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An Agent-Based Computational Laboratory for Testing the Economic Reliability of Wholesale Power Market Designs

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Abstract— In April 2003 the U.S. Federal Energy Regulatory Commission proposed the Wholesale Power Market Platform (WPMP) for adoption by all U.S. wholesale power markets. The WPMP market design envisions day-ahead, real-time, and ancillary service markets maintained and operated by an independent system operator or regional transmission organization. Previous work reports on the development of an agent-based model for testing the economic reliability of the WPMP market design. This paper reports on the implementation of this model as an agent-based computational laboratory. Initial experiments focusing on optimal power flow solution methods for the day-ahead and real-time markets are also discussed.

I. Introduction

Electricity generators participating in restructured wholesale power markets must make repeated price and quantity offers for the sale of power. Typically the number of these generators is relatively small, and some have relatively large market shares. Moreover, generator supplies must continually be balanced in real time against the demands of load-serving entities in order to maintain the stable operation of the transmission grid.

These characteristics provide generators with a potentially large scope for the exercise of strategic behavior. They can use their offers as signaling or punishment devices in an attempt to support profitably higher prices across generators (general seller market power). They can also attempt to create locally profitable price spikes (local seller market power) either by withholding capacity from the market or by deliberately inducing congestion on local transmission lines to prevent the import of external power.

The summer 2000 meltdown in the restructured California wholesale power market is thought to have resulted in part from strategic generator behaviors encouraged by inappropriate market design features ([1], [19]). Other regions of the country, fearing similar disaster, have reacted by delaying or even halting their restructuring efforts.

For the restructuring of wholesale power markets, then, it is highly desirable to test the economic reliability of proposed market designs in advance of implementation. In the short run, the market designs should support the efficient production and allocation of power from existing facilities, as well as appropriate limitations on the ability of market participants to exercise market power through strategic behavior. In the longer run, the market designs should encourage the efficient development and siting of new transmission lines and new generation capacity.

In June 2002, the U.S. Federal Energy Regulatory Commission (FERC) issued a Notice of Proposed Rulemaking advocating a standard market design for common adoption by all U.S. wholesale power markets [6]. After an extended period of discussion and criticism, FERC issued a White Paper [7] proposing a revised design referred to as the Wholesale Power Market Platform (WPMP).

The WPMP design encompasses real-time and day-ahead markets, ancillary services, and the recommended use of locational marginal pricing and tradable financial transmission rights. All of these aspects are to be overseen either by an Independent System Operator (ISO) or a Regional Transmission Organization (RTO). FERC highlights four primary objectives for this design. First, it should establish a customer-based competitive wholesale power market providing reliable service. Second, it should ensure fair and open access to the transmission grid at reasonable prices. Third, it should induce good price signals to encourage appropriate investment in new generation and transmission. Fourth, it should provide for effective market oversight and market power mitigation.

Variants of the WPMP design have been implemented or accepted for implementation in several regions of the U.S. The basic WPMP architecture was strongly influenced by the wholesale power market designs implemented in the 1990s by the ISOs in New York (NYISO) and the Mid-Atlantic States (PJM). In March 2003 the ISO in New England (ISO-NE) implemented a Standard Market Design (SMD) which is in basic compliance with FERC's originally proposed standard market design and hence also with the WPMP. The California ISO (CAISO) filed to adopt the WPMP soon after the issuance of FERC's White Paper. The Midwest ISO (MISO) filed for adoption of the WPMP in July 2003, withdrew this filing in October 2003 due to strongly expressed stakeholder concerns, and then refiled in May 2004 for adoption in March 2005. Texas (ERCOT) currently plans to launch a version of the WPMP in October 2006.

On the other hand, strong opposition to the WPMP design persists among stakeholders in the Southeast and the Northwest, and even in regions such as the Midwest which have filed to adopt the design. Much of this opposition appears to arise from three perceived concerns: inadequate reliability testing of the WPMP design; stranded costs and benefits; and inadequate accommodation in the WPMP design for special local conditions (e.g., relatively heavy reliance on hydroelectric power in the Northwest).

Unfortunately, the complexity of the WPMP design makes it difficult to test its economic reliability using standard analytical and statistical tools. A recent statistical study [4] by the U.S. Department of Energy investigates the potential for consumer cost savings under the original standard market design [6] proposed by FERC. However, this DOE study includes many cautions regarding modeling assumptions introduced for reasons of analytical and statistical tractability (e.g., continual market equilibrium, absence of strategic bidding, and demand held constant across tested cases). Moreover, no attempt is made to assess overall market efficiency or market power impacts.

Research groups at a number of different institutions are now undertaking the agent-based modeling of wholesale and retail electricity markets.[1] In particular, Koesrindartoto and Tesfatsion [16] report on their development of an agent-based model for testing the economic reliability of the WPMP design in advance of implementation. Specifically, this model consists of strategic generators and load-serving entities participating in a dynamic ISO-operated wholesale power market whose architecture embodies core features of the WPMP design as implemented in New England's SMD. This appears to be the first agent-based model specifically designed to study the WPMP/SMD protocols.

The present paper reports on the implementation of this WPMP/SMD model as a computational laboratory using Repast,[2] a toolkit designed specifically for agent-based modeling. This computational laboratory, referred to as AMES (Agent-based Modelling of Electricity Systems), is being used to test the extent to which the core WPMP/SMD protocols are capable of sustaining efficient, orderly, and fair market outcomes over time despite attempts by market participants to gain individual advantage through strategic pricing, capacity withholding, and induced transmission congestion.

II. The Basic AMES Framework

A. Background: WPMP/SMD Design Features

Locational Marginal Pricing (LMP) is the pricing of electrical power according to the location of its withdrawal from, or injection into, a transmission grid. The idea of LMP for power markets was apparently first advocated in [25]. In recent years it has gained widespread acceptance as the correct pricing approach for wholesale power markets restructured as centralized or pool-based trading systems managed by some form of system operator.

The LMP at any given pricing location k on a commercial network overlaying a physical transmission grid is the minimum incremental cost of servicing one additional unit of load (i.e., demand) at k, taking into account production costs, congestion costs, and transmission losses through energy dissipation. Congestion costs and transmission losses can arise if the least-cost servicing of the additional unit of load requires additional generation at a pricing location other than k.

In July 2002, FERC issued a Notice of Proposed Rulemaking (NOPR) advocating the common adoption of a standard market design by all U.S. wholesale power markets [6]. This design was based on an LMP approach to the pricing of power. Specifically, it called for the establishment of wholesale power markets incorporating the following core features as a complement to direct buyer-seller bilateral procurement:

- A transmission system operated by an independent transmission organization;
- Administration by the independent transmission organization of a day-ahead market for forward financial contracts and a real-time (spot) market for balancing and settlement;
- Transmission congestion management by means of LMP;
- Provision of tradable Financial Transmission Rights (FTRs) in the day-ahead market as a means to lock-in a fixed price for transmission service;

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[1] These institutions include the Los Alamos National Laboratory, the Argonne National Laboratory, Carnegie-Mellon University, CSIRO-Australia, Helsinki University, Iowa State University, London Business School, the Pacific Northwest National Laboratory, and the Sandia National Laboratory. See [28] for annotated pointers to some of this work. See also [12] and [29] for introductory readings and web resources on agent-based economic modeling.

[2] Originally developed by researchers at the University of Chicago and the Argonne National Laboratory, Repast is now managed by the non-profit volunteer organization ROAD (Repast Organization for Architecture and Development). See [30] for a comprehensive Repast self-study guide that includes annotated links to readings, tutorials, and software downloads.

- Provision of ancillary services (e.g., regular resource adequacy assessments to ensure real-time balancing of power inflows and outflows);
- Procedures for monitoring and for market power mitigation in the real-time market.

The New England wholesale power market constitutes part of the Eastern Interconnect, a large AC transmission grid that serves the majority of the Eastern United States and parts of Canada ([2],[3]). The New England Independent System Operator (ISO-NE), created in 1997, is a not-for-profit organization responsible for the administration of New England's wholesale power market. On March 1, 2003, the ISO-NE implemented the Standard Market Design (SMD) for the New England wholesale power market. As explained in the ISO-NE's SMD Reference Guide [9], the SMD is fully compliant with the standard market design proposed in FERC's 2002 NOPR.

In April 2003, in response to comments received on its 2002 NOPR, FERC issued a White Paper in which it revised its originally proposed standard market design in three principal ways [7]. First, it clarified the requirements for an ISO or Regional Transmission Organization (RTO) to qualify as an independent transmission organization. Second, it clarified the requirements for market power mitigation. Third, it relaxed several requirements of the original standard market design to allow for more regional flexibility (e.g., use of LMP and FTRs to manage congestion is now strongly recommended rather than required). The revised standard market design was named the Wholesale Power Market Platform (WPMP). New England's SMD remains in close conformity with this revised standard market design.

B. Overview of AMES

Our primary objective is to test the economic reliability of the basic WPMP design by means of systematic computational experiments. As explained in Section II-A, the Standard Market Design (SMD) implemented for the New England wholesale power market in March 2003 is a rubber-meets-the-road implementation of the WPMP design.

Our computational laboratory implementation of a wholesale power market - referred to as AMES (Agent-based Modelling of Electricity Systems) - incorporates in stylized form several core elements of the WPMP design as implemented in New England's SMD. By adhering closely to the architecture of the SMD, we are able to take advantage of the voluminous SMD training guides, operational manuals, and reports publicly released by the ISO-NE for the use of ISO-NE senior personnel and general market participants. These publications provide a wealth of specific implementation details missing from the more abstract WPMP template.

The two primary guidelines used for the construction of AMES have been Market Rule 1 [10] and Operations Manual M-11 [11]. Market Rule 1 lays out general provisions applicable to the operation of the SMD, including an overview of market operations, calculation of LMPs, and accounting and billing procedures. M-11 details the rules and regulations governing the schedule and dispatch of resources in the SMD. Specifically, it describes the flow of activities in the market one day prior to a typical Operating Day as well as during a typical Operating Day and within a typical Operating Hour.

AMES incorporates the following six core features of the WPMP/SMD architecture:

1) The participants in the AMES wholesale power market include an Independent System Operator (ISO), a collection of Load-Serving Entities (LSEs), and a collection of Generators.[3]
2) The AMES ISO undertakes the daily management of a Day-Ahead Market and a Real-Time Market, as well as a Supply Re-Offer period for Generators.
3) The AMES ISO determines commitments and LMP pricing for the Day-Ahead Market based on Generator supply offers and LSE demand bids (forward financial contracting);
4) Any differences that arise at settlement from the contracts cleared in the Day-Ahead Market are settled by the AMES ISO in the Real-Time Market at real-time LMPs.
5) The AMES wholesale power market operates over an AC transmission grid.
6) Transmission grid congestion is managed via the inclusion of congestion components in LMPs.

AMES is a fully modular and extensible framework, capable in principle of handling realistically dimensioned transmission grids as well as additional architectural features of the WPMP/SMD design. As explained in the following section, however, we are initially focusing on demonstration models operating over small-scale transmission grids that have from two to five buses (branch connection points).[4]

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[3] An ISO is an organization charged with the primary responsibility of maintaining the security of a power system and often with system operation responsibilities as well. The ISO is "independent" to the extent that it does not have a conflict of interest in carrying out these responsibilities, such as an ownership stake in generation or transmission facilities within the power system. An LSE is an electric utility, transmitting utility, or Federal power marketing agency that has an obligation under Federal, State, or local law, or under long-term contracts, to provide electrical power to end-use (residential or commercial) consumers or to other LSEs with end-use consumers. An LSE aggregates individual end-use consumer demand into "load blocks" for bulk buying at the wholesale level. A Generator is a company that produces and sells electrical power in bulk at the wholesale level. For more precise definitions as set out by the North American Electric Reliability Council (NERC), see [20].

[4] Here we follow the dictum of Kirschen and Strbac [15, p. 175]: "Never trust a technique proven on the basis of a two-bus system."

III. Experimental Design

A. Overview

AMES permits systematic experimentation to explore the sensitivity of wholesale market performance to changes in structural features and behavioral assumptions when the market is operating under basic WPMP/SMD protocols. Six issues of particular interest have been selected for this long-term project:

(1) What effects on Optimal Power Flow (OPF) and LMP solutions are observed when the AMES ISO uses alternative solution methods (e.g., DC power flow approximation) for Bid-Based Security-Constrained Unit Commitment (BSCUC) and for Security-Constrained Economic Dispatch (SCED) in the Day-Ahead Market and the Real-Time Market, respectively?

(2) What effects on market performance are observed when the AMES Generators use alternative learning methods to determine their supply offers for the Day-Ahead Market?

(3) What effects on market performance are observed when the AMES LSEs use alternative learning methods to determine their demand bids for the Day-Ahead Market?

(4) What effects on longer-run market power outcomes are observed for different initial specifications of relative market concentration (i.e., the number and sizes of Generators relative to the number and sizes of LSEs)?

(5) What effects on market performance are observed when market participants are permitted to purchase Financial Transmission Rights (with or without a secondary market for resale)?

(6) What effects on market performance are observed when market participants can self-schedule bilateral trades?

The next subsection discusses in greater detail our planned experiments for issue (1).

B. OPF Solution Methods for BSCUC and SCED

Discussion:

The BSCUC and SCED activities carried out by the AMES ISO each involve the solution of an OPF problem. In the AMES Day-Ahead Market the objective function for the OPF problem is the maximization of total net benefits conditional on supply offers and demand bids and on various transmission-related constraints. In the AMES Real-Time Market the objective function for the OPF problem is the minimization of total variable cost conditional on uncleared day-ahead supply offers, any in-day deviations in generation and load from day-ahead commitments, and various transmission related constraints.

The Newton-Raphson method [31] is now commonly used in the electric power industry to determine solutions to OPF problems in either form. For example, based on his experiences as a principal engineer of power supply planning at ISO-NE, Rau [24, Chapter 8, Appendix B] considers a number of illustrative electricity markets both with and without demand-side bidding to reflect the organizational form of the day-ahead market and real-time market, respectively, in the ISO-NE. He uses the Newton-Raphson option provided in Microsoft's Excel Solver to obtain one-time OPF solutions for each of these illustrative markets.

Nevertheless, as is well known, realistically rendered OPF problems are complicated constrained nonlinear programming (NLP) problems that can be difficult to solve using the Newton-Raphson method. Convergence to a solution can be exceedingly slow if the surrounding region is "flat." The method can also become entrapped at local optima. Finally, the method can fail to converge within a practical amount of time (or at all) if the initial starting point is not sufficiently close to a solution point, or if calculations become ill-conditioned along the successive approximation path due to bifurcations or other nonlinear phenomena. The more complicated the nature of the constraints, the more likely these problems are to arise. Difficulties of similar magnitude are encountered applying other NLP solution methods as well, such as the lambda iteration method, general gradient methods, interior point methods, and various other approaches based on successive linear approximation. See, for example, the introductory discussion in [21].

In recognition of these problems, the ISO-NE regularly uses a linearized DC power flow approximation for security-constrained economic dispatch in the New England Real-Time Market. A full AC OPF analysis is only undertaken for "suspicious contingencies" [17, pp. 22-23,34], meaning contingencies whose indicated consequences appear to be more serious. This greatly simplifies and speeds up the required real-time calculations.

What evidence exists regarding the magnitude and potential importance of the errors resulting from linearized DC approximations? Overbye et al. [21, p. 8] conclude that, for the static (single period) comparative calculations they carried out for two specific case studies, a DC power flow approximation did a "fairly good job of revealing the congestion patterns that would actually occur using the full AC system model." Although significant deviations were found in the number of binding constraints, and in LMP values at some buses, the authors note that this is to be expected; small differences in branch flows can result in changes in the set of binding constraints, which in turn can result in discrete and potentially large differences in bus LMPs.

However, in a study of reactive power support examining the performance of a linearized DC approximation for the solution of a NLP reactive OPF problem, Pudjianto et al. (2002) were less sanguine about their findings. Although the overall reactive requirement calculated by the DC approximation was reasonably accurate, the authors found that the individual generator commitments resulting from the DC approximation varied considerably from the commitments resulting from the direct solution of the NLP reactive OPF problem using an interior point algorithm.

From an economic point of view, the sharp discrepancies found in these studies between the LMPs derived for a power system using a DC power flow approximation and the LMPs derived for the same power system using full AC power flow constraints is disturbing. LMP pricing in restructured wholesale power markets is supposed to provide correct signals for the efficient use of scarce existing transmission and generation facilities.[5] Moreover, it seems fair to say that little is known about the magnitude and importance of dynamic error accumulation when a DC power flow model is used in "tracking mode" to obtain approximate OPF solutions in rapid succession for a real-time market operating over an AC transmission grid, as in the ISO-NE.[6]

Treatment:

A core part of AMES is a RePast/Java module for generating OPF/LMP solutions both with and without demand-side bidding. Gross [8] and Weber [32] have been important guides in the development of our OPF problem formulation. Weber, in particular, discusses in great detail the possible application of the Newton-Raphson method to the solution of the classic OPF problem for AC transmission grids.[7]

The Weber OPF problem formulation has apparently been incorporated into a proprietary commercial software product, Simulator (PowerWorld Inc.), originally developed in [22]. Some non-proprietary software is available for OPF problems, such as the Matlab tookits PSAT (Power System Analysis Toolbox) developed by Milano [18] and MATPOWER developed by Zimmerman, Murillo-Sanchez, and Gan [33]. However, the vast majority of the available software products for solving OPF problems are proprietary.[8]

Moreover, we have been unable to find any open-source OPF software in Java, our chosen development language for AMES. Ultimately it might become necessary to port to a different language, perhaps with distributed processing, to ensure sufficient capability to handle power systems scaled up to more realistic dimensions. Scalability is particularly important for the most time-critical aspect of the WPMP/SMD: namely, security-constrained economic dispatch for the real-time market requiring accurate continually-updated assessments of real-time conditions in the overall power system ("state estimation"). For now, however, our basic aim is to develop a user-friendly wholesale power market framework permitting intensive computational experimentation on small-scale problems incorporating both strategic market participants and realistically rendered transmission constraints.

We are currently using the AMES framework to investigate the extent to which satisfactory OPF and LMP solutions can be obtained for the Day-Ahead and Real-Time Markets operating through time over an AC transmission grid under the WPMP/SMD protocols. Experiments are being conducted with both two-bus and three-bus transmission grids to explore the effects of loop-flow effects on market performance as we move from the two-bus to the three-bus case. In addition, we plan to investigate the nature of error accumulation when AC constraints are replaced by a linearized DC power flow approximation.

As a longer term goal, we also plan to explore the potential applicability to OPF problems of previously developed automatic differentiation, adaptive homotopy continuation, and nonlocal sensitivity techniques ([13], [14], [26], [27]). These techniques are designed for parameterized nonlinear systems of equations of the form $F(x, \beta^o) = 0$. Given relatively weak regularity conditions on the system function $F(\cdot)$, the techniques permit the accurate and efficient determination of system solutions $x(\beta^o)$ as well as the "nonlocal sensitivity" tracking of solution branches $x(\beta)$ as the parameter vector β moves along a specified path of interest. The techniques accomplish this by implementing three design criteria that could be critically important for OPF problems: (i) all derivative evaluations should be exact up to round-off and truncation error and automatically generated; (ii)

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[5] Whether LMP pricing is capable, even in principle, of providing correct signals for the efficient development and siting of new transmission and generation facilities remains controversial. See, for example, [15, p. 256].

[6] Tracking mode refers to the common practice of using a previously calculated solution as the starting point for calculating a next needed solution.

[7] As a cautionary note, Weber's otherwise excellent presentation of the AC OPF problem includes several typographical errors, duplicate uses of notation, and incomplete or delayed explanations of variable relationships which could be confusing for non-engineers.

[8] Examples of proprietary software that incorporates both an electricity market simulation component and real-time dispatch with OPF calculations include: EMCAS (Argonne National Laboratory); Gridview (ABB); LMPSIM (Shaw PTI); MAPS (General Electric); Marketecture (Los Alamos National Laboratory); PROMOD VI (Siemens AG); PROSYM (Henwood); and UPLAN (LCG). Examples of proprietary software that incorporates real-time dispatch with OPF calculations but no electricity market simulation component include: TRACE (EPRI); SCOPE (Nexant/PCA); Simulator (PowerWorld); PSSE/E (PTI); and IPSA/LMP (UMIST). Finally, DOE/EIA's well-known National Energy Modelling System (NEMS) incorporates an Electricity Market Module (EMM) but assumes unconstrained dispatch (no transmission constraints or costs); see EIA [5].

all algebraic operations should be replaced by ordinary differential equation operations to improve the stability of numerical operations; and (iii) the computation should be adaptive in the sense that the trajectory along which calculation proceeds adapts locally in order to step around regions where calculations become ill-conditioned, e.g., neighborhoods of saddle-node bifurcation points.[9]

IV. Conclusion

In this initial development phase, only core elements of the WPMP/SMD design have been incorporated into AMES and many simplifications have been made. However, AMES is modular and extensible. Additional aspects of the WPMP/SMD design can be incorporated at a later time to more fully reflect its dynamic operational capabilities. Chief among these aspects are ancillary services (e.g., operating reserves, regulation, and installed capacity), contingency analysis, and market power mitigation procedures. We envision the slow building up of AMES through an iterative participatory process involving stakeholders and researchers engaging in multiple loopings through a three-stage cycle: field study; model design; and computational experiments.

Our longer-run goal is to have AMES provide a useful component in larger-scale critical infrastructure frameworks encompassing regions of the U.S. where the WPMP/SMD design has been implemented or proposed for adoption.

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[9] Roughly, a saddle-node bifurcation for a parameterized system of equations is a parameter point where a solution branch splits into two distinct solution branches, or where two solution branches coalesce into one.

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