Estimation of A Sensitivity-Based Metric for Detecting Market Power

HyungSeon Oh and Robert J. Thomas, *Fellow, IEEE*

Abstract **– The abuse of market power is a potentially serious problem for market designers. Few if any indices exist to measure the potential for market power in real-time. In references [1-2] an expression for a dispatch-to-price sensitivity matrix, M, was derived. The expression requires information about network topology and parameters as well as the rules used to operate the market. While computing the matrix is conceptually easy for those with all the market and system information (e.g., an ISO), the method is probably impractical for market participants due to the inaccessibility of much of the information. In this paper we suggest a method for estimating the M-matrix by using publicly available data. This suggests that any market participant who does the computation will know when conditions permit them to lower/raise prices through decreased/increased bids and/or offers.**

Index Terms **– Dispatch sensitivity matrix, market power, null space, Kuhn Tucker optimality conditions, power transfer distribution factor (PTDF) matrix**

I. INTRODUCTION

If a market is competitive the electric power generated by others can substitute for the electric power provided by any generator. However, it is possible that a generator or subset of generators will have very low substitutability because of their location in a network. When this happens market power is said to exist. When generators exploit market power prices will increase without an attendant reduction in the quantity dispatched. As market power increases, the dispatch sensitivity with respect to price approaches zero, and the potential revenue for such generators will increase accordingly.

A few standard metrics such as the HHI, a hedge ratio, and the Lerner index have been used in an attempt to measure market power ([1], [3]). The main problem associated with these metrics is that they are not suitable for real-time market monitoring. Furthermore, they do not account for transmission network effects, which are substantial. Murillo-Sanchez et al [1] presented a mathematical derivation for a dispatch to price sensitivity matrix M by using information that is available only to ISO. By using this M-matrix approach, it is possible to identify subsets of generators that have market power (e.g., [1], [4]). While the method is practical for ISO's who have all the information necessary to compute the M-matrix, it is impractical for market participants, such as generators, because they do not have access to the same level of information. If the actual M matrix can be estimated with a good precision by using only publicly available data, market power can be assessed by all market participants.

In this paper, we present a method for estimating the M matrix. Using the technique, M matrices for several operating conditions of a modified IEEE 30-bus system are estimated and are compared to the true M matrices. This is done to show through one example the accuracy of the estimation.

II. THE DISPATCH SENSITIVITY MATRIX

Currently, those participating in markets for energy only pay real power prices. For this case, and when interconnecting network effects are not considered, the price paid for real power is the sensitivity of total system cost with respect to dispatch. The M matrix is by definition the sensitivity of dispatch to price. Define $C(g,\lambda)$ to be the total system cost for the vector of generation dispatch levels g and input prices λ. If $z(g,\lambda^*)=\nabla_\lambda C(g,\lambda^*)=z^*$ are the optimal levels of generation that minimize cost while satisfying the constraint $\sum_{i=1}^{n} g_i = P_d + P_{loss}$. With g^* the dispatch vector and λ^* the corresponding locational marginal price (LMP) vector we have

This project was support in part by the US Department of Energy through the Consortium for Electric Reliability Technology Solutions (CERTS) and in part by the National Science Foundation Power Systems Engineering Research Center (PSERC).

H. Oh and R. J. Thomas are with the Department of Electrical and Computer Engineering, Cornell University, Ithaca, NY 14853 (e-mail: hso1@cornell.edu; rjt1@cornell.edu).

$$M = \nabla_{\lambda} z(g^*, \lambda^*) = \nabla_{\lambda\lambda} C(g^*, \lambda^*)$$
$$\text{or} \qquad (1)$$
$$\Delta g = M \Delta \lambda$$

Note that the M matrix is the second derivative of dispatch with respect to price and is therefore symmetric. Symmetry can also be observed from the equation derived in [1] for M:

$$M = \left(\frac{\partial g_1}{\partial y}\right)\left\{ H_{22}^{-1}\left(\frac{\partial g_2}{\partial y}\right)^T \left[\left(\frac{\partial g_2}{\partial y}\right) H_{22}^{-1}\left(\frac{\partial g_2}{\partial y}\right)^T\right]^{-1} \left(\frac{\partial g_2}{\partial y}\right) H_{22}^{-1} - H_{22}^{-1} \right\}\left(\frac{\partial g_1}{\partial y}\right)^T \qquad (2)$$

where g_1, g_2, y and H_{22} are the real power mismatch at generation buses, all other constraints, control variables other than real power injection, and weighted Hessian, respectively.

Performing a full AC Optimal Power Flow (ACOPF) produces a dispatch point which satisfies all voltage, generation and line flow constraints. In order to create a reasonable approximation to (2) we begin by solving an economic dispatch problem that includes the network. All the participating generators submit offers into the market, and then the market is "cleared". Note that the solution to the original economic dispatch problem with offers replaced by price returns the same dispatch. Since all offers submitted by generators are LMP's in this formulation, all generators are marginal. As a result, one can construct the following equivalent economic dispatch problem:

$$\min_g \lambda^{*T} g$$
$$\text{subject to} \qquad (3)$$
$$1^T g = P_{loss}(g) + P_D$$
$$Fg \le \overline{flow}$$

where λ^* is the vector of LMP offers and P_{loss} is the real power lossed in the network. As before, g contains the generation setpoints. Each column of F is obtained from the appropriate column of the power transfer distribution factor (PTDF) matrix that relates generation power injection to line flow. The dimension of matrix F is k × n where k is the number-of-lines and n is the number of dispatched generators. The vector $\overline{flow}$ contains the real-power capacity of the lines. Note that in this problem the LMP is obtained first while leaving the generation dispatch a variable.

One can solve equations (3) by forming the Lagrangian as follows:

$$L = \lambda^{**T} g + \mu\left(P_D + P_{loss} - 1^T g\right) + \sigma\left(\overline{fl} - Wg\right) \qquad (4)$$

where μ is the shadow price of the power balance equation and σ is the shadow price of binding line constraints. Note that g is the sensitivity of total system cost to changes in LMP and λ is the sensitivity of total system cost to changes in real power injection.

Since equation (4) is homogeneous in price and of degree one, a change in price in the direction of the LMP will not alter generation dispatch. Therefore, M has one structural eigenvector whose associated eigenvalue is zero. That is,

$$\Delta g = M \Delta \lambda\big|_{\Delta\lambda = c\lambda^*} = cM\lambda^* = 0 \qquad (5)$$

where c is non zero scalar.

The Kuhn Tucker optimality conditions are:

$$f = \nabla_g L = \lambda^* - \mu^*\left(1 - \nabla_g P_{loss}^*\right) = 0$$
$$h = \nabla_\mu L = 1^T g^* - P_D - P_{loss}\left(g^*\right) = 0 \qquad (6)$$
$$fl = \nabla_\sigma L = \overline{flow} - Eg^* = 0$$

where matrix E is comprised of the rows of F corresponding to the lines whose constraints are binding. Consequently, the dimension of matrix E is m'-by-n where m' is the number of congested lines.

Generation setpoints and shadow prices can be obtained by solving equations (6). If offers in the original optimization problem (3) are replaced by the corresponding LMP solution and then re-solved, the solution should be invariant. Suppose that the price is perturbed from the LMP solution. In this case the real power injections and the shadow prices (μ and σ) will change. We assume, however, that the subset of active constraints will not change under price perturbation. Note that a linear program with convex constraints has its solution at a corner point and a small change in offers will not move that solution to a different corner point. The optimality conditions in terms of the perturbation about the original solution are then

$$\Delta f = \Delta\lambda + \mu^*\left(\nabla_{gg}P^*_{loss}\right)\Delta g - \Delta\mu\left(1-\nabla_g P^*_{loss}\right) - E^T\Delta\sigma = 0$$
$$\rightarrow 1-\nabla_g P^*_{loss} = \frac{1}{\Delta\mu}\left[\Delta\lambda + \mu^*\left(\nabla_{gg}P^*_{loss}\Delta g\right)\right] - \frac{1}{\Delta\mu}E^T\Delta\sigma \qquad (7)$$

$$\Delta h = \left(1-\nabla_g P^*_{loss}\right)^T\Delta g = 0 \qquad (8)$$

$$\Delta fl = E\left(g^* + \Delta g\right) - Eg^* = E\Delta g = 0 \qquad (9)$$

Combining (7), (8) and (9), by using equation (1), and with $\Delta\mu$ a non-zero scalar it is straightforward to show the following expression for the M matrix:

$$\Delta\lambda^T\left[I + \mu^*\left(\nabla_{gg}P^*_{loss}\right)M\right]^T M\Delta\lambda = 0 \qquad (10)$$

Note that equation (10) is satisfied for all $\Delta\lambda$. Consequently, one can write the following:

$$\left[B^{-1} + \mu^* M\right]^T B^T M = A^T B^T M = 0 \quad \leftrightarrow M\left(BA\right) = 0 \qquad (11)$$

where $A \equiv B^{-1} + \mu^* M$ and $B \equiv \nabla_{gg}P^*_{loss}$

Note that the B matrix is symmetric since B is a Hessian of system loss with respect to generation. Consequently, B^{-1} and hence A are symmetric. Note that

$$A\lambda = \left[B^{-1} + \mu^* M\right]\lambda = B^{-1}\lambda + \mu^* M\lambda = B^{-1}\lambda \qquad (12)$$

and

$$E\Delta g = EM\Delta\lambda = 0 \rightarrow EM = 0 \qquad (13)$$

The left hand side of the arrow in (13) holds for all perturbations of LMP.

Since the LMP vector lies in the null space of M [1], the null space of M is spanned by the LMP vector plus the row vectors of E matrix. From equation (11), A^TB^TM = ABM = 0 since A and B are symmetric matrices. Consequently, each row vector of the AB matrix is in the null space of M, i.e., each row vector of AB is a linear combination of e_j (j = 1, …, m') and λ^T where e_i is the i[th] row of the E matrix. Therefore, the matrix AB can be expressed in terms of E and the LMP vector as follows:

$$AB = \begin{pmatrix} \alpha_1^1 e_1 + & \cdots & +\alpha_{m-1}^1 e_{m-1} + \alpha_m^1\lambda^T \\ \alpha_1^2 e_1 + & \cdots & +\alpha_{m-1}^2 e_{m-1} + \alpha_m^2\lambda^T \\ \vdots & \ddots & \vdots \\ \alpha_1^n e_1 + & \cdots & +\alpha_{m-1}^n e_{m-1} + \alpha_m^n\lambda^T \end{pmatrix} = \begin{bmatrix} \alpha_1^{m\times m} \\ \alpha_2^{(n-m)\times m} \end{bmatrix}\begin{pmatrix} E \\ \lambda^T \end{pmatrix} = \begin{bmatrix} \alpha_1^{m\times m} \\ \alpha_2^{(n-m)\times m} \end{bmatrix} L \qquad (14)$$

where the α's are proportionality factors, m = m' + 1, and L represents an E matrix with one additional row containing the LMP vector.

Multiplying by B^{-1} on both sides yields

$$A = \begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} LB^{-1} = \begin{bmatrix} \alpha_1^{m\times m} \\ \alpha_2^{(n-m)\times m} \end{bmatrix}\begin{bmatrix} G_1^{m\times m} & G_2^{m\times(n-m)} \end{bmatrix} = \begin{pmatrix} \alpha_1 G_1 & \alpha_1 G_2 \\ \alpha_2 G_1 & \alpha_2 G_2 \end{pmatrix} \qquad (15)$$

where G is LB^{-1}.

Since A is symmetric we may write:

$$\left(\alpha_1 G_2\right)^T = G_2^T\alpha_1^T = \alpha_2 G_1 \qquad (16)$$

$$\rightarrow \alpha_2 = G_2^T\alpha_1^T G_1^{-1} = G_2^T G_1^{-T}\alpha_1 \qquad (17)$$

Combining equations (16) and (17) gives:

$$A = \begin{pmatrix} \alpha_1 \\ G_2^T G_1^{-T}\alpha_1 \end{pmatrix}\begin{pmatrix} G_1 & G_2 \end{pmatrix} = G^T G_1^{-T}\alpha_1 G \qquad (18)$$

Note that since G is known, α_1 is the only unknown in equation (18).

From equation (12) one finds:

$$A\lambda = G^T G_1^{-T}\alpha_1 G\lambda = B^{-1}\lambda \quad \rightarrow I\lambda = BG^T G_1^{-T}\alpha_1 G\lambda \qquad (19)$$

Note that:

$$G\lambda = \begin{pmatrix} G_1 & G_2 \end{pmatrix}\begin{bmatrix} \lambda_1^{m\times 1} \\ \lambda_2^{(n-m)\times 1} \end{bmatrix} = G_1\lambda_1 + G_2\lambda_2 \qquad (20)$$

Let C be $BG^TG_1^{-T}$, then:

$$C = BG^T G_1^{-T} = \begin{bmatrix} B_1^{m\times n} \\ B_2^{(n-m)\times n} \end{bmatrix} G^T G_1^{-T} = \begin{bmatrix} C_1^{m\times m} \\ C_2^{(n-m)\times m} \end{bmatrix} \quad (21)$$

Combining equations (19) and (21) gives:

$$\begin{pmatrix} \lambda_1 \\ \lambda_2 \end{pmatrix} = C\alpha_1 G\lambda = \begin{pmatrix} C_1\alpha_1 G\lambda \\ C_2\alpha_1 G\lambda \end{pmatrix} \rightarrow \lambda_2 = C_2 C_1^{-1}\lambda_1 \quad (22)$$

One can also find price explicitly as follows:

$$\lambda = \begin{pmatrix} \lambda_1 \\ \lambda_2 \end{pmatrix} = \begin{pmatrix} \lambda_1 \\ C_2 C_1^{-1}\lambda_1 \end{pmatrix} = CC_1^{-1}\lambda_1 \quad (23)$$

By substituting equation (21) into (23) the LMP is

$$\begin{aligned} \lambda &= \left(BG^T G_1^{-T}\right)\left(B_1 G G_1^{-T}\right)^{-1}\lambda_1 = BG^T\left(B_1 G^T\right)^{-1}\lambda_1 \\ &= B\left(LB^{-1}\right)^T\left[B_1\left(LB^{-1}\right)^T\right]^{-1}\lambda_1 = L^T\left(B_1 B^{-1} L^T\right)^{-1}\lambda_1 \end{aligned} \quad (24)$$

Equations (22) and (24) can be combined to yield

$$C_1\alpha_1 G\lambda = C_1\alpha_1 G\left[BG^T\left(B_1 G^T\right)^{-1}\lambda_1\right] = I\lambda_1 \quad (25)$$

Equation (25) is valid for all λ_1 which means

$$\alpha_1 = C_1^{-1}\left(B_1 G^T\right)\left(GBG^T\right)^{-1} = G_1^T\left(GBG^T\right)^{-1} \quad (26)$$

The A and M matrices can be found by combining equations (18) and (26)

$$\begin{aligned} A &= G^T G_1^{-T}\alpha_1 G = G^T\left(GBG^T\right)^{-1} G \\ &= B^{-1}L^T\left(LB^{-1}L^T\right)^{-1}LB^{-1} \end{aligned} \quad (27)$$

$$M = \frac{B^{-1}}{\mu^*}\left[L^T\left(LB^{-1}L^T\right)^{-1}LB^{-1} - I\right] \quad \text{where } L = \begin{pmatrix} E \\ \lambda^T \end{pmatrix} \quad (28)$$

Matrix M can be calculated by using equation (28) with publicly available and predictable data such as LMP, B and the PTDF matrix for the network.

Note that equation (28) applies for a system where there are no "must-run" generating units. By must-run units we mean generators whose dispatch is fixed, perhaps contractually, or because of market mitigation policies, or for some other reason. A perturbation of price for must-run units is therefore not allowed. For a system containing z "must-run" units, equation (28) is modified to take account of the must-run units. In this case the difference vectors for price, $\Delta\lambda$, and dispatch Δg, are rearranged such that elements for the z- must-run generators are located at the bottom, i.e.,

$$\Delta g_{new} = P\Delta g, \quad \Delta\lambda_{new} = P\Delta\lambda \quad (29)$$

where P is a permutation matrix for the rearrangement. For the rearranged vectors, one can define a new M matrix:

$$\begin{aligned} &\Delta g_{new} = M_{new}\Delta\lambda_{new} = M_{new}P\Delta\lambda = P\Delta g \\ &\leftrightarrow M_{new} = PMP^T \end{aligned} \quad (30)$$

The new M matrix is then

$$M_{new} = \begin{bmatrix} M_{reduced}^{(n-z)\times(n-z)} & 0^{(n-z)\times z} \\ 0^{z\times(n-z)} & 0^{z\times z} \end{bmatrix} \quad (31)$$

This rearrangement essentially separates the system into two systems in which a change in one does not affect the other. Consequently, $M_{reduced}$ can be estimated by applying equation (28) with reduced E, B and λ that exclude the z-must-run generators. Finally, the full M matrix can be reconstructed from the matrix M_{new} by computing

$$M = P^T M_{new} P \quad (32)$$

Due to the separation, the space spanned by M is divided into two subspaces of dimensions (n - z) and z such that the two subspaces are independent. The eigenvectors of M are thus divided into two groups that span, each group spanning one of the two subspaces. Eigenvectors spanning the (n - z) dimensional subspace contain zero elements for z-generators, and those spanning the z-dimensional subspace do so for (n - z) generators. It is also worthwhile to note that each of the z-generators is separated from each other. Therefore, eigenvectors spanning the z-dimensional subspace are unit vectors parallel to the price of the z-generators. Note that eigenvalues related to the separation are zero since the eigenvectors span the null space of M.

To estimate the M matrix, one needs to evaluate μ^*, the shadow price for the power balance equation. If demand is located at a single bus, then μ^* is the nodal price at the bus. However, in general, demand is distributed throughout the network. Consequently, it is difficult to define an aggregate shadow price. By definition, μ^* is the cost to deliver one more unit of real power to an aggregated load bus. Since there are different probabilities for each demand bus to require one more unit, μ^* can be evaluated with using a probability distribution and a shadow price for each demand as follows:

$$\mu^* = \sum_i p_i \mu_i^* \approx \sum_i \left(\frac{D_i}{D_{total}} \right) \mu_i^* \qquad (33)$$

where D_i stands for the real power demand at the i[th] bus. Note that the demand probability distribution is approximated by its demand profile.

Market power is very closely related to M matrix since change in revenue according to change in price can be calculated in a following way:

$$\begin{aligned} \Delta r_i &= \Delta(\lambda_i g_i) = \lambda_i^* \Delta g_i + g_i^* \Delta \lambda_i \\ &= \lambda_i^* \left(\sum_j M_{ij} \Delta \lambda_j \right) + g_i^* \Delta \lambda_i \qquad (34) \\ &= \left[Diag(\lambda_i^*) M \Delta \lambda \right]_i + \left[Diag(g_i^*) \Delta \lambda \right]_i \end{aligned}$$

$$\Delta R = \left[Diag(\lambda_i^*) M + Diag(g_i^*) \right] \Delta \lambda = N \Delta \lambda \qquad (35)$$

If an agent owns multiple generators, then equation (35) can indicate if it has market power as a group.

III. CASE STUDIES

To test the accuracy of the estimation method shown in equation (28), the modified IEEE 30-bus system shown in Figure 1 is used. For the system, true and estimated M matrices for various offers are calculated. Table I shows a comparison between them when no line is congested, and consequently no market power exists.

As is shown in Table I, equation (28) provides a means for determining a close estimate of the true M matrix element by element.

When transmission lines become more and more congested, a simple economic dispatch problem does not model an actual system properly. Consequently, a large error in estimating M matrix is expected. Table II shows a comparison between two M matrices under the condition that several lines are congested. Note that no individual generator has market power in this case.

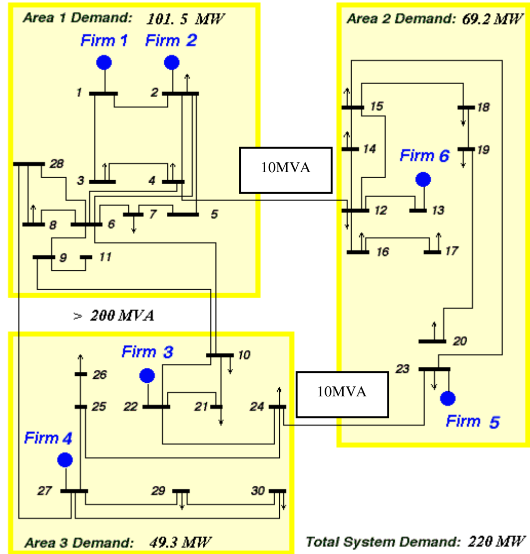

Fig. 1. Modified IEEE 30 bus and 6 generator system

TABLE I
Comparison between true and estimated M matrices for the case where no line is congested

Mtrue Mest	G1	G2	G3	G4	G5	G6
G1	-58.20 -58.81	47.71 47.66	2.33 2.39	1.78 1.88	-0.04 0.33	5.98 6.10
G2	47.71 47.66	-77.28 -77.20	9.40 9.50	6.60 6.49	-0.05 -0.51	13.38 13.83
G3	1.78 1.88	9.40 9.50	-16.2 -16.4	1.38 1.45	2.72 2.38	0.60 0.85
G4	2.33 2.39	6.60 6.49	1.38 1.45	-12.30 -12.37	1.48 1.65	1.09 0.93
G5	-0.04 0.33	-0.05 -0.51	2.72 2.38	1.48 1.65	-9.63 -8.73	5.61 4.96
G6	5.98 6.10	13.38 13.83	0.60 0.85	1.09 0.93	5.61 4.96	-26.3 -26.3

TABLE II
Comparison between true and estimated M matrices for the case where several lines are congested

Mtrue Mest	G1	G2	G3	G4	G5	G6
G1	-62.4 -62.5	57.60 57.46	2.68 2.58	2.43 2.33	0.00 -0.00	-0.46 -0.51
G2	57.60 57.46	-73.6 -73.7	9.04 8.97	7.72 7.57	-0.00 -0.11	-0.71 -0.78
G3	2.68 2.58	9.04 8.97	-19.1 -19.1	1.98 1.79	3.19 3.08	2.12 2.03
G4	2.43 2.33	7.72 7.57	1.98 1.79	-14.3 -14.4	1.48 1.39	0.88 0.82
G5	0.00 -0.00	-0.00 -0.11	3.19 3.08	1.48 1.39	-11.0 -11.0	6.34 6.27
G6	-0.46 -0.51	-0.71 -0.78	2.12 2.03	0.88 0.82	6.34 6.27	-8.16 -8.38

As expected, the error between the true and estimated M matrices becomes larger than in the previous case. But the estimated M matrix is still reasonable accurate for our purpose, namely, as an indicator of who has market power.

One might notice that reactive power flow over a line is not considered in this study. In general, reactive power generation and flow may be also changed when price is perturbed. For some cases, the change is not negligible. However, equation (28) still approximates true M matrix well if the change is not substantial or if the change is approximately proportional to that of real power.

Table III shows results from the case when the change is substantial and is not proportional to real power. As expected, the error becomes substantial. However, the main purpose of estimating M matrix is to estimate market power. Therefore, it is useful to check to see if the estimated M matrix indicates potential market power. For this purpose, the revenue sensitivity matrices are evaluated for the same case by using equation (35) and shown in Table IV. In this case, elements of the true N matrix for G5 and G6 has positive subset sum. The situation indicates a "win-win" situation as defined in [4]. The N matrix derived from the estimated M also indicates the same results.

TABLE III
Comparison between true and estimated M matrices for the case where several lines are congested and some generators have market power

Mtrue Mest	G1	G2	G3	G4	G5	G6
G1	-57.2 -53.3	57.72 56.92	-1.08 -6.67	0.59 1.65	-1.08 -2.43	1.13 2.51
G2	57.72 56.92	-62.8 -65.4	-0.12 7.53	5.11 2.25	2.64 4.43	-2.64 -4.45
G3	-1.08 -6.67	-0.12 7.53	-16.3 -12.9	17.26 11.81	-1.40 -1.86	1.37 1.83
G4	0.59 1.65	5.11 2.25	17.26 11.81	-22.7 -15.3	-0.18 -0.11	0.16 0.07
G5	-1.08 -2.43	2.64 4.43	-1.40 -1.86	-0.18 -0.11	-0.79 -0.99	0.78 0.95
G6	1.13 2.51	-2.64 -4.45	1.37 1.83	0.16 0.07	0.78 0.95	-0.77 -0.92

VI. CONCLUSION

In this paper we proposed a method for estimating market power based on dispatch to price sensitivity matrix. We showed that computing an estimate of the sensitivities requires only publicly available data. Through case studies we conclude that the method works reasonably well. Some cases have a larger error than others, but it still does a good job of identifying potential market power. The mathematical relationship between the true M matrix and the estimated one, that is, the error between them, is still a topic of research.

TABLE IV
Comparison between true and estimated N matrices for the case where several lines are congested and some generators have market power

Ntrue Nest	G1	G2	G3	G4	G5	G6
G1	-3044 -2841	3099 3058	-58 -358	32 88	-58 -130	61 135
G2	3131 3089	-3360 -3505	-7 409	278 122	143 241	-143 -241
G3	-23 -140	-3 158	-284 -214	362 248	-29 -39	29 39
G4	17 48	148 65	498 341	-609 -397	-5 -3	5 2
G5	-326 -729	791 1330	-418 -557	-55 -32	-210 -269	233 286
G6	269 598	-630 -1061	327 437	37 16	186 228	-160 -195

V. REFERENCES

[1] C. E. Murillo-Sanchez, S. M. Ede, T. D. Mount, R. J. Thomas and R. D. Zimmerman, "An Engineering Approach to Monitoring Market Power in Restructured Markets for Electricity", presented at the 24th Annual International Association for Energy Economics International Conference, Houston, TX, April 2001.

[2] B. C. Lesieutre, R. J. Thomas and T. D. Mount, "A Revenue Sensitivity Approach for the Identification and Quantification of Market Power in Electric Energy Markets", Power Engineering Society General Meeting (2003) 838-842.

[3] A. R. Kian, R. J. Thomas, R. D. Zimmerman, B. C. Lesieutre and T. D. Mount, "Identifying the Potential for Market Power in Electric Power Systems in Real-Time", Proceedings of the 37th HICSS Conference on System Sciences (2004) 1-5.

[4] B. C. Lesieutre, R. J. Thomas and T. D. Mount, "A Revenue Sensitivity Approach for the Identification and Quantification of Market Power in Electric Energy Markets", Power Engineering Society General Meeting (2003) 838-842.

VI. BIOGRAPHIES

HyungSeon Oh received the MS. degree in Materials Science and Engineering in 2002 and the Ph. D. degree in Electrical and Computer Engineering in 2005 from Cornell University. He is currently a Postdoctoral Research Associate at the Department of Electrical and Computer Engineering, Cornell University. His research interest includes stochastic optimization, electric power economics, computer simulation and nonlinear dynamics.

Robert J. Thomas is a professor in Electrical and Computer Engineering at the Cornell University. His current research interests are broadly in the areas of analysis and control of nonlinear continuous and discrete-time systems with applications to large-scale electric-utility systems. He has been a member of the IEEE United States Activity Board's Energy Policy Committee since 1991 and was the committee's Chair from 1997-1998. He was a member of the IEEE Technology Policy Council, has served as the IEEE-USA Vice President for Technology Policy, and has been a member of several university, government and industry advisory Boards or Panels.