A Revenue Sensitivity Approach for the Identification and Quantification of Market Power in Electric Energy Markets

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***Abstract*—In this paper we present a practical approach for identifying and measuring market power in an electric energy market. To do so we determine which participants or groups of participants have the ability to increase their own revenues without affecting the rest of the market, and then apply a relative measure to quantify the extent of market power exploitation. We present a 30-bus, 6-generator example in which two generators in a load pocket are found to have and use market power. Using price and revenue signals from a repeated auction, we explain how these generators learn to exploit their power over time. Experimental results are also presented and analyzed.**

***Index Terms*—Deregulation, Electric Energy Markets, Market Power.**

I. INTRODUCTION

Concerns over energy price variations in recently deregulated energy markets and suspicions that in some instances certain companies have been able to manipulate energy prices[1] has increased the need for a practical measure for market power. In this paper we extend prior work on the use of price elasticities to identify market participants who have the ability to manipulate the market to their advantage [2]. Here we examine a matrix of revenue/price sensitivities to identify generating participants with the ability to simultaneously increase offer prices and revenues.

Commonly used notions of market power focus on the ability to increase market prices beyond competitive levels. For example, in the area of electric energy markets the FERC proposal for standard market design states, "Market power is the ability to raise price above the competitive level"[3]. The problem with such definitions is that they refer to a benchmark which is impossible to measure: competitive price. When a market is believed to be competitive, then the price it produces *defines* the competitive price. When a market is not competitive the competitive price is unknown and is incalculable. (If it is calculable, then there is no need for a market!) One might like to believe that a calculation of competitive price is possible if one has access to all fuel cost data, efficiency data, and more for every generator in the market; however any such calculation would be open to differing interpretations and decisions based on such a calculation would likely languish in the legal system for years. It is impractical.

From a practical point of view we seek a measure for market power that requires only the available information used to operate the electric energy market. Based on energy offers we seek to identify those generators with the ability to increase their own revenues by raising prices, with little effect on the market otherwise. This is in contrast to a competitive environment in which one would need to lower offer prices to garner an increase in market share to increase revenues.

In this paper, our examples assume that demand is inelastic and we study only the effect of offer price on the market. Our approach is directly applicable and remains practical in more general settings in which other market inputs can be considered. We also note and discuss how dynamics associated with a repeated auction enable a pair of generators to exploit joint market power. This ability is observed in electricity market experiments at Cornell University.

II. POTENTIAL MARKET POWER

In this section we present a method to identify generators or groups of generators that have *potential market power.* In Section IV we propose a relative measure to quantify how much market power is exploited. Our approach is to distinguish generators that have the (incremental) ability to increase revenues by increasing offer prices, without affecting the revenues of other generators. To do so we construct a matrix of revenue/offer price sensitivities.

The revenue, R_i, for a particular generator is given by

$$R_i = z_i \lambda_i \qquad (1)$$

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where z_i is its dispatch and λ_i is its nodal price. The derivative of the revenue of the i^{th} generator, R_i, to the offer price of the j^{th} generator, w_j, at the operating point (z^*, λ^*) is given by

$$\frac{dR_i}{dw_j} = \lambda_i^* \frac{dz_i}{dw_j} + z_i^* \frac{d\lambda_i}{dw_j} \qquad (2)$$

Because electric energy markets typically use block offers for energy (quantity,price), the terms in (2) are not straightforward to calculate. To obtain the derivatives in (2) we perform two optimal power flows (OPF). The first uses the generators' block offers and capacity limits to establish the operating point. In the second OPF we replace the block offers with the nodal prices from the first OPF and remove the capacity limits. Both OPFs give the same dispatch and result in the same revenues. The second OPF allows us to calculate the desired derivatives for (2). Keep in mind that we are only identifying those generators with *potential* market power; those that have the ability to increase revenue by increasing offer price. The model used in the second OPF achieves this goal irrespective of the block offers used in the market and the first OPF.

We note that in the second OPF

$$\frac{d\lambda_i}{dw_j} = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{otherwise} \end{cases} \qquad (3)$$

and we refer the reader to [2] in which a method for calculating $dz_i/d\lambda_j$ is presented. Combining the derivatives for all the generators we obtain a linear incremental/offer price model of the form

$$\Delta R = A\Delta w \qquad (4)$$

where ΔR and Δw represent incremental changes in revenue and offer price from the operating point, and A is the matrix whose elements are the derivatives defined in (2). Now our task is to examine matrix A to determine which generators or groups of generators have potential market power. At this point it is instructive to consider a concrete example.

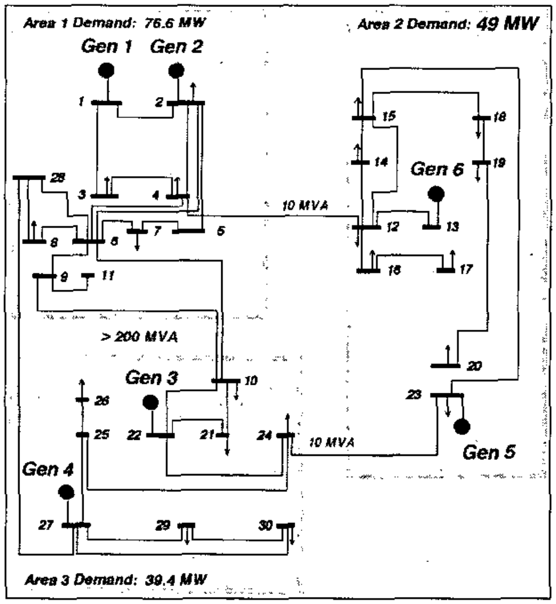
A. 30 Bus, 6 GeneratorExample

We consider the 30 bus, 6 generator system shown in Figure 1 [2]. The two lines connecting the "load pocket" in Area II to the other areas are limited to 10 MVA each. The total system load is 165 MW with 49 MW in the load pocket. The capacity for each generator is 60 MW. The total loads in the load pocket and in the entire system are much lower than the capacity of the system. A base case solution for the full nonlinear AC optimal power flow is shown in Table 1.

Table 1: Base Case dispatch and nodal prices

	G1	G2	G3	G4	G5	G6
Dispatch (MW)	31.7	36.0	34.0	36.0	17.6	12.0
Price ($/MWh)	40.0	40.1	40.0	40.1	55.0	54.3

Figure 1: 30 Bus, 6 Generator System



Given the evident difference in prices for generators 5 and 6 (located within the load pocket) compared to the rest, one may ask whether these generators enjoy some amount of market power. The answer is not obvious since the load is considerably lower than the capacity. The matrix of revenue/offer price sensitivities, A, for this base case solution is shown in Table 2. Each element in the matrix represents a sensitivity defined in (2), the proportion in revenue change for the i^{th} generator (row i in the matrix) due to a change in nodal price at the j^{th} generator (column j of the matrix).

Table 2: Base Case Sensitivities

	1	2	3	4	5	6
1	-3298	3231	31	65	52	-49
2	3219	-3695	244	263	315	-310
3	31	244	-544	308	-234	229
4	65	263	307	-597	-127	125
5	38	230	-170	-93	-160	173
6	-36	-229	169	92	175	-159

This matrix has a two expected features. The negative diagonal entries indicate that no generator, acting alone, can simultaneously increase revenues by increasing its own offer price. Also, the sum of each row is positive. This means that if all generators raise their offer price in the same manner, then the combined effect will increase the revenue of each generator.

The interesting an important observation is that generators 5 and 6 can increase their individual revenues by simultaneously increasing their offer prices. They are the only *pair* of generators with this ability. Furthermore, one should also note that increasing their offers in a particular proportion (nearly unity) will have very little effect on the revenues of the remaining four generators (since the values in rows 1-4 for column 5 are very nearly opposite to those in column 6). Based on this analysis it appears that generators 5 and 6 should be able to raise prices and increase revenue without changing the revenues of the other generators.

B. Experiment

The incremental analysis of the previous subsection suggests that generators 5 and 6 share potential market power. It is a separate question as to whether they can effectively exploit this potential. This was tested in a classroom setting. In an experiment at Cornell University, students representing the generators were allowed to offer into an energy market comprising the network shown in Figure 1 including the line limits, a uniform price auction, and generator cost curves that should yield dispatch and prices similar to those shown in Table 1 (if the market were competitive). Specifically, in a sequence of rounds, every student had the ability to specify a price for each of three fixed blocks of energy which represent the capacity of their generator. A price cap of \$80/MHh was imposed. Dynamically, it was observed that the prices in Area II, on average, steadily increased over time and after seventy-five rounds the dispatch and price achieved the values shown in Table 3. Had the experiment been allowed to continue past seventy-five rounds, it is expected that the price in the load pocket would have approached the price cap of \$80/MWh.

Table 3: Experiment dispatch and nodal prices

	G1	G2	G3	G4	G5	G6
Dispatch (MW)	37.9	34.9	30.1	34.9	14.9	14.6
Price (\$/MWh)	48.5	48.7	48.5	48.6	72.0	70.0

It is clear that the generators in the load pocket were able to exploit their potential market power in the experiment to their mutual advantage. By increasing both price and dispatch generator 6 fared slightly better than generator 5, but both increased their revenues from the base case.

III. MARKET DYNAMICS

We have argued that an analysis of the matrix of revenue/offer price sensitivities, and in particular the block associated with generators 5 and 6, shows that these two generators have the ability to raise revenues by raising offer prices. In this section we perform a more careful analysis to show that the domain (space) of possible price increases that result in increased revenues for both generators is small; a clear majority of price increase combinations will result in a loss of revenue for one of the generators. Nevertheless, we argue that the two generators will naturally find their "win/win" combinations over time, based on price and revenue signals provided by the market.

Consider the revenue/offer price relation from Table 2 for generators 5 and 6 only:

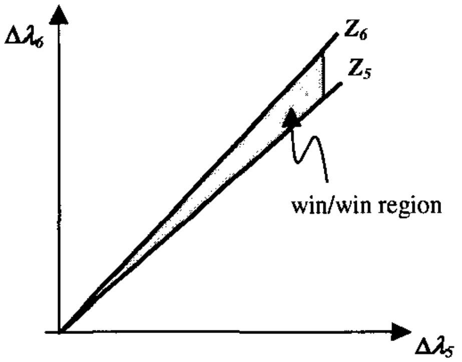
$$\begin{bmatrix} \Delta R_5 \\ \Delta R_6 \end{bmatrix} = \begin{bmatrix} -160 & 173 \\ 175 & -159 \end{bmatrix} \begin{bmatrix} \Delta\lambda_5 \\ \Delta\lambda_6 \end{bmatrix} \tag{6}$$

Setting $\Delta R_5=0$ and $\Delta R_6=0$ defines the "zero-revenue increase" lines for the generators as functions of the their nodal prices:

$$\begin{aligned} Z_5: &\quad -160\Delta\lambda_5 + 173\Delta\lambda_6 = 0 \\ Z_6: &\quad 175\Delta\lambda_5 - 159\Delta\lambda_6 = 0 \end{aligned} \tag{7}$$

These lines are shown graphically in Figure 2. The zero revenue increase lines for generators 5 and 6 are denoted by Z_5 and Z_6 respectively. Above Z_5, generator 5 will increase revenue, and below Z_6, generator 6 will increase revenue. Between these lines lies a win/win region for which price increases will result in increased revenue for both generators. The win/win region is clearly small, yet the experimental results suggest that people will find this region. How is this possible without direction collusion?

Figure 2: Win/win region for price increases.

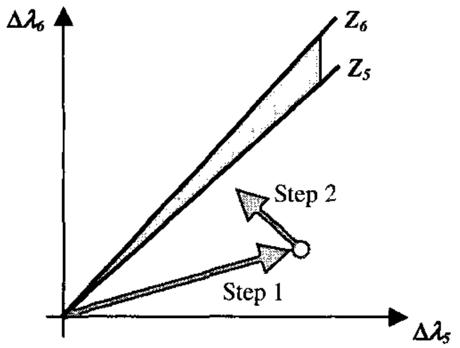


The sequential market forms a dynamic process. At each round the market provides price and revenue signals. Acting only on these signals generators 5 and 6 will naturally tend towards operation in the win/win region, without explicit collusion.

Consider the price increase represented by "step 1" in Figure 3. This particular change in offers results in a price increase and revenue *decrease* for generator 5. Generator 6 experiences an increase in both price and revenue. For the following round, shown as "step 2" in Figure 3, the natural response is for generator 5 is to decrease price and for generator 6 to continue to increase price. Taken together, this has the combined effect of movement towards the win/win region.

The actual dynamics will depend on the price increments the generators employ, but with the feedback signals provided by the market it should be expected that the generators will eventually learn to exploit their market power

Figure 3: Steps towards the win/win region.



IV. RELATIVE MARKET POWER

In the preceding sections we presented an approach to identify generators with potential market power and provided an explanation of how this power might be exploited without direct collusion. In this section we discuss a measure for the extent to which market power is being exercised. Following the suggestion for a measure of market power in [2], we compare the operating point nodal prices to two reference prices that represent cases of no market power and extreme market power.

The lower reference price, λ_{LOW}, is obtained by appropriately decreasing the offers of the generators with potential market power until the matrix of revenue/price sensitivities no longer identifies these generators as having potential market power. The high reference price, λ_{HIGH}, will typically be the price cap, if defined, or some other suitable high price otherwise. (One should confirm that the generators of interest continue to maintain potential market power at λ_{HIGH}.) With the two reference prices for each generator of interest, relative market power can be defined as

$$RMP = \frac{\lambda - \lambda_{LOW}}{\lambda_{HIGH} - \lambda_{LOW}} \tag{5}$$

where λ is the nodal price for a generator. By focusing on price, this definition follows traditional investigations of market power, however, we emphasize that it does not require knowledge of "competitive price" and it is calculable using available information. It is practical.

The values for relative market power for the base case and the experimental case (after 75 rounds) for the example in Section II are presented in Table 4 below. The RMP measure suggests that generators 5 and 6 exploited market power more in the experiment than in the base case.

Table 4: Relative Market Power

	Base Case	Experiment
G5	0.32	0.70
G6	0.32	0.66

One must be careful when comparing the values in Table 4, the RMP is calculated relative to other participants in the market. The low and high prices that are used in calculating the RMP only consider possible changes in offers for the generators identified to have potential market power; the offers for the other generators are kept constant. Since the prices for the other four generators differ between the base case and the experiment, the reported relative market power is operating point specific. However, taking into account the prices for the remaining generators also increased in the experiment makes the RMP for generators 5 and 6 even more dramatic. It indicates that the prices for the generators in the load pocket clearly rose more sharply than the rest of the generators.

In practice it may not be appropriate to compare values of RMP for different operating conditions. Rather, one may have knowledge of the RMP for present conditions and will have to decide whether the RMP for one or more generators is too high. We note that some exercise of market power can be beneficial. In the example, one could argue that elevated prices within the load pocket may attract lost-cost generation to the area, or motivate increasing the capacity of the power transfer capabilities between areas. Elevated prices provide needed economic signals. On the other hand, extreme high prices for an extended period may place an intolerable economic burden on consumers. Policies concerning market power are beyond the scope of the paper. It is hoped that the measures here will serve to aid those who make and implement such policies.

V. CONCLUSIONS

In this paper we have summarized some of our research on metrics for electric energy markets. We emphasize the need for practical measures that rely on available information. We feel that any market power metric that requires knowledge of competitive price will not be practical in an on-line operational setting. It will require information that is not generally available and will be open to subjective interpretations.

Our approach is to first identifying those participants that have the ability to increase their revenue through the aspects of the market they control (in this paper, offer prices). This is not subjective. There are well-defined procedures that dictate how the market operates and how it is settled. We simply observe how the outcome (in terms of revenue) can change due to possible variations in the participants' inputs. This first step will identify participants with potential market power. It does not necessarily indicate that this power is being used, only that the potential exists.

The second portion of our approach includes a measure of relative market power to quantify the extent to which market power is being used. We use energy price in this metric, however one might consider other quantities such as revenue. (In the load pocket example presented here, a similar metric based on revenue yields similar results since the dispatch does change appreciably.) How this measure of relative market power is used will be determined by policy and practice. For example, to decide whether an RMP of 0.3 indicates a large amount or small amount of market power.

Since the approach to identify and quantify market power suggested here is objective, once an excessive amount of market power is observed it will place the burden of justifying behavior onto the participants. We establish that they have the ability to increase their revenues (through offer price increases in this paper) and provide a relative metric to show how much this ability is being used. It is possible, for instance in our six- generator example, that the generators 5 and 6 may argue that they are old, expensive units and that the base cases prices are to be expected. Accepting this to be the case, generators 5 and 6 must acknowledge that they would have trouble competing if additional lower-cost generation were introduced into the area, or if line capacities were increased.

There is more research to be conducted in this area. Related to this work, and to be reported elsewhere, we have explored efficient analytical techniques to identify load pockets, and generators with potential market power. (In this paper's example, the load pocket is obvious, but it need not be in a larger system.) We have also begun to explore the dynamic aspects of the market to explain how generators may exploit joint market power, without direct collusion, as do generators 5 and 6 in this paper.

VI. REFERENCES

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[3] U.S. Federal Energy Regulatory Commission, Standard Market Design, NOPR RM01-12-000, §393, July 2002.