Integrating power and reserve trade in electricity networks

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Abstract

As power markets become liberalised and include more intermittent generation, the trade of reserve energy will become more important. We propose a novel bidding mechanism to integrate power and reserve markets. It facilitates planning for bidding in both markets and adds expressivity to reserve bids.1

1 Introduction

The currently most popular power market design is to conduct two separate ahead-markets for each hour of the following day - one market to trade binding commitments to transfer power (the day-ahead market), and one market to trade optional intervals of power (the reserve market). In a real-time balancing phase, the differences between the outcome of the day-ahead market and actual demand are settled by executing parts of the intervals sold in the reserve market. The System Operator (SO) most often functions as the market maker, who, in our case, clears both markets simultaneously. Formally, during the day-ahead phase, a generator \( g \), with a capacity \( P_{L_g}, P_{U_g} \) and a convex cost function \( c_g(P) \), sells a default amount of power \( P_{\text{def}}^g \) and offers an optional interval \( [0, P_{\text{opt}}^g] \). During balancing, the SO can execute \( P_{\text{exe}}^g \in [0, P_{\text{opt}}^g] \) per generator \( g \). In both phases combined, \( g \) will sell at least \( P_{\text{def}}^g \) and at most \( P_{\text{max}}^g = P_{\text{def}}^g + P_{\text{opt}}^g \leq P_{U_g} \).

The trade volume of reserve power is expected to grow: We are faced with decreasing certainty of supply caused by the advent of intermittent generation, i.e. renewables like solar and wind, and hope to use technologies like storage systems and Demand Response to manage this problem. This paper explores this new research challenge, beginning with the standard use case of reserve capacity offered by supply.

Although there is in fact only one product (power capacity) which can be offered in both markets, the bids for fixed power and reserves are currently made separately. This causes several problems for bidders. First, the success in one market depends strongly on the accuracy of assumptions made about the outcomes in the other market - this includes, but is not limited to, the problem of calculating opportunity costs for unsold parts of \( P_{\text{opt}}^g \). It would simplify this planning problem if \( g \) could make assumptions about the outcome for \( P_{\text{opt}}^g \) while constructing the bid for \( P_{\text{def}}^g \), and vice versa. Second, one convex cost function cannot be represented by two convex bid functions - therefore, the bid for reserves are currently restricted to only a constant price for each activated unit in \( P_{\text{exe}}^g \). As the costs to produce \( P_{\text{exe}}^g \) are convex, this leads to imprecise bids by design, which increases the volatility of prices.

We propose a novel, bundled bid format for generators and an associated clearing mechanism for an integrated power- and reserve market. The bid format helps \( g \) with the problem of bidding in two dependent markets by allowing to include an assumption about the ratio between \( P_{\text{def}}^g \) and \( P_{\text{opt}}^g \). It also allows to offer \( P_{\text{opt}}^g \) with a convex price function, which allows for a constant per-unit profit, independent of \( P_{\text{exe}}^g \). The profit maximisation problem which \( g \) faces becomes less complex and its outcomes can be more stable against uncertainty and misconceptions about market outcomes. We formulate the two-stage clearing process of the SO as a Strictly Convex Quadratic Programming problem [1], which we have successfully implemented in the well-known electricity network simulation framework AMES [3] (which incorporates transmission constraints into power pricing).

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2 The bid format

Generator \( g \) maps amounts of power to total prices via a quadratic bid function. Quadratic functions are widely used to model bids in power markets because they are sufficiently realistic and their derivatives are continuous, and thus marginal prices are well-defined. To also express bidding for reserve capacity \( P^\text{opt}_g \) within these supply functions, we propose that \( g \) fixes the ratio \( r = P^\text{opt}_g / P^\text{max}_g \) for each bid, such that knowing \( P^\text{def}_g \) determines \( P^\text{opt}_g = P^\text{def}_g r \). For example, with \( r = \frac{1}{4} \), we denote that \( P^\text{def}_g \) will certainly be sold and \( [0, P^\text{opt}_g] = \left[0, \left(\frac{1}{4} P^\text{def}_g\right) / \frac{3}{2}\right] \) is the optional interval. Thus, the market clearing determines the two intervals \([0, P^\text{def}_g]\) and \([P^\text{def}_g, P^\text{max}_g]\), allowing \( g \) to price \( P^\text{def}_g \) and \( P^\text{exe}_g \) on the same function.

At \( r = 0 \), no flexibility is offered and the generator has full certainty how much he sells \( (P^\text{def}_g = P^\text{max}_g, P^\text{opt}_g = 0) \). This resembles traditional bid functions with no reserve offer. At \( r = 1 \), everything is flexible and the SO will assume full flexibility over \( P^\text{exe}_g \) in the balancing phase \( (P^\text{def}_g = 0, P^\text{opt}_g = P^\text{max}_g) \). Generator \( g \) can place several bids \( b_{g,r} \), each using a different \( r \in [0,1] \).

With values for \( r > 0 \), \( g \) will want to account for costs of (potentially) lost opportunity in the bid. He can increase the slope of the bid function, such that the expected total revenue, when taking an expected probability distribution over \( P^\text{exe}_g \) into account, compensates these costs.

3 The market mechanism

We now formulate a Constraint Satisfaction Problem for the day-ahead phase. The SO conducts a one-shot auction. Demand is modelled by agents \( l \in L \), where \( L \) stands for Load-serving-entities (LSE), who only submit the requested amounts for fixed power \( P^\text{def}_l \) and reserve power \( P^\text{opt}_l \). The SO chooses one bid \( b_{g,r} \) per generator \( g \) and announces a market clearing price \( \gamma_{\text{exe}} \), which defines how much each unit in \( \sum_g P^\text{def}_g \) will be paid for. The marginal clearing price of the balancing phase \( \gamma_{\text{exe}} \) will be higher - its theoretical maximum is known as it will also be determined from the winning bids \( b_{g,r} \). Via \( \gamma_{\text{exe}} \), each generator can look up on \( b_{g,r} \) how much power \( P^\text{def}_g \) he is committed to supply and this also tells him how much reserve capacity \( P^\text{opt}_g \) he needs to keep available. The optimisation goal of the SO is to minimise generation costs. One approach is to only minimise the costs which are known for sure in this phase \( (\sum_g P^\text{def}_{g,r}) \), another is to include an estimation of the costs of the balancing phase \( (\sum_g P^\text{exe}_g \gamma_{\text{exe}}) \). The first constraint to this optimisation requires that demand is satisfied: \( \sum_g P^\text{def}_g = \sum_l P^\text{def}_l \). Secondly, the SO needs to make sure that each generator will stay within his generation limits: \( P^\text{L} \leq P^\text{def}_g \leq P^\text{U} (1 - r) \). Each generator agrees to hold back reserve capacity \( P^\text{opt}_g = P^\text{def}_g r \). The overall reserve capacity needs to match the demand for reserves. Hence, we add the third constraint \( \sum_g P^\text{opt}_g \geq \sum_l P^\text{opt}_l \).

The number of functions each generator can bid is a parameter of the mechanism. This is a trade-off between the time complexity of finding a solution and the freedom of the generators to bid on many \( r \).

During the balancing phase, LSEs announce their balancing requirements \( P^\text{exe}_g \in [0, P^\text{opt}_g] \). In order to find \( \gamma_{\text{exe}} \) and thereby allocate each generator a value for \( P^\text{exe}_g \), the SO translates the interval \([P^\text{def}_g, P^\text{max}_g]\) of each successful bid \( b_{g,r} \) from the day-ahead phase into a new bid function \( P^\text{exe}_g \) in the interval \([0, P^\text{opt}_g]\). These translated bids are then used to minimise \( \sum_g P^\text{exe}_g \gamma_{\text{exe}} \).

References

