Privacy-Preserving Flexibility Provisioning with an Optimization Approach for Enhanced TSO-DSO Interaction in Modern Power Systems

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***Abstract*—Achieving a carbon-neutral power grid involves significant transformations, including the integration of flexibility-providing units (FPUs) predominantly connected to low-voltage distribution systems (DSs). Although these transformations complicate grid management, DS flexibility offers substantial potential for market development and grid optimization. However, leveraging DS flexibility requires seamless interoperability between the Transmission and Distribution System Operators (TSOs and DSOs), often hindered by data privacy concerns. This paper introduces a novel optimization approach for utilizing DS flexibility while preserving data privacy. The DS is linearized at multiple operating points to derive sensitivity matrices and associated base values, shared with the TSO without disclosing sensitive data. These matrices are incorporated as constraints into a piecewise mixed-integer linear programming (MILP) framework by the TSO, enabling efficient market clearing while preventing congestion induced by activated flexibilities. Benchmarking against standard power flow shows promising results, while preserving data privacy and facilitating the integration of DS flexibility.**

***Index Terms*—data privacy, flexibility provisioning, interoperability, network management, TSO-DSO interaction.**

I. INTRODUCTION

The power system is rapidly transforming, driven by increased electrification through technologies such as electric vehicles (EVs) and heat pumps. Millions of these components are expected to be integrated into low-voltage distribution systems (DSs), presenting challenges, such as overloading and operational inefficiencies [1], [2]. Simultaneously, these components serve as valuable sources of flexibility and can be categorized as flexibility-providing units (FPUs).

Flexibility plays a central role in modern energy systems, and is becoming increasingly important. The term flexibility describes the ability of an energy system or its components to adapt to generation, consumption, or storage patterns in response to external demands or incentives. This adaptability is essential to meet the challenges of the energy transition. These include, among other things, the integration of renewable energies, which are characterized by their variability, and ensuring grid stability [3].

Consequently, effective low-voltage DS management is becoming critical due to the complexities of the ongoing power system transformation. For Transmission System Operators (TSOs), this transformation brings added challenges, yet it also present opportunities for DS flexibility to play a key role in addressing these issues [4]. Leveraging DS flexibility can reduce operational costs and support a more cost-efficient energy market. For instance, DS flexibility can be utilized in day-ahead, intraday, and balancing markets, contributing to enhanced grid stability and substantial cost reduction, particularly in areas such as manual reserves [5].

Interoperability between TSOs and Distribution System Operators (DSOs) is essential for efficient power systems, but is hindered by data privacy concerns [6], missing standards and regulatory frameworks, etc. Analyses leveraging DS flexibility in TSO operations often require sensitive data, such as network topology, which complicates collaboration. Addressing these challenges requires innovative privacy-preserving solutions. In addition, the rise of FPUs in low-voltage grids necessitates computationally efficient approaches to enable effective flexibility provisioning in DSs [7]. For that, machine learning (ML) methods addressing TSO-DSO data privacy primarily focus on medium-voltage grids, which face scalability issues in low-voltage grids owing to their complexity [8].

To address these challenges, the DigIPlat project, under which this study is conducted, aims to develop a privacy-friendly, interoperable platform for flexibility markets. It focuses on standardizing digital solutions to enhance transnational flexibility markets and optimizing balancing energy calls while considering network constraints [9].

In this context, sensitivity matrix-based approaches have proven to be effective [10]. Building on this, we introduce an innovative optimization framework to economically utilize DS flexibility, while preventing grid congestion and addressing stakeholder privacy concerns. For this, the DS model is piecewise linearized by a first-order Taylor expansion using

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sensitivity matrices and base values (such as voltage magnitudes and element loadings at selected operating points) generated at various operating points. This allows DSOs to share only non-confidential data with TSOs, avoiding the exchange of sensitive information such as network topology. The linearized model is integrated into a mixed-integer linear program (MILP) for DS flexibility provisioning, enabling computationally efficient solutions despite increasing grid complexity. This framework supports various market conditions and objective functions. Thus, DS flexibility can be effectively utilized while maintaining data privacy.

To test the proposed method, a realistic low-voltage grid model is essential. As grid models are not accessible from DSOs due to privacy concerns, we employ a method for the automated generation of low-voltage DS models using open-source data [11]. This approach creates detailed grid models for real-world analyses, demonstrating the effectiveness of the testing method.

II. FLEXIBILITY FOR BALANCING ENERGY MARKETS

Flexibility in power systems can be considered in several ways. Technical flexibility includes the ability to adjust both active and reactive power by increasing or reducing the generation and consumption. Temporal flexibility refers to the speed and duration with which flexibility can be activated. Characteristics such as preparation time, ramp-up or ramp-down time, and maximum activation duration play a role. In addition, spatial flexibility focuses on the geographical location of flexibility and its relevance to congestion management. Finally, the commercial dimension includes the requirements for marketing flexibility, such as minimum bid sizes, pricing mechanisms, and linking of flexibility markets with other market segments [12].

This article focuses on leveraging DS flexibility for balancing energy (BE), which is necessary for stabilizing the grid when there are imbalances between generation and consumption. It is procured and activated by TSOs to compensate for frequency deviations and to ensure system security. For this, products such as frequency control reserves (FCR), automatic frequency restoration reserves (aFRR), and manual frequency restoration reserves (mFRR) exist, which differ in their activation time and delivery requirements [13], [14].

In the present paper, we primarily analyze the technical and temporal dimensions of flexibility and the integration of BE. We aim to create framework conditions that support the effective and interoperable use of flexibility, thereby promoting both economic efficiency and system stability. Integrating BE into flexibility mechanisms offers significant potential for increasing the efficiency of the overall system. However, this requires close coordination among various market participants, including DSOs. A key issue is that activating BE in the DS can cause congestion in certain grid areas [15]. Furthermore, standardized mechanisms for exchanging information on grid capacities without incurring data-protection risks are lacking. These deficits lead to high operating costs, grid congestion, and missed opportunities for utilizing flexibility [9]. DSOs often lack transparency in market operations, and TSOs struggle to use DS flexibility while considering local grid constraints [16]–[18]. Privacy concerns from DSOs further complicate the exchange of sensitive grid data such as topologies and operating parameters [6]. However, the current market framework insufficiently fulfills these requirements [3], [19].

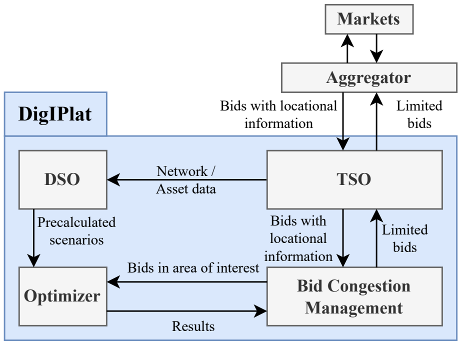


Fig. 1. Proposed interoperability framework for privacy protected flexibility provisioning by DSO to electricity markets via TSO and Aggregators using a novel optimization approach that considers network congestion.

Interoperable platforms can play a crucial role by enabling standardized, data-protection-compliant communication between TSOs, DSOs, and flexibility service providers. In the DigIPlat project, we developed an interoperable platform for flexibility markets that focuses on standardizing digital solutions to enhance transnational flexibility markets. The introduced framework (see Fig. 1) can be accessed via a web-based interface that acts as a demonstrator (see Fig. 3). The process begins with the DSOs calculating data protection-compliant grid scenarios in advance. Market participants then submit bids, some of which are aggregated. A bid congestion manager (BCM) disaggregates the bids based on the geographical position of the underlying assets. These disaggregated bids are checked by an optimizer, which decides whether they should be activated in full, in part, or not at all. The results are then reaggregated by the BCM and transmitted to the market. This methodology fits seamlessly into existing market mechanisms and shows how operational improvements and cost savings can be realized [20]. By focusing on both technical and economic aspects, the approach not only addresses the need for privacy-friendly network models and optimized plant-specific bid activation, but also highlights measurable market benefits, including reduced system costs and enhanced grid stability.

Building on the identified challenges and the proposed framework for grid-aware BE provision, the following section outlines the methodology employed to develop, implement, and evaluate the optimization approach.

III. METHODOLOGY

A. Automatic Generation of Low Voltage Distribution Grid

In [11], we introduced an automated algorithm for generating low-voltage distribution grid models using open-source data with minimal inputs. The algorithm utilizes public datasets such as street layout data from OpenStreetMap [21] and operates in two stages. First, it generates a 20 kV grid topology, including 20/0.4 kV substations, using k-means clustering for substation placement and the Traveling Salesman Problem (TSP) optimization for line routing. Second, it creates a 400 V grid by solving a minimum cost flow optimization problem, producing a realistic PowerFactory model for residential areas [22]. For this study, the Bergwald region in Karlsruhe, Germany is modeled (see Fig. 3).

The optimization identifies six 20/0.4 kV substations and 241 buildings, with substations connected to varying numbers of buildings based on the results. Power flow calculations verify the model's validity, ensuring that the voltage and loading parameters remain within limits, and the layout is validated using DSO-provided data. The model allows the customization of buildings with FPUs, such as EVs, batteries, PVs, and heat pumps, enabling analyses for different time frames and operational points required for piecewise linearization, which will be discussed in detail in the following section. However, FPU and transformer tap changer controls are excluded. This detailed model supports the evaluation of the proposed method under real-world conditions.

B. Piecewise Linearization of the Distribution Grid

During DS flexibility provisioning, it is necessary to adjust active power generation or consumption depending on the type of FPUs. Considering a network with n nodes, the active power adjustment, denoted by $\Delta\mathbf{P} \in \mathbb{R}^n$, modifies the total n power injections $\mathbf{P} + \Delta\mathbf{P}$, where $\mathbf{P} \in \mathbb{R}^n$ represents the initial active power injections. These adjustments result in corresponding changes in v nodal voltages $\Delta\mathbf{V} \in \mathbb{R}^v$ and l branch loadings $\Delta\mathbf{L} \in \mathbb{R}^l$ such as lines and transformers. To avoid congestion in the power system during the flexibility provisioning process, it is crucial to ensure that these parameters remain within operational limits. We define the relationship between the power injections and the system parameters as follows:

$$F_V : \mathbb{R}^n \to \mathbb{R}^v, (\mathbf{P} + \Delta\mathbf{P}) \mapsto (\mathbf{V} + \Delta\mathbf{V}), \tag{1}$$

$$F_L : \mathbb{R}^n \to \mathbb{R}^l, (\mathbf{P} + \Delta\mathbf{P}) \mapsto (\mathbf{L} + \Delta\mathbf{L}), \tag{2}$$

where $\mathbf{V}$ and $\mathbf{L}$ are the initial nodal voltage magnitudes and branch loadings, respectively. The functions F_V and F_L map the total power injections to the resulting nodal voltages and branch loadings. For this, the initial values, along with the adjustments $\Delta\mathbf{P}$, determine the changes $\Delta\mathbf{V}$ and $\Delta\mathbf{L}$. Due to the inherent nature of power flow equations, F_V and F_L are nonlinear. Given the complexity of low-voltage grids with diverse and numerous FPUs, computationally efficient methods are essential.

To approximate the mapping functions, linear sensitivity factors such as the Power Transfer Distribution Factor (PTDF) can be used to determine how the active power flow changes in relation to changes in power injections at other buses [23]. Similarly, to approximate the changes in voltage magnitudes ($\Delta\mathbf{V}$) and branch loadings ($\Delta\mathbf{L}$), we can define transfer distribution factors specific to voltage magnitudes (VTDF) and branch loadings (LTDF). Similar to the PTDFs, the VTDF and LTDF determine how nodal voltages and branch loadings change when power injection changes at the buses. With the use of these factors, $\Delta\mathbf{V}$ and $\Delta\mathbf{L}$ can be expressed as follows:

$$\Delta\mathbf{V} = \mathbf{VTDF}\Delta\mathbf{P}, \tag{3}$$

$$\Delta\mathbf{L} = \mathbf{LTDF}\Delta\mathbf{P}. \tag{4}$$

At the linearization point, with $\mathbf{V}$ and $\mathbf{L}$ known, these equations approximate F_V and F_L efficiently leveraging linear sensitivity factors. This approach addresses the complexity of low-voltage grids and updates the network conditions during flexibility provisioning as follows:

$$\widetilde{\mathbf{V}} = \mathbf{V} + \mathbf{VTDF}\Delta\mathbf{P}, \tag{5}$$

$$\widetilde{\mathbf{L}} = \mathbf{L} + \mathbf{LTDF}\Delta\mathbf{P}, \tag{6}$$

where $\widetilde{\mathbf{V}}$ and $\widetilde{\mathbf{L}}$ represent the updated voltage magnitudes and branch loadings, respectively, using the linear approximation with active power adjustment ($\Delta\mathbf{P}$). It is important to note that while sensitivity matrices are typically derived using DC power flow in the literature, in this study, they are calculated based on AC power flow. Additionally, as indicated by the formulation, only $\Delta\mathbf{P}$ is considered when calculating the changes $\Delta\mathbf{V}$ and $\Delta\mathbf{L}$. The impacts of other factors, such as changes in reactive power or the voltage regulation effects, are not accounted for in this approximation. It is also important to recognize that the VTDF and LTDF values are calculated for a specific operational point, typically referred to as the base scenario. Therefore, new VTDF and LTDF values must be recalculated for different day types or specific time frames.

The linearization accuracy diminishes with distance from the linearization point. To address this, we use piecewise linear approximation to improve flexibility provisioning across a broader range. In this approach, the system is linearized around m different pre-calculated operation points within a given time frame. The index set $\mathcal{I} := \{0, 1, ..., m-1\}$ contains all the operating points. This results in m tuples of $(\mathbf{P}_i, \mathbf{V}_i, \mathbf{L}_i, \mathbf{VTDF}_i, \mathbf{LTDF}_i), i \in \mathcal{I}$, which hold the information necessary for the linear approximations. Consequently, Equations (5) and (6) can be extended for multiple operating points, as follows:

$$G_{V,i}(\Delta\mathbf{P}_i) = \widetilde{\mathbf{V}}_i = \mathbf{V}_i + \mathbf{VTDF}_i\Delta\mathbf{P}_i \qquad i \in \mathcal{I}, \tag{7}$$

$$G_{L,i}(\Delta\mathbf{P}_i) = \widetilde{\mathbf{L}}_i = \mathbf{L}_i + \mathbf{LTDF}_i\Delta\mathbf{P}_i \qquad i \in \mathcal{I}, \tag{8}$$

where $\widetilde{\mathbf{V}}_i$ and $\widetilde{\mathbf{L}}_i$ represent the updated voltage magnitudes and branch loadings, respectively, calculated for the i-th operational point after the active power adjustment $\Delta\mathbf{P}_i$. Functions $G_{V,i}$ and $G_{L,i}$ serve as approximation functions for the nodal voltage magnitudes and branch loadings.

For a well-defined piecewise linear approximation, each approximation requires a region where it is sufficiently accurate. Therefore, the input space $\mathbb{R}^n$ is divided into convex polygons using a Voronoi tessellation. Each power injection vector $\mathbf{P}_i$ at linearization point i forms the center of a convex polygon $\mathcal{P}_i$, defined by a distance minimum condition:

$$\mathcal{P}_i = \{\mathbf{X} \in \mathbb{R}^n \mid d(\mathbf{X}, \mathbf{P}_i) < d(\mathbf{X}, \mathbf{P}_j), \forall i, j \in \mathcal{I}, i \neq j\}, \tag{9}$$

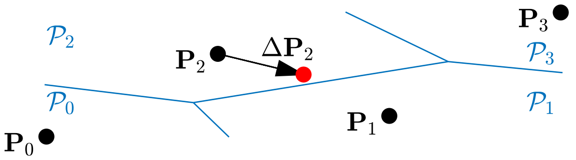


Fig. 2. Schematic representation of the tessellated input space with non-boundary violating update $\mathbf{P}_2 + \Delta\mathbf{P}_2$.

where $d(\cdot,\cdot)$ is the Euclidean distance. This results in non-overlapping directly adjacent partitions over the entire input domain. The nonlinear network functions F_V and F_L can be linearly approximated inside $\mathcal{P}_i$ by $G_{V,i}(\Delta\mathbf{P}_i)$ and $G_{L,i}(\Delta\mathbf{P}_i)$ respectively, if $\mathbf{P}_i + \Delta\mathbf{P}_i \in \mathcal{P}_i$ holds. The partitioning and the update $\mathbf{P}_i + \Delta\mathbf{P}_i$ are shown schematically in Fig. 2. The boundaries of the convex polygons $\mathcal{P}_i$ are shown in blue. The update lies inside $\mathcal{P}_2$, meaning $G_{V,2}(\Delta\mathbf{P}_2)$ and $G_{L,2}(\Delta\mathbf{P}_2)$ would be the appropriate approximations.

With this method, the selection of a linear approximation can be incorporated into an optimization problem for which the distance between the linearization point and the update is minimized. Thus, the approximation error is kept small.

C. Optimization Approach for Flexibility Provisioning

The polygon $\mathcal{P}_i$ is defined via the nonlinear Euclidean distance and is therefore unsuitable for a linear program. Instead, a linear auxiliary function is defined to check for $\mathbf{P}_i + \Delta\mathbf{P}_i \in \mathcal{P}_i$. In general, a r-dimensional hyperplane is defined by $\mathbf{N}^T(\mathbf{X} - \mathbf{A}) = 0 \quad \forall \mathbf{X} \in \mathbb{R}^r$, where $\mathbf{A}$ lies on the plane. When applied to the space of power injections, one can set $\mathbf{A}$ as the midpoint between two linearization points and the normal vector $\mathbf{N}$ as the connecting vector. Then, the auxiliary function is defined as follows:

$$H_{i,j}(\Delta\mathbf{P}_i) = (\mathbf{P}_i - \mathbf{P}_j)^T \left(\mathbf{P}_i + \Delta\mathbf{P}_i - \frac{\mathbf{P}_i + \mathbf{P}_j}{2} \right). \quad (10)$$

Consequently, if $H_{i,j}(\Delta\mathbf{P}_i) \geq 0 \, \forall j \in \mathcal{I}, i \neq j$ holds, then $\mathbf{P}_i + \Delta\mathbf{P}_i \in \mathcal{P}_i$. In the context of flexibility provisioning, the linearization point $\mathbf{P}_i$ can be described as the total of fixed, market-independent power injections ($\mathbf{P}_{Fix,i}$) and power injections through activated flexibilities ($\mathbf{P}_{Flex,i}$):

$$\mathbf{P}_i = \mathbf{P}_{Fix,i} + \mathbf{P}_{Flex,i}. \quad (11)$$

By adding the power adjustment $\Delta\mathbf{P}_i$ to (11), the term $\mathbf{P}_{Flex,i} + \Delta\mathbf{P}_i$ represents the updated power injections through the activated flexibilities. Assuming that the market yields a bid constellation with costs $\mathbf{c} \in \mathbb{R}^n$, the associated volumes $\mathbf{P}_M \in \mathbb{R}^n$ and requests a total balancing power of $P_E \in \mathbb{R}$ (derived from balancing energy BE), our method fully activates, partially activates, or excludes the bids. Therefore, the adjusted dispatched bids are limited to

$$\mathbf{P}_{Flex,i} + \Delta\mathbf{P}_i \geq \mathbf{P}_{LB} := \min\left(\mathbf{0}, \mathbf{P}_M\right), \quad (12)$$

$$\mathbf{P}_{Flex,i} + \Delta\mathbf{P}_i \leq \mathbf{P}_{UB} := \max\left(\mathbf{0}, \mathbf{P}_M\right). \quad (13)$$

The operators $\min$ and $\max$ are considered element-wise. Hereby, the lower and upper power injection bounds $\mathbf{P}_{LB}$ and $\mathbf{P}_{UB}$ are extracted from the (positive and negative) market volumes $\mathbf{P}_M$.

The optimization process aims to create a minimum-cost bid constellation under the constraint that the limits of the grid are respected. Therefore, the updated branch loadings $\widetilde{\mathbf{L}} \in [\mathbf{L}_{LB}, \mathbf{L}_{UB}]$ and voltage magnitudes $\widetilde{\mathbf{V}} \in [\mathbf{V}_{LB}, \mathbf{V}_{UB}]$, where the indices LB and UB denote the lower and upper bounds, respectively. A mixed-integer linear program is formulated to optimize the adjustments $\Delta\mathbf{P}_i$ with the binary decision variables $b_i \in \{0,1\}$ to choose the appropriate approximation:

$$\min_{\Delta\mathbf{P}_i, b_i} \quad \sum_{i \in \mathcal{I}} \mathbf{c}^T (\mathbf{P}_{Flex,i} + \Delta\mathbf{P}_i) b_i \quad (14a)$$

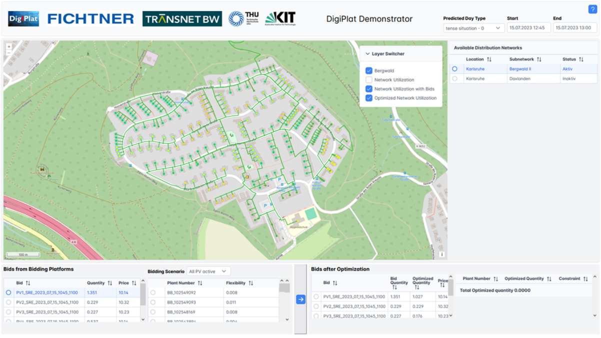
s.t.

$$\begin{aligned}
&\Delta\mathbf{P}_i \geq (\mathbf{P}_{LB} - \mathbf{P}_{Flex,i}) b_i && \forall i \in \mathcal{I}, && (14b)\\
&\Delta\mathbf{P}_i \leq (\mathbf{P}_{UB} - \mathbf{P}_{Flex,i}) b_i && \forall i \in \mathcal{I}, && (14c)\\
&G_{L,i}(\Delta\mathbf{P}_i) \geq \mathbf{L}_{LB} b_i + \mathbf{L}_i (1 - b_i) && \forall i \in \mathcal{I}, && (14d)\\
&G_{L,i}(\Delta\mathbf{P}_i) \leq \mathbf{L}_{UB} b_i + \mathbf{L}_i (1 - b_i) && \forall i \in \mathcal{I}, && (14e)\\
&G_{V,i}(\Delta\mathbf{P}_i) \geq \mathbf{V}_{LB} b_i + \mathbf{V}_i (1 - b_i) && \forall i \in \mathcal{I}, && (14f)\\
&G_{V,i}(\Delta\mathbf{P}_i) \leq \mathbf{V}_{UB} b_i + \mathbf{V}_i (1 - b_i) && \forall i \in \mathcal{I}, && (14g)\\
&H_{i,j}(\Delta\mathbf{P}_i) b_i \geq 0 && \forall i, j \in \mathcal{I}, i \neq j, && (14h)\\
&\sum_{i \in \mathcal{I}} b_i = 1, && && (14i)\\
&\sum_{i \in \mathcal{I}} (\mathbf{P}_{Flex,i} + \Delta\mathbf{P}_i) = P_E. && && (14j)
\end{aligned}$$

Equation (14a) minimizes the total cost of the dispatched bids after a power adjustment. (14i) ensures that only one decision variable is 1. The appropriate approximation is determined by (14h). Next, (14b) and (14c) guarantee that (12) and (13) hold. Equations (14d)–(14g) ensure that the power adjustment does not introduce any congestion. Finally, (14j) ensures that the required balancing energy volume is satisfied. The proposed optimization problem provides a robust framework for balancing the flexibility provision while preventing congestion, as demonstrated in the following case study.

IV. CASE STUDY

This paper evaluates the proposed method by benchmarking it against the standard power flow (PF) approach, which does not account for data privacy. The Bergwald grid model, detailed in Section III-A, is employed for the case studies. To solve the MILP formulation, we utilize GUROBI [24]. The analysis focuses on a single time frame in which the TSO requires 1.8 MW flexibility from the DS. However, the proposed methodology is versatile and can be applied to various day types and time frames. Additionally, for this time frame, three linearization points are selected to evaluate the method across a wide range of operations: one where all offered bids are activated, another where half of them are activated, and a third where none are activated. The voltage limits are set to $\mathbf{V}_{LB} = 0.95 p.u., \mathbf{V}_{UB} = 1.05 p.u.$, whereas



DigiPlat Demonstrator

Predicted Day Type: tense situation - 0
Start: 15.07.2023 12:45
End: 15.07.2023 13:00

Layer Switcher
- ☑ Bergwald
- ☐ Network Utilization
- ☑ Network Utilization with Bids
- ☑ Optimized Network Utilization

Available Distribution Networks

	Location	Subnetwork	Status
○	Karlsruhe	Bergwald II	Aktiv
○	Karlsruhe	Daxlanden	Inaktiv

Bids from Bidding Platforms

	Bid	Quantity	Price
○	PV1_SRE_2023_07_15_1045_1100	1.351	10.14
○	PV2_SRE_2023_07_15_1045_1100	0.229	10.32
○	PV3_SRE_2023_07_15_1045_1100	0.227	10.23

Bidding Scenario: All PV active

	Plant Number	Flexibility
○	BB_102549092	0.008
○	BB_102549093	0.011
○	BB_102548169	0.008

Bids after Optimization

	Bid	Bid Quantity	Optimized Quantity	Price
○	PV1_SRE_2023_07_15_1045_1100	1.351	1.027	10.14
○	PV2_SRE_2023_07_15_1045_1100	0.229	0.229	10.32
○	PV3_SRE_2023_07_15_1045_1100	0.227	0.176	10.23

Plant Number	Optimized Quantity	Constraint

Total Optimized quantity 0.0000

Fig. 3. Optimization results in the demonstrator of the DigIPlat platform.

the branch loading limits are $\mathbf{L}_{LB} = -100\%, \mathbf{L}_{UB} = 100\%$. The negative lower bound guarantees in (14) that the direction of load flow can be reversed.

We assume that each building in Bergwald offers a specific amount of flexibility. However, these offered bids may lead to network congestion in the DS. To address this issue, the optimization problem defined in (14) is solved by the TSO. The solution selects from the offered flexibility such that it avoids creating congestion in the DS while ensuring the delivery of 1.8 MW flexibility at the TSO-DSO interface.

The optimization results are visualized using a web-based demonstrator developed in the DigIPlat project, as shown in Fig. 3. The demonstrator highlights that no congestion occurs in the DS after optimization. It is important to note that the demonstrator was created solely for project purposes to enhance the explanation of the process in this paper. Under normal operational conditions, the TSO does not have access to sensitive information.

While the linearized approach introduces approximation errors, its accuracy is validated by comparing the results against PF. The flexibility usage as a result of the optimization process is used as input for the PF, which enables to calculate key grid parameters including the voltages and loadings of branches. The optimization and PF results are then compared and presented in Table I using metrics such as mean absolute error (MAE) and root mean square error (RMSE). The results show discrepancies close to zero, indicating the high accuracy of the optimization approach. To further evaluate the performance of the proposed method, the voltage magnitudes of the critical busbars and loading values of the critical lines and transformers in the network are illustrated in Fig. 4 and Fig. 5, respectively. As is evident from the figures, the results obtained from the proposed method closely match those derived from the PF. In addition, all values are well within the operational limits, ensuring that no violations occur.

The proposed method provides results comparable to the standard PF approach while preserving data privacy. The TSO can calculate and meet flexibility requirements without accessing sensitive data from the DS and avoiding congestion in the DS. This demonstrates the effectiveness and practicality of the new approach for enhancing grid operations while addressing the interoperability and data privacy challenges.

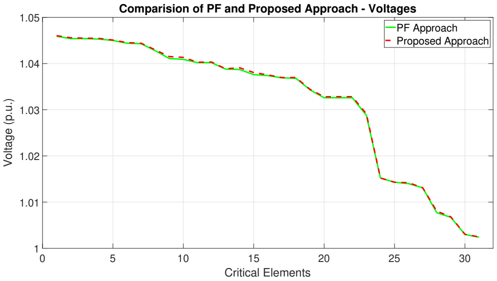


Fig. 4. Comparison of PF and the proposed approach for voltage magnitudes.

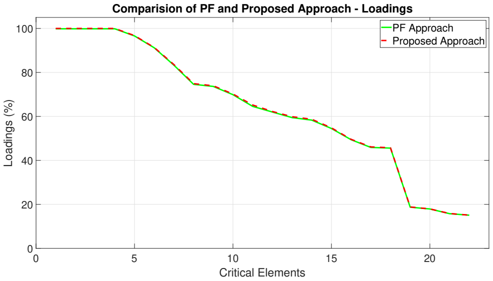


Fig. 5. Comparison of PF and the proposed approach for loadings.

V. CONCLUSION

This paper proposes a novel optimization approach to enhance interoperability and address data privacy concerns between TSOs and DSOs. Our approach uses piecewise linearization of the DS model with sensitivity matrices and associated base values, which are shared with the TSOs without disclosing sensitive data. These elements are incorporated into a mixed-integer linear programming (MILP) framework, enabling TSOs to utilize DS flexibility for various operations.

The proposed method is benchmarked against standard power flow to assess its effectiveness. The results demonstrate that it achieves satisfactory outcomes while maintaining data privacy and reducing computational complexity, even with a high grid component integration. By ensuring data privacy, the framework facilitates the integration of flexibility-providing units (FPUs) into energy markets and enables TSOs to calculate DS flexibility without causing internal congestion. This supports an efficient and reliable congestion management across power systems.

Future work will focus on refining the methodology by optimizing the operating point selection for linearization and testing the approach on a more comprehensive grid model, incorporating factors such as the FPU control behavior and transformer tap operations.

TABLE I
RMSE AND MAE METRICS OF THE PARAMETERS

Metrics	Voltages (p.u.)	Loadings (%)
MAE	2.3×10^{-5}	6.1×10^{-3}
RMSE	2.6×10^{-5}	9.8×10^{-3}

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