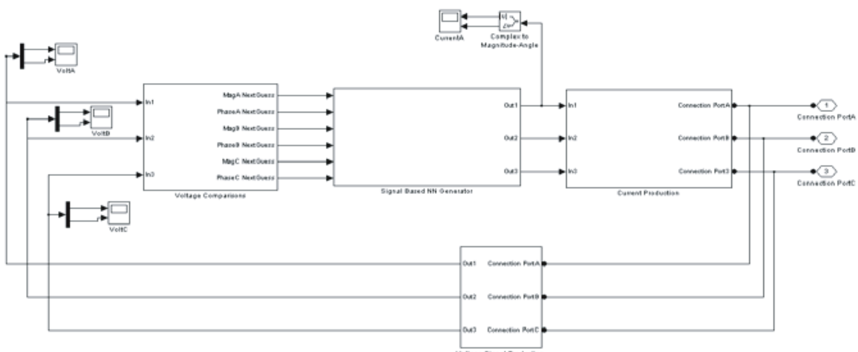

Fig. 4. Neural network test system for electrical generator

The generator NN was then integrated into Simulink as shown in Fig. 4. This system interacts with the generator load, which is connected through the connection ports on the right side of the figure. A Matlab script was created that allows the Simulink model to be called iteratively until a solution is reached. The neural network-based system showed very good agreement with the original Simulink model. Using a convergence tolerance of 0.0004 for the relative iteration change of the voltage values, the maximum relative error in the voltage values was 0.00056 and the maximum relative error in the current values was 0.0022. Execution time comparisons showed a dramatic time reduction when using the NN. The Simulink model required about 114,000 iterations and 27 minutes CPU time to simulate 30 seconds real time on a 531-MHz computer. The NN-based system was able to determine solutions for over half the cases in less than 15 seconds on a 2.16-GHz computer. All cases were completed in less than 120 seconds. Further reductions in the execution time are anticipated, as well as the ability to perform transient analysis.

6 Summary

The research conducted at Purdue University, the Georgia Institute of Technology, and PC Krause and Associates address the critical areas needed to achieve the overall goal of an accurate real-time predictive simulation of the terrestrial electric power grid: faster-than-real-time simulation, distributed dynamic sensing, the development of neural-network-based behavioral models for situations where physics-based models are impracticable, and visualization for situation awareness and identification of vulnerabilities. DDDAS provides a framework for the integration of the results from these coupled areas of research to form a powerful new tool for assessing and enhancing power grid security.

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