Testing Alternative Market Designs for Energy and VArs in a Deregulated Electricity Market

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Abstract

Reactive power (VArs) --- with its ability to support voltage and sustain power flows on transmission lines --- is an essential component of supplying electricity and maintaining the operating reliability of a transmission network. Yet there is an ongoing debate among regulators about how to compensate generators for supplying this vital resource in a deregulated market. This paper presents experimental results obtained from a series of market tests using the software platform POWERWEB to evaluate the performance of various real-time market designs for energy (real power) and VArs. The first test corresponds to the traditional arrangements that are currently used to procure VArs using a simple fixed price contract for VArs and a uniform price auction for energy. Since the production of VArs by a generator within the limits of a Capability Curve does not increase operating costs, the only real cost to a generator producing VArs is when the generator is required to reduce the production of energy in order to increase the production of VArs --- the opportunity cost of forgone energy. The second test is similar to the Federal Energy Regulatory Commission's current proposal to introduce a VAr market where sellers submit price offers and receive the nodal VAr prices, in the same way that generators are paid a nodal price for energy in existing markets. The basic problem with a VAr market is that VArs can only travel economically for short distances, and the exercise of locational market power may be of particular concern. We therefore also tested the effect of having interruptible load and dispatchable sources of reactive VArs on the competitiveness of a VAr market. The results show that both mechanisms, particularly interruptible load, are effective ways of mitigating market power.

JEL Classifications: C90, D44, L94, Q48
Keywords: Reactive power, Electricity market design.

1. Introduction

With the transition from regulatory price controls to market determined prices for real power a reality in many countries, as well as a number of US states,[1] attention is now turning to the formation of a spot market for the equally essential, yet lesser known component of AC power flow, reactive power.

Reactive power[2] (VArs) is an essential component of supplying electricity and maintaining the operating reliability of a transmission network through its ability to support voltage and sustain power flows on transmission lines. Indeed, the shortage of reactive power in a network can have serious repercussions including voltage collapse and ultimately blackouts.[3] For example, on the 23 September 2003 over 4 million homes and businesses in Denmark and Sweden lost power for four hours[4]; and on 28 August 2003 an estimated 400,000 people were without power in London. Both blackouts were attributed to voltage collapse.[5] Conversely, the optimal supply of reactive power has the ability to alleviate transmission constraints and ultimately lead to cheaper real power through increased market contestability.

While the importance of reactive power is unquestionable, there exists considerable debate about how to best ensure adequate supply of this essential commodity. Salient questions have been raised about whether generators should be compensated for supplying reactive power, and if so, what form this compensation should take. In

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[1] Countries that have deregulated their electricity markets include: Australia, New Zealand, Germany, Spain and the United Kingdom. According to the official energy statistics from the U.S. Government, as of October 2002 "twenty-four states and the district of Columbia have either enacted enabling legislation or issued a regulatory order to implement retail access. (Source: Energy Information Administration)

[2] Stoft (2002), gives the following definition of reactive power: "An AC power flow can be decomposed into two components: real power which always flows from generator to load, and reactive power which flows back and forth with no net transfer of power in either direction" [p, 452]. Reactive Power is produced by Synchronous Generators, Synchronous Compensators, Supervar, and Transmission Lines. For a more detailed discussion of reactive power see Sauer (2003).

[3] Another example of a major blackouts caused by voltage collapse occurred in Italy on the 28 September 2003 and affected 57 million people.

[4] "Danish capital loses power" BBC News, 23 September, 2003.

[5] On the 14 August 2003 approximately 50 million people lost power in the northeastern United States and eastern Canada, with outage-related financial losses estimated at $6 billion. "Insufficient reactive power was an issue in the blackout" (U.S. – Canada Power System Outage Task Force, April 2004)

response the Federal Energy Regulatory Commission (FERC) has identified a number of real-time pricing options including: paying nothing; unit specific opportunity costs; prices announced in advance; and market clearing prices determined through a spot market auction.[6]

Each real time pricing option has advantages and weaknesses. For example, paying nothing or unit specific opportunity costs (and to a lesser extent with contract prices) raises concerns surrounding the inability for suppliers to cover their fixed costs and lack of incentives to spur future investment.[7] While the provision of reactive power in a deregulated market setting has the potential to provide better investment signals and greater efficiency through market determined prices, it does present major challenges in terms of market design. This is due to the fact that VArs can only travel economically for short distances, which combined with the high concentrations of suppliers of reactive power in particular areas, mean that the exercise of locational market power may be of particular concern. Unfortunately, the presence of market power could mean that signals provided by such a market may be both costly and unreliable.

The Federal Energy Regulatory Commission acknowledges these market power concerns and has adopted a wisely measured approach, stating in 2005 that "….the idea of a bid-based reactive power spot market is new and we believe it is too soon to implement one. Simulation and experimentation are needed to understand the effects of alternative markets designs."[8] This paper helps address this gap in the empirical literature by presenting and evaluating the results of several reactive power market design experiments that were conducted at Cornell University during 2005/2006. The results from these experiments provide valuable insights into the practicality of a bid-based reactive power spot market and how best to proceed.

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[6] FERC has also identified a number of capacity payment options including: A cost-based payment, a capacity markets payment, prices determined through auction and pay nothing [p.12, see footnote 7]. Note that this paper is focused only on real time pricing.

[7] If the fixed contract price was high enough it could produce an incentive to invest.

[8] Page 15, Federal Energy Regulatory Commission (2005), "Principles for Efficient and Reliable Reactive Power Supply and Consumption"

The paper is structured as follows: The first section presents details of the experimental design including: descriptions of the various tests, background of the market participants and information regarding the software platform used. Next a summary of the market performance in the various tests is provided for both real and reactive power. This is complemented with an examination of the specific bidding behavior of selected market participants. The paper concludes with a discussion of the various real-time pricing options in light of this new information and provides recommendations on the design of future reactive power market experiments.

2. Experimental Design and Subjects

The experiments analyzed in this paper were conducted as a pilot test at Cornell University's Laboratory for Experimental Economics and Decision Research in the fall semester of 2005. Market participants for the first set of experiments (Tests 1, 2 and 3) were recruited from the fall 2005 class of AEM 655/ECE 551: Power Systems Engineering and Economics and consisted of a mixture of Masters and PhD students from the Applied Economics and Management, Economics and Electrical Engineering Departments at Cornell University. Tests 1 and 3 were conducted with two separate groups each with 6 market participants. Test 2 was conducted with one group of 6 market participants.[9] To provide the correct financial incentives, all participants were compensated with salient monetary rewards corresponding to a percentage of amount of profit they earned in the experiment (Siegel and Goldstein, 1959).

Appendix A provides a detailed description of the market rules used in these experiments. The important elements of the experiment can be summarized as follows:

- All experiments used the software platform POWERWEB (see Zimmerman et. al., 1999).
- All experiments consisted of 6 market participant, with each having 3 generation options (low, medium and high cost).

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[9] A group size of 6 was chosen in order to create a relatively competitive situation. Communication between market participants was not allowed during the experiments.

- In tests 1-3 there was a single buyer of electricity (the system operator) with inelastic demand.
- The maximum allowed offer in the real power market was \$100/MWh and nodal prices were set using a uniform price auction.
- The configuration of the transmission network, with location of generators, is given in Figure 1.
- Each test lasted at total of 60 trading periods --- 30 periods with treatment A and 30 periods with treatment B.

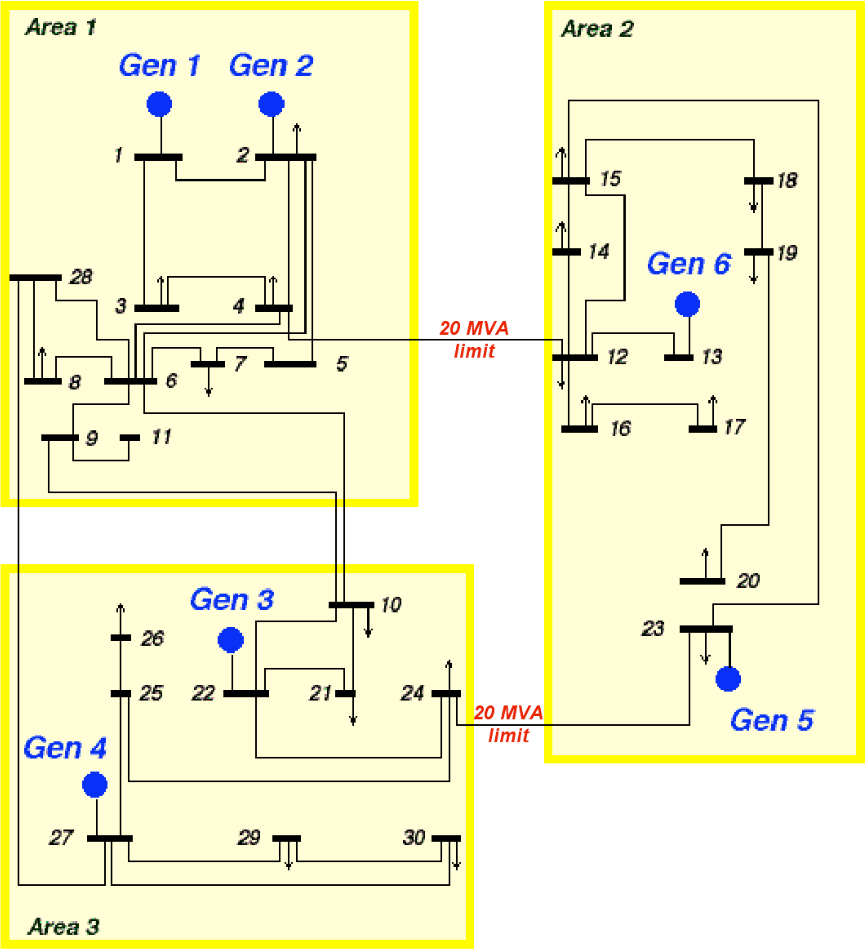

FIGURE 1: 30 bus transmission network

The following experiments (Tests 1-3) were conducted in the Fall 2005:

Test #1: Pay nodal prices for real energy and a contract price of $5/MVAr for reactive power (VArs).

This test corresponds to the typical arrangements that are currently used to procure VArs in the transition from regulated to a deregulated market.[10] It is consistent with FERC preliminary recommendation that "for the present, while spot price auction markets are being further studied, we recommend paying real time prices for actual reactive power production based on the provider's own opportunity cost or based on administratively determined prices announced in advance, in order to encourage suppliers to produce reactive power where it is needed."[11]

In this test the Independent System Operator (ISO) executes contracts with suppliers to provide VArs at a predetermined price whenever they are needed. The maximum amounts of VArs (positive and negative) that can be provided by each generating unit are know by the ISO (i.e. the ISO and the supplier agree on a specific capability curve for each unit and this curve limits the production of VArs from a unit even if some of the capacity is withheld from the energy auction). Since the price and the maximum quantities of VArs are determined by the contract for each unit, the participant's decisions are limited to specifying the price and quantity offers for energy only.

Test #2: Pay nodal prices for real energy and nodal prices for reactive power (VArs).

This test corresponds to the current proposal by the Federal Energy Regulatory Commission (FERC) to introduce a new market for selling VArs in the transition to deregulation. In this market, the Independent System Operator (ISO) determines the optimal patterns of dispatch for energy and VArs by minimizing the cost of meeting load using the price/quantity offers for energy and the price offers for VArs as the costs. The maximum amount of VArs (positive and negative) that can be provided by each

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[10] This is also the approach used to procure reactive power in the United Kingdom and India.
[11] ibid. p. 15

generating unit are know by the ISO (i.e. the ISO and the supplier agree on a specific capability curve for each unit and this curve limits the production of VArs from a unit even if some of the capacity is withheld from the energy auction). In this market, the participants were paid the nodal prices for both energy and VArs for the dispatched quantities, and these nodal prices will never be lower than the corresponding offers. The maximum allowed offers (and the price paid) are $100/MWh for energy and $50/MVAr for VArs.[12]

Test #3: Pay nodal prices for energy and nodal prices for VArs in a market with:

1) Interruptible load, and

2) Dispatchable sources of VArs.

The auction for energy and VArs is the same as it was for test 2. The main change is that regulators were concerned about the ability of firms to exploit the market for VArs. As a result, they have decided to make the market more responsive to high offer prices by 1) having 30MW of interruptible load distributed around the network, and as an alternative 2) having 30MVAr of dispatchable sources of reactive power distributed around the network. This test is included to see which approach is the most effective as a way to mitigate market power. Note that periods 1-30 tested interruptible load and periods 31-60: tested distributed source of VArs.

Within test treatments:

Tests 1 and 2 contained two treatments, each one lasting for 30 trading periods. The first treatment used normal capability curves, representing operating conditions with an ample supply of reactive power. In the second treatment, the total supply of VArs available from generating units was reduced to 2/3 of the amount available in first treatment. This had the effect of shifting the capability curve inwards and creating a possible shortage of

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[12] This is consistent with FERC's suggestion to "cap the suppliers' bids [sic] while allowing all accepted suppliers to receive a market clearing price in the spot market that reflects the highest accepted bid." (p.15)

reactive power. These operating conditions represent conditions when the system is stressed due to contingencies occurring and there is a need for “dynamic” VArs.

3. Summary of Market Performance of the Reactive Power Market

Test #1 can be thought of as our base case as if reflects the true opportunity costs of procuring reactive power.[13] It can be seen from Figure 2 below that reactive power is very inexpensive most of the time (reflecting the low marginal cost of production when a generator is not on the capability curve) and occasionally very expensive (reflecting the opportunity cost of being on the capability curve).[14] Not surprisingly the second treatment, where there was less reactive power available in the system, produced higher reactive power prices when contingencies occurred (e.g. merchant power transfers).

It is important to note that while the contract price of VArs in Test 1 procured reactive power at the lowest cost compared to the other market designs, the true nodal VAr prices are very erratic and not a very attractive source of income. Also, the contract price of $5/MVAr may be insufficient to provide market participants with the investment incentives needed to build additional sources of reactive power.

Table 1: Average Reactive Power Prices

	Test 1				Test 2		Test 3			
	Group 1		Group 2		Group 1		Group 1		Group 2	
Reactive Power	Period A	Period B	Period A	Period B	Period A	Period B	Period A	Period B	Period A	Period B
Avg Price $/MVAr	5.00	5.00	5.00	5.00	11.06	22.63	13.59	9.97	20.02	21.40
Avg. Comp. Price $/MVAr	5.00	5.00	5.00	5.00	0.003	5.12	4.64	3.31	4.64	3.31

Period A: Trading periods 1-30, Period B: Trading periods 31-60

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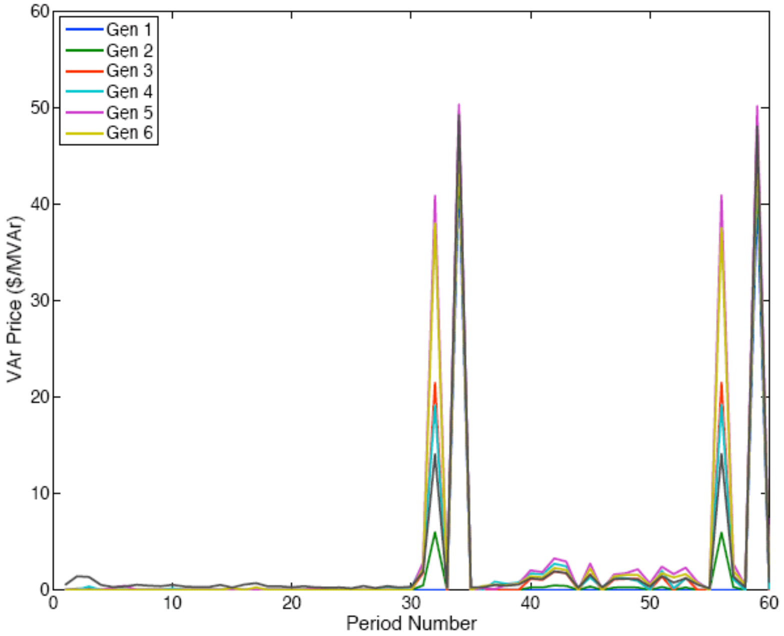
[13] Generators submit price/quantity offers for energy and are required to supply VArs when needed. They are paid the nodal price for energy and a fixed price for VArs through a contract with the ISO. Note that while reactive power was being bought at a fixed contract price of $5/MVAr, the prices reported here are based on the actual opportunity cost of the reactive power.

[14] Nodal VAr prices are only >>0 on the capability curve.

FIGURE 2: Nodal VAr Prices for Six Generators in Test 1.



Note that Periods 1-30: Normal Capability Curves

Periods 31-60: Restricted Capability Curves

Test #2 subsequently allowed generators to offer in prices at which they were willing to sell their reactive power. The maximum allowed offer was set at $50/MVAr. Generators were not able to submit VAr quantity offers. From Figure 3 it can be seen that the prices paid to generators were substantially higher than they were in Test #1. The fact that nodal VAr prices were greater than zero most of the time and therefore did not reflect the true cost of producing VArs, suggests the exercise of market power by generators.[15] Furthermore, the differences between VAr prices paid to different generators also increased substantially.[16] This result highlights the concerns that a reactive power market would be susceptible to the exercise of locational market power by generators due to the fact that VArs do not travel economically for long distances.[17]

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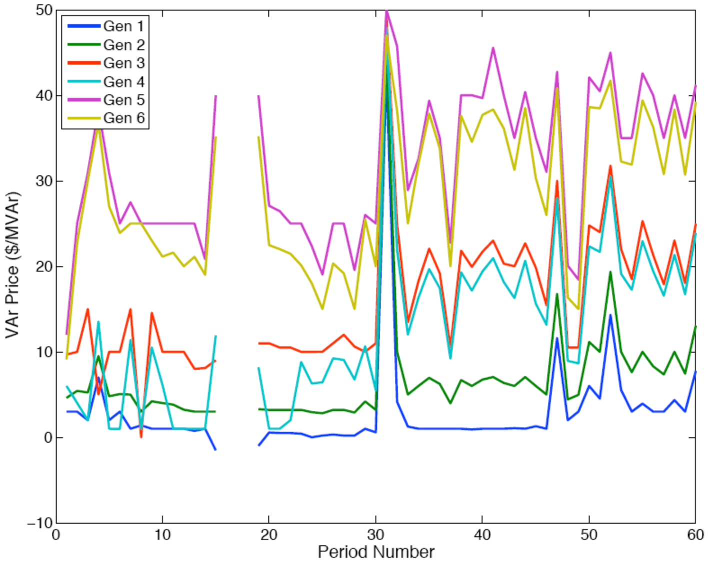
[15] In Test 2, Group 1, Period A and B, Player 6 made high profits by offering their reactive power into the market at prices around $15-$25. With this strategy they were dispatched most of the time and received a high market price.

[16] In Test 2, Group 1, Period A and B, Player 3 offered in reactive power for all three generators at very low prices (almost all were below $3, with some as low as $0.2). This strategy was not very successful as the VAr price at this generators node was very low.

[17] Allowing generators to submit price and quantity offers for VArs has the capacity to lower VAr capability and create even greater exercise market power.

This raises the question as to whether the greater investment incentives that higher, yet still erratic, reactive power prices would provide justifies introducing a market where generators do not have the incentive to submit "honest" offers and is thus driven by market power.[18]

FIGURE 3: Nodal VAr Prices for Six Generators in Test 2.



Note that Periods 1-30: Normal Capability Curves
Periods 31-60: Restricted Capability Curves
(Gaps in the sequence correspond to trading periods
In which the software did not find a solution)

With the concerns surrounding the locational exercise of market power realized in Test #2, we now consider how regulators could make such markets harder to exploit. Test #3 examined two possible approaches to make the market more responsive to high offer prices. They were 1) having 30MW of interruptible load distributed around the network, and as an alternative 2) having 30MVAr of dispatchable sources of reactive power.

From Figures 4 and 5, it can be seen that interruptible load (periods 1-30) showed an overall downward trend in the price of reactive power. Dispatchable sources of VArs (periods 31-60) performed similarly --- although with an increased number of high price

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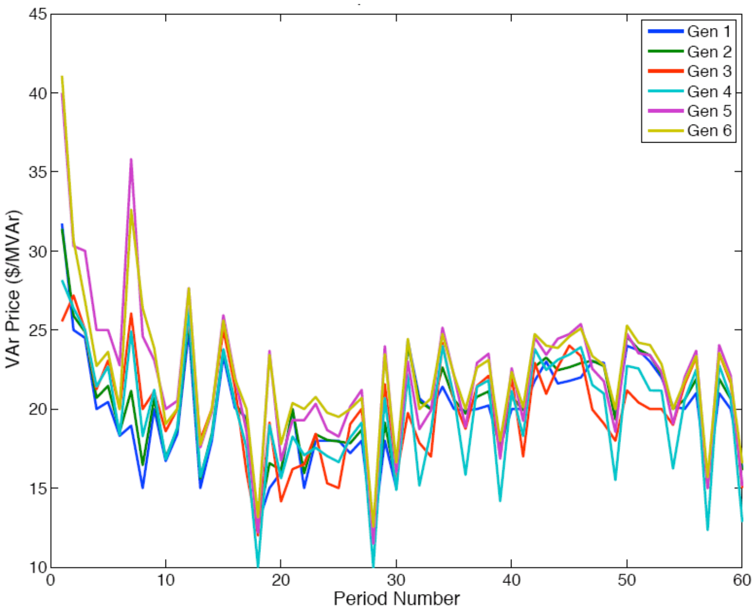
[18] These high prices could be justified by using long-run efficiency as the regulatory objective.

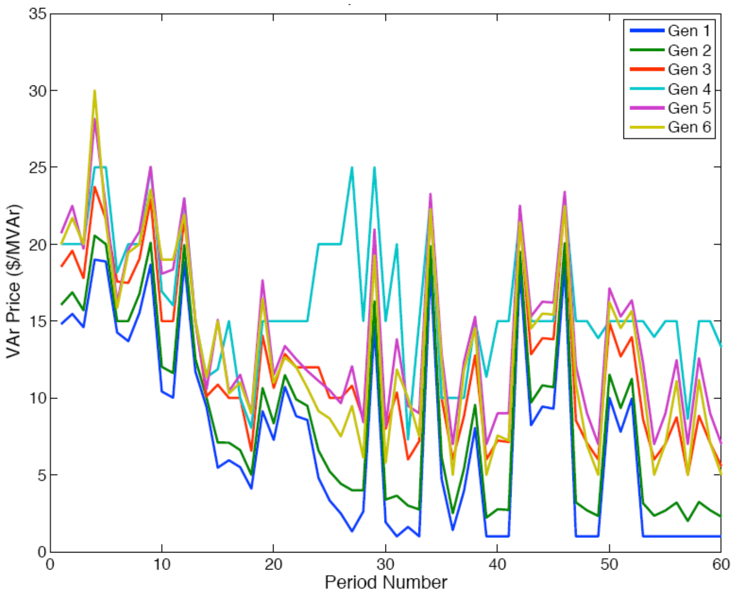
spikes due to the increased reliance on importation of reactive power. So while nodal VAr prices were still greater than zero most of the time for all generators and there was still no incentive to submit "honest" offers for VArs, both approaches had the effect reducing locational market power. The market prices for VArs were lowered and there were much smaller locational differences in prices. Nodal VAr prices were also less erratic. This suggests that incorporating either interruptible load or distributed resources may be an important feature of a successful market for VArs.

FIGURE 4: Nodal VAr Prices for Six Generators in Test 3, Group 2.



Note that Periods 1-30: Interruptible Load
Periods 31-60: Distributed Sources of VArs

FIGURE 5: Nodal VAr Prices for Six Generators in Test 3, Group 2.



Note that Periods 1-30: Interruptible Load
Periods 31-60: Distributed Sources of VArs

4. Summary of Market Performance of the Real Power Market

While the main focus of this papers is on the performance of the reactive power markets under various market designs, it is important to examine what effects the alternative reactive market designs had on the competitiveness of the real power market.[19,20]

Throughout all three experiments the optimal strategy for suppliers in the real power market appeared to be to offer all of two lower cost generators at close to marginal cost. The amount of high cost generator capacity that was offered depended on the forecasted load and the competitiveness of the real power market. For example, if it was a high demand period and the market was competitive the generator should offer some of high cost generator's capacity at just above marginal cost in order to maximize the number of units dispatched. If the market was not competitive the generator should offer in one unit high cost generator's capacity at a high offer price in the hope that it will be dispatched

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[19] See Appendix C for graphs of the real power price for the different tests.
[20] This is likely to be more of an issue if generators were allowed to submit price and quantity offers for VArs.

and set the market price.[21] Withholding power from the two lower cost generators was usually not profitable.[22]

Table 2 presents the average real power prices from the difference experiments. As expected, Test 3 with interruptible load (and to a lesser extent, with a local source of dynamic VArs) provided the lowest overall average real power prices, with average prices of $55.06 and $53.35. This interruptible load, which that was available at $70/MWh, allowed the market operator to limit the effect of speculation by suppliers. Since all loads were specified with fixed power factors, using interruptible load reduced the demand for both energy and VArs simultaneously. The results in Tests 1 and 2 did not have an appreciable effect on the competitiveness of the real power market.

Table 2: Average Real Power Prices

	Test 1				Test 2		Test 3			
	Group 1		Group 2		Group 1		Group 1		Group 2	
Real Power	Period A	Period B	Period A	Period B	Period A	Period B	Period A	Period B	Period A	Period B
Avg Price $/MWh	71.42	69.53	58.14	81.13	71.95	76.25	55.06	64.86	53.35	63.23

Period A: Trading periods 1-30, Period B: Trading periods 31-60

5. Concluding Thoughts and Future Experiments

The fixed contract for VArs (Test #1) resulted in the lowest reactive power prices, but this market probably doesn't provide strong enough investment incentives for generators to build generating equipment with the capability of producing a wide range of (positive and negative) reactive power. Even though the contract price could be higher, suppliers will always be reluctant to provide dynamic VArs on the capability curve when the nodal price of energy is high. Paying the opportunity cost for foregone energy production is an

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[21] For example: In Test 1, Group 1, Period A, Player 3 made the highest profit ($48,028). There offer strategy closely matched the one explained above. Similarly in Test 2, Period A and B, Player 1 made the highest profit with a similar strategy.

[22] In Test 1, Group 1, Period B, Player 2 ($30,360) withheld nearly all of there generator 2 capacity (and all of 3 capacity) --- even when price far exceeded the marginal cost. This strategy would have raised the market price and thus benefited of other players, but the low quantity dispatched ultimately hurt this players. This strategy was also used in Test 1, Group 2, Period B, Player 1 who made the lowest profit ($32,219). Similarly, in Test 2, Period A and B, Player 2; Test 3, Group 1, Period A and B, Player 2; and Test 3, Group 1, Period A and B, Player 5 all withheld generation from their second generator.

effective way to deal with this problem. However, it is unlikely that a pure market solution will provide efficient levels of VAr capability. Requiring a minimum VAr capability for new generating units is a practical solution in the same way that dual-fuel capability is a requirement for new gas turbines in some markets.

Introducing a market for reactive power on the other hand provides greater investment incentives through higher reactive power prices, but these high prices are driven by locational market power (Test #2). If this option is chosen, our experiments suggest that a reactive power market should be designed with some mechanism to curb the locational market power (Test 3) --- which reactive power markets are prone to due to the fact that reactive power can only travel short distances.

When the demand for VArs comes from loads, it may be relatively expensive to get VArs from generators that are long way from where the problem is. Having a local source of dynamic VArs or interruptible load is more efficient. Interruptible load has the additional advantage of mitigating high prices in the real power market. Our overall conclusion is that it is usually sensible to get reactive power from a source close to the location of the demand for VArs. There is a lot of potential for placing more reliance on Distributed Resources for reactive power. The objective of our next series of experiments is to determine the effectiveness of different incentives for getting loads to provide reactive power when and where it is needed.

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APPENDIX A: Description of the Network

In each market there is a single buyer of electricity (the system operator) who has the obligation to meet demand (load) at least cost. Each supplier can generate a maximum of 60 megawatts (MW) of electricity, and this production capacity is divided into three blocks of generating capacity with different operating costs. The cost structures of all suppliers are identical to each other but their locations on the network are different. The locations of all six suppliers are given in Figure 1. Note that all of an individual supplier’s generators are located together.

THE TRANSMISSION NETWORK

In this experiment, the generators and the loads are connected by a transmission network, shown in Figure 1, which must be operated at all times in a manner consistent with the laws of physics governing the flow of electricity. A small percentage of the energy produced is dissipated by transmission losses, and the system operator must purchase more than the total load. For a given pattern of load, the exact amount generated is dependent on where the power is produced. In addition, the operation of the network is constrained by the physical limitations of the equipment used to generate and transmit the power. This implies that there are limits to the amount of power that can be transmitted from one part of the network to another. Congestion, which occurs when these limits are reached, can make it impossible for the system operator to utilize inexpensive generation, forcing the system operator to purchase more expensive generation from a different location.

After all the offers have been collected from the suppliers, the system operator will choose to accept the least expensive offers which are able to meet the load while satisfying all of the constraints of the transmission system. The prices paid to each supplier are nodal prices, specific to their location. Each nodal price is equal to the marginal cost to the system operator of meeting an additional unit of demand at the corresponding node.

In a network without congestion and with minimal losses, a Uniform Price Auction determines the least-cost pattern of generation by paying the Last Accepted Offer to all accepted offers. In this type of auction, the system operator ranks the supplier's offers from the least expensive to the most expensive, and accepts offers in order from the lowest to the highest offer price until sufficient capacity is purchased to meet the load. The system operator pays all purchased capacity the same (uniform) price, and this price is equal to the offer for the most expensive capacity purchased. However, as losses and congestion increase, the system operator is forced to accept offers out of order (some expensive units may be accepted while less expensive ones are rejected), and the prices at the different nodes vary and move away from a single uniform price.

Appendix B: The Marginal Cost of Reactive Power

While reactive power is produced at no additional cost this does not mean that its marginal cost is always zero. The marginal cost of reactive powers is zero when a generator is not required to withhold capacity. On the other hand if a generator is made to withhold capacity, the marginal cost of producing reactive power depends on the tradeoff between real and reactive power, which is determined by the slope of the capability curve, and the profit which the generator would have been earned on those units that were withheld in the real power market. For example, if a generator was forced to withhold 10 MW in order to produce 2 MVArs and it would have made a profit of $10/MWh, the marginal cost of a MVAr is $50.

Theory tells us that generators shouldn't submit an offer for reactive power below the marginal cost of the reactive power i.e. the generator should at least be indifferent between having to withhold real power and not having to withhold real power, and that in a genuinely competitive market, generators offers should equal marginal cost. The main problem surrounds how to calculate the marginal cost of reactive power ex-ante --- as there is considerable uncertainty surrounding a number of key inputs.

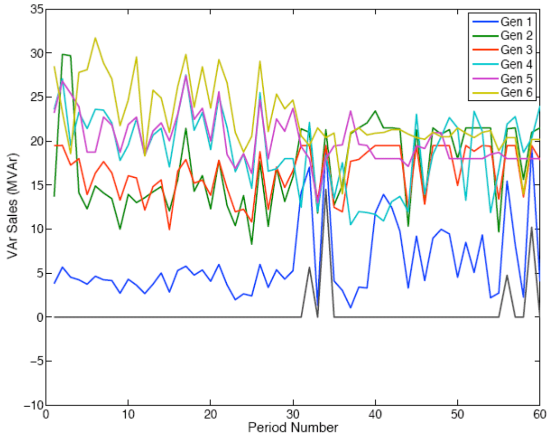
Specifically the generator needs to know:

- What is the probability that they will not be required to withhold capacity? In this case the marginal cost of reactive power is zero.
- If they are required to withhold capacity, exactly how many units of reactive power will be needed? i.e. how far along the capability curve they will be required to go. This determines the tradeoff between real and reactive power.
- How much profit they will lose on the withheld real power? This depends in part on the competitiveness of the real power market and also the marginal cost of the withheld generator.

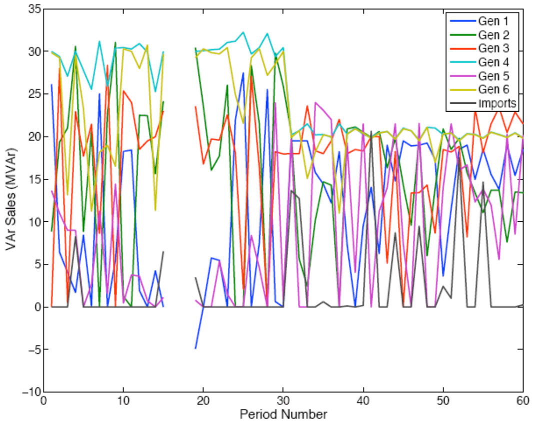
Differing expectations about the above uncertainties will lead to different estimates of the marginal cost of reactive power and hence different offers. This in turn leads to difficulties in determining what the competitive offer --- although the prices seen in tests 2 and 3 would seem to far exceed competitive amounts.

Appendix C: Reactive Power Quantities Graphs

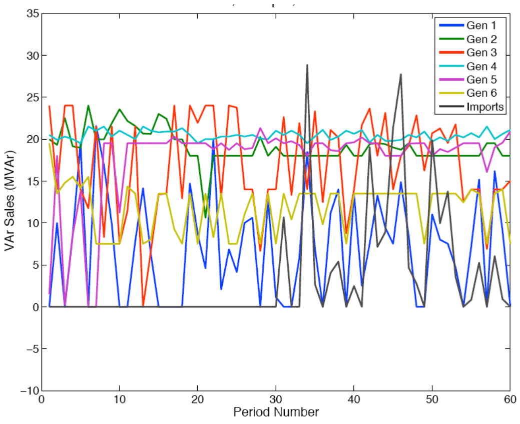
Test #1, Group 1



Test #2

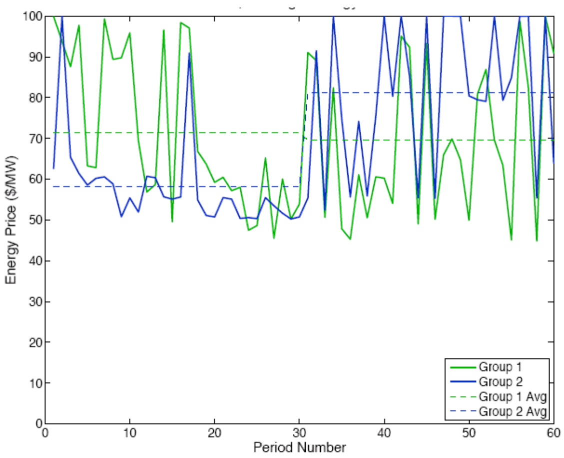


Test #3, Group 2

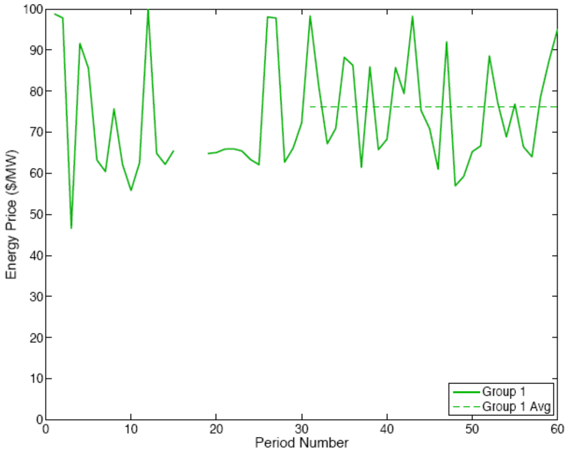


Appendix D: Real Power Price Graphs

Test #1



Test #2



Test #3