Grid-Impact Aware P2P Trading and Implications on Flexibility Markets

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***Abstract*—This paper investigates the impact of peer-to-peer (P2P) markets on the safe operation of local distribution grids, and proposes control instruments, which can be applied by distribution system operators (DSO) to ensure grid safety while enabling P2P trading. The grid impact is captured through quantified modifications to the network states, and thus the DSO's flexibility needs, that can result from P2P trades. In this regard, a P2P market formulation modeled as a generalized Nash equilibrium problem is adopted, in addition to a local flexibility market (LFM) formulation, through which the DSO can procure flexibility for congestion management. Two DSO control instruments are then proposed: (i) a preventive blocking method, through which the DSO can block (ex-ante) the possibility of trades if they are deemed to harm the grid, and (ii) an incentive scheme, through which the DSO provides incentives to encourage the realization of P2P trades that are deemed helpful to the grid. A structured comparison of these methods, as compared to free P2P trading (i.e., without DSO intervention) is then conducted. The results showcase the varying impacts that P2P trades can have on the grid, being at instances helpful (resolving congestions) and at others harmful (exacerbating congestions). The results showcase that the proposed preventive blocking method, outperforms the alternatives for ensuring grid-safety while abiding by regulatory and practical requirements.**

***Index Terms*—Peer-to-peer markets, flexibility markets, congestion management, distribution systems.**

I. INTRODUCTION

The growing uptake of distributed energy sources (DERs), digitization of the end-user space, and the electrification of the end-users' energy domain have opened up the space for new forms of decentralized energy trading. Indeed, peer-to-peer (P2P) trading, a mechanism through which end-users (peers) – which can be prosumers due to their ability to consume, produce, and possibly store energy – exchange energy with one another (typically in a local geographic or grid setting), is increasing gaining focus [1], [2]. Such P2P trading mechanisms enable users to (i) source energy from peers when in shortage (as compared to only from their electricity supplier/retailer as had been the standard case), and (ii) sell their surplus to other peers. This, as a result, supports driving the costs of consumption for prosumers and maximizing potential revenues that can be generated from their locally-produced energy, and thus further drive the uptake of DERs.

Even though P2P trading can be a financial mechanism between peers, it nonetheless entails physical power injections and withdrawals from the grid, and hence would directly impact the state of operation of the distribution system in which these P2P activities take place. The work in [3] provides a short overview of the P2P impacts on the distribution grid operation. Indeed, when in stressed conditions, P2P trading can impact the congestion levels in the system and possibly risk the safe operation of the grid. As a result, different works in the literature have explored mechanisms to take grid constraints into account – either fully or through control inputs – to potentially limit the negative impacts of the P2P trading on the grid. The works in [4], [5] have explored methods for restricting/blocking P2P trades that are deemed to endanger the safe grid operation. On the other hand, the authors in [6], [7] propose including network charges in the P2P formulation, to account for the grid use. The works in [8]–[12] have, on the other hand, proposed including distribution grid constraints explicitly in the P2P market clearing, or including the distribution system operator (DSO) as a player in the game-theoretic P2P market setting, whose sole goal is to ensure the grid safety of the P2P market outcomes.

Different methods vary (i) in their effectiveness (in terms of the level of guaranteeing grid-safety and how this indicator is to be measured), (ii) in their efficiency (in terms of the impact on the efficiency of the P2P market as well as the costs induced to the system for corrective actions to be taken to account for P2P energy exchanges), and (iii) importantly, in their practical implementation potential. The latter particularly concerns the complexity of the proposed grid-aware schemes, which can be prohibitive in practical settings, in addition to the feasibility of the proposed method in light of the regulated role of the DSO and the regulatory setting of P2P markets and local flexibility procurement mechanisms [13].

In this paper, we explore the *impact of P2P trading on the distribution grid operation*, under different operating conditions. The P2P grid impact is measured by the consequences it induces on the flexibility needs of the DSO, which are procured through a local flexibility market (LFM) [14], [15]. We adopt a P2P trading problem [16], formulated as a generalized Nash equilibrium game and solved as a variational equilibrium. In addition, we introduce an LFM problem, which considers in the formulation the impacts of P2P trading, and thus aims to allow the DSO to manage previously available congestions as well as any changes to such congestions (positive or negative) that can be introduced

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by the P2P market trading.

Through a free P2P market (considered as Model Case 1), we showcase that, when left-unchecked, the impact of the P2P trading on the grid can be wide-ranging, from instances in which the P2P trading can unintentionally resolve grid congestions (thus, avoiding the need for additional flexibility procurement by the DSO) to instances in which the P2P trading exacerbates congestions, thus significantly increasing the flexibility needs of the DSO and, thus, the associated costs. We also derive closed-form expressions to quantify the impacts of the P2P trading on the state of the grid, allowing us to introduce two practical, easy-to-implement DSO control instruments, through which the DSO can provide inputs to the P2P market process to steer or bound the P2P market outcomes towards a grid-safe solution. The first proposed instrument (refereed to as Model Case 2), is a *Preventive Blocking* mechanism in which the DSO exercises the right to block, ex-ante, possible P2P trades, if those trades are foreseen to harm the safe operation of the grid. The second proposed instrument (referred to as model Case 3) is a *Corrective Incentive Mechanism* in which the DSO provides subsidies to incentivize P2P trades that are deemed helpful to the grid and discourage/penalize harmful P2P trades.

Using a developed case study (based on the Matpower 69-bus distribution system [17]), we compare the performances of these model cases, against a benchmark in which no P2P trading takes place (Model Case 0). The comparison is based on a set of computed indices including the level of grid safety, impact on congestions within the grid, impact on flexibility needs and its procurement costs, and the level of limitations imposed on the volume of energy traded in the P2P market. Our results showcase that control inputs are largely required by the DSO to ensure grid-safe operation, especially in grid-stressed conditions. In addition, the preventive blocking method provides a well-suited solution as it can deliver grid-safe P2P trading, while providing a simple to implement method that is in line with commonly defined DSO regulatory processes.

II. MARKET MODELS

We consider a distribution system with a set $\mathcal{N}$ of nodes and a set $\mathcal{L}$ of lines, where $|\mathcal{N}| = N$ and $|\mathcal{L}| = L$, represented by a graph $\mathcal{G}(\mathcal{N}, \mathcal{L})$. Over this system, a P2P market and a flexibility market are organized, which are introduced next. The goal of the P2P market is to allow P2P energy exchange (enabling peers to meet their energy needs and valorize their surpluses), while the role of the flexibility market is to allow the DSO to resolve anticipated congestions in the distribution grid, that are due to original load/generation schedules as well as modifications introduced by the P2P trades.

A. P2P Market Model

Consider a set of peers $\mathcal{A}$, where $a_n \in \mathcal{A}$ denotes a peer located at node $n \in \mathcal{N}$. Let $\hat{g}_n$ be the energy self-generated by a_n, e.g., through DER, and g_n be the generation a_n receives from its retailer/supplier. We let h_n denote the total energy demand of a_n. In addition, a_n can engage in P2P trading to meet its consumption needs or to sell its surplus. Let $\mathcal{B}_n \subseteq \mathcal{A} \setminus \{a_n\}$ be the set of agents with whom a_n can trade. We denote by s_{nm} the power purchased by a_n from its peer $a_m \in \mathcal{B}_n$, at a cost ω_{nm}, where $s_{nm} \geq 0$ denotes a_n purchasing s_{nm} from a_m, and $s_{nm} \leq 0$ denotes a_m purchasing $-s_{nm}$ from a_n. We let $\boldsymbol{s}_n$ denote the vector of P2P trades by a_n, and $\bar{s}_{nm}$ be the capacity limit on the s_{nm} P2P trade such that $\bar{s}_{nm} = \bar{s}_{mn}$. We denote the decision vector of a_n by $\boldsymbol{\pi}_n(g_n, h_n, \boldsymbol{s}_n)$, wherein each $a_n \in \mathcal{A}$, given its available self-generated $\hat{g}_n$ aims to choose g_n, h_n, and $\boldsymbol{s}_n$ to maximize its utility. Thus, the P2P market model [16], [18] is a setting in which each agent $a_n \in \mathcal{A}$ aims to solve the following problem.

$$\max_{\boldsymbol{\pi}_n} \; U_n(h_n) - K_n(g_n) - \sum_{m \in \mathcal{B}_n} s_{nm}\omega_{nm} \tag{1a}$$

$$\text{subject to:} \quad \underline{g}_n \leq g_n \leq \bar{g}_n, \tag{1b}$$

$$\underline{h}_n \leq h_n \leq \bar{h}_n, \tag{1c}$$

$$s_{nm} \leq \bar{s}_{nm}, \forall m \in \mathcal{B}_n, \tag{1d}$$

$$h_n = \hat{g}_n + g_n + \sum_{m \in \mathcal{B}_n} s_{nm}, \tag{1e}$$

$$s_{nm} = -s_{mn} \forall m \in \mathcal{B}_n, \;\; (\lambda_{nm}). \tag{1f}$$

The objective function (1a), which we denote by $\Pi_n(\boldsymbol{\pi}_n)$, contains three cost elements. $\sum_{m \in \mathcal{B}_n} s_{nm}\omega_{nm}$ is the cost incurred by a_n for its P2P trades, while $U_n(h_n)$ and $K_n(g_n)$ are, respectively, the utility received from consuming h_n and the cost paid for purchasing g_n from the retailer. $U_n(h_n)$ is typically considered to be strictly concave and defined around a target consumption level denoted by h_n^o, while $K_n(g_n)$ is a quadratic cost function, as detailed in [16] and references therein. As such, in our work, we follow a similar utility and cost expressions as in [16], wherein[1],

$$U_n(h_n) = -\mu_n(h_n - h_n^o)^2 + \nu_n, \tag{2}$$

$$K_n(g_n) = \frac{1}{2}\alpha_n h_n^2 + \beta_n h_n + \gamma_n. \tag{3}$$

As for the constraints, (1b) and (1c) capture the generation purchasing and consumption limits (where $\bar{g}_n$ and $\underline{g}_n$ are the upper and lower limits on purchased generation, and $\bar{h}_n$ and $\underline{h}_n$ are the upper and lower limits on consumption needs), (1d) sets the P2P capacity trading limits with all other peers, and (1e) is the energy balance for a_n. Constraint (1f), with dual variable λ_{nm}, is a P2P trading reciprocity constraint, ensuring that the trades between agents specified in each of the their respective problems match. This creates an interconnection between the feasibility spaces of the problems of all agents, giving rise to what is known as a generalized Nash equilibrium (GNE) problem coupled only by shared constraints. The GNE can be solved as a variational equilibrium (VE) problem, in which the dual variables of the coupling constraints are equal. A VE is then defined as follows.

Definition 1: A VE, $\mathcal{V} := \{\boldsymbol{\pi}^*_{a_n}, \forall a_n \in \mathcal{A}\}$, of the game defined by Problems 1 is a set of solutions that solve Problems 1, $\forall a_n \in \mathcal{A}$, thus being a GNE, while having

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[1] $\mu_n, \nu_n, \alpha_n, \beta_n$, and γ_n are all positive parameters.

$$\lambda_{nm} = \lambda_{mn}, \forall a_n \in \mathcal{A}, \, a_m \in \mathcal{B}_n. \tag{4}$$

As proven in [16, Prop. 6], this VE solution is equivalent to a centralized social economic welfare maximizing solution, which collectively solves all Problems 1 (i.e., for all $a_n \in \mathcal{A}$) in one co-optimized problem (summing up the objective functions of all the individual problems subject to the aggregation of all independent and shared constraints), thus allowing the solution of the P2P market clearing problem centrally [16].

B. Local Flexibility Market Model

The LFM is set up by the DSO to resolve anticipated congestions resulting from expected base generation and load profiles within the system. As the P2P trading will impact these base generation and loads, it would then directly impact (negatively or positively) the state of congestion in the network, and the outcomes and costs of the LFM. We formulate this process next.

We let: p_n denote the net power injection at node $n \in \mathcal{N}$; p_n^o and d_n^o denote, respectively, the base anticipated power injection and load at node $n \in \mathcal{N}$; P_{jk} denote the power flow over line $(j,k) \in \mathcal{L}$, which is upper-bounded by the line capacity denoted by $\bar{P}_{jk}$. We also define $\boldsymbol{X} \in \mathbb{R}^{L \times N}$ to be the injection-flows sensitivity matrix (referring to, e.g., power transfer distribution factors – PTDFs), defined over the sets of lines and nodes of $\mathcal{G}$ where element $((j,k),n)$, i.e., $\chi_{(j,k),n}$, captures the change to line flow P_{jk} due to an increase in net injection at node n (p_n). The vector of base power injections and loads $\boldsymbol{p}^o$ and $\boldsymbol{d}^o$, and modifications thereto due to P2P trades, can lead to anticipated congestions in the grid which can be rectified using flexibility offered by flexibility service providers (FSPs) in an LFM.

In the LFM, let $\mathcal{F}_n^U$ and $\mathcal{F}_n^D$ be the set of FSPs offering, respectively, upwards and downward flexibility at node $n \in \mathcal{N}$, and let the $\mathcal{F}_U \triangleq \bigcup_{n \in \mathcal{N}} \mathcal{F}_n^U$ and $\mathcal{F}^D \triangleq \bigcup_{n \in \mathcal{N}} \mathcal{F}_n^D$, be the union set of upward and downward FSPs. We then denote by $\bar{\delta}_{f,n}^u$ and $\bar{\delta}_{f,n}^d$, respectively, the maximum offered upward or downward flexibility volume by FSP f connected at node $n \in \mathcal{N}$ to the LFM at bid price $c_{f,n}^u$ and $c_{f,n}^d$, respectively. As such, the LFM clearing problem, through which a system operator (SO) can procure flexibility at minimum cost to meet its congestion management needs, can be formulated as:

$$\min_{\boldsymbol{\delta}^u, \boldsymbol{\delta}^d} \sum_{n \in \mathcal{N}} \left(\sum_{f \in \mathcal{F}_n^U} c_{f,n}^u \delta_{f,n}^u - \sum_{f \in \mathcal{F}_n^D} c_{f,n}^d \delta_{f,n}^d \right) \tag{5a}$$

subject to:

$$p_n = p_n^o - d_n^o - \sum_{a_m \in \mathcal{B}_n} s_{nm} + \sum_{f \in \mathcal{F}_n^U} \delta_{f,n}^u - \sum_{f \in \mathcal{F}_n^D} \delta_{f,n}^d, \; \forall n \in \mathcal{N}, \tag{5b}$$

$$P_{jk} = \sum_{n \in \mathcal{N}} p_n \chi_{(j,k),n}, \; \forall \{j,k\} \in \mathcal{L}, \tag{5c}$$

$$\sum_{n \in \mathcal{N}} p_n = 0, \tag{5d}$$

$$-\bar{P}_{jk} \leq P_{jk} \leq \bar{P}_{jk}, \forall (j,k) \in \mathcal{L}, \tag{5e}$$

$$0 \leq \delta_{f,n}^u \leq \bar{\delta}_{f,n}^u, \; \forall f \in \mathcal{F}_n^U, \, \forall n \in \mathcal{N}, \tag{5f}$$

$$0 \leq \delta_{f,n}^d \leq \bar{\delta}_{f,n}^d, \; \forall f \in \mathcal{F}_n^D, \, \forall n \in \mathcal{N}. \tag{5g}$$

Decision variables $\delta_{f,n}^u$, $\forall f \in \mathcal{F}_n^U, n \in \mathcal{N}$, and $\delta_{f,n}^d$, $\forall f \in \mathcal{F}_n^D, n \in \mathcal{N}$, stacked in vectors $\boldsymbol{\delta}^u$ and $\boldsymbol{\delta}^d$, respectively, are the flexibility quantities cleared by the market to meet the grid needs at minimum cost, as captured in (5a). Equation (5b) captures the net nodal injections, as a function of the base injection and offtake quantities and the procured flexibility, as well as the net load from the P2P trades, $\sum\limits_{a_m \in \mathcal{B}_n} s_{nm}$, as $s_{nm} > 0$ is an increased power consumption at n. Constraint (5c) captures the power flow equations, returning the flows over all lines $\mathcal{L}$ resulting from the net injections p_n at all $n \in \mathcal{N}$. Constraint (5d) captures the power balance equation, while (5e) imposes the line flow limits (in the reference and opposite directions), thus ensuring that additional congestions are prevented and existing ones are resolved. Constraints (5f) and (5g) represent the bid quantity limits.

III. P2P TRADING GRID IMPLICATIONS AND DSO CONTROL INSTRUMENTS

As can be seen from the flexibility market formulation in (5), the trades resulting from the P2P market have a direct effect on the net injections at every node (5b), thus impacting the line flows (5c) and, as a result, the congestions and the overall cost to the DSO captured by the LFM cost function (5a). A decrease in the LFM cost captures a setting in which the P2P trades, even though they are done independently by the peers to maximize their own revenues, can unintentionally help the grid by attenuating congestions. On the other hand, an increase in the LFM cost captures the opposite setting in which the P2P trades worsen congestions in the grid (either exacerbating existing ones or creating new ones). As such, through these formulations, we can analyze whether the P2P market serves to harm or help the grid, and propose mechanisms in which helpful trades are incentivized or harmful trades are disincentivized or blocked.

Indeed, for every pair of peers (a_n, a_m), located, respectively, at nodes n and m, the effect ΔP_{ij} of their P2P trade $s_{nm} \geq 0$ on a line $(i,j) \in \mathcal{L}$ is given by:

$$\Delta P_{ij} = s_{nm}(\chi_{(i,j),m} - \chi_{(i,j),n}). \tag{6}$$

Thus, for a line (i,j) and a pair of peers (a_n, a_m), we define $\Delta\chi_{(i,j),(n,m)} = (\chi_{(i,j),m} - \chi_{(i,j),n})$. As such, if $s_{nm} > 0$: (i) $\Delta\chi_{(i,j),(n,m)} > 0$ increases the flow over (i,j) in its reference direction (decreases it in the opposite direction), (ii) $\Delta\chi_{(i,j),(n,m)} < 0$ decreases P_{ij} in its reference direction, and (iii) $\Delta\chi_{(i,j),(n,m)} = 0$ implies that the trading between a_n and a_m has no impact on P_{ij}. Hence, the impact of any pair of trades on the grid can be quantified ex-post without the need to solve the full P2P matching problem in Problem 1. We define the line occupancy ratio τ_{ij} for $(i,j) \in \mathcal{L}$ as the percentage usage of (i,j)'s capacity, as $\tau_{ij} = (|P_{ij}|/\bar{P}_{ij}) \times 100$. We define a line (i,j) to be critical if τ_{ij} exceeds a certain percentage limit $\bar{\tau}_{ij}$.[2] Let $\mathcal{C}^+$ and $\mathcal{C}^-$ be the set of lines that are critical and whose flow is, respectively, in the reference or opposite direction. As such, we can define the set of trades between (a_n, a_m) such that $s_{nm} > 0$ (i.e., a_n buys from a_m) which are either helpful or harmful to lines (i,j) in $\mathcal{C}^+$ (denoted, respectively, by $\mathcal{S}_{n,m}^{\mathcal{C}^+,-}$ and $\mathcal{S}_{n,m}^{\mathcal{C}^+,+}$), or helpful or harmful to lines (i,j) in $\mathcal{C}^-$ (denoted, respectively, by $\mathcal{S}_{n,m}^{\mathcal{C}^-,+}$ and $\mathcal{S}_{n,m}^{\mathcal{C}^-,-}$) as follows[3] (where $\wedge$ is the AND logical operator):

$$\mathcal{S}_{n,m}^{\mathcal{C}^+,-} := \{(a_n \in \mathcal{A}, a_m \in \mathcal{B}_n) | (i,j) \in \mathcal{C}^+ \wedge \Delta\chi_{(i,j),(n,m)} < 0\}, \quad (7)$$

$$\mathcal{S}_{n,m}^{\mathcal{C}^+,+} := \{(a_n \in \mathcal{A}, a_m \in \mathcal{B}_n) | (i,j) \in \mathcal{C}^+ \wedge \Delta\chi_{(i,j),(n,m)} > 0\}, \quad (8)$$

$$\mathcal{S}_{n,m}^{\mathcal{C}^-,+} := \{(a_n \in \mathcal{A}, a_m \in \mathcal{B}_n) | (i,j) \in \mathcal{C}^- \wedge \Delta\chi_{(i,j),(n,m)} > 0\}, \quad (9)$$

$$\mathcal{S}_{n,m}^{\mathcal{C}^-,-} := \{(a_n \in \mathcal{A}, a_m \in \mathcal{B}_n) | (i,j) \in \mathcal{C}^- \wedge \Delta\chi_{(i,j),(n,m)} < 0\}. \quad (10)$$

Based on this characterization, the DSO can implement instruments impacting the P2P markets – blocking, or incentivizing/disincentivizing trades – to safeguard grid operation. In this regard, we propose three different model cases of analysis (compared to case 0, which includes no P2P market).

Model Case C_0 – Benchmark: This is a benchmark case, in which only the LFM market exists, and which is used to analyze the impact of the existence of the P2P market – in the following cases – on the grid.

Model Case C_1 – Free P2P Trading: In this setting, the P2P market runs freely without any interference by the DSO, while the LFM subsequently corrects the initial congestions and any modifications caused by the P2P trading (i.e., as captured in the sequence of Problem 1 followed by Problem 5). The analysis of this case model then allows investigating when P2P trades are left unchecked, whether they would necessarily harm the grid or whether it can be at instances beneficial.

Model Case C_2 – P2P Trades Preventive Blocking: In this setting, we propose a mechanism in which the DSO reserves the right to preventively block trades that are harmful to critical lines, where such set of harmful trades can be identified as derived in (8) and (10). As such, in C_2, from the set of all possible trades, the formulation in Problem 1 would set $\bar{s}_{nm} = 0 \ \forall (a_n, a_m) \in \{\mathcal{S}_{n,m}^{\mathcal{C}^+,+} \cup \mathcal{S}_{n,m}^{\mathcal{C}^-,-}\}$, based on inputs from the DSO, thus preventing harmful trades while not interfering with the remaining trades. The subsequent LFM run (in Problem 5) would then capture the level of grid safety introduced by this method and the impact on the LFM cost. The downside of this method is that it can lead to a reduction in the volume of P2P trades (impacting the P2P market efficiency).

Case C_3 – P2P Corrective Trades Incentives: In this proposed setting, the DSO, instead of preventing harmful P2P trades, it provides price incentives (subsidies) to encourage trades that are helpful to the system (i.e., that reduce flows over critical lines, thus acting as a corrective mechanism). As such, in C_3, the DSO offers incentive mechanisms to make helpful trades more appealing and harmful ones less appealing to their respective peers. This is accomplished using subsidies on the trading costs ω_{nm} and ω_{mn} for the P2P trade between a_n and a_m, thus impacting the P2P matching and trading problem (Problem 1). In this regard, for a pair of peers (a_n, a_m), if $(a_n, a_m) \in \{\mathcal{S}_{n,m}^{\mathcal{C}^+,-} \cup \mathcal{S}_{n,m}^{\mathcal{C}^-,+}\}$, i.e. their trade is helpful for reducing flows over critical lines, we let $\tilde{\omega}_{nm} = (1-W)\omega_{nm}$ and $\tilde{\omega}_{mn} = (1+W)\omega_{mn}$, where W is a cost adjustment factor (i.e., the subsidy level), rendering it more attractive for a_n to buy from a_m and help the grid. This process would be done for each critical line. Thus, the costs for a pair of P2P trades might be updated multiple times depending on its contributions to relieving or exacerbating congestions in the system. The updated costs $\tilde{\omega}_{nm}$ and $\tilde{\omega}_{mn}$, would then replace their original counterparts, ω_{nm} and ω_{nm} in Problem 1. This option would be attractive to the DSO if the cumulative subsidies provided would be lower than the corresponding costs that would be incurred by purchasing flexibility from the LFM to aid in reducing the congestions by a similar volume.

We next introduce a comparative case study between the model cases.

IV. CASE STUDY

The case analysis considers the Matpower 69-bus system [17] including adjustments to line limits to create a congested grid (2 congested lines – connecting buses 12 and 68, and 44 and 45 – out of 67, an average occupancy ratio of 65%, and 60.29% of lines with occupancy ratio above 60%). A set of 172 flexibility bids are considered from 46 nodes. The bid prices are randomly generated from a uniform distribution in $[10, 20]$ €/MWh for downward flexibility and $[45, 55]$ €/MWh for upward flexibility. The bid quantities are also generated randomly as a proportion of the base load and generation. In C_0 all bids are considered in the LFM. Then, for consistency of comparison with C_0, when introducing the P2P market in C_1–C_3, we consider that a proportion of these flexibility bids are rather buy and sell offers by peers in the P2P market (and are thus not considered in the LFM). As such, we arbitrarily select a subset of the flexibility bids (70 out of 172, i.e., 40%) to take part instead in the P2P market, generating peers spread through different nodes in the grid.

We next compare between the four model cases. The comparison is based on a set of key performance indicators (KPIs): (i) the resulting total cost of the LFM, (ii) the number of congested lines after the run of the P2P market and prior to the LFM, (iii) the sum of overflows over the congested lines (where overflow θ_{ij} over congested line $(i,j) \in \mathcal{L}$ is defined as $\theta_{ij} = |P_{ij}| - \bar{P}_{ij}$), (iv) the weighted overflow average over the congested lines (weighted based on the capacity of the lines)[4], and (v) the cumulative P2P traded volumes in the P2P market (reflecting the conservativeness level of the control instrument implemented by the DSO). In cases C_2 and C_3, the

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[2] $\bar{\tau}_{ij}$ is a reliability measure by the DSO for defining critical lines where $\bar{\tau}_{ij} \geq 100\%$ would include in the critical set only congested lines, while a lower value (e.g., 80%) would also include lines considered at risk of being congested (e.g., 80% loading).

[3] A similar mechanism can be extended to consider over- or under-voltage classification using voltage sensitivity matrices.

[4] The sum and weighted average overflows provide an indication of the loading of the congested lines, but should not be interpreted as the volume of flexibility needed to resolve the congestions, as a 1 MWh flexibility procured from a node can serve to concurrently reduce the overflow over multiple lines, as captured by the PTDF matrix, $\boldsymbol{X}$.

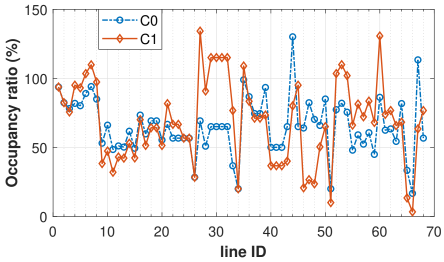

Fig. 1. Case comparison C_0 vs. C_1 prior to the LFM run.

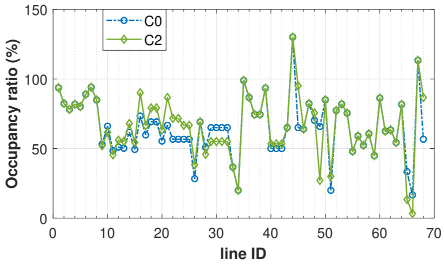

Fig. 2. Case comparison C_0 vs. C_2 prior to the LFM run.

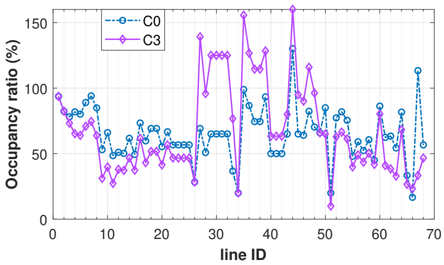

Fig. 3. Case comparison C_0 vs. C_3 prior to the LFM run.

TABLE I

SUMMARY OF RESULTS FOR $C_0 - C_3$. CL= NUMBER OF CONGESTED LINES; O. SUM = SUM OF OVERFLOWS (MW); O. W.A. = OVERFLOW WEIGHTED AVERAGE (MW), LFM C. = COST OF THE LFM MARKET (NORMALIZED WITH RESPECT TO LFM COST IN C_0); P2P V. = VOLUME OF ENERGY TRADED IN THE P2P MARKET (MWH).

Case	CL	O. Sum	O. w.a.	LFM C.	P2P V.
C_0	2	0.04	0.02	1	N/A
C_1	12	1.92	0.26	19.383	2.59
C_2	2	0.04	0.02	1.005	1.17
C_3	12	0.85	0.13	9.797	1.22

line occupancy ratio for the classification of whether a line as critical is taken as $\overline{\tau}_{ij} = 80\%$, while the cost adjusting factor W in C_3 is taken as 0.2.

The impact of the P2P market on the occupancy ratios of all grid lines, considering P2P trading under cases C_1, C_2, and C_3 (as compared to C_0) are shown in Fig. 1–Fig. 3. We note here that the results in these plots are after the P2P market run and prior to the run of the LFM, as after the LFM run, all congestions are successfully resolved. The full comparative results between the different model cases based on the defined set of KPIs is shown in Table I.

As can be seen in Fig. 1, C_1 results in a more heavily-congested grid setting as compared to C_0. Indeed, the unchecked P2P trading resulted in an increase in the number of congestded lines from 2 to 12 and has significantly increased the loading of the lines. However, markedly, Fig. 1 captures that the P2P trading unintentionally led to resolving the original two congestions that existed in the grid (C_0), while it created 12 new congestion instances. As can be seen in Table I, the sum and weighted average overflows increased, leading to a resulting cost of the LFM that is almost 20-fold that of the original case (C_0), thus capturing the significant negative impact that the P2P trading, in this case, has had on the system. One can then observe that, when left unchecked, the P2P trading can at instances either help or harm the grid, while as shown in C_1, these two aspects can concurrently take place. Given the case-dependence of this result, this generates operational uncertainty to the DSO regarding the possible risks that P2P trading can entail, incentivizing, thus, the DSO to provide guiding inputs to the P2P market to allow as much as possible free P2P trading but while ensuring the grid operational safety, as safeguarding reliable grid operation is a key responsibility for the DSO.

The preventive blocking method in C_2, as shown in Fig. 2, successfully prevents the P2P market from causing additional grid congestions, as the number of congested lines (prior to the LFM market run) remains at 2 (similarly to the original case of C_0). The P2P trades under C_2 yield a slight change to the loading of the different lines (increasing and decreasing some occupancy ratios but only for lines whose occupancy ratios are below 80%), as different P2P trades would still impact the flows in the grid, but not in a manner to increase congestion risks. As can be seen from Table I, the sum and weighted average overflow over congested lines, as well as the cost of the subsequent LFM, remain largely unchanged as compared to the original case C_0. This level of grid protection comes at a cost of restricting some P2P trades, resulting in a 54.83% decrease in the volume of energy traded in the P2P market, as compared to the free P2P trading setting in C_1. Indeed, as the grid is heavily loaded (17 out of 68 lines with occupancy ratios above 80%), a higher volume of P2P trades had to be restricted. The results in C_2 showcase that a regulated P2P market can operate in a grid safe manner, while the level of restrictions applied would change depending on the state of the grid in a manner similar to a traffic light concept regulated by the critical line threshold $\overline{\tau}_{ij}\ \forall(i,j) \in \mathcal{L}$. Under more stressed conditions, higher restrictions would apply as compared to light loading conditions. Indeed, in the case analyzed, had the grid state been such that all lines are loaded below 80%, none of the P2P trades would have been restricted, thus yielding a free P2P trading.

In C_3, cost adjustments are implemented for trades impacting the flows over the critical set of lines. As the critical set contains 17 lines (i.e., lines with $\tau_{ij} \geq 80\%$), the costs of a certain P2P pair may be updated up to 17 times, in case this trade impacts the flow over every line in the critical set. As can be seen from Fig. 3 and Table I, even though the incentives had not been able to prevent the occurrence of congestions (as compared to C_1), as 12 congestions remain in Fig. 3, the collective overflow over the congested lines has been significantly more limited than that in C_1, especially when considering the overflow volumes (sum and weighted average), as can be seen in Table I. This has led to a decrease in LFM cost in C_3 to almost half that of C_1, even though this cost is still almost 10 times that of C_0 and C_2. This captures the persistent cost of the P2P market on the grid even when the corrective subsidies are applied. This indicates that a higher subsidy amount would be needed to further reduce the flows over congested lines. However, this would face additional challenges as it entails additional monetary compensations to be played by the DSO for those subsidies, thus limiting their practical case (as the DSO can alternatively purchase the required flexibility as part of the LFM, thus providing a benchmark against which the subsidies can be weighted). C_3 has led to a lower reduction of the volume of P2P trades, where this volume for C_3 is 52.9% less than that for C_1, as compared to a 54.83% reduction in the case of C_2 as compared to C_1. This, hence, further highlights the advantages of C_2 as with this 1.93% reduction difference in volume of P2P trades, C_2 was able to achieve complete grid safety for the P2P trading. We additionally note here, that beyond the technical KPIs, such subsidy schemes (as in C_3) may face regulatory and legal challenges as they entail direct impact to the P2P trading costs and market outcomes.

V. EVALUATION AND CONCLUSIONS

This paper has introduced P2P and LFM market formulations to quantify the impact of P2P trading on the distribution grid. Two DSO instruments, aiming to safeguard the grid while enabling P2P trading, are proposed and compared, namely, (i) a preventing P2P trades blocking method and (ii) an incentive mechanism based method, which are then compared to the case of free P2P trading without any DSO interference.

The results have shown that unchecked P2P trading can introduce uncertainty to grid safety as it can concurrently impact flows positively and negatively – at instances helping the system and at instances harming it – thus requiring the application of control measures by the DSO, especially in stressed grid conditions. The application of incentives/disincentives was shown to lead to safer P2P trading outcomes as compared to the fully unchecked case. However, this method does not offer guarantees for grid safety and faces challenges such as: (i) the selection and fine tuning of the incentives/disincentives to effectively encourage helpful P2P trades, and discourage harmful ones, while ensuring that the costs of such subsidy schemes do not outweigh their benefits (as compared to resolving congestion using the LFM); (ii) the application of such subsidy schemes may face legal/regulatory barriers as it risks inducing market distortions and discriminatory behavior. The preventive trades blocking mechanism, on the other hand, has provided an easily implementable alternative, which was shown to effectively yield grid-safe P2P trading for the studied case. The level of restrictions applied to the P2P trades would depend on the loading condition of the grid. In a setting in which the DSO can implement checks and impose limits to meet its duty for ensuring a reliable operation of the grid, this trade blocking mechanism can provide a practical and effective solution which is in line with regulatory guidelines.

We note that the derived numerical results apply to the case studied. Different cases may impact the effectiveness and efficiency of the two methods. This highlights the need for the DSO and regulators to inspect their practical case to determine the method to be applied – and to fine-tune its parameters – and opens up the space for future research in this direction.

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