Bidding Strategy of Virtual Power Plant for Participating in Energy and Spinning Reserve Markets—Part I: Problem Formulation

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***Abstract*—This paper addresses the bidding problem faced by a virtual power plant (VPP) in a joint market of energy and spinning reserve service. The proposed bidding strategy is a non-equilibrium model based on the deterministic price-based unit commitment (PBUC) which takes the supply-demand balancing constraint and security constraints of VPP itself into account. The presented model creates a single operating profile from a composite of the parameters characterizing each distributed energy resources (DER), which is a component of VPP, and incorporates network constraints into its description of the capabilities of the portfolio. The presented model is a nonlinear mixed-integer programming with inter-temporal constraints and solved by genetic algorithm (GA).**

***Index Terms*—Bidding strategy, energy market, spinning reserve market, virtual power plant.**

Nomenclature

Sets and Indices:

i, j	Index for buses.
t	Index for hours.
S_b	Set of branches of VPP.
S_{dg}	Set of DGs.
$S_{\mathrm{hour},i}$	Set of permitted hours in which interruptible load may be curtailed if necessary.
S_{int}	Set of interruptible loads.
S_{str}	Set of electrochemical storages.
S_n	Set of nodes of VPP.

Variables:

E_t	Bid of VPP to energy market (positive and negative values indicate purchasing from and selling to energy market, respectively).
$I_{i,t}$	Binary variable denoting commitment status of a DG.
$J_{i,t}$	Binary variable denoting start-up decision for a DG.
$K_{i,t}$	Binary variable denoting shout-down decision for a DG.
$\mathrm{Load}_{E,t}$	Supplied load of VPP if the accepted bid for spinning reserve market not called on to produce.
$\mathrm{Load}_{ER,t}$	Supplied load of VPP if the accepted bid for spinning reserve market called on to produce.
$\mathrm{Loss}_{E,t}$	VPP power losses if the accepted bid for spinning reserve market not called on to produce.
$\mathrm{Loss}_{ER,t}$	Power losses of VPP if the accepted bid for spinning reserve market called on to produce.
$P_{\mathrm{curt},i,t}$	Un-served load for trading in energy market.
$P_{\mathrm{dg},i,t}$	Generation of a DG for energy market.
$P_{g,i,t}$	Total real power production at node i.
$P_{i,t}$	Real power injection to node i.
$P_{\mathrm{str},i,t}$	Amount of charged/discharged capacity of electrochemical storage at hour t in KW (negative and positive values indicate discharging and charging states, respectively)
$Q_{g,i,t}$	Reactive power production at node i.
$Q_{i,t}$	Total reactive power injection to node i.
$R_{\mathrm{curt},i,t}$	Un-served load for providing spinning reserve service.
$R_{\mathrm{dg},i,t}$	Generation of a DG for spinning reserve market.
R_t	Bid of VPP to spinning reserve market.
$S_{ij,t}$	Apparent power flow from node i to node j.

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$V_t(V_{1,t}, V_{2,t}, \ldots, V_{N_n,t})$	Voltage amplitudes vector
$V_{i,t}$	Voltage amplitude at node i.
$\theta_t(\theta_{1,t}, \theta_{2,t}, \ldots, \theta_{N_n,t})$	Voltage angles vector.
$\theta_{i,t}$	Voltage angle at node i.

Constants:

AR_k	Adequacy reserve maintained by VPP.
$E_{\mathrm{exch}}^{\max}$	Referred to the thermal rating of the interconnection, the transformer capacity, or the contracted capacity for exchanging power between VPP and the upstream grid.
LOAD_t	Total forecasted load of VPP.
MSR_i	Ramping capability for reserve of a DG in KW/min.
MUT_i, MDT_i	Minimum up and down time limits of a DG in hours.
N_n	Number of nodes of VPP.
$P_{\mathrm{curt},i}^{\max}$	Upper limit for curtailing on interruptible load.
$P_{d,i,t}$	Real power demand at node i.
$P_{\mathrm{dg},i}^{\min}, P_{\mathrm{dg},i}^{\max}$	Lower and upper limits on generation of a DG.
$P_{\mathrm{str},i}^{\max}$	Installed capacity of electrochemical storage in KWh.
$Q_{d,i,t}$	Reactive power demand at node i.
$R_{dgu,i}, R_{dgd,i}$	Ramping up and ramping down limit of a DG in KW/h.
$R_{\mathrm{str-ch},i}, R_{\mathrm{str-dch},i}$	Maximum charge and discharge rate of electrochemical storage in KW.
$S_{ij}^{\max}$	Capacity of the line between node i and node j.
$T_{i,t}^{\mathrm{on}}, T_{i,t}^{\mathrm{off}}$	Number of hours for which DG unit has been on/off at hour t.
$V_i^{\max}, V_i^{\min}$	Maximum and minimum voltage magnitude at node i.
$\rho_{E,t}$	Price of energy market.
$\rho_{R,t}$	Price of spinning reserve market.
$\rho_{L,t}$	VPP's retail energy rate.

Costs:

$C_{\mathrm{dg},i,t}(P_{\mathrm{dg},i,t})$	Generation cost function of a DG.
$C_{\mathrm{int},i,t}(P_{\mathrm{curt},i,t})$	Cost curve of an interruptible consumer to curtail its load.
$C_{\mathrm{str}}(P_{\mathrm{srt},i,t})$	Operational cost of an electrochemical storage.
$SC_{\mathrm{dg},i,t}, SHC_{\mathrm{dg},i,t}$	Start up and shut down costs of a DG.

I. Introduction

THE world is going to use distributed generation (DG) for promoting energy efficiency and use of renewable sources in alternative to traditional generation. In this respect, several supportive regulations for DG are provided in the whole world, which are briefly reviewed in the following. In order to support renewable-based DG, a separate green market for their electricity generation is being proposed [1]–[4]. Two types of these separate green markets are Green Certificate Market (GCM) and Tradable Renewable Energy Credit Market (TRECM). GCM facilitates the participation of renewable resources into the liberalized market [1], [2]. All of the electricity consumers (distribution companies or other consumers) are obliged to buy a certain share of their consumptions from this market. Although TRECM supports DG the same as GCM does, it has an advantage in comparison with the GCM. It allows the generated unit of electricity to be divided into two parts: the physical electricity and the associated greenness. By separating the environmental attributes of renewable energy generation from physical unit of electricity, TRECM allows the green power attributes to be sold or traded separately from the physical unit of energy and so paid for it [3], [4]. Besides, numerous supportive regulations such as European RES Directive for development of renewable resources [5]–[7], European CHP Directive for energy efficiency improvement [5], [6], [8], and similar supportive regulations in other countries, Renewable Portfolio Standard (RPS) in several countries [9]–[11], Kyoto protocol which has a role in the reduction of greenhouse gas emissions, and so on are the factors that accelerate DG growth.

It should be mentioned that the current policy of installing DG has been focused on connection rather than integration; typically, DG has been installed with a "fit and forget" approach, based on the legacy of a passive distribution network [12]–[14]. Clearly, under this regime, DG is not visible to the system so while it can replace the energy produced by centralized units, it lacks the conditions required to provide system supports and security activities. So centralized generation capacities must be retained to perform this function. With growing pressure to increase DG penetration, this passive approach will lead to raising the costs of investment and operation of the system and ultimately impact the pace of DG adoption [12]–[15]. To solve this problem, DG should be integrated into system operation under an active control paradigm which allows it to participate in both energy and ancillary service markets. This goal can be achieved via VPP concept which is to aggregate DER either for the purpose of trading electrical energy or to provide system support services [16]. VPP is under investigation in many projects such as Europe union project virtual fuel cell power plant [17], Fenix project [18], etc. A result of literature review shows that there is no consensus regarding the definition of VPP. In the following, the most important ones are mentioned to give an overview of this integration approach.

The European Union (EU) project of virtual fuel cell power plant defines VPP as a group of interconnected decentralized residential micro-chp, using full cell technology installed in multifamily houses, small enterprises, public facilities, etc., for individual heating, cooling, and electricity production [17].

According to Fenix definition [18], VPP is a flexible representation of a portfolio of DER that can be used to make contracts in the wholesale market and to offer services to the system operator. VPP aggregates the capacity of many diverse DER; it creates a single operating profile from a composite of the parameters characterizing each DER and can incorporate the impact of network on aggregate DER output. There are two types of VPP, the commercial VPP (CVPP) and technical VPP (TVPP). $\mathrm{CVPP_S}$ perform commercial aggregation and do not take into consideration any network operation aspects that active distribution network have to consider for a stable operation. TVPP consists of DER from the same geographic location and includes the real-time influence of the local network on DER aggregated profile as well as representing the cost and operating characteristics of the portfolio. These concepts are discussed in detail in [14].

VPP is combining different types of renewable and nonrenewable generators and storage devices to be able to appear on the market as one power plant with defined hourly output. In other words, different power generation and storage devices with weakness (e.g., stochastic output) and strength (e.g., high energy short term storage) are combined in a complementary way [19].

In European project CRISP, VPP is an aggregation of DER units dispersed among the network, but controllable as a whole generating system. Moreover, a superior ordinate entity which aggregates VPP, i.e., a large-scale virtual power plant (LSVPP), is defined as an aggregation of VPP or of DER units dispersed widely among the network, controllable as a whole generating system [20]. Two aspects of a VPP can be derived from this definition. Firstly, different levels of aggregation are possible, and secondly, dispersed DER units are controllable by the VPP.

This paper considers VPP the same as TVPP defined in [18] as a comprehensive definition which takes into account the influence of local network on DER aggregated profile. VPP is investigated as a participant of day-ahead energy and spinning reserve markets. Bidding plays an important role for VPP to maximize its profit in the markets. A non-equilibrium model based on the deterministic PBUC is presented to design a bidding strategy for VPP in which it takes the DER constraints, the supply-demand balancing constraint, and also the security constraints of VPP including its network constraints into account. In the presented model, VPP may be a participant of energy market with dual role including producer and consumer based on the direction of exchanged power with the upstream grid. Moreover, it can provide spinning reserve service regardless of its role in energy market. The presented model creates a single operating profile from a composite of the parameters characterizing each DER which is a component of VPP, and incorporates network constraints into its description of the capabilities of the portfolio.

The rest of the paper is organized as follows. Definitions and assumptions on the component of VPP, its control strategy, the market framework, and any information required by VPP to optimize its bidding strategy are presented in Section II. Bidding strategy of VPP is discussed in Section III and formulated in Section IV. Discussion and conclusion are presented in the final section.

II. Definitions and Assumptions

A. VPP Components

VPP under study contains distribution network with DGs, electrochemical storages, and end consumers (both interruptible and non-interruptible loads). DG units are managed and owned by VPP. End consumers of VPP are supplied with a given retail energy rate. VPP signs a contract with interruptible consumers in which the upper limit of curtailing $(P_{\mathrm{curt}}^{\max})$, the cost of curtailing, and permitted hours for curtailing (S_{hour}) are determined. A penalty (cost of curtailing) is paid to each interruptible consumer for curtailing its consumption. DGs and interruptible loads may be used for trading in both energy and spinning reserve markets, but electrochemical storages are only applied in energy market.

B. Control Strategy of VPP

VPPs may be controlled in distributed or centralized manner [21]. Distributed control is based on the multi-agent system (MAS), which is well addressed in [22] and [23]. In this strategy, each DER unit can be controlled by its agent that participates in electronic markets where optimized control decisions can be found. The application of this control strategy is presently limited to control actions where the location is not important (e.g., power exchange and balancing services) [24]. In centralized control, the DERs are centrally controlled by Control Coordination Center (CCC), and the market transactions of VPP are handled by it. In centralized control method, it is able to execute both technical and economical functions, in order to gain more benefit of integration of DERs [21], [25].

The advantages and required infrastructures of these control strategies are addressed in [21] and [25]. Application of distributed and centralized control of VPP can be found in CRISP project and European virtual fuel cell power plants, respectively [17], [20].

In this paper, VPP is assumed to be centrally controlled and the aim of CCC is to maximize the individual profit of VPP by making good proposals for energy and spinning reserve markets.

C. Market Framework

The market framework considered in this work is a joint model for energy and ancillary service, here spinning reserve. It is a common structure in the market systems and has advantages which are discussed in [26] and [27]. The aim of VPP is to maximize its individual profit by making good proposals for these markets. The market framework is shown in Fig. 1. It should be mentioned that the ISO's day-ahead market is a double-auction market, in which all market participants including VPPs submit bids and offers with price and MW pairs.

D. Required Information Assumptions

The information required by VPP to optimize its bidding strategy is assumed as follows.

1) VPP can estimate the loads and prices of energy and spinning reserve markets for 24 h based on historical data. The communication infrastructure for this purpose is discussed in [25]. Smart metering establishes an information flow

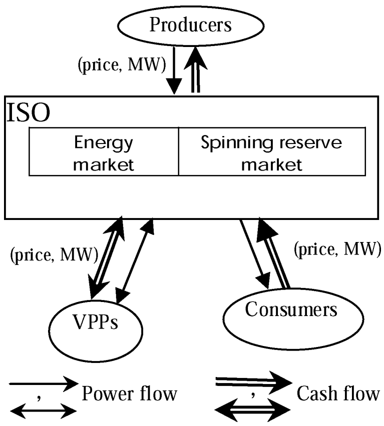

Fig. 1. Market framework.

for metering purposes to the aggregator, here CCC [28]. Time series of measurement data or other techniques such as neural networks [29] can be used to forecast the loads of 24 h of market day. Moreover, case-based reasoning can be used for nodal load estimation [30]. In [31], a literature review is provided on different techniques and models for energy price forecasting.

2) The VPP's retail energy rates are given.
3) The cost curve of a consumer to curtail its load is assumed based on [32] to be as a function of un-served load (P_{curt}) and modeled as a quadratic polynomial $[C(P_{\mathrm{curt}}) = \alpha_{\mathrm{int}} \cdot P_{\mathrm{curt}}^2 + \beta_{\mathrm{int}}, \cdot P_{\mathrm{curt}}]$ in which given coefficients α_{int} and β_{int} quantify the cost of un-served load.
4) All DG units are assumed to be dispatchable and the cost function of each DG is assumed to be a function of its real power output (P_{dg}) and modeled as $C(P_{\mathrm{dg}}) = \alpha_{\mathrm{dg}} P_{\mathrm{dg}}^2 + \beta_{\mathrm{dg}} P_{\mathrm{dg}}$ in which α_{dg} and β_{dg} are positive coefficients of quadratic cost function. The start up and shut down costs can be considered if they are not negligible.
5) The operational cost of electrochemical storage is generally concerned with maintenance costs, and based on [33], it is assumed to be a linear function of the absolute of its charged or discharged capacity at each hour. That is, $C_{\mathrm{str}}(P_{\mathrm{srt}}) = \alpha_{\mathrm{str}} \cdot |P_{\mathrm{str}}| + \beta_{\mathrm{str}}$, in which α_{str} and β_{str} are positive coefficients of linear cost function of electrochemical storage.

III. Bidding Strategy of VPP in Competitive Markets

Devising a good bidding strategy is very important for a market participant to maximize its potential profit. A bid contains information on how much power, at which price, in which area, and at what time a market participant is willing to buy or sell. A detailed literature survey on bidding strategies in electricity markets is provided in [34]. The authors of [35] review briefly the developed approaches to design bidding strategies for traditional generation companies (Gencos). These approaches can be categorized into two groups: equilibrium models and non-equilibrium models. Equilibrium models such as supply function equilibrium and Cournot equilibrium are widely applied for developing Gencos' bidding strategies and analyzing market power in energy markets [35]–[40]. However, unit constraints such as minimum on/off time, ramping limits, and startup and shut down costs are not considered in most of the equilibrium models because the existence of equilibrium could not be proven when integer variables are used in those models. Accordingly, the simulated market equilibrium without the unit prevailing constraints could deviate largely from practical operation. Meanwhile, there may be some computational problems when equilibrium models are applied to a large system with many market participants. However, equilibrium models would be very important for analyzing the potential market power of a Genco and the optimal bidding strategy of Gencos with market power [41], [42].

One of the most important non-equilibrium models is PBUC [41]–[44]. The basis of this approach is discussed in [44]. In this approach, the precision of market price forecasting could have a direct impact on PBUC solution. Due to electricity market dynamics, which could make it difficult to forecast market prices accurately, it would be very important to consider the market price uncertainty [41], [43].

The PBUC is a suitable approach for bidding in multiple markets (energy and ancillary services) and can consider inter-temporal effects and integer variables such as minimum on/off time and ramping limits of generators. Since this paper is concentrated on participating VPP in both energy and spinning reserve markets, a non-equilibrium model based on the PBUC is extended to design bidding strategy of VPP. It is to be mentioned that there are noticeable differences between bidding strategy of a traditional Genco and a VPP based on PBUC as follows.

1) A traditional Genco is only a producer; however, a VPP may be an entity with dual role including producer and consumer based on the direction of exchanged power with upstream grid.
2) In bidding strategy of a traditional Genco using non-equilibrium models based on the forecasting market prices, the supply-demand balancing constraint does not exist; however, it is a critical constraint for VPP.
3) Unlike the traditional Genco, the DER that belongs to VPP may be connected to various points in distribution network; so the network characteristics (network topology, impedances, losses, and constraints) impact the making proposals of VPP. As a result, VPP considers the constraints of both network and DERs when it bids to the markets.

Regarding two later distinctions, the proposed model for bidding strategy of VPP is called security-constrained price-based unit commitment (SCPBUC).

IV. Strategic SCPBUC for VPP

VPP makes a proposal (including price and MW pairs) to exchange power with energy market as well as to bid a part of its capacity to spinning reserve market by forecasting the markets prices and then scheduling of DG, determining charging and discharging states of the electrochemical storages, and choosing the interrupting options based on the forecasted prices while all economical and technical aspects are considered. The objective function of bidding problem is maximizing the total benefit of VPP (revenue-cost) obtained in both markets as well as selling power to end consumers. Energy market could be settled either in uniform pricing or pay-as-bid pricing scheme. The spinning reserve market is assumed to be settled based on the bids for capacity. In some markets, the winner players are additionally paid for the amount of energy called on to produce, and the price of real providing spinning reserve service is determined based on the market rules [45]. Since the player (VPP) can not anticipate the amount of energy it will be called on to produce in spinning reserve market, in this paper, the same as [44], the revenue of real providing of spinning reserve is not considered and the SCPBUC is formulated based on the forecasted price of spinning reserve market concerned with the capacity. This means that VPP will maximize its minimum expected benefit. The price uncertainty is not taken into consideration in this paper, and it could be a subject for future work.

A. Objective Function

$$
\begin{aligned}
\text{Max Benefit} = &-\sum_{t=1:24} \rho_{E,t} \times E_t + \sum_{t=1:24} \rho_{R,t} \times R_t \\
&+ \sum_{t=1:24} \rho_{L,t} \times \text{Load}_t \\
&- \sum_{\substack{i\in S_{\text{dg}}\\ t=1:24}} \left(C_{\text{dg},i,t}(P_{\text{dg},i,t} + R_{\text{dg},i,t}) \cdot I_{i,t}\right. \\
&\left.+ SC_{\text{dg},i,t} \cdot J_{i,t} + SHC_{\text{dg},i,t} \cdot K_{i,t}\right) \\
&- \sum_{\substack{i\in S_{\text{int}}\\ t\in S_{\text{hour},i}}} C_{\text{int},i,t}(P_{\text{curt},i,t} + R_{\text{curt},i,t}) \\
&- \sum_{i\in S_{\text{str}}} C_{\text{str},i,t}(P_{\text{str},i,t}) \\
\text{Load}_t = \text{LOAD}_t &- \sum_{\substack{i\in S_{\text{int}}\\ t\in S_{\text{hour},i}}} (P_{\text{curt},i,t} + R_{\text{curt},i,t}).
\end{aligned} \tag{1}
$$

B. Constraints

VPP operator should ensure the technical feasibility of scheduled DER and also steady state security and adequacy of VPP when it is making proposals for markets. These constraints should be met at all times, either the accepted bids for spinning reserve market called on to produce or not.

1) Supply-Demand Balancing Constraint: If spinning reserve bids not called on to produce, we see (2) at the bottom of the page.If spinning reserve bids called on to produce, we see (3) at the bottom of the page.

2) DG Constraints: These are shown in (4)-(10) at the bottom of the page.

$$
\begin{cases}
E_t + \sum_{i\in S_{\text{dg}}} P_{\text{dg},i,t} - \eta_{\text{str}} \sum_{i\in S_{\text{str}}} P_{\text{str},i,t} = \text{Load}_{E,t} + \text{Loss}_{E,t} \\
\text{Load}_{E,t} + \sum_{\substack{i\in S_{\text{int}}\\ t\in S_{\text{hour},i}}} P_{\text{curt},i,t} = \text{LOAD}_t \qquad \forall t = 1:24
\end{cases} \tag{2}
$$

$$
\begin{cases}
E_t + R_t + \sum_{i\in S_{\text{dg}}} P_{\text{dg},i,t} + \sum_{i\in S_{\text{dg}}} R_{\text{dg},i,t} - \eta_{\text{str}} \sum_{i\in S_{\text{str}}} P_{\text{str},i,t} = \text{Load}_{ER,t} + \text{Loss}_{ER,t} \\
\text{Load}_{ER,t} = \text{Load}_{E,t} - \sum_{\substack{i\in S_{\text{int}}\\ t\in S_{\text{hour},i}}} R_{\text{curt},i,t} \qquad \forall t = 1:24
\end{cases} \tag{3}
$$

$$P_{\text{dg},i}^{\min} \le P_{\text{dg},i,t} \cdot I_{i,t} + R_{\text{dg},i,t} \cdot I_{i,t} \le P_{\text{dg},i}^{\max} \tag{4}$$

$$R_{i,t} I_{i,t} \le \min\left\{10 \times MSR_i, P_{\text{dg},i}^{\max} - P_{\text{dg},i,t}\right\} \tag{5}$$

$$\begin{cases} P_{\text{dg},i,t+1} - P_{\text{dg},i,t} \ge R_{dgu,i} \\ \forall i \in S_{\text{dg}}, \quad \forall t = 1:24 \end{cases} \text{in case the output is increased} \tag{6}$$

$$\begin{cases} P_{\text{dg},i,t} - P_{\text{dg},i,t+1} \ge R_{dgd,i} \\ \forall i \in S_{\text{dg}}, \quad \forall t = 1:24 \end{cases} \text{in case the output is decreased} \tag{7}$$

$$\left[T_{i,t-1}^{\text{on}} - MUT_i\right] \times \left[I_{i,t-1} - I_{i,t}\right] \ge 0 \quad \forall i \in S_{\text{dg}}, \quad \forall t = 1:24 \tag{8}$$

$$\left[T_{i,t-1}^{\text{off}} - MDT_i\right] \times \left[I_{i,t-1} - I_{i,t}\right] \ge 0 \quad \forall i \in S_{\text{dg}}, \quad \forall t = 1:24 \tag{9}$$

$$\begin{cases} I_{i,t} - I_{i,t-1} \le J_{i,t} \\ I_{i,t-1} - I_{i,t} \le K_{i,t} \\ I_{i,t} - I_{i,t-1} \le J_{i,t} - K_{i,t} \end{cases} \tag{10}$$

3) Electrochemical Storage Constraints: These are shown in (11)-(13) at the bottom of the page.

4) Constraint of Interruptible Load:

$$0 \le P_{\mathrm{curt},i,t} \le P_{\mathrm{curt},i}^{\max} \quad \forall i \in S_{\mathrm{int}}, \quad \forall t \in S_{\mathrm{hour},i} \tag{14}$$

$$0 \le P_{\mathrm{curt},i,t} + R_{\mathrm{curt},i,t} \le P_{\mathrm{curt},i}^{\max} \forall i \in S_{\mathrm{int}}, \quad \forall t \in S_{\mathrm{hour},i}. \tag{15}$$

5) Steady-State Security Constraints of VPP:

1) Kirshohf laws:

$$P_{i,t}(\theta_t, V_t) - P_{g,i,t} + P_{d,i,t} = 0 \quad , t = 1:24 \tag{16}$$

$$Q_{i,t}(\theta_t, V_t) - Q_{g,i,t} + Q_{d,i,t} = 0 \quad , t = 1:24. \tag{17}$$

2) Apparent power flow limit of lines, from node i to node j:

$$S_{ij,t}(\theta_t, V_t) \le S_{ij}^{\max}, \quad \forall ij \in S_b, \quad t = 1:24. \tag{18}$$

3) Bus voltage limits:

$$V_i^{\min} \le V_{i,t} \le V_i^{\max} \quad \forall i \in S_n, \quad t = 1:24. \tag{19}$$

4) Capacity of interconnection is shown in (20) and (21) at the bottom of the page.
5) *VPP adequacy constraint:* VPP seeks to ensure that there is enough committed DG, electrochemical storage capacity, interruptible load, and power purchase capacity from main grid to meet a reserve margin at each hour; see (22) and (23).

If spinning reserve bids are not called on to produce:

$$\begin{aligned}&\sum_{i \in S_{\mathrm{dg}}} P_{\mathrm{dg},i}^{\max} \cdot I_{i,t} - \sum_{i \in S_{\mathrm{dg}}} P_{\mathrm{dg},i,t} \cdot I_{i,t} \\ &+ \eta_{\mathrm{str},i} \sum_{i \in S_{\mathrm{str}}} \left[cap_{i,0} + \sum_{l=1}^{t} P_{\mathrm{str},i,l} \right] \\ &+ \sum_{i \in S_{\mathrm{int}}} \left[P_{\mathrm{curt},i}^{\max} - P_{\mathrm{curt},i,t} \right] \\ &+ E_{\mathrm{exch}}^{\max} - E_t \ge AR_t \quad \forall t = 1:24. \end{aligned} \tag{22}$$

If spinning reserve bids are called on to produce:

$$\begin{aligned}&\sum_{i \in S_{\mathrm{dg}}} P_{\mathrm{dg},i}^{\max} \cdot I_{i,t} - \sum_{i \in S_{\mathrm{dg}}} \left(P_{\mathrm{dg},i,t} + R_{\mathrm{dg},i,t} \right) \\ &+ \eta_{\mathrm{str},i} \sum_{i \in S_{\mathrm{str}}} \left[cap_{i,0} + \sum_{l=1}^{t} P_{\mathrm{str},i,l} \right] \\ &+ \sum_{i \in S_{\mathrm{int}}} \left[P_{\mathrm{curt},i}^{\max} - P_{\mathrm{curt},i,t} - R_{\mathrm{curt},i,t} \right] \\ &+ E_{\mathrm{exch}}^{\max} - E_t - R_t \ge AR_t, \quad \forall t = 1:24. \end{aligned} \tag{23}$$

C. Solving the Problem

The optimization problem is a nonlinear mixed-integer programming with inter-temporal constraints. Mathematical techniques are not suitable for solving this problem, since they are model-based and the precise model of system is needed for derivation. Moreover, they start from one point and the probability of involving in the local optimum is high for these types of methods. On the other hand, GA is a population-based, data-based, and free-derivative method and takes the advantages of genetic operators so that the chance of being involved in a local optimum is less in comparison with mathematical methods. Therefore, GA has the potential of obtaining near global solution, while including the constraints [46]. GA in power system solutions has been employed successfully to solve the generation scheduling in electric power systems [47]–[50]. Therefore, in this paper, GA is used to solve the optimization problem. In what follows, the applied GA is briefly discussed.

Each chromosome includes the output of DGs, charge/discharge capacities of storages, and load curtailment values allocated to energy and spinning reserve markets. Based on the above values concerned with the energy market, 24 backward/forward power flow [51] is run for each chromosome to calculate VPP power losses and the value of exchanged power with the upstream grid which is equal to the bid for energy market at each hour (E_t). The security and adequacy constraints of VPP (16)–(18), and (20) are checked based on the power flow results. Then the power flow program is again run considering

$$-\left(cap_{0,i} - P_{\mathrm{str},i}^{\min}\right) \le \sum_{k=1}^{t} P_{\mathrm{str},i,k} \le P_{\mathrm{str},i}^{\max} - cap_{0,i} \qquad \forall i \in S_{\mathrm{str}}, \quad \forall t = 1,2,\ldots 24, \tag{11}$$

$$\begin{cases} P_{\mathrm{str},i,t} \le R_{\mathrm{str-ch},i} \\ \forall i \in S_{\mathrm{str}}, \quad \forall t = 1,2,\ldots 24 \end{cases} \text{if the storage is charged,} \tag{12}$$

$$\begin{cases} -P_{\mathrm{str},i,t} \le R_{\mathrm{str-dch},i} \\ \forall i \in S_{\mathrm{str}}, \quad \forall t = 1,2,\ldots 24 \end{cases} \text{if the storage is discharged,} \tag{13}$$

$$|E_t| \le E_{\mathrm{exch}}^{\max} \quad \forall t = 1:24 \quad \text{if spinning reserve bids not called on to produce} \tag{20}$$

$$|E_t + R_t| \le E_{\mathrm{exch}}^{\max} \quad \forall t = 1:24 \quad \text{if spinning reserve bids called on to produce} \tag{21}$$

all generation of DGs and load interrupting values associated with both markets and also the charge and discharge capacities of storages. The value of exchanged power with upstream network calculated in this case is the algebraic sum of VPP bids for both energy and spinning reserve markets $(E_t + R_t)$. After calculating R_t, the objective function is calculated. The security and adequacy constraints (16), (17), (19), (21) are checked based on the power flow results. After checking all constraints, the objective function is calculated and a penalty term is applied when the constraints are violated. The penalty function can be in two forms: 1) constant penalty and 2) variable penalty. The constant penalty approach is known to be less effective for complex problems than the variable penalty [46]. In this paper, the variable penalty is employed as a function of the distance from the feasible area. For each infeasible chromosome, the summation of absolute distances of violated constraints is determined. Then this summation is subtracted from the objective function value of the worst feasible chromosome in current population. This value is considered as the value of objective function of the infeasible chromosome. By this approach, infeasible chromosomes are not discarded, and therefore, their information can be used for improving the algorithm search.

In reproduction processes, roulette-wheel selection is applied for creating children for the next generation. Moreover, by the test-and-set approach, it is found that two points crossover, with the fraction of 0.7 providing good results. The mutation rate is also found by test-and-set approach to be 0.1. The algorithm stops if there is no improvement in the objective function for a certain number of consecutive generations. In this paper, the stop criterion is set for each test system by set-and-test approach.

V. Conclusion

This paper is concentrated on the participation of a VPP in a joint market of energy and spinning reserve service. A non-equilibrium model based on the deterministic PBUC is proposed to design the bidding strategy of VPP simultaneously for both markets. In addition to the constraints of DER, the proposed model takes the security constraints of VPP and also its supply-demand balancing constraint into account and called as the SCPBUC model. This model integrates many DER in the same geographical area and takes into account the real-time influence of the local network in this process. This integration as a VPP may inject/absorb power to/from the main grid, and also it may provide spinning reserve service. This model makes it possible to integrate DER not only to be visible in energy market but also to be visible for system operator.

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