PNNL-14987

Modeling Power Systems as Complex Adaptive Systems

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December 2004

Prepared for
the U.S. Department of Energy
under Contract DE-AC06-76RL01830

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Abstract

Physical analogs have shown considerable promise for understanding the behavior of complex adaptive systems, including macroeconomics, biological systems, social networks, and electric power markets. Many of today's most challenging technical and policy questions can be reduced to a distributed economic control problem. Indeed, economically based control of large-scale systems is founded on the conjecture that the price-based regulation (e.g., auctions, markets) results in an optimal allocation of resources and emergent optimal system control. This report explores the state-of-the-art physical analogs for understanding the behavior of some econophysical systems and deriving stable and robust control strategies for using them. We review and discuss applications of some analytic methods based on a thermodynamic metaphor, according to which the interplay between system entropy and conservation laws gives rise to intuitive and governing global properties of complex systems that cannot be otherwise understood. We apply these methods to the question of how power markets can be expected to behave under a variety of conditions.

Contents

1.0 Executive Summary

The transactive control system is a prototype model of a system of abstract machines interacting using contract networks, a method of distributed system control developed at Stanford University by Reid Smith in 1980. We believe a new theory of control is required to describe the properties of systems of economically and physically interacting devices under this method control. Transactive machines are designed to obey certain local rules already extant in most complex engineered systems. What remains unresolved is a theory using these rules to predict the global average behavior of networked systems composed of large numbers of such machines.

The analogue to such a theory has long existed: statistical mechanics of microscopic atoms and molecules predicts aggregate thermodynamic properties of bulk systems (e.g., pressure, temperature, internal energy). Two requirements of actual machines strongly suggest that ultimately discrete (*viz.* quantum) statistical mechanics may be an appropriate tool: 1) the majority of machines undergo discrete state transitions (e.g., on or off, two-stage, digital control), and 2) some machines have exclusionary properties for certain states which prevent other machines from occupying those states once they occupy them (e.g., ancillary service contracts, remedial action schemes for under-frequency load shedding). Ultimately we seek a model predicting time-dependent behavior of systems of these machines. However, many average properties of these complex systems are time-independent when the system is at equilibrium and can be satisfactorily described using statistical mechanics in the classical limit (for large numbers of machines). Thus we will generally restrict ourselves to modeling time-independent solutions for the scope of this work. With a few exception noted in the text, we leave the treatment of the time-dependent properties of non-equilibrium and properties of small systems to future investigations.

Many of the problems which we seek to solve with respect to power-markets and demand responsive loads ultimately require us to answer a single key question: "what is the probability of a system load Q between the time t and the time $t+dt$?" This question, and a closely related question regarding the price of power, has traditionally been answered using empirical methods. We seek a first-principle method with which we may determine the system load and price of power based on known properties of loads.

In the past, using empirical methods has been an acceptable practice because the load control behaviors were not coupled to the price of power. Therefore feedback mediated by the systems was largely non-existent and the complex emergent behaviors were rarely observed. Indeed, it is the very lack of response to price that has led to current situation in which price volatility can adversely affect system behavior. However, the PNNL's vision of the future is predicated on a change in the assumption and any empirical model of load behavior is therefore called into question. Not having access to real-world data, we have begun the development of simulations that will permit us to observe hypothesized systems. While this is an important step in the right direction, it is not likely to bring us the tools we need to understand the more subtle and rare emergent behaviors that might occur. A first-principles model of price-mediated system behavior is necessary.

Work completed in recent years at PNNL has suggested that statistical mechanics may provide a mathematical framework to achieve this goal. Data collected from various ISOs in recent years reveal

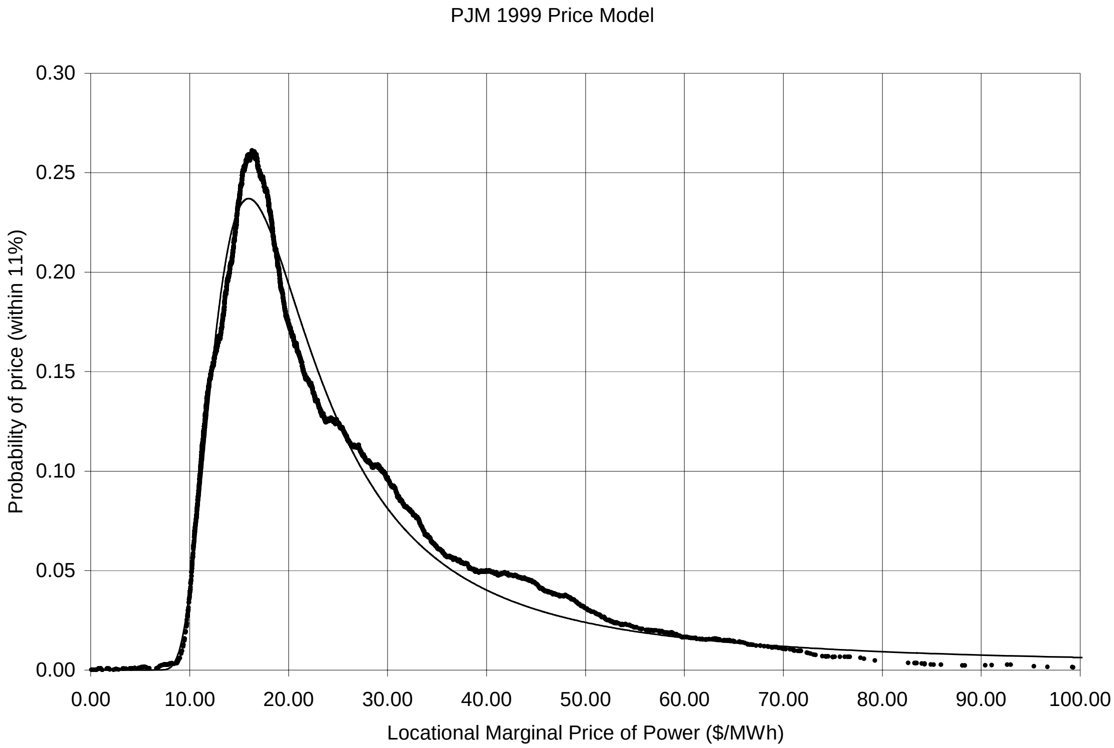

Figure 1: **The Pennsylvania-Jersey-Maryland Interconnect locational marginal price (LPM) history for 1999 (dots) and the theoretical curve (narrow line) for an ideal gas having a Maxwellian velocity distribution as the analog to system load.**

load and price histograms that are reminiscent of Maxwellian probability distribution functions (see Figure 1). Simple models of buyer/seller behavior in power distribution systems have been studied and rigorous definitions for market entropy, value of activity, and market potentials have been derived. Careful analysis of HVAC and waterheater behavior when influenced by market-based prices reveal emergent load behavior that are neither expected, nor allowed for in the grid operations models. We have come to the conclusion that a significant opportunity lies in the application of statistical mechanics to market-based power systems control.

When considering the impact of transactive controls in power transmission and distribution systems, we would like to answer questions such as the following:

- What is the susceptibility of a retail distribution system to changes wholesale market prices? This question goes to the heart of what we mean by demand response. It seems reasonable to expect that distribution systems operated as markets according to the transactive control model will have varying degrees of responsiveness to market price volatility depending on the amount of power trading within them. We would like to quantify this effect for a relatively ideal model such that we can begin to explain the phenomenon more rigorously.

- What is the degree to which markets affect load diversity? We have already seen that markets can decrease load diversity in certain cases. Is it also possible that market mechanics can restore load diversity? We have some evidence to suggest that markets cause “bunching” of the natural stand-by duty cycles of certain loads. We would like to quantify the effect in a way that allows us to predict whether this is a beneficial and detrimental effect on the power system.

- Certain control strategies (such a frequency-based load shedding) have state-exclusion behaviors that are difficult to model using traditional/empirical load modeling methods. We would like to model these phenomena rigorously enough to predict what level of resources (e.g., Grid-Friendly Appliances) are adequate to provide a certain level of system security.

Modern power system models compute the values for various system properties by explicitly solving the many-body steady–state problem, typically by manipulating a sparse matrix representation of the power flow network topology. However, the introduction of market behaviors and demand response into these systems has created three complications: 1) they have transformed the model into a dense matrix, 2) the dual nature of the model (economic and physical) creates serious obstacles to producing efficient models and solvers, and 3) the scale of the model is increased by several orders of magnitude. As a result, the evolving market-based power grid may not be tractably computable using today's methods and computing systems. Our approach addresses these problems by defining a more suitable model of system properties, which provides useful tools for determine the average properties of systems with extremely large numbers of machines, often many orders of magnitude large than the systems we foresee within the next few decades. Ultimately we expect the mesoscale modeling gap can be addressed by retrodicting the potentials based on the observations of the large scale systems without needing very detailed observation of the microscale behaviors of the individual machines. By recasting the problem in this form, we expect to enable significant contributions from several areas, including 1) *q*-fermion theory to deduce from the ensemble data the occupation number and set of eigenvalues distribution associated with the underlying quantum potentials (Dutt et al. 1994), 2) solving the inverse scattering problem using super-symmetric quantum mechanics to obtain the set of potentials which produce these eigenvalues (Jeffrey 2004); and 3) applying the various superpotentials from which the family of quantum potentials is derived (Cooper et al. 1994), to produce models for comparison with available data, and to predict the outcome of future market behaviors.

We have observed in data collected that load behavior is not strictly continuous. For example, almost all residential systems have a very small number of discrete states, often only two or three. In addition, the hysteresis of most thermostatic devices (such as heaters, air-conditioners, refrigerators, freezers, and water-tanks) causes them to cycle between two states with a minimum cycle time. Finally, the low degree of precision of typical sensors and the extensive use of digital control cause both the sensing and actuating processes of loads to exhibit discrete state transition phenomenology. Taken together, we conclude that the behavior of a significant number of small machines on power grids is discrete in nature. Therefore we expect that the potentials of the machines, acting as resources in markets would also be discrete in nature. Hence we expect to find a quantum harmonic oscillator, and indeed many other potentials to be relevant to the problems of modeling the interactions of loads in power markets.

9.0 Conclusions

We have considered the consequences of using concepts adopted from statistical mechanics in Part 1 as they relate to the response of highly distributed energy systems to bulk power markets. We defined how a market interacts with the system and rigorously derived its minimal cost configuration. We have observed that the transition to the super distributed energy system has inherent obstacles, which we have quantified.

We have seen that the Ising model of highly distributed energy systems reveals the existence of an important phase transition in the behavior of these systems when topological considerations are included. Below a critical level of trading activity in the system, the system cannot indefinitely sustain any distributed energy behavior at all, and only at or above the critical level of activity can the system engage in an effective market-based control of distributed resources.

The assumptions made in the derivation have placed restrictions on the conditions for which these results are accurate. For example, we have assumed configurations of the system that preclude the use these models for extreme conditions such as those observed with trading activity is very low with respect to the value of the trades. Despite the utility of the Ising model, we recommend investigation of the Potts model to account for other possible states that customer equipment may occupy, such as failed or withheld. Finally, we recommend further analysis of the drop in correlation distance in very active highly distributed energy systems because the Ising model suggests that under certain conditions, the behavior of market-based control systems may become largely insensitive to the latency of the communication network.

Two different modeling methods (SQ and ETP) were developed and used to evaluate various demand response control strategies for both electric water heaters and HVAC systems. In addition, we also studied some implementation issues. Although the results are promising in many aspects, more widely spread analysis is required to gain further insight into the affects of load curtailment on the distribution system dynamics.

In Section 7 developed a standby state queueing model to simulate the price response of a load consisting of thermostatically controlled appliances in a competitive electricity market. An aggregated load consists of thousands of TCAs, while the number of states a TCA can reside in may be no more than 100. We expect that applying a queue representation brings a computational advantage over simulating the behavior of each individual unit.

By analyzing the load shifts caused by the set point changes in response to price, the impacts on load diversity was studied. The results reveals the fundamental reason for the reduced load diversity in large scale direct load control systems, which has been observed and discussed by Weller (1988). The results also indicate that by responding to price changes, a diversified TCA type of load becomes synchronized, and their behaviors present a dynamic response. Therefore, to design a successful load response program for aggregated TCAs, one needs to examine the load shifting characters to ensure that the shifted load peaks will occur after the peak-price time. The synchronized load peak can be much higher than that of the diversified load. The stress on the distribution system should also be considered. The methodology developed in this research is expected to be used to create DSM simulation tools that are able to take the load-shifting behavior into consideration.

In Section 6 we presented a method to include the modeling of uncertainties in the TCA load cycling times and random load consumptions by modifying the entries of the state transition matrix of a SQ model. From the load survey data, probability distribution functions of the cycling time and consumer behavior patterns can be obtained. State transition matrixes for each hour can then be tuned and used by the SQ model introduced in (Lu et al. 2004c) to simulate the price response of loads aggregated by TCAs. The eigenvalues of the state transition matrix can be used to evaluate the system damping rate, which indicates the ability of the system to restore load diversity. Because the computation time of a SQ model is determined by the number of states used to model the TCA load cycling periods and the sparsity of the state transition matrix, it has computational advantages over unit-based simulation, thus holding promise as an useful equivalent load model for transmission level studies.

In Section 7 we investigated several control strategies including an optimal control strategy for an LSE to implement TCA set point-control in a competitive electricity market, where the market clearing price is insensitive to the bid price of a single load bid. A state queueing model has been used to simulate the aggregated water heater load response. Economic benefits are calculated and feeder load profiles are obtained to evaluate control strategies including load curtailment, preheating and coasting, and modified preheating and coasting. The results suggest that the modified preheating and coasting control is cost saving and result in least dynamics on feeder load profile.

Future work will be focused on developing control strategies to minimize the energy cost in real time market. The possibility of using TCAs to provide ancillary service, where the load needs to respond to frequency deviations, is also going to be investigated.

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