A Model and Simulation of Competitive Electric Power Systems

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Abstract-- A framework for analyzing competitive electric power systems has been developed. A model and simulation based upon the framework, as well as applications and extensions, are presented. The applications include an analysis of the potential gains from trade of a large-scale synchronous interconnection between the Electric Reliability Council of Texas (ERCOT) and the Southwest Power Pool and a study on market concentration in ERCOT. Extensions to simulate strategic behavior and to compare bilateral and centrally dispatched markets are also discussed. The model and simulation, collectively referred to as the Generalized Competitive Electric Power System Model (GCEPSM), incorporate object classes to represent basic market players and functions and allows for user specification of market parameters and structures.

1 Introduction

The once firm foundation of the electric utility industry, previously grounded in principles of natural monopoly, is eroding. The promises of restructuring include more efficient allocation of resources, more responsive and transparent pricing, enhanced customer service, lower costs and rates, and greater customer choice and flexibility. Though recent events have challenged this notion, there is general agreement that given proper structure and controls, competition and market discipline can still deliver many of these promises. Not surprisingly, great debate centers on the cause of past failures and the optimal structure to overcome them.

Because the evaluation of competitive power system structures is a topic of great interest and importance, there are several groups creating simulations of electricity markets[1]. These simulations offer a range of capabilities, with some modeling various aspects of the system better than others. Each allows for the control of generation and load and each includes some representation of a transmission and distribution system; however, shortcomings remain.

To examine issues surrounding the debate over market structure and to attempt to address shortfalls of other simulation tools, the Generalized Competitive Electric Power System Model (GCEPSM) was developed. In particular, the GCEPSM offers a means to perform detailed studies of various scenarios of interest, including comparisons of different market structures, transmission tariff designs, and the strategies, numbers and strengths of participants. This paper briefly describes the GCEPSM. Section 2 introduces the structure and major object components and features. Section 3 presents several

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[1] Some groups with products or work in this area include:
Intelligent Energy Systems Pty Limited, www.intelligentsys.com.au; Henwood Energy Services Incorporated, www.hesinet.com,; PowerWorld Corporation, www.powerworld.com; Electric Power Research Institute, http://vulcan.ee.iastate.edu/~sheble/download.html; Energy Modeling Forum, www.stanford.edu/group/EMF.

applications and extensions of the basic GCEPSM. These include a gains-from-trade analysis, tariff comparisons, bilateral and pool-based implementations, a single strategic player extension, and a model of the Spanish power pool. Finally, Section 4 closes with some concluding comments.

2 Model Features and Structures

This section presents a general description of the Generalized Competitive Electric Power System Model (GCEPSM), introducing the basic features, object prototypes, and overall simulation procedure. Particular applications, to be described in Section 3, require specification of the exact model and dictate the resulting version.

2.1 Features

The model represents features of the electric system along several dimensions: geographical, temporal, and electrical. These are described in the following subsections.

2.1.1 Geographical

The generation units and loads are distributed throughout multiple "areas" and "regions." Areas are aggregations of supply and demand entities in the system, and regions consist of areas. Areas and regions are typically based on physical geography, but they could be based upon the electrical layout of the system. The user determines the number and scale of areas and regions.[2]

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[2] In the current implementation, the number of areas and regions and the numbers of the other features described in this section are specified at compile-time; however, in a future implementation, these will be specified at run-time.

The arbitrary nature of scale is an important feature in lending flexibility to the approach. For example, areas may correspond to service territories of utilities, and regions may correspond to reliability councils. In this case, areas might be Austin Energy and the Lower Colorado River Authority, while the region may be the Electric Reliability Council of Texas (ERCOT). If the scale were larger, ERCOT could instead be specified as an area with North America as the region. For a smaller scale, the area could be specified as the campus of The University of Texas at Austin, with the region being the city of Austin. Implementations of the GCEPSM with as many as 4,000 separate supply and demand entities in 27 areas have been constructed.

2.1.2 Temporal

In addition to geographical aggregations of the system, there are also aggregations of time. Any feasible number of time periods of arbitrary and varying length can be modeled. For example, 8,760 periods can be defined to represent each hour of a year, or there may be 100 periods with one for each season for a quarter century. In the current implementation, time periods are independent of each other so that start-up costs and other inter-temporal issues are not explicitly represented.

There are also additional, so-called “non-time” periods which are used when system states are desired that exist outside the time frame under study in the model. An example is a system peak load period in a simulation that models a year using the average load of each month. The periods for the months are “time” periods, while the peak period would be considered a “non-time” period. This non-time period information allows for the consideration of reserve margins at the time of the peak. In tabulating statistics for the year such as total energy served or total energy generated in a particular area, only the time periods would contribute. Each period can be of different duration.

2.1.3 Transmission and Distribution

A feature that sets competitive electric power systems apart from traditional commodities markets is the transmission and distribution system. In addition to the number and scale of areas and regions, the interconnection between them must be specified as well. The GCEPSM must therefore allow for the representation of a transmission system. All implementations to date of systems with limited transmission capability have modeled transmission as an area-to-area pipeline network. The Independent System Operator for ERCOT has used a pipeline model, and an attempt to model ERCOT made a pipeline a natural choice. However, the modular design of the GCEPSM allows for the substitution of a loadflow-based model for the pipeline model in a later enhancement to the model.

Regardless of how transmission is modeled, there will typically be a cost associated with access to and use of the power grid. For versions with point-to-point transmission tariffs, the model applies tariffs for transactions between buyers and sellers in the system. These tariffs can be a combination of: a "postage-stamp" rate where one price allows access to any point in the network and a distance sensitive rate. This structure was designed to capture the essential characteristics of the ERCOT tariff. The GCEPSM does not contain explicit physical distance information. However, since the model can use the locations of the seller and the buyer, virtually any distance-based tariff can be represented. In addition to transmission tariffs, there can be other transaction costs.

2.1.4 Extensions

Another important feature of the GCEPSM is modularity of design. The object-oriented nature of the simulation allows for classes to be updated or changed without requiring a significant re-write or overhaul. Replacing the pipeline transmission network with a loadflow-based network is one example of this flexibility.[3] Modularity not only allows for incremental improvement but also increases flexibility with respect to scenario comparisons.

2.2 Object Prototypes

Just as some features are common to all simulation implementations, each particular study uses a prototypical simulation structure with several basic object classes. These object classes are described in the following sub-sections. Because some supply-side and demand-side components have analogous characteristics, one object class is sometimes used to represent both components. There are also object classes that are not fundamental to the model but are used in each simulation to facilitate operation. In the following subsections, the actor, center, message, broker, system operator, and network classes are described.

2.2.1 Actor

The actor object class represents the seller and buyer components. Actors aggregate supply and demand entities by ownership, in part, to perform revenue and profit calculations. Sellers and buyers are functionally analogous, therefore, only one object class is used. Actors contain information regarding their identity, the logic of their constituent entities, and their financial situation. The identity is merely a name for the actor. The logic determines the way in which an actor behaves. One type of logic, for example, is to act completely truthfully and competitively. An actor may instead be strategic and anti-competitive. Finances are represented as a cash amount, and revenues from operation will impact this cash amount.

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[3] Again, in the current implementation, such changes are generally accomplished by recompiling the code. Future versions will allow these alternatives to be specified in a data file.

Each actor maintains a listing of all supply and demand entities under its control. Other functions include the ability to add or remove production or consumption units from the internal list, generate asks and bids based upon the logic and units under control, and otherwise interact with the market to disclose or discover information such as market outcomes.

2.2.2 Center

Centers aggregate supply and demand entities by geography in order to specify and enforce transmission constraints and tariffs. Just as sellers and buyers need only one object class for representation, so too do generation and load centers. An instance of the center object class can be a generation center or a load center. In either case, the types of data and functions performed are essentially the same. Much like actors, centers have an identifying name. Unlike an actor, however, a center must be associated with a location. A number of parameters characterize the supply or demand function. A maximum capacity may also be specified. Each center may also track its financial status and adjust its cash account by revenues from operation or value from consumption.

2.2.3 Message

The message object class defines the asks and bids that actors create. This common message structure allows for great flexibility. Actors under various regulatory schemes will submit asks and bids that are structurally similar. As a result, changes in system design, such as from centralized to distributed dispatch, do not require that every other element in the simulation be changed. Messages contain information concerning four main areas: identification, timing, pricing, and quantity.

The identification portion stores the identity of the originating actor, the executing actor, the executing center, and any location or additional information. The originating actor may be the same as the executing actor. The timing section specifies when the ask or bid starts and stops, or whether the ask or bid is valid over a window of time and for what duration. If the timing arrangements are set out and standardized by market design, this information may be unnecessary. Pricing contains information on the cost or value characteristics of the ask or bid. The quantity portion defines the maximum and minimum size of transaction for the message. The maximum and minimum refer to the absolute limits of the message quantity and have a physical basis.

2.2.4 Broker

2.2.4.1 Bilateral Markets

The primary role of the broker in a bilateral market is to match asks and bids. Therefore, instances of the broker object class must interface with actors and the System Operator (SO) component. Brokers communicate with actors by using messages. How the matching is performed depends upon market design. In general, for bilateral markets, the broker forms proposed transactions and submits them to the SO. The SO can then approve, curtail, or fully reject the proposal. The broker charges a fee and tracks its own financial performance.

2.2.4.2 Pool-Based Markets

In a pool market, the SO will accumulate messages and perform the central dispatch. The broker serves to convert the message data structure from the actors into a form usable by the dispatching function. The broker also converts the results from the dispatching function into messages that the actors can understand. Therefore the broker in the centralized dispatch implementation does not perform a true market role but acts as a data translator.

2.2.5 System Operator

2.2.5.1 Bilateral Markets

The SO must manage use of the network. The SO understands the transmission tariff structure and imposes such tariffs on transactions. A broker may query the SO as to the tariffs, and it can submit proposed transactions for approval. The SO has the authority to curtail or reject the proposed transactions. This determination is dictated by rules designed into the SO and by system conditions. These system conditions are based on the understanding of the SO and loading on the physical network. The SO also collects transmission payments, distributes revenue to the appropriate parties, and takes the role of a transmission limit enforcer and tariff administrator.

2.2.5.2 Pool-Based Markets

In pool-based markets, the SO performs the centralized dispatch for the system. For pool-based implementations thus far, a linear program is used to dispatch the system.

2.2.6 Network

In order for the SO to evaluate the state of the transmission and distribution (T&D) system, it must have access to the physical network. The network object class represents this physical entity. The network does not have any intelligence or judgment, whereas the SO does. In implementations to date of systems with limited transmission capability, the network is a point-to-point pipeline model with simultaneous import and export limits.

2.3 Simulation Process

The basic simulation proceeds through discrete units of time, and each period is composed of several steps. With each step, players make their decisions and execute their actions. The basic steps for bilateral contracts are outlined below.

Step B1. Sellers/Buyers submit asks/bids to SO via Broker
Step B2. SO returns contracts/curtailments
Step B3. "World" object simulates physical operation
Step B4. Accounts are settled
Step B5. Goto Step B1 and start next period

The basic steps for the pool-based simulation process are outlined below.

Step P1. Sellers/Buyers submit/bids to the pool via Broker
Step P2. Pool determines dispatch and informs players
Step P3. "World" object simulates physical operation
Step P4. Accounts are settled
Step P5. Goto Step P1 and start next period

The steps of both systems closely resemble each other, and so switching from one structure to another or to a variation in between does not result in the need for major change in the fundamentals of the operation of the simulation.

2.4 Summary

The basic features, functions, and parts of the GCEPSM have been presented. Additionally, object prototypes were described along with a listing of steps in the simulation process. While generic, these examples lay the groundwork for understanding a fully specified implementation, several examples of which will be presented in the next section. This groundwork clarifies the presentation of specific versions of the GCEPSM that have been created. Each version shares the same fundamental components, though their exact makeup and behavior may be quite different from one version to the next. As the particular application of the GCEPSM changes, the features included also change.

3 Applications and Extensions

The GCEPSM has been applied to several case studies and implemented to demonstrate fundamental design concepts. Some of these applications and extensions are described briefly below and include:

gains-from-trade from an expanded interconnection,
market concentration calculation,
single strategic player behavior,
centralized and distributed dispatch comparison,
simulation of the Spanish power pool.

These case studies are described in detail in the following sections.

3.1 Gains-From-Trade and Alternate Tariffs

A substantial case study for the Synchronous Interconnection Committee (SIC) was performed (Avera 1999). The SIC was established by the Texas Legislature to examine issues surrounding the creation of a large-scale synchronous interconnection between the Electric Reliability Council of Texas (ERCOT) and the Southwest Power Pool (SPP). The GCEPSM was applied to investigate the potential gains-from-trade offered by an expanded market.

Twenty-seven areas in two regions represented ERCOT and simplified portions of the Eastern Interconnection including the SPP. The ERCOT region contains 11 areas while the Eastern Interconnection region has 12 areas from the SPP and four additional areas representing portions of the Eastern Interconnection surrounding the SPP. The areas are shown in Figure 1.

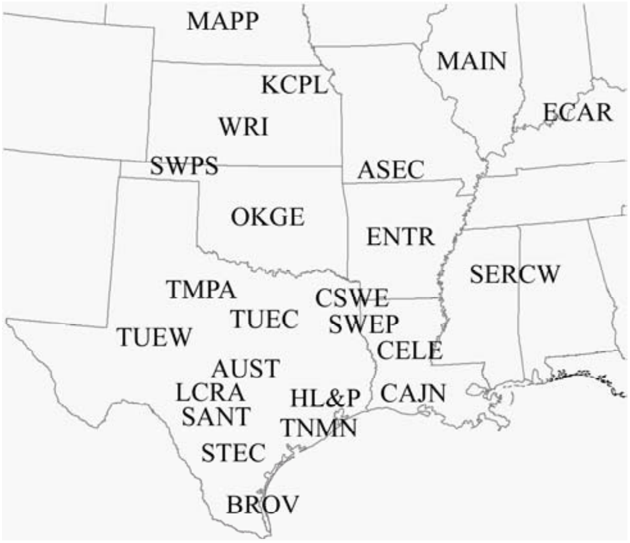

Figure 1. Diagram with approximate locations for most areas used for the SIC gains-from-trade study. The two areas not shown are geographic aggregations for areas in northern and central SPP.

Historical loads for 1996 and projections for 2003 were used with 36 periods in each year. To evaluate the benefits of synchronous interconnect, gains-from-trade were defined as the difference in total cost to serve load between: 1) the existing DC interconnection and 2) the proposed synchronous interconnection.

The results for the base-case assumptions are summarized in Table 1. Several sensitivity cases were also run, including increased and decreased fuel prices, different demand levels and patterns, and alternate tariffs. The results for reduced tariffs based only on marginal losses are also shown in Table 1.

Gains From Trade Summary

Year	Tariff	Gains
1996	base	12.6
1996	reduced	107.5
2003	base	4.1
2003	reduced	31.0

Table 1. Summary of gains-from-trade of the SIC study, in millions of dollars, for the base case transmission tariff and the reduced transmission tariff.

3.2 Market Concentration

Another topic of study performed for the SIC included effects on market power. Staff of the Public Utility Commission of Texas (PUCT) used a modified version of the gains-from-trade GCEPSM implementation to measure market concentration using the Hisrchman-Herfindahl Index. Full results are reported in Chapter 7 of the SIC report (Avera 1999). The PUCT staff concluded that the proposed synchronous interconnection would have had a modest mitigating effect on market concentration in 1996 and little effect by 2003.

3.3 Single Strategic Player Behavior

A more direct investigation of market power involved an extension to allow for a seller to behave strategically by manipulating its own ask price (Lin 1998). The strategic player adjusts the ask price for its power while the asks and bids from all other market participants remain fixed. By repeating the simulation of a period, the GCEPSM implementation allows the strategic player to determine the best set of asks to maximize its profit. Figure 2 illustrates the excess profit evolution over several iterations. Excess profits are the profits that exceed the level received if the player based asked strictly on marginal costs.

Figure 2. Excess profit evolution over 50 iterations for the single strategic player, AUST.

The strategic player, AUST, increases its ask price, and thus its profit. At some price level, however, the ask prices from AUST are sufficiently high to price the last block of power offered out of the market. In this case, the quantity of profitable power sold is reduced resulting in a decrease in profits from the previous iteration. The strategic player then reduces the ask price to be more competitive. This continues until AUST converges on the most profitable set of ask prices.

3.4 Centralized and Bilateral Dispatch Comparison

To demonstrate the flexibility to model bilateral contracts markets as well as those with centralized dispatch, the implementation for the bilateral trades system in the SIC case was modified for centralized dispatch. A linear program was used to perform centralized bid-based dispatch. Only modest modifications were needed to convert the broker into a data format translator to facilitate connection between the actors with their messages and the linear program used to dispatch the entire system.

A run using the distributed dispatch version was performed using input data changes to make the system comparable to that of the centralized dispatch version. In particular, transmission tariffs were set to zero and no transmission limits were enforced. The total cost of service was equal in both implementations, as expected. In future work, we hope to compare bilateral and pool markets when significant transmission congestion exists.

3.5 Simulation of the Spanish Power Pool

As a further test of flexibility, the GCEPSM was applied to the Spanish power pool. Two implementations were made: one using the same linear programming modifications for a centrally dispatched system, and another using a bilateral broker. Using data from a study by the Comisión Nacional del Sistema Eléctrico (CNSE) (Ocana 1998), the GCEPSM versions attempted to match the results from the CSNE. The study includes only thermal and pondage hydro units, a downward sloping demand function, four areas, and six time periods. For this and the original CSNE study, transmission limits and tariffs are not applied. The exact treatment of hydro resources for the CNSE study is not known; however, the results of one approach to modeling hydro dispatch within GCEPSM along with those reported by CNSE are listed in Table 2.

Comparison of Results Between CSNE and GCEPSM

	CSNE		GCEPSM	
Period	Output MW	Price PTA/kWh	Output MW	Price PTA/kWh
P1p	14,446	3.77	14,980	3.41
P1ll	14,445	3.77	14,980	3.41
P1v	11,621	3.43	11,820	3.28
P2p	11,834	3.42	12,075	3.28
P2ll	11,835	3.42	12,075	3.23
P2v	10,778	3.42	11,100	3.10

Table 2. Comparison of simulation results for the Spanish power pool. The GCEPSM implementation utilized scheduled pondage hydro dispatch with thermal units providing the remaining demand.

In the reported GCEPSM approach, hydro resources were dispatched fully. Less aggressive hydro usage would lead to higher prices and lower output. This may explain the differences in Table 2. GCEPSM results from the centrally-dispatched and bilateral versions agreed within the message block size resolution.

The study was unable to demonstrate an exact match between GCEPSM and CNSE. Lack of complete data regarding the CNSE inputs and their treatment of hydro resources required assumptions that may be responsible for the differences. This points to the fact that a host of implementation details can change the outcome of markets and also change the outcome of market simulations, so that a flexible tool such as GCEPSM is particularly useful in evaluating differences between the outcomes of two different market structures, while keeping all other issues the same.

4 Conclusion

The Generalized Competitive Electric Power System Model was developed to allow for flexible modeling of various market structures. Several implementations of the model were created to demonstrate the concept. These versions include a large case study to estimate gains-from-trade with modifications to measure market concentration, an extension to directly model strategic behavior, a centrally dispatched structure to compare with bilateral contracts structures, and application to details of the Spanish power pool. A future paper will describe the SIC study in detail.

While these implementations do not fully exploit the potential of the GCEPSM, they do demonstrate the flexibility of the approach. Essentially one model was applied to a wide number of diverse circumstances and contexts. Further development is clearly needed to refine the implementations. However, work to date lays a firm foundation for such improvements.

Acknowledgement

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