Multi-Agent Electricity Market Modeling with EMCAS

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Abstract

Electricity systems are a central component of modern economies. Many electricity markets are transitioning from centrally regulated systems to decentralized markets. Furthermore, several electricity markets that have recently undergone this transition have exhibited extremely unsatisfactory results, most notably in California. These high stakes transformations require the introduction of largely untested regulatory structures. Suitable tools that can be used to test these regulatory structures before they are applied to real systems are required. Multi-agent models can provide such tools. To better understand the requirements such as tool, a live electricity market simulation was created. This experience helped to shape the development of the multi-agent Electricity Market Complex Adaptive Systems (EMCAS) model. To explore EMCAS' potential, several variations of the live simulation were created. These variations probed the possible effects of changing power plant outages and price setting rules on electricity market prices.

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Multi-agent Modeling of Electricity Markets

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INTRODUCTION

Electric utility systems around the world continue to evolve from regulated, vertically integrated monopoly structures to open markets that promote competition among suppliers and provide consumers with a choice of services. The unbundling of the generation, transmission, and distribution functions that is part of this evolution creates opportunities for many new players or agents to enter the market. It even creates new types of industries, including power brokers, marketers, and load aggregators or consolidators. As a result, fully functioning markets are distinguished by the presence of a large number of companies and players that are in direct competition. Economic theory holds that this will lead to increased economic efficiency expressed in higher quality services and products at lower retail prices. Each market participant has its own, unique business strategy, risk preference, and decision model. Decentralized decision-making is one of the key features of the new deregulated markets.

Many of the modeling tools for power systems analysis that were developed over the last two decades are based on the implicit assumption of a centralized decision-making process. Although these tools are very detailed and complex and will continue to provide many useful insights into power systems operation [Conzelmann et al., 1999; Koritarov et al., 1999, Harza, 2001], they are limited in their ability to adequately analyze the intricate web of interactions among all the market forces prevalent in the new markets. Driven by these observations, Argonne National Laboratory's Center for Energy, Environmental, and Economic Systems Analysis (CEEESA) has started to develop a new deregulated market analysis tool, the Electricity Market Complex Adaptive Systems (EMCAS) model. Unlike those of conventional electric system models, the EMCAS agent-based modeling (ABM) techniques do not postulate a single decision maker with a single objective for the entire system. Rather, agents are allowed to establish their own objectives and apply their own decision rules. Genetic algorithms are used to provide a learning capability for certain agents. With its agent-based approach, EMCAS is specifically designed to analyze multi-agent markets and allow testing of regulatory structures before they are applied to real systems.

OVERVIEW OF THE AGENT-BASED MODELING CONCEPT

The complex interactions and interdependencies between electricity market participants are much like those studied in Game Theory [Picker, 1997]. Unfortunately, the strategies used by many electricity participants are often too complex to be conveniently modeled using standard Game Theoretic techniques. In particular, the ability of market participants to repeatedly probe markets and rapidly adapt their strategies adds additional complexity. Computational social science offers appealing extensions to traditional Game Theory.

Computational social science involves the use of ABMs to study complex social systems [Carley et. al., 1998][Epstein & Axtell, 1996]. An ABM consists of a set of agents and a framework for simulating their decisions and interactions. ABM is related to a variety of other simulation techniques, including discrete event simulation and distributed artificial intelligence or multi-agent systems [Law & Kelton, 2000; Pritsker, 1986]. Although many traits are shared, ABM is differentiated from these approaches by its focus on achieving "clarity through simplicity" as opposed to deprecating "simplicity in favor of inferential and communicative depth and verisimilitude" [Sallach & Macal, 2001].

An agent is a software representation of a decision-making unit. Agents are self-directed objects with specific traits. Agents typically exhibit bounded rationality, meaning that they make decisions using limited internal decision rules that depend only on imperfect local information.

A wide variety of ABM implementation approaches exist. Live simulation where people play the role of individual agents is an approach that has been used successfully by economists studying complex market behavior. General-purpose tools such as spreadsheets, mathematics packages, or traditional programming languages can also be used. However, special-purpose tools such as Swarm, and the Recursive Agent Simulation Toolkit are among the most widely used options [Burkhart et al., 2000; Collier & Sallach, 2001].

Several electricity market ABMs have been constructed, including those created by Bower and Bunn [2000], Petrov and Sheblé [2000], as well as North [2000a, 2000b, 2001]. These models have hinted at the potential of ABMs to test electricity market structures under controlled conditions.

THE EMCAS CONCEPT

EMCAS is an electricity market model related to several earlier models [VanKuiken, et al., 1994; Veselka, et al., 1994]. The underlying structure of EMCAS is that of a time continuum ranging from hours to decades. Modeling over this range of time scales is necessary to understand the complex operation of electricity marketplaces.

On the scale of decades, the focus is long-term human decisions constrained by economics. On the scale of years, the focus is short-term human economic decisions constrained by economics. On the scale of months, days, and hours, the focus is short-term human economic decisions constrained by economics and physical laws. On the scale of minutes or less, the focus is on physical laws that govern energy distribution systems. In EMCAS, time scales equate to decision levels. There are six decision levels implemented in the model, with decision level 1 representing the smallest time resolution, that is, the hourly or real-time dispatch. Decision level 6 on the other side is where agents perform their long-term, multi-year planning.

EMCAS includes a large number of different agents to model the full range of time scales (see Figure 1). The focus of agent rules in EMCAS varies to match the time continuum. Over longer time scales, human economic decisions dominate. Over shorter time scales, physical laws dominate. Many EMCAS agents are relatively complex or "thick" compared to typical agents. EMCAS agents are highly specialized to perform diverse tasks ranging from acting as generation companies to modeling transmission lines. To support specialization, EMCAS agents include large numbers of highly specific rules. EMCAS agent strategies are highly programmable. Users can easily define new strategies to be used for EMCAS agents and then examine the marketplace consequences of these strategies. EMCAS and its component agents are currently being subjected to rigorous quantitative validation and calibration.

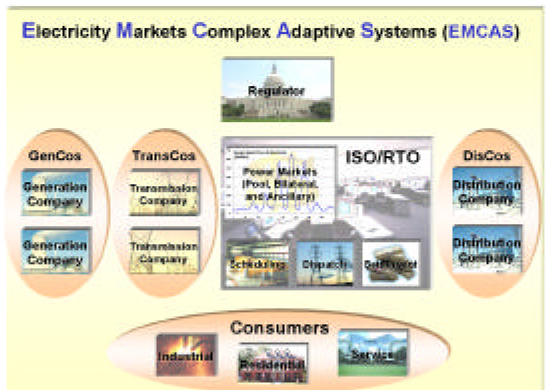


Figure 1: EMCAS Structure and Agents

EMCAS PROTOTYPING: A POWER MARKET SIMULATION GAME

To better understand the requirements of an electricity market structure testing tool, a live electricity market simulation was created. The market game that was developed used individuals to play the role of generation companies. One additional person played the role of the ISO/RTO.

Each generation company in the market simulation game had three identical generators. The generators included a small natural-gas-fired turbine generator, a medium-sized natural-gas-fired combined cycle unit, and a large coal-fired power plant. Players were allowed up to five bid blocks for each unit. Players submitted bids electronically. The bids were collected and used by the system operator. Players based their bids on public information electronically posted by the system operator. This information included historical and projected prices, demands, supply, and weather.

The system operator collected the players' bids on a periodic basis and used to them to simulate the operation of an electricity spot market. The simulation calculated MCPs and player profits based on internally derived demands, supplies, and weather. The actual simulation demands, supply, and weather differed from the publicly posted projections by small random amounts. Generating units also suffered from unannounced random outages.

An initial market simulation game was run with six players. The price results from this run are shown in Figure 2. Subsequently, a second market game with 10 players was run. Experience from these market simulation games suggested that the development of an electricity market ABM might be extremely beneficial. This experience helped to shape the development of EMCAS.

EMCAS AND THE GAME

An EMCAS case has been created based on the previously described market game. Specific agents representing individual market game players were implemented by using EMCAS' agent architecture. The strategies of the individual players were determined by asking them to write short descriptions of their approaches after the completion of the game and then following up the writing with a series of focused interviews. Once the strategies were determined, agents implementing each of the strategies were programmed.

The individual agents developed to emulate the market game players were run using the same data originally used for the game. The resulting prices are similar to those found in the individual market game as shown in Figure 2. The main difference is that the prices near hour 40 are higher in the EMCAS case because the EMCAS agents were programmed to use the evolved final strategies of the players. Many of the market game players had begun the game using a relatively cautious approach to bidding. As the game progressed, they learned to become much more aggressive. For example, several players developed "hockey stick" strategies that have low prices for the majority of each generator's capacity followed by extremely high prices for the last few megawatts. This approach can be effective because players have little to risk and much to gain. The risk is minimal because the vast majority of their generation bids are likely to be accepted. The gain is potentially high because MCP pricing will assign the last few megawatts high prices to all generation during times of shortage. The result lends new meaning to the hockey term "high sticking."

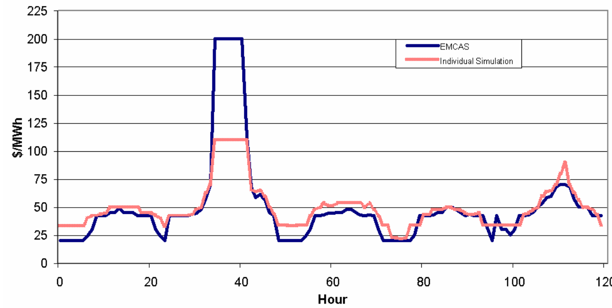


Figure 2: Market Clearing Prices - EMCAS versus Market Game

The EMCAS agents were programmed with the final, more aggressive strategies of the human players. Thus, EMCAS tended to have higher prices throughout the simulation. Once EMCAS was able to replicate the original market game, it was used to explore its suitability as an electricity market structure testing tool.

CHANGING THE RULES

To explore EMCAS' potential, several variations of the original market game case were created and simulated. These variations probed the effects of changing power plant outages and price setting rules on electricity market prices. As previously mentioned, EMCAS and its component agents are currently being subjected to rigorous quantitative validation and calibration. All of the EMCAS results presented here are intended to explore EMCAS' potential to be used as an electricity market structure testing tool. As such, they are not intended to represent complete analyses of the issues described.

Figure 3 shows the results for the baseline case. This EMCAS run assumes a Pay-MCP market without power plant outages with prices closely following the assumed daily load pattern. The first variation to the base case that was tested was the effect of power plant outages in a Pay-MCP market. The hourly prices are shown in Figure 4. In this example, the overall effect of power plant outages is to greatly increase market prices during periods of peak demand. This suggests that an important concern for regulators setting pricing rules is the relative balance between system supply and demand. In particular, systems that have demands that approach the maximum generation supply may experience significant price spikes under Pay-MCP. Such systems might fare better under Pay-as-Bid because they could potentially be victimized by strategies such as high sticking.

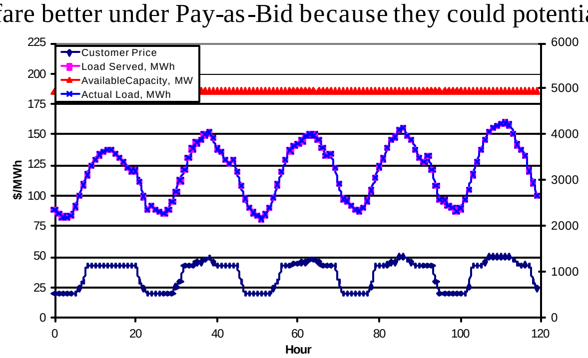


Figure 3: Pay-MCP without Outages

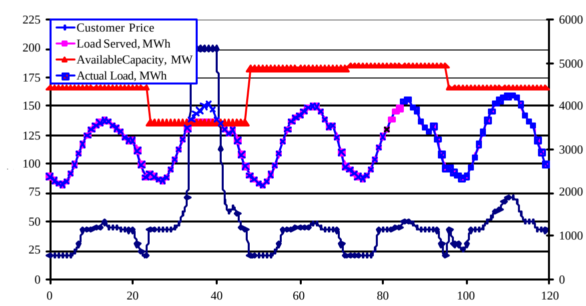
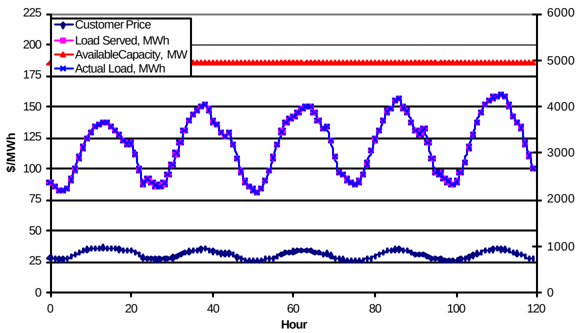


Figure 4: Pay MCP with Outages

In the second variation, the market was set up as Pay-as-Bid. Agent pricing strategies were suitably modified to reflect the new price setting rule. The actual hourly loads, the hourly loads served, the available generation capacity, and the resulting hourly prices are shown in Figure 5. In this case, all of the loads were served, so the actual hourly loads and the hourly loads served are the same. In this example, the overall effect of Pay-as-Bid is to noticeably reduce price fluctuations. This observation suggested a third experiment.

The third variation looked at the effect of Pay-as-Bid price setting with power plant outages. As before, agent pricing strategies were suitably modified to reflect the price setting rule. The hourly prices are shown in Figure 6. As with the previous Pay-as-Bid example, in this run, the overall effect is to substantially reduce price volatility compared to Pay-MCP, particularly during times when high demands intersect with reduced supplies.



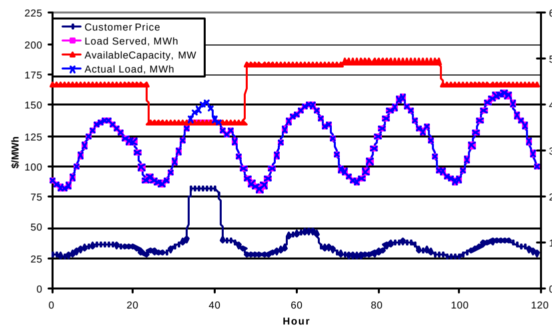


Figure 5: Pay-as-Bid without Outages **Figure 6: Pay-as-Bid with Outages**

THE PROFIT MOTIVE

Considering the lower and more stable prices found under Pay-as-Bid, it appears that this form of pricing is better for consumers under this simplified model run. Producers, however, may have a different view. While prices are lower and more stable under Pay-as-Bid, producers lose money under this approach, as shown in Figure 7. Naturally, unprofitable markets tend to drive producers out. This can greatly reduce long-term competition and result in cyclical price trends with long periods. Clearly, market rules must balance the interests of producers and consumers in order to preserve long-term market stability.

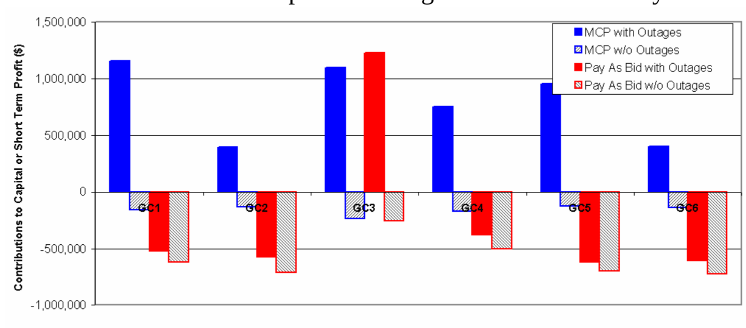


Figure 7: Generation Company Profits under Various Market Rules and Outages Regimes

CONCLUSIONS

As electric utility systems around the world continue to move toward open, competitive markets, the need for new modeling techniques will become more obvious. Although traditional optimization and simulation tools will continue to provide many useful insights into market operations, they are typically limited in their ability to adequately reflect the diversity of agents participating in the new markets, each with unique business strategies, risk preferences, and decision processes. Rather than relying on an implicit single decision maker, ABM techniques, such as EMCAS, make it possible to represent power markets with multiple agents, each with their own objectives and decision rules. The CAS approach allows analysis of the effects of agent learning and adaptation. The simple test runs presented in this paper clearly demonstrate the value of using EMCAS as an electricity market structure testing tool, where regulatory structures can be tested before they are applied to real systems.

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