Virtual Power Plant Bidding Model Considering Ramping Capability

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***Abstract*—Virtual power plants (VPPs) can aggregate distributed energy resources (DERs) to provide ancillary services for power systems, creating new profit opportunities. Ancillary services such as frequency regulation require providers to have sufficient ramping capability to follow rapidly changing control commands. If the ramping capability requirement is overlooked, the VPP's bidding may exceed its capability, reducing its earnings in performance-based markets or risking disqualification. This paper systematically integrates the requirement for ramping capability into the operational framework of VPPs that provide ancillary services. We leverage historical control commands to formulate chance constraints in the bidding model, mandating that the VPP's ramping capability meets the needs of ancillary services with a specified probability.**

***Index Terms*—Virtual power plant, profit allocation, ancillary services, ramp rate, incentive compatibility.**

I. Introduction

In this paper, we systematically integrate the consideration of resource ramping capabilities into the operational framework of VPPs providing ancillary services. In the interaction strategy between the VPP and the market, we use historical data to model the probabilistic requirements of the ramp rate for ancillary services considering regulation signal uncertainty and embed it into the VPP bidding model as a chance constraint to ensure sufficient ramping capability. Our method contributes to enhancing the technical and commercial viability of VPPs to thoroughly exploit the flexibility of DERs, thus better supporting the integration of renewable energy.

Our contributions are as follows:

- We systematically integrate ramp rate constraints into the operational model of VPPs providing ancillary services. Leveraging historical control signals, we model the ramping requirements of ancillary services with chance constraints and embed the constraints into the VPP operation model, thereby avoiding overly diminishing the VPP's performance score due to insufficient ramping capabilities.

II. VPP Operation with Ramping Capability Requirements

In this section, we present the optimal bidding and power disaggregation strategy for a VPP providing ancillary services considering the requirement for ramp capabilities. Since DERs have generation capabilities or consumption demands, the corresponding income or cost under energy prices also needs to be considered in the operation of VPPs, even though our focus is on the ancillary services market.

In the subsequent mathematical formulation, we use subscripts t, s, i to denote variables pertinent to the time interval t, GO signal scenario s, and resource i. We use subscripts $\mathrm{ch}(\mathrm{dis})$ and init to represent the (dis)charging and initial states, respectively. For instance, $p^{\mathrm{ch}}_{t,s,i}$ represents the charging power of resource i during time interval t under scenario s, with "charging" implying power drawn from the grid. In terms of parameter notation, we use underlines/overlines to indicate lower/upper boundaries. The state of resources, e.g., the battery state of charge (SOC) or indoor temperature, is denoted by e. The state of resource i at the onset of time interval t is represented by $e_{t,i}$; let $e_{T+1,i}$ represent the state after the time horizon, where T is the ending time slot.

A. VPP profit model

The VPP aims to maximize its profit v^{VPP} over the time horizon, which is the income from the power market minus operation costs, formulated as:

$$v^{\mathrm{VPP}} = \sum_{t=1}^{T} (Income^{\mathrm{e}}_t + Income^{\mathrm{reg}}_t + Income^{\mathrm{res}}_t - Cost_t) \tag{1}$$

where $Income^{\mathrm{e}}_t$, $Income^{\mathrm{reg}}_t$, and $Income^{\mathrm{res}}_t$ are the incomes from the energy market, regulation market, and reserve market, respectively. $Cost_t$ is the cost of dispatching the DERs. The incomes and costs are calculated as expected values based on the market price forecast and the distribution of control signals. To keep the notation simple, we use $s = (s^{\mathrm{reg}}, s^{\mathrm{res}})$ to represent the scenario of the control signal; thus, $\pi_{t,s}$ is the probability of the joint distribution of the frequency regulation and reserve signals. δ^{reg}_s and δ^{res}_s are the representative values of regulation and reserve signals to represent scenario s, respectively, e.g., $\delta^{\mathrm{reg}}_s = 0.95$ for the scenario of $\delta^{\mathrm{reg}} \in [0.9, 1)$. The detailed calculation of the profit model is as follows:

$$Income^{\mathrm{e}}_t = Pr^{\mathrm{e}}_t (\tilde{p}_t + \sum_{s \in S} \pi_{t,s} (\delta^{\mathrm{reg}}_s Cap^{\mathrm{reg}}_t + \delta^{\mathrm{res}}_s Cap^{\mathrm{res}}_t)) \Delta t \tag{2a}$$

$$Income^{\mathrm{reg}}_t = s^{\mathrm{perf}} (Pr^{\mathrm{reg,cap}}_t + Pr^{\mathrm{reg,mil}}_t a^{\mathrm{mil}}_t) Cap^{\mathrm{reg}}_t \Delta t \tag{2b}$$

$$Income^{\mathrm{res}}_t = Pr^{\mathrm{res}}_t Cap^{\mathrm{res}}_t \Delta t \tag{2c}$$

$$Cost_t = \sum_i \sum_{s \in S} \pi_{t,s} (c^{\mathrm{dis}}_i p^{\mathrm{dis}}_{t,s,i} + c^{\mathrm{ch}}_i p^{\mathrm{ch}}_{t,s,i}) \Delta t \tag{2d}$$

where Pr^{e}_t, $Pr^{\mathrm{reg,cap}}_t$, $Pr^{\mathrm{reg,mil}}_t$, and Pr^{res}_t are the prices of energy, regulation capacity, regulation mileage, and reserve service, respectively. $\tilde{p}_t$ is the amount of energy purchased by the VPP in the market, which is also the baseline output of the

VPP. Following the convention of power plants, $p > 0$ signifies the injection of energy into the power grid. $Cap_t^{\rm reg}$ and $Cap_t^{\rm res}$ are the bids for regulation and reserve capacities, respectively. The exchanged energy with the grid (2a), i.e., the sum of the baseline output and the deployed energy for regulation and reserve, are settled at energy prices. The income from the regulation market is performance-based (2b), where the performance score $s^{\rm perf}$ and the expected regulation mileage $a_t^{\rm mil}$ are regarded as known parameters given by the GO. $c_i^{\rm dis}$ and $c_i^{\rm ch}$ ($/kWh) are the levelized operation cost of discharging and charging the DERs (2d), respectively, here regarded as parameters submitted by the DERs. $p_{t,s,i}^{\rm dis}$ and $p_{t,s,i}^{\rm ch}$ are the discharging and charging power of DER i at time interval t and signal scenario s.

B. DER operation constraints

The VPP needs to ensure that the operation of each DER i is feasible. The constraints are formulated in the form of generalized ES models, which can express the technical constraints of typical DERs such as ES, EV, TCL, and photovoltaic (PV), including the power limits (3a), the state limits (3b), the energy balance equation (3c), and the initial states (3d):

$$\underline{p}_{t,i}^{\rm dis} \le p_{t,s,i}^{\rm dis} \le \overline{p}_{t,i}^{\rm dis},\ \underline{p}_{t,i}^{\rm ch} \le p_{t,s,i}^{\rm ch} \le \overline{p}_{t,i}^{\rm ch},\ \forall t, \forall s \tag{3a}$$

$$\underline{e}_{t,i} \le e_{t,i} \le \overline{e}_{t,i},\ \forall t \tag{3b}$$

$$\begin{aligned} e_{t+1,i} =& \theta_i e_{t,i} + \sum_s \pi_{t,s}(\eta_i^{\rm ch} p_{t,s,i}^{\rm ch} - \frac{1}{\eta_i^{\rm dis}} p_{t,s,i}^{\rm dis})\Delta t \\ &+ w_{t,i}\Delta t\ :\ \lambda_{t,i}^e,\ \forall t \end{aligned} \tag{3c}$$

$$e_i^{\rm init} - e_{t,i} = 0,\ t = 1 \tag{3d}$$

where θ_i is the self-discharge coefficient of the energy storage units, $\eta_i^{\rm ch}$ and $\eta_i^{\rm dis}$ are the charging and discharging efficiencies, respectively, and $w_{t,i}$ is the net energy consumption of DER i at time interval t. The dual variable $\lambda_{t,i}^e$ is the shadow price of the energy balance equation, which represents the marginal cost of the energy state. The heat dissipation and impact of the ambient temperature on the room temperature are represented by the dissipation rates θ and w, respectively, of the TCLs. For details on the operation constraints, refer to [1].

C. Ancillary service constraints

a) Capacity constraints: We define the up (dn) response capacity of DER i as the range by which it can deviate upward (downward) from the baseline output, expressed as:

$$Cap_{t,i}^{\rm up} := \max_s.\{p_{t,s,i}\} - \tilde{p}_{t,i},\ Cap_{t,i}^{\rm dn} := \tilde{p}_{t,i} - \min_s.\{p_{t,s,i}\} \tag{4}$$

where $Cap_{t,i}^{\rm up}$ and $Cap_{t,i}^{\rm dn}$ are the up-response and down-response capacities provided by resource i, respectively, and $\tilde{p}_{t,i}$ is the baseline power of DER i, i.e., the allocated power in the signal scenario of $(\delta_s^{\rm reg}, \delta_s^{\rm res}) = (0, 0)$. $\max_s.\{p_{t,s,i}\}$ and $\min_s.\{p_{t,s,i}\}$ are the maximum and minimum powers of DER i in the signal scenarios, respectively. The VPP needs to ensure that the total response capacity of the resources satisfies the bids for regulation and reserve services, formulated as ($\forall t$):

$$\sum_i Cap_{t,i}^{\rm up} \ge Cap_t^{\rm reg} + Cap_t^{\rm res}\ :\ \lambda_t^{\rm cap,up}, \tag{5a}$$

$$\sum_i Cap_{t,i}^{\rm dn} \ge Cap_t^{\rm reg}\ :\ \lambda_t^{\rm cap,dn}, \tag{5b}$$

$$(Cap_{t,i}^{\rm up}, Cap_{t,i}^{\rm dn}, Cap_t^{\rm reg}, Cap_t^{\rm res}) \ge 0. \tag{5c}$$

where the dual variables $\lambda_t^{\rm cap,up}$ and $\lambda_t^{\rm cap,dn}$ are the shadow prices of the capacity constraints, which represent the marginal capacity cost for the VPP to provide ancillary services.

b) Power balance: In each signal scenario, the VPP needs to ensure that the total power output of the resources matches the control signal, formulated as ($\forall t \forall s$):

$$\sum_i (p_{t,s,i}^{\rm dis} - p_{t,s,i}^{\rm ch}) = \tilde{p}_t + \delta_s^{\rm reg} Cap_t^{\rm reg} + \delta_s^{\rm res} Cap_t^{\rm res},\ \forall t \forall s. \tag{6}$$

c) Energy reserve ratio: As mentioned above, the VPP needs to ensure that the energy reserve ratio of the resources satisfies the requirements of the ancillary service market, formulated as ($\forall t \forall s \forall i$):

$$\underline{e}_{t,i} \le \theta_i e_{t,i} + (\eta_i^{\rm ch} p_{t,s,i}^{\rm ch} - \frac{1}{\eta_i^{\rm dis}} p_{t,s,i}^{\rm dis}) h^{\rm req} + w_{t,i} h^{\rm req} \le \overline{e}_{t,i}. \tag{7}$$

where $h^{\rm req}$ is the required energy reserve ratio.

d) Ramp rate constraints: The VPP needs to ensure that the ramping capability of the resources satisfies the ramp rate demand, formulated as ($\forall i, \forall i$):

$$0 \le R_{t,i}^{\rm up} \le \overline{R}_{t,i}^{\rm up},\ 0 \le R_{t,i}^{\rm dn} \le \overline{R}_{t,i}^{\rm dn} \tag{8a}$$

$$h^{\rm R} R_{t,i}^{\rm up} \le Cap_{t,i}^{\rm up} + Cap_{t,i}^{\rm dn} \tag{8b}$$

$$h^{\rm R} R_{t,i}^{\rm dn} \le Cap_{t,i}^{\rm up} + Cap_{t,i}^{\rm dn} \tag{8c}$$

$$\sum_i R_{t,i}^{\rm up} \ge \varepsilon_t^{\rm up} Cap_t^{\rm reg} + \varepsilon_t^{\rm res} Cap_t^{\rm res} : \lambda_t^{\rm R,up} \tag{8d}$$

$$\sum_i R_{t,i}^{\rm dn} \ge \varepsilon_t^{\rm dn} Cap_t^{\rm reg} : \lambda_t^{\rm R,dn} \tag{8e}$$

where $R_{t,i}^{\rm up}$ and $R_{t,i}^{\rm dn}$ are the up- and down-ramp capabilities provided by resource i, respectively, subject to its ramp rate limits $\overline{R}_{t,i}^{\rm up}$ and $\overline{R}_{t,i}^{\rm dn}$ (8a). In addition to meeting the ramp rate requirements, resources also need to be capable of ramping for a certain duration $h^{\rm R}$. Within $h^{\rm R}$, the change in power cannot exceed the adjustable capacity of the resource's power (8b-8c). In our case study, we set the parameter h such that the resources can continuously follow the control signal within the response capacity. $\varepsilon_t^{\rm up}$ and $\varepsilon_t^{\rm dn}$ are the ramp rate demand for providing per unit regulation capacity. $\varepsilon_t^{\rm res}$ is the ramping requirement for reserve services, which is typically stipulated by the market, such as being able to complete the response within 10 minutes. The dual variables $\lambda_t^{\rm R,up}$ and $\lambda_t^{\rm R,dn}$ are the shadow prices of the ramp rate constraints, which represent the marginal cost of the ramp rate.

D. Optimal bidding model

Thus, the optimal bidding problem of the VPP can be formulated as:

$$\max \ v^{\mathrm{VPP}} \tag{9a}$$

$$\text{s.t. } (3)-(8) \tag{9b}$$

The decision variables include the bids in the market $\{\tilde{p}_t, Cap_t^{\mathrm{reg}}, Cap_t^{\mathrm{res}}\}$, which will be submitted to the market; the response capacity and the ramp capability of the resources $\{Cap_{t,i}^{\mathrm{up(dn)}}, R_{t,i}^{\mathrm{up(dn)}}\}$, which will be used to calculate the contribution of the resources; and the charging and discharging power of the resources in each signal scenario $\{p_{t,s,i}^{\mathrm{dis(ch)}}\}$, which is simultaneously optimized with the bids. The bidding model has a linear objective function and linear constraints and can be solved by commercial solvers, and the shadow prices of the constraints $\{\lambda_{t,i}^{e}, \lambda_t^{\mathrm{cap,up(dn)}}, \lambda_t^{\mathrm{R,up(dn)}}\}$ can be obtained, which will be used to account for the coupling between bidding, power disaggregation, and profit allocation of the VPP.

E. Optimal power disaggregation

The bidding model employs control signal scenarios and their representative values. Since the real signal space is continuous and cannot be traversed with representative values, a real-time power disaggregation module is also needed.

The VPP determines the charging and discharging power of each resource p_i^{ch} and p_i^{dis} in real time based on the received regulation and reserve signals $\delta_{\hat{t}}^{reg}$ and $\delta_{\hat{t}}^{res}$ at the control signal interval $\hat{t}$ in the time slot t. The power adjustment command is then $p^{\mathrm{cmd}} = \delta_{\hat{t}}^{\mathrm{reg}} Cap_t^{\mathrm{reg}} + \delta_{\hat{t}}^{\mathrm{res}} Cap_t^{\mathrm{res}}$.

a) Power disaggregation objective: The power disaggregation aims to minimize the cost of responding to the control signals, including the immediate operating costs $Cost_i^{\mathrm{imd}}$ induced within $\Delta\hat{t}$ and the opportunity cost representing the impact on the VPP's total profit over the time horizon $Cost_i^{\mathrm{opp}}$:

$$\min. \sum_i (Cost_i^{\mathrm{imd}} + Cost_i^{\mathrm{opp}}) \tag{10a}$$

$$Cost_i^{\mathrm{imd}} = (c_i^{\mathrm{dis}} p_i^{\mathrm{dis}} + c_i^{\mathrm{ch}} p_i^{\mathrm{ch}})\Delta\hat{t}, \ \forall i \tag{10b}$$

$$Cost_i^{\mathrm{opp}} = \lambda_{t,i}^{e} (\eta_i^{\mathrm{ch}} p_i^{\mathrm{ch}} - \frac{1}{\eta_i^{\mathrm{dis}}} p_i^{\mathrm{dis}})\Delta\hat{t}, \ \forall i \tag{10c}$$

where $\lambda_{t,i}^{e}$ is the Lagrange multiplier corresponding to the state constraint (3c) for resource i and time t at the optimum of the bidding problem. By incorporating $Cost_i^{\mathrm{opp}}$ into the objective function, the control strategy becomes optimal, i.e., the power disaggregation strategy is consistent with the optimum of the bidding strategy, and the VPP's total profit is maximized [1].

b) Power disaggregation constraints: The power disaggregation problem is subject to the power constraints of the DERs (11b), ensuring that the total power output of the resources matches the control signal (11a):

$$\sum_i (p_i^{\mathrm{dis}} - p_i^{\mathrm{ch}}) = \tilde{p}_t + \delta_{\hat{t}}^{\mathrm{reg}} Cap_t^{\mathrm{reg}} + \delta_{\hat{t}}^{\mathrm{res}} Cap_t^{\mathrm{res}} : \lambda_{\hat{t}}^{\mathrm{bal}} \tag{11a}$$

$$\underline{p}_{\hat{t},i}^{\mathrm{dis}} \le p_i^{\mathrm{dis}} \le \overline{p}_{\hat{t},i}^{\mathrm{dis}}, \ \underline{p}_{\hat{t},i}^{\mathrm{ch}} \le p_i^{\mathrm{ch}} \le \overline{p}_{\hat{t},i}^{\mathrm{ch}}, \ \forall i \tag{11b}$$

where $\lambda_{\hat{t}}^{\mathrm{bal}}$ is the shadow price of the power balance constraint; $\underline{p}_{\hat{t},i}^{\mathrm{dis(ch)}}$ and $\overline{p}_{\hat{t},i}^{\mathrm{dis(ch)}}$ are the lower and upper bounds of the discharging (charging) power of resource i at time $\hat{t}$, respectively, which are problem parameters calculated by (12):

$$\begin{aligned}
\underline{p}_{\hat{t},i}^{\mathrm{dis}} &= \max\left\{\underline{p}_{t,i}^{\mathrm{dis}}, p_{t,0,i} - Cap_{t,i}^{\mathrm{dn}}, \ p_{\hat{t},i}^{\mathrm{dis}} - R_{t,i}^{\mathrm{dn}}\Delta\hat{t}\right\} \\
\overline{p}_{\hat{t},i}^{\mathrm{dis}} &= \min\left\{\overline{p}_{t,i}^{\mathrm{dis}}, p_{t,0,i} + Cap_{t,i}^{\mathrm{up}}, \ p_{\hat{t},i}^{\mathrm{dis}} + R_{t,i}^{\mathrm{up}}\Delta\hat{t}\right\} \\
\underline{p}_{\hat{t},i}^{\mathrm{ch}} &= \max\left\{\underline{p}_{t,i}^{\mathrm{ch}}, -p_{t,0,i} - Cap_{t,i}^{\mathrm{up}}, \ p_{\hat{t},i}^{\mathrm{ch}} - R_{t,i}^{\mathrm{up}}\Delta\hat{t}\right\} \\
\overline{p}_{\hat{t},i}^{\mathrm{ch}} &= \min\left\{\overline{p}_{t,i}^{\mathrm{ch}}, -p_{t,0,i} + Cap_{t,i}^{\mathrm{dn}}, \ p_{\hat{t},i}^{\mathrm{ch}} + R_{t,i}^{\mathrm{dn}}\Delta\hat{t}\right\}
\end{aligned} \tag{12}$$

Here, the power limits at $\hat{t}$ are determined by the power limits, the response capacities, and the ramping capabilities of the DERs. For example, $\overline{p}_{\hat{t},i}^{\mathrm{dis}}$ does not exceed the response capacity of DER i in the signal scenarios at time slots t and $Cap_{t,i}^{\mathrm{dn}}$, which has been optimized by the bidding model. Additionally, it does not exceed $p_{\hat{t},i}^{\mathrm{dis}} + R_{t,i}^{\mathrm{up}}\Delta\hat{t}$, constrained by the ramp rate, where $p_{\hat{t},i}^{\mathrm{dis}}$ is the current discharging power at $\hat{t}$. After obtaining the results from (12), if $p_{\hat{t},i}^{\mathrm{dis(ch)}} > 0$, then let $\overline{p}_{\hat{t},i}^{\mathrm{ch(dis)}} = 0$ to avoid simultaneous discharging and charging. The following modifications are needed to ensure the feasibility of the power limits: if $e_{\hat{t},i} < \underline{e}_{t,i} (e_{\hat{t},i} > \overline{e}_{t,i})$, then implement the maximum charging (discharging) power, where $e_{\hat{t},i}$ is the current energy state at $\hat{t}$; if $\underline{p}_{\hat{t},i}^{\mathrm{dis(ch)}} > \overline{p}_{\hat{t},i}^{\mathrm{dis(ch)}}$, then let $\underline{p}_{\hat{t},i}^{\mathrm{dis(ch)}} = \overline{p}_{\hat{t},i}^{\mathrm{dis(ch)}}$.

The above power disaggregation problem is a small-scale deterministic linear programming problem that can be solved online using a fast algorithm that only requires geometric operations. Details of this method can be found in our previous research [1] and will not be reiterated here.

References

[1] Q. Chen, R. Lyu, H. Guo, and X. Su, "Real-time operation strategy of virtual power plants with optimal power disaggregation among heterogeneous resources," *Appl. Energy*, vol. 361, p. 122876, May 2024.