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A Holistic P2P market for active and reactive energy trading in VPPs considering both financial benefits and network constraints

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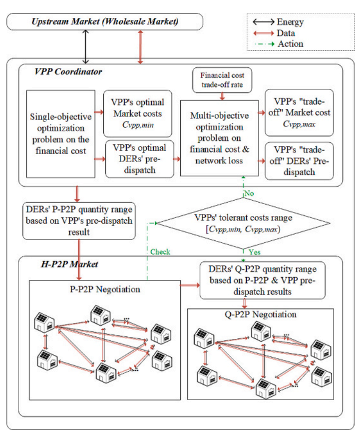
HIGHLIGHTS

- A novel synergistic model integrating a holistic P2P market in an internal centralized VPP environment.
- Simultaneous active and reactive energy trading in the holistic P2P market regulated by the VPP coordinator.
- A novel transactive voltage/VAR control concept with P2P reactive energy trading for the internal VPP voltage control.
- An innovative multi-stage P2P negotiation mechanism to converge the active and reactive energy transaction decisions.

GRAPHICAL ABSTRACT



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ABSTRACT

Due to the rise of distributed energy resources (DERs), virtual power plants (VPPs) have gained intensive academic and industrial attention. While current centralized VPPs benefit from their large aggregated capacity in the wholesale market, they lack effective incentivizing participants for asset investment and market participation. Conversely, the peer-to-peer (P2P) market offers better profits for prosumers through direct trading; however, transactions hinge on approval from associated authorities, such as electricity retailers, who read their power meters. Such an approval procedure becomes complex, even impossible, when more retailers are involved. Hosting the P2P market in a VPP environment can conveniently resolve this issue. This paper proposes a novel holistic P2P (H-P2P) market model hosted in a VPP environment to provide the VPP participants with financial incentives and optimize the network and market operations simultaneously. The proposed new market structure and trade principle allow the proposed H-P2P market to trade active and reactive energies for both financial benefits and network constraints. Using the novel transactive voltage/VAR control (TVVC) method proposed in this paper, the reactive energy trading through the P2P market can support effective voltage regulation and incentivize the VPP participants to provide such voltage control ancillary services actively. Finally, a novel multi-stage P2P negotiation process is introduced to divide the VPP regulatory, active and reactive energy convergence

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stages, which allows faster P2P decision-making with improved computing efficiency than the conventional multi-period alternating direction method of multipliers (ADMM). The case study validates that the proposed H-P2P market can increase the financial incentives of the prosumers who install PVs and batteries by a large extent and the pure load units by a relatively smaller percentage.

1. Introduction

In recent developments within the energy sector, there has been a significant trend towards integrating distributed energy resources (DERs), driven by sustainability imperatives and efforts to mitigate carbon emissions. Simultaneously, the transition to smart grids is paving the way for a more responsive, efficient, and reliable energy system. Amidst these shifts, the concept of virtual power plants (VPPs) has been widely studied in academia and applied in the energy industry. A VPP aggregates multiple DERs installed by the VPP participants, including renewable energy sources (RESs), energy storage systems (ESSs), electric vehicles (EVs), and controllable loads [1]. There are more than 91.7 GW VPPs worldwide [2], and the global VPP market size has reached USD 0.71 billion and is expected to increase to USD 6.47 billion in 2028 [3].

In the existing VPP business models, most VPPs act as centralized aggregators to dispatch the flexible resources of their participants. The VPP aggregators trade electricity or network services in the upper-level markets, such as the wholesale and ancillary services markets, on behalf of their participants [4–8]. Meanwhile, their participants can buy electricity from the VPP aggregators based on the tariff structure of the signed contract, usually a flat or time-of-use (ToU) tariff. Some VPP business models allow prosumers to sell extra electricity or provide services back to the VPP aggregators with limited incentives [9–11]. Consequently, the financial benefits for the VPP participants are limited, leading to low proactivity in investing in further DER installations and participating in the VPP.

The peer-to-peer (P2P) energy trading established directly among VPP participants can be a potential solution for incentivizing the VPP participants. Recently, increasing studies have been carried out on the P2P trading market in the energy communities, e.g., microgrid clusters [12–15], prosumer groups [16–19] and [35–37], and smart building communities [20–22]. Long et al. [12] propose a two-stage control method for P2P energy sharing in community microgrids. A P2P trading model interacting with a two-stage retail market for microgrid clusters is introduced by Huang et al. [13]. Duvignau et al. [14] establish a P2P energy-sharing model considering comprehensive cost optimization in a small community. Zhang et al. [15] apply a data-driven distributionally robust optimization method for P2P energy trading within microgrid clusters. Moreover, many researchers pay attention to P2P trading within prosumer groups. Elkazaz et al. [16] propose a P2P trading model between prosumers in a community with a hierarchical energy management structure. Lee et al. [17] apply game theory to the P2P modeling among flexible prosumers, buyers, and sellers groups. A P2P trading model integrated electricity and carbon market is established among local prosumers by Li et al. [18]. In [19], Zhang et al. propose a penalty mechanism for P2P trading among prosumers with energy management systems. Meanwhile, for the research on P2P trading within smart building communities, Qiu et al. [20] propose a P2P energy trading considering carbon allowance trade solved by reinforcement learning. The P2P model proposed by Lyu et al. [21] shares battery and electric vehicles' energy for smart buildings. Meanwhile, the PV energy is shared in a residential household community in the model of Li and Ma [22].

However, a crucial prerequisite has been overlooked in these studies: these local P2P transactions must be recognized and approved by authoritative bodies, such as system operators, energy retailers, regulators, and so on.

The structure of VPPs can enable internal P2P energy trading effectively. Since VPPs own smart metering, sensing devices, and communications infrastructure, they can foster an environment where the participants can execute their P2P transactions without needing recognition or acceptance from any external authorities [23–24]. The research on P2P energy trading within a VPP environment is in an early stage [25–27]. Yang et al. [25] develope a blockchain-based energy management system for DERs registered in a VPP. Morstyn et al. [26] considere an incentive-based P2P platform for intra-VPP prosumers. The main-side consortium blockchains are considered for a VPP by Yin et al. [27].

However, one of the significant network challenges in these VPP and P2P models is the voltage fluctuation issue caused by the high integration of DERs [28]. Various voltage control methods have been implemented in the VPPs, allowing constrained P2P transactions, as summarized and compared in Table 1.

Dynge et al. [29] analyze the voltage issues caused by P2P trading with an optimal power flow (OPF) model to estimate voltage changes. However, the voltage violation problem is not addressed without integrating with P2P trading. Lee et al. [17], Li et al. [18], Xia et al. [31], and Shi et al. [32] adopte voltage constraints in P2P transaction optimization problems. Nonetheless, the voltage control methods in [17–18] and [31–32] may adversely affect the profitability of P2P transactions because of the additional operational constraints on voltage for P2P participants. Moreover, authors in [35–37] consider advanced AC network constraints in the P2P mechanism. Additionally, Huang et al. [13], Samende et al. [30], Ullah and Park [33], Botelho et al. [34] considere voltage regulation as one of the factors when calculating distribution locational marginal prices (DLMPs).

However, this pricing scheme can introduce unfair benefit distribution within the P2P market, thus decreasing the P2P participants' incentives.

The research gaps are summarized as follows:

- From the perspective of VPPs, the financial incentives for these centralized VPP models are limited for their participants. Consequently, the participants tend to be discouraged from investing in DERs' assets and participating in the VPP.
- From the perspective of P2P, a necessary premise not discussed in the literature is the recognition and acceptance of these P2P transactions by authoritative bodies.
- The proactivity of P2P participants providing voltage control ancillary services in a centralized VPP can be challenging.

This paper proposes a novel holistic P2P (H-P2P) market model integrated into an internal VPP environment to provide VPP participants with financial incentives and optimize the network and market operations simultaneously. The VPP market and P2P trading principle are designed with new models and validated via comprehensive simulations on a 33-bus system.

The main contributions of the paper are as follows:

- A novel synergistic model integrating an H-P2P market in an internal VPP environment is proposed to trade active and reactive energies simultaneously. In addition, the VPP aggregator becomes a coordinator applying a novel regulatory strategy to balance the multi-stakeholder clashed interests. The case study results show that a significant percentage of the electricity bills can be reduced for the prosumers who own PV and battery units and about a relatively smaller decrease for the pure load units when they participate in the proposed H-P2P market.

- A novel transactive voltage/VAR control (TVVC) method with P2P reactive energy trading for the internal VPP voltage control is proposed. The TVVC method is cost-effective for the VPP coordinator to ensure voltage regulation and incentivize the prosumers to provide ancillary services. The simulation results show that the transaction can guarantee voltage regulation and incentivize VPP participants to actively provide voltage control ancillary services.
- A novel multi-stage P2P negotiation mechanism is introduced to converge the active and reactive power transaction decisions in different stages. This process allows faster P2P decision-making with a lower calculation burden than the conventional multi-period alternating direction method of multipliers (ADMM) in the literature.

The rest of this paper is organized as follows. Section 2 comprehensively overviews the conventional centralized VPP model and the P2P energy trading mechanism. Section 3 introduces the synergistic design of the integrated H-P2P and VPP model, detailing the market structure and regulatory philosophy. Section 4 focuses on incorporating the TVVC method within the internal VPP environment. The case study and simulation results are illustrated in Section 5, followed by the conclusion and future works in Section 6.

2. An overview of conventional VPP and P2P energy trading models

This section comprehensively overviews the conventional centralized VPP models and distributed P2P energy trading models.

2.1. Conventional centralized VPP model

Centralized VPPs aggregate energy consumers and participants who have installed and incorporated different DERs, such as PV systems and battery energy storage systems (BESSs). Conventional VPP models are formulated as optimization problems aiming to provide market and/or network operations through efficient management and dispatch of the participant DERs. Depending on the specific focus of the individual VPP aggregator, the optimization objective of a VPP can be minimizing the market costs, operational costs associated with DERs, network power losses, voltage deviation, or a combination of these objectives.

The conventional centralized VPP model with multiple objectives can be expressed as follows:

$$min\sum_{t\in T}\left\{\begin{array}{c}\alpha\left(\pi_{ws}(t)P_{vpp+,\delta 1i}(t)-\pi_{tou}(t)\sum_{i\in I}P_{load,i}(t)\right)\Delta t\\ +\beta\sum_{ij\in L}l_{ij}(t)r_{ij}(t)+\chi\left(\sum_{t\in T}c_{\deg}\frac{P^{dch}_{ess,i}(t)+P^{ch}_{ess,i}(t)}{\overline{E}_{ess,i}}\Delta t\right)\end{array}\right\} \tag{1}$$

$s.t.$

$$\begin{aligned}&P_{vpp+}(t)\delta_{0i}+P_{pv,i}(t)+P_{ess,i}(t)-P_{load,i}(t)\\&\quad=\sum_{k\in i}(l_{ik}(t)r_{ik}+P_{ik}(t))+\sum_{i\in j}P_{ij}(t)\end{aligned} \tag{2}$$

$$\begin{aligned}&Q_{vpp+}(t)\delta_{0i}+Q_{pv,i}(t)+Q_{ess,i}(t)+Q_{cb,i}(t)-Q_{load,n,i}(t)\\&\quad=\sum_{k\in i}(l_{ik}(t)x_{ik}+Q_{ik}(t))+\sum_{i\in j}Q_{ij}(t)\end{aligned} \tag{3}$$

$$v_i(t)=v_j(t)+2\left(P_{ij}(t)r_{ij}+Q_{ij}(t)x_{ij}\right)+l_{ij,t}\left(r_{ij}^2+x_{ij}^2\right) \tag{4}$$

$$\left\|\begin{array}{c}2P_{ij}(t)\\2Q_{ij}(t)\\l_{ij}(t)-v_i(t)\end{array}\right\|_2\leq l_{ij}(t)+v_i(t) \tag{5}$$

$$\underline{V}^2\leq v_i(t)\leq\overline{V}^2 \tag{6}$$

$$0\leq P^{ch}_{ess,i}(t)\leq\overline{P}^{ch}_{ess,i}b^{ch}_{ess,i}(t) \tag{7}$$

$$0\leq P^{dch}_{ess,i}(t)\leq\overline{P}^{dch}_{ess,i}\left(1-b^{ch}_{ess,i}(t)\right) \tag{8}$$

$$P_{ess,i}(t)=\frac{1}{\eta^{dch}_{ess,i}}P^{dch}_{ess,i}(t)-\eta^{ch}_{ess,i}P^{ch}_{ess,i}(t) \tag{9}$$

$$\left|Q_{ess,i}(t)\right|\leq\sqrt{\overline{S}^2{}_{ess,i}-P^2_{ess,i}(t)} \tag{10}$$

$$E_{ess,i}(1)=E_{initial,i}\text{ and }E_{ess,i}(T)=E_{final,i} \tag{11}$$

$$E_{ess,i}(t+1)=E_{ess,i}(t)-P_{ess,i}(t)\Delta t\,if\,t\neq T \tag{12}$$

$$\overline{E}_{ess,i}\underline{SOC}\leq E_{ess,i}(t)\leq\overline{E}_{ess,i}\overline{SOC} \tag{13}$$

Table 1
Comparison among the existing voltage control methodologies in the energy communities allowing P2P trading.*

Authors	Year	P2P environment	Addressed voltage issue?	Coordinated the voltage cotrol with the P2P?	Addressed financial incentives of the voltage control services?	Methodology
Huang et al. [13]	2022	MGC*	Yes	Yes	Limited	DLMP
Lee et al. [17]	2022	PS*	Yes	Yes	No	Use voltage and loss sensitivities to limit prosumers' bidding
Li et al. [18]	2023	PS*	Yes	Yes	No	Support P2P results by network configuration problem
Dynge et al. [29]	2021	SBC*	Yes	No	No	Check voltage profile after P2P using OPF
Samende et al. [30]	2023	MGC*	Yes	Yes	Limited	DLMP
Xia et al. [31]	2022	MGC*	Yes	Yes	No	Integrate VVC as P2P trading problem constraints
Shi et al. [32]	2023	MGC*	Yes	Yes	No	Integrate VVC as P2P trading problem constraints
Ullah and Park [33]	2022	MGC*	Yes	Yes	Limited	DLMP
Botelho et al. [34]	2022	MGC*	Yes	Yes	Limted	DLMP
Yang et al. [35–37]	2022–2023	PS*	Yes	Yes	Limited	AC network-constrained P2P
Proposed	2023	VPP*	Yes	Yes	Yes	Reactive energy P2P trading based on the TVVC problem

* SBC: smart building community; PS: prosumers group; MGC: microgrid cluster; and VPP: virtual power plant.

$$\left|Q_{pv,i}(t)\right| \leq \sqrt{\overline{S}^2_{pv,i} - P^2_{pv,i}(t)} \tag{14}$$

$$v_0(t) = \left(V_{ref} + tap(t)\Delta V_T\right)^2 \tag{15}$$

$$\sum_{t\in\mathbf{T}} \left|tap(t+1) - tap(t)\right| \leq \overline{tap} \tag{16}$$

$$\begin{cases} \sum_{t\in\mathbf{T}} \left|c_{i,n}(t+1) - c_{i,n}(t)\right| \leq \overline{c}_{i,n} \\ Q_{cb,i}(t) = \sum_{n\in\mathbf{N}_{\mathbf{capacitor}}} c_{i,n}(t) q_{i,n}(t) \end{cases} \tag{17}$$

Table 2 lists the variables, parameters, and indices of the VPP model.

The objective function (1) comprises three terms. The first term aims to minimize the total VPP cost when purchasing active energy in the wholesale market (WSM) and reselling it to the internal loads with a ToU tariff. The second term denotes the total network power loss minimization, and the last term is the minimization of the aggregated operational cost for dispatching VPP participant DER units, e.g., the BESS unit degradation. In this model, the battery degradation cost formulated using the depth of discharge is utilized, and c_{deg} is the unit cost for ESS degradation. By tuning the weight factors α, β, and χ, the VPP aggregator can alter its operation priority. If two weighting factors are set to zero, the model simplifies to a single-objective problem.

The network constraints in this centralized VPP model comprise the active and reactive power balances (2)–(3), Ohm's law squared application (4), the second-order cone formulation for complex power constraint (5), and the voltage magnitude squared (6) constraints. The power balances are formulated based on the DistFlow method [38–39], demonstrating that the total active and reactive power generations equal the total active and reactive consumptions at any time interval.

The VPP-dispatched DERs constraints are detailed in (7)–(14), including the constraints of BESSs (7)–(13) and PVs (14). For BESS units, both active power and reactive power outputs are formulated. Eqs. (7)–(10) represent the BESSs' active power and their inverters' reactive power output constraints. The energy stored in BESSs is restricted by (11)–(13). For PVs, it is assumed that the active power output can be accurately forecasted, and the reactive power output from PV inverters is constrained by (14).

Additionally, the model considers constraints related to network-supporting devices such as capacitor banks (CBs) and on-load tap changers (OLTCs); they are owned and managed by the VPP aggregator. OLTC constraints are given by the reference bus constraint (15) and the daily operation time constraint (16). The CBs' daily operation is limited by (17). However, the nonlinearity of this formulation makes this problem difficult to solve. The detailed formulation of reducing nonlinearity based on [40] is presented in the Appendix. The reformulated problem (1)–(14) and (36)–(38) is a second-order cone programming problem that can be readily solved.

Table 2
VPP models nomenclature.

A. Indices	
$\mathbf{T}$, t	time set and indices
$\mathbf{I}$, i	network nodes set and indices
$\mathbf{L}$, ij	network branches set and indices
δ_{0i}	Kronecker delta function indexing VPP and main grid connection at the reference bus $i = 0$
$\mathbf{N}_{\mathbf{capacitor}}$	CB's capacitors set
B. Parameters	
ΔT	time intervals
$z_{ij} = r_{ij} + \mathrm{i}x_{ij}$	line impedance
π_{ws}	wholesale price
π_{tou}	time-of-use price
$P_{load,i}$, $Q_{load,i}$	active, reactive load
$P_{pv,i}$	active PV generation
$\eta^{ch}_{ess,i}$, $\eta^{dch}_{ess,i}$	ESS charging\discharging efficiencies
$\underline{SOC}$, $\overline{SOC}$	ESS state of charge (%) limits
ΔV_T	OLTC's one-tap voltage regulation
V_{ref}	reference bus voltage
C. Variables	
v_i	node voltage squared
l_{ij}	line current squared
$P_{ij} + \mathrm{i}Q_{ij}$	line power flow
$P_{vpp+}\delta_{0i}$, $Q_{vpp+}\delta_{0i}$	active and reactive power injected from the main grid to VPP
$P_{vpp-,i}$	active power brought from the VPP using ToU
$b^{ch}_{ess,i}$	binary variable for ESS charging state
$E_{ess,i}$	ESS stored energy
$Q_{pv,i}$, $Q_{ess,i}$	PV\ESS inverter reactive power compensation
$Q_{cb,i}$	CB reactive power compensation
tap	OLTC tap status
$c_{i,n}$	binary variable for the nth capacitor state in CB

2.2. Conventional distributed P2P trading models

P2P trading markets operate within a shared economy community, facilitating direct transactions between energy buyers and sellers in a distributed manner. In the P2P trading market context, the participants have increased flexibility and incentives in installing and operating DER assets. The conventional P2P trading models primarily rely on active energy transactions. Reviewing the existing literature reveals three principal formulation approaches: optimization problems, game theory, and blockchain. This paper mainly focuses on optimization problem formulation using the distributed algorithm based on the consensus ADMM algorithm, a widely used algorithm for effective solutions in the existing literature [41–42].

This paper aims to integrate the centralized VPP model and the following distributed P2P trading negotiation process solved by a consensus ADMM algorithm:

$$\begin{aligned} P^{iter+1}_{p2p,i}(t) = \operatorname*{argmin}_{P_{p2p,i}} \sum_{t\in T} f_{p-p2p,i}(t) \\ + \sum_{t\in T} \sum_{m\in\omega^p_i} \pi^{iter}_{p,im}(t) \left(\frac{P^{iter}_{p2p,im}(t) + P^{iter}_{p2p,mi}(t)}{2} - P_{p2p,im}(t) \right) \\ + \sum_{t\in T} \sum_{m\in\omega^p_i} \frac{\rho}{2} \left(\frac{P^{iter}_{p2p,im}(t) + P^{iter}_{p2p,mi}(t)}{2} - P_{p2p,im}(t) \right)^2 \end{aligned} \tag{18}$$

$$s.t. P_{p2p,i}(t) = \sum_{m\in\boldsymbol{\omega}^{\mathbf{p}}_{\mathbf{i}}} P_{p2p,im}(t) \tag{19}$$

$$\underline{P}_{p2p,i}(t) \leq P_{p2p,i}(t) \leq \overline{P}_{p2p,i}(t) \tag{20}$$

$$\underline{P}_{p2p,i}(t) \leq P_{p2p,im}(t) \leq \overline{P}_{p2p,i}(t) \tag{21}$$

$$\pi^{iter+1}_{p,im}(t) = \pi^{iter}_{p,im}(t) - \rho \left(\frac{P^{iter+1}_{p2p,im}(t) + P^{iter+1}_{p2p,im}(t)}{2} \right) \tag{22}$$

Table 3
P2P models nomenclature.

A. Indices	
$\boldsymbol{\omega}^{\mathbf{p}}_{\mathbf{i}}$, $\boldsymbol{\omega}^{\mathbf{q}}_{\mathbf{i}}$	P-P2P and Q-P2P trading partners
B. Parameters	
$iter$	consensus ADMM iteration number
ε^{primal}, ε^{dual}	consensus ADMM primal and dual converge criteria
C. Variables	
$P_{p2p,im}$, $Q_{p2p,im}$	P-P2P and Q-P2P trading quantity from i to m
$\pi_{p,im}$, $\pi_{q,im}$	perceived P-P2P and Q-P2P price from i to m

$$\begin{cases} \sum_{i\in I}\sum_{m\in\omega_i^p}\left(P_{p2p,im}^{iter+1}(t)+P_{p2p,mi}^{iter+1}(t)\right)^2 \le \varepsilon^{primal^2} \\ \sum_{i\in I}\sum_{m\in\omega_i^p}\left(P_{p2p,im}^{iter+1}(t)-P_{p2p,im}^{iter}(t)\right)^2 \le \varepsilon^{dual^2} \end{cases} \tag{23}$$

Table 3 lists the P2P model nomenclature.

Throughout each iteration in the negotiation process, individual P2P participants solve their local optimization problem (18)–(21), followed by the dual variable update (22) after each iteration. The objective function of each P2P participant (18) should be closed and convex. The local constraints of P2P participants comprise the total P2P trade constraints (19)–(20) and each transaction limit (21). Additional constraints, e.g., the BESS constraints, may be included according to the models and trading strategies of P2P participants. Inspired by [41–42], the variable $\pi_{p,im}(t)$ computed during each iteration in (22) represents the shadowed price for trading between participants *i* and *j*.

Eq. (23) introduces the global stopping criteria of the consensus ADMM algorithm iterations, The first and second subequations represent the primal and dual residuals limits. The primal residual is formulated by the trade reciprocity within each P2P pair; the dual residual is formulated by the decision variable difference between two iterations. Meanwhile, the parameters ε^{primal} and ε^{dual} are the primal and dual global feasibility tolerances, respectively.

3. Synergistic model integrating an H-P2P market in an internal VPP environment

The conventional centralized VPP and distributed P2P trading models introduced in Section 2 encounter various real-world application challenges and limitations. On the one hand, the financial incentives for the conventional VPP models are not highly appealing, leading to limited proactive participation and investments from the VPP participants. On the other hand, for the conventional P2P models, the prerequisites have been ignored, resulting in unrecognized and unaccepted transactions by the authoritative bodies. This section proposes and details a novel synergistic model that integrates an H-P2P market inside a centralized VPP, allowing the VPP participants to trade active and reactive energies simultaneously. In this case, the role of the VPP aggregator transforms into a coordinator, shedding its single-stakeholder status by delivering some authority to the participants to manage and dispatch their DER assets. This model paves the way for a mutually beneficial outcome, whereby it increases incentives for existing and potential VPP participants and concurrently enhances the attractiveness and expansion potential for VPP coordinator.

Despite the apparent benefits for both VPP coordinator and participants, potential conflicts of interest could still arise prior to further VPP expansion due to the nature of centralized and distributed modeling for the existing VPP-joining external markets and the internal P2P market. The VPP coordinator and participants compete for similar financial benefits: the VPP coordinator earns revenues by aggregating the DERs of VPP participants and providing various ancillary services to the grid; in contrast, the P2P market's participants gather revenues directly from energy transactions with other participants.

The synergistic model proposed in this paper incorporates a new interest-balancing strategy to address this issue. It enables the H-P2P trading market to be supervised and regulated by the VPP coordinator, providing a solution for balancing the interests of all involved stakeholders.

3.1. Proposed market framework

As shown in Fig. 1, the high-level market design proposed in this paper considers two electricity markets: the upstream WSM and the H-P2P market, including the active-P2P (P-P2P) and reactive-P2P (Q-P2P) trading inside the VPP environment.

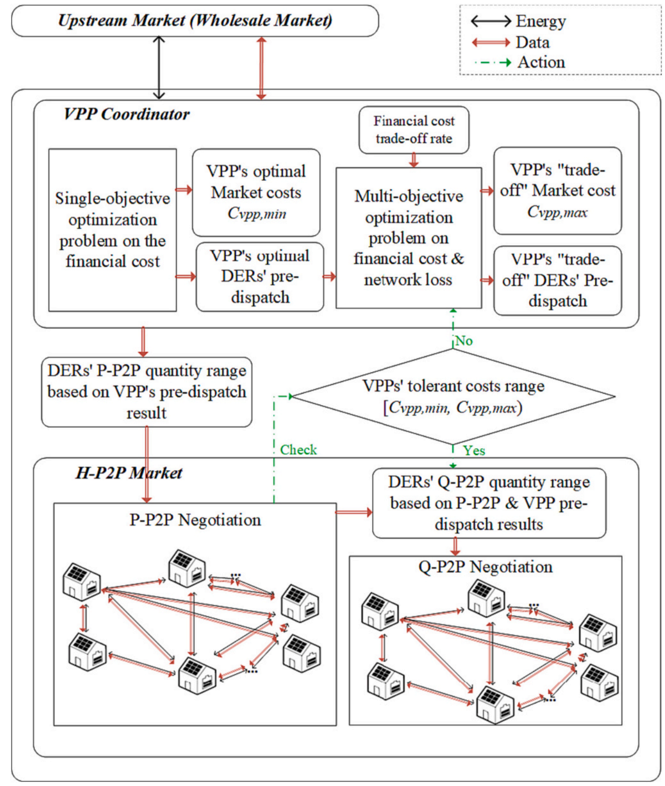


Fig. 1. Proposed H-P2P market in an internal VPP environment.

Algorithm. H-P2P markets in internal VPP environment

1. Initialization
Network parameters and PV/Load forecast
2. Active Power Markets
VPP solves (24) for the "optimal" cost and pre-dispatching.
VPP solves (25) for the "trade-off" cost and pre-dispatching.
Calculate required P-P2P regulatory information (27).
If the local P-P2P market is open, **do**
Send P-P2P regulatory information (27) to participants.
P-P2P negotiation (28), (18)-(23)
VPP coordinator checks (27) and decide on final WSM bids.
If (27) is satisfied **go to 3**
Else do the P-P2P market closes.
VPP dispatches DERs centrally.
End
End
3. Reactive Power Markets
VPP coordinator solves centralized VVC problem (30).
Calculate the required reactive power compensation (31).
If the in TVVC mode, **do**
Send Q-P2P regulatory information (31) to participants.
Q-P2P negotiation (32)-(35).
VPP coordinator checks if the requirement (31) is satisfied.
If (31) is satisfied **End**
Else do transfer TVVC mode to centralized VVC mode.
VPP dispatches DERs centrally to compensate for remaining reactive power.
End
End

For the proposed active power trading design, the VPP coordinator provides an environment for local P-P2P trading and conducts bidding with the upper-level WSM. The VPP coordinator regulates the proposed P-P2P trading. Consequently, the P2P participants can obtain more energy choices and higher profits without excessively depleting the VPP profits. Firstly, through a pre-dispatch process, the VPP coordinator sets the acceptable scale and the potential role of each DER within a specific period in the local P-P2P market. The VPP coordinator will solve a single-objective optimization problem to get an optimal financial cost for the VPP coordinator. Then, the VPP coordinator performs the multi-objective optimization by introducing an additional financial cost trade-off rate, meaning that the VPP's financial cost cannot exceed the minimum cost obtained in the single-objective optimization problem by more than this rate. The results of two optimization problems of the VPP coordinator serve as the bounds for the P2P optimization problem, which will restrict the search space for the individual optimization problems in P-P2P. The VPP coordinator publishes this P-P2P information, and the DERs in the VPP conduct active energy negotiations with each other. When all P-P2P bilateral contracts are determined, and the tolerant cost range of VPP coordinators is confirmed unviolated, the active energy market results will be sent to the reactive energy market.

The proposed novel reactive energy trading design refers to the local Q-P2P trading in the VPP internal environment. The VPP coordinator allows the local Q-P2P trading to facilitate voltage regulation and increase the incentives of its participants. This paper defines this strategy as the concept of TVVC. It is worth mentioning that the term "trading" for reactive energy does not mean transferring the reactive energy through the lines physically. Instead, "trading" refers to a cost-effective strategy performed by the VPP coordinator to ensure the voltage level and incentivize the inverters to provide ancillary services. Similar to P-P2P trading, Q-P2P trading is under the regulation of the VPP coordinator.

Firstly, the VPP coordinator solves a DER-inverter-based VVC problem to determine the reactive energy amount each DER must provide, according to the final active energy dispatch and trading results. Then, the reactive energy amount required by the VPP coordinator is sent to participants with DER inverters. Instead of profits in the conventional financial compensation method, this paper assumes that DERs can gain income through local Q-P2P trading within this pre-required range. After negotiation in the local Q-P2P market, the amount of reactive energy that cannot be satisfied will be gathered and compensated by the VPP coordinator.

The algorithm for the proposed H-P2P market integrated into an internal VPP environment, which can trade active and reactive energy simultaneously, is summarized in the pseudocode Algorithm.

3.2. P-P2P trading regulated by the VPP coordinator

This section proposes a multi-stage process in that P-P2P trading is supervised and regulated by the VPP coordinator.

3.2.1. Pre-dispatching stage of VPP coordinators

Mathematically, the interests conflict brought by P-P2P to the VPP coordinator is mainly on increasing the financial cost since opening the P-P2P market will reduce $P_{vpp\text{-}}(t)$ values in the conventional VPP's objective (1) and hence increase the total cost of the VPP coordinator. To trade off their interests to the utmost extent, the VPP coordinator sends the regulatory information to the P-P2P trading participants by solving pre-dispatch optimization problems sequentially. The VPP coordinator solves a single-objective problem as follows:

$$\begin{aligned}&\left\{P_{ess,i}^{(1)}(t)\,,\underline{C}_{vpp}\right\}\\&=argmin\sum_{t\in\mathbf{T}}\left\{\left(\pi_{ws}(t)P_{vpp+}(t)-\pi_{tou}(t)P_{vpp-}(t)\right)\Delta t\right\}\end{aligned}\tag{24}$$

s.t.(2)–(14), (36)–(38).

In this optimization problem, the objective is the minimization of the VPP coordinator's total cost, ignoring other objective terms in (1). Consequently, the results of this problem $\underline{C}_{vpp}$ should be the optimal possible VPP coordinator cost, and $P_{ess,i}^{(1)}(t)$ indicates the optimal dispatch of the ESS units for the VPP coordinator. The value $\underline{C}_{vpp}$ is then utilized in a constraint (26), limiting the VPP coordinator's total cost of the second optimization problem, which is shown as follows:

$$\begin{aligned}&\left\{P_{ess,i}^{(2)}(t)\,,\overline{C}_{vpp}\right\}\\&=\operatorname{argmin}\sum_{t\in T}\left\{\begin{array}{c}\left(\pi_{ws}(t)P_{vpp+}(t)-\pi_{tou}(t)P_{vpp-}(t)\right)\Delta t\\+\sum_{ij\in L}l_{ij}(t)r_{ij}(t)+\sum_{t\in T}c_{\deg}\dfrac{P_{ess,i}^{dch}(t)+P_{ess,i}^{ch}(t)}{\overline{E}_{ess,i}}\Delta t\end{array}\right\}\end{aligned}\tag{25}$$

s.t.(2)–(14), (36)–(38)

$$\underline{C}_{vpp}\le\sum_{t\in\mathbf{T}}\left(\pi_{ws}(t)P_{vpp+}(t)-\pi_{tou}(t)P_{vpp-}(t)\right)\Delta t\le\underline{C}_{vpp}+a\left|\underline{C}_{vpp}\right|\tag{26}$$

In this multi-objective problem (25)–(26), the objectives for this VPP coordinator include the total financial cost, the internal network loss, and the DER operational cost. Moreover, a trade-off rate a is introduced as the VPP coordinators' willingness on its cost sacrifice in the problem (25), and it is used to constrain the VPP cost (26). In other words, a is proposed to be the highest interest transfer percentage from the VPP coordinator to the P-P2P trading. This rate should be evaluated during the planning stage for the VPP coordinator who intends to open the internal market. For instance, $a = 20\%$ means the VPP coordinator is willing to increase 20% of the current financial cost and transfer this interest to its internal P-P2P trading, increasing its longer-term profits and attractions. The solutions to this multi-objective optimization problem, $\underline{C}_{vpp}, P_{ess,i}^{(2)}(t)$ and $P_{dsl,i}^{(2)}(t)$, are called the trade-off cost and dispatch for the VPP coordinator.

Consequently, the VPP coordinator will allow its participants to trade active power from other participants if the VPP's cost does not exceed the allowable range of (25) and (26) solutions. To ensure this P-P2P trading prerequisite, the VPP coordinator will gather and send the regulatory information to each participant before the P-P2P trading in the proposed H-P2P market. Specifically, the regulatory information includes the acceptable traded quantity and the potential role of each DER within a specific period in P-P2P trading. The regulatory information sent by the VPP coordinator can be categorized based on features of different DERs as follows:

$$\begin{cases}min\left(0P_{ess,i}^{(1)}(t)-P_{ess,i}^{(2)}(t)\right)\le P_{p2p,i}(t)\backslash P_{p2p,im}(t)\\P_{p2p,i}(t)\backslash P_{p2p,im}(t)\le max\left(0P_{ess,i}^{(1)}(t)-P_{ess,i}^{(2)}(t)\right)\\0\le P_{p2p,i}(t)\backslash P_{p2p,im}(t)\le P_{pv,i}(t)\\-P_{load,i}(t)\le P_{p2p,i}(t)\backslash P_{p2p,im}(t)\le 0\end{cases}\tag{27}$$

As shown in the first two sub-equations of (27), the dispatchable units, e.g., the ESS, will receive information on the allowable trading active energy ranges and the potential trading roles (buyers/sellers). For ESS units, the trading ranges are obtained from VPP's pre-dispatch process (24)–(26). The ESS units can be either buyers or sellers depending on the solutions from (24)–(26). Their trading roles are settled in $P_{ess,i}^{(1)}(t)$ and $P_{ess,i}^{(2)}(t)$ have the same signs; otherwise, the ESS units should decide whether to buy or sell active energy during the P-P2P negotiation process. For the non-dispatchable units, including the PV generators and the non-flexible loads, their potential P-P2P trading roles and the allowable trading ranges are fixed.

3.2.2. P-P2P negotiation stage

In the local P-P2P market, all DERs will conduct bilateral transactions based on the information (27) published by the VPP coordinator. The P-P2P negotiation is a distributed optimization problem solved by a consensus ADMM algorithm with stopping criteria of (23). During each ADMM iteration, each P-P2P participant will solve an optimization problem with constraints of (19) and additional constraints (27) from the VPP coordinator, and the individual objectives will be formulated as follows:

$$\sum_{t\in\mathbf{T}} f_{p-p2p,i}(t) = \sum_{t\in\mathbf{T}} \left\{ \frac{1}{2} a_i^p(t) P_{p2p,i}(t) + b_i^p(t) P_{p2p,i}(t) \right\} \tag{28}$$

The objective (28) for the i-th VPP participant indicates the willingness to trade in the P2P market. It can be represented as a quadratic function as shown in [41–42], where $a_i^p(t)$and $b_i^p(t)$are the quadratic and linear coefficients. It is worth mentioning that the financial cost of the H-P2P market is shadowed in the negotiation procedure. Each participant will update this price using (22) during each iteration. This cost value can be resolved when the consensus of all transactions is reached, as follows:

$$-\sum_{m\in\omega_i^{\mathbf{p}}} \pi_{p,im}^{iter+1}(t) P_{p2p,im}^{iter+1}(t) \tag{29}$$

However, even with the consensus ADMM negotiation process with the regulatory limits (27), the VPPs' tolerant interest transfer constraints (26) still need to be confirmed after the P-P2P trading is converged. If the P-P2P trading sacrifices too many financial benefits of the VPP, the VPP coordinator will close the P-P2P market and dispatch the remaining DERs' capacity to fulfil its financial benefit by resolving the problem (25).

4. TVVC method and Q-P2P trading

This section introduces the proposed TVVC method, which leverages reactive power transactions to incentivize the inverter-based VVC. Meanwhile, the H-P2P market is presented, where the VPP coordinator simultaneously accepts and regulates the P-P2P and Q-P2P trading.

4.1. Transactive voltage/VAR control

A significant issue that can arise within a regional VPP network is its internal bus voltage violation. This issue can become severe because of the extensive penetration of renewables. Conventionally, the centralized VPP manages the internal voltage levels using voltage regulation devices, such as the OLTCs and CBs, and the reactive power compensation from its participants' inverters. In this conventional VVC strategy, the financial incentives are negligible or restricted for the VPP participants' provision of VVC services.

In the context of this paper, a TVVC method is proposed to establish profitable inverter-based VVC and offer adequate incentives to the VPP participants, which is because the distributed P2P transactions are integrated into the internal VPP environment, and the VPP participants have the authority over the control and operation of their DER assets. It is important to note that the phrase "reactive energy trading" does not literally signify the physical transfer of reactive energy through the lines. Instead, trading refers to a cost-effective strategy implemented by the VPP coordinator. When integrated into the Q-P2P trading, there is inherent competition between the VPP coordinator and participants over financial gains and reactive energy quantities. According to the distinct nature of conventional VVC and TVVC, while the VPP coordinator's primary aim is to maintain the voltage levels within the VPP internal network, participants are more financially driven. In the unrestricted Q-P2P scenario, participants might overproduce or underproduce reactive energy to maximize their profits, leading to potential voltage issues. Although the VPP participants conflict with the VPP coordinator over opposes, they still rely on the VPP platform to realize the advantages of Q-P2P trading. Hence, it is apparent that the Q-P2P trading process needs constraints from the VPP coordinator.

4.2. Q-P2P trading regulated by the VPP coordinator

As described in the proposed market design of Section 3.1, the proposed TVVC method can be seen as a process of implementing Q-P2P trading regulated by the VPP coordinator in the internal VPP environment. The regulation from the VPP coordinator mainly results from the Q-P2P trading quantities conflict between the VPP coordinator and the VPP participants under the TVVC method. If no regulations from VPP are imposed on the Q-P2P transactions, the Q-P2P trading scale after the negotiation may be overly large or small. The former will exacerbate the voltage problem inside the VPP, and the latter will not be able to guarantee sufficient reactive energy compensation for the VPP.

Consequently, a multi-stage process is proposed for TVVC and Q-P2P trading with primary regulatory considerations on participants' performance levels of VVC. In other words, for Q-P2P trading, the VPP coordinator acting as a regulator must establish thresholds for the reactive energy traded. This ensures that Q-P2P trading does not harm voltage levels or network stability.

The VPP coordinator will solve a centralized VVC optimization problem to confirm the desired inverters' reactive power compensation, as follows:

$$\left\{ Q_{ess,i}^{(1)}(t), Q_{pv,i}^{(1)}(t) \right\} = argmin \sum_{t\in\mathbf{T}} \left\{ C_{vpp} + \sum_{ij\in\mathbf{L}} l_{ij}(t) r_{ij}(t) + C_{\deg} \right\} \tag{30}$$

$s.t.$(2)–(6), (10), (14), (36)–(38).

The P-P2P trading negotiation (28)–(29) has converged at this stage. Meanwhile, the VPP coordinator's total cost, C_{vpp}, and the battery degradation cost, C_{deg}, have been determined and confirmed within the acceptable ranges. Problem (30) can be seen as a single-objective optimization problem minimizing the total VPP internal network loss. By solving (30), the VPP coordinator will obtain the requested reactive energy compensation results from the DERs' inverters, including the PV and ESS inverters owned by the VPP participants. These results will formulate the VPP coordinators' acceptable scale of the Q-P2P trading, which is also the regulatory information sent by the VPP coordinator to the Q-P2P trading, as follows:

$$\begin{cases} min\left(0, Q_{ess,i}^{(1)}(t)\right) \le Q_{p2p,i}(t) \backslash Q_{p2p,im}(t) \le max\left(0, Q_{ess,i}^{(1)}(t)\right) \\ min\left(0, Q_{pv,i}^{(1)}(t)\right) \le Q_{p2p,i}(t) \backslash Q_{p2p,im}(t) \le max\left(0, Q_{pv,i}^{(1)}(t)\right) \\ -Q_{load,i}(t) \le Q_{p2p,i}(t) \backslash Q_{p2p,im}(t) \le 0 \end{cases} \tag{31}$$

In the next stage, where all the owners of DER inverters obtained the information (31), the Q-P2P trading is conducted as a distributed optimization problem solved by a consensus ADMM algorithm, as follows:

$$\begin{aligned} Q_{p2p,i}^{iter+1}(t) = \underset{Q_{p2p,i}}{\text{argmin}} \sum_{t\in T} \left\{ \frac{1}{2} a_i^q(t) Q_{p2p,i}(t) + b_i^q(t) Q_{p2p,i}(t) \right\} \\ + \sum_{t\in T} \sum_{m\in\omega_i^q} \pi_{q,im}^{iter}(t) \left(\frac{Q_{p2p,im}^{iter}(t) + Q_{p2p,mi}^{iter}(t)}{2} - Q_{p2p,im}(t) \right) \\ + \sum_{t\in T} \sum_{m\in\omega_i^q} \frac{\rho}{2} \left(\frac{Q_{p2p,im}^{iter}(t) + Q_{p2p,mi}^{iter}(t)}{2} - Q_{p2p,im}(t) \right)^2 \end{aligned} \tag{32}$$

$s.t.$(30)

$$Q_{p2p,i}(t) = \sum_{m\in\omega_i^{\mathbf{q}}} Q_{p2p,im}(t) \tag{33}$$

$$\pi_{q,im}^{iter+1}(t) = \pi_{q,im}^{iter}(t) - \rho \left(\frac{Q_{p2p,im}^{iter+1}(t) + Q_{p2p,mi}^{iter+1}(t)}{2} \right) \tag{34}$$

During each ADMM iteration, each Q-P2P participant updates the proposed P2P traded reactive energy quantities by individually solving the optimization problem (32)–(33) and then adjusts the reactive shadowed prices as per (34). The Q-P2P iterative process continues until the following stopping criterion is satisfied:

$$\begin{cases} \sum_{i \in I} \sum_{m \in \omega_i^q} \left(Q_{p2p,im}^{iter+1}(t) + Q_{p2p,mi}^{iter+1}(t) \right)^2 \leq \varepsilon^{primal^2} \\ \sum_{i \in I} \sum_{m \in \omega_i^q} \left(Q_{p2p,im}^{iter+1}(t) - Q_{p2p,im}^{iter}(t) \right)^2 \leq \varepsilon^{dual^2} \end{cases} \tag{35}$$

The objectives in (32) indicate the willingness of each DER to attend the Q-P2P market coordinated by the VPP coordinator. This objective explains that the owners of DER inverters are motivated to prioritize Q-P2P trading because higher reactive energy trading volumes in the Q-P2P yield more significant profits. Following the Q-P2P negotiation closing, the VPP coordinator will switch the VVC strategy from TVVC to the conventional VVC, indicating that the VPP coordinator will centrally dispatch any remaining reactive power compensation requests.

5. Case study

5.1. Cases design

A 33-bus system is utilized to simulate a VPP integrating and regulating the proposed H-P2P markets. The 33-bus system has been widely used to perform distribution system tests. Fig. 2 shows the installation location of five ESS units (400 kW, 1000kWh), and Fig. 3 shows the forecasted RESs (eight PV generators in total) profiles and loads. The curves of PV generations and loads show typical profiles but different capacities. In this network, one OLTC ($\pm 10 \times 1\%$) device is connected to the slack bus to adjust the voltage of the root bus transformer's low-voltage side. Buses 15 and 27 connect to one CB (5 × 100kVar) separately.

The VPP coordinator model assumes that the coordinator treats the weighting coefficients α, β, and χ as the same. Meanwhile, the trade-off percentage shown in (26), a, is set to 20%, which means the VPP coordinator is willing to compromise 20% of its maximum benefits to the P-P2P market. The pricing data used by the VPP coordinator are set as follows: the upstream market data is provided by the Australian Energy Market Operator (AEMO) [43]. The VPP sells electricity to the registered loads on a ToU price extracted from AGL Australia [44], as shown in the last subfigure in Fig. 5. In the H-P2P model, the penalty ρ is assumed to be 1, and both ε^{primal} and ε^{dual}, which are the minimum primal and dual residuals to determine the convergence, are set to 10^{-4}. The coefficients parameters of H-P2P participants' quadratic functions are inspired by Baroche et al. [41] and tuned based on 24 h a day, two types of P2P energy market, and 32 participants.

The simulations are conducted using MATLAB R2020a on a 64-bit laptop with a 1.30GHz CPU and 16.0GB RAM. The Gurobi solver solves the optimization problems.

The simulations are conducted for 4 cases with different VPP strategies, as listed in Table 4. The simulation results of the total cost of VPP participants and network loss under different VPP strategies are also listed in Table 4. By comparing Cases 1, 2, and 3 with the base case separately in Table 4, it can be observed that for the proposed model, the more active participation of the VPP participants, the less is expected to be the total cost they paid. Among them, P-P2P trading can save DERs' costs to the greatest extent. Similarly, after comparing Cases 2 and 3 with the base case and Case 1, operating the TVVC method and the Q-P2P for the VPP coordinator can significantly reduce the network power loss. However, the profiting method for the VVC will not affect the network power loss.

Fig. 4 illustrates the voltage profiles for each node in the 33-bus network. Specifically, Fig. 4(a) and (b) depict cases with and without VVC, respectively. Fig. 4(a) represents both the base case and case 1, as listed in Table 4, while Fig. 4(b) encompasses cases 2 and 3. This implies that the TVVC method introduced in this paper enhances the financial benefits for P2P participants without affecting the network behavior.

5.2. Impact on VPP participant's financial incentives

This section explicitly analyses the proposed model's benefits to the VPP participants from a financial point of view. Fig. 5(a)-(d) show the savings of different types of VPP participants participating in the internal-VPP P-P2P and Q-P2P trading, respectively.

Their savings on the P-P2P trading are presented by the percentage of each participant's total cost difference between Case 1 and the base case over the base case cost, as shown in Fig. 5(a) and (b). Meanwhile, the Q-P2P market benefits the participants of pure loads and PV/ESS installation, as shown in Fig. 5(c) and (d). They are calculated based on the cost difference between Cases 2 and 3 as a percentage of the base case.

The savings of the participant who installed PV/ESS units (20%–50% for P-P2P and 5%–10% for Q-P2P) is generally more significant than that of pure loads (10%–30% for P-P2Pamd 0%–5% for Q-P2P). These results indicate that the H-P2P market encourages the VPP participants' installation and investment of the RES and ESS units. Meanwhile, the P-P2P market can benefit VPP participants more since the active energy market size is larger than that of the reactive energy market. In addition, the P-P2P market saves the most during the period from 2 pm to 6 pm, the peak period of PV power generation, and during the morning peak load period. During the peak load period from 6 pm to 10 pm, the Q-P2P market saves the most cost. Consequently, the VPP coordinator should make more efforts on regulation and investment in P-P2P trading, while Q-P2P trading can mainly act as an auxiliary tool for VVC and further enhance participants' incentives.

Fig. 6 compares the VPP optimal and trade-off pre-dispatch results on ESS active power in kW obtained by solving the optimization problems (24)–(25). The former provides the optimal solution for the VPP coordinator without considering the benefits of the ESS units. At the same time, the latter represents the concession VPP is willing to make to ESS units to develop the P-P2P market and attract more potential participants. Mathematically, the latter result is the generation capacity that ESS units must satisfy in order to participate in the VPP, i.e., these two optimization results provide ESS with a tradable scope to participate in the P2P market.

As shown in Fig. 6, these two results are related to the wholesale and the ToU prices. For example, all these ESS units are required to generate electricity when the ToU price peaks, i.e., around 8 pm. Meanwhile, they must charge electricity when the wholesale price is relatively low, i.e., at midday. It can be seen the trading range of ESS8 in the P2P trading market is more flexible.

5.3. H-P2P negotiation results

Fig. 7(a) compares the trading prices of the P-P2P trading with the buy and sell prices provided by the VPP coordinator. Since the P2P transactions have different settled prices, only the average and maximum prices at each time point are shown in this figure. The P2P transactions can undoubtedly increase the PV/ESS units' profits. As for the load units, when there is a P-P2P transaction, the P2P price is always lower than the VPP ToU prices, saving the customers' costs. Fig. 7(b)

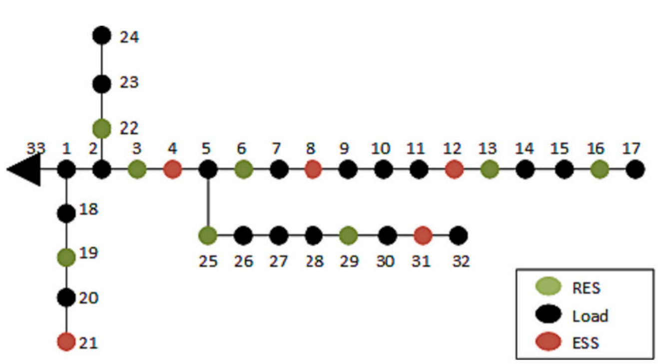


Fig. 2. IEEE 33-bus test network.

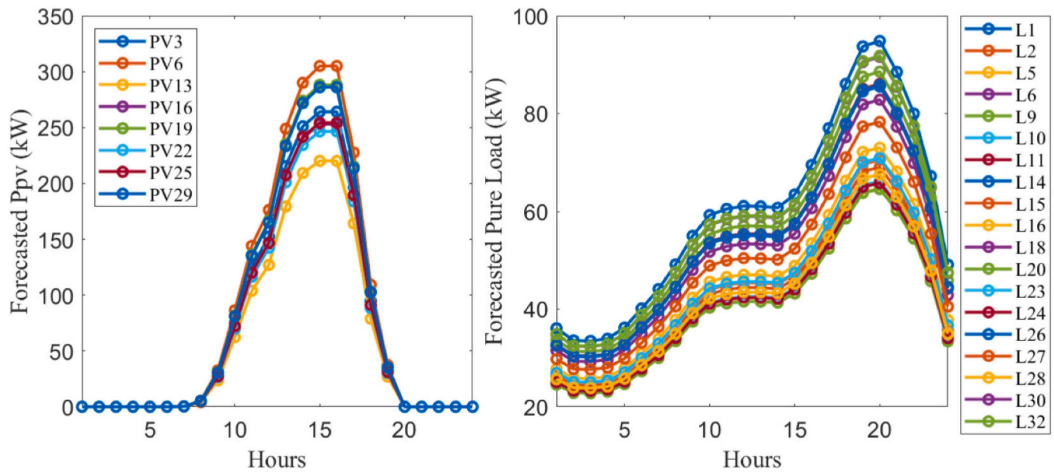


Fig. 3. Forecasted data of PV and pure load.

Table 4
Scenario and simulation results.

Cases Design		Base	1	2	3
VPP Strategy	WSM	√	√	√	√
	P-P2P	×	√	√	√
	Centralized VVC	×	×	√	√
	TVVC & Q-P2P	×	×	×	√
Results	Participants' Cost ($)	5884.58	4146.88	4020.00	3910.06
	Network Loss (MWh)	0.2538	0.2538	0.1362	0.1362
	Total Savings ($)	–	1737.7	1864.58	1974.52

compares the Q-P2P market prices and the VPP coordinator's tariffs. Specifically, when there is no local market, the load will buy reactive energy at the ToU price from the VPP coordinator, and PV/ESS inverters will provide VVC services through compensation. Therefore, according to Fig. 6(b), all P2P transaction prices are located within the range of VPP buying and selling prices, which means all sellers and buyers in the Q-P2P market can benefit from this price difference.

Fig. 8(a) and (b) represent the total amount of P-P2P and Q-P2P transactions, respectively. The timeslots for most P-P2P and Q-P2P transactions are 3 pm and 7 pm, respectively. During this period, when the electricity price in the WSM is low, the VPP coordinator advocates ESSs to store electricity to guarantee the VPP's benefits. The ESSs can trade with the PVs in the local market and import from the upper market through the VPP coordinator. With no local market, ESSs only consider the degradation cost, not the financial cost. However, under the proposed model, the actual transaction amount in the local market of electricity purchased by the ESSs from the PVs is paid by the VPP coordinator to ensure the ESSs units' benefits.

5.4. Impacts on VPP coordinator behaviors

Opening local H-P2P markets will impact the VPP environment. Fig. 9(a) and (b) show the final bidding of VPP in the upper WSM and the centralized VVC reactive energy dispatch in the day-ahead timescale. The blue bars represent the total amount of VPP WSM bids when there is no local P-P2P market, and the blue dotted lines represent the VPP bids with the local market. The orange line, representing the WSM price, shows that the VPP tends to buy electricity when the price is low and buy electricity when the price is high. As shown in Fig. 9(a), since the local P2P market operates under the regulation of the VPP coordinator, it will not significantly change the bidding behavior of the VPP. However, the local market will slightly increase the electricity purchased by the VPP, while the electricity sold will decrease slightly. Therefore, the local market will reduce the total revenue of the VPP coordinator.

Similarly, in Fig. 9(b), when the local P2P market for reactive energy is open, the overall amount of the reactive energy compensation requested by the VPP is reduced, thereby reducing the benefits of the VPP.

5.5. Consensus ADMM algorithm convergence

This section illustrates the convergence and evaluates the performance of the consensus ADMM algorithm. In the proposed H-P2P model, this algorithm is employed by P-P2P trading and Q-P2P trading negotiations separately. Fig. 10(a) and (b) detail the convergence speed, primal and dual residuals, and iteration counts for the P-P2P and Q-P2P negotiations, respectively. It is evident that the P-P2P trading achieves

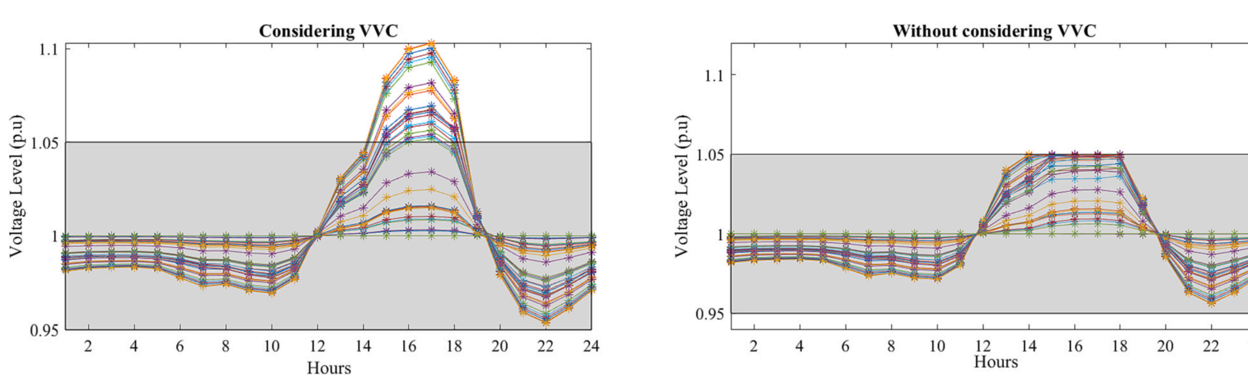
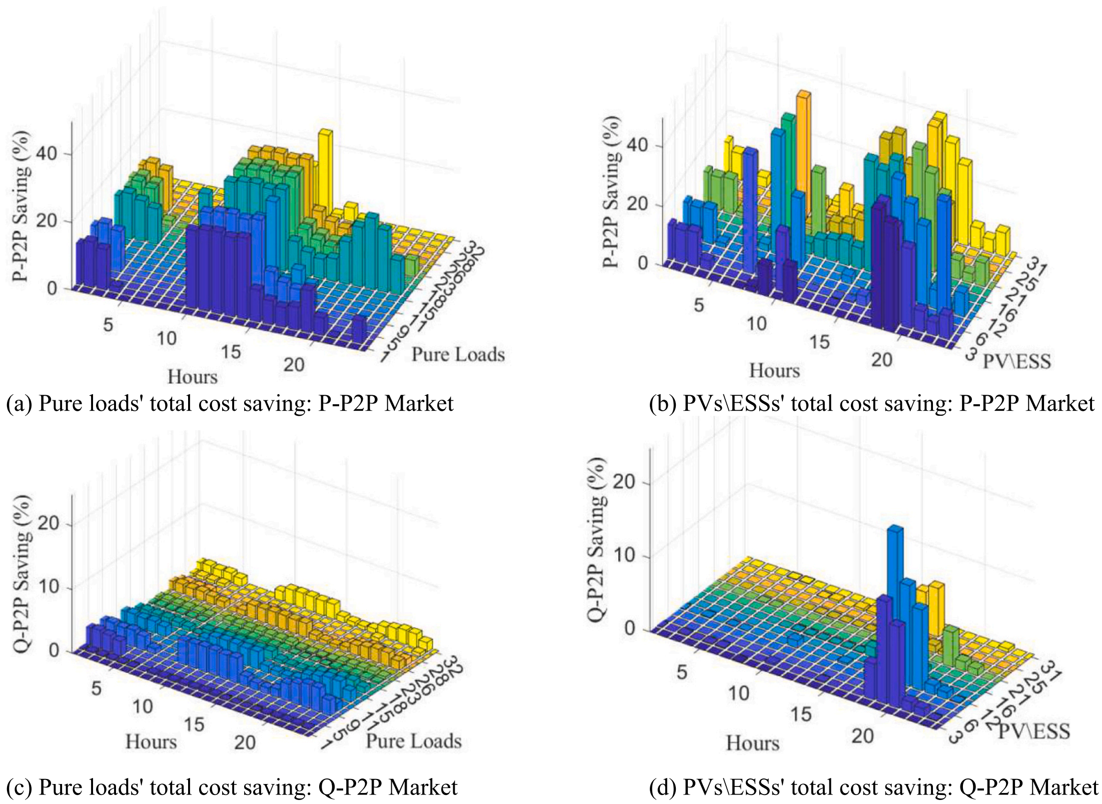


Fig. 4. Voltage profiles (a) with VVC and (b) without VVC.



(a) Pure loads' total cost saving: P-P2P Market

(b) PVs\ESSs' total cost saving: P-P2P Market

(c) Pure loads' total cost saving: Q-P2P Market

(d) PVs\ESSs' total cost saving: Q-P2P Market

Fig. 5. VPP customers' total cost saving comparison.

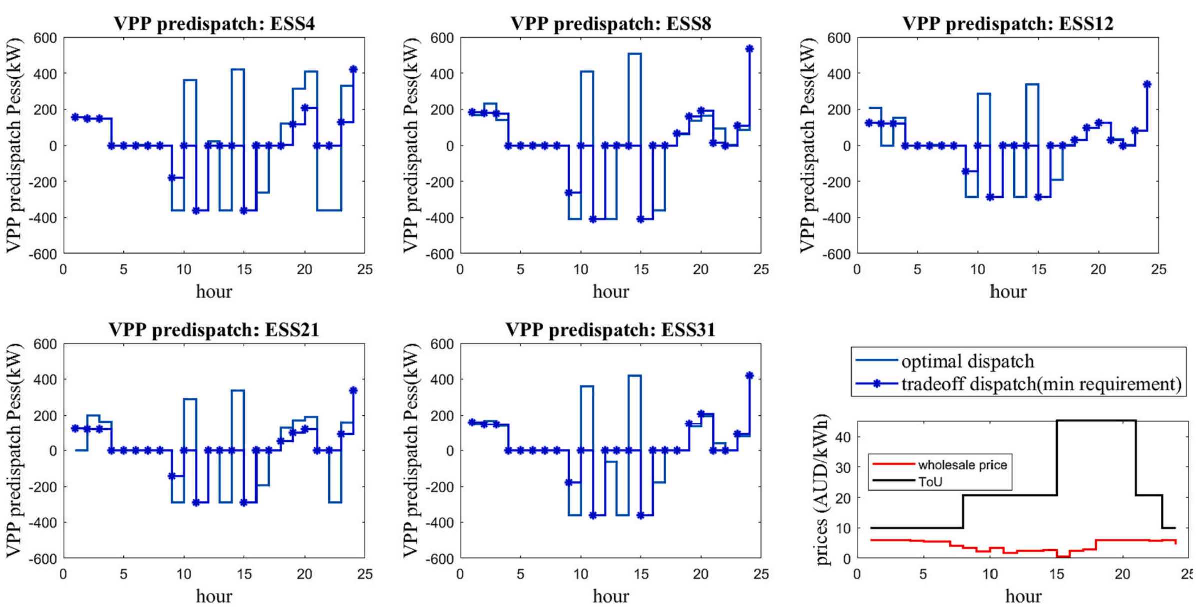


Fig. 6. VPP optimal and tradeoff pre-dispatch results on ESS units calculated by optimization problems (24)–(25).

consensus after 3345 iterations, bringing primal and dual residuals lower than 10^{-4}. This process consumes about 76 min. Meanwhile, Q-P2P trading converges after 55 min with 2832 iterations.

Consequently, given the time efficiencies and performance observed in both P-P2P and Q-P2P negotiations, the consensus ADMM algorithm is proved to be suitable and effective for reaching the feasibility of the proposed model.

6. Conclusion

This paper proposes an H-P2P market in a VPP environment. In this VPP, the P2P market is regulated by a VPP coordinator, which can realize simultaneous P-P2P and Q-P2P transactions. The proposed model is simulated based on the 33-bus system. The results show that the proposed model can provide considerable opportunities for VPP customers to trade with each other, reducing their electricity costs significantly. Hence, this model can attract more potential future registered

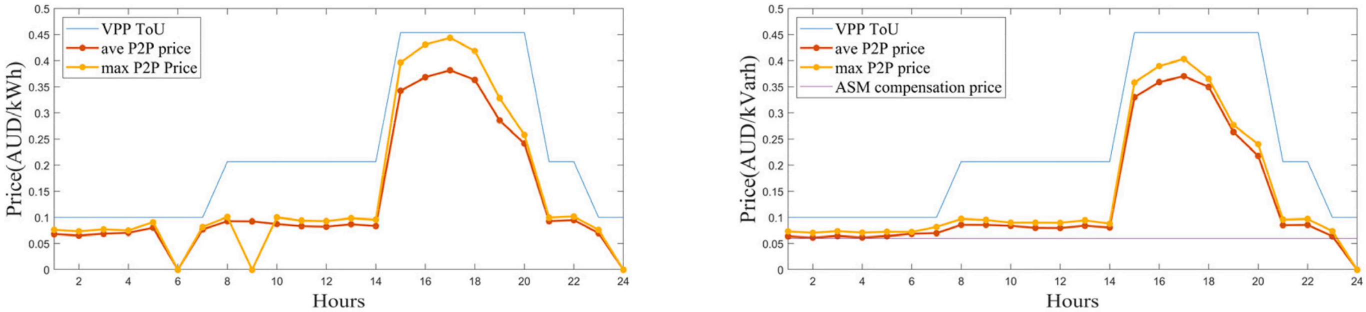


Fig. 7. Comparison between VPP prices and (a) P-P2P and (b) Q-P2P prices.

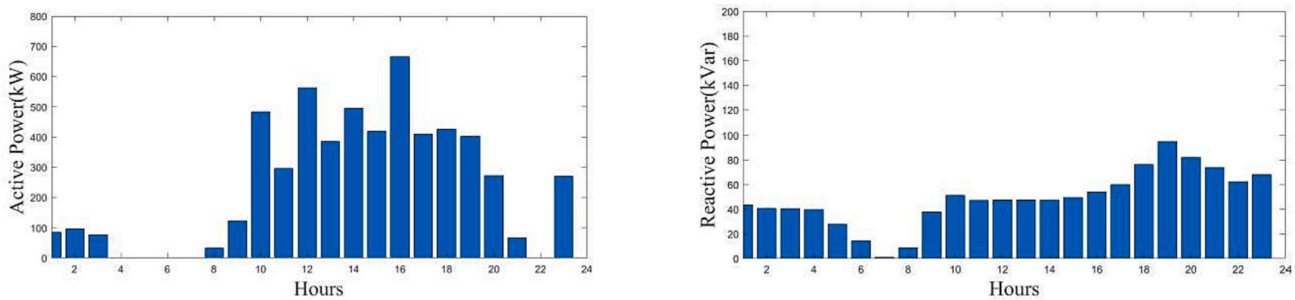


Fig. 8. Total P2P traded power in (a) local P-P2P market, and (b) local Q-P2P market.

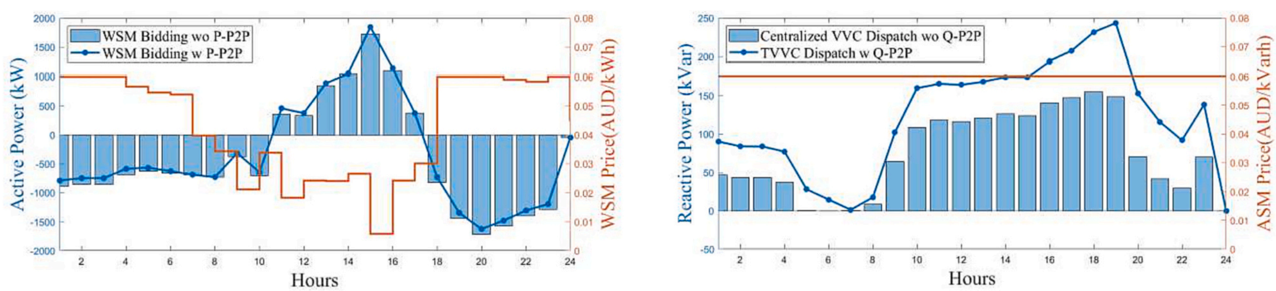


Fig. 9. Total VPP day-ahead bids on (a) WSM and (b)ASM.

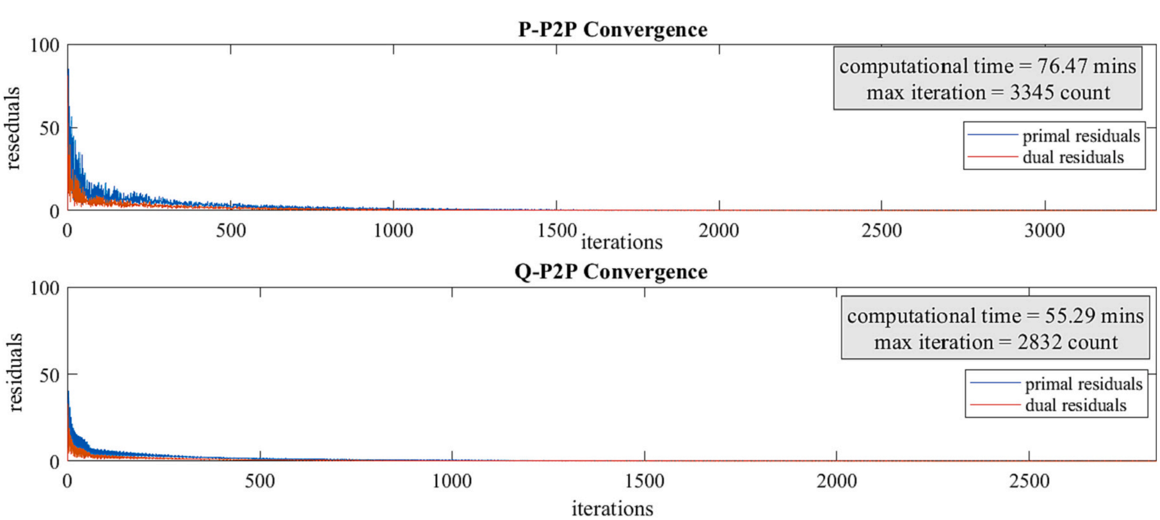


Fig. 10. Consensus ADMM algorithm convergence on (a) P-P2P trading and (b) Q-P2P trading.

clients to the VPP. Moreover, when the total number of users remains unchanged, this model will not seriously impact the interests of the VPP coordinator.

This paper assumes that the DERs can accurately predict PV and the upper market price. A more accurate model that can consider multiple uncertainties will be developed in our future work to achieve optimal performance and improved stability in practical applications.

CRediT authorship contribution statement

Yuan Meng: Visualization, Validation, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization, Writing – original draft, Writing – review & editing. **Jing Qiu:** Visualization, Validation, Supervision, Methodology, Conceptualization, Formal analysis, Investigation, Resources, Writing – review & editing. **Cuo Zhang:** Methodology, Investigation, Writing – review & editing. **Gang Lei:** Visualization, Validation, Methodology, Writing – review & editing. **Jianguo Zhu:** Visualization, Validation, Supervision, Resources, Methodology, Formal analysis, Conceptualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Appendix A. Nonlinearity reduction of the VPP model

OLTC and CB constraints given by the DisFlow model (15)–(17) generate nonlinearity to the optimization problem. To overcome the nonlinearity and simplify the mathematical model, the reformulated constraints are shown as follows [38–40]:

$$\begin{cases} tap(t) = \sum_{k=0}^{2\overline{tap}} (k - \overline{tap}) d_k(t) \\ v_{0,t} = \sum_{k=0}^{2\overline{tap}} \left[\left(V_{ref} + (k - \overline{tap}) \Delta V \right)^2 d_k(t) \right] \\ \sum_{k=0}^{2\overline{tap}} d_k(t) = 1 \end{cases} \tag{36}$$

$$\begin{cases} tap(t+1) - tap(t) \le \beta(t) \\ tap(t) - tap(t+1) \le \beta(t) \\ \sum_{t \in \mathrm{T}} \beta(t) \le \overline{tap} \end{cases} \tag{37}$$

$$\begin{cases} \zeta_{i,n}(t) = c_{i,n}(t) + c_{i,n}(t+1) - 2\gamma_{i,n}(t) \\ \gamma_{i,n}(t) \le c_{i,n}(t), \gamma_{i,n}(t) \le c_{i,n}(t+1), \gamma_{i,n}(t) \ge c_{i,n}(t) + c_{i,n}(t+1) - 1 \\ \sum_{t \in T} \zeta_{i,n}(t) \le \overline{cap_{i,n}} \\ Q_{cb,i}(t) = \sum_{n \in N_{\text{capacitor}}} c_{i,n}(t) Q_{i,n}(t) \end{cases} \tag{38}$$

The *tap* status for this OLTC is denoted by a set of ancillary binary variables $d_k(t)$. Another ancillary integer variable represents the tap change status limit $\beta_t \in [-\overline{tap}, \overline{tap}]$. Moreover, the CBs' daily operation limits are given by constraint (38), where $\zeta_{i,n}(t)$ and $\gamma_{i,n}(t)$ are two binary ancillary variables to assist in formulating CB constraints and where $\gamma_{i,n}(t) = c_{i,n}(t) * c_{i,n}(t+1)$. Additionally, $\zeta_{i,n}(t)$ represents the status change states of CBs from t to the next time slot.

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