Prequalification of Distribution Resources in a Coordinated Market Environment

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***Abstract*—The decentralization of power systems and the rapid deployment of renewable energy sources (RES) has upgraded the role of the Distribution System Operator (DSO) from a passive network observer to an active system operator. This requires effective collaboration and coordination with the Transmission System Operator (TSO) to avoid any congestion issues in the distribution grid. In this paper, the local market coordination scheme is considered, where DSO has priority to procure services from distributed energy resources (DERs) in an optimization-based separate local market. In this framework, a prequalification scheme is proposed and developed to enable the participation of DERs in central markets without risking the stability of the distribution system. The proposed prequalification scheme allows the DSO to detect and manage congested lines in the distribution grid preventing decisions by the TSO that can threaten the distribution system stability. Simulation results on the IEEE 33-bus system illustrate the effectiveness of the prequalification scheme in managing potential congestions in the distribution grid that might occur by the actions of the TSO.**

***Index Terms*—Congestion management, DSO-TSO coordination, flexibility, local market, prequalification,**

I. Introduction

The global energy sector is going through a vast transformation. The realization of concerns expressed by the scientific community regarding climate change years ago is now forcing many countries to act in order to reverse these effects. In this attempt, electric power systems are becoming greener by the massive deployment of RES while system operators are working towards overcoming any operational challenges posed by the uncertain and intermittent RES power generation.

Given the increased penetration of RES in the distribution grid, the DSOs should actively manage their networks to avoid undesired situations, as highlighted in several reports [1], [2]. Towards this direction, more flexible resources could be considered to cope with the increased uncertainty characterizing the RES power output [3], [4]. In a modern power system, DERs could be employed in the provision of ancillary services, such as frequency control, voltage control, and congestion management for enhancing their operational capabilities. In such a framework, the TSO-DSO coordination is necessary for avoiding any congestion issues in the distribution system when DERs need to provide ancillary services to the transmission system [5]. According to [5], successful TSO-DSO coordination lies on four main pillars: (i) integration of DER flexibility into energy markets; (ii) design of coordination schemes for flexibility procurement and activation; (iii) development of transmission and distribution optimization techniques; and (iv) data exchange between operators.

According to a survey study conducted by authors of [3], many coordination schemes have been proposed in the literature, and they managed to distinguish the five more general schemes. Active distribution system management that enables the optimal operation of the distribution system has been proposed in the literature, assuming perfect TSO-DSO coordination in a regulated environment [6], [7]. The more representative scheme to the current situation is the Centralized market model for ancillary services, examined in [8]. The Centralized model gives priority to the TSO to procure services in a system-wide approach. Hence, the DSO's role is limited to a prequalification stage aiming at ensuring that the activation of DER bids will not impact negatively the distribution system. This scheme is simple but does not consider the threats imposed to the distribution system, while smaller DERs compete in a market with larger players in an unfair way. In [8], the TSO conducts congestion management using all the resources of the power system aiming at minimizing the activation cost, while the DSO has no role in congestion management. In the Shared Balancing Responsibility market model each operator runs its market to balance its system using local resources while respecting a pre-defined power flow at the points of transmission-distribution interconnection. This model ensures the independence of each system, but it is not optimal since it limits the operators to use a portion of the available flexible resources, and at the same time, it restricts the participation of resources in other markets. In [9] this scheme is considered in a game-theoretic approach to minimize the activation cost for congestion management and the DSO uses resources for voltage support. The Common market model is considered in [10] and [11]. This model proposes a common market for the two operators. It is more complicated since it is larger and contradicting actions may occur, leading to inefficient utilization of resources. In [10] the DSO procures services for congestion management, while the TSO procures tertiary services. The market aims at minimizing the cost for the two operators. In [11], the operators conduct congestion management aiming at minimizing the cost. Finally, the Local Market (LM) model gives priority to the DSO to procure services

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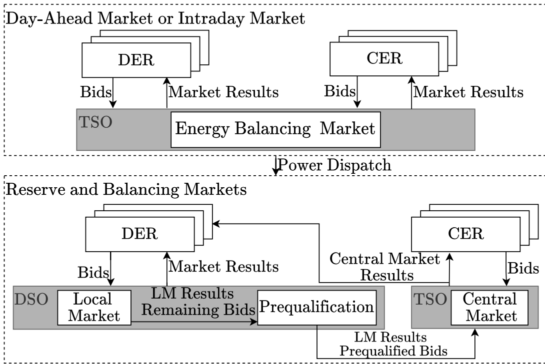

Fig. 1. Local Market model.

in a separate market before a central market. In between the two markets, prequalification is needed to transfer unused bids from the LM to the central market without risking the stability of the distribution grid. This model upgrades the role of DSO and simplifies the balancing procedure since each operator looks after its system without restricting the participation of DERs in other markets. Nevertheless, it is crucial to perform a prequalification before transferring bids from the local to the central market to ensure that TSO actions do not threaten the distribution system. The LM model was considered in [8], [9], [11] in the same context as other schemes (i.e., congestion management and minimization of the activation cost), without considering the prequalification stage.

In the Centralized market and LM models, DERs can participate in transmission-level markets, thus, the DSO has to maintain the system integrity. In [12], a prequalification scheme is proposed for the Centralized model, where the DSO guides the DERs to modify their bids before submitting them based on chance-constrained optimization. In [13] prequalification is carried out by the DSO to determine whether DERs are allowed to participate in the TSO's market, without proposing a modification scheme for their bids. To the best of the authors' knowledge, despite the fact that several studies considered the LM scheme in managing congestions, the prequalification has not received the appropriate attention; therefore the contribution of this paper is the development of a two-stage prequalification scheme, integrated into the LM scheme that will enable the safe participation of DERs in the central market. In the first stage, the proposed method identifies possible TSO actions that can affect the stability of a distribution system. The second stage derives prequalified bids that guarantee the stability of the system irrespective of the activation decision of the central market. The effectiveness of the proposed prequalification method is validated through a case study on the IEEE 33-bus test system to assess its ability to manage potential congestions in the distribution grid.

The rest of this paper is organized as follows. In Section II, the structure of the LM model is described, while the proposed prequalification scheme is formulated in Section III. The validation results for the proposed method are presented in Section IV and the paper concludes in Section V.

II. Local Market Model

The LM model (Fig. 1) implies an independent local market operated by the DSO that takes place after the energy balancing markets such as the day-ahead or intraday market. Following the energy balancing markets, the DSO is responsible to take corrective actions to ensure the proper operation of the distribution system, aiming at minimizing the activation cost. The DSO gets all the necessary information related to load and generation at each bus (assuming that all the market players are required to provide consumption and generation data for each distribution bus) by the operators of the energy balancing market and can procure services in a separate market to satisfy the desired system constraints. In this context, we formulate a mathematical program (Problem 1) defining a LM as:

$$\underset{\mathbf{P},\mathbf{P}^G,\mathbf{P}^D,\boldsymbol{\delta},\mathbf{P}^F}{\text{Minimize}} \sum_{g\in G} C_g^G|P_g^G| + \sum_{d\in D} C_d^D|P_d^D| \tag{1a}$$

subject to

$$P_i = \sum_{j\in\mathcal{N}} B_{ij}(\delta_i - \delta_j), \qquad \forall i\in\mathcal{N} \tag{1b}$$

$$P_i^{DA} + \sum_{g\in\mathcal{G}_i} P_g^G - \sum_{d\in\mathcal{D}_i} P_d^D = P_i, \qquad \forall i\in\mathcal{N}\setminus\mathcal{N}^{TD} \tag{1c}$$

$$P_i^{DA} + \sum_{g\in\mathcal{G}_i} P_g^G - \sum_{d\in\mathcal{D}_i} P_d^D = P_i + P_i^{TD}, \quad \forall i\in\mathcal{N}^{TD} \tag{1d}$$

$$P_g^{G-} \le P_g^G \le P_g^{G+}, \qquad \forall g\in\mathcal{G} \tag{1e}$$

$$P_d^{D-} \le P_d^D \le P_d^{D+}, \qquad \forall d\in\mathcal{D} \tag{1f}$$

$$P_{ij}^F = B_{ij}(\delta_i - \delta_j), \qquad \forall (i,j)\in\mathcal{L} \tag{1g}$$

$$-P_{ij}^{F,max} \le P_{ij}^F \le P_{ij}^{F,max}, \qquad \forall (i,j)\in\mathcal{L} \tag{1h}$$

where, C_g^G and C_d^D are the bid prices for generator g and demand d, respectively. P_g^G and P_d^D are the power regulation of generation and demand, respectively, P_i is the net real power injection at bus i, and P_i^{TD} is the flow at the interconnection point between the transmission and distribution systems. B_{ij} is the susceptance of line (i,j) and δ_i is the voltage angle of bus i. P_i^{DA} is the net real power injection at bus i based on the input received by the day-ahead market operator (assuming a single day-ahead market). $P_g^{G\pm}$, $P_d^{D\pm}$ are the regulation limits of generation g and demand d. P_{ij}^F is the power flow through the line (i,j) , and $P_{ij}^{F,max}$ is its flow limit. $\mathcal{N}$ is the set of buses, $\mathcal{N}^{TD}$ is the subset of interconnection buses and $\mathcal{L}$ is the set of lines. $\mathcal{G}$ and $\mathcal{D}$ are the sets of generators and demands, while $\mathcal{G}_i$ and $\mathcal{D}_i$ are the subsets of generators and demands at bus i, respectively. Finally, $\mathbf{P}^G$, $\mathbf{P}^D$, $\mathbf{P}$, $\boldsymbol{\delta}$ and $\mathbf{P}^F$ are the vector forms of $P_g^G, \forall g\in\mathcal{G}$, $P_d^D, \forall d\in\mathcal{D}$, P_i and δ_i, $\forall i\in\mathcal{N}$, and P_{ij}^F, $\forall(i,j)\in\mathcal{L}$, respectively. In this study, the DSO conducts only congestion management through the LM, so DC power flow is considered. The DSO maintains the balanced operation of the power system through (1b)-(1d) which ensure that the power injection at each bus, P_i, will satisfy the power injection determined in the day-ahead market P_i^{DA} plus the DER power regulation, P_g^G and P_d^D. Any deficit or surplus of power is satisfied by the transmission system through the interconnection point, P_i^{TD}. The DSO guarantees that the regulation of resources is based on their bid's volume

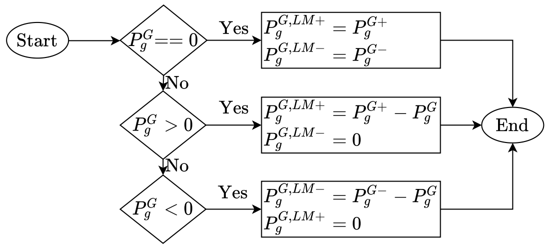

Fig. 2. Pre-processing flow diagram.

through constraints (1e) and (1f). Constraints (1g) and (1h) determine the power flow of a line and keep it within its limits.

Following the LM execution, a pre-processing stage is performed for determining the limits of the remaining bids. As indicated in Figure 2, the regulation limits of a non-activated bid will be forwarded unchanged to the prequalification block. In case the power regulation was positive the upper limit of the bid will be modified to consider the current regulation of the DER (defined by the LM) while the lower limit will be set equal to zero. Similar reasoning holds for the third case where the DER regulation is negative. The generated set of *remaining bids* consists of the new limits for every generator g, $P_g^{G,LM\pm}$, and demand d, $P_d^{D,LM\pm}$.

After the pre-processing stage, the new set of bids is passed to the prequalification stage along with the set of power injection per bus determined in the LM, P_i^{LM}. In this work, the prequalification is divided into two stages; the first stage identifies potential congestions in the distribution system, and the second stage modifies, if necessary, the bids to prevent those congestions, as explained in Section III. The final stage of the LM model regards the execution of the central market that is operated by the TSO. This market, which is the closest to the delivery time, takes as input the prequalified set of bids and the set of power injection per bus determined in the LM. The TSO procures services that can be satisfied by DERs and centralized resources to balance the transmission system. The prequalification stage proposed in this study guarantees that every DER participating in the central market will not threaten the distribution system. The central market is out of the scope of this paper.

III. Prequalification Scheme

In this section, the proposed two-stage prequalification method is formulated.

A. Stage I: Identification of Potentially Congested Lines

Stage I aims to identify *potentially congested lines*, i.e., lines that become congested under any combination of DERs power regulation in the central market. Towards this direction, each line $(i,j) \in \mathcal{L}$ is examined separately to find its maximum possible power flow P_{hk}^F by solving Problem 2

$$\underset{\mathbf{P},\mathbf{P}^G,\mathbf{P}^D,\boldsymbol{\delta},\mathbf{P}^F}{\text{Maximize}} |P_{hk}^F|, \qquad \forall (h,k) \in \mathcal{L} \tag{2a}$$

subject to (1b), (1g)

$$P_i^{LM} + \sum_{g\in\mathcal{G}_i} P_g^G - \sum_{d\in\mathcal{D}_i} P_d^D = P_i, \qquad \forall i \in \mathcal{N} \setminus \mathcal{N}^{TD} \tag{2b}$$

$$P_i^{LM} + \sum_{g\in\mathcal{G}_i} P_g^G - \sum_{d\in\mathcal{D}_i} P_d^D = P_i + P_i^{TD}, \quad \forall i \in \mathcal{N}^{TD} \tag{2c}$$

Algorithm 1 Proposed prequalification stage

1: **while** TRUE **do**
2: Define $\mathcal{L}^{PC}$ by solving Problem 2, $\forall\,(i,j) \in \mathcal{L}$
3: **if** $\mathcal{L}^{PC} = \emptyset$ **then** EXIT **end if**
4: $(h,k) \leftarrow \underset{(i,j)\in\mathcal{L}^{PC}}{\text{argmax}} \{|P_{ij}^F| - P_{ij}^{F,max}\}$.
5: **if** $P_{hk}^F > 0$ **then**
6: Obtain α using Algorithm 2 with Problem 3
7: $P_g^{G,LM-} \leftarrow \alpha P_g^{G,LM-}, \ \forall g \in \mathcal{G}_{hk}$
8: $P_d^{D,LM+} \leftarrow \alpha P_d^{D,LM+}, \ \forall d \in \mathcal{D}_{hk}$
9: **else if** $P_{hk}^F < 0$ **then**
10: Obtain α using Algorithm 2 with Problem 4
11: $P_g^{G,LM+} \leftarrow \alpha P_g^{G,LM+}, \ \forall g \in \mathcal{G}_{hk}$
12: $P_d^{D,LM-} \leftarrow \alpha P_d^{D,LM-}, \ \forall d \in \mathcal{D}_{hk}$
13: **end if**
14: **end while**

Algorithm 2 Bisection Procedure

$\alpha^+ \leftarrow 1$, $\alpha^- \leftarrow 0$
while $(\alpha^+ - \alpha^- \geq \epsilon)$ **do**
$\alpha \leftarrow (\alpha^+ + \alpha^-)/2$
Solve Problem 3 or 4 to obtain a new value P_{hk}^F
if $|P_{hk}^F| > P_{hk}^{F,max}$ **then**
$\alpha^- \leftarrow \alpha$
else
$\alpha^+ \leftarrow \alpha$
end if
end while

$$P_g^{G,LM-} \leq P_g^G \leq P_g^{G,LM+}, \qquad \forall g \in \mathcal{G} \tag{2d}$$

$$P_d^{D,LM-} \leq P_d^D \leq P_d^{D,LM+}, \qquad \forall d \in \mathcal{D} \tag{2e}$$

$$P_{ij}^F = B_{ij}(\delta_i - \delta_j), \qquad \forall (i,j) \in \mathcal{L} \tag{2f}$$

where, P_i^{LM} is the net real power injection at bus i declared by the LM, and $P_g^{G,LM\pm}$, $P_d^{D,LM\pm}$ are the pre-processed limits. The solution of the problem must satisfy the power balance constraints using the DC power flow (Eq. (1b), (1g), (2b), and (2c)) and respect the regulation limits, (2d) and (2e), based on the set of bids determined through the procedure of Figure 2. Let the optimal value of P_{hk}^F from the solution of Problem 2 be P_{hk}^{F*}. Then, the set of potentially congested lines $\mathcal{L}^{PC} \subseteq \mathcal{L}$ consists of the lines whose maximum power flow exceeds their flow limits, i.e., $|P_{hk}^{F*}| > P_{hk}^{F,max}$.

B. Stage II - Congestion Prevention

Stage II aims to modify the limits of DERs to guarantee that no combination of activated bids from the central market leads to congestion in the distribution system, as outlined in Algorithm 1. First, the set of potentially congested lines $\mathcal{L}^{PC}$ is defined following the procedure described in Stage I; if $\mathcal{L}^{PC} = \emptyset$ the algorithm terminates (Lines 2-3). Potential congestion is eliminated by reducing the DERs bids. Towards this direction, the most congested line (h,k) is identified (Line 4). Under normal power flow, $P_{hk}^F > 0$, a bisection procedure is executed that iteratively constrains the lower bounds of generators and upper bounds of demands located at buses powered by line (h,k) under the normal power flow,

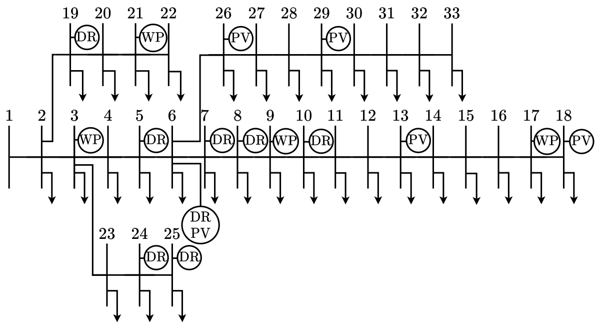

Fig. 3. Line utilization without LM.

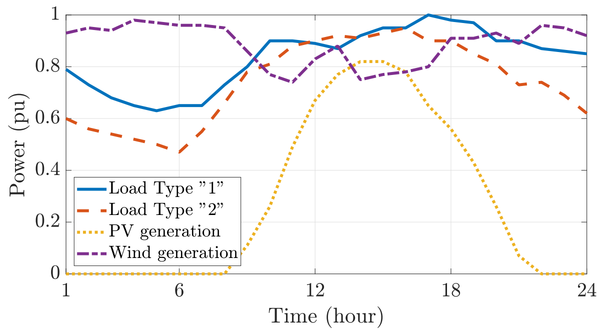

Fig. 4. Load and generation profiles.

defined through sets $\mathcal{G}_{hk}$ and $\mathcal{D}_{hk}$. This is achieved through the solution of Problem 3 in each iteration of the bisection procedure (Lines 5-6).

$$\underset{\mathbf{P},\mathbf{P}^G,\mathbf{P}^D,\boldsymbol{\delta},\mathbf{P}^F}{\text{Maximize}} |P_{hk}^F| \tag{3a}$$

subject to (1b), (2c), (2d), (1g),

$$\alpha P_g^{G,LM-} \leq P_g^G \leq P_g^{G,LM+}, \qquad \forall g \in \mathcal{G}_{hk} \tag{3b}$$

$$P_g^{G,LM-} \leq P_g^G \leq P_g^{G,LM+}, \qquad \forall g \in \mathcal{G}_i \backslash \mathcal{G}_{hk} \tag{3c}$$

$$P_d^{D,LM-} \leq P_d^D \leq \alpha P_d^{D,LM+}, \qquad \forall d \in \mathcal{D}_{hk} \tag{3d}$$

$$P_d^{D,LM-} \leq P_d^D \leq P_d^{D,LM+}, \qquad \forall d \in \mathcal{D}_i \backslash \mathcal{D}_{hk} \tag{3e}$$

Under reversed power flow, $P_{hk}^F < 0$, the same bisection procedure is executed to constrain the upper bounds of generators and lower bounds of demands in sets $\mathcal{G}_{hk}$ and $\mathcal{D}_{hk}$, through the solution of Problem 4 (Lines 9-10).

$$\underset{\mathbf{P},\mathbf{P}^G,\mathbf{P}^D,\boldsymbol{\delta},\mathbf{P}^F}{\text{Maximize}} |P_{hk}^F| \tag{4a}$$

subject to (1b), (2c), (2d), (1g),

$$P_g^{G,LM-} \leq P_g^G \leq \alpha P_g^{G,LM+}, \qquad \forall g \in \mathcal{G}_{hk} \tag{4b}$$

$$P_g^{G,LM-} \leq P_g^G \leq P_g^{G,LM+}, \qquad \forall g \in \mathcal{G}_i \backslash \mathcal{G}_{hk} \tag{4c}$$

$$\alpha P_d^{D,LM-} \leq P_d^D \leq P_d^{D,LM+}, \qquad \forall d \in \mathcal{D}_{hk} \tag{4d}$$

$$P_d^{D,LM-} \leq P_d^D \leq P_d^{D,LM+}, \qquad \forall d \in \mathcal{D}_i \backslash \mathcal{D}_{hk} \tag{4e}$$

The outcome of the bisection procedure is a parameter α that guarantees minimal volume rejection under the proposed scheme while keeping the line within limits. The value of α is used to update the corresponding limits of generators and demands (Lines 7-8 or 11-12). The bisection procedure is detailed in Algorithm 2. Initially, the lower α^- and upper α^+ bounds of parameter α are set equal to 0 and 1, respectively. Then, an iterative procedure is followed where in each iteration Problem 3 ($P_{hk}^F > 0$) or 4 ($P_{hk}^F < 0$) is solved; if the power

TABLE I
LOAD CLASSIFICATION

Bus	Peak Load (kW)	Type	Bus	Peak Load (kW)	Type
2	100	1	18	90	2
3	90	1	19	90 (DR)	1
4	120	1	20	90	1
5	60 (DR)	2	21	90	1
6	60 (DR)	2	22	90	2
7	200 (DR)	1	23	90	2
8	200 (DR)	1	24	420 (DR)	2
9	60	2	25	420 (DR)	1
10	60 (DR)	2	26	60	2
11	45	2	27	60	2
12	60	2	28	60	1
13	60	1	29	120	1
14	120	1	30	200 (DR)	1
15	60	2	31	150	2
16	60	1	32	210	1
17	60	2	33	60	2

TABLE II
GENERATION CLASSIFICATION

Bus	3	6	9	13	17	18	21	26	29
Capacity (kW)	300	150	300	150	300	75	450	110	75
Type	WP	PV	WP	PV	WP	PV	WP	PV	PV

TABLE III
REJECTED BID VOLUME

$P_i^{G,LM+}$	$P_i^{G,LM-}$	$P_i^{D,LM+}$	$P_i^{D,LM-}$
0	1.6 MW (16.68%)	17.95 MW (86.11%)	0

flow is above the line's limit then α^- is set equal to α, otherwise, α^+ is set equal to α. The process iterates until $\alpha^+ - \alpha^-$ is lower than ϵ.

IV. CASE STUDY

The effectiveness of the proposed method is examined on the IEEE 33-bus test system (Fig. 3). We consider two types of system load, according to their profile, and two types of generating resources (i.e., solar and wind parks) with storage capabilities. The profiles for the DERs and the two load types are depicted in Figure 4. Table I shows the peak load, the load type, and whether a load participates in demand response (DR) schemes per bus, while the type and capacity of generating resources are shown in Table II. Finally, the bid price is set to 200€/MW for all resources.

A. Local Market - Results

The DSO has to satisfy the equilibrium of demand and supply through the LM while managing congestions using the resources of the distribution system. In the case of no LM, it is highly probable that the decisions of the energy balancing market might cause congestion issues to the distribution grid. This is shown in Figure 5, in which the eight most loaded lines are shown in case of no LM. As indicated, five out of the eight lines are congested. However, in the existence of the LM, the congestions are successfully overcome as shown in Figure 6. In the LM, 30.1% of the submitted bids were activated, representing 23.6% of the available DERs volume. It should be noted that the congested lines are near the interconnection point therefore they transfer power to several loads. It is evident that the active management of the distribution grid by the DSO can be enhanced through the presence of LM. According to the LM model (Fig. 1), the set of remaining bids are first pre-processed and then send to the prequalification scheme.

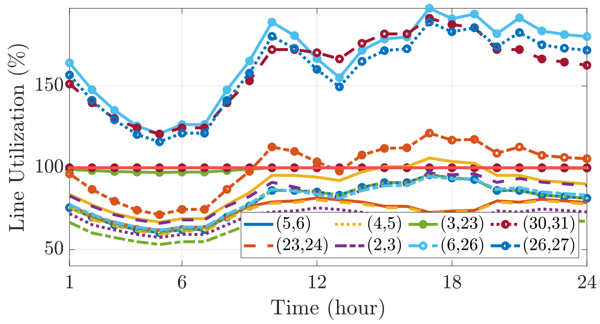

Fig. 5. Highest flows before LM.

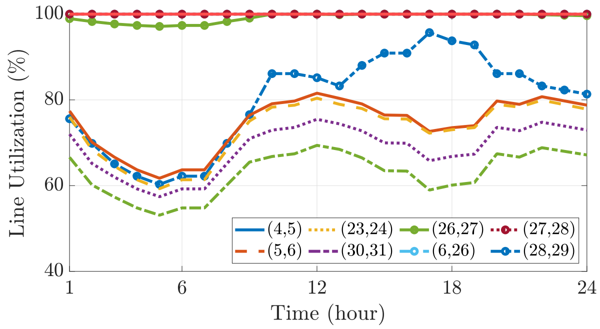

Fig. 6. Highest flows after LM.

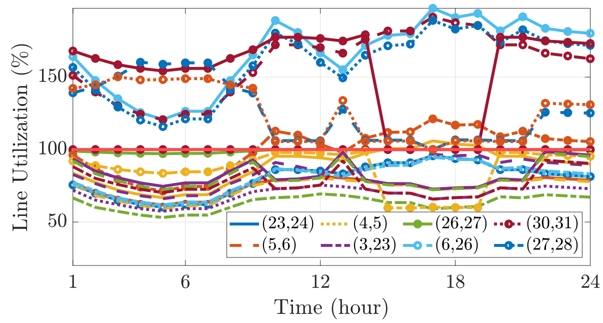

Fig. 7. Highest possible flows before prequalification.

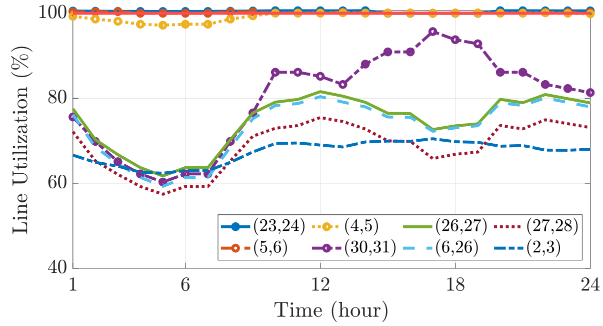

Fig. 8. Highest possible flows after applying the proposed method.

B. Prequalification - Results

The prequalification is executed based on the new set of bids derived using Algorithm 1. Figure 7 shows the eight lines resulting from Stage I that can potentially get congested after the execution of the central market. In particular, lines (23,24), (4,5), and (5,6) belong to set $\mathcal{L}^{PC}$ showing that the prequalification stage is vital for the system's stability. Figure 8 shows the highest possible loading of lines after the prequalification stage, revealing that all the lines are within limits and that the proposed method manages to eliminate potential congestions. Table III shows how much bid volume is rejected in the prequalification stage, indicating that considering the direction of flow results in zero volume rejection for the upper generation and lower demand limits. Conversely, the percentage of rejection for the upper demand limits is higher since demands provide flexibility all day, while generators like PV can provide flexibility during sunshine. Also, the location of DERs with respect to the potentially congested line plays a significant role in their activation.

V. Conclusions

This paper proposes a two-stage prequalification scheme within the Local Market coordination model. The developed scheme ensures the stability of the distribution system regardless of the TSO's actions in the central market in two stages. The first stage identifies possible congestions, while the second stage modifies the bids that directly affect the stability of the distribution system.

The method is validated in a case study, where the congestion experienced by the test system after the day-ahead market is temporarily managed through the local market. Nonetheless, the remaining bids that are passed to the central market can still lead to congestion, as shown by the first stage of the proposed method. Then, the second stage prequalifies bids by rejecting a certain amount of bid volume, illustrating that no combination of activated bids can lead to congestion.

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