An Empirical Study of Applied Game Theory: Transmission Constrained Cournot Behavior

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***Abstract*—Restructured energy markets present opportunities for the exercise of market power, meaning market players can potentially maintain prices in excess of competitive prices. In this paper, we investigate Cournot equilibrium in a simple example network. We analyze three market players in a transmission-constrained system and consider nonconstant marginal cost. Several scenarios are evaluated that show a pure strategy equilibrium can break down even when a transmission constraint exceeds the value of the unconstrained Cournot equilibrium line flow.**

***Index Terms*—Game theory, Cournot, transmission constraints, pricing of power, market models.**

I. Introduction

As restructuring continues to move forward in the U.S., state legislators as well as customers are interested in the impact of electricity industry restructuring. The concept underpinning restructuring is that open competition will replace the regulatory framework as the major factor in determining the market price for energy.

States currently restructuring, such as Texas, have the advantage of reviewing the "lessons learned" from other states and countries that preceded them. The U.K. experience that resulted initially in a duopoly shows that market power can be present in a restructured electricity market. More recently, high prices in the California market have prompted the imposition of price caps.

Much research has focused on the characteristics of market "equilibrium" [1]. Questions that are of interest include the following.

1) Is there a pure strategy equilibrium?
2) How do transmission constraints affect the equilibrium?
3) Are there multiple equilibria?

The existence of an equilibrium is an important concept in game theory. If a unique equilibrium exists, then it is reasonable that market savvy players might eventually reach this point to maximize profit. A pure strategy is when market players choose their actions deterministically [2]. Thus, a pure strategy equilibrium is when market players reach an equilibrium through a consistent set of deterministic actions. In contrast, a mixed strategy equilibrium exists when firms choose their actions probabilistically in equilibrium. Multiple equilibria are present when there exist several such mutually consistent actions (whether pure strategy or mixed strategy) that companies could use to maximize profit. This paper presents an empirical analysis that examines whether or not a pure strategy equilibrium exists in a simple transmission-constrained Cournot market.

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II. Brief Review and Extension of Literature

The current literature has many examples of oligopolistic models applied to the electric utility industry to model a restructured market. A common modeling approach is to assume Cournot behavior, which is when companies choose quantities as strategies; however, there is a growing body of work on supply function behavior where companies choose supply functions as strategies.

- Green and Newbery [3] examined generation restructuring in the U.K with a supply function model. Because of market ownership in the generation market, the U.K. was effectively served by a duopoly. Market competition did not produce prices that resembled marginal cost.
- Ocana and Romero [4] considered market structure, price levels, and price variability and how these additional factors impact hydro generation strategies.

  Traditional economic oligopoly models do not consider transmission constraints. In an actual electricity system, however, market prices are a function of Kirchoff's laws, as well as economic principles. The following studies focused on electrical characteristics combined with economic models:
- Borenstein *et al.* [5] studied the competitive effects of a transmission line that connected a two utility system. Their work not only included Cournot behavior for a duopoly but also included a mixed strategy analysis. Additionally their work included an empirical analysis of the California electricity market modeled as a duopoly. They showed that transmission constraints can disrupt a pure strategy Cournot equilibrium even when the flow in the unconstrained Cournot equilibrium is feasible with respect to the transmission constraint.
- Younes and Ilic [6] studied oligopolistic competition using Cournot, Bertrand, and supply functions in a three-bus, two-generator system. They concluded that transmission line congestion potentially creates submarkets that could encourage strategic behavior by participants to increase profits.
- Stoft [7] considered market power issues when generators faced a demand curve that is limited by transmission constraints. This study utilized a two-bus system connected

by one line and a three-bus system. The typical economic profit function was expanded to include transmission congestion contracts (TCCs).[1]

- Berry *et al.*,[8] model a two- and four-bus system. The four bus system is defined by two generation buses and two load buses. The system has five transmission connections. Their paper analyzed competitive and imperfectly competitive markets with a focus on price and profit impacts to the holders of transmission congestion rights.

This paper builds upon the current literature by doing the following.

1) Considering three market players in a looped transmission-constrained system. This builds one step closer to realism. Borenstein *et al.* [5] considered a two player market. Younes and Ilic [6] considered a three-bus system with two generators and one load. Berry *et al.*[8] analyzed a four bus system with two generators and two loads. Stoft [9] considered both two buses with two generators and three buses with two generators and one load. Borenstein and Bushnell [10] considered multiple players in the California model but did not model loop flow. The best response function of a two player market can be displayed two-dimensionally. When there are three market players, the best response functions are surfaces in three-dimensional (3-D) space.
2) Considering nonconstant marginal cost. The use of constant marginal cost can potentially lead to results that are not realistic. References [5] and [7] used constant marginal cost in their analysis.
3) Considering nonsymmetric market players. It is doubtful that an actual market would have a high degree of symmetry. Using symmetric players can lead to results that are not realized in actual markets due to the fact that market players will most likely have differing marginal cost curves.
4) Modeling both load and generation at each bus in the system. Most current literature uses examples where load and generators are separated. This approach would best fit a "micro" view of an electrical system. Modeling both load and generation at each aggregated bus within the electrical system is more appropriate to represent a market of several interconnected utilities or geographic regions. This is more of a regional view utilizing an equivalenced system.
5) Empirically analyzing the existence of a pure strategy equilibrium as transmission limits change. We will show an example where a pure strategy equilibrium fails to exist even when transmission constraints exceed the line flow that would result from the unconstrained equilibrium condition.

III. Case Study

In the following sections, we present the model, the perfect competition benchmark, and the Cournot solution.

[1]Transmission congestion contracts are financial instruments that represent tradable transmission rights and pay the owner the difference between two nodal prices.

A. Model

There are three hypothetical utilities used in this study. They are designated as Utilities A, B, and C and are interconnected with three transmission lines as shown in Fig. 1. This *triangular* connection[2] is the simplest electrical connection that demonstrates the physical characteristics of Kirchoff's voltage law. The line flows are approximated using a dc line flow solution. The transmission lines are characterized by the following parameters.

- The transmission lines have equal impedance.
- The lines are considered lossless.

Finally it is assumed that the utilities compete in a power pool type of arrangement that requires each utility to bid into a central operator that determines the market clearing price for energy.

Each utility has a marginal cost function and each consumer group has a demand function. The demand is simply the derivative of the benefit function with respect to quantity. The marginal cost is the derivative of the total cost function with respect to quantity.

The inverse demand curve of each consumer group has the relationship

$$Pi = \beta_i - \alpha_i d_i \quad i = A, B, C \tag{1}$$

where d_i is the demand in region i and P_i is the price in region i. In the absence of transmission constraints, the price is uniform across the regions and the individual inverse demand curves can be combined to produce an equivalent industry demand curve

$$P = \theta - \rho d \tag{2}$$

where d is the total demand and P the uniform price. The marginal cost of each utility supplier has the relationship

$$\mathrm{MC}_i = \gamma_i + \phi_i q_i \quad i = A, B, C. \tag{3}$$

If no generation capacity constraints and no transmission constraints are binding then for the competitive solution, P will equal MC_i. The price P will be uniform throughout the system.

The role of the central operator is to maximize total welfare subject to the constraints on the system

$$\begin{aligned} &\max \sum_{i=A}^{C} \text{Benefit}_i - \text{Cost}_i, \\ &\text{ST Transmission thermal limits} \\ &\quad \text{Total supply} = \text{total demand} \\ &\quad \text{Kirchoff's laws.} \end{aligned} \tag{4}$$

The benefit function is given by

$$\text{Benefit}_i = \beta_i q_i - 1/2 \alpha_i d_i^2. \tag{5}$$

The total cost function is given by

$$\mathrm{Cost}_i = 1/2 \phi_i q_i^2 + \gamma_i q_i + \eta_i. \tag{6}$$

[2]This connection was popularized by William Hogan and has been reused by many authors in current literature.

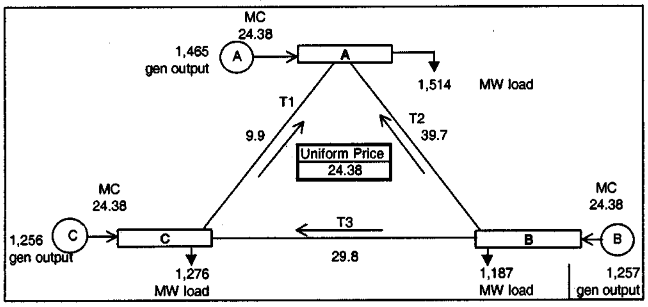

Fig. 1. Perfect competition load flow solution.

The profit equation for each utility is given by

$$\pi_i = P_i q_i - \text{Cost}_i \quad i = A, B, C. \tag{7}$$

1) Utility Data: The benefit and cost data for each utility are given in Table I. There is a fixed cost component of the total cost for each utility. The total cost equation is intended to represent a portfolio of generation. Although Fig. 1 shows only one generator at each bus, this should be interpreted as the injection of the entire generating portfolio at the bus.

B. Perfect Competition Benchmark

The purpose of this section is to determine the resulting price for energy and transmission line flows for the perfectly competitive market. This price is used for comparisons to the prices that result from the imperfectly competitive Cournot model to be presented in Section III-C. The competitive solution is equivalent to a transmission-constrained economic dispatch based on true costs and benefits.

1) Transmission Unconstrained: Fig. 1 summarizes the resulting price, generation (production), demand (load), and transmission line flows. Marginal costs are measured in $/MWh. Transmission line flow, generation, and demand are measured in MW. The results in Fig. 1 are computed when there are no transmission constraints present.

2) Transmission Constrained Results: When the transmission line capacities are reduced from the unconstrained flow, locational price differences occur. Figs. 2 and 3 show profit and price, respectively, as the capacity of T2 is varied from just above 0 MW to 39.7 MW. The unconstrained solution has a flow of 39.7 MW on T2, as shown in Fig. 1. The interesting result of these figures is that there can be significant effects on profit for relatively small changes in transmission capacity. The effect of varying the capacities of transmission lines T1 and T3 are both qualitatively similar to the case of varying the capacity of line T2; however, varying these capacities has less impact on price and profit than varying the capacity of line T2.

Varying the capacity of line T2 shows the most dramatic result. The maximum change in price is 3.7%, ($24.38/MWh reduced to $23.48/MWh.) The change in profit, however, is much greater. Utility B's profit is reduced 20%, ($5 482 to $4 381.)

Up to this point variations in price and profit were solely due to transmission constraints. Market players have been assumed to bid their true marginal cost to the central operator.

TABLE I
BENEFIT AND COST DATA

		Utility A	Utility B	Utility C
Inverse Demand	β_i =	108.4096	103.8238	105.6709
$P_i = \beta_i - ½\ \alpha_i q_i$	α_i =	0.0555	0.066909	0.063703
Total Cost	ϕ_i =	0.015718	0.021052	0.012956
$C_i = 1/2\ \phi_i\ q_i^2 + \gamma_i q_i + \eta_i$	γ_i =	1.360575	-2.07807	8.105354
	η_i =	9490.366	11128.95	6821.482
Industry Demand	θ =	106.1176		
$P = \theta - \rho Q$	ρ =	0.0206		

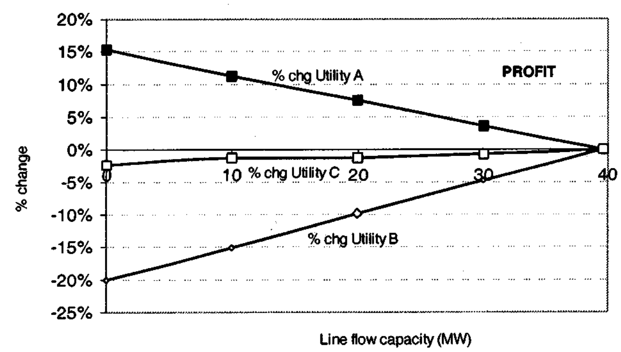

Fig. 2. Percent change in profit varying line T2.

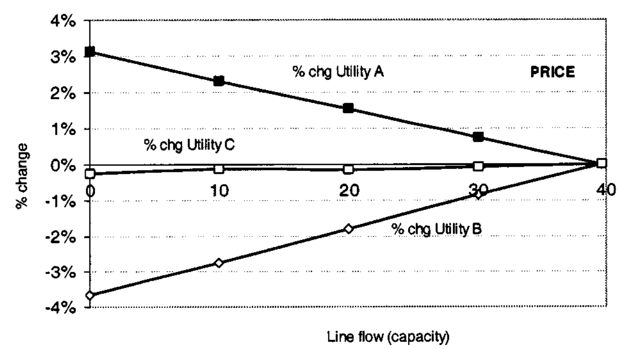

Fig. 3. Percent change in price varying line T2.

C. Cournot

In the Cournot model, each firm chooses its output assuming that it affects the price through the inverse demand relationship (2), but assuming that the other firms keep their outputs constant independent of price [2]. This paper considers the equilibrium of a single round bid game.

For Utility A, the profit function is given by

$$\begin{aligned}\pi_A = {} & (\theta - \rho(q_A + q_B + q_C))q_A \\ & - (1/2\phi_A q_{A^2} + \gamma_A q_A + \eta_A). \end{aligned} \tag{8}$$

Note that for the price P_i in (7), the uniform price P from (2) has been substituted as a function of all market participant's bid quantities. Since the profit function π_A of Utility A in (8) is concave and quadratic, the profit maximizing condition is given by setting the partial derivative equal to zero. The partial derivative of π_A with respect to the quantity q_A is

$$\begin{aligned}\partial\pi_A/\partial q_A = {} & (\theta - \rho q_A - \rho q_B - \rho q_C) \\ & - \rho q_A - \phi_A q_A - \gamma_A. \end{aligned} \tag{9}$$

Likewise the partial derivatives for utilities B and C can be can also be computed. The simultaneous set of equations for the three utilities is given by

$$\begin{bmatrix} 2\rho+\phi_A & \rho & \rho \\ \rho & 2\rho+\phi_B & \rho \\ \rho & \rho & 2\rho+\phi_C \end{bmatrix} \begin{bmatrix} qA \\ qB \\ qC \end{bmatrix} = \begin{bmatrix} \theta-\gamma_A \\ \theta-\gamma_B \\ \theta-\gamma_C \end{bmatrix}. \tag{10}$$

In (10), note that all the off diagonal terms in the coefficient matrix are ρ. The diagonal terms are $2\rho+\phi_i$ where $0<\rho<1$ and $0<\phi_i<1$, therefore the diagonal terms are larger than the sum of the off-diagonal terms and consequently the coefficient matrix is positive definite. Therefore, (10) has a unique solution. A more complete theoretical treatment is given in [6].

The three simultaneous equations that define the Cournot best responses are also the equations that define the three best response planes in space. Utility A's best response to Utilities B's and C's quantities is given by

$$\mathrm{BR}_A(q_B,q_C)=(\theta-\gamma_A)/(2\rho+\phi_A)-\rho q_B-\rho q_C. \tag{11}$$

This function is called Utility A's best response function. Given choices q_B and q_C by Utilities B and C, Utility A maximizes profit by setting

$$q_A=\mathrm{BR}_A(q_B,q_C). \tag{12}$$

1) Transmission Unconstrained: The unconstrained Cournot best response planes can be seen in Fig. 4 and are denoted as "BR_A" for example. The transmission unconstrained Cournot–Nash pure strategy equilibrium is the solution of (10), which is the intersection of all three planes in Fig. 4. Table II shows the numerical solution.

The transmission line flows that result from the unconstrained pure strategy equilibrium are summarized in Table III.

An important observation that can be made at this point is that by behaving in a Cournot manner, the utilities can significantly alter the transmission line flows compared to the competitive case. For example, the flow on line T2 is nearly double the flow compared to the competitive case.

2) Transmission Constrained Results: When transmission constraints are present in the imperfectly competitive market, Cournot behavior will produce locational price differences similar to a competitive market with constraints present. This increases the difficulty of computing the profit maximizing condition of the utilities. The profit maximizing function of each utility now has an imbedded transmission-constrained welfare maximization problem within the profit maximizing function. The generation and transmission line constraints are included in the welfare maximization subproblem. The profit function of each utility is given in (13), shown at the bottom

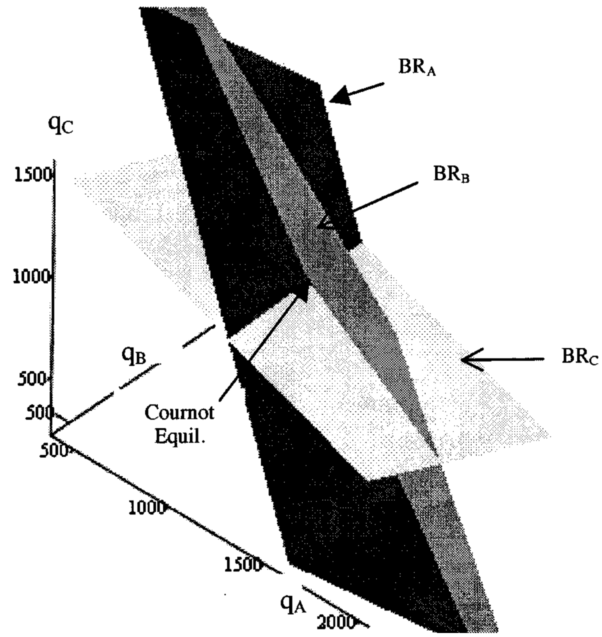

Fig. 4. Unconstrained Cournot best response planes.

TABLE II
UNCONSTRAINED COURNOT SOLUTION

	Utility A	Utility B	Utility C
Output (MW)	1,105	1,046	995
Cournot market price ($/MWh)	41.45	41.45	41.45

TABLE III
TRANSMISSION LINE FLOW COMPARISON

	Full Competition		Cournot	
Line	MW flow	direction	MW flow	direction
T1	9.85	C to A	29.4	C to A
T2	39.65	B to A	71.7	B to A
T3	29.80	B to C	42.3	B to C

of the page. In (13), player i maximizes its profit given that the price P_i will be determined by the solution of the inner transmission-constrained benefit maximization problem.

To simplify the analysis and figures, we consider an upper bound constraint on line T1 in one direction only. Later, we will briefly discuss what happens if the flow constraint is the more usual bi-directional constraint. The direction of flow that we constrain is from bus C to bus A. The opposite direction, bus A to bus C will remain unconstrained. Suppose that the "allowable" flow on line T1 is reduced from infinite capacity to 100 MW. For clarity, only Utility A's best response is shown in Fig. 5. The prices and quantities are the same as for the unconstrained Cournot solution, which are shown in Table II. Note

$$\max_{q_i}\left\{ P_i q_i - \mathrm{Cost}_i \left| \left\{ \max \sum_{j=A}^{j=C} \mathrm{benefit}_j \;\middle|\; \begin{matrix}\text{Transmission}\\ \text{Constraints}\end{matrix} \right\} \right. \right\}_{q_{i,\min}\le q_i\le q_{i,\max}} \quad \text{for } i=A,B,C \tag{13}$$

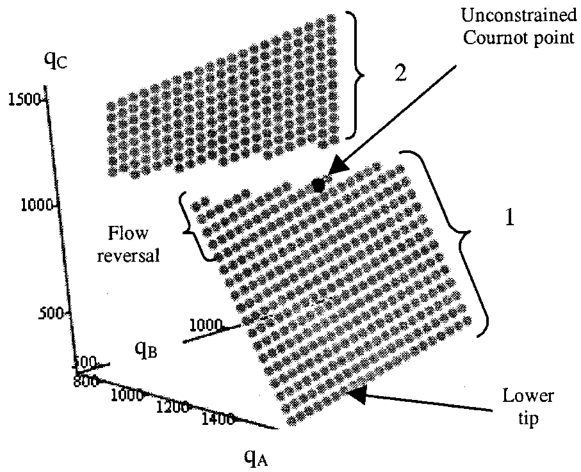

Fig. 5. Utility A best response for T1 constrained at 100 MW.

that the best response surface is no longer a "well behaved" flat plane as shown in Fig. 4. Fig.5 shows that A's best response can be described by two regions.

Region one is identical to the unconstrained best response plane up to the level that there is a discrete jump to region two. The lower tip of region one is formed by Utility A supplying a large amount of generation while Utilities B and C supply at minimum or near minimum levels of output.

Utility A's profit maximizing response to B's and C's increase in generation is to reduce its output. For generation by B and C near to the lower tip, A's best response results in line flows on line T1 from the bus A to bus C direction. Recall that this direction is unconstrained. In the vicinity of the unconstrained equilibrium point, A's best response is to reverse the line flow on line T1, thus it is now in the bus C to bus A direction. Region two is formed because of the 100 MW constraint in that direction.

In region two of Fig. 5, Utilities B and C have increased generation and Utility A's profit maximizing response is to withhold generation and let the line constrain, thereby maximizing profit with the constrained line. In region two, the prices are no longer uniform across the system. There is locational price separation, shown in Table IV, just as in the competitive market with transmission constraints. Note the discrete step between regions one and two. It is because of this "step" that we will show that a pure strategy Cournot equilibrium fails to exist in some scenarios.

The best responses of all three utilities can be seen in Fig. 6. Note that all three best response surfaces still intersect and this defines the pure strategy Cournot–Nash equilibrium.

The transmission-constrained equilibrium solution point does not change compared to the unconstrained case due to the unidirectional 100 MW constraint.

Utility C's best response has three separate regions and is not shaped like A's. This is due to the fact that Utility C's profit maximizing behavior is altered due to the constraint in the bus C to bus A direction. For generation levels by A and B that are low, C's best response is to also limit output. In Fig. 7, line T1 is further constrained to 66 MW in the bus C to bus A direction. Only the best response surfaces for Utilities A and C are shown. Utility B has been omitted for clarity.

TABLE IV
REGION 1 AND 2 COMPARISON OF PRICES AND QUANTITIES

Region 1, uniform price	Utility A	Utility B	Utility C
Output (MW)	1,105	1,046	995
Cournot market price ($/MWh)	41.45	41.45	41.45
Region 2, locational price	**Utility A**	**Utility B**	**Utility C**
Output (MW)	844	893	1,425
Cournot market price ($/MWh)	54.74	40.45	26.16

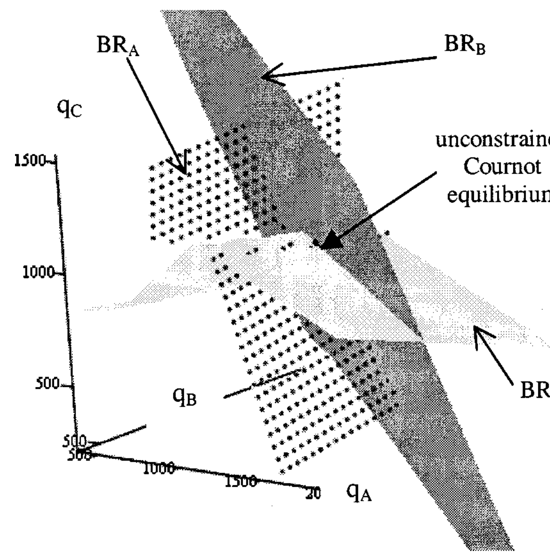

Fig. 6. Utilities A, B, and C best responses for T1 constrained to 100 MW.

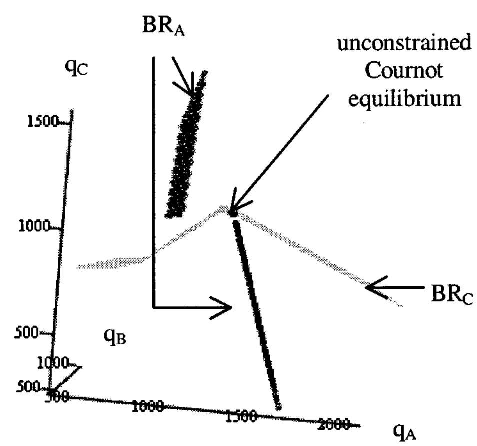

Fig. 7. Utilities A and C best responses for T1 constrained to 66 MW.

When transmission line T1 is limited to 66 MW, there is no longer a pure strategy equilibrium. Utilities B and C still have best response surfaces that pass through the unconstrained Cournot equilibrium point but Utility A's best response "jumps" from region one to region two before it passes through the unconstrained point. The size of region one of Utility A's best response has reduced, while region two has increased. This is due to the tightened unidirectional transmission constraint. Both Utilities A and C increase profit by withholding supply thus allowing transmission line T1 to "load up" to full capacity. The existence of a transmission constraint that exceeds the value of the unconstrained line flow has disrupted the pure strategy equilibrium.

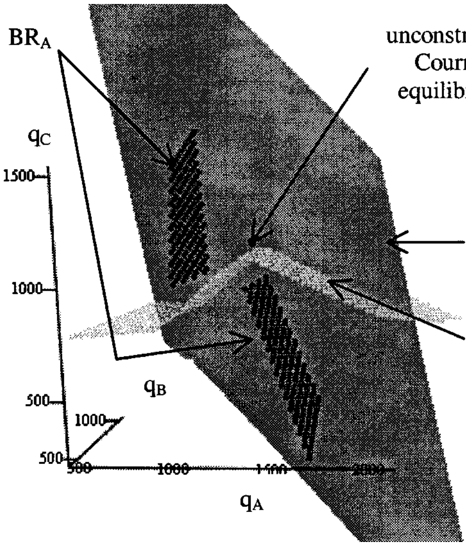

Fig. 8. Utilities A, B, and C best responses for T1 constrained to 20 MW.

If the constraint is further tightened, the best response points that occurred in region one are moved to region two, thus continuing to reduce the size of region one. Continuing to tighten the constraint will move more of the best responses from region one to region two. Fig. 8 shows the best response surfaces for all three utilities when the constraint on line T1 is reduced to 20 MW.

Utility A's best response "jumps" from region one to region two before it passes through the unconstrained equilibrium and Utility C's best response no longer passes through the unconstrained equilibrium. A new equilibrium would exist if there were a simultaneous intersection of all three surfaces, but there is no such intersection. We find no existence of a pure strategy equilibrium at even tighter line constraints.

So far only a unidirectional constraint has been discussed for simplicity in both figures and analysis. Though no figures are shown for the cases, if it were assumed that the line flows were constrained in both directions the best response of utility C at the upper end would have a discrete jump that resembles that of A's in the figures. Likewise, A's lower tip would have a "kink" that resembles C's best response due to the constraint in the opposite direction than we have considered here. The disruption of a pure strategy equilibrium is qualitatively similar to the unidirectional constraint case and occurs at the same line constraints. A pure strategy equilibrium fails to exist in the bidirectional constraint case.

IV. CONCLUSION

This paper has shown that utilities behaving strategically can significantly alter line flows, thereby potentially increasing the difficulty of transmission planning and operations as well as maintaining prices in excess of the competitive price. This could potentially increase the difficulty of planning the transmission system for an independent operator. Moreover, this phenomenon poses serious difficulties for proposals for congestion management protocols, such as in ERCOT, that rely on identifying *a priori* which lines are likely to be constrained.

Figs. 7 and 8 show that the problem could be further complicated due to the fact that a transmission line constraint could induce a behavioral change even if the equilibrium flow in the absence of the constraint is significantly less than the transmission limit. That is to say that one could expect that Utility A might change its profit maximizing behavior with a limit on T1 at or near 29.4 MW. But Utility A will change its behavior with a constraint of 66 MW, which is roughly twice the flow on line T1 in the unconstrained case. This phenomenon was analyzed for the case of two players and a single line in [5].

It was shown in this simple network that varying the line capacities in the competitive market resulted in prices on the order of \$24/MWh. In the unconstrained Cournot example, utilizing strategic behavior, the resulting prices were on the order of \$42/MWh, which is about 75% higher. Transmission-constrained Cournot equilibria were also investigated. The equilibria were disrupted when a unidirectional constraint was imposed that had a limit that was much higher than the unconstrained Cournot flow. In the case of a transmission constraint that disrupts the pure strategy equilibrium, the outcome of the market is much less certain and will depend upon a host of other issues.

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