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Impact of P2P Trading on the Dynamic Performance of Transmission Grids

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Abstract:
Peer-to-peer (P2P) markets facilitate the integration of distributed energy resources, reduce distance between generation and consumption, and provide a convenient opportunity to reduce congestion on the transmission grid. In this context, P2P markets are usually investigated under the assumption that P2P trades are limited in size and number, thus ignoring the possible impact of the transmission network and its dynamic performance. However, the transmission grid is required to accommodate all the transactions that can not be satisfied in P2P markets, e.g., due to local high prices or low generation. Accordingly, as P2P markets gain momentum, there is an increasing interest in assessing their potential impact on the transmission grid dynamic performance. This paper evaluates through extensive realistic simulations, the sensitivity of the frequency of the transmission grid to different parameters related to the P2P markets, such as variations in price, number of market participants, frequency of market clearance, and proposes a countermeasure to mitigate such an impact. The results show that P2P trading indeed affects system dynamics and an increasing number of P2P transactions may even lead to instability of the transmission system, but the proposed market price strategies are able to mitigate such undesirable effects.

1 Introduction

Small and micro generation, such as local energy communities (LECs) and microgrids (MGs), along with new paradigms of energy markets, most notably peer-to-peer (P2P) energy markets, appear as promising tools to decarbonize energy generation, facilitate the utilization of renewable sources and decrease the distance between generation and consumption. However, given that conventional hourly or sub-hourly markets cause deterministic frequency deviations which are among the biggest deviations observed by transmission system operators (TSOs) in normal operation, the question arises whether new energy market setups, such as P2P trading, can also have negative effects of system dynamics. In many studies, the operation of LECs is often considered as either fully independent from the grid or limited to the distribution level. Such assumptions are reasonable when the share of LECs is relatively small and does not impose a burden on grid operators. However, to actually contribute to the decarbonization of energy generation, LECs must operate at scale rather than as isolated entities, and as the number and capacity of LECs increase, their energy transactions can give rise to a very large number of operations, characterized by small amounts of energy trades occurring in a relatively small time scale. It remains to establish if and in which way these trades impact on power system dynamic performance, in particular on the frequency of the transmission system, and what countermeasures can be used to mitigate the impact. To address this research question, extensive simulations areconducted and illustrated, analysing frequency and voltage fluctuations in the transmission system under the operation of P2P markets with different characteristics. We show that high volumes of trades may actually threat the stability of the power grid, and that smart market price strategies may be used to mitigate instability issues.

1.1 Literature Review

In recent years, there has been an increasing interest in the identification of new forms of energy transactions that are able to facilitate the integration of the many small and micro distributed energy resources available at the distribution system level [1–4]. These include microgrids (MGs), virtual power plants (VPPs), and local energy communities (LECs), and from now on we shall refer to them as energy clusters (ECs), intending clusters of energy consumers/producers equipped with a local energy market for P2P energy trades. Among the mainmilano advantages of decentralized energy production and distribution are the reduction of energy costs for energy consumers and increase of profit for energy producers due to decreasing operational and transport costs, increasing flexibility due to the higher involvement of consumers into the energy market and reduction of the burden of the main grid due to local balancing of demand and supply.

There is the need to properly operate available resources through fair and efficient energy sharing and trading. Given the small capacity of these resources, typical energy trading approaches consists in common investment in generation capacities, where the energy is distributed according to the agreements [5], and peer-to-peer (P2P) markets, where some of the community members own generation capacities and sell the excess energy to the community members [6, 7]. Moreover, as they may not always be self-sufficient and able to work in island mode, ECs require access to the main grid to support security of supply and to compensate possible imbalances, or to directly buy energy when its price on the local market is too high [8].

Fully unsupervised and not coordinated energy trades inside EC may prevent the operation of the network within its technical limits. As local energy markets are located at the level of distribution grids, local transactions, for example, during P2P trading, must be approved or adjusted by distribution system operator (DSOs), to take into account the technical constraints of the distribution grid [1]. There are several ways to include physical network constraints in EC models. Often additional fees are included, e.g., using distribution locational marginal prices to compensate network usage charges [9], applying an electrical distance approach to allocate grid costs [10], or using power transfer distribution factors [11].

Another common approach considers two stages: first energy is dispatched without considering network constraints; then, energy is adjusted if the exchanges are not feasible [12]. For example, in [13] the P2P market includes an iterative approach to equalize the buying and selling energy in the market. At the upper level, the DSO is in charge of minimizing power losses considering security constraints and multi-time period network reconfiguration. However, the coordination of the increasing number of distributed resources only at the distribution level may not be sufficient to limit the impact on the power system as a whole [14].

In [15], the authors review existing challenges for large-scale implementation of a local energy market from the point of view of shareholders, including DSOs and transmission system operators (TSOs). In the same vein, the effect of local energy markets on the French and German TSOs is presented in [8].

The critical level of integration of "greedy" MGs, that maximize their welfare is assessed in [16]. In [17], the authors propose a price-signal based method to mitigate the negative impact of MGs on the system frequency.

Only recently, the relation between local energy trading and transmission grid has become a topic of interest, due to the increasing number of small scale producers. In particular, an extensive literature review of [18] from 2021 concludes there are no studies on the impact of local energy markets on transmission network operation. Among the recent studies that highlight the importance of DSO-TSO coordination is [19], where it is argued that even if the DSO typically provides local flexibility services, overall grid security is still the responsibility of TSO. As distributed energy resources proliferate, close coordination between DSOs and the TSO is essential to ensure system stability. With this aim, reference [19] proposed a frequency-regulation framework that combines the TSO-level AGC system with a DSO-managed peer-to-peer energy-trading model at the distribution level.

In [20] a general framework for DSO/TSO the coordination is presented. The authors propose a clearing procedure for the local energy market based on the nodal distribution locational marginal price and suggest that the prices for the transmission network in the wholesale market should be provided to the DSO and incorporated in the computation of distribution locational marginal prices. This scheme, however, is only presented as a concept, while the main focus of the study is on the distribution grid level. In [21], the authors proposed a model of a TSO-P2P market coordination to meet frequency constraints and also TSO-DSO-P2P market coordination to address congestion, voltage, and frequency concerns. Their findings suggest that while P2P markets can support TSO frequency requirements, they also lead to increased network losses. Moreover, coordinated TSO-DSO services demand additional flexibility from renewable energy sources and result in lower social welfare compared to baseline scenarios.

In [22] a hierarchical market structure is proposed where MGs are dispatched at the distribution level, and DSOs submit bids for real-time balancing at the transmission level. Due to the variability of MG generation and consumption — driven by Renewable Energy Source (RES) and load fluctuations — DSO bids are backed by conventional generation units operating at the transmission level.

Another hierarchical market design is proposed in [23], where the TSO sends price signals to the P2P market during periods of congestion to incentivize demand reduction. Another framework that formalizes the interaction among energy communities, consisting of several nanogrids, DSO, and TSO, is described in [24]. In this scenario, energy communities provide flexibility services (e.g., load shifting, reserve capacity) through the DSO to the TSO. The authors emphasize that, given the small scale of ECs, a customized flexibility market design is essential.

Although the design of energy markets has been largely investigated in the literature, as per the previous overview, and even if some real-world pilots have been already implemented and tested [25], its wide deployment would also require adaptation of actual system operators' control strategies. From this perspective, there is a general consensus on the need for DSO-TSO coordination. Conversely, there are no studies that quantitatively assess the impact of a large number of small-scale trades at the level of the transmission grid and its dynamic performance. In addition, the introduction of ECs at the transmission grid level — whether through DSOs or directly, as flexibility resources — may continue to present the same challenges that ECs were originally intended to resolve, such as fluctuations in RES and load variability, as well as jeopardizing the expected reduction of reserves based on conventional generation units. It is therefore crucial to assess not only the operational benefits that ECs offer to the TSOs but also the potential drawbacks in case of widespread penetration in the power grid.

1.2 Contributions

The main objective of this manuscript is to quantitatively evaluate the impact of a large-scale integration of ECs, that are based on P2P energy trades, on the transmission system frequency. In particular, the P2P trading scheme suggested in [11] is extended to include also the price of the energy on the main market and embedded within a detailed electro-mechanical model of the power system to analyze the overall behavior. The main contributions of this work are as follows:

- Discuss the effect of the size of P2P markets and the number of transactions per time interval on the dynamic performance (frequency deviations) of the power system. With this aim, we also assess the effect of different levels of prices on the number of transactions of internal (P2P) and external market.
- Evaluate the ability of closed-loop market price strategies to stabilize the frequency of the power system.

1.3 Organization

The manuscript is organized as follows. Section 2 describes the dynamic model of the system as well as the procedures for buyers and sellers in the local P2P trading markets. Section 3 presents a comprehensive case study and discusses the impact of local markets on the overall power systems dynamics, as well as a possible countermeasure to mitigate such an impact. Section 4 draws main conclusions and outlines future work directions.

2 Modelling

2.1 Power System Model

The transmission and distribution systems are modelled through conventional Root Mean Square (RMS) models of transmission lines, generators and loads. This leads to a set of Differential-Algebraic Equations (DAEs), as follows:

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{u}) , \tag{1}$$

$$\boldsymbol{0} = \boldsymbol{g}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{u}) , \tag{2}$$

where $\boldsymbol{f}$ are the differential equations and $\boldsymbol{g}$ are the algebraic equations; $\boldsymbol{x}$ ($\boldsymbol{x} \in R^{n_x}$) are the state variables, $\boldsymbol{y}$ ($\boldsymbol{y} \in R^{n_y}$) are the algebraic variables, and $\boldsymbol{u}$ ($\boldsymbol{u} \in R^{n_u}$) are discrete events. This set of equations includes lumped models of the transmission system and conventional dynamic models of synchronous machines (e.g., 6th order models) and their controllers, such as automatic voltage regulators, turbine governors, and power system stabilizers.

In this work, discrete events, namely the vector of variables $\boldsymbol{u}$, are utilized to model P2P trades, i.e., the pair of powers and prices of each resource connected to the distribution grid that participate to P2P markets. The modelling of this discrete events is given next.

2.2 P2P Energy Trading

The P2P trading process utilised in this paper is based on the model proposed in [11]. For convenience, we briefly recall the main features of this model below. The trading process is organized in two stages: in the first stage, matches between potential buyers and sellers are found based on their offers; and in the second stage, the final price and quantities of transactions are defined.

2.2.1 Matching stage: Initially, peers (buyers j and sellers i) submit their offers $O_j = (p_j, \lambda_j)$ and $O_i = (p_i, \lambda_i)$, which include bundles of amount of energy p_j and p_i they would like to buy/sell respectively, and price λ_j and λ_i they would like to pay/receive for that amount.

It is assumed that buyers/sellers maximize their economic surpluses individually, so that the marginal price for a specific power quantity is:

$$\lambda_{ij} = \alpha_i p_{ji} + \beta_i(1 + g_i)\,, \tag{3}$$

$$\lambda_{ji} = -\alpha_j p_{ij} + \beta_j(1 - g_j)\,, \tag{4}$$

where λ_{ij} is the minimum price that the seller i is willing to accept for selling the amount of energy p_{ij}; likewise, λ_{ji} is the maximum price that the buyer j is willing to pay for buying the amount of energy p_{ji}.

Finally, α and β are parameters to describe the slopeness of the buying/selling functions.

After the submission of the offers, the sellers are sorted in ascending order according to their submitted price, while buyers are sorted in the descending price order. In this case, buyers with the highest price are matched with the sellers with the lowest price.

2.2.2 Negotiation stage: The negotiation procedures for sellers and buyers are summarized in Algorithm 1 and 2 respectively. Sellers and buyers calculate their reservation price (minimum/maximum price at which they agree to sell/buy) for an offered amount of energy:

$$\lambda^k_{ij,r} = \alpha_i p^k_{ji} + \beta_i(1 + g^k_i)\,, \tag{5}$$

$$\lambda^k_{ji,r} = -\alpha_j p^k_{ij} + \beta_j(1 - g^k_j)\,, \tag{6}$$

where k is the index of iteration and $\lambda_{ij,r}$ refers to the price that the seller would ask for selling the amount of energy p_{ji} requested by the buyer, and *vice versa* (Algorithms 1 and 2, line 1).

In case the reservation prices of seller and buyer are close enough ($|\lambda^k_{ij,r} - \lambda^k_{ji,r}|/\lambda^k_{ij,r} < \epsilon_\lambda$, where ϵ_λ is a small value), the prices and offers are updated in the following way:

$$\begin{cases} p^{k+1}_{ij} = \max(\underline{p}_i, p^k_{ji}) \\ \lambda^{k+1}_{ij} = \alpha_i p^{k+1}_{ij} + \beta_i(1 + g^k_i)\,, \end{cases} \tag{7}$$

$$\begin{cases} p^{k+1}_{ji} = \min(\bar{p}_j, p^k_{ij}) \\ \lambda^{k+1}_{ji} = -\alpha_j p^{k+1}_{ji} + \beta_j(1 - g^k_j)\,, \end{cases} \tag{8}$$

where $\underline{p}_i$ is the minimum quantity of energy the seller is willing to sell and $\bar{p}_j$ is the maximum energy the buyer would accept to buy (Algorithms 1 and 2, line 6).

If there is a significant difference between the offered price of the buyer and the demanded price of the seller, then the bidden quantities are compared instead. If they are close enough ($|p^k_{ij} - p^k_{ji}|/p^k_{ij} < \epsilon_p$, where ϵ_p is a small value), and $\lambda^k_{ji} > \lambda^k_{ij}$, the offer is accepted and purchase prices are set in the following way (Algorithms 1 and 2, line 10):

$$\frac{\lambda^{k+1}_{ij} + \lambda^{k+1}_{ji}}{2}\,. \tag{9}$$

Alternatively, the prices are updated as follows (Algorithms 1 and 2, line 12):

$$\lambda^{k+1}_{ij} = \max(\lambda^k_{ij,r}, \lambda^k_{ij} - \mu_{\lambda,i})\,, \tag{10}$$

$$\lambda^{k+1}_{ji} = \min(\lambda^k_{ji,r}, \lambda^k_{ji} - \mu_{\lambda,j})\,, \tag{11}$$

where μ_λ is a small positive constant to adjust the price of sellers/buyers.

In case there is no agreement, sellers and buyers need to reduce their "greediness" level and recalculate the bids, considering an updated greediness parameter:

$$g^{k+1}_i = \max(0, g^k_i - \mu_{g,i})\,, \tag{12}$$

$$g^{k+1}_j = \max(0, g^k_j - \mu_{g,j})\,, \tag{13}$$

where μ_g is a small positive constant to decrease greediness of sellers/buyers (Algorithms 1 and 2, line 16).

$$\begin{cases} p^{k+1}_{ij} = \max(\underline{p}_i, p^k_{ij} - \mu_{p,i}(p^k_{ij} - p^k_{ji})) \\ \lambda^{k+1}_{ij} = \alpha_i p^{k+1}_{ij} + \beta_i(1 + g^{k+1}_i)\,, \end{cases} \tag{14}$$

$$\begin{cases} p^{k+1}_{ji} = \min(\bar{p}_j, p^k_{ji} + \mu_{p,j}(p^k_{ji} - p^k_{ij})) \\ \lambda^{k+1}_{ji} = -\alpha_j p^{k+1}_{ji} + \beta_j(1 - g^{k+1}_j)\,. \end{cases} \tag{15}$$

The algorithm assumes that in case of inability to reach an agreement with a seller (after a certain amount of iterations), then the consumer purchases energy directly from the main grid.

2.3 Market Model

The proposed market model takes into account the possibility that distributed energy resources may find more convenient to buy energy from the main market rather than from the peers participating in the local P2P market, inside their EC. To achieve this results, we modify the procedure described in [11] by including an additional parameter, namely g^{lim}_j , that we denote as the "greediness threshold".

Buyers reduce their greediness until a certain threshold, below which they check the electricity price on the main market. If buyers' offered price is lower then the price on the market, they continue the negotiation with trading peers. If buyers finally buy the required energy from the main market, the P2P negotiation is assumed to have failed, so both seller (Algorithm 1, line 18) and buyer (Algorithm 2, line 19) quit negotiations.

In case of P2P negotiation failure, a small share of consumers will still prefer to buy energy in the P2P market, even if the prices are higher than on the market, as they would reach an agreement before checking the market price. However, a quota of consumers will eventually buy energy from the main market rather than from the P2P one. The price of energy is the key decision factor.

The complete procedure of the proposed market model with inclusion of local P2P trading markets is presented in Algorithms 1 and 2 for sellers and buyers, respectively.

3 Evaluation of Dynamic System Performance

We consider a case study that is based on a modified version of the IEEE 39-bus test system [26]. In the original test system there are 19 buses that contain constant loads, and here we assume that each of these buses includes an energy cluster, which is formed by a number of sellers and buyers, that varies in different simulations as we describe below. We model P2P energy exchange mismatches as power imbalances that need to be compensated at the transmission system level by the other generators connected to the grid. These imbalances are caused by the additional requirements of P2P clusters - we assume that each peer has a minimum and maximum amount of extra load they require, and based on the price of the local P2P market, the actual load may be nearer the upper bound (if P2P prices are low) or near the lower bound (if P2P prices are high). All simulations are carried out using the power system simulator Dome [27]. Full details of the power system modeling are not provided here for simplicity, but they can be found, for example, in [28].

The parameters for the buyers/sellers functions and minimum and maximum values of demanded/generated energy are chosen randomly in the ranges summarized in Table 1. The base case scenario includes 50 sellers and 50 buyers connected to each load bus, and assumes that their demand energy is updated every 10 minutes. With this setup, the resulting average price on the internal market is equal to 7.1 cents/kWh, the average demand per EC is 2.31 MW and the

Algorithm 1 Negotiation algorithm for seller $i \in N_s$

Initialization: $k \leftarrow 1, p_{ij}^k \leftarrow \bar{p}_i, \lambda_{ij}^k \leftarrow \alpha_i p_{ij}^k + \beta_i(1+g_i^k)$
while $|O_{ij}^{k+1} - O_{ij}^k| < \epsilon$ **or** $k \leq K$ **do**
  Receive O_{ji}^k from the buyer
  Calculate $\lambda_{ij,r}^k$ using (5)
  if $|\lambda_{ij,r}^k - \lambda_{ji,r}^k|/\lambda_{ij,r}^k < \epsilon_\lambda$ **then**
    Update p_{ij}^{k+1} and λ_{ij}^{k+1} using (7)
  else
    if $|p_{ij}^k - p_{ji}^k|/p_{ij}^k < \epsilon_p$ **then**
      if $\lambda_{ji}^k \geq \lambda_{ij}^k$ **then**
        Update λ_{ij}^{k+1} using (9)
      else
        Update λ_{ij}^{k+1} using (10)
      end if
      Set $p_{ij}^{k+1} \leftarrow p_{ji}^k$ and $g_i^{k+1} \leftarrow g_i^k$
    end if
    Update g_i^{k+1}, p_{ij}^{k+1}, and λ_{ij}^{k+1} using (12) and (14)
    if $g_j < g_j^{lim}$ and $\lambda_{market} \leq \lambda_{ij}$ **then**
      Break
    end if
  end if
  Set $k+1 \leftarrow k$
  Send O_{ij}^{k+1} to the buyer
end while

Algorithm 2 Negotiation algorithm for buyer $i \in N_b$

Initialization: $k \leftarrow 1, p_{ji}^k \leftarrow \bar{p}_j, \lambda_{ji}^k \leftarrow -\alpha_j p_{ji}^k + \beta_j(1 - g_j^k)$
while $|O_{ji}^{k+1} - O_{ji}^k| < \epsilon$ **or** $k \leq K$ **do**
  Receive O_{ij}^k from the buyer
  Calculate $\lambda_{ji,r}^k$ using (6)
  if $|\lambda_{ij,r}^k - \lambda_{ji,r}^k|/\lambda_{ij,r}^k < \epsilon_\lambda$ **then**
    Update p_{ji}^{k+1} and λ_{ji}^{k+1} using (8)
  else
    if $|p_{ij}^k - p_{ji}^k|/p_{ij}^k < \epsilon_p$ **then**
      if $\lambda_{ij}^k \leq \lambda_{ji}^k$ **then**
        Update λ_{ji}^{k+1} using (9)
      else
        Update λ_{ji}^{k+1} using (11)
      end if
      Set $p_{ji}^{k+1} \leftarrow p_{ij}^k$ and $g_j^{k+1} \leftarrow g_j^k$
    end if
    Update g_j^{k+1}, p_{ji}^{k+1}, and λ_{ji}^{k+1} using (13) and (15)
    if $g_j < g_j^{lim}$ **then**
      if $\lambda_{market} \leq \lambda_{ij}$ **then**
        Break
      end if
    end if
  end if
  Set $k+1 \leftarrow k$
  Send O_{ji}^{k+1} to the buyer
end while

standard deviation of $\omega_{\rm coi}$, that is, the frequency of the center of inertia of the system, is equal to 1.1×10^{-4} pu Hz.

In the remainder of the section, we change the base case study to assess the impact on the power exchanged among peers and on the system frequency of the market price (Section 3.1); size and number of P2P transactions (Sections 3.2 and 3.3); and market price strategy (Section 3.4).

Table 1 Parameters of Sellers and Buyers

	Sellers	Buyers
α	$[0.09, 0.5]$	$[0.5, 0.8]$
β	$[4, 6]$	$[9, 18]$
$p_{\rm min}$	0	$[1, 5]$
$p_{\rm max}$	$[1, 10]$	$[1.5\, p_{\rm min}, 2\, p_{\rm min}]$

3.1 *Effect of market price*

Figure 1 shows the standard deviation of $\omega_{\rm coi}$, where the market price is "manually" set to low, average, and high values. By low, average and high value of the market price, we mean a price that is consistently lower, similar, or higher, respectively, than the price inside the energy communities.

Figure 1 shows that the market price does have an impact on the system frequency. In particular, the lower the price, the higher the fluctuations (Fig. 1.a) in the frequency. This is explained by the fact that, when it is more economically profitable, buyers may be attracted to buy energy from the grid rather than from their peers within the P2P market, giving rise to problems at the level of the transmission grid. Conversely, medium/high market price, may significantly reduce fluctuations of the frequency, because fewer energy transactions occur at the level of the transmission grid, while they occur at the local level of the more convenient P2P market, as shown in Figs. 1.b and 1.c.

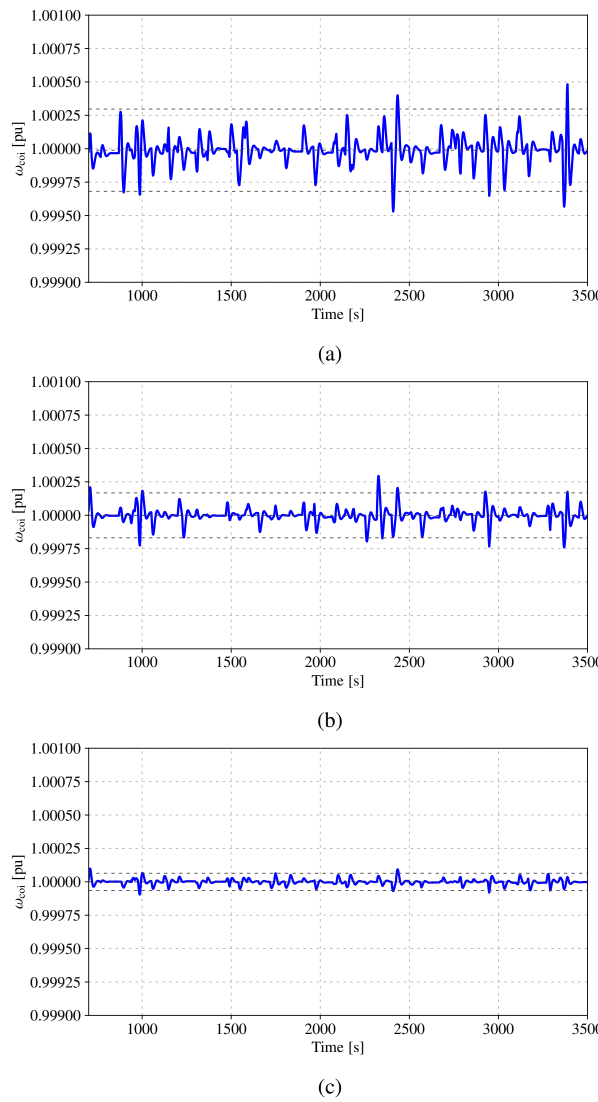

Fig. 1: Variation of $\omega_{\rm coi}$ with (a) low market price (b) medium market price (c) high market price.

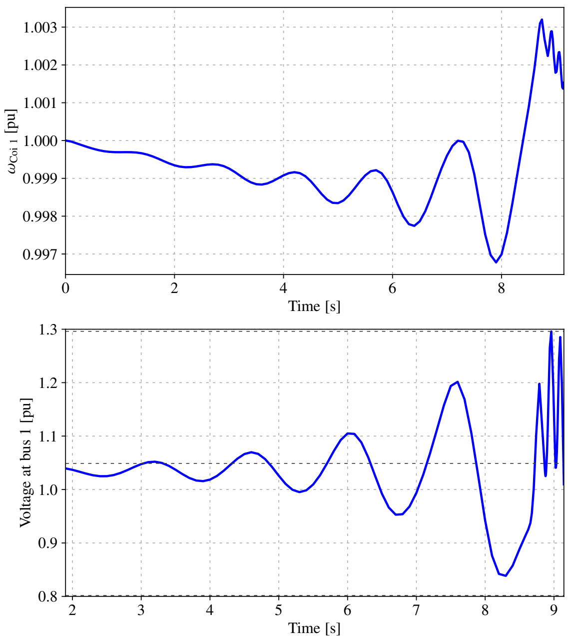

Fig. 2: Frequency (upper panel) and voltage (lower panel) fluctuation with high number of P2P transactions.

3.2 Effect of size and capacity of P2P transactions

In this section, we evaluate the impact of the size of the EC on the frequency of the transmission system. As the number of peers participating in the trading inside EC increases, then the amount of exchanged energy increases as well, and so does the number of failed negotiations. Accordingly, more energy needs to be compensated with energy bought on the common market, and this may cause an additional burden on the transmission system. To illustrate this effect, we gradually increase the number of P2P market players, for each market price level, and we compute the resulting standard deviation of ω_{coi} for each case. We assume that the number of buyers and sellers is the same, so that all the local demand may be covered by local generation. However, if the negotiations between peers are not successful, buyers refer to the main market to fulfil their residual energy demand. For energy producers, the lower generation threshold is set to zero, meaning that they can decide not to sell any energy, if they want so. In practice, this may occur if (i) producers own fully dispatchable generators and decide the quantity of generated energy; or (ii) if producers own storage systems and store the excess energy instead of selling it.

The outcome of this scenario is shown in Fig. 3, where the continuous, dashed and dot-dashed lines correspond to low, average and high market prices, respectively. In the first case, consumers prefer to buy energy from the market, rather than from local sellers. This leads to increase load consumption, and consequently, to increase the standard deviation of ω_{coi} — it raises from 0.3×10^{-4} pu Hz to 1.5×10^{-4} pu Hz, with the increase of peers from 5 to 120. Note also that a higher number of connected P2P players may give rise to instability issues in the power grid (see Fig. 2). On the other hand, if the market price is at an intermediate level, more buyers may choose local sellers.

Finally, if the energy price on the external market is high, very few, if any at all, buyers choose to buy energy from the main market. In these cases, independently from the number of buyers/sellers, the frequency of the system does not vary significantly (standard deviation is stable around 0.2×10^{-4} pu Hz), as the majority of energy trades occurs at the level of energy communities, that are not noticeable at the level of the transmission grid.

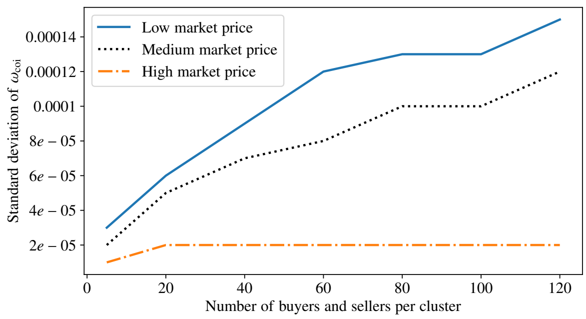

Fig. 3: Standard deviation of ω_{coi}, depending on the number of P2P market players.

3.3 Effect of number of operations of P2P transactions per time interval

The number of transactions per time interval also has an effect on the stability of the system frequency. Figures 4 and 5 show the total load demand from the P2P market and frequency fluctuations of the center of inertia (ω_{coi}), in the case of a small and large number of transactions, respectively. As expected, frequency fluctuations increase when there are more requests in the P2P market. The standard deviation of ω_{coi} for different levels of transactions and different market prices is shown in Fig. 6. Fewer transactions cause a smaller deviation in system frequency, and, as before, a higher market price further reduces the standard deviation of ω_{coi}.

3.4 Effect of market price strategy: countermeasure to mitigate impact

While higher prices on the electricity market may limit the fluctuation of the system frequency, it may be unfair towards other buyers not participating in P2P markets to always keep high prices. Moreover, TSOs may also become interested in operating in energy markets. In fact, transmission systems are generally controlled by national regulatory authorities, which also fix their prices and rates. Moreover, a common practice of regulatory authorities is to fix also price and revenue caps, although, new recently proposed policies can change this [29]. New policies do not only consider financial aspects, but a broader range of parameters, that may include, for example, environmental impact, customer satisfaction, social obligations, etc. In these cases, TSOs should also consider the “opinion” of P2P markets. Unreasonably high prices, only for P2P markets, when they are not justified by the stability of the system, may raise concerns. Conversely, a more reasonable alternative is to increase the price only when the demand of P2P market causes significant negative effect on the stability of the transmission grid.

This solution is schematically depicted in Fig. 8: the P2P market gives rise to a number of mismatched trades that need to be compensated by the TSO. When the energy trades with the TSO become significant, either in number or in size, the standard deviation of ω_{coi} increases, to signal a degradation in the dynamic performance of the TSO. Accordingly, market price λ_{market} is increased to dissuade people from buying from the grid. The number of trades with the TSO then decreases as they are not as economically convenient as before, and safer values of ω_{coi} are recovered, thus prompting a price decrease. For instance, we assume now that the price switches between a low and a higher level (upper panel of Fig. 8), and this helps achieving a reduction in the standard deviation of the frequency from 1.1×10^{-4} pu Hz to 0.6×10^{-4} pu Hz (lower panel of Fig. 8).

4 Conclusion

The paper proposes a market model that takes into account local P2P trading markets and evaluates the effects of these local trades on the dynamic performance of the system, in particular, on the frequency

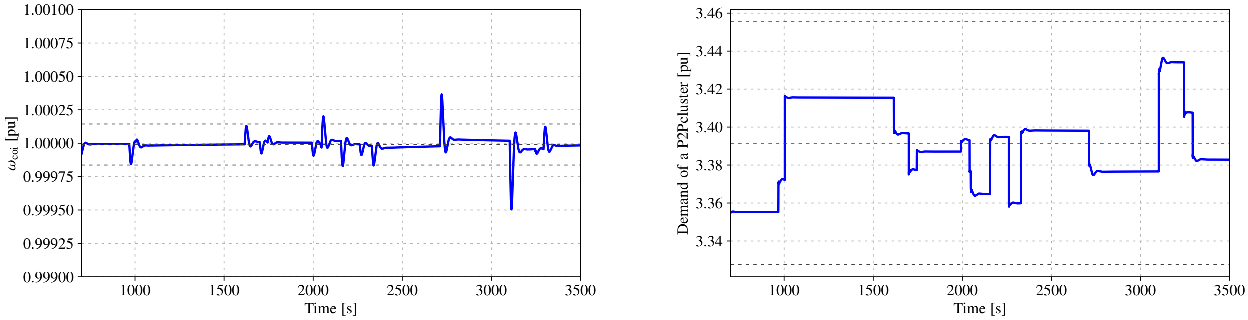

Fig. 4: Variation of system frequency (left panel) and demand (right panel) for a small number of transactions per time.

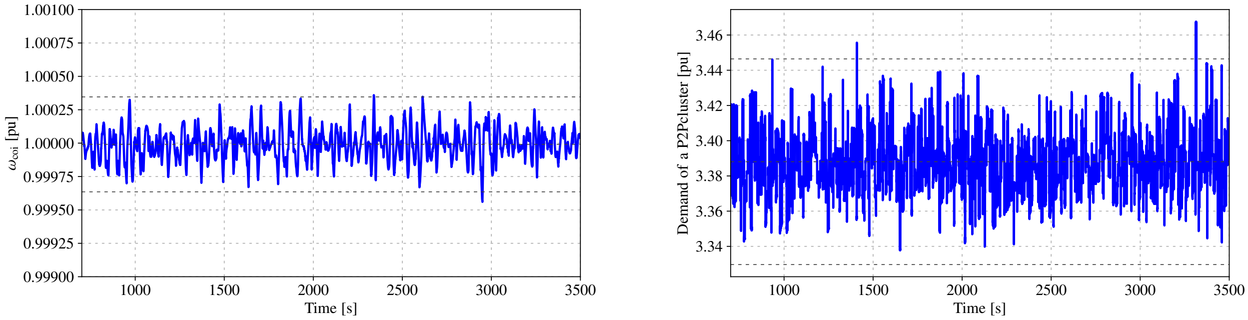

Fig. 5: Variation of system frequency (left panel) and demand (right panel) for a large number of transactions per time.

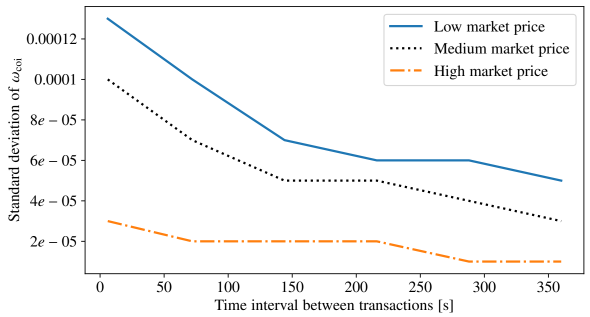

Fig. 6: Standard deviation of ω_{coi} for different levels of P2P transactions.

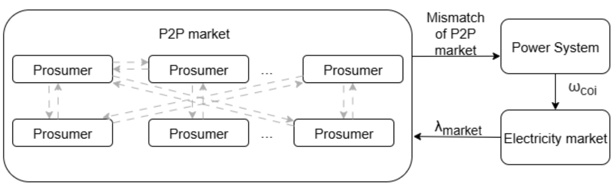

Fig. 7: Link between P2P negotiation and market price

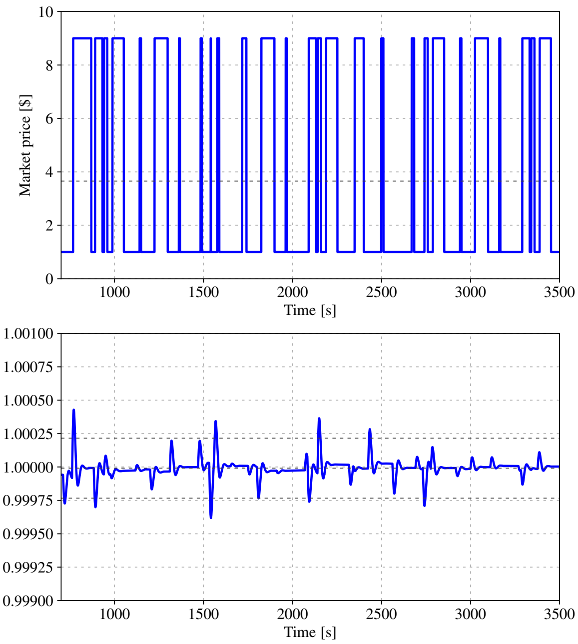

Fig. 8: Price on the market is changing depending on the frequency deviation. Upper panel: market price; lower panel: ω_{coi}.

stability of transmission grid. Results obtained based on extensive simulations show that the market price of energy plays a pivotal role, as it is able to hide, or to resurface, the energy exchanges occurring inside EC. Accordingly, this gives the TSO some extra flexibility because the market price may be used in feedback loop to automatically regulate the system frequency.

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Author Contributions

Ekaterina Dudkina: conceptualization, methodology, software, validation, visualization, writing - original draft, writing - review and editing. Emanuele Crisostomi: conceptualization, methodology, software, supervision, validation, visualization, writing - original draft, writing - review and editing. Federico Milano – conceptualization, methodology, software, supervision, validation, visualization, writing - original draft, writing - review and editing.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data available on request from the authors.

5 References

1 I. Azim, W. Tushar, T. K. Saha, C. Yuen, and D. Smith, “Peer-to-peer kilowatt and negawatt trading: A review of challenges and recent advances in distribution networks,” *Renewable and Sustainable Energy Reviews*, vol. 169, p. 112908, 2022.

2 E. Dudkina, E. Crisostomi, and D. Poli, “A review of P2P energy markets and a possible application for remote areas,” *IEEE ISGT Europe*, pp. 869–873, 2020.

3 T. Sousa, T. Soares, P. Pinson, F. Moret, T. Baroche, and E. Sorin, “Peer-to-peer and community-based markets: A comprehensive review,” *Renewable and Sustainable Energy Reviews*, vol. 104, pp. 367–378, 2019.

4 H. Ruan, H. Gao, H. B. Gooi, and J. Liu, “Active distribution network operation management integrated with P2P trading,” *Applied Energy*, vol. 323, p. 119632, 2022.

5 V. Z. Gjorgievski, S. Cundeva, and G. E. Georghiou, “Social arrangements, technical designs and impacts of energy communities: A review,” *Renewable Energy*, vol. 169, pp. 1138–1156, 2021.

6 E. Dudkina, D. Fioriti, E. Crisostomi, and D. Poli, “On the impact of different electricity markets on the operation of a network of microgrids in remote areas,” *Electric Power System Research*, vol. 212, 2022.

7 C. Park and T. Yong, “Comparative review and discussion on P2P electricity trading,” *Energy Procedia*, vol. 128, pp. 3–9, 2017.

8 C. Schmitt, K. Schumann, K. Kollenda, A. Blank, O. Rebenaque, T. Dronne, A. Martin, P. Vassilopoulos, F. Roques, and A. Moser, “How will local energy markets influence the pan-european day-ahead market and transmission systems? A case study for local markets in France and Germany,” *Applied Energy*, vol. 325, 2022, 119913.

9 J. Kim and Y. Dvorkin, “A P2P-dominant distribution system architecture,” *IEEE Transactions on Power Systems*, vol. 35, no. 4, pp. 2716–2725, 2019.

10 A. Paudel, L. P. M. I. Sampath, J. Yang, and H. B. Gooi, “Peer-to-peer energy trading in smart grid considering power losses and network fees,” *IEEE Transactions on Smart Grid*, vol. 11, no. 6, pp. 4727–4737, 2020.

11 M. Khorasany, A. Paudel, R. Razzaghi, and P. Siano, “A new method for peer matching and negotiation of prosumers in peer-to-peer energy markets,” *IEEE Transactions on Smart Grid*, vol. 12, no. 3, pp. 2472–2483, 2020.

12 Y. Liu, L. Wu, and J. Li, “A two-stage peer-to-peer energy trading model for distribution systems with participation of utility,” *CSEE Journal of Power and Energy Systems*, vol. 7, no. 5, pp. 893–902, 2021.

13 C. Mu, T. Ding, Y. Huang, S. Zhu, P. Siano, M. Shahidehpour, and X. Shen, “Distributed collaboration method for peer-to-peer transactions in reconfigurable distribution network,” *IEEE Transactions on Power Systems*, vol. 40, no. 4, pp. 3029–3042, 2025.

14 F. F. González, E. Sauma, and A. H. van der Weijde, “Community energy projects in the context of generation and transmission expansion planning,” *Energy Economics*, vol. 108, p. 105859, 2022.

15 S. C. Doumen, P. Nguyen, and K. Kok, “Challenges for large-scale local electricity market implementation reviewed from the stakeholder perspective,” *Renewable and Sustainable Energy Reviews*, vol. 165, p. 112569, 2022.

16 P. Ferraro, E. Crisostomi, M. Raugi, and F. Milano, “Analysis of the impact of microgrid penetration on power system dynamics,” *IEEE Transactions on Power Systems*, vol. 32, no. 5, pp. 4101–4109, 2016.

17 P. Ferraro, E. Crisostomi, R. Shorten, and F. Milano, “Stochastic frequency control of grid-connected microgrids,” *IEEE Transactions on Power Systems*, vol. 33, no. 5, pp. 5704–5713, 2018.

18 V. Dudjak, D. Neves, T. Alskaif, S. Khadem, A. Pena-Bello, P. Saggese, B. Bowler, M. Andoni, M. Bertolini, Y. Zhou *et al.*, “Impact of local energy markets integration in power systems layer: A comprehensive review,” *Applied Energy*, vol. 301, p. 117434, 2021.

19 L. Debbarma, S. Debbarma, K. Roy, S. D. Roy, and P. Singh, “Enhancing grid frequency support by integrating RTEM and P2P energy trading models in coordination with AGC system,” *IEEE Transactions on Industry Applications*, vol. 61, no. 4, pp. 5612–5625, 2025.

20 A. Papalexopoulos, R. Frowd, and A. Birbas, “On the development of organized nodal local energy markets and a framework for the TSO-DSO coordination,” *Electric Power Systems Research*, vol. 189, p. 106810, 2020.

21 J. Marques, T. Soares, and H. Morais, “P2P flexibility markets models to support the coordination between the transmission system operators and distribution system operators,” *Sustainable Energy, Grids and Networks*, vol. 34, p. 101055, 2023.

22 Y. Du and F. Li, “A hierarchical real-time balancing market considering multi-microgrids with distributed sustainable resources,” *IEEE Transactions on Sustainable Energy*, vol. 11, no. 1, pp. 72–83, 2018.

23 J. Li, S. Ge, H. Liu, Q. Yu, S. Zhang, C. Wang, and C. Gu, “An electricity and carbon trading mechanism integrated with TSO-DSO-prosumer coordination,” *Applied Energy*, vol. 356, p. 122328, 2024.

24 L. Mendicino, D. Menniti, A. Pinnarelli, N. Sorrentino, P. Vizza, C. Alberti, and F. Dura, “DSO flexibility market framework for renewable energy community of nanogrids,” *Energies*, vol. 14, no. 12, p. 3460, 2021.

25 C. L. Gunarathna, R. J. Yang, S. Jayasuriya, and K. Wang, “Reviewing global peer-to-peer distributed renewable energy trading projects,” *Energy Research & Social Science*, vol. 89, p. 102655, 2022.

26 T. Athay, R. Podmore, and S. Virmani, “A practical method for the direct analysis of transient stability,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-98, no. 2, pp. 573–584, 1979.

27 F. Milano, “A Python-based software tool for power system analysis,” in *IEEE PES General Meeting*. IEEE, 2013, pp. 1–5.

28 F. Milano, *Power system modelling and scripting*. Heidelberg: Springer, 2010.

29 TenneT, “Smarter incentives for transmission system operators,” 2018, available at www.oxera.com.