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Exploring the Vickrey-Clarke-Groves Mechanism for Electricity Markets ⋆

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Abstract: Control reserves are power generation or consumption entities that ensure balance of supply and demand of electricity in real-time. In many countries, they are procured through a market mechanism in which entities provide bids. The system operator determines the accepted bids based on an optimization algorithm. We develop the Vickrey-Clarke-Groves (VCG) mechanism for these electricity markets. We show that all advantages of the VCG mechanism including incentive compatibility of the equilibria and efficiency of the outcome can be guaranteed in these markets. Furthermore, we derive conditions to ensure collusion and shill bidding are not profitable. Our results are verified with numerical examples.

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1. INTRODUCTION

The liberalization of electricity markets leads to opportunities and challenges for ensuring stability and efficiency of the power grid. For a stable grid, the supply and demand of electricity at all times need to be balanced. This instantaneous balance is reflected in the grid frequency. Whereas scheduling (yearly, day-ahead) is based on forecast supply and demand of power, the *control reserves* (also referred to as ancillary services) provide additional controllability to balance supply and demand of power in real-time. With increasing volatile renewable sources of energy, the need for control reserves also has increased. This motivates analysis and design of optimization algorithms and market mechanisms that procure these reserves.

The objective of this paper is a game theoretic exploration of an alternative market mechanism for the control reserves with potential improvements. To further discuss this, we briefly discuss relevant features of the existing market mechanism. Control reserves are categorized as primary, secondary, and tertiary. Primary reserves balance frequency deviations in timescale of seconds. Secondary reserves balance the deviations on a timescale of seconds to minutes not resolved by primary control. Tertiary reserves restore secondary reserves and typically act 15 minutes after a disturbance to frequency. The secondary and tertiary control reserves in several countries are procured in a market. In the Swiss market for example, the auction mechanism implemented by the Transmission System Operator (TSO) minimizes the cost of procurement of required amounts of power, given bids (Abbaspourtorbati and Zima, 2016).

In a pay-as-bid mechanism, since payments to winners are equal to their bid prices, a rational player may overbid to ensure profit. As an alternative to pay-as-bid, we explore the *Vickrey Clarke Groves* (VCG) mechanism. This is one of the most prominent auction mechanisms. The first analysis of the VCG mechanism was carried out by (Vickrey, 1961) for the sale of a single item. This work was subsequently generalized to multiple items by (Clarke, 1971) and (Groves, 1973).

It has been shown that the VCG mechanism is the only mechanism that possesses *efficiency* and *incentive compatibility*. Efficiency implies that goods are exchanged between buyers and sellers in a way that creates maximal social value. Incentive compatibility means that it is optimal for each participant to bid their *true value*. Variants of the VCG mechanism have been successfully deployed generating billions of dollars in Spectrum auctions, for instance, in the 2012 UK spectrum auction (Cramton, 2013; Day and Cramton, 2012) and in advertising, for instance, by Facebook [1] (Varian and Harris, 2014). For further discussion on the VCG mechanism and its application to real auctions we recommend (Milgrom, 2004; Klemperer, 2004).

Investigation must be performed before applying the VCG mechanism. As outlined in the paper of Ausubel and Milgrom (Ausubel et al., 2006), coalitions of participants can influence the auction in order to obtain higher collective profit. These peculiarities occur when the outcome of the auction is not in the *core*. The core is a solution concept in coalition game theory where prices are distributed so that there is no incentive for participants to leave the coalition (Osborne and Rubinstein, 1994). This has recently moti-

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[1] https://developers.facebook.com/docs/marketing-api/pacing

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vated the study and application of VCG auctions where the outcome is projected to the core (Cramton, 2013; Abhishek and Hajek, 2012).

The electricity market can be thought of as a reverse auction. In contrast to an auction with multiple goods, in an electricity market, each participant can bid for continuum values of power. Furthermore, to clear this market, certain constraints, such as balance of supply and demand and network constraints need to be guaranteed. Due to the differences between an electricity market and an auction mechanism for multiple items (such as spectrum or adverts), there are conceptual and theoretical advances in VCG mechanism that need to be analyzed.

In this paper, we apply the VCG mechanism to control reserve markets and provide a mathematically rigorous analysis of it. We show that efficiency and incentive compatibility of the VCG mechanism will hold even in the case of stochastic markets, see Theorem 1. On the other hand, we provide examples where shill bidding might occur. The remainder of the paper develops ways to resolve this issue. In particular, building upon a series of results based on coalitional game theory, in Theorem 4 we show how a simple pay-off monotonicity condition removes incentives for shill bidding and other collusions. The proofs developed significantly simplify the arguments of Ausubel and Milgrom (Ausubel et al., 2006).

The paper is organized as follows. In Section 2 we introduce the VCG mechanism for control reserve markets, analyzing its positive and negative aspects. Throughout Section 3 we investigate conditions that can mitigate these problems making the mechanism competitive. We conclude with specific simulations based on data available from Swissgrid (the Swiss TSO) showing the applicability of VCG mechanism to the Swiss ancillary service market.

2. ELECTRICITY AUCTION MARKET SETUP

We briefly describe the control reserve market of Switzerland. The formulation and results derived are generalizable to alternative markets, with similar features as will be discussed. The Swiss system operator (TSO), Swissgrid, procures secondary and tertiary reserves in its reserves markets. These consist of a weekly market where secondary reserves are procured and daily markets where both secondary and tertiary reserves are procured. Each market participant submits a bid that consists of a price per unit of power (CHF/MW, swiss franc per megawatt) and a volume of power which it can supply (MW). Offers are indivisible and thus, must be accepted entirely or rejected. Moreover, *conditional offers* are accepted. This means that a participant can offer a set of bids, of which only one can be accepted. If an offer is accepted, the participant is paid for its availability irrespective of whether these reserves are deployed (an additional payment is made in case of deployment). This availability payment, under the current swiss reserve market, is pay-as-bid. An extensive description of the Swiss Ancillary market is given in (Abbaspourtorbati and Zima, 2016).

We abstract the control reserve market summarized above as follows. Let L denote the set of auction participants and $|L| = N$. Let $B_j = (c_j, p_j)$ be all the bids placed by participant j, where $p_j \in \mathbb{R}^{n_j}$ is the vector of power supplies offered (MW) and $c_j \in \mathbb{R}^{n_j}$ are their corresponding requested costs (or prices). Here n_j is the number of bids from participant j. Let $B = \{B_j, j \in L\}$ be the set of all bids and $n = \sum_{j=1}^{n} n_j$. Given a set B, a mechanism defines which bids are accepted with a *choice function*, $f(B) \in \{0,1\}^n$ and a payment to each participant, *payment rule* $q_j(B)$. The *utility* of participant j is hence

$$u_j(B) = q_j(B) - \bar{c}_j^\top f_j(B), \tag{1}$$

where $\bar{c}_j \in \mathbb{R}^{n_j}$ is participant j's true cost of providing the offered power p_j and $f_j(B) \in \{0,1\}^{n_j}$ is the binary vector indicating his accepted bids.

The transmission system operator's objective function is

$$J(x, y; B) = c^\top x + D(x, y).$$

The variable $x \in \{0,1\}^n$ selects the accepted bids, $y \in \mathbb{R}^p$ can be any additional variables entering the TSO's optimization and $D : \{0,1\}^n \times \mathbb{R}^p \to \mathbb{R}$ is a general function. In most electricity market, the objective is to minimize the cost of procurement subject to some constraints:

$$J^\star(B) = \min_{x,y} \; J(x, y; B) \quad \text{s.t.} \quad g(x, y, p) \le 0 \tag{2a}$$

$$x^\star(B) = \operatorname*{argmin}_{x} \left\{ \min_{y: g(x,y,p) \le 0} J(x, y; B) \right\} \tag{2b}$$

The above constraints correspond to procurement of the required amounts of power, e.g. in the Swiss reserve markets accepted reserves must have a deficit probability of less than 0.2%. We let X be the feasible values of x for this optimization. The optimization defines a general class of models, where the cost function is affine in c and the prices of bids do not enter the constraints.

2.1 The pay-as-bid mechanism

In the current pay-as-bid mechanism we recognize:

$$f(B) = x^\star(B)$$
$$q_j(B) = c_j^\top x_j^\star(B), \quad j \in L.$$

It follows that each participant's utility is $u_j(B) = (c_j - \bar{c}_j)^\top x_j^\star(B)$. As such, rational participants would bid more than their true values to make profit. Consequently, under pay-as-bid, the TSO attempts to minimize inflated bids rather than true costs. Thus, pay-as-bid cannot guarantee power reserves are procured cost effectively.

2.2 The VCG mechanism

The VCG mechanism is characterized with the same choice function as the pay-as-bid mechanism but a different payment rule.

Definition 1. The *Vickrey-Clarke-Groves* (VCG) choice function and payment rule are defined as:

$$f(B) = \operatorname*{argmin}_{x \in X} J(x, y; B) = x^\star(B),$$
$$q_j(B) = h(B^{-j}) - \left(J^\star(B) - c_j^\top x_j^\star(B)\right) \quad \forall j \in L,$$

where B^{-j} denotes the vector of bids placed by all participants excluding j. The function h must be carefully chosen to make the mechanism meaningful. Namely, we require that payments go from the TSO to power plants, *positive transfers*, and that power plants will not face negative utilities participating to such auctions, *individual*

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