Electric Power Market Experiments with Optimal Topology Control

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Abstract

The purpose of this experimental study is to provide engineering students an energy trading experience in electricity market and to test a new topology control capability in a market with human participants. Students in electrical engineering department participated in repeated experiments using a developed in-house market-simulation software package. Proposed optimal topology control algorithm guarantees to find a better topology that meets at least the same N-1 contingency criterion and yields a better objective function value than the original topology does. A semi-definite programming solver is developed to find a lower bound for an optimal power flow problem. We observed a significant change in pricing when optimal topology control was employed. From direct exposure through participation and submitted reports, students were able to pick up on and intuitively understand how optimal transmission topology control method might yield the most favorable market results.

1. Introduction

Development of an energy market simulator is a trending topic in power economics. A simulator can be used as an excellent teaching tool to give students the opportunity to learn the fundamentals of power economics while participating in several market simulation experiments. The first web-based electric power market simulator was developed at Cornell University for teaching purposes in 1997 [1]. R. Zimmerman and R. Thomas designed a program called PowerWeb [2], a simulator that is still online and freely available to anyone for academic purposes. J. Bushnell and S. Borenstein developed an electric power market simulator as a teaching tool to be used at UC Davis and UC Berkeley, and it has been adapted and run in courses at various universities including Stanford, Yale, and MIT [3] with the main audience of this simulator being MBA students. Bushnell and Borenstein’s simulator covers the fundamentals of trading in energy market while neglecting many technical constraints that an electrical network typically experiences, resulting in a simulator suitable for those studying economics but not suitable for those studying electrical engineering. Q. Trinh and M. Saguan developed a simulator capable of comparing human behavior and computer behavior [4]. First year master students from an engineering department in KU Leuven, out of Belgium participated in these simulations. OPF formulation used in the research neglects several electrical constraints including transmission line flow limits and voltage reliability limits that have significant impacts on locational marginal pricing (LMP) and congestion managements [5-6]. Human subjects participated in experiments alongside artificially intelligent computer agents playing the role of human subjects. Many valuable contributions being reported on upon comparing the results gathered from both human subjects and computer agents. These results however, depend greatly on the quality of the computer agent algorithm, a parameter difficult to control.

We developed an electric power market strategy game for a course co-offered to senior undergraduate and graduate students. Students take on the role of the decision maker to decide offers for their electrical generator. A periodic but stochastic load is created for each trading period to represent the variance on real and reactive power demand. This load function is able to model different load levels in the order of non-peak, shoulder, peak, shoulder, and non-peak. The developed HTML-perl based software allows participants to log in into a restricted, locally hosted web page to join an open game-session. All the participants of the game submit their offers into the market for the current trading period, and a central dispatcher collects the offers for solving AC OPF using both MATPOWER software package [7] and our in-house SDP (semi-definite programming) package. In order to properly simulate a real market environment, the computation time was limited to find an optimal topology in 10 seconds.

We want to emphasize that our software package is flexible to accommodate current state-of-art policies to test on the market environments. For example, we may...
get an econometrically efficient solution using transmission topology control without sacrificing engineering reliability. While finding a solution for such a policy is in the research domain, we still need to determine the usefulness of the technique. One efficient way is testing with human subjects, and seeing how they explore the opportunities that the policy may bring. In our best knowledge, this is the first attempt present in power economics literature to implement transmission topology control with a full AC model into the economic dispatch problem within a market simulation.

This paper is organized as follows. Section 2 describes the method of grading and the rewards to mitigate the motivation gap. Section 3 explains the developed software package and structure of the market game. Section 4 describes the various market structures simulated in detailed structure and gives an algorithm for transmission topology control method. Finally, Section 5 shares the results of an experiment under uniform price auction structure with transmission topology control.

2. Cash Rewards and Grading

The experiments were held over a course offered during the spring semesters at the State University of New York at Buffalo. All students participated voluntarily in the market experiments, and they were rewarded with cash (their grades were independent with their earnings). Like other experiments described in Ref. [1], [2], we awarded cash according to the method for mitigating the motivation gap of the students [4]. A potential alternative way of mitigating the motivation gap is grading students according to the success in the experiments. Instructors of similar courses [3, 4] used grading as a reward in claim of increasing the reliability of the results gathered from the simulations; however, the authors of this paper believe that grading of the course should not be determined out of success in the experiment because a commonly used objective of electric power market is meeting the required power demand with the lowest operating cost.

For grading purposes; however, we asked students to submit one page essay after each set of experiments covering the following topics: what was learned from the experiment, which strategy they preferred to use, and what results their strategy yielded. By utilizing this method, we could follow the student's development as well as raising the opportunity to remedy any misunderstanding the student might have before the next experiment starts.

3. Simulation Platform

In this section of the paper, the methodology to collect the data will be described and the algorithm for finding a solution with topology control will be defined, and the quality of the collected data (experimental results) will be discussed.

The simulator is implemented in a combination of software including perl, MATLAB, Java, MySql, and HTML. The web server, database server, computational server, and perl CGI code all currently reside on an OSX based computer running Mountain Lion. The simulator uses an Apache web server and a MySql Database server supported by XAMPP [8]. The computational server uses MATLAB for all mathematical calculation including SDP OPF solution and MATPOWER [9] to find a solution to the AC OPF problem.

3.1. Simulation Software Package

The simulator starts with a secured HTML web page created for the students to securely log in the simulator with their own dedicated username and password. The main page allows students to choose either a multiplayer or a single player option. Single player option enables students to practice the game in their free time out of the scheduled experiment period. Students are allowed to create a single player session as many as they want. Secondly, multiplayer option is for the scheduled experiment period. Up to six users can join a multiplayer session to perform an experiment; however, the maximum number of users depends on the number of generators exist in the power network used. i.e., a modified IEEE 30-bus system [10] is used in the simulator and it has 6 generators. After all the users join the multiplayer session, the web browser is redirected automatically to the auction page. The auction page is an HTML web page embedded inside perl and Java code. It is the only page that allows participants to submit their offers for the trading period. The experiments were held during the 3-hour course period. In order to complete the whole experiment, students only have 2 minutes for each trading period to submit the offers. However, the time limit is a flexible variable in the software so that it may be changed according to the experiment needs.

The market participants submit price-and-quantity offers for their real power generation up to 5 blocks. The offer curve of each generator is created from the block offers submitted by the participants. An offer curve is an equivalent piece-wise linear function.

After all participants of the multiplayer session submit their offer by using the auction page, the offers
are collected by the computational server and are stored in the database server. The computational server runs MATPOWER to find the solution of AC OPF with the submitted offers. It also runs the in-house SDP solver to find the lower bound of the system cost for the original network topology. AC OPF problem minimizes the total operating cost of the system subject to real and reactive power balance equalities, maximum real and reactive power generation limits, voltage reliability limits, and transmission line flow limits. The mathematical formulation of the problem is given in Problem (1)

\[
\textbf{Optimal Power Flow problem (OPF)} \quad (1)
\]

\[
P_{g_i} - P_{d_i} = \sum_{i \in G} V_i (G_{ij} \cos(\theta_{ij}) + B_{ij} \sin(\theta_{ij}) \forall i \in N
\]

\[
Q_{g_i} - Q_{d_i} = \sum_{i \in G} V_i (G_{ij} \sin(\theta_{ij}) - B_{ij} \cos(\theta_{ij}) \forall i \in N
\]

\[
P_{g_i} \leq P_{g_i} \leq P_{g_i} \max \forall i \in G
\]

\[
Q_{g_i} \leq Q_{g_i} \leq Q_{g_i} \max \forall i \in G
\]

\[
V_i \leq V_i \max \forall i \in N
\]

\[
|S_{ij}| \leq S_{ij} \max \forall (i,j) \text{ and } (j,i) \in B
\]

where \( i \) and \( j \) are bus indices, \( f(P_{g_i}) \) is the piecewise linear offer function of the generator located at bus \( i \), \( P_{g_i} \) and \( Q_{g_i} \) are real and reactive power generation at bus \( i \) respectively, \( P_{d_i} \) and \( Q_{d_i} \) are real and reactive power load at bus \( i \), \( V_i \) is the voltage magnitude at bus \( i \), \( \theta_{ij} \) is the voltage angle difference between bus \( i \) and \( j \), \( G_{ij} \) and \( B_{ij} \) are the real and imaginary components of the admittance between bus \( i \) and \( j \) respectively. \( |S_{ij}| \) is the absolute apparent power flow from bus \( i \) to \( j \). \( P_{g_i} \max, Q_{g_i} \max, V_i \max \) are the maximum limits of real power generation, reactive power generation, and voltage magnitude at bus \( i \) respectively. \( S_{ij} \max \) is the maximum apparent power flow limit of the transmission line connecting bus \( i \) to \( j \). \( P_{g_i} \min, Q_{g_i} \min, V_i \min \) are the minimum limits of real power, reactive power generation, and voltage magnitude at bus \( i \) respectively. Finally, \( N \) is the set of the buses in transmission network, \( G \) is the set of buses associated with a generator, and \( B \) is a set of branches (transmission lines) connecting bus \( i \) to \( j \).

After a solution is returned, the results are saved into the database server to keep record, and the output data is sent back to the web server to announce the result. To sum up, a trading period in our software starts with collecting the offers from the participants and ends with showing the output data to the participants. Each experiment with 50 trading periods scheduled for 2-hour period of the course, with the rest of the course being reserved for discussion with the students on the strategies performed and on the analysis of the results gathered in the previous experiment.

4. Transmission Topology Control

Problem (1) finds a dispatch point to minimize the operating cost of the system subject to power balance equalities and technical limits in order to realize a reliable service condition. The way of transferring power from where it is generated to where it will be consumed is with the use of transmission lines. The combination of all transmission lines within a system is called transmission network where all lines except those down for maintenance are considered in operation and they are capable of transferring power to consumers.

Transmission topology control (transmission switching) is defined as a method to alter the transmission network in a way that leads to lower transmission losses [11]. Here, we are going to discuss transmission topology control with a different objective function. Recent studies have shown that incorporating transmission topology control into the economic dispatch problem can decrease overall operating cost [12], [13] so that we will keep our attention to minimize operating cost of the system as an objective function. However, this problem (the optimal topology control with AC power flow) is a mixed integer nonlinear program, which is computationally difficult to solve. Here, we also keep our attention in AC power flow rather than DC to create a realistic energy market environment for the students. We also would like to demonstrate the effects of the transmission losses and the voltage reliability limits in transmission topology control problem.

Even if a solution exists in MINLP, the computational time is long and impractical to use in a real energy market [14, 15]. In order to complete simulations with students in a class period, we implemented a tool for transmission topology control into our simulator with some limitations to decrease the computational time. It is worthwhile to note that the optimal topology must obey the “N-1 contingency criterion” imposed by FERC [13, 16] so does our simulator.

The first limitation is to allow only one transmission line switching in each trading period. Therefore, the simulator solves \( N+1 \) multiple economic dispatch problems in order to find the lowest operating cost, where \( N \) is the number of transmission lines. Figure 1 illustrates the flowchart of the algorithm described in this section. To the best knowledge of the authors, this is the first attempt in the literature exercising transmission topology control in a power
market simulation with the participation of human subjects.

### 4.1. SDP Relaxation of OPF

SDP OPF is a convex relaxation of classical AC OPF formulated in rectangular form by ignoring the \( \text{rank}(W) = 1 \) constraint, where \( W = xx^T \). Bai [17] first presented an SDP technique to solve AC OPF with no consideration of transmission line flow limits. Lavaei and Low [18] expanded the formulation of AC OPF with transmission line flow limits and proved that if the solution of SDP satisfies the rank-1 condition of \( W \), it can be surmised that the solution is the global optimizer for a non-linear AC OPF problem [19], [20], [21].

However, in general, the rank-1 condition is not satisfied which leads to an infeasible solution for (1). Therefore, the solution of SDP relaxation will only be considered as a lower bound of an AC OPF problem. This follows the principles of Lemma 1 as stated below.

**Lemma 1:** If the total operating cost of the system with the reconfigured network topology found by interior point method is less than the total operating cost of the system with the original network found by SDP, then the solution of OTC is guaranteed to be a better solution than the original network.

**Proof:** The solution of SDP is a lower bound for the original AC OPF. It guarantees that the global optimal solution of the original AC OPF yields a system cost higher than, or equal to that of the SDP solution. If a feasible solution gathered by OTC (switching a single line) returns a lower operating cost than that of the SDP solution, it has been proven that the reconfigured topology guarantees a globally better solution than the original network, i.e.:

\[
\text{Cost}_{\text{switching}}^{\text{MATPOWER}} < \text{Cost}_{\text{SDP}}^{\text{original}} \leq \text{Cost}_{\text{ACOPF}}^{\text{original}}
\]

where superscript and subscript represent the network topology and the solver used for finding solutions, respectively.

Here we will discuss a solution technique for SDP OPF. Computational time for solving an SDP OPF problem is extremely expensive when the size of the positive semi-definite (PSD) matrix \( W \) is quite large. Jabr [22] proposed a method to exploit the sparsity in SDP OPF problem. The idea of exploiting sparsity is first studied by Nakata et. al. [23], [24] for general SDP problems. It is proved that a large PSD matrix can be decomposed into several small size PSD matrices if and only if the graph is chordal.

Unfortunately, transmission networks cannot generally be drawn as a chordal graph. It is beyond the scope of this paper to discuss about graph theory; however, we are going to give an example to demonstrate our solution technique. Figure 2 shows a power network represented in a graph with 7-bus and 8 branches. Finding a chordal graph completion with minimum number of fictitious edges is an NP-hard problem [23], [25].
Molzahn [26] proposed a method to extend a transmission network graph to a chordal graph by forming a positive definite matrix out of relations of buses. The presented method here guarantees to extend on chordal graph; however, it doesn’t provide a minimum fill-in. We will define a relationship matrix where the blue and red boxes represent the nonzero elements of matrix factorization where the blue and red boxes represent real and fictitious edges respectively.

Let \( R \in \mathbb{R}^{n \times m} \) where \( n \) represents the number of edges, and \( m \) represents the number of vertices. If \( R_{ij} \) edge connects vertex \( i \) and \( j \), then \( R_{ij} = 1 \) and \( R_{ji} = -1 \), and all other components of \( R \) are zero.

\[
C = R^T \ast R + I
\]  

(2)

Eq. 2 gives a positive definite matrix where \( I \in \mathbb{R}^{m \times m} \) is an identity matrix. A symbolic Cholesky factorization \( (LL^T) \) with minimum degree ordering of resultant positive definite matrix \( (C \in \mathbb{R}^{m \times m}) \) gives a lower triangular matrix where the non-zero elements of \( L \in \mathbb{R}^{m \times m} \) after back permutation show the complete chordal extension of the given graph. Figure 3 shows the nonzero elements of matrix \( L \) after Cholesky factorization where the blue and red boxes represent real and fictitious edges respectively.

Nakata [23] proved that a large matrix can be completed to a PSD matrix if and only if all matrices created by maximal cliques are PSD. By using this fact, we formed our SDP OPF formulation with several small sizes PSD matrix constraints rather than having a large PSD matrix constraint. In SDP OPF formulation, the associated PSD matrix \( W \in \mathbb{R}^{2m \times 2m} \) is formed below for our 7-bus system.

\[
W^{14 \times 14} = \begin{bmatrix}
W_{11} & \cdots & W_{17} & W_{18} & \cdots & W_{114} \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
W_{14} & \cdots & W_{147} & W_{148} & \cdots & W_{1414}
\end{bmatrix}
\]

Instead of having a constraint of \( W \succeq 0 \) where \( (\succeq) \) represents positive definite matrix, we have 4 small size PSD matrix constraint reformed by maximal cliques. The first matrix associated with the first maximal clique given above is formed below; the rest can be formed accordingly.

\[
A^{6 \times 6} = \begin{bmatrix}
W_{11} & W_{15} & W_{17} & W_{18} & W_{112} & W_{114} \\
W_{51} & W_{55} & W_{57} & W_{58} & W_{512} & W_{514} \\
W_{71} & W_{75} & W_{77} & W_{78} & W_{712} & W_{714} \\
W_{91} & W_{95} & W_{97} & W_{98} & W_{912} & W_{914} \\
W_{121} & W_{125} & W_{127} & W_{128} & W_{1212} & W_{1214} \\
W_{141} & W_{145} & W_{147} & W_{148} & W_{1412} & W_{1414}
\end{bmatrix}
\]
Since the method presented here decomposes a PSD matrix into multiple PSD matrices, some elements of each individual matrix are actually equal so that the equality constraint for each element appearing in two or more matrices is needed in the formulation. The resultant SDP OPF problem with both small size PSD matrix constraints and associated equality constraints has exactly same feasible region as the problem with single PSD matrix.

Solving multiple small-size PSD matrices are computationally more efficient than solving a single large PSD matrix. A large scale OPF problem such as IEEE 300-bus system becomes solvable after the application of this method. The fastest solution presented at [26] to be 4.84 sec for IEEE 118-bus system and 13.18 sec for IEEE 300-bus system. By adopting the phenomena presented above we developed an in-house SDP OPF solver [28] with matrix decomposition. We solve SDP OPF in 0.56 sec for the IEEE 30-bus system and 4.56 sec for IEEE 118 bus system.

5. Results and Discussion

An in-house multiplayer energy market simulator was used to simulate 25 trading periods. Six graduate students took a role of a generator in IEEE 30-bus system. Students were able to make the offer decision for a generator. The total power demand was randomly created for each trading period so that our simulation results can show various effects of transmission topology control under different load levels. Here we will discuss the total operating cost, real power loss, and locational marginal price of a simulation completed by human subjects for 25 trading periods.

Switching only a single branch per trading period is considered an acceptable method of transmission switching, capable of searching for a better OPF solution. Our future research activities will focus on the understanding of the concepts of transmission switching and the effects of transmission topology control on various market components.

The first component of our research is the total operating cost of the system. It is also the objective function of the main problem given in Problem 1. Figure 5 illustrates the results of total operating costs of the system gathered from 25 consecutive trading periods. Cost curve actually follows the trend of load deviation. Real and reactive power load parameters are different in each trading period. Human subjects submit generator offers to maximize their own profits as it is in real energy market.

Figure 5. Operating Costs for 25 periods

The 5th trading period, as magnified in Figure 5, illustrates how the results differ with and without N-1 contingency condition. Although there exists a topology with a better solution, due to no satisfaction of N-1 contingency constraint, our proposed algorithm finds another topology that is still less costly than the original network but also satisfies the N-1 contingency constraint. Our OTC algorithm found a topology that leads 5% cost reduction within 22nd trading period, and 10% within the 16th trading period.

Figure 6 shows the real power losses in MW, respective to each trading period. Generally, our OTC algorithm returns a solution with less power losses than original network solution; however, one interesting instance deserving careful attention is the 5th trading period as seen in Figure 6. During this period the operating cost of the system after OTC with N-1 contingency is less than the cost of the original network, yet higher power losses were observed as opposed to our expectation (the parameters of 5th trading period also may be found at [10]).

Figure 6. Real power losses for 25 periods
Another analysis is that there exists a large variance between the LMP values gathered on the original case and those gathered after transmission switching. The proposed algorithm may find a topology with less number of congested lines and less number of binding voltage constraints than those of the original topology.

In our experiments, we observed up to 88% reduction in the LMPs associated with optimal topology control as illustrated in Figure 7. LMP at Bus 20 for the 16th trading period with the original topology is 555.93 $/MWh. After imposing OTC with N-1 condition algorithm, LMP at Bus 20 reduces to 64.38 $/MWh. This bus is chosen in purpose to highlight the maximum reduction of LMP observed within our experiments.

Analysis of our experimental results on LMP variance showed that transmission topology control could not guarantee an increase or a decrease on LMP at any bus; however, the smoothness of the resultant LMP curve after transmission switching operation is promising.

6. Conclusions and Future Research

A web-based electric power market simulator has been developed for a course offered at the State University of New York at Buffalo. The simulator combines fundamentals of electrical engineering and economic models and present them in an online simulation package. Students are able to learn how electric power systems work with topology-controlled OPF. Transmission topology control, a state-of-art technique under power economics, is implemented and tested by the simulation software package with human participation. The optimal topology found from our algorithm is guaranteed to be at least as reliable and as optimal as the original topology. This is the first attempt to implement new technology with a full AC model in an educational simulation package, and the package is flexible enough to accommodate introduction of new techniques. Parallel computation algorithm that yields a better topological solution to AC OPF problem was presented. The simulation results are reported and analyzed. Our experimental results showed that a severe LMP reduction up to 88% was observed when utilizing the optimal transmission topology control.

Future research will focus on the impact of the topology control on market power. As shown in [29], market power can occur due to the limited line capacity of the transmission network to support the power flow. In such a case, we can assess market power in terms of lines. It would be meaningful to study the impact by controlling topology – either completely open a line (completely switching) or partially reduce its capacity (partial switching).

10. References


