Are Ramp Offers Appealing to Strategic Producers?

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***Abstract*—The increasing renewable energy integration makes the net load (i.e., demand minus renewable injection) profiles of power systems volatile with short but steep ramps. This letter explores whether such profiles bring a new opportunity for strategic producers with fast (e.g., gas-fired) generators to gain more profit by strategic offering not only in terms of "price", but also in terms of "ramp". To answer such a question, we develop a bi-level optimization model, which seeks to maximize a strategic producer's profit through making most beneficial ramp and price offering decisions. The results obtained from a simple test case shows the ability of strategic producer to further increase its profit by withholding a part of its ramping capability.**

***Index Terms*—Ramp offers, strategic producer, renewable energy, bi-level optimization.**

I. Introduction

RENEWABLE energy integration makes the daily net load (i.e., demand minus renewable injection) profile of power systems increasingly volatile with short but steep ramps. One well-known example is the daily net load pattern in California, called "duck curve" [1], with a steep drop in the early morning (∼8am) due to solar power injection, then a steep rise in the late afternoon (∼5pm) due to solar power disconnection, and then another drop but slighter in the late night (∼11pm). This pattern raises concern that the conventional generators may not be able to accommodate sufficient ramp, resulting in overgeneration and curtailed renewable energy. This concern encourages real-world power markets, e.g., the California ISO and the Midcontinent ISO, to design markets for ramp products [2]-[3].

We are interested in answering these main questions: Does such a volatile net load profile with steep ramps bring a new business opportunity for producers with fast (e.g., gas-fired) generators? Is it appealing to those producers to offer *strategically* in terms of "ramp" along with (or without) "price"? If so, how? These questions could also be interesting for market regulators who desire to design markets with reduced market power potential - note that market power could be exercised in different ways, possibly one is ramp [4].

To answer these central questions, we consider an hourly basis day-ahead electricity market. The generators are allowed to offer at prices and ramps, likely different than their true production costs and ramping capabilities. We investigate this problem from a specific strategic producer's point of view, and aim to determine its most beneficial price and ramp offers. To this purpose, we develop a bi-level programming model, whose upper-level problem maximizes the strategic producer's profit and determines its strategic ramp and price offers, and whose lower-level problem clears the market for given offers from the market operator's point of view. For such a producer, the offering decisions of all other market parties, i.e., other producers and demands, are exogenous (fixed values), but likely uncertain. For the sake of simplicity, we ignore all potential uncertainty sources, though there is no technical barrier and it is straightforward to model those uncertainties by stochastic or robust programming.

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II. Model

This section provides a compact formulation for the proposed bi-level model, given by (1)-(11), consisting of an upper-level problem (1)-(3) and a lower-level problem (4)-(11). Note that the lower-case symbols are variable vectors, whereas the upper-case ones are parameter vectors. The vectors with superscripts "S", "O" and "D" correspond to strategic producer, other (rival) producers and demands, respectively. In addition, subscript n refers to market parties located at node n:

$$\underset{\widehat{\mathbf{p}}^{\mathrm{S}},\widehat{\mathbf{r}}^{\mathrm{S}},\mathbf{q}^{\mathrm{S}},\mathbf{q}^{\mathrm{O}},\mathbf{q}^{\mathrm{D}},\delta,\lambda_n}{\text{Maximize}} \quad \mathbf{q}^{\mathrm{S}}\left(\lambda_n - \mathbf{C}^{\mathrm{S}}\right) \tag{1}$$

$$\text{subject to:} \quad \widehat{\mathbf{r}}^{\mathrm{S}} \leq \mathbf{R}^{\mathrm{S}} \tag{2}$$

$$\widehat{\mathbf{p}}^{\mathrm{S}} \geq 0 \tag{3}$$

$$\lambda, \mathbf{q}^{\mathrm{S}} \in \arg \underset{\mathbf{q}^{\mathrm{S}},\mathbf{q}^{\mathrm{O}},\mathbf{q}^{\mathrm{D}},\delta}{\text{maximize}} \quad \left(\mathbf{q}^{\mathrm{D}}\mathbf{U}^{\mathrm{D}} - \mathbf{q}^{\mathrm{S}}\widehat{\mathbf{p}}^{\mathrm{S}} - \mathbf{q}^{\mathrm{O}}\mathbf{C}^{\mathrm{O}}\right) \tag{4}$$

$$\text{subject to:} \quad \mathbf{q}_n^{\mathrm{S}} + \mathbf{q}_n^{\mathrm{O}} = \mathbf{q}_n^{\mathrm{D}} + f(\delta_n) \quad : \lambda_n \tag{5}$$

$$0 \leq \mathbf{q}^{\mathrm{S}} \leq \mathbf{Q}^{\mathrm{S}} \tag{6}$$

$$-\widehat{\mathbf{r}}^{\mathrm{S}} \leq r(\mathbf{q}^{\mathrm{S}}) \leq \widehat{\mathbf{r}}^{\mathrm{S}} \tag{7}$$

$$0 \leq \mathbf{q}^{\mathrm{O}} \leq \mathbf{Q}^{\mathrm{O}} \tag{8}$$

$$-\mathbf{R}^{\mathrm{O}} \leq r(\mathbf{q}^{\mathrm{O}}) \leq \mathbf{R}^{\mathrm{O}} \tag{9}$$

$$0 \leq \mathbf{q}^{\mathrm{D}} \leq \mathbf{L}^{\mathrm{D}} \tag{10}$$

$$-\mathbf{F} \leq f(\delta) \leq \mathbf{F} \tag{11}$$

The upper-level objective function (1) maximizes the strategic producer's profit, which is equal to its production quantity $\mathbf{q}^{\mathrm{S}}$ times the difference of nodal market-clearing price λ_n and production cost $\mathbf{C}^{\mathrm{S}}$. Note that λ_n and $\mathbf{q}^{\mathrm{S}}$ are both market-clearing outcomes, and come from the lower-level problem (4)-(11). The strategic offers of the producer include its ramp offers $\widehat{\mathbf{r}}^{\mathrm{S}}$ and price offers $\widehat{\mathbf{p}}^{\mathrm{S}}$, which both are determined in the upper-level problem. The upper-level constraint (2) limits the ramp offers of the strategic producer to its actual ramping capabilities, i.e., $\mathbf{R}^{\mathrm{S}}$. Note that (2) allows the strategic producer to withhold the entire or a part of its ramping capability. The upper-level constraint (3) enforces the price offers to be non-negative. The strategic ramp and price offers affect the market clearing problem, i.e., the lower-level problem (4)-(11).

For given strategic price and ramp offers, the market operator maximizes the social welfare of the market in (4), which is the value of consumers (utility $\mathbf{U}^{\mathrm{D}}$ times consumption $\mathbf{q}^{\mathrm{D}}$) minus the cost claimed by the strategic and all other

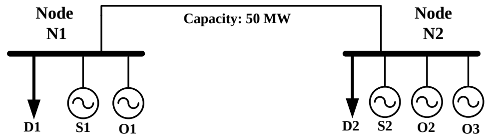

Fig. 1. Two-node power system

producers. Note that vector $\mathbf{C}^{\mathrm{O}}$ includes the price offers of other producers, and $\mathbf{q}^{\mathrm{O}}$ are their production quantity vectors. The market-clearing problem is constrained by (5)-(11). The power balance at each node is enforced by (5), and its dual variable gives the nodal market-clearing price. Note that function $f(\delta_n)$ represents the power flow on transmission lines connected to node n. This linear function employs the usual DC power flow description, which depends on nodal voltage angles δ. Constraints (6) and (7) correspond to the generators belonging to the strategic producer. In details, (6) limits their production to capacities $\mathbf{Q}^{\mathrm{S}}$. In addition, (7) restricts their hourly production change, modeled by function $r(\mathbf{q}^{\mathrm{S}})$, to their ramp offers. Constraints (8) and (9) are similar to (6) and (7), but for the rival generators. Constraint (10) limits the consumption level of each demand to its maximum load, i.e., $\mathbf{L}^{\mathrm{D}}$. Finally, constraint (11) imposes the capacity of transmission lines, i.e., $\mathbf{F}$. Pursuing simplicity, we exclude operating reserve products from our problem.

The solution technique of bi-level programming models is well-known today. Briefly, the lower-level problem (4)-(11) is a linear programming problem, and can be replaced by its Karush-Kuhn-Tucker optimality conditions. The resulting mathematical program with equilibrium constraints is then linearized and solved [5].

III. Numerical Results

We consider a two-node power system (see Fig. 1) with five conventional generators and two demands. Generators S1 and S2 belong to the strategic producer, whereas generators O1 to O3 are the rivals. The technical characteristics of all generators are given in Table I. The transmission line capacity is 50 MW. We consider three hours (t1, t2, and t3), with the total net load of 80 MW, 170 MW, and 200 MW, respectively. In every hour, demand D1 consumes 35% of the total net load in that hour, and the remaining net load is consumed by demand D2. The bid prices of both demands are identical in all hours, which are \$80/MWh. We assume that the price offers of each generator can be changed hourly, but its ramp offer should be the same throughout the time horizon considered (3 hours). In addition, we consider an identical offer for both ramp up and down capabilities.

We analyze four different cases, in which the strategic producer offers: Case 1) non-strategically[1], Case 2) strategic ramps but non-strategic prices, Case 3) strategic prices but non-strategic ramps, and Case 4) strategic prices and ramps.

Table II gives the results obtained, i.e., ramp offers, price offers, and profit of the strategic producer in different cases.

[1]This means that the producer offers trustfully its actual production costs and ramp capabilities as its price and ramp offers. We use this case as a benchmark.

TABLE I
Data for conventional generators

	S1	S2	O1	O2	O3
Capacity [MW]	30	100	50	100	10
Production cost [\$/MWh]	40	9	30	10	12
Ramp up/down rate [MW/h]	30	40	30	20	5
Initial dispatch [MW]	0	0	0	80	0

TABLE II
Price offers, ramp offers, and profit of the strategic producer

Case		Case 1	Case 2	Case 3	Case 4
Is strategic ramp offering allowed?		No	Yes	No	Yes
Is strategic price offering allowed?		No	No	Yes	Yes
Generator S1	Price offer in hour t1 [\$/MWh]	40	40	0	0
	Price offer in hour t2 [\$/MWh]	40	40	80	80
	Price offer in hour t3 [\$/MWh]	40	40	80	80
	Ramp offer [MW/h]	30	0	30	30
Generator S2	Price offer in hour t1 [\$/MWh]	9	9	0	0
	Price offer in hour t2 [\$/MWh]	9	9	80	20
	Price offer in hour t3 [\$/MWh]	9	9	80	80
	Ramp offer [MW/h]	40	13.3	40	35
Profit of the strategic producer [\$]		940	3813.3	5325	5365

Compared to the non-strategic Case 1, the strategic producer's profit (last row) significantly increases if it is allowed to behave strategically in terms of either ramp (Case 2), or price (Case 3), or both (Case 4). The strategic offering in terms of price (Case 3) gives more market power to the strategic producer with respect to the strategic ramp offers (Case 2). However, their combination, i.e, the strategic offering in terms of both price and ramp (Case 4), brings more opportunity for the strategic producer to further manipulate the market-clearing outcomes and consequently increase its profit. Specifically in Case 4, the strategic producer offers at prices which are different than its production costs, and withholds a part of its ramp capability.

IV. Conclusions

This letter develops a bi-level model for a producer, who is allowed to behave strategically in terms of ramp and price. The results obtained from a simple test case demonstrates the ability of the strategic producer to further increase its profit through withholding a part of its ramping capability.

An extension of interest is a multi-period model, evaluating the social pros and cons of a market policy that enforces the producers to submit long-time ramp offers, e.g., once per month, or six-month, or year. However, such an analysis is complex per se, and may require sampling methods to find representative days, and/or decomposition techniques.

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