Market Order Prequalification for TSO-DSO Coordination

Ioannis Papayiannis, Markos Asprou, Lenos Hadjidemetriou and Stelios Timotheou
Department of Electrical and Computer Engineering and KIOS Research and Innovation Center of Excellence
University of Cyprus, Nicosia, Cyprus
{papayiannis.ioannis, asprou.markos, hadjidemetriou.lenos, timotheou.stelios}@ucy.ac.cy

***Abstract*—The increasing deployment of Distributed Energy Resources (DERs) creates an urgent need for active distribution grid management and effective coordination between the Transmission System Operator (TSO) and Distribution System Operator (DSO). Several TSO-DSO coordination models have been proposed in the literature. Two of these models, the Centralized Market and the Local Market model, require a market order prequalification stage. Prequalification is essential to ensure the distribution grid thermal limits are not violated when DER orders are activated in the central market (operated by the TSO). In this study, a market order prequalification scheme, applicable to both coordination models, is proposed to create a new set of market orders, ensuring that the distribution lines will not get congested under any order activation scenario. The effectiveness of the proposed prequalification scheme and the performance of the two coordination models are evaluated through a case study using a test system comprising the IEEE 9-bus system (transmission) and the IEEE 33-bus test feeder (distribution).**

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

I. INTRODUCTION

Modern power systems, especially distribution grids, are evolving from passive to active systems comprising a diversified portfolio of resources. These energy resources are mainly decentralized and renewable with intermittent generation that poses several challenges to the operators. In this sense, there is a need for solutions that ensure the operability of power systems under high penetration of DERs; although there is no single solution providing a globally accepted framework to deal with these challenges.

One of the first remedial actions to ensure the integrity of power systems against the threats imposed by the high DER penetration is the active management of distribution grids [1], [2]. In this context, the role of the DSO is upgraded to deal with integrity threats such as the violation of voltage limits and the congestion of distribution lines [2], [3]. Secondary identified threats include low power quality conditions due to the high share of power electronics and the increased probability for the erroneous operation of the protection system under highly volatile environment and reverse power flow conditions [4]. However, the active participation of the DSO in the operation of the power system increases the need for coordination with the TSO. Coordination between the operators is crucial to avoid contradicting actions threatening the stability of the power system and increasing the operation cost. Effective coordination is achieved through the integration of DER flexibility, optimization algorithms, coordination models, and data exchange agreements [5].

In the literature, several TSO-DSO coordination models are proposed. Five main models are identified and classified in [5] based on the level of data exchange, the structure of the electricity markets, and the level of DER integration. The first is the Shared Balancing Responsibility Model which suggests two different markets for the TSO and DSO needs. In this model, the TSO and DSO procure flexibility from resources located in their grid while respecting a pre-defined profile of power exchange at the interconnection points. The performance of this model has been evaluated in [1], [6], [7] with the main conclusion that the economic efficiency is compromised due to the two-market structure. The next two models are the TSO-DSO Common Market Model and the Integrated Market Model. The former suggests a common market where Centralized Energy Resources (CERs) and DERs can participate and the two operators procure flexibility, while the latter model allows commercial entities (e.g., generation companies) to procure flexibility too. These models were evaluated in [8]–[11], demonstrating good performance at the cost of high complexity and data exchange. The last two models are the Centralized Market (CM) and the Local Market (LM) models. In the CM model, the role of the DSO is limited to a prequalification stage and all resources can participate in a central balancing market operated by the TSO to balance the energy while minimizing the cost of activated resources. Although this is a simple model it does not ensure the operational requirements of the distribution grid which is undesirable in modern power systems [7], [9]. On the contrary, the LM model enables the DSO to procure DER flexibility through a local market for the distribution grid operational requirements. The non-activated DER market orders have to be transferred to the central market by the DSO. Despite the safer distribution grid operation, the two-market structure sacrifices

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This work is supported in part by the Republic of Cyprus through the Research and Innovation Foundation under Project CULTURE/AWARD-YR/0322B/0003 (INVERGE), and in part by the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 957739 (OneNet), and in part by the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 739551 (KIOS CoE - TEAMING) and from the Republic of Cyprus through the Deputy Ministry of Research, Innovation and Digital Policy.

economic efficiency, while the liquidity of DER orders can lead the local market to failure [7], [9], [10].

In this study, the CM and LM models are considered, since they allow the TSO to activate DER orders without the supervision of the DSO. This feature means that there is a risk of creating congestion or violating voltage limits in the distribution grid after the central market is cleared, as shown in [12]. Thus, a prequalification stage is required to ensure that the orders transferred to the central market will not drive the distribution grid to abnormal conditions. The topic of prequalification is timely since the hosting capacity of the distribution grid infrastructure is limited and cannot accommodate the integration of additional resources, without violating its operational limits. In [12], an iterative prequalification method is proposed. The orders are modified by multiplying their volume with a coefficient that is calculated through a bisection algorithm to maximize the volume of the generated set of orders. In [13], a chance-constrained program is proposed that identifies orders that will possibly create congestion. In the same fashion, [14] indicates orders that should be modified based on a traffic lights approach. Both approaches require the DER to modify its order's volume, requiring extra actions that may cause delays.

In this study, we propose a straightforward, yet effective prequalification scheme that can be integrated into the CM and LM models. The proposed method, in contrast to existing methods, identifies resources that may create congestion and incorporates an order modification algorithm that modifies the volume of orders based on how much they contribute to the potential congestion. Market orders consist of the price, volume, and direction (i.e., buy or sell). In the case of the CM model, the integration of the prequalification stage enables the DSO to have indirect control over the DER activation. In the case of the LM model, it ensures that the distribution grid is within operational limits independent of the TSO's actions in the central market. In addition, the operational framework for the two coordination models is well-defined. Although the two models have been utilized in the literature, to the authors' knowledge no study has utilized these models to a highly congested grid and incorporated the prequalification stage. In this sense, comparing the two models in an environment with high DER penetration will stress their performance and demonstrate their value and viability in future power systems. In addition, operators need to have full knowledge of the model performance to choose the proper model to coordinate their operations and respect both the transmission and distribution grid while facilitating DER integration.

The rest of this paper is organized as follows. Section II presents the operational framework of the coordination models' and the related mathematical formulations. The proposed prequalification scheme and its formulation are given in Section III. Section IV demonstrates the results of a case study, while conclusions are presented in Section V.

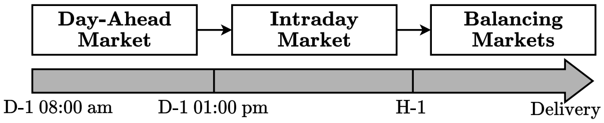


Fig. 1: Timeline for different market structures.

II. COORDINATION FRAMEWORK AND FORMULATION

In this study, the power system is modeled using the DC power flow equations since the operators only balance real power and manage congestion. Let $\mathcal{N}^{TS}$ and $\mathcal{N}^{DS}$ be the sets of transmission and distribution buses, respectively. $\mathcal{N}^{TD} \subseteq \mathcal{N}^{DS}$ consists of distribution buses connected to the primary transmission grid. Flexible demands and generators across the power system are in sets $\mathcal{D}$ and $\mathcal{G}$, respectively. DERs are in sets $\mathcal{D}^{DS} \subseteq \mathcal{D}$ and $\mathcal{G}^{DS} \subseteq \mathcal{G}$ and CERs are in sets $\mathcal{D}^{TS} \subseteq \mathcal{D}$ and $\mathcal{G}^{TS} \subseteq \mathcal{G}$. Subsets of resources at a specific bus i are distinguished by using the subscript i (e.g., $\mathcal{G}_i^{DS}$ denotes generating resources at distribution bus i). $\mathcal{L}^{TS}$ and $\mathcal{L}^{DS}$ are the sets of transmission and distribution lines, respectively.

A. Centralized Market Model

The operation of the CM model is similar to the current operating practices where the DSO has almost no role in the market, and the TSO clears the market considering only the transmission grid. As illustrated in Fig. 1, the Day-Ahead (DAM) and Intraday (IDM) markets are first taking place to balance energy without considering network constraints. The DAM opens at 08:00 am and closes at 12:00 pm, one day before delivery (D-1). The DAM clears at 1:00 pm to balance power at the transmission grid level for the delivery day (D). The D-day is divided into 24 hourly products, and the clearing algorithm considers each product separately (i.e., no temporal coupling). The IDM allows the participants to sell or buy power based on updated forecasts. It is a continuous market that instantly matches orders and closes one hour before delivery (H-1) of each product. The output of the two markets is the power dispatch for each participant and the DAM clearing price or the accepted bid price for the IDM.

The balancing markets are the tools used by the operators to ensure safe grid operation. These markets run after the closure of the IDM (i.e, from H-1 to delivery). The CM model, Fig. 2, suggests that DERs submit orders to the DSO, who prequalifies them to create a new set of orders for the central market. The central market runs after the prequalification stage and closes and clears minutes before the delivery of a specific product. The TSO procures flexibility from DERs and CERs to balance the transmission grid and manage congestion. Problem 1, comprising (1a)-(1h), provides the formulation for the linear program solved to clear the central market. The objective of this market is to minimize the regulation cost of all resources

$$\text{Minimize} \sum_{d \in \mathcal{D}} C_d^D |\Delta p_d^D| + \sum_{g \in \mathcal{G}} C_g^G |\Delta p_g^G| \qquad \text{(1a)}$$

where parameter C_d^D is the order price of demand $d \in \mathcal{D}$ and C_g^G is the order price of generator $g \in \mathcal{G}$. Δp_d^D and Δp_g^G are the power regulation variables for demand d and generator g,

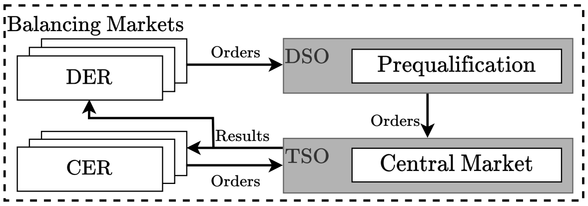


Fig. 2: Balancing markets under Centralized Market model.

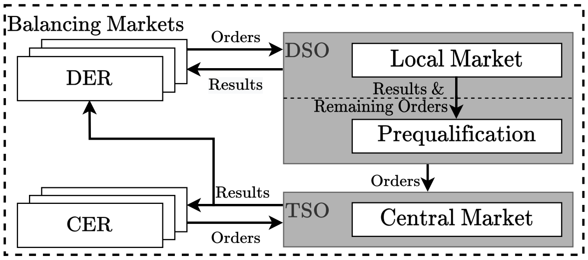


Fig. 3: Balancing markets under Local Market model.

respectively. The volume of each order bounds the amount of power the TSO can procure. Constraints (1b) and (1c) bound the regulation of centralized demands and generators

$$P_d^{D-} \leq \Delta p_d^D \leq P_d^{D+}, \qquad \forall d \in \mathcal{D}^{TS}, \tag{1b}$$

$$P_g^{G-} \leq \Delta p_g^G \leq P_g^{G+}, \qquad \forall g \in \mathcal{G}^{TS}, \tag{1c}$$

where P_d^{D-} and P_g^{G+} are the offering volumes (i.e., sell order, the power injection at the corresponding bus decreases) of demands $d \in \mathcal{D}^{TS}$ and generators $g \in \mathcal{G}^{TS}$, and P_d^{D+} and P_g^{G-} are the corresponding bidding volumes (i.e., buy order, the power injection increases). The power balance of the transmission grid is ensured by the power balance (1d) and the power injection (1e) equality constraints.

$$P_i^{PM} + \sum_{g \in \mathcal{G}_i} \Delta p_g^G - \sum_{d \in \mathcal{D}_i} \Delta p_d^D = p_i, \qquad \forall i \in \mathcal{N}^{TS}, \tag{1d}$$

$$p_i = \sum_{j \in \mathcal{N}^{TS}} B_{ij}(\delta_i - \delta_j), \qquad \forall i \in \mathcal{N}^{TS}, \tag{1e}$$

where p_i is the power injection variable, and δ_i is the voltage angle at bus i, B_{ij} is the susceptance of line (i,j), and P_i^{PM} is the power injection at bus $i \in \mathcal{N}^{TS}$ from the previous market. Sets $\mathcal{D}_i$ and $\mathcal{G}_i$ consist of centralized and distributed resources directly connected to transmission bus i, or connected to the related distribution grid. Next, the power flow of transmission line (i,j) p_{ij}^F, is calculated through (1f). The thermal limit of the line, $P_{ij}^{F,max}$, is respected through constraint (1g)

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

$$-P_{ij}^{F,max} \leq p_{ij}^F \leq P_{ij}^{F,max}, \qquad \forall (i,j) \in \mathcal{L}^{TS}, \tag{1g}$$

where p_{ij}^F is power flow variable of line (i,j). Finally, the available flexibility of DERs is offered through constraint (1h)

$$\mathbf{A}_i^{DS} \begin{bmatrix} \Delta \mathbf{P}^{g \in \mathcal{G}_i^{DS}} \\ \Delta \mathbf{P}^{d \in \mathcal{D}_i^{DS}} \end{bmatrix} \leq \mathbf{b}_i^{DS}, \qquad \forall i \in \mathcal{N}^{TS}, \tag{1h}$$

where $\mathbf{A}_i^{DS}$ is the coefficient matrix for DER orders at the distribution feeder connected to transmission bus i. $\Delta \mathbf{P}^g$ and $\Delta \mathbf{P}^d$ are the vector forms of the power regulation variables for the DERs in the corresponding distribution grid ($g \in \mathcal{G}_i^{DS}$ and $d \in \mathcal{D}_i^{DS}$), and $\mathbf{b}_i^{DS}$ is the prequalified upper bound for the considered DERs. Following the clearance of the central market, the market operator communicates the results to the market participants.

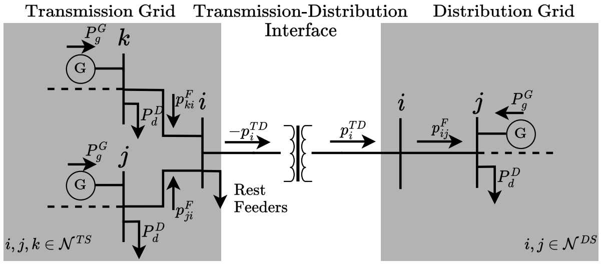


Fig. 4: Transmission-Distribution interface single-line diagram.

B. Local Market Model

The LM coordination model, Fig. 3, suggests a separate local market, where the DSO procures DER flexibility to balance and secure the distribution grid. The introduced local market runs after the IDM and before the central market. The local market clearing algorithm solves Problem 2 with objective (2a) and constraints (2b)-(2h). The objective of the problem aims to minimize the regulation cost and is given by,

$$\text{Minimize} \sum_{d \in \mathcal{D}^{DS}} C_d^D |\Delta p_d^D| + \sum_{g \in \mathcal{G}^{DS}} C_g^G |\Delta p_g^G| \tag{2a}$$

Similar to the central market, the objective is to minimize the regulation cost by utilizing orders of DERs. The orders volume is expressed through constraints (2b) and (2c) as,

$$P_d^{D-} \leq \Delta p_d^D \leq P_d^{D+}, \qquad \forall d \in \mathcal{D}^{DS}, \tag{2b}$$

$$P_g^{G-} \leq \Delta p_g^G \leq P_g^{G+}, \qquad \forall g \in \mathcal{G}^{DS}. \tag{2c}$$

The distribution grid balance is achieved through power balance (2d), (2e), and power injection (2f) constraints.

$$P_i^{PM} + \sum_{g \in \mathcal{G}_i^{DS}} \Delta p_g^G - \sum_{d \in \mathcal{D}_i^{DS}} \Delta p_d^D = p_i, \quad \forall i \in \mathcal{N}^{DS} \backslash \mathcal{N}^{TD}, \tag{2d}$$

$$P_i^{TD,PM} + \Delta p_i^{TD} = p_i^{TD}, \qquad \forall i \in \mathcal{N}^{TD}, \tag{2e}$$

$$p_i = \sum_{j \in \mathcal{N}^{DS}} B_{ij}(\delta_i - \delta_j), \qquad \forall i \in \mathcal{N}^{DS}, \tag{2f}$$

where, Δp_i^{TD} denotes the regulation of power exchange, and p_i^{TD} the total power exchange with the transmission grid through distribution bus i. The interaction at the interface between the two grids is visualized in Fig. 4. $P_i^{TD,PM}$ denotes the power exchange derived from the previous market. Finally, the congestion management of distribution lines ($\mathcal{L}^{DS}$) is achieved through constraints (2g) and (2h).

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

$$-P_{ij}^{F,max} \leq p_{ij}^F \leq P_{ij}^{F,max}, \qquad \forall (i,j) \in \mathcal{L}^{DS}. \tag{2h}$$

Following the local market clearing, the remaining orders are passed to the prequalification stage to build the set of orders that should be transferred to the central market. Nevertheless, the orders have to be pre-processed before the prequalification stage. The pre-processed orders for generator g (i.e., $P_g^{G,BM+}$ and $P_g^{G,BM-}$) are calculated through (3a) and (3b), and orders for demand d (i.e., $P_d^{D,BM+}$ and $P_d^{D,BM-}$) are calculated through (3c) and (3d).

$$P_g^{G,BM+} = \min\left(P_g^{G+}, P_g^{G+} - \Delta P_g^G\right), \quad \forall g \in \mathcal{G}^{DS}, \quad (3a)$$

$$P_g^{G,BM-} = \max\left(P_g^{G-}, P_g^{G-} - \Delta P_g^G\right), \quad \forall g \in \mathcal{G}^{DS}, \quad (3b)$$

$$P_d^{D,BM+} = \min\left(P_d^{D+}, P_d^{D+} - \Delta P_d^D\right), \quad \forall d \in \mathcal{D}^{DS}, \quad (3c)$$

$$P_d^{D,BM-} = \max\left(P_d^{D-}, P_d^{D-} - \Delta P_d^D\right), \quad \forall d \in \mathcal{D}^{DS}. \quad (3d)$$

III. ORDER PREQUALIFICATION

The prequalification of market orders is an essential stage that should be carried out in the framework of coordination models that allow the TSO to procure DER flexibility without considering the distribution grid. The two models considered in this study are the only models allowing this; thus, the DSO has to make sure that the orders forwarded to the central market will not be able to threaten the distribution grid under any activation scenario. A straightforward and effective prequalification scheme is proposed in this work to create a new set of orders. The prequalification scheme suggests that every distribution line should be examined to find the maximum possible power flow with the initial set of orders and identify lines that might get congested. The proposed prequalification scheme can only be applied to radial systems, where the power flow of a line is solely influenced by resources at the downstream buses. Let $\mathcal{D}_{ij} \subseteq \mathcal{D}^{DS}$ and $\mathcal{G}_{ij} \subseteq \mathcal{G}^{DS}$ denote the set of demands and generators at the downstream buses of line (i,j). The maximum possible conventional power flow of line (i,j) is calculated by adding the volume of all buying orders available at the downstream buses of line (i,j) to the current power flow, as in (4a). In an environment with high shares of DERs the reverse power flow should be considered, too; this is achieved by calculating the minimum possible power flow, as in (4b).

$$\overline{p}_{ij}^F = P_{ij}^{F,PM} - \sum_{g \in \mathcal{G}_{ij}} P_g^{G,BM-} + \sum_{d \in \mathcal{D}_{ij}} P_d^{D,BM+}, \forall (i,j) \in \mathcal{L}^{DS}, \quad (4a)$$

$$\underline{p}_{ij}^F = P_{ij}^{F,PM} + \sum_{d \in \mathcal{D}_{ij}} P_d^{D,BM-} - \sum_{g \in \mathcal{G}_{ij}} P_g^{G,BM+}, \forall (i,j) \in \mathcal{L}^{DS}, \quad (4b)$$

where $\overline{p}_{ij}^F$ and $\underline{p}_{ij}^F$ are the maximum and minimum possible power flows for line (i,j), respectively. $P_{ij}^{F,PM}$ is the power flow derived from the previous market (i.e., local market or IDM), and $P_g^{G,BM\pm}$ and $P_d^{D,BM\pm}$ are the order volumes from the submitted orders (CM model) or the pre-processed orders (LM model). The calculation of $\overline{p}_{ij}^F$ and $\underline{p}_{ij}^F$ follows the calculation of the amount of overload for both directions as

$$p_{ij}^{OL+} = \begin{cases} 0, & \overline{p}_{ij}^F - P_{ij}^{F,max} \leq 0 \\ \overline{p}_{ij}^F - P_{ij}^{F,max}, & \overline{p}_{ij}^F - P_{ij}^{F,max} > 0 \end{cases}, \forall (i,j) \in \mathcal{L}^{DS}, \quad (5a)$$

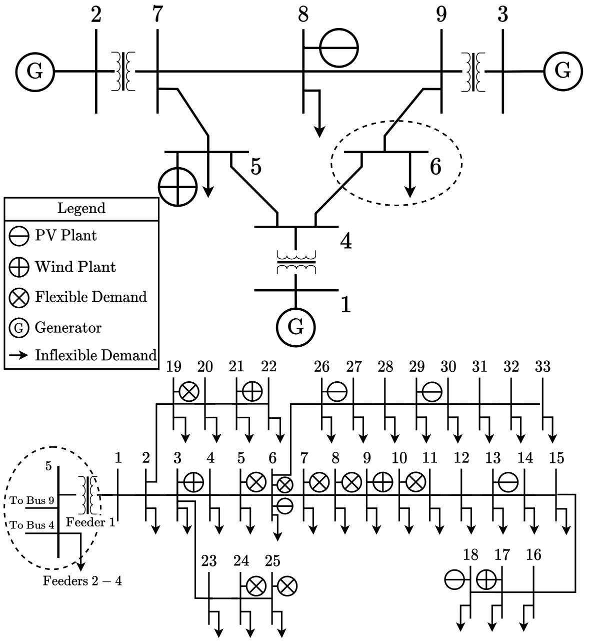


Fig. 5: Transmission grid and distribution feeder single-line diagram.

$$p_{ij}^{OL-} = \begin{cases} 0, & \underline{p}_{ij}^F + P_{ij}^{F,max} \geq 0 \\ |\underline{p}_{ij}^F| - P_{ij}^{F,max}, & \underline{p}_{ij}^F + P_{ij}^{F,max} < 0 \end{cases}, \forall (i,j) \in \mathcal{L}^{DS}, \quad (5b)$$

where p_{ij}^{OL+} is the conventional overload (i.e., $P_{ij}^F > 0$) and p_{ij}^{OL-} is the reverse overload of line (i,j) (i.e., $P_{ij}^F < 0$). Finally, the volume of orders that may create congestion is modified in a weighted manner. Each line is examined separately, and a new set of constraints is built to manage possible congestion for the specific line. Equations (6a) and (6b) show how the lower and upper bounds on generator g are calculated considering line (i,j),

$$P_{g,ij}^{Gnew-} = P_g^{G,BM-} + \frac{-P_g^{G,BM-}}{\sum_{d \in \mathcal{D}_{ij}} P_d^{D,BM+} - \sum_{g \in \mathcal{G}_{ij}} P_g^{G,BM-}} p_{ij}^{OL+},$$
$$\forall g \in \mathcal{G}_{ij}, \forall (i,j) \in \mathcal{L}^{DS}, \quad (6a)$$

$$P_{g,ij}^{Gnew+} = P_g^{G,BM+} - \frac{P_g^{G,BM+}}{\sum_{g \in \mathcal{G}_{ij}} P_g^{G,BM+} - \sum_{d \in \mathcal{D}_{ij}} P_d^{D,BM-}} p_{ij}^{OL-},$$
$$\forall g \in \mathcal{G}_{ij}, \forall (i,j) \in \mathcal{L}^{DS}, \quad (6b)$$

where $P_{g,ij}^{Gnew\pm}$ are the new order volumes for generator g considering line (i,j). The same approach is applied to demands. Once all lines in $\mathcal{L}^{DS}$ are considered, the most conservative orders for each DER are selected to ensure that all lines will be safe in the central market. Finally, the new orders are transferred to the central market.

IV. CASE STUDY - RESULTS

The effectiveness of the proposed prequalification scheme and the performance of the two considered coordination models are evaluated through a comprehensive case study, where the CM and LM models are developed and tested. Fig. 5, depicts the power system used in the simulation. The

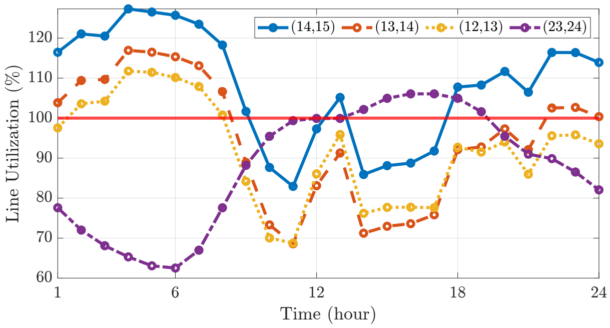


Fig. 6: Distribution lines utilization - Pre-local market.

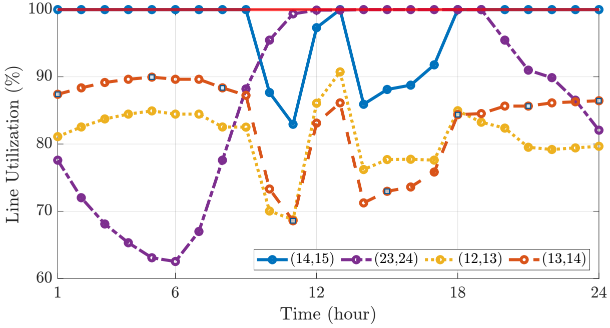


Fig. 7: Distribution line utilization - Post-local market.

IEEE 9-bus test system is used as the transmission grid, and the IEEE 33-bus test feeder is used to apply the proposed algorithms. The test feeder is one out of the four distribution feeders connected to the substation of transmission bus 6 and represents approximately 25% of its load. The results for 24 hours for the balancing markets are presented serially based on the time they are obtained in each coordination model.

A. *Local market*

The local market runs before the prequalification stage when the LM model is adopted; on the contrary, the CM model proceeds without this stage. Fig. 6 shows the power flow of the four most congested distribution lines after the IDM. The congestion observed in the distribution grid is supposed to be managed through the local market, while the CM model does not offer this ability. The power flows of the most utilized distribution lines, following the clearing of the local market, are shown in Fig. 7. The results show that the local market successfully manages to bring the power flows within limits.

B. *Prequalification stage*

Both coordination models suggest the execution of the prequalification stage at this point. The first step of the proposed scheme is the calculation of the maximum possible power flow for each line based on the current orders. Fig. 8a illustrates the maximum possible power flow of potentially congested lines before running the prequalification for the CM model and Fig. 8b for the LM model. In both models, there exist activation combinations leading to congestion that is higher when the CM model is adopted since lines are already congested due to the absence of a local market. After running the prequalification stage, the new orders are used to calculate again the highest possible power flows in order to prove its effectiveness (see Fig. 8c for the CM and Fig. 8d for the LM models). The results indicate that the LM model does not allow the violation of thermal limits when an effective prequalification scheme is utilized. Regarding the CM model, already congested lines, due to the IDM, will remain congested. However, prequalification of market orders eliminated the risk of further overloading lines or overloading other lines. The following indicator is established to measure the Mean Thermal Limit Violation (MTLV) for the 24-hour period after the IDM, after the local market, and before and after the prequalification stage, considering a 1-hour time resolution. Equation (7) calculates the MTLV in the considered grid based on the maximum possible overload for each line and time instant.

$$MTLV = \frac{1}{24|\mathcal{L}|}\sum_{h=1}^{24}\sum_{(i,j)\in\mathcal{L}}[\max(P^{OL+}_{ij,h}, P^{OL-}_{ij,h})] \quad (7)$$

TABLE I: MTLV for the CM and LM models (%)

Model	After IDM	After LM	Before Prequali.	After Prequali.
CM	0.5723	N/A	2.2071	0.5723
LM	0.5723	0	0.6487	0

TABLE II: Total Operating Cost

Model	Local market	Central market	Total
CM	N/A	€50,483	€50,483
LM	€1,280	€52,946	€54,226

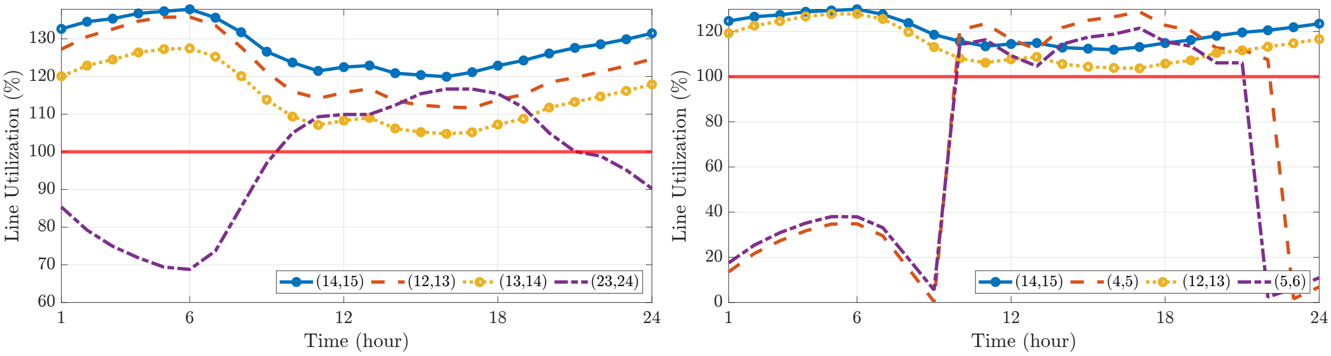
The results tabulated in Table I confirm that there is no congestion after the local market is cleared. In addition, the potential overloading of lines is higher in the case of the CM model due to existing congestion and the fact that no order was activated earlier, in the absence of a local market. After the execution of the prequalification, the LM model successfully manages congestion, while the other model limits congestion to the post-IDM levels.

C. *Central market*

The new set of DER orders, along with CER orders are used to clear the central market, which balances the transmission grid based on the updated power exchange with active distribution grids and the updated forecast for the centralized demands and generators. It is assumed that the demands increased by 5% since the clearing of the IDM and that there is no congestion in the transmission grid; the central market successfully cleared in both CM and LM models. The total operating cost is tabulated in Table II, showing less cost for the CM model. However, this is expected since there is no local market and the congestion in the distribution is not managed. In addition, the two-market approach compromises economic efficiency since the cheapest resources are utilized in the local market leaving fewer, more expensive orders for the central market that has to deal with the changes in the power exchange due to the local market. On the other hand, the central market deals only with the changes in centralized demand and generation.

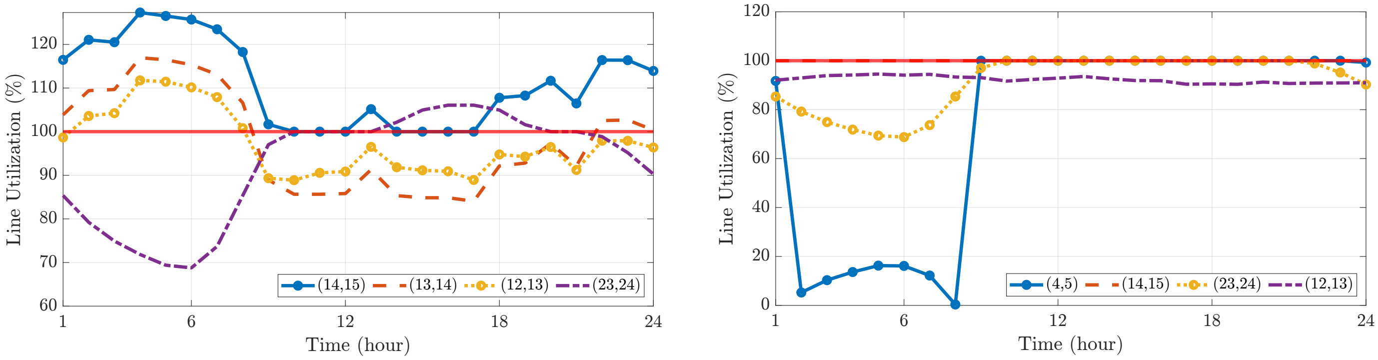
V. CONCLUSIONS

In this study, an order prequalification scheme is proposed and incorporated into two TSO-DSO coordination models



(a) Centralized Market model - Before prequalification

(b) Local Market model - Before prequalification



(c) Centralized Market model - After prequalification

(d) Local Market model - After prequalification

Fig. 8: Maximum possible power flow before and after the application of the proposed prequalification method for both coordination models.

to enhance coordination in an environment with high DER penetration. The proposed scheme modifies in a weighted manner the market orders of resources that may overload a distribution line if activated to ensure that the actions of the TSO will not affect the distribution grid. The effectiveness of the proposed scheme was evaluated on a power system where the two coordination models were used. The comparison between the two models revealed the inability of the CM model to cope with distribution grid-related issues. In addition, the proposed prequalification scheme managed to successfully eliminate the risk of creating congestion in the case of the LM model, while did not allow for intensifying the existing congestion in the CM model. This study indicates that the LM model is superior to the CM model since it respects the grid constraints for transmission and distribution, even though it is more complex and less efficient in terms of cost.

REFERENCES

[1] A. Saint-Pierre and P. Mancarella, "Active distribution system management: A dual-horizon scheduling framework for DSO/TSO interface under uncertainty," *IEEE Trans. on Smart Grid*, vol. 8, no. 5, pp. 2186–2197, 2017.

[2] C. Feng, Z. Li, M. Shahidehpour, F. Wen, W. Liu, and X. Wang, "Decentralized short-term voltage control in active power distribution systems," *IEEE Trans. on Smart Grid*, vol. 9, no. 5, pp. 4566–4576, 2018.

[3] R. A. Verzijlbergh, L. J. De Vries, and Z. Lukszo, "Renewable energy sources and responsive demand. Do we need congestion management in the distribution grid?," *IEEE Trans. on Power Syst.*, vol. 29, no. 5, pp. 2119–2128, 2014.

[4] J. P. Holguin, D. C. Rodriguez, and G. Ramos, "Reverse Power Flow (RPF) detection and impact on protection coordination of distribution systems," *IEEE Trans. on Industry Appl.*, vol. 56, no. 3, pp. 2393–2401, 2020.

[5] H. Gerard, E. I. Rivero Puente, and D. Six, "Coordination between transmission and distribution system operators in the electricity sector: A conceptual framework," *Utilities Policy*, vol. 50, pp. 40–48, Feb. 2018.

[6] C. Rodio, G. Giannoccaro, S. Bruno, M. Bronzini, and M. La Scala, "Optimal dispatch of distributed resources in a TSO-DSO coordination framework," in *Proc. 2020 AEIT Int. Annu. Conf. (AEIT),* Catania, Italy, pp. 1–6, 2020.

[7] N. Savvopoulos, T. Konstantinou, and N. Hatziargyriou, "TSO-DSO coordination in decentralized ancillary services markets," in *Proc. 2019 Int. Conf. on Smart Energy Syst. and Technol. (SEST),* Porto, Portugal, pp. 1–6, 2019.

[8] A. Sanjab, H. Le Cadre, and Y. Mou, "TSO-DSOs stable cost allocation for the joint procurement of flexibility: A cooperative game approach," *IEEE Trans. on Smart Grid*, vol. 13, no. 6, pp. 4449–4464, 2022.

[9] C. Madina, P. Kuusela, M. Rossi, and H. Aghaie, "Optimised TSO-DSO coordination to integrate renewables in flexibility markets," in *Proc. 2019 16th Int. Conf. on the Eur. Energy Market (EEM),* Ljubljana, Slovenia, pp. 1–6, 2019.

[10] A. Roos, "Designing a joint market for procurement of transmission and distribution system services from demand flexibility," *Renewable Energy Focus*, vol. 21, pp. 16–24, 2017.

[11] A. Vicente-Pastor, J. Nieto-Martin, D. W. Bunn, and A. Laur, "Evaluation of flexibility markets for Retailer–DSO–TSO coordination," *IEEE Trans. on Power Syst.*, vol. 34, no. 3, pp. 2003–2012, 2019.

[12] I. Papayiannis, M. Asprou, L. Hadjidemetriou, and S. Timotheou, "Prequalification of distribution resources in a coordinated market environment," in *Proc. 2022 IEEE Power & Energy Soc. General Meeting (PESGM),* Dencer, CO, USA, pp. 1–5, 2022.

[13] H. S. Moon, Y. G. Jin, Y. T. Yoon, and S. W. Kim, "Prequalification scheme of a distribution system operator for supporting wholesale market participation of a distributed energy resource aggregator," *IEEE Access*, vol. 9, pp. 80434–80450, May 2021.

[14] C. Edmunds, S. Galloway, I. Elders, W. Bush, and R. Telford, "Design of a DSO-TSO balancing market coordination scheme for decentralised energy," *IET Gener. Transmiss. & Distribution*, vol. 14, pp. 707–718, Mar. 2020.