

# Grid-Cognizant TSO and DSO Coordination Framework for Active and Reactive Power Flexibility Exchange: The Swiss Case Study

Mohsen Kalantar-Neyestanaki  
Bid & System Engineer  
Traction Team, ALSTOM  
Zürich, Switzerland  
mohsen.kalantar.n@gmail.com

Rachid Cherkaoui  
Power Systems Group (PWRS)  
École Polytechnique Fédérale de Lausanne (EPFL)  
Lausanne, Switzerland  
rachid.cherkaoui@epfl.ch

**Abstract**—This paper first designs a holistic coordination framework between transmission system operator (TSO) and distribution system operators (DSOs) to modernize traditional top-to-down (from transmission system to distribution systems) power flexibility provision mechanism to a bi-directional power flexibility provision mechanism between TSO and DSOs. More specifically, it empowers TSO and DSOs to exchange both active and reactive power flexibility without having to reveal their confidential grids data. Above all, it allows TSO to take advantage of the potential active and reactive power flexibility of the proliferating number of distributed energy resources (DERs) installed in distribution systems. Secondly, it develops a linearized power flow model for transmission networks. Leveraging the designed framework along with the developed linearized power flow model, it finally offers a two-stage linear stochastic optimization method to help TSO optimally book its required active and reactive power flexibility from both power plants and distribution systems. In particular, it considers constraints and active/reactive power losses of the transmission network. The performance of the proposed framework is evaluated considering a real-world transmission network, i.e. the Swiss transmission network.

**Index Terms**—TSO-DSO collaboration, active and reactive power flexibility, frequency and voltage control services, ancillary services, two-stage linear stochastic optimization.

## I. INTRODUCTION

### A. Motivations

Electricity generation from renewable energy sources (RES) including wind and solar energy is attaining significant levels in almost all electric power systems around the globe [1]. Although this massive integration of RES helps to alleviate environmental concerns, it might jeopardize the security of electric power systems and set off a variety of challenges for grid operators mainly due to simultaneous realization of:

- surge in uncertainties stemming from stochastic power generation of RES.
- fall in available power flexibility owing to the phase-out of conventional dispatchable power plants.

Active (and respectively reactive) power flexibility refers to the additional bi-directional active (reactive) power a resource provides to the grid by regulating its operating point. Grid operators respectively leverage active and reactive power flexibility to regulate frequency and voltage throughout the grid, most importantly, to counteract the impact of uncertainties and contingencies. Given that the conventional power plants have been the main sources of active/reactive power flexibility (main providers of frequency/voltage control services), their decommissioning is diminishing the available sources of power flexibility [2], [3]. In this emerging architecture, grid operators are encountering non-traditional problems, thereby requiring supplementary active/reactive power flexibility to securely steer the grid and guarantee power quality, voltage/frequency regulation, and congestion management [4]. For instance, the main reason of immense blackouts, such as South Australia [5] and Southern California [6] blackouts, was voltage collapse resulting from lack of reactive power flexibility needed to prevent further voltage drop. Moreover, spikes in the price of power flexibility are appearing more frequently in recent years [7]. These unprecedented issues all together bear testimony to the importance of the reliable and adequate provision of both active and reactive power flexibility.

### B. Literature Review

To avoid lack of power flexibility, a promising solution widely recognized in the literature is to unlock and tap the power flexibility of proliferating distributed energy resources (DERs) located in distribution level. In this respect, the existing literature offers three mainstreams of methods. The first mainstream of methods restrict themselves exclusively to the distribution level and strive to unlock and deploy the active/reactive power flexibility of DERs to deal with local issues at distribution networks. Work in [8] developed a two-stage hierarchical optimization model to deploy the power flexibility of DERs in order to mitigate the congestion in distribution networks. [9] proposed a communication-free coordination approach to manage the power flexibility of

---

Submitted to the 23rd Power Systems Computation Conference (PSCC 2024).

DERs, thereby, providing frequency control service to the local network. Work in [10] presented two algorithms namely rule-based algorithm and optimization-based algorithm to capture the power flexibility of DERs and provide voltage control service to the distribution network.

In contrast, the second mainstream of methods broaden their scope of application. They set out to coordinate and aggregate the active/reactive power flexibility of DERs located in distribution level with the purpose of providing it to the transmission network at the TSO-DSO interface. In this respect, [11] and [12] introduced the concept of flexibility provision capability (FPC) curve/area. FPC curve of a distribution network is a curve in P-Q plane characterizing the extreme amount of the active and reactive power flexibility that distribution network can provide to the transmission network at its TSO-DSO interface. The area surrounded by the FPC curve is called FPC area. Moreover, work in [12] constructed a set of robust optimization problems to robustly predict the FPC area of a distribution network while considering grid/DERs constraints and uncertainties of demand/stochastic generation. Therefore, it ensures that, during real-time grid operation, the DSO can provide to the TSO any amount of active and reactive power flexibility corresponding to the points located inside its FPC area without deteriorating the security of the distribution network. Relying on this method, a day prior to the real-time grid operation, each DSO can firstly predict and then offer to the TSO its FPC area associated with each time interval of the next day. Work in [13] turned its attention to the real-time grid operation stage and proposed a two-stage distribution network control strategy to empower DSOs optimally procure the active/reactive power flexibility of DERs in order to satisfy at best both active and reactive power flexibility request of the TSO. Works in [14]–[18] concentrated on the reactive power flexibility provision to the TSO. To this end, [14] introduced a centralized control scheme and evaluated the financial incentives required for encouraging distribution networks to participate in this control scheme. In line with [14], [15] and [16] developed a model-free control scheme to aggregate the reactive power flexibility of dispersed small-scale photovoltaic systems or battery storage located in distribution level, whereas [15] and [18] defined a centralized optimization-based control scheme to tap the reactive power flexibility of utility-scale DERs and provide it to the TSO.

The third mainstream of methods have less been well addressed. This mainstream aims to improve the coordination between TSO and DSO in such a way that the TSO can also benefit from the active/reactive power flexibility of DERs installed in distribution level. Works in [19]–[21] offered an active power flexibility allocation method to optimally book the TSO's required size of active power flexibility from not only power plants but also distribution systems.

### C. Contributions

To the best knowledge of the authors, the existing literature lacks a TSO-DSO coordination framework to enable TSO and DSOs exchange both active and reactive power flexibility with

each other. In this context, the main contributions of the paper can be summarized as:

- It designs a holistic TSO-DSO coordination framework where TSO and DSOs establish their collaboration on the basis of the FPC areas. This framework facilitates the TSO and DSO collaboration, thereby, boosting unlocking the potential active/reactive power flexibility of DERs.
- It develops a decision making tool for TSOs to help them optimally book their required active and reactive power flexibility via FPC areas. Leveraging a linearized AC power flow model, it is able to account for grid's active and reactive power losses and, most notably, the nodal voltage magnitude constraints. Therefore, it can ensure that power plants accomplish their voltage regulation task against all uncertainties and contingencies without reaching their maximum/minimum reactive power limits. Accordingly, it helps TSOs steer their grids far from risks associated with under-voltage/over-voltage issues triggering voltage collapse.
- It allows TSO to take advantage of all existing power flexibility resources including dispatchable power plants and DERs located in distribution networks.
- It follows the decentralized energy and flexibility market structure, thus, it is a tailored tool for most of European TSOs.
- It evaluates the efficiency of the developed framework and decision making tool on a real-world transmission network, i.e. the Swiss transmission network operated by Swissgrid.

## II. TSO-DSO COORDINATION FRAMEWORK

The emerging smart grids enable new automated control strategies for managing proliferating number of DERs installed in distribution networks. These novel control strategies are able to aggregate the potential active/reactive power flexibility of the DERs and provide it to the transmission network at the TSO-DSO interface while respecting all constraints of the distribution network [12], [13]. More specifically, these kind of methods have been revolutionizing the paradigm of treating distribution networks as sources of uncertainties to sources of active/reactive power flexibility. Accordingly, distribution networks can be categorized into **flexible** and **inflexible** ones.

- 1) **Flexible distribution networks:** They coordinate and deploy the power flexibility of DERs to tackle the local flexibility demand at the distribution network, furthermore, they offer the surplus power flexibility of those DERs to the transmission network at their TSO-DSO interface.
- 2) **Inflexible distribution networks:** They are managed in a traditional way where the DERs' power flexibility is not unlocked and tapped. Therefore, instead of providing power flexibility to the transmission network, these inflexible distribution networks are sources of uncertainties which require power flexibility.

An efficient TSO-DSO coordination framework is needed to help TSO benefit from the power flexibility of DERs installed

in distribution level, thereby improving the security of the whole electric power system. However, TSO and DSOs are independent operators/organizations, they therefore prefer to exchange such a active/reactive flexibility while sharing as less as possible data with each other. To address this issue, this paper leverages the concept of FPC area, introduced in [12], and develops a holistic TSO-DSO collaboration framework where TSO and DSO can easily coordinate their flexibility demand/capability with each other using FPC areas, thereby exchanging active/reactive power flexibility without revealing their confidential grids data. On the other hand, the common-practice for steering the electric power systems is that the grid operators schedule the operation of their grid prior to the real-time grid operation, e.g. day-ahead or hours-ahead. In line with this widely accepted procedure, this paper organizes the TSO-DSO coordination in two stages. These two stages are elaborated by referring to a time horizon with duration of  $H$  (e.g. 24-hour of the next day) embracing a number of time intervals each with duration of  $\tau$  as shown in Fig. 1:

- 1) **Flexibility Coordination Stage (Planning):**  $t_{\text{DSO}}$  hours prior to the beginning of the time horizon  $H$ , each flexible distribution network exploits the methodology introduced in [12] and predicts its FPC areas associated with each time interval  $t$ . Accordingly, it, for each time interval  $t$ , offers a set of FPC areas with different prices to the TSO as shown in Fig. 2. After collecting the offered FPC areas of all flexibility providers including flexible distribution networks and flexible power plants<sup>1</sup>, the TSO solves the optimal active/reactive power flexibility allocation problem introduced in section III. Consequently,  $t_{\text{TSO}}$  hours prior to the beginning of the time horizon  $H$ , the TSO books its required FPC area from flexible distribution networks and flexible power plants for each time interval  $t$ .
- 2) **Flexibility Exchange Stage (Operation):** During real-time grid operation, the TSO might require active/reactive power flexibility to securely steer its grid against uncertainties and contingencies. Considering its grid situation, the TSO might request from each flexibility provider to activate (provide) an specific amount of active/reactive power flexibility corresponding to a point located inside the TSO's booked FPC area from that flexibility provider.

### III. UNIFIED ACTIVE & REACTIVE POWER FLEXIBILITY ALLOCATION

This section implements the TSO's unified active and reactive power flexibility allocation problem as a two-stage decision making process where "flexibility coordination stage" corresponds with *here&now* decisions and "flexibility exchange stage" with *wait&see* decisions. As a result, it extracts a two-stage linear stochastic optimization formulation for the problem. In this regard, let  $i$  and  $j$  be the indices

<sup>1</sup>Dispatchable power plants which are able to provide power flexibility to the TSO.

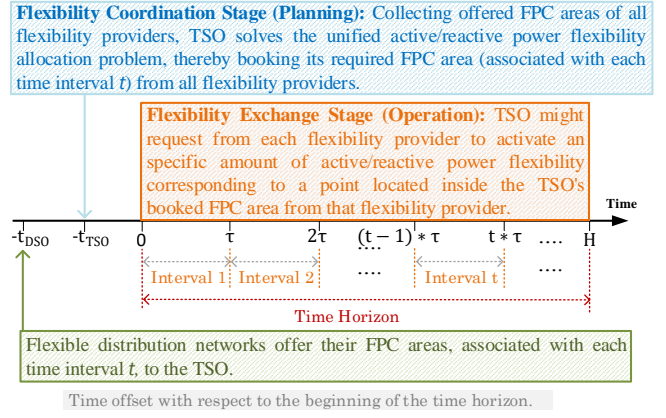


Fig. 1. Timeline of the designed TSO-DSO coordination framework.

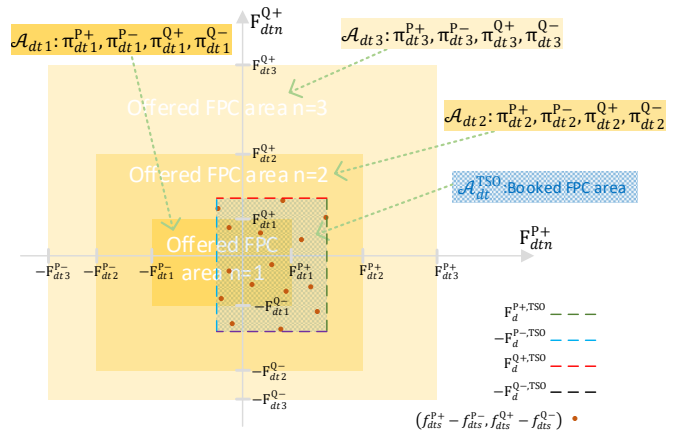


Fig. 2. Offered FPC areas of flexible distribution network  $d$  for time interval  $t$ .

for buses;  $r$  the index for the reference (slack) bus;  $B$  the set of all buses excluding the reference bus;  $B^G$  the set of buses hosting power plants (including the reference bus  $r$ );  $B^D$  the set of buses without power plants;  $l$  the index for transmission lines/transformers;  $L$  the set of transmission lines/transformers;  $t$  and  $t'$  the indices for time intervals;  $T$  the set of time intervals belonging to the time horizon  $H$ ;  $s$  the index for scenarios modeling the forecast errors of demand and renewable generation as well as contingencies;  $S$  the set of scenarios;  $d$  the index for (flexible and inflexible) distribution networks;  $D^{\text{Flex}}$  the set of flexible distribution networks;  $D^{\text{Inflex}}$  the set of inflexible distribution networks;  $D$  the set of all distribution networks ( $D = D^{\text{Flex}} \cup D^{\text{Inflex}}$ );  $g$  the index for (stochastic and dispatchable) power plants;  $G^{\text{Flex}}$  the set of flexible power plants, i.e. dispatchable power plants like hydro plants;  $G^{\text{Inflex}}$  the set of inflexible power plants, i.e. stochastic power plants like solar/wind plants;  $G$  the set of all power plants ( $G = G^{\text{Flex}} \cup G^{\text{Inflex}}$ );  $D_i^{\text{Flex}} / D_i^{\text{Inflex}}$  the set of flexible/inflexible distribution networks connected to bus  $i$ ;  $G_i^{\text{Flex}} / G_i^{\text{Inflex}}$  the set of flexible/inflexible power plants connected to bus  $i$ ;  $n$  the index for the offered FPC areas to the TSO;  $O_d / O_g$  the set of offered FPC areas to the TSO by

flexible distribution network  $d$  / flexible dispatchable power plant  $g$ . Superscripts  $*^{P+}$ ,  $*^{P-}$ ,  $*^{Q+}$ ,  $*^{Q-}$  are respectively used to indicate the quantity of  $*$  associated with upward active, downward active, upward reactive and downward reactive power flexibility. Operator  $|\cdot|$  denotes the element-wise absolute values of its argument. Then, the problem is formulated relying on the following considerations:

### 1) Decentralized Energy & Flexibility Market

It follows the decentralized energy and flexibility market structure where the outcome of the day-ahead energy market is known. Thus, for each time interval  $t$  belonging to the time horizon  $H$ :

- The scheduled active and reactive power absorption of distribution network  $d$  (for all  $d \in D$ ) from its TSO-DSO interface, i.e.  $\hat{P}_{dt}$  and  $\hat{Q}_{dt}$ , are known.
- The scheduled/predicted active power generation of dispatchable/stochastic power plant  $g$  (for all  $g \in G$ ) are known, i.e.  $\hat{P}_{gt}$ . Moreover, the TSO's defined set-point for the voltage magnitude of the interconnecting bus of that plant, i.e.  $|\hat{V}_{gt}|$ , is known.

### 2) Flexibility Coordination Stage

For each time interval  $t$ :

- Flexible distribution network  $d$  offers a set of FPC areas, i.e.  $\mathcal{A}_{dtn}$ , with different booking prices i.e.  $\pi_{dtn}^{P+}$ ,  $\pi_{dtn}^{P-}$ ,  $\pi_{dtn}^{Q+}$ ,  $\pi_{dtn}^{Q-}$  to the TSO. Afterwards, TSO books its required FPC area from flexible distribution network  $d$ , i.e.  $\mathcal{A}_{dt}^{\text{TSO}}$ . It is noteworthy that  $\mathcal{A}_{dtn}$  (and respectively  $\mathcal{A}_{dt}^{\text{TSO}}$ ) is characterized by its 4 non-negative boundaries, namely offered (booked) upward and downward active/reactive power flexibility, i.e.  $F_{dtn}^{P+}$ ,  $F_{dtn}^{P-}$ ,  $F_{dtn}^{Q+}$  and  $F_{dtn}^{Q-}$  ( $F_{dt}^{P+, \text{TSO}}$ ,  $F_{dt}^{P-, \text{TSO}}$ ,  $F_{dt}^{Q+, \text{TSO}}$  and  $F_{dt}^{Q-, \text{TSO}}$ );
- Power plant  $g$  (for all  $g \in G$ ), during the real-time grid operation, is responsible to automatically regulate its reactive power injection in such a way that the voltage magnitude of its interconnecting bus is preserved equal to the voltage set-point defined by the TSO, i.e.  $|\hat{V}_{gt}|$ . Therefore, the optimal power flexibility allocation problem treats all buses hosting power plants ( $i \in B^G$ ) as  $PV$  buses, to put it simply, their reactive power injections depend on the nodal injections of the other buses (as characterized in (29)) and their voltage magnitudes are fixed equal to their respective set-points, i.e.  $|\hat{V}_{gt}|$ . Accordingly, it is assumed that there are long-term contracts between TSO and power plants where power plants are committed to accomplish automatic voltage regulation during the real-time grid operation without any additional cost. As a consequence, the TSO needs to neither book (in flexibility coordination stage) nor request from power plants to activate their reactive power flexibility (in flexibility exchange stage).
- Flexible power plant  $g$  offers a set of FPC areas, i.e.  $\mathcal{A}_{gtn}$ , with different booking prices i.e.  $\pi_{gtn}^{P+}$ ,  $\pi_{gtn}^{P-}$  to the TSO. Afterwards, TSO books its required FPC area from flexible power plant  $g$ , i.e.  $\mathcal{A}_{gt}^{\text{TSO}}$ . It is noteworthy

that  $\mathcal{A}_{gtn}$  (and respectively  $\mathcal{A}_{gt}^{\text{TSO}}$ ) is characterized by its 4 non-negative boundaries, namely offered (booked) upward and downward active power flexibility, i.e.  $F_{gtn}^{P+}$  and  $F_{gtn}^{P-}$  ( $F_{gt}^{P+, \text{TSO}}$  and  $F_{gt}^{P-, \text{TSO}}$ ) along with minimum and maximum reactive power generation limit of power plant  $g$ , i.e.  $-Q_{gt}^{\text{Min}}$  and  $Q_{gt}^{\text{Max}}$ .

### 3) Flexibility Exchange Stage

In time interval  $t$  and scenario  $s$ :

- Flexible distribution networks  $d$  (for all  $d \in D^{\text{Flex}}$ ) is able not only to follow its scheduled operating point, i.e.  $\hat{P}_{dt}$  and  $\hat{Q}_{dt}$ , but also to provide active and reactive power flexibility to the transmission network at its TSO-DSO interface i.e.  $f_{dts}^P$  and  $f_{dts}^Q$ .  $f_{dts}^P$  (and respectively  $f_{dts}^Q$ ) is formed of the sum of two non-negative components called upward, i.e.  $f_{dts}^{P+}$ , and downward, i.e.  $f_{dts}^{P-}$  active power flexibility (upward, i.e.  $f_{dts}^{Q+}$ , and downward, i.e.  $f_{dts}^{Q-}$  reactive power flexibility) as:

$$f_{dts}^P = f_{dts}^{P+} - f_{dts}^{P-} \quad (1)$$

$$f_{dts}^Q = f_{dts}^{Q+} - f_{dts}^{Q-} \quad (2)$$

- In contrast to the flexible distribution networks, inflexible distribution network  $d$  (for all  $d \in D^{\text{Inflex}}$ ) is sources of active and reactive power uncertainties, i.e.  $\Delta P_{dts}$  and  $\Delta Q_{dts}$ . Therefore, it may deviate from its scheduled operating point, i.e.  $\hat{P}_{dt}$  and  $\hat{Q}_{dt}$ .
- Dispatchable power plant  $g$  (for all  $g \in G^{\text{Flex}}$ ) can provide active power flexibility to the transmission network i.e.  $f_{gts}^P$ .  $f_{gts}^P$  is formed of the sum of two non-negative components called upward, i.e.  $f_{gts}^{P+}$ , and downward, i.e.  $f_{gts}^{P-}$  active power flexibility as:

$$f_{gts}^P = f_{gts}^{P+} - f_{gts}^{P-} \quad (3)$$

- Stochastic power plant  $g$  (for all  $g \in G^{\text{Inflex}}$ ) is source of active power uncertainties, i.e.  $\Delta P_{gts}$ . Therefore, it may deviate from its predicted power generation, i.e.  $\hat{P}_{gt}$ .

### A. Objective function

The objective function is designed to help TSO optimally steer its grid, thereby minimizing the cost of TSO, i.e.  $C^{\text{TSO}}$ , over both flexibility coordination (planning) and flexibility exchange (operation) stages:

$$\min C^{\text{TSO}} = C^{\text{Planning}} + \sum_{t \in T} EC_t^{\text{Operation}}, \quad (4)$$

1)  $C^{\text{Planning}}$  represents the cost of TSO in coordination stage where the TSO books FPC areas. More specifically, it specifies the TSO's cost associated with booking FPC areas  $\mathcal{A}_{dt}^{\text{TSO}}$  and  $\mathcal{A}_{gt}^{\text{TSO}}$ :

$$C^{\text{Planning}} = \sum_{t \in T} \sum_{d \in D^{\text{Flex}}} [\pi_{dt}^{P+} F_{dt}^{P+, \text{TSO}} + \pi_{dt}^{P-} F_{dt}^{P-, \text{TSO}} + \pi_{dt}^{Q+} F_{dt}^{Q+, \text{TSO}} + \pi_{dt}^{Q-} F_{dt}^{Q-, \text{TSO}}] + \sum_{t \in T} \sum_{g \in G^{\text{Flex}}} [\pi_{gt}^{P+} F_{gt}^{P+, \text{TSO}} + \pi_{gt}^{P-} F_{gt}^{P-, \text{TSO}}], \quad (5)$$

where  $\pi_{dt}^{P+}$ ,  $\pi_{dt}^{P-}$ ,  $\pi_{dt}^{Q+}$ ,  $\pi_{dt}^{Q-}$ ,  $\pi_{gt}^{P+}$  and  $\pi_{gt}^{P-}$  are the booking prices associated with  $\mathcal{A}_{dt}^{\text{TSO}}$  and  $\mathcal{A}_{gt}^{\text{TSO}}$  and can be calculated as detailed in (16).

2)  $EC_t^{\text{Operation}}$  represents the expected cost of TSO over time interval  $t$  in flexibility exchange stage where the TSO deploys active/reactive power flexibility to preserve the power quality of its grid and avoid curtailing demand. Accordingly, it embraces two parts:

$$EC_t^{\text{Operation}} = EC_t^{\text{Flexibility}} + EC_t^{\text{ENS}} \quad (6)$$

where  $EC_t^{\text{Flexibility}}$  represents TSO's expected cost due to deploying upward/downward active/reactive power flexibility:

$$\begin{aligned} EC_t^{\text{Flexibility}} = & \sum_{s \in \mathbb{S}} \tau \rho_s \pi_t^{P+} \left[ \sum_{d \in \text{DFlex}} f_{dts}^{P+} + \sum_{g \in \text{GFlex}} f_{gts}^{P+} \right] + \\ & + \sum_{s \in \mathbb{S}} \tau \rho_s \pi_t^{P-} \left[ \sum_{d \in \text{DFlex}} f_{dts}^{P-} + \sum_{g \in \text{GFlex}} f_{gts}^{P-} \right] + \\ & + \sum_{s \in \mathbb{S}} \tau \rho_s \pi_t^{Q+} \left[ \sum_{d \in \text{DFlex}} f_{dts}^{Q+} \right] + \\ & + \sum_{s \in \mathbb{S}} \tau \rho_s \pi_t^{Q-} \left[ \sum_{d \in \text{DFlex}} f_{dts}^{Q-} \right] \end{aligned} \quad (7)$$

where  $\rho_s$  is the probability of occurrence of scenario  $s$ ;  $\pi_t^{P+}$ ,  $\pi_t^{P-}$ ,  $\pi_t^{Q+}$  and  $\pi_t^{Q-}$  are prices for deploying upward active, downward active, upward reactive and downward reactive power flexibility during the real-time grid operation.  $EC_t^{\text{ENS}}$  represents TSO's expected cost pertained to energy not supplied of consumers, i.e.  $EC_t^{\text{ENS}}$

$$EC_t^{\text{ENS}} = \text{VOLL} \sum_{s \in \mathbb{S}} \tau \rho_s \sum_{d \in \text{D}} P_{dts}^{\text{NS}} \quad (8)$$

where VOLL is value of lost load for energy not supplied;  $P_{dts}^{\text{NS}}$  is the not supplied (i.e. curtailed) demand of distribution network  $d$  in time interval  $t$  and scenario  $s$ .

### B. Constraints Associated with Flexibility Coordination Stage

For each offered FPC area  $\mathcal{A}_{dtn}$  (and respectively  $\mathcal{A}_{gtn}$ ), a binary variables  $u_{dtn}$  ( $u_{gtn}$ ) is designated to characterize the booking prices associated with  $\mathcal{A}_{dt}^{\text{TSO}}$  ( $\mathcal{A}_{gt}^{\text{TSO}}$ ), thereby determining the coefficients used in (5). For the sake of brevity, the following just elaborates the way that binary variable  $u_{dtn}$  can be mathematically modeled. However, binary variable  $u_{gtn}$  can also be modeled in the same way. Binary variable  $u_{dtn}$  takes 1 if  $\mathcal{A}_{dtn}$  is the smallest offered FPC area that  $\mathcal{A}_{dt}^{\text{TSO}} \subset \mathcal{A}_{dtn}$  and 0 otherwise. In order to mathematically express this logical relationship, lets first introduce the auxiliary binary variable  $u'_{dtn}$  denoting whether  $\mathcal{A}_{dt}^{\text{TSO}} \subset \mathcal{A}_{dtn}$  or not.  $u'_{dtn}$  can be mathematically modeled as:

$$u'_{dtn} = u'_{dtn}^{P+} u'_{dtn}^{P-} u'_{dtn}^{Q+} u'_{dtn}^{Q-} \quad (9)$$

where binary variable  $u'_{dtn}^{P+}$  (and similarly  $u'_{dtn}^{P-}$ ,  $u'_{dtn}^{Q+}$  and  $u'_{dtn}^{Q-}$ ) indicates whether  $F_{dt}^{P+, \text{TSO}} - F_{dtn}^{P+} \leq 0$  or not. These logical relationships can be mathematically expressed as [22]:

$$m_{dtn}^{P+} u'_{dtn}^{P+} \leq F_{dt}^{P+, \text{TSO}} - F_{dtn}^{P+} \leq M_{dtn}^{P+} (1 - u'_{dtn}^{P+}) \quad (10)$$

$$m_{dtn}^{P-} u'_{dtn}^{P-} \leq F_{dt}^{P-, \text{TSO}} - F_{dtn}^{P-} \leq M_{dtn}^{P-} (1 - u'_{dtn}^{P-}) \quad (11)$$

$$m_{dtn}^{Q+} u'_{dtn}^{Q+} \leq F_{dt}^{Q+, \text{TSO}} - F_{dtn}^{Q+} \leq M_{dtn}^{Q+} (1 - u'_{dtn}^{Q+}) \quad (12)$$

$$m_{dtn}^{Q-} u'_{dtn}^{Q-} \leq F_{dt}^{Q-, \text{TSO}} - F_{dtn}^{Q-} \leq M_{dtn}^{Q-} (1 - u'_{dtn}^{Q-}) \quad (13)$$

where parameters  $m_{dtn}^{P+}$  and  $M_{dtn}^{P+}$  (and similarly  $m_{dtn}^{P-}$ ,  $M_{dtn}^{P-}$ ,  $m_{dtn}^{Q+}$ ,  $M_{dtn}^{Q+}$ ,  $m_{dtn}^{Q-}$ ,  $M_{dtn}^{Q-}$ ) are respectively the lower and upper bounds for  $F_{dt}^{P+, \text{TSO}} - F_{dtn}^{P+}$ . These bounds can be easily determined referring to Fig. 2. Finally, the binary variable  $u_{dtn}$  is characterized via constraints (14)-(15) where among all offers, i.e.  $n \in \text{O}_d$ , the smallest  $\mathcal{A}_{dtn}$  having  $u'_{dtn} = 1$  is detected:

$$0 \leq u_{dtn} \leq 1 - u'_{dt(n-1)} \quad (14)$$

$$0 \leq u_{dtn} \leq u'_{dtn} \quad (15)$$

Accordingly, the booking price for upward active power flexibility from flexible distribution network  $d$  in time interval  $t$  can be easily characterized as:

$$\pi_{dt}^{P+} = \sum_{n \in \text{N}} \pi_{dtn}^{P+} u_{dtn} \quad (16)$$

In the same way, the other booking prices used in (5), i.e.  $\pi_{dt}^{P-}$ ,  $\pi_{dt}^{Q+}$ ,  $\pi_{dt}^{Q-}$ ,  $\pi_{gt}^{P+}$  and  $\pi_{gt}^{P-}$ , can be calculated.

For each time interval  $t$  and for each flexibility provider, the TSO is allowed to book at most the largest offered FPC area. To put it simply,  $\mathcal{A}_{dt}^{\text{TSO}}$  (and respectively  $\mathcal{A}_{gt}^{\text{TSO}}$ ) is restricted by  $\mathcal{A}_{dtn'}$  ( $\mathcal{A}_{gtn'}$ ) where index  $n'$  corresponds to the largest offered FPC area of flexible distribution network  $d$  (flexible power plant  $g$ ) for time interval  $t$ :

$$0 \leq F_{dt}^{P+, \text{TSO}} \leq F_{dtn'}^{P+} \quad (17)$$

$$0 \leq F_{dt}^{P-, \text{TSO}} \leq F_{dtn'}^{P-} \quad (18)$$

$$0 \leq F_{dt}^{Q+, \text{TSO}} \leq F_{dtn'}^{Q+} \quad (19)$$

$$0 \leq F_{dt}^{Q-, \text{TSO}} \leq F_{dtn'}^{Q-} \quad (20)$$

$$0 \leq F_{gt}^{P+, \text{TSO}} \leq F_{gtn'}^{P+} \quad (21)$$

$$0 \leq F_{gt}^{P-, \text{TSO}} \leq F_{gtn'}^{P-} \quad (22)$$

### C. Constraints Associated with Flexibility Exchange Stage

During the real-time grid operation, the TSO is allowed to deploy any amount of active/reactive power flexibility belonging to its booked FPC areas, i.e.  $\mathcal{A}_{dt}^{\text{TSO}}$  and  $\mathcal{A}_{gt}^{\text{TSO}}$ :

$$-F_{dt}^{P-, \text{TSO}} \leq f_{dts}^P \leq F_{dt}^{P+, \text{TSO}} \quad (23)$$

$$-F_{dt}^{Q-, \text{TSO}} \leq f_{dts}^Q \leq F_{dt}^{Q+, \text{TSO}} \quad (24)$$

$$-F_{gt}^{P-, \text{TSO}} \leq f_{gts}^P \leq F_{gt}^{P+, \text{TSO}} \quad (25)$$

Furthermore, to avoid under/over-voltage issues, the TSO must ensure that each power plant  $g$  can accomplish its voltage regulation task without reaching its maximum/minimum

reactive power generation limits, i.e.  $Q_{gt}^{\text{Max}} / Q_{gt}^{\text{Min}}$ , (for all  $g \in G, t \in T, s \in S$ ):

$$Q_{gt}^{\text{Min}} \leq Q_{gts} \leq Q_{gt}^{\text{Max}}, \quad (26)$$

where  $Q_{gts}$ , characterized in (29), denotes the reactive power generation of power plant  $g$  in time interval  $t$  and scenario  $s$ .

The following is intended to linearly model all grid constraints. To this end, two variables  $\Delta P_{its}$  and  $\Delta Q_{its}$  are firstly introduced:

For each bus  $i$  in  $B$ , the net deviation of the nodal active power injection from its scheduled operating point in time interval  $t$  and scenario  $s$  can be calculated as:

$$\begin{aligned} \Delta P_{its} = & \sum_{d \in D_i^{\text{Flex}}} f_{dts}^{\text{P}} + \sum_{d \in D_i^{\text{Inflex}}} \Delta P_{dts} + \\ & + \sum_{g \in G_i^{\text{Flex}}} f_{gts}^{\text{P}} + \sum_{g \in G_i^{\text{Inflex}}} \Delta P_{gts}, \end{aligned} \quad (27)$$

For each bus  $i$  in  $B^{\text{D}}$ , the net deviation of the nodal reactive power injection from its scheduled operating point in time interval  $t$  and scenario  $s$  can be calculated as:

$$\Delta Q_{its} = \sum_{d \in D_i^{\text{Flex}}} f_{dts}^{\text{Q}} + \sum_{d \in D_i^{\text{Inflex}}} \Delta Q_{dts}, \quad (28)$$

Relying on a linearized AC power flow model, the following variables are expressed as linear functions of  $\Delta P_{its}$  (calculated in (28)) and  $\Delta Q_{its}$  (calculated in (29)):

#### 1) Reactive Power Generation of Power Plants:

Considering the fact that each power plant controls its reactive power injection in such a way that the voltage magnitude of its interconnecting bus is preserved equal to the voltage set-point defined by the TSO, i.e.  $|\hat{V}_{gt}|$ . Therefore, for each power plant  $g$ , its reactive power injection in time interval  $t$  and scenario  $s$ , i.e.  $Q_{gts}$ , depends on  $\Delta P_{its}$  (calculated in (28)) and  $\Delta Q_{its}$  (calculated in (29)) and can be expressed as a linear function with constant coefficients  $Q_{gt}^0$ ,  $Q_{git}^{\text{P}}$  and  $Q_{git}^{\text{Q}}$ :

$$Q_{gts} = Q_{gt}^0 + \sum_{i \in B} Q_{git}^{\text{P}} \Delta P_{its} + \sum_{i \in B^{\text{D}}} Q_{git}^{\text{Q}} \Delta Q_{its}, \quad (29)$$

#### 2) Active Power Flexibility Provision of the Slack power plant:

The slack power plant  $g$ , connected to the reference bus  $r$ , provides active power flexibility so that the voltage phase angle of its interconnecting bus is fixed to zero. Therefore, its active power flexibility provision in time interval  $t$  and scenario  $s$ , i.e.  $f_{gts}^{\text{P}}$ , depends on  $\Delta P_{its}$  (calculated in (28)) and  $\Delta Q_{its}$  (calculated in (29)) and can be expressed as a linear function with constant coefficients  $\mathbb{P}_{gt}^0$ ,  $\mathbb{P}_{git}^{\text{P}}$  and  $\mathbb{P}_{git}^{\text{Q}}$  (just for  $g$  connected to the reference bus  $r$ ):

$$f_{gts}^{\text{P}} = \mathbb{P}_{gt}^0 + \sum_{i \in B} \mathbb{P}_{git}^{\text{P}} \Delta P_{its} + \sum_{i \in B^{\text{D}}} \mathbb{P}_{git}^{\text{Q}} \Delta Q_{its}, \quad (30)$$

It should be noted that the active power flexibility provision of all flexible power plants, i.e.  $f_{gts}^{\text{P}}$ , excluding the slack power plant are independent optimization variables and their optimal values are determined by solving the optimization problem.

#### 3) Nodal Voltage Magnitude:

For each bus  $i$  in  $B^{\text{D}}$ , the nodal voltage magnitude in time interval  $t$  and scenario  $s$ , i.e.  $|V_{its}|$ , can be expressed as a linear function with constant coefficients  $V_{it}^0$ ,  $V_{ijt}^{\text{P}}$  and  $V_{ijt}^{\text{Q}}$ :

$$|V_{its}| = V_{it}^0 + \sum_{j \in B} V_{ijt}^{\text{P}} \Delta P_{jts} + \sum_{j \in B^{\text{D}}} V_{ijt}^{\text{Q}} \Delta Q_{jts}, \quad (31)$$

Therefore, the nodal voltage magnitude constraints are linearly characterized as (for all  $i \in B^{\text{D}}, t \in T, s \in S$ ):

$$V_i^{\text{Min}} \leq |V_{its}| \leq V_i^{\text{Max}}, \quad (32)$$

where  $V_i^{\text{Min}}$  and  $V_i^{\text{Max}}$  respectively denote the minimum and maximum allowable voltage magnitude of node  $i$ . It is noteworthy that the voltage magnitude of the other buses (i.e.  $i \in B^{\text{G}}$ ) are fixed to their defined voltage set-point, i.e.  $|\hat{V}_{gt}|$ .

#### 4) Apparent Power Flow in Branches

The apparent power flow entering the from-end (and respectively the to-end) of transmission line/transformer  $l$  in time interval  $t$  and scenario  $s$  can be expressed as linear function of  $\Delta P_{its}$  (calculated in (28)) and  $\Delta Q_{its}$  (calculated in (29)) with constant coefficients  $S_{gt}^{\text{F},0}$ ,  $S_{git}^{\text{F},\text{P}}$  and  $S_{git}^{\text{F},\text{Q}}$  ( $S_{gt}^{\text{T},0}$ ,  $S_{git}^{\text{T},\text{P}}$  and  $S_{git}^{\text{T},\text{Q}}$ ):

$$S_{lts}^{\text{F}} = S_{lt}^{\text{F},0} + \sum_{i \in B} S_{lit}^{\text{F},\text{P}} \Delta P_{its} + \sum_{i \in B^{\text{D}}} S_{lit}^{\text{F},\text{Q}} \Delta Q_{its}, \quad (33)$$

$$S_{lts}^{\text{T}} = S_{lt}^{\text{T},0} + \sum_{i \in B} S_{lit}^{\text{T},\text{P}} \Delta P_{its} + \sum_{i \in B^{\text{D}}} S_{lit}^{\text{T},\text{Q}} \Delta Q_{its}, \quad (34)$$

Hence, maximum power flow limit of transmission lines/ transformer  $l$  can be linearly expressed (for all  $l \in L, t \in T, s \in S$ ):

$$0 \leq S_{lts}^{\text{F}} \leq S_l^{\text{Max}}, \quad (35)$$

$$0 \leq S_{lts}^{\text{T}} \leq S_l^{\text{Max}}, \quad (36)$$

where  $S_l^{\text{Max}}$  denotes the maximum power flow limit of transmission lines/transformer  $l$ .

Objective function (4) along with constraints (1)-(3), (6)-(8), (10)-(36) and the linear equivalent counterparts of (5) and (9), introduced in the appendix, casts the problem as a two-stage mixed integer stochastic optimization problem. Optimization variables pertained to the flexibility coordination stage, i.e. *here&now* decision variables, are:

$$\begin{aligned} \{ & F_{dt}^{\text{P}+, \text{TSO}}, F_{dt}^{\text{P}-, \text{TSO}}, F_{dt}^{\text{Q}+, \text{TSO}}, F_{dt}^{\text{Q}-, \text{TSO}}, \\ & F_{gt}^{\text{P}+, \text{TSO}}, F_{gt}^{\text{P}-, \text{TSO}}, u_{dtn}, u'_{dtn}, u_{dtn}^{\text{P}+}, u_{dtn}^{\text{P}-}, \\ & u'_{dtn}{}^{\text{Q}+}, u'_{dtn}{}^{\text{Q}-}, u_{gtn}, u'_{gtn}, u_{gtn}^{\text{P}+}, u_{gtn}^{\text{P}-} \} \end{aligned} \quad (37)$$

and optimization variables pertained to the flexibility exchange stage, i.e. *wait&see* decision variables, are:

$$\begin{aligned} \{ & f_{dts}^{\text{P}+}, f_{dts}^{\text{P}-}, f_{dts}^{\text{Q}+}, f_{dts}^{\text{Q}-}, f_{gts}^{\text{P}+}, f_{gts}^{\text{P}-}, \\ & Q_{gts}, F_{dts}^{\text{NS}}, |V_{its}|, S_{lts}^{\text{F}}, S_{lts}^{\text{T}} \} \end{aligned} \quad (38)$$

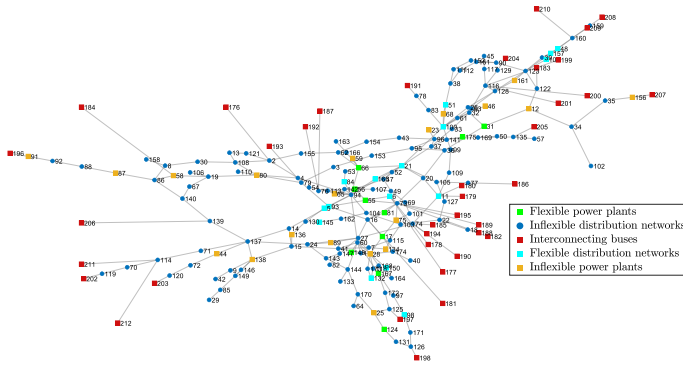


Fig. 3. Single line diagram of the Swiss electric transmission network.

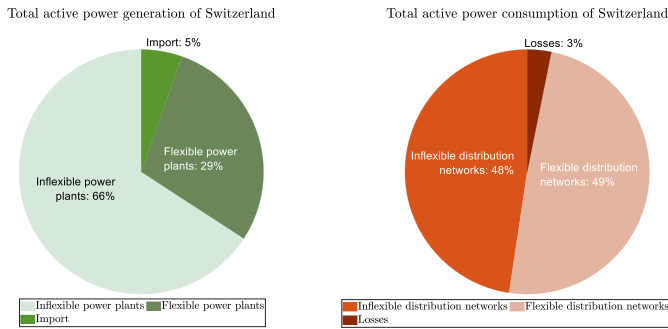


Fig. 4. Share of different entities from active power consumption/generation of Switzerland.

#### IV. CASE STUDY & RESULTS

##### A. Case Study

The electric transmission network of Switzerland, 6700 km in length, is selected as the case study. This grid is formed of 284 transmission lines and 25 transmission transformers interconnecting 212 buses at two voltage levels 380 kV and 220 kV. This grid is connected to the electric transmission networks of Italy, France, Austria and Germany via 37 interconnecting buses. This case study is constructed on the basis of data provided by Swissgrid, given that nuclear generation has been totally replaced by renewable stochastic generation. Fig. 3 illustrates the single line diagram of this grid whose buses are colored in 5 different colors considering the entity they are hosting:

- Flexible (dispatchable) power plants;
- Inflexible (stochastic) power plants;
- Buses connecting the grid to the neighboring grids, i.e. interconnecting buses;
- Flexible distribution networks;
- Inflexible distribution networks;

Following the time-line of the problem depicted in Fig. 1, the duration of each time interval, i.e.  $\tau$ , and the duration of the time horizon, i.e.  $\mathcal{H}$ , are respectively considered 1 hour and 24 hours which model 24-hour of the next day. Moreover,  $t_{\text{DSO}}$  and  $t_{\text{TSO}}$  are respectively considered 2 hours and 1 hour prior to the beginning of the time horizon  $\mathcal{H}$ .

Then, the performance of the proposed TSO-DSO coordination framework is investigated over a time interval where the total active power consumption of Switzerland is 6750 MW and the transmission grid's losses is 209 MW. This demand is supplied thanks to 347 MW imported power from neighboring countries, 2020 MW generated power of flexible power plants and 4592 MW generated power of inflexible power plants, as detailed in Fig. 4. As it can be seen, renewable generation contributes to 66% of the total generation of Switzerland. The power factor of both flexible and inflexible distribution networks range between 0.9 and 1. Inflexible distribution networks are assumed as constant power factor loads, while flexible distribution networks might change their power factor with the purpose of providing active/reactive power flexibility. Active power generation of inflexible power plants and active power demand of inflexible distribution networks are associated with uncertainties due to forecast errors, i.e.  $\Delta P_{gts}$  and i.e.  $\Delta P_{dts}$ . These uncertainties are assumed to be independent and identically distributed [23]. Therefore,  $\Delta P_{gts}$  of inflexible power plants are sampled from Gaussian distributions with 0 mean and such that the root mean square error (RMSE) of the total stochastic (renewable) generation of Switzerland is 10% of the total predicted one. In the same way,  $\Delta P_{dts}$  of inflexible distribution networks are sampled from Gaussian distributions with 0 mean and such that the RMSE of the total demand of Switzerland is 5% of the total predicted one. Accordingly, the uncertainties associated with reactive power consumption of inflexible distribution networks, i.e.  $\Delta Q_{dts}$ , are determined considering the constant power factor of inflexible distribution networks and  $\Delta P_{dts}$ . The grid contingencies, including power plant outages and line/transformer outages, are modeled based on sequential Monte Carlo simulation [24]. Following the elaborated approach, 1000 scenarios are generated to model uncertainties and contingencies.

Swissgrid regularly publishes the results of its flexibility market, i.e. the price of its deployed and booked active power flexibility [25]–[28]. After processing this data, the price of upward/downward deployed active power flexibility, i.e.  $\pi_t^{P+}$  and  $\pi_t^{P-}$ , are assumed equal to the annual average price of the respective product over 2019:

$$\pi_t^{P+} = 102 \text{ Euro/MWh} \quad (39)$$

$$\pi_t^{P-} = 35 \text{ Euro/MWh}, \quad (40)$$

The price of upward/downward deployed reactive power flexibility, i.e.  $\pi_t^{Q+}$  and  $\pi_t^{Q-}$ , are selected equal to the 3 Euro/MVarh as reported in [25].

To simplify the visualization of the results, it is supposed that all flexibility providers offer two FPC areas to the TSO. The first FPC area (the smaller FPC area) of each provider, i.e.  $n = 1$ , corresponds to 50% of its flexibility provision capability while the second FPC area (the larger FPC area), i.e.  $n = 2$ , corresponds to 100% of its flexibility provision capability. Moreover, it is assumed that all providers offer their first FPC areas with the same price (low price) and they offer their second FPC areas with the same price (high price). To

determine the booking prices of FPC areas, i.e.  $\pi_{dtn}^{P+}$ ,  $\pi_{dtn}^{P-}$ ,  $\pi_{dtn}^{Q+}$ ,  $\pi_{dtn}^{Q-}$ ,  $\pi_{gtn}^{P+}$  and  $\pi_{gtn}^{P-}$ , the prices of upward/downward booked active power flexibility of Swissgrid over 2019 are processed and they are clustered into two groups representing the low and high prices. Accordingly, the booking prices of upward/downward active power flexibility for the first FPC area, i.e.  $n = 1$ , (and respectively the second FPC area, i.e.  $n = 2$ ,) are considered equal to the annual average price of the respective product for low (and respectively high) price cluster over 2019. To put it simply, for all  $d \in D^{\text{Flex}}$  and for all  $g \in G^{\text{Flex}}$ :

$$\pi_{dtn}^{P+} = \pi_{gtn}^{P+} = \begin{cases} 8.7 \text{ Euro/MWh} & \text{if } n = 1 \\ 23.5 \text{ Euro/MWh} & \text{if } n = 2 \end{cases} \quad (41)$$

$$\pi_{dtn}^{P-} = \pi_{gtn}^{P-} = \begin{cases} 8.6 \text{ Euro/MWh} & \text{if } n = 1 \\ 22.9 \text{ Euro/MWh} & \text{if } n = 2 \end{cases} \quad (42)$$

In the absence of data associated with booking prices of upward/downward reactive power flexibility, the booking prices of upward and downward reactive power flexibility are respectively assumed equal to 0.1 of the booking price of upward and downward active power flexibility:

$$\pi_{dtn}^{Q+} = \begin{cases} 0.87 \text{ Euro/MWh} & \text{if } n = 1 \\ 2.35 \text{ Euro/MWh} & \text{if } n = 2 \end{cases} \quad (43)$$

$$\pi_{dtn}^{Q-} = \begin{cases} 0.86 \text{ Euro/MWh} & \text{if } n = 1 \\ 2.29 \text{ Euro/MWh} & \text{if } n = 2 \end{cases} \quad (44)$$

Value of lost load (VOLL) is chosen equal to 40000 Euro/MWh and minimum/maximum nodal voltage limits are considered equal to 0.95 pu and 1.05 pu. Then, YALMIP-MATLAB interface [29] is leveraged to cast the problem and GUROBI optimization solver [30] is selected to solve the problem on a Windows based system with a 2.9 GHz core i7 CPU and 32 GB of RAM.

### B. TSO-DSO Coordination for Optimal Allocation of Power Flexibility

Based on the designed TSO-DSO coordination framework, first, all flexibility providers offer their FPC areas to the TSO, i.e.  $\mathcal{A}_{gtn}$  and  $\mathcal{A}_{dtn}$ . These offered FPC areas are illustrated in dark and light yellow colors in Fig. 5 and Fig. 6. Then, TSO feeds these offered FPC areas into its two-stage mixed integer linear stochastic optimization problem (formulated in section III). Relying on the solution of this optimization problem, the TSO books its required FPC area from each flexibility provider as illustrated in blue color in Fig. 5 and Fig. 6. Moreover, each dark orange point in Fig. 5 and Fig. 6 represents the amount of active/reactive power flexibility that TSO needs to deploy

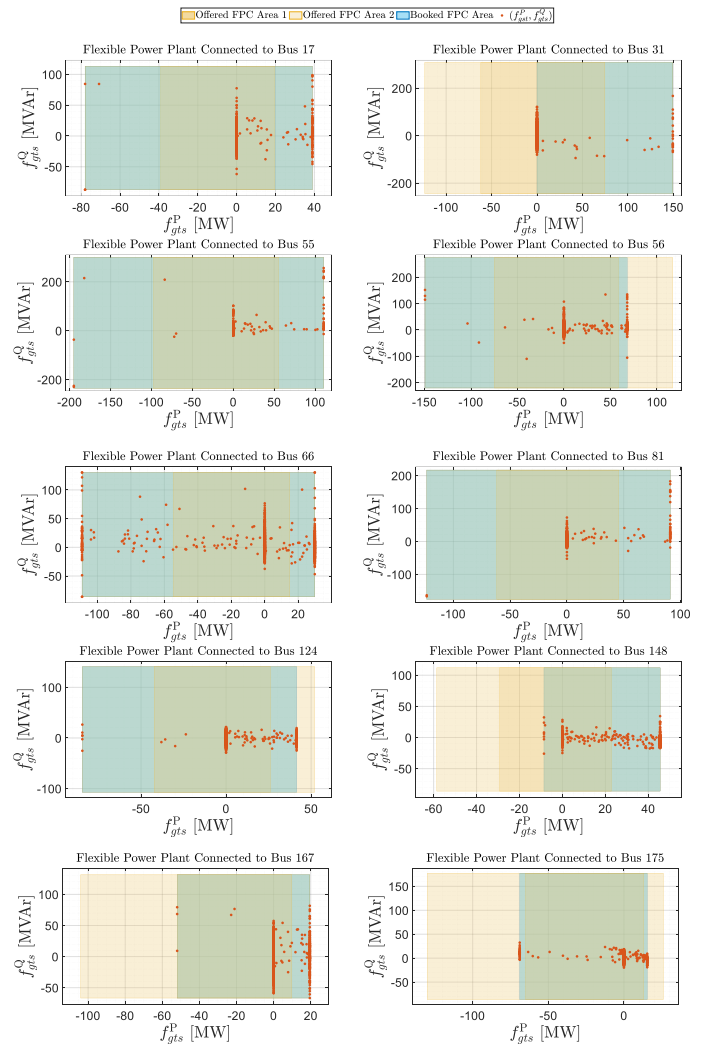


Fig. 5. Offered FPC areas of flexible power plants (i.e.  $\mathcal{A}_{gtn}$ ) as well as the TSO's booked FPC areas from flexible power plants (i.e.  $\mathcal{A}_{gt}^{\text{TSO}}$ ).

from the respective flexibility provider over each individual scenario to supply demand while respecting grid's constraints.

It is worth noting that in contrast to the free of charge reactive power flexibility provision of the power plants, booking/deploying reactive power flexibility from flexible distribution networks involves additional cost for TSO. However, the achieved results (illustrated in Fig. 5 and Fig. 6) reveal that TSO needs to book and deploy reactive power flexibility from flexible distribution networks in addition to the one coming from power plants. Moreover, the achieved results reveal that the TSO books active power flexibility from both flexible power plants and flexible distribution networks, although all flexible power plants and flexible distribution networks are offering the same prices for their active power flexibility. In sum, the achieved results highlight that flexible distribution networks play an important role in providing the required power flexibility of TSO, especially, in electric power system with high share of stochastic generation. It should



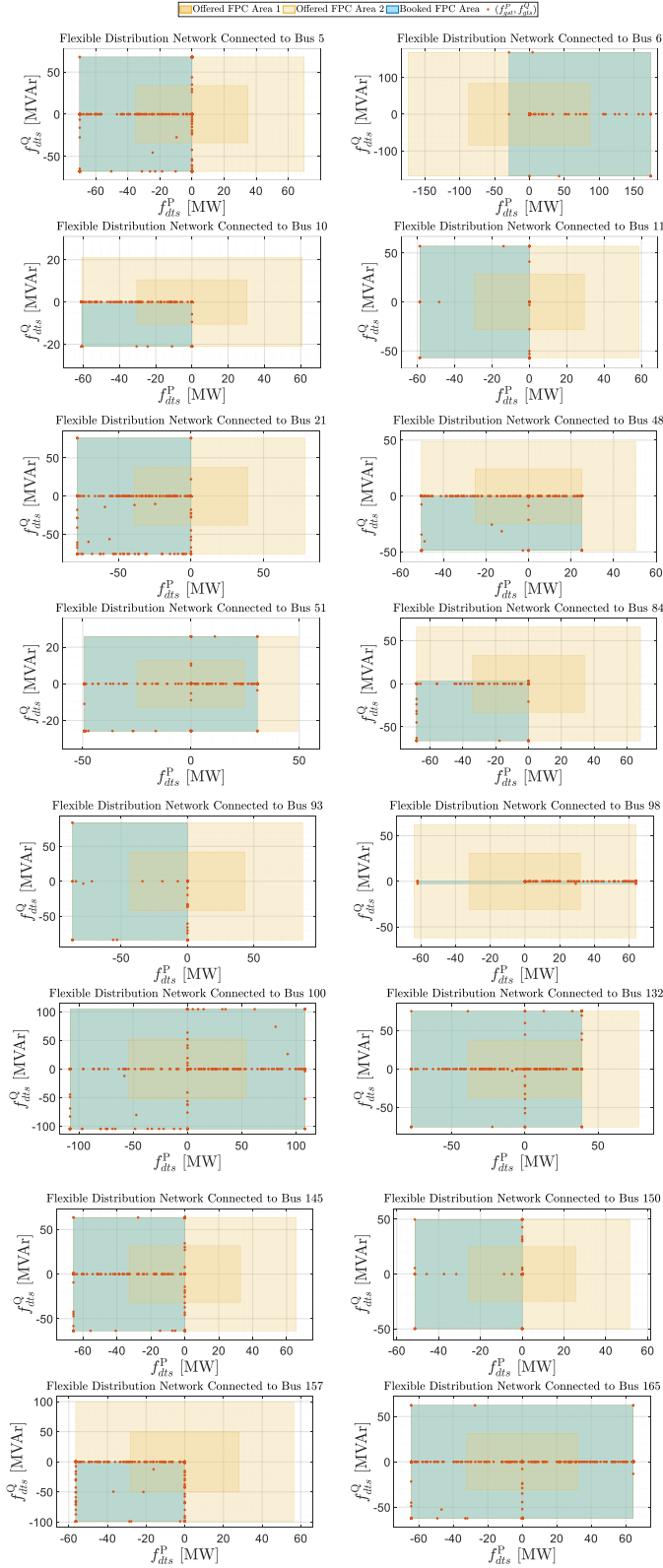


Fig. 6. Offered FPC areas of flexible distribution networks (i.e.  $\mathcal{A}_{dtn}$ ) as well as the TSO's booked FPC areas from flexible distribution networks (i.e.  $\mathcal{A}_{dt}^{TSO}$ ).

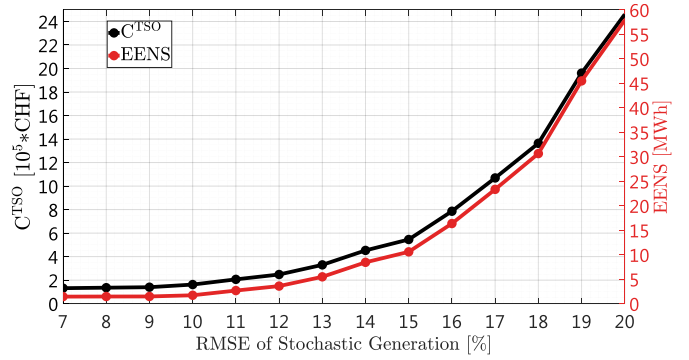


Fig. 7. Impact of RMSE of stochastic generation prediction on the TSO's cost and EENS.

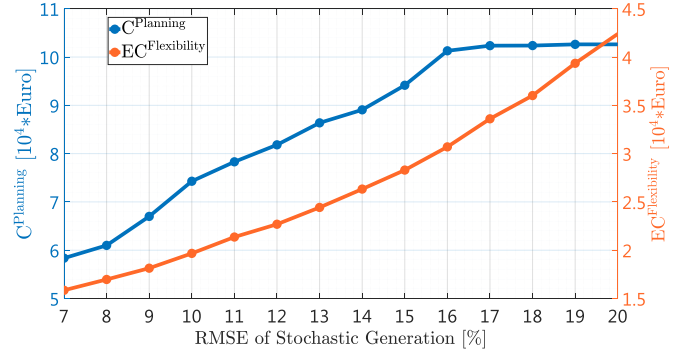


Fig. 8. Impact of RMSE of stochastic generation prediction on  $C^{Planning}$  and  $EC_t^{Flexibility}$ .

be highlighted that considering the TSO's booked flexibility (illustrated in Fig. 5 and Fig. 6), the expected energy not supplied of the Swissgrid is expected to be 2.6738 MWh, i.e. 0.037% of the total demand of the network.

### C. Impact of the Precision of Stochastic Generation Prediction on the TSO's Costs and Reliability

The amount of power flexibility that TSO books from different flexibility providers (and its associated cost) depends on the amount of uncertainties stemming from demand and stochastic generation. On the other hand, the magnitude of these uncertainties is largely affected by the precision of the prediction approach used to predict demand and stochastic generation. In this respect, this sub-section aims to investigate the impact of the precision of stochastic generation prediction on the TSO's cost and TSO's reliability. In this way, it quantifies the economic and technical benefits of precise stochastic generation prediction for TSO. To this end, it changes the RMSE of the total stochastic (renewable) generation of Switzerland from 7% to 20% of the total predicted one.

The impact of the precision of stochastic generation prediction on the total cost of TSO, i.e.  $C^{TSO} = C^{Planning} + EC_t^{Flexibility} + EC_t^{LNS}$ , and on the reliability of the transmission system, i.e. expected energy not supplied (EENS), are shown in Fig. 7. Fig. 7 reveals that both  $C^{TSO}$  and EENS constantly increase when RMSE of stochastic generation pre-

diction increases, i.e. precision of prediction decreases. However,  $C^{\text{TSO}}$  and EENS significantly increase when RMSE goes beyond 15%. To discover the reason behind this significant increase, Fig. 8 illustrates the cost of TSO due to booking flexibility, i.e.  $C^{\text{Planning}}$  along with expected cost of TSO due to deploying flexibility, i.e.  $EC_t^{\text{Flexibility}}$ . As it can be seen, when RMSE increases up to 15%,  $C^{\text{Planning}}$  and  $EC_t^{\text{Flexibility}}$  constantly rise because the TSO books and deploys greater deal of power flexibility to preserve the security of its grid against increasing uncertainties. To put it simply, TSO needs greater deal of power flexibility to 1-satisfy grid's constraints, 2-deal with increase and decrease of grid's active/reactive power losses, 3-restrict the load not supplied and accordingly 4-restrict the expected cost of TSO related to load not supplied, i.e.  $EC_t^{\text{LNS}}$ . However, when RMSE goes beyond 15%, the TSO faces with the shortage of power flexibility, i.e. the TSO's required power flexibility is greater than the offered power flexibility of flexibility providers. Therefore, TSO completely books all offered FPC areas, and as a result,  $C^{\text{Planning}}$  stays constant for RMSE beyond 15%. This shortage of power flexibility gives rise to surge in EENS and accordingly  $EC_t^{\text{LNS}}$  and  $C^{\text{TSO}}$  because TSO cannot deal with severe, i.e. large uncertainties. On the other hand, it should be noted that  $EC_t^{\text{Flexibility}}$  still rises even for RMSE beyond 15% due to the fact that the TSO needs to deal with larger uncertainties on average.

Last but not least, it should be highlighted that Fig. 7 is very informative not only for Swissgrid but also for other TSOs due to the fact that the above-mentioned analysis has been carried out on the basis of the prices extracted from the Swissgrid's flexibility market. For example, TSOs can use this figure as an indicator to find out whether it is economic to invest on their prediction framework to improve the precision of their prediction or not.

#### D. Investigating the Computational Burden of the Method

This section is intended to elaborate on the computational burden of the method. To this end, it should be highlighted that YALMIP-MATLAB interface [29] and GUROBI optimization solver [30] are selected to implement the method on a Windows based system with a 2.9 GHz corei7 CPU and 32 GB of RAM. The computation time of the method for a real-world electric transmission network, i.e. the electric transmission network of Switzerland, is 408 seconds while considering 1000 scenarios. This low computation burden of the method is achieved thanks to the linear tractable formulation presented for the method. The tractability and agility of the method make it as an applicable and practical solution for large real-world transmission networks. Moreover, the computation time of the method can even be improved if this method is implemented on industry-grade computers and benefited from parallelization techniques.

### V. CONCLUSION

This paper firstly established a novel TSO-DSO coordination framework with the purpose of enabling TSO and DSO

to exchange bi-directional active/reactive power flexibility with each other. Therefore, both active and reactive power flexibility of DERs located in flexible distribution networks can be provided to the TSO. The privileged feature of this framework is that TSO and DSO can implement it without having to disclose their confidential grids data. Moreover, this framework follows a sequential market structure to suit the Switzerland's flexibility market that is separate from the energy market. Then, the paper mathematically models this framework as a two-stage mixed integer linear stochastic optimization problem. In addition to maximum power flow limit of branches, this model considers the nodal voltage magnitude limits as well as grid's losses.

Last but not least, the paper opted a real-world electric transmission network, i.e. the Swiss transmission network, as a case study. The achieved results bear testimony to the paramount importance of the active and reactive power flexibility of flexible distribution networks in electric power systems with high share of stochastic generation. To securely steer the grid against increasing uncertainties, TSO needs both active and reactive power flexibility of flexible distribution networks.

### APPENDIX

#### 1) Linear Equivalent for Non-linear Expression (5):

Product of binary variable  $u$  and continuous variable  $x$  results in a non-linear term, i.e.  $ux$ . This non-linear term has a linear equivalent counterpart consisting of an auxiliary continuous variable, i.e.  $y$ , and two linear constraints:

$$ux^{\text{Min}} \leq y \leq ux^{\text{Max}}, \quad (45)$$

$$-(1-u)x^{\text{Max}} \leq y-x \leq -(1-u)x^{\text{Min}}, \quad (46)$$

where parameters  $x^{\text{Min}}$  and  $x^{\text{Max}}$  denotes the lower and upper bounds of  $x$ . Constraints (45) and (46) together enforce  $y$  become equal  $x$  if and only if binary variable  $u$  is 1 and 0 otherwise. Therefore, non-linear term  $ux$  can be replaced by continuous auxiliary variable  $y$  bound via (45) and (46).

#### 2) Linear Equivalent for Non-linear Expression (9):

Product of  $N$  binary variables  $u_k$ , i.e.  $\prod_{k=1}^N u_k$  suffers from non-linearity. However, this non-linear term has a linear equivalent counterpart formed of a continuous auxiliary variable  $z$  and  $N+1$  linear constraints:

$$0 \leq z \leq u_k, \quad \forall k = 1, 2, \dots, N \quad (47)$$

$$\sum_{k=1}^N u_k - N + 1 \leq z, \quad (48)$$

Constraints (47) and (48) together enforce  $z$  take 1 if an only if all binary variables  $u_k$  are 1 and 0 otherwise. Therefore, non-linear term  $\prod_{k=1}^N u_k$  can be replaced by continuous auxiliary variable  $z$  bound via (47) and (48).

### DISCLAIMER

The views expressed in this article are solely those of the authors and do not necessarily represent those of Swissgrid, EPFL or ALSTOM.

## ACKNOWLEDGMENT

The authors deeply express their gratitude to Dr. Walter Sattinger, Dr. Marek Zima, and Dr. Jonas Muehlethaler for providing all required data of Swissgrid network and their useful advices. This project is carried out within the frame of the Swiss Centre for Competence in Energy Research on the Future Swiss Electrical Infrastructure (SCCER-FURIES) with the financial support of Swissgrid and the Swiss Innovation Agency (Innosuisse - SCCER program).

## REFERENCES

- [1] J. Rissman, C. Bataille, E. Masanet, N. Aden, W. R. Morrow, N. Zhou, N. Elliott, R. Dell, N. Heeren, B. Huckestein, J. Cresko, S. A. Miller, J. Roy, P. Fennell, B. Cremmins, T. Koch Blank, D. Hone, E. D. Williams, S. de la Rue du Can, B. Sisson, M. Williams, J. Katzenberger, D. Burtraw, G. Sethi, H. Ping, D. Danielson, H. Lu, T. Lorber, J. Dinkel, and J. Helseth, "Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070," *Applied Energy*, vol. 266, p. 114848, May 2020.
- [2] G. C. Kryonidis, C. S. Demoulias, and G. K. Papagiannis, "A new voltage control scheme for active medium-voltage (MV) networks," *Electric Power Systems Research*, vol. 169, pp. 53–64, Apr. 2019.
- [3] G. Fusco and M. Russo, "A Decentralized Approach for Voltage Control by Multiple Distributed Energy Resources," *IEEE Transactions on Smart Grid*, pp. 1–1, 2021.
- [4] J. Höckner, S. Voswinkel, and C. Weber, "Market distortions in flexibility markets caused by renewable subsidies – The case for side payments," *Energy Policy*, vol. 137, p. 111135, Feb. 2020.
- [5] "Black System South Australia 28 September 2016," tech. rep., Australian Energy Market Operator, Sept. 2016.
- [6] "1200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report," tech. rep., North American Electric Reliability Corporation, 2017.
- [7] S. Goutte and P. Vassilopoulos, "The value of flexibility in power markets," *Energy Policy*, vol. 125, pp. 347–357, Feb. 2019.
- [8] E. Luo, P. Cong, H. Lu, and Y. Li, "Two-Stage Hierarchical Congestion Management Method for Active Distribution Networks With Multi-Type Distributed Energy Resources," *IEEE Access*, vol. 8, pp. 120309–120320, 2020.
- [9] S. Acharya, M. S. E. Moursi, and A. Al-Hinai, "Coordinated Frequency Control Strategy for an Islanded Microgrid With Demand Side Management Capability," *IEEE Transactions on Energy Conversion*, vol. 33, pp. 639–651, June 2018.
- [10] A. Kulmala, S. Repo, and P. Järventausta, "Coordinated Voltage Control in Distribution Networks Including Several Distributed Energy Resources," *IEEE Transactions on Smart Grid*, vol. 5, pp. 2010–2020, July 2014.
- [11] F. Capitanescu, "TSO–DSO interaction: Active distribution network power chart for TSO ancillary services provision," *Electric Power Systems Research*, vol. 163, pp. 226–230, Oct. 2018.
- [12] M. Kalantar-Neyestanaki, F. Sossan, M. Bozorg, and R. Cherkaoui, "Characterizing the Reserve Provision Capability Area of Active Distribution Networks: A Linear Robust Optimization Method," *IEEE Transactions on Smart Grid*, vol. 11, pp. 2464–2475, May 2020.
- [13] M. Kalantar-Neyestanaki and R. Cherkaoui, "Coordinating Distributed Energy Resources and Utility-Scale Battery Energy Storage System for Power Flexibility Provision Under Uncertainty," *IEEE Transactions on Sustainable Energy*, pp. 1–1, 2021.
- [14] M. Zerva and M. Geidl, "Contribution of active distribution grids to the coordinated voltage control of the swiss transmission system," in *2014 Power Systems Computation Conference*, pp. 1–8, Aug. 2014.
- [15] G. Valverde, D. Shchetinin, and G. Hug-Glanzmann, "Coordination of Distributed Reactive Power Sources for Voltage Support of Transmission Networks," *IEEE Transactions on Sustainable Energy*, vol. 10, pp. 1544–1553, July 2019.
- [16] D. B. Arnold, M. D. Sankur, M. Negrete-Pincetic, and D. S. Callaway, "Model-Free Optimal Coordination of Distributed Energy Resources for Provisioning Transmission-Level Services," *IEEE Transactions on Power Systems*, vol. 33, pp. 817–828, Jan. 2018.
- [17] S. Karagiannopoulos, C. Mylonas, P. Aristidou, and G. Hug, "Active Distribution Grids Providing Voltage Support: The Swiss Case," *IEEE Transactions on Smart Grid*, pp. 1–1, 2020.
- [18] A. Abessi, V. Vahidinasab, and M. S. Ghazizadeh, "Centralized Support Distributed Voltage Control by Using End-Users as Reactive Power Support," *IEEE Transactions on Smart Grid*, vol. 7, pp. 178–188, Jan. 2016.
- [19] M. Kalantar-Neyestanaki, M. Bozorg, F. Sossan, and R. Cherkaoui, "Allocation of Frequency Control Reserve from Aggregated Resources of Active Distribution Systems," in *2018 Power Systems Computation Conference (PSCC)*, pp. 1–8, June 2018.
- [20] M. Kalantar-Neyestanaki, M. Bozorg, F. Sossan, and R. Cherkaoui, "Allocation of Active Power Reserve from Active Distribution Networks Using a Cost-Benefit Approach: Application to Swissgrid Network," in *2019 IEEE Milan PowerTech*, pp. 1–6, June 2019.
- [21] M. Kalantar-Neyestanaki and R. Cherkaoui, "Risk-aware Active Power Flexibility Allocation from TSO–DSO Interconnections: The Switzerland's Transmission Network," pp. 6513 – 6523, May 2022. *IEEE Systems Journal*.
- [22] H. P. Williams, *Model Building in Mathematical Programming*. England: John Wiley & Sons, 2013.
- [23] M. Bozorg, F. Sossan, J.-Y. Le Boudec, and M. Paolone, "Influencing the bulk power system reserve by dispatching power distribution networks using local energy storage," *Electric Power Systems Research*, vol. 163, pp. 270–279, Oct. 2018.
- [24] W. Li, *Risk Assessment of Power Systems*. United States of America: John Wiley & Sons, 2014.
- [25] "Tariffs and remuneration rates for the Swiss transmission grid," tech. rep., Swissgrid Ltd, Aarau, 2021. <https://www.swissgrid.ch/en/home/customers/topics/tariffs.html>.
- [26] "Energy statistic Switzerland," tech. rep., Swissgrid Ltd, Aarau, 2021. <https://www.swissgrid.ch/en/home/customers/topics/energy-data-ch.html>.
- [27] Swissgrid, "Tender for control power," tech. rep., Swissgrid Ltd, Aarau, 2021. <https://www.swissgrid.ch/en/home/customers/topics/ancillary-services/tenders.html>.
- [28] "Balance energy in the Swissgrid control area," tech. rep., Swissgrid Ltd, 2021. <https://www.swissgrid.ch/en/home/customers/topics/bgm/balance-energy.html>.
- [29] J. Lofberg, "YALMIP : a toolbox for modeling and optimization in MATLAB," in *2004 IEEE International Conference on Robotics and Automation*, pp. 284–289, Sept. 2004.
- [30] "Gurobi Optimizer Reference Manual," 2020.