Coordinated Trading of Capacity and Balancing Products in Multi-Area Local Flexibility Markets.

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November 23, 2022

Abstract

In a scenario with high penetration of renewable and distributed energy resources, Local Flexibility Markets (LFMs) emerge to enhance operation of distribution networks. They deal with new consumption patterns, flexibility, and storage systems to mitigate imbalances and congestions. In recent years, efforts toward the definition of stand-alone LFMs have been made, enabling energy trading in isolated systems. This paper present an alternative solution for congestion and imbalance mitigation using capacity and balancing flexibility products. Products prices are defined considering their intrinsic relation with traditional markets, what enhances compatibility and enables full deployment of this local structures. Besides of that, using the properties of an adaptive ADMM algorithm, the market clearing problem is solved under a Multi-Area setting while information privacy is preserved. The feasibility of the proposed approach is demonstrated on a radial network based on the IEEE 34 bus system, where the solution for the two-area LFM is found in four tens iterations. Furthermore, the scalability analysis provides shows a linear relation between the number of areas and the convergence.

Keywords
Local markets, coordination, capacity products, balancing products, ADMM

Nomenclature

Parameters are in upper case letter and variables in lower case letter. $|\Omega|$ denotes the cardinality of the set Ω.

Acronyms

ADMM	Alternating Direction Method of Multipliers.
BESS	Battery Energy Storage System.
DSO	Distribution System Operator.
FG	Flexible Generator.
FL	Flexible Load.
LFM	Local Flexibility Market.
LMO	Local Market Operator.
SOC	State of Charge.

Indices and sets

a, f, g, s	Indices for agents, FLs, FGs, BESSs.
$\Omega_a, \Omega_f, \Omega_g, \Omega_s$	Sets for agents, FLs, FGs and BESSs.
$t,\ \Omega_t$	Index and set for time periods, $t \in \Omega_t$.
$i, j,\ \Omega_i$	Indices and set for buses, $(i, j) \in \Omega_i$.
$p,\ \Omega_p$	Index and set for areas of the market $p \in \Omega_p$.
k	Iteration counter.

*Á. Paredes and J. A. Aguado work were partially supported by Junta de Andalucia (Spain) Project Ref: P20_01164 and by the University of Málaga. Á. Paredes was also supported by the FPU grant (FPU19/03791) funded by the Spanish Ministry of Education.

Parameters

$B_{i,j}$	Susceptance of the line i, j (S).
$\overline{P}_{i,j}$	Thermal limit of the line i, j (kW).
$S^{c,u}_{a,t}$, $S^{c,d}_{a,t}$	Capacity c product prices of agent a in period t in upward u and downward d directions (€/kW).
$S^{b,u}_{a,t}$, $S^{b,d}_{a,t}$	Balancing b product prices of agent a in period t in upward u and downward d directions (€/kWh).
S_t	Wholesale market price at period t (€/kWh).
$P^{sch}_{a,t}$	Scheduled sch power for agent a in period t (kW).
$\overline{P}_a$, $\underline{P}_a$	Upper and lower bound for agent a (kW).
P^{conv}_s	Converter power rating for BESS s (kW).
$\overline{SOC}_s$, $\underline{SOC}_s$, $SOC0_s$	Upper bound, lower bound and initial SOC of BESS s (kWh).
γ_k	Penalty factor at iteration k (p.u.).
ε	Convergence tolerance (p.u.).

Variables

$\sigma^{c,u}_{a,t}$, $\sigma^{c,d}_{a,t}$	Capacity c products of agent a in period t in upward u and downward d directions (kW).
$\omega^{b,u}_{a,t}$, $\omega^{b,d}_{a,t}$	Balancing b products of agent a in period t in upward u and downward d directions (kWh).
$soc_{s,t}$	State of charge for BESS s in period t (kWh).
$\theta_{i,t}$	Voltage phase angle in bus i in period t (rad).
$p_{i,j,t}$	Power flow between bus i and j in period t (kW).
$cc_{a,t}$, $cb_{a,t}$	Cost of capacity and balancing products traded by agent a in period t (€).
λ^{imb}_t	Dual variable associated to the overall balance imb equation in period t (€/kWh).
λ^u_t λ^d_t	Lagrange multipliers associated to upward u and downward d capacity restrictions in period t (€/kW).
x^p	General variable x of area p.

1 Introduction

In a scenario with distributed resources, energy communities and individuals helping the operation of distribution systems, the irruption of Local Flexibility Markets (LFMs) is unavoidable [17]. LFMs naturally arise as a new layer of the traditional market structures to solve local issues using local resources, reducing grid reinforcements and helping Distribution System Operators (DSOs) in their daily operation tasks [18]. In this sense, these markets solve operational problems of distribution systems, such as congestions [8] and imbalances [21]. Some examples of pilot projects whose objective is to thoroughly investigate this approach from a centralized perspective are CoordiNET [10], INTERFACE [14], and DREAM-GO [9].

In this context, depending on the type of architecture proposed of the LFM different agents are included in its definition. Reference [12] situates the aggregator as the central entity of the market, beware of the delivery of flexible products to the DSO, using also the figure of balance responsible parties which oversees the balance between load and generation. Another approach presented in [15] assign balancing obligations to the DSO, and in [3] distributed energy resources directly participates in the market. Although this scheme incentives the participation of agents, new operation schemes that preserve privacy while ensuring system-wide efficiency are needed for the sake of a fast deployment [6]. Viewed in this way, most of the market platforms proposed override the solution of upstream markets, in benefit of the local one [11, 16, 20]. To overcome this issue, this paper considers the price link between flexibility products and the wholesale market price. Thus, the local clearing methodology can be fully integrated with the current structures. Additionally, capacity and energy products are jointly integrated in this market, incentivizing trading and enhancing liquidity [13].

Conventionally, electrical markets have been cleared using a centralized fashion, where the market operator has all the information about market participants, their asks and offers [18]. Conversely, in a context with high penetration of distributed energy resources deployed over several areas with rising concerns about privacy issues, decentralized approaches must be addressed. Among them, peer-to-peer trading [11] provides solution to a market clearing problem where agents directly interacts with each other, hierarchical approaches [16] can be also used for decentralization, but assume that some agents have control over others, sending, for example, grid usage prices to obtain a determined market response [20]. In this paper, a protocol based on the Alternating Direction Method of Multipliers (ADMM) is used to coordinately solve the multi-area LFM in a decentralized setting, without compromising current regulatory foundation.

The major contributions of this paper are:

- A novel multi-area LFM platform fully compatible with current electrical market structures that mitigates imbalances and congestions by means of using capacity and balancing products of distributed energy resources.

- A coordinated and decentralized market clearing protocol for the multi-area LFM using an adaptive ADMM that preserve the privacy of the participating agents.
- A scalability analysis of the market clearing algorithm for different number of areas.

The remaining of this paper is organized as follows. Section II defines and formulates the centralized version of the LFM. Then, Section III presents the decentralization process and the coordination mechanism among areas. Section IV offers simulation results and a scalability assessment. Lastly, Section V concludes the paper.

2 Multi-Area LFM clearing problem formulation

An overview of the Multi-Area LFM market structure proposed in this paper is presented in Fig. 1. Agents present their offers within their areas when the DSO organizes a market to mitigate congestions or imbalances. The Local Market Operator (LMO) coordinates the market solution, helping agents to interact among them without sharing private information. The proposed multi-area LFM is cleared after the wholesale market, correcting deviations inside a time horizon near to real-time.

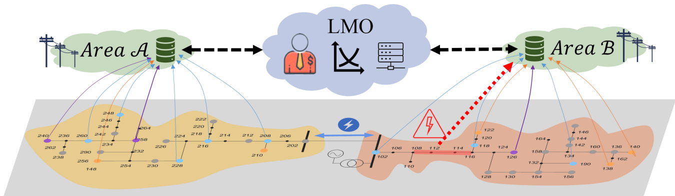

Figure 1: Multi-Area LFM information exchanges representation among agents, DSOs and LMO when mitigating a congestion.

The market includes Flexible Loads (FLs), Flexible Generators (FGs) and Battery Energy Storage Systems (BESSs) as agents distributed in $|\Omega_p|$ independent areas which do not aim to share information. Two different products are traded, capacity products are used to hold back the capabilities of the assets in anticipation of future operational problems [19]. Then, if necessary, balancing products are bought to finally solve the contingency. This section will describe the market clearing problem formulation.

2.1 Objective function

The market mitigate congestions and imbalances at minimum expenditure. The cost for balancing and capacity products is minimized all over areas $p \in \Omega_p$, for all agents $a \in \Omega_a$ and time periods $t \in \Omega_t$ using the next objective function,

$$\min \sum_{p\in\Omega_p} \sum_{t\in\Omega_t} \sum_{a\in\Omega_a} (cb^p_{a,t} + cc^p_{a,t}) \tag{1}$$

Balancing and capacity product costs are detailed in (2) and (3), respectively. Energy products are related with wholesale market prices following [13].

$$cb_{a,t} = (S_t - S^{b,u}_{a,t})\,\omega^{b,u}_{a,t} + (S^{b,d}_{a,t} - S_t)\,\omega^{b,d}_{a,t} \qquad \forall a \in \Omega_a, \forall t \in \Omega_t \tag{2}$$

$$cc_{a,t} = S^{c,u}_{a,t}\,\sigma^{c,u}_{a,t} + S^{c,d}_{a,t}\,\sigma^{c,d}_{a,t} \qquad \forall a \in \Omega_a, \forall t \in \Omega_t \tag{3}$$

This objective is subject to market, agent and network constraints, as following sections assess.

2.2 Market constraints

Balancing and capacity market rules are described in this section. Let imb^p_t be the imbalance created by area p in period t. The balance of the system is maintained if and only if the sum over all areas $p \in \Omega_p$ adds up to zero, as presented in (4). This restriction ensures that the market clearing solution is consistent with former wholesale market solution. The imbalance of each area is calculated in (5) as the difference between the power output of the agents prior and after the market clearing [13]. The dual variable associated to this equation, λ^{imb}_t, represents the marginal costs for balancing products.

$$\sum_{p\in\Omega_p} imb^p_t = 0 \quad : \lambda^{imb}_t \qquad \forall t \in \Omega_t \tag{4}$$

$$imb_t^p = \sum_{a\in\Omega_a^p} (P_{a,t}^{sch} - p_{a,t}^{am}) = 0 \qquad \forall p \in \Omega_p, \forall t \in \Omega_t \quad (5)$$

The total volume of capacity products needed in the network is defined as a function of the imbalance created in each direction. Let Δt be the time period duration, and R^u, R^d be upward and downward rate between products. Then capacity volume for upward and downward directions are presented in (6) and (7), respectively. R^u and R^d stands between $[1.05, 1.10]$ to cover events with uncertainty [19]. Dual variables λ_t^u and λ_t^d, associated to these equations, represent the marginal cost of the capacity products.

$$\sum_{p\in\Omega_p} cap_t^{u,p} \cdot \Delta t \geq R^u \sum_{p\in\Omega_p} bal_t^{u,p} \quad : \lambda_t^u \qquad \forall t \in \Omega_t \quad (6)$$

$$\sum_{p\in\Omega_p} cap_t^{d,p} \cdot \Delta t \geq R^d \sum_{p\in\Omega_p} bal_t^{d,p} \quad : \lambda_t^d \qquad \forall t \in \Omega_t \quad (7)$$

Balancing $bal_t^{u,p}, bal_t^{d,p}$ and capacity $cap_t^{u,p}, cap_t^{d,p}$ products volume for upward u and downward d directions in area p and period t, are computed from (8) to (11).

$$bal_t^{u,p} = \sum_{a\in\Omega_a^p} \omega_{a,t}^{b,u} \qquad \forall p \in \Omega_p, \forall t \in \Omega_t \quad (8)$$

$$bal_t^{d,p} = \sum_{a\in\Omega_a^p} \omega_{a,t}^{b,d} \qquad \forall p \in \Omega_p, \forall t \in \Omega_t \quad (9)$$

$$cap_t^{u,p} = \sum_{a\in\Omega_a^p} \sigma_{a,t}^{c,u} \qquad \forall p \in \Omega_p, \forall t \in \Omega_t \quad (10)$$

$$cap_t^{d,p} = \sum_{a\in\Omega_a^p} \sigma_{a,t}^{c,d} \qquad \forall p \in \Omega_p, \forall t \in \Omega_t \quad (11)$$

Besides of this, capacity and energy products are also related from an agent perspective in (12). This restriction avoid that agents push balancing products further away of what have been previously cleared in the capacity dimension [1].

$$\omega_{a,t}^u \leq \sigma_{a,t}^u \Delta t, \;\; \omega_{a,t}^d \leq \sigma_{a,t}^d \Delta t \qquad \forall a \in \Omega_a, \forall t \in \Omega_t \quad (12)$$

2.3 Agent constraints

FLs demand is enclosed between a lower and upper bound $\underline{P}_f \leq p_{f,t}^{am} \leq \overline{P}_f$. The demand of FL f in period t after market clearing is presented in (13), being only influenced by balancing products $\omega_{f,t}^{b,u}$ and $\omega_{f,t}^{b,d}$. Upper bounds for capacity products $\sigma_{f,t}^{c,u}, \sigma_{f,t}^{c,d}$ are shown in (14) based on the demand limits $\underline{P}_f, \overline{P}_f$ and scheduled demand $P_{f,t}^{sch}$.

$$p_{f,t}^{am} = P_{f,t}^{sch} + \frac{1}{\Delta t}(\omega_{f,t}^{b,u} - \omega_{f,t}^{b,d}) \qquad \forall f \in \Omega_f, \forall t \in \Omega_t \quad (13)$$

$$\sigma_{f,t}^{c,u} \leq \overline{P}_f - P_{f,t}^{sch}, \;\; \sigma_{f,t}^{c,d} \leq P_{f,t}^{sch} - \underline{P}_f \qquad \forall f \in \Omega_f, \forall t \in \Omega_t \quad (14)$$

Similarly, the generation output after market operation $p_{g,t}^{am}$ is presented in (15) considering that FG g is able to modify its generation in both directions $\underline{P}_g \leq p_{g,t}^{am} \leq \overline{P}_g$, e.g. biomass plant. Being disconnection ($\underline{P}_g = 0$) considered as the lowest limit for generation production, capacity offers bounds are set in (16).

$$p_{g,t}^{am} = P_{g,t}^{sch} + \frac{1}{\Delta t}(\omega_{g,t}^{b,u} - \omega_{g,t}^{b,d}) \qquad \forall g \in \Omega_g, \forall t \in \Omega_t \quad (15)$$

$$\sigma_{g,t}^{c,u} \leq \overline{P}_g - P_{g,t}^{sch}, \;\; \sigma_{g,t}^{c,d} \leq P_{g,t}^{sch} \qquad \forall g \in \Omega_g, \forall t \in \Omega_t \quad (16)$$

Operation limits for BESSs are set by the State of Charge (SOC) and the converter rating P_s^{conv}. Power of BESS s after market operation is only modified by balancing products $\omega_{s,t}^{b,u}, \omega_{s,t}^{b,d}$ as computed in (17). Converter rating set bounds for power of BESSs, $-P_s^{conv} \leq p_{s,t}^{am} \leq P_s^{conv}$ for all $s \in \Omega_s$ and periods $t \in \Omega_t$. Bounds for the SOC of BESS s are set considering $\underline{SOC}_s \leq soc_{s,t} \leq \overline{SOC}_s$. For the sake of a realistic modelling, initial and last SOC are fixed considering $soc_{s,0} = soc_{s,|\Omega_t|} = SOC0_s$. Let η_s^C, η_s^D be the charging and discharging efficiencies of the BESS s, SOC is calculated in (18). Lastly, capacity products limits are computed from (19) to (21).

$$p_{s,t}^{am} = \frac{1}{\Delta t}(\omega_{s,t}^{b,u} - \omega_{s,t}^{b,d}) \qquad \forall s \in \Omega_s, \forall t \in \Omega_t \quad (17)$$

$$soc_{s,t} = soc_{s,t-1} + \eta_s^C \omega_{s,t}^{b,u} - \frac{\omega_{s,t}^{b,d}}{\eta_s^D} \qquad \forall s \in \Omega_s, \forall t \in \Omega_t \quad (18)$$

$$\sigma_{s,t}^{c,u} \leq P_s^{conv},\ \sigma_{g,t}^{c,d} \leq P_s^{conv} \qquad \forall s \in \Omega_s, \forall t \in \Omega_t \quad (19)$$

$$\sigma_{s,t}^{c,u} \leq \frac{\overline{SOC}_s - soc_{s,t-1}}{\eta_s^C \Delta t} \qquad \forall s \in \Omega_s, \forall t \in \Omega_t \quad (20)$$

$$\sigma_{s,t}^{c,d} \leq \frac{\eta_s^D (soc_{s,t-1} - \underline{SOC}_s)}{\Delta t} \qquad \forall s \in \Omega_s, \forall t \in \Omega_t \quad (21)$$

2.4 Network constraints

We assume a DC modelling of the grid, presenting node balance in (22) and branch thermal limits $\overline{P}_{i,j}$ in (23). This approach is widely used in market studies, as it allows modelling congestions and imbalances without limiting the physical interpretation of the dual variables of the problem [4].

$$\sum_{j \in \Omega_i} B_{i,j}(\theta_{i,t} - \theta_{j,t}) = p_{i,t} + p_{a,t}^{am} \qquad \forall i \in \Omega_i, \forall t \in \Omega_t \quad (22)$$

$$-\overline{P}_{i,j} \leq B_{i,j}(\theta_{i,t} - \theta_{j,t}) \leq \overline{P}_{i,j} \qquad \forall i,j \in \Omega_i, \forall t \in \Omega_t \quad (23)$$

3 Solution Approach for decentralized Multi-Area LFMs

In the decentralized version of the problem, each area presents its offers to the LMO. To this end, we use an adaptive ADMM scheme where the penalty factor γ_k is modified in each iteration k [4]. The multi-area market clearing problem is decentralized and solved iteratively.

3.1 Coordination procedure

The coordination of the solution is attained exchanging information through tie-lines, as Fig. 2 shows. To this end, each area shares information about the imbalance imb_t^p, balancing products $bal_t^{u,p}, bal_t^{d,p}$, capacity products $cap_t^{u,p}, cap_t^{d,p}$, and voltage phase angle θ_t^p at interconnection. After solving the clearing problem each area send information to LMO which update and distributed dual information among areas.

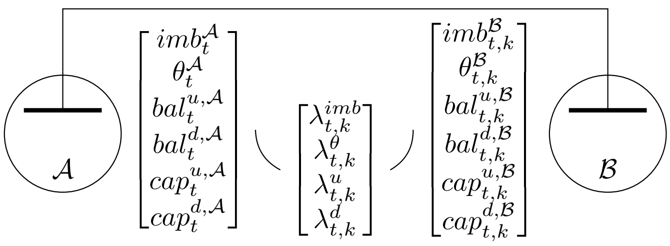

Figure 2: Representation of the information exchanges to attain coordination when solving the market clearing problem.

3.2 Area subproblem

This section describes the subproblem for one area $\mathcal{A}$ in a two-area LFM, as presented in Fig. 2. Let $\boldsymbol{\lambda}_k$ be the vector of multipliers and $\boldsymbol{u}_k^{\mathcal{A}}$ be the vector of complicating constraints. The subproblem has the form,

$$\begin{aligned} \min \sum_{t \in \Omega_t} \sum_{a \in \Omega_a^{\mathcal{A}}} (cb_{a,t}^{\mathcal{A}} + cc_{a,t}^{\mathcal{A}}) + \boldsymbol{\lambda}_k \boldsymbol{u}_k^{\mathcal{A}} + \frac{\gamma_k}{2} \|\boldsymbol{u}_k^{\mathcal{A}}\|_2^2 \\ \text{subject to } (2) - (5),\ (8) - (11),\ (12) - (23) \end{aligned} \quad (24)$$

Vectors $\boldsymbol{u}_k^{\mathcal{A}} = [\boldsymbol{u}_{k,1}^{\mathcal{A}}, \cdots, \boldsymbol{u}_{k,t}^{\mathcal{A}}]$ and $\boldsymbol{\lambda}_k = [\boldsymbol{\lambda}_{k,1}, \cdots, \boldsymbol{\lambda}_{k,t}]^T$ are defined from (25) to (30).

$$\boldsymbol{u}_{k,t}^{\mathcal{A}} = [h_{t,k}^{imb,\mathcal{A}}\ h_{t,k}^{\theta,\mathcal{A}}\ g_{t,k}^{u,\mathcal{A}}\ g_{t,k}^{d,\mathcal{A}}] \qquad \forall t \in \Omega_t \quad (25)$$

$$\boldsymbol{\lambda}_{k,t} = [\lambda_{t,k}^{imb}\ \lambda_{t,k}^{\theta}\ \lambda_{t,k}^{u}\ \lambda_{t,k}^{d}]^T \qquad \forall t \in \Omega_t \quad (26)$$

$$h_{t,k}^{imb,\mathcal{A}} = imb_t^{\mathcal{A}} + imb_{t,k}^{\mathcal{B}} \qquad \forall t \in \Omega_t \quad (27)$$

$$h_{t,k}^{\theta,\mathcal{A}} = \theta_t^{\mathcal{A}} - \theta_{t,k}^{\mathcal{B}}, \qquad \forall t \in \Omega_t \quad (28)$$

$$g_{t,k}^{u,\mathcal{A}} = R^u \left(bal_t^{u,\mathcal{A}} + bal_{t,k}^{u,\mathcal{B}}\right) - \left(cap_t^{u,\mathcal{A}} + cap_{t,k}^{u,\mathcal{B}}\right) \qquad \forall t \in \Omega_t \quad (29)$$

$$g_{t,k}^{d,\mathcal{A}} = R^d \left(bal_t^{d,\mathcal{A}} + bal_{t,k}^{d,\mathcal{B}}\right) - \left(cap_t^{d,\mathcal{A}} + cap_{t,k}^{d,\mathcal{B}}\right) \qquad \forall t \in \Omega_t \quad (30)$$

3.3 Multipliers and penalty factor update

After solve all the subproblems, Lagrange's multipliers are updated following (31).

$$\boldsymbol{\lambda}_{t,k+1} = \boldsymbol{\lambda}_{t,k} + \gamma_k \boldsymbol{u}_{t,k}^T \qquad \forall t \in \Omega_t \quad (31)$$

Penalty factor γ_k is updated in (32) using primal $\|r_k\|_2$ and dual $\|s_k\|_2$ residuals [2, 4]. Primal residual is computed as $\|r_k\|_2 = \|\boldsymbol{u}_k\|_2$. Considering z_k as the vector of complicating variables, dual residual is defined so that $\|s_k\|_2 = \|z_k - z_{k-1}\|_2$. Parameters μ and τ are fixed to 22 and 25, respectively.

$$\gamma_{k+1} = \begin{cases} \tau\gamma_k & if \ \ \|r_k\|_2 > \mu\|s_k\|_2 \\ \gamma_k/\tau & if \ \ \|s_k\|_2 > \mu\|r_k\|_2 \\ \gamma_k & otherwise \end{cases} \quad (32)$$

3.4 Stopping criterion and clearing algorithm

The stopping criterion is presented in (33). Typical choices for ε ranges between 10^{-2} and 10^{-3} for complicating variables [5]. A flowchart of the decentralized Multi-Area LFM clearing problem is presented in Fig. 3.

$$\max\{\|r_k\|_2, \|s_k\|_2\} \leq \varepsilon \quad (33)$$

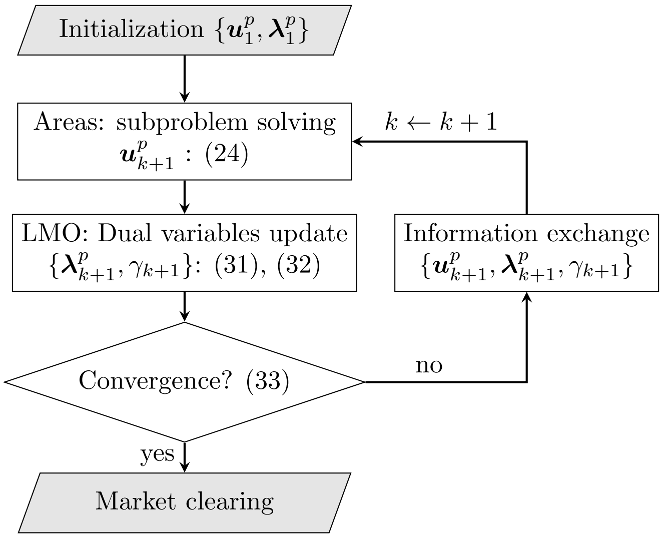

Figure 3: Flowchart of the decentralized clearing problem protocol for Multi-Area LFM joint balancing and capacity markets.

4 Case Study and Simulation Results

Figure 4 lays out a case study based on the IEEE-34 test network [7]. This case study demonstrates the feasibility of the proposed approach to mitigate congestions and imbalances. Without loss of generality, LFM is solved for periods of $\Delta t = 15$ minutes. Then, the scalability properties are investigated.

4.1 Case Study

A congestion in line 202-206 of the network presented in Fig. 4 is mitigated with this approach. The result of the Multi-Area LFM is presented in Fig. 5. The power flow through line 202-206 is limited to 500 kW, this congestion

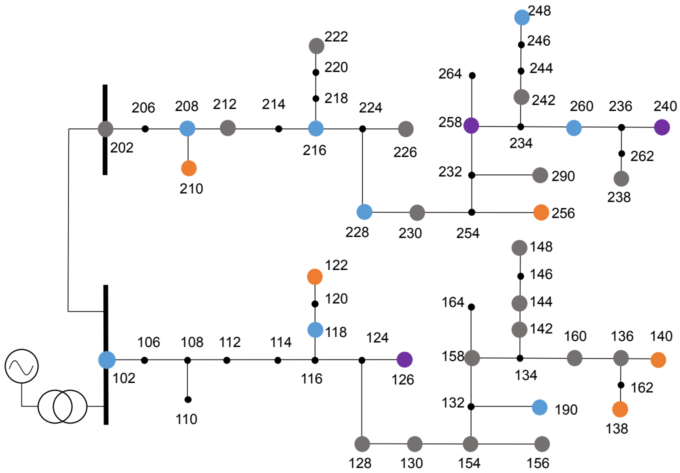

Figure 4: IEEE-34 based case study. Static loads - grey, FLs - blue, FGs - orange and BESSs - purple.

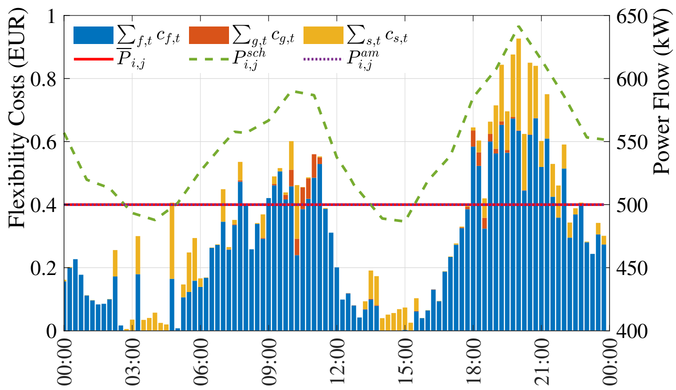

Figure 5: Costs of the products exchanged by FLs (blue), FGs (orange) and BESSs (yellow) and power flow through line 202-206 before (dashed green) and after (dashed purple) market operation. Thermal limit is presented in red.

is solved by means of using the flexibility products of FLs, FGs, and BESSs. The power flow after market clearing is coincident with the thermal limit.

Figure 6 compares residuals evolution for the standard and the adaptive version of the ADMM protocol. Considering a convergence criterion of $\varepsilon = 10^{-3}$, 41 iterations and 48 s are needed to simulate a complete day of operation in a personal computer with an Intel i7-4720 HQ 2.60 GHz with 16 GB of RAM under GAMS software. Opposed to the adaptive version, dual residual of the standard ADMM does not reach the convergence criterion established.

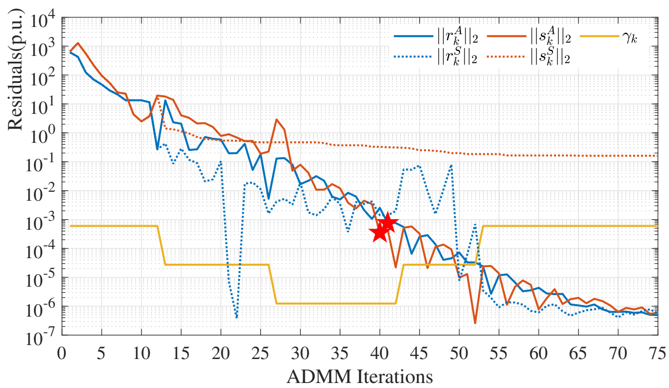

Figure 6: Primal (blue) and dual (orange) residuals evolution considering standard ($||r_k^S||_2, ||s_k^S||_2$) (dashed) and adaptive ($||r_k^A||_2, ||s_k^A||_2$) version (solid) and penalty factor γ_k evolution through iterations (yellow).

Evolution of the total costs and the imbalance among areas is presented in Fig. 7. Each iteration represents interaction between area $\mathcal{A}$ and $\mathcal{B}$ through LMO before reaching convergence. During first iterations, only area $\mathcal{B}$ provide downward flexibility as a response to the congestion. In following iterations, area $\mathcal{A}$ balances the market with upward flexibility. Convergence is reached when imbalances of all areas are compensated. The total cost is

29.799 € for a total volume of 4.468 MWh for the operation of the whole day.

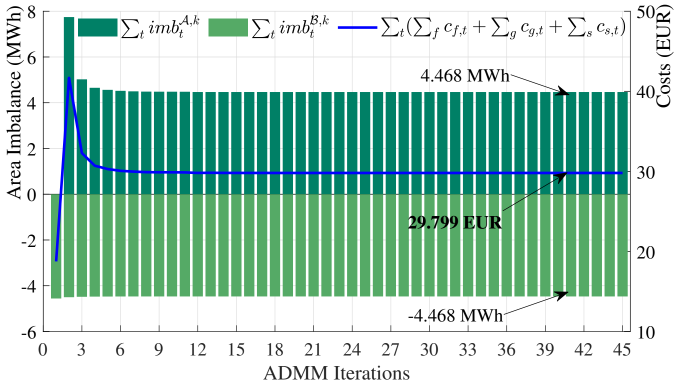

Figure 7: Evolution of the $\sum imb_{t,k}^{p}$ and costs of operation. Upward and downward directions are represented by positive and negative semiaxis, respectively.

Flexibility products distribution is shown in Fig. 8. Capacity products are traded in a 15-min time basis, resulting in high power low energized transactions. The marginal price of capacity products increases in periods with high needs, e.g. 10:00 or 21:00, as more expensive agents came into action.

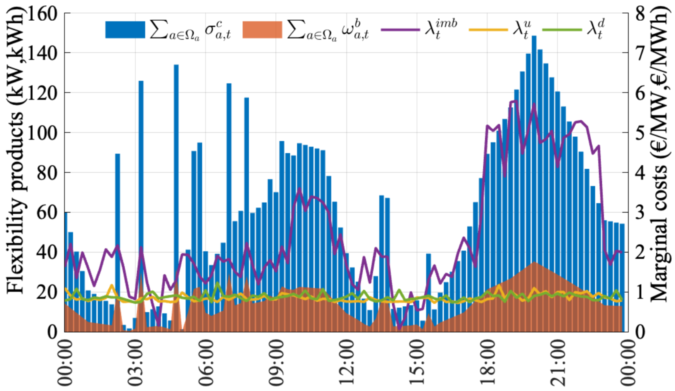

Figure 8: Representation of the capacity products (blue), energy products (orange), and marginal costs for balancing (purple), upward (yellow) and downward (green) capacity products.

4.2 Scalability

Scalability of the proposed approach is assessed by adding new IEEE-34 networks to the model, so each one is defined as an independent area. Number of participating agents increase from 16 assets, in the case study with two areas, to 60 assets, in the case study with 8 areas. The adaptive ADMM converge iterations presents a linear relationship with the number of areas p so $k \sim O(p)$, as Fig. 9 presents. However, as the number of areas increases, it also does the number of subproblems to be solved, so the time to reach convergence grows with the second power of the areas $t \sim O(p^2)$.

5 Conclusions

This paper has presented a Multi-Area LFM for congestion and imbalance mitigation using balancing and capacity products. The former protects against uncertainty of flexibility sources holding back the capabilities of the agents, and the latter provides solution to operational constraints. The market clearing problem is solved using an adaptive ADMM protocol, while preserving information privacy of the agents.

Flexibility products quantity, overall imbalance, voltage phase angle at interconnection as well as dual variables are the signals that attain coordination in the market clearing protocol, achieving serviceable solutions for network operation.

A case study based on the IEEE-34 bus system demonstrate the relevance of an adaptive ADMM algorithm for coordination, achieving better results than the standard version. Furthermore, from the scalability analysis

(a) (b)

Figure 9: Impact of the number of areas on iterations and time for convergence.

performed, iterations are linearly related with then number of areas and the elapsed time is reasonable for local communities to operate near real time.

Future lines of research will explore new descriptions of joint energy and capacity LFMs, explicitly considering the uncertainty sources of the assets involved in the market operation, and the parallelization of the ADMM protocol.

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