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Risk-Aware Active Power Flexibility Allocation From TSO–DSO Interconnections: The Switzerland's Transmission Network

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***Abstract*—The power flexibility of the proliferating distributed energy resources located in distribution networks could be aggregated and provided to the transmission system. Considering the lack of a framework to help transmission system operator (TSO) to benefit from these potential power flexibility resources, first, the article establishes a framework for modeling aggregated flexibilities of distribution networks (AFENs) as seen from TSO's perspective. Then, it develops a two-stage linear stochastic optimization model to optimally book the TSO's required size of active power flexibility from AFENs and dispatchable power plants (DPPs). The model leverages a cost-benefit method and a dc load-flow model to minimize the TSO's total cost, namely the sum of 1-expected cost of active power flexibility allocation from AFENs and DPPs and 2-expected cost of energy not supplied. To achieve a risk-aware economic balance between these two incurred costs of TSO, the model relies on the value of lost load index as a metric. The method considers credible contingencies along with forecast errors of renewable generation and loads as scenarios. Finally, the method is applied to the transmission grid of Switzerland, operated by Swissgrid, to illustrate its effectiveness.**

***Index Terms*—Active power flexibility, cost-benefit approach, distributed energy resource (DER), stochastic optimization, transmission networks.**

NOMENCLATURE

Indices and Sets

g	Index of dispatchable/stochastic power plants.
i, j	Index of buses.
k	Index of AFENs.
l	Index of loads.
n	Index of offered blocks of flexibility.
s	Index of scenarios.
t, t'	Index of time periods.
$\mathbb{A}$	Set of AFENs.
$\mathbb{A}_i$	Set of AFENs connected to bus i.
$\mathbb{B}$	Set of indices of all buses.
$\mathbb{B}_i$	Set of indices of all buses connected to bus i.
$\mathbb{DP}$	Set of dispatchable power plants (DPPs).
$\mathbb{DP}_i$	Set of DPPs connected to bus i.
$\mathbb{L}_i$	Set of loads connected to bus i.
$\mathbb{N}$	Set of offered blocks of flexibility.
$\mathbb{SP}_i$	Set of stochastic power plants (SPPs) connected to bus i.
$\mathbb{S}$	Set of scenarios.
$\mathbb{T}$	Set of time periods forming the time horizon.

Auxiliary Variables (at Distribution Level)

$f_{kts}^{\text{DDG}+}, f_{kts}^{\text{DDG}-}$	Upward and downward active power flexibility that TSO deploys from the aggregated dispatchable distributed generator (DDG) of AFEN k in time period t and scenario s [MW].
$f_{kts}^{\text{EES}+}, f_{kts}^{\text{ESS}-}$	Upward and downward active power flexibility that TSO deploys from the aggregated energy storage system (ESS) of AFEN k in time period t and scenario s [MW].
$f_{kts}^{\text{FL}+}, f_{kts}^{\text{FL}-}$	Upward and downward active power flexibility that TSO deploys from the aggregated flexible load of AFEN k in time period t and scenario s [MW].

Auxiliary Parameters (at Distribution Level)

$\text{P}_{kt}^{\text{DDG}}$	Scheduled active power for the aggregated DDG of AFEN k in time period t [MW].
$\text{P}_{kt}^{\text{ESS}}$	Scheduled active power for the aggregated ESS of AFEN k in time period t [MW].
P_{kt}^{L}	Scheduled active power for the net load (including firm and flexible loads and nondispatchable DGs) of AFEN k in time period t [MW].

Variables (at Transmission Level)

$f_{gts}^{\text{G}+}, f_{gts}^{\text{G}-}$	Upward and downward (P-constrained) active power flexibility that TSO deploys from dispatchable power plant (DPP) g in time period t and scenario s [MW].
$f_{kts}^{\text{P}+}, f_{kts}^{\text{P}-}$	Upward and downward P-constrained active power flexibility that TSO deploys from AFEN k in time period t and scenario s [MW].
$f_{kts}^{\text{PE}+}, f_{kts}^{\text{PE}-}$	Upward and downward P&E-constrained active power flexibility that TSO deploys from AFEN k in time period t and scenario s [MW].

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$F_g^{\mathrm{G}+}$, $F_g^{\mathrm{G}-}$ Size of the upward and downward active power flexibility that TSO books from DPP g [MW].

$F_k^{\mathrm{P}+}$, $F_k^{\mathrm{P}-}$ Size of the upward and downward P-constrained active power flexibility that TSO books from AFEN k [MW].

$F_k^{\mathrm{PE}+}$, $F_k^{\mathrm{PE}-}$ Size of the upward and downward P&E-constrained active power flexibility that TSO books from AFEN k [MW].

P_{kts}^{SL}, P_{lts}^{SL} Involuntary shed load of AFEN k/load l in time period t and scenario s [MW].

θ_{its} Voltage phase angle at bus i in time period t and scenario s [rad].

Parameters (at Transmission Level)

$\mathrm{A}_{gts}^{\mathrm{G}}$ Binary parameter where 1 means power plant g is available in time period t and scenario s , otherwise 0.

$\mathrm{A}_{ijts}^{\mathrm{L}}$ Binary parameter where 1 means the transmission line connecting bus i to bus j is available in time period t and scenario s.

B_{ij} Series susceptance of the transmission line connecting bus i to bus j [p.u.].

$\mathrm{E}_k^{\mathrm{PE}+,\max}$, $\mathrm{E}_k^{\mathrm{PE}-,\max}$ Energy limit of the total upward and downward P&E-constrained active power flexibility that AFEN k offers to the TSO [MWh].

$\mathrm{F}_{gn}^{\mathrm{G}+,\max}$, $\mathrm{F}_{gn}^{\mathrm{G}-,\max}$ Power limit of the nth block of the upward and downward (P-constrained) active power flexibility that DPP g offers to the TSO [MW].

$\mathrm{F}_{kn}^{\mathrm{P}+,\max}$, $\mathrm{F}_{kn}^{\mathrm{P}-,\max}$ Power limit of the nth block of the upward and downward P-constrained active power flexibility that AFEN k offers to the TSO [MW].

$\mathrm{F}_{kn}^{\mathrm{PE}+,\max}$, $\mathrm{F}_{kn}^{\mathrm{PE}-,\max}$ Power limit of the nth block of the upward and downward P&E-constrained active power flexibility that AFEN k offers to the TSO [MW].

$\mathrm{P}_{ij}^{\max}$ Rated power limit of the transmission line connecting buses i to j [MW].

$\mathrm{P}_{kt}, \mathrm{P}_{lt}$ P_{gt} Scheduled active power for consumption of AFEN k/load$l$and generation of power plant g in time period t [MW].

VOLL_i Value of lost load for energy not supplied at bus i [Euro/(MWh)].

$\Delta\mathrm{P}_{gts}, \Delta\mathrm{P}_{lts}$ Deviation from the scheduled active power for stochastic power plant (SPP) g/load$l$in time period t and scenario s [MW].

$\pi_{gn}^{\mathrm{G}+}, \pi_{gn}^{\mathrm{G}-}$ Price offer of DPP g for nth block of the upward and downward (P-constrained) active power flexibility, i.e., $\mathrm{F}_{gn}^{\mathrm{G}+,\max}/\mathrm{F}_{gn}^{\mathrm{G}-,\max}$ [Euro/MW].

$\pi_{kn}^{\mathrm{P}+}, \pi_{kn}^{\mathrm{P}-}$ Price offer of AFEN k for nth block of the upward and downward P-constrained active power flexibility, i.e., $\mathrm{F}_{kn}^{\mathrm{p}+,\max}/\mathrm{F}_{kn}^{\mathrm{p}-,\max}$ [Euro/MW].

$\pi_{kn}^{\mathrm{PE}+}, \pi_{kn}^{\mathrm{PE}-}$ Price offer of AFEN k for nth block of the upward and downward P&E-constrained active power flexibility, i.e., $\mathrm{F}_{kn}^{\mathrm{PE}+,\max}/\mathrm{F}_{kn}^{\mathrm{PE}-,\max}$ [Euro/MW].

π_t^+, π_t^- Price of the deployed upward/downward active power flexibility in time period t [Euro/(MWh)].

ρ_s Probability of occurrence of scenario s.

τ Duration of each time period [h].

$\mathcal{H}$ Duration of the time horizon [h].

I. Introduction

ENVIRONMENTAL challenges along with the recent progress in renewable energy technologies are leading to a transition toward a green electricity generation future [1]–[3]. For example, in Switzerland with around 38% nuclear electricity generation, it has been planned to phase out nuclear plants by 2050, thereby opening the way for electricity generation from renewable energy sources [4]. This transition is giving rise to not only a significant fall in the size of conventional dispatchable power plants (DPPs), but also a surge in uncertainties stemming from forecast errors of renewable generation. In other words, the recent transition is putting the electric power system in the situation where the size of power flexibility providers pales in comparison with the size of uncertainties. Consequently, the traditional mechanisms for power flexibility provision, that rely only on the power flexibility of DPPs, are no longer able to efficiently accomplish their tasks, i.e., preserving the security of supply and respecting the grid's constraints. In order to realize this transition, a special attention should be payed to the power flexibility provision issue to guarantee voltage and frequency regulation in the presence of large amount of stochastic renewable energy resources like solar and wind [5]–[8].

Tracking the evolution of distribution networks from passive to active ones illustrates that they are hosting proliferating number of distributed energy resources (DERs) [9]. In order to keep the security and quality of supply in this emerging architecture, a solution is to aggregate the power flexibility of DERs located in distribution networks to provide it to the transmission grid [5], [10]–[12]. This solution necessitates a tighter collaboration between DSOs, i.e., distribution system operators and TSOs, i.e., transmission system operators, to exchange such flexibility [13]. The active power flexibility is defined as additional bidirectional active power a resource is able to provide to the grid by adjusting its operating point, i.e., increasing or decreasing its active power consumption/generation [5]. The question that naturally arises in this context is:

What is the optimal size of active power flexibility that a TSO must book from flexibility providers (including aggregated flexibilities of distribution networks) over a specified time horizon (next day)?

It is notable that TSO incurs costs due to booking and deploying active power flexibility while benefiting from it in terms of reduction in the expected cost of energy not supplied. Therefore, the optimum solution should make a balance between the costs and benefits of the booked active power flexibility.

Across the world, TSOs procure their required active power flexibility[1] through either integrated or sequential market structure [14]–[16]. Integrated[2] market structure corresponds to the case where both energy and flexibility markets are simultaneously cleared. However, sequential market structure corresponds to the case where energy and flexibility markets are sequentially (and separately) cleared. The former is the current structure used in North America, while the latter is the structure implemented in Switzerland and some other European countries. The main focus of this article is the Switzerland's flexibility market; thus, it opts for the sequential market structure and tries to facilitate the participation of aggregated resources of distribution networks in the flexibility market.

Traditional practices [17]–[22] quantify the TSO's required size of active power flexibility based on either deterministic or probabilistic criterion while relying just on the active power flexibility of DPPs only and neglecting the potential active power flexibility available in the distribution networks. The deterministic approaches ignore the stochastic nature of the contingencies and uncertainties, thereby setting the adequate size of active power flexibility equal to a predefined amount such as the capacity of the largest online generating unit or a fraction of the peak load [17]. Although deterministic approaches can be easily implemented, they cannot provide any information about the risk of the system. To deal with this issue, the probabilistic approaches are designed which consider the stochastic nature of the contingencies and uncertainties. These approaches fall into either statistic-based or optimization-based methods. The former neglects the transmission network constraints and quantifies the adequate size of active power flexibility based on the statistical assessments of the historical contingencies such as generators outage and forecast errors, whereby they try to satisfy a target risk level [18], [19]. The latter constructs optimization problems aiming to determine the optimum size of active power flexibility in such a way that a desired level of reliability metrics, such as loss of load probability and/or expected energy not supplied (EENS), are respected [20]–[22].

The above approaches may end up to a suboptimal solution because:

- They just incorporate a risk criterion in their problem, thereby minimizing the TSO's incurred cost due to booking and deploying active power flexibility instead of balancing costs and benefits of the active power flexibility.
- They neglect the capability of distribution networks for active power flexibility provision, most notably, some of them neglect grid's constraints.
- They follow integrated energy and flexibility market structure, whereas flexibility market of Switzerland is fully separated from the energy market.

[1] Reserve and flexibility terms are interchangeably used throughout the article.

[2] The integrated market structure is also referred as joint energy and flexibility market structure.

The above-mentioned restrictions found in [17]–[22] paved the way to the method proposed in this article. In line with the aggregation approach proposed in [23], this article presents a framework to help TSOs to take advantage of the aggregated flexibilities of distribution networks (AFENs), whereby it tries to facilitate a tighter collaboration between TSO and DSOs. The contribution of the article is fourfold:

- It develops a linear risk-aware optimization model to quantify the TSO's required size of active power flexibility (over a desired time horizon, e.g., next day) while balancing costs and benefits of the active power flexibility. Therefore, it prevents from overbooking of active power flexibility, which is uneconomic, and under-booking of active power flexibility, which is unreliable.
- In addition to the active power flexibility of DPPs, it considers the active power flexibility of AFENs, thereby quantifying the TSO's required size of active power flexibility from both DPPs and AFENs. More importantly, it takes into account grid's constraints by leveraging dc power flow model.
- It follows a sequential energy and flexibility market structure to suit the Switzerland's flexibility market that is separate from the energy market.
- For a real transmission grid, i.e., the Switzerland's transmission grid, it evaluates the TSO's economic/technical benefits resulting from the active power flexibility provision of AFENs.

This method is implemented relying on a two-stage stochastic optimization model where scenarios include forecast errors of stochastic renewable generation and demand as well as transmission lines/power plants outages. To the best of our knowledge, the treatment of this problem is missing in the literature.

It should be highlighted that the developed method explicitly and implicitly brings various benefits to different stakeholders:

- It lays a ground where AFENs can offer their potential active power flexibility to the TSO. In this way, it helps to unlock the potential power flexibility of DERs, thereby, generating a profit for DERs owners.
- Thanks to unlocking the potential power flexibility of DERs, it improves the security/reliability of the whole electric power system while decreasing the cost associated with flexibility allocation. The whole community including all stakeholders enjoy from these two benefits,[3] i.e., higher reliability (security in supply) along with lower cost.
- It may help TSOs to avoid/postpone transmission grid expansion thanks to introducing new flexibility providers (i.e., AFENs) distributed throughout the transmission grid.
- It helps TSOs to take advantage of the flexibility of DERs located in distribution networks.
- It helps TSO to economically allocate its required active power flexibility while preserving the reliability of its network.
- It quantifies the technical and economic benefits of AFENs. As a result, it reveals the benefit of AFENs and promotes all stakeholders to invest more on this novel flexibility provision structure.

[3] The presented results in Section V quantify these two benefits.

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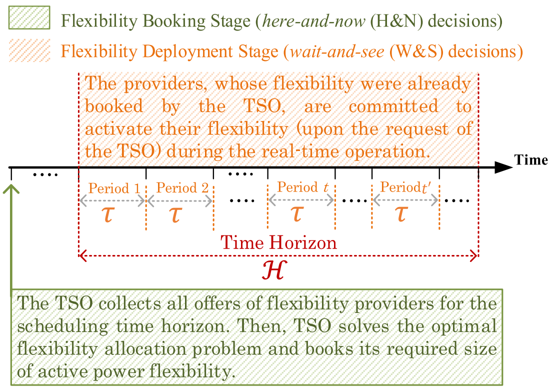

Fig. 1. General procedure of active power flexibility allocation.

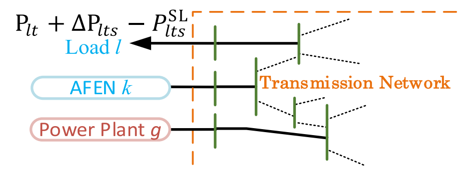

Fig. 2. All entities of the power system form the TSO's viewpoint.

The remainder of this article is organized as follows: The problem is described in Section II. Section III presents a framework to model AFENs from TSO's viewpoint. The problem is formulated as a two-stage stochastic optimization problem in Section IV. Then, the method is applied to a real transmission network, i.e., Switzerland's transmission grid operated by Swissgrid, and the achieved results are presented in Section V. Finally, Section VI states the main conclusions.

II. Problem Statement

This article follows sequential energy and flexibility market structure where energy and flexibility markets are sequentially cleared. More specifically, the day-ahead energy market is first cleared and accordingly the scheduled operating point of all entities (i.e., $\mathrm{P}_{kt}, \mathrm{P}_{lt}$, and P_{gt}) are determined with the time resolution of τ. Then, the active power flexibility is allocated in the following two stages [24], [25] as sketched in the timeline of Fig. 1:

1) *Flexibility booking stage [here-and-now (H&N) decisions]:* A day prior to the real-time operation when the day-ahead energy market is already cleared, all active power flexibility providers first evaluate the amount of active power flexibility that they are able to provide to the TSO over the selected time horizon $\mathcal{H}$, whereby they submit their flexibility offers (consisting of the size and price) to the TSO. Then, the TSO solves an optimization problem to quantify and book its required size of active power flexibility from each provider. In this stage, no real product is exchanged between TSO and active power flexibility providers but TSO pays the cost of its booked flexibility. In this way, TSO ensures the availability of an adequate amount of flexibility throughout the selected time horizon.
2) *Flexibility deployment Stage [wait-and-see (W&S) decisions]:* This stage pertains to the real-time operation where the actual amount of the TSO's required active power flexibility turns out. In case of need, the TSO asks the active power flexibility providers to activate all/a part of the active power flexibility already booked. Accordingly, TSO pays the cost of activated flexibility in addition to the cost of booked flexibility already payed.

Following the presented sequential energy and flexibility market structure where energy market is separately cleared before the flexibility market, the article assumes that the outcome of the energy market is known/given. More specifically, the scheduled operating point of all entities (i.e., $\mathrm{P}_{kt}, \mathrm{P}_{lt}$, and P_{gt}) are known for each time period t. Then, the article introduces a method to help TSOs to make an optimal decision in the first stage of the flexibility allocation procedure, i.e., flexibility booking stage. To this end, the article leverages a cost-benefit method [26] and develops a linear risk-aware optimization model for TSOs. It is mathematically formulated as a two-stage linear stochastic optimization problem and empowers TSO to determine the optimal size of active power flexibility that it should book from all providers throughout the time horizon $\mathcal{H}$, so that the total cost of TSO is minimized. It should be noted that the size of booked active power flexibility from each provider is a unique value for the whole time horizon $\mathcal{H}$.

III. Resource Modeling Framework

Different entities such as AFENs, stochastic power plants (SPPs), DPPs, and loads are connected to the transmission network as shown in Fig. 2. In the following, these entities are modeled from TSO's viewpoint.

A. Modeling the AFENs

In the emerging distribution networks, the number of DERs including distributed generators (DGs), energy storage systems, and flexible loads is progressively increasing. DGs accommodated in distribution networks fall into dispatchable and nondispatchable sources. Dispatchable DGs (DDGs) are able to provide active power flexibility to the grid, whereas non-DDGs (e.g., wind and solar units) whose active power generation is subject to uncertainties increase the demand for flexibility. In addition to the DDGs, flexible loads and ESSs are also able to provide active power flexibility to the grid. Thanks to aggregators[4] who organize and aggregate DERs, a new entity entitled AFEN is formed. In this way, the TSO can take advantage of the active power flexibility of DERs. The model of an AFEN from DSO's and TSO's viewpoint is shown in Fig. 3.

1) From DSO's viewpoint: An AFEN consists of an aggregated load, an aggregated ESS, and an aggregated DDG, as shown in Fig. 3. In addition to the flexible loads, which are sources of flexibility, the aggregated load embraces the non-DDGs (negative loads) and firm loads, which are sources

[4]A third market player so-called aggregator who organizes and aggregates DERs to provide active power flexibility to the transmission network.

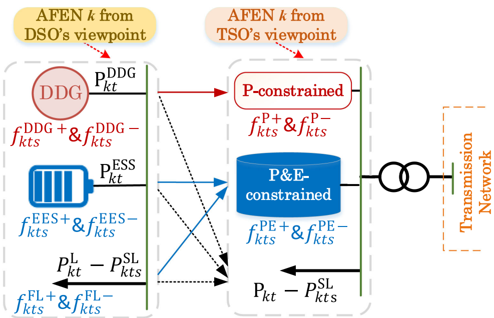

Fig. 3. Model of AFEN k in time period t and scenario s from DSO's/TSO's viewpoint.

of uncertainties. It is assumed that deviations from scheduled active power of non-DDGs and loads are compensated by exploiting the local flexibilities of the AFEN. The corresponding flexibilities of these aggregated resources (i.e., $f^{\mathrm{FL}+}_{kts}, f^{\mathrm{FL}-}_{kts}, f^{\mathrm{ESS}+}_{kts}, f^{\mathrm{ESS}-}_{kts}, f^{\mathrm{DDG}+}_{kts}, f^{\mathrm{DDG}-}_{kts}$) are defined as auxiliary variables. It should be noted that these auxiliary variables are only under the control of the aggregator but not the TSO. Therefore, they are translated to the variables which can be controlled by the TSO, i.e., $f^{\mathrm{P}+}_{kts}, f^{\mathrm{P}-}_{kts}, f^{\mathrm{PE}+}_{kts}, f^{\mathrm{PE}-}_{kts}$. The relationships between both sets of variables are as follows:

$$f^{\mathrm{P}+}_{kts} = f^{\mathrm{DDG}+}_{kts} \qquad \forall k \in \mathbb{A}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S} \tag{1}$$

$$f^{\mathrm{P}-}_{kts} = f^{\mathrm{DDG}-}_{kts} \qquad \forall k \in \mathbb{A}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S} \tag{2}$$

$$f^{\mathrm{PE}+}_{kts} = f^{\mathrm{EES}+}_{kts} + f^{\mathrm{FL}+}_{kts} \quad \forall k \in \mathbb{A}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S} \tag{3}$$

$$f^{\mathrm{PE}-}_{kts} = f^{\mathrm{EES}-}_{kts} + f^{\mathrm{FL}-}_{kts} \quad \forall k \in \mathbb{A}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S}. \tag{4}$$

2) From TSO's viewpoint: An AFEN is formed of 1) a P-constrained (i.e., power constrained) active power flexibility source ($f^{\mathrm{P}+}_{kts}, f^{\mathrm{P}-}_{kts}$), 2) a P&E-constrained (i.e., power and energy constrained) active power flexibility source ($f^{\mathrm{PE}+}_{kts}, f^{\mathrm{PE}-}_{kts}$), along with 3) an equivalent load, as illustrated in Fig. 3. They, respectively, represent 1) the part of active power flexibility restricted only by the power limits ($\sum_n \mathrm{F}^{\mathrm{P}+,\max}_{kn}, \sum_n \mathrm{F}^{\mathrm{P}-,\max}_{kn}$) like those of DDGs, 2) the part of active power flexibility restricted by both power limits ($\sum_n \mathrm{F}^{\mathrm{PE}+,\max}_{kn}, \sum_n \mathrm{F}^{\mathrm{PE}-,\max}_{kn}$) and energy limits ($\mathrm{E}^{\mathrm{PE}+,\max}_{\mathrm{k}}, \mathrm{E}^{\mathrm{PE}-,\max}_{\mathrm{k}}$) similar to those of flexible loads and ESSs, and 3) the net active power schedule for the AFEN expressed as

$$\mathrm{P}_{kt} = -\mathrm{P}^{\mathrm{DDG}}_{kt} - \mathrm{P}^{\mathrm{ESS}}_{kt} + \mathrm{P}^{\mathrm{L}}_{kt} \qquad \forall k \in \mathbb{A}, \forall t \in \mathbb{T} \tag{5}$$

note that a part of P_{kt} might involuntary be shed in time period t and scenario s, it is indicated by P^{SL}_{kts}. The variables on the left side of (1)–(4) represent the active power flexibility that TSO deploys from AFEN k in time period t and scenario s. The boundaries of these variables throughout the time horizon ($\sum_n \mathrm{F}^{\mathrm{P}+,\max}_{kn}, \sum_n \mathbf{F}^{\mathrm{P}-,\max}_{kn}, \sum_n \mathrm{F}^{\mathrm{PE}+,\max}_{kn}, \sum_n \mathrm{F}^{\mathrm{PE}-,\max}_{kn}$, $\mathrm{E}^{PE+,\max}_{k}, \mathrm{E}^{\mathrm{PE}-,\max}_{k}$) are offered by AFEN k to the TSO. Then, TSO solves the optimal flexibility allocation problem defined in Section IV. The output of this problem quantifies the optimal size of active power flexibility ($F^{\mathrm{P}+}_{k}, F^{\mathrm{P}-}_{k}, F^{\mathrm{PE}+}_{k}, F^{\mathrm{PE}-}_{k}$) that TSO

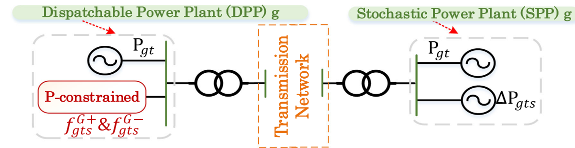

Fig. 4. Model of dispatchable/stochastic power plant g from TSO viewpoint in time period $\boldsymbol{t}$ and scenario $\boldsymbol{s}$.

should book from each AFEN throughout the time horizon to minimize its total cost.

B. Modeling the Loads

Those distribution networks which are managed in a traditional way and do not take advantage of the power flexibility of DERs are considered as aggregated loads. In contrast with AFENs, these (kind of distribution networks) aggregated loads are sources of uncertainties as shown in Fig. 2. The net active power consumption of aggregated load l is formed of three terms: 1) its scheduled active power consumption in time period t (i.e., P_{lt}), 2) the part of its demand that might involuntary be shed in time period t and scenario s (i.e., $\mathrm{P}^{\mathrm{SL}}_{lts}$), and 3) the deviation from its scheduled active power in time period t and scenario s (i.e., $\Delta\mathrm{P}_{lts}$). Finally, it should be highlighted that the main difference between these aggregated loads and the aggregated loads of the AFENs is that the former does not exploit the power flexibility of DERs and accordingly is a source of uncertainties, whereas the latter exploits the power flexibility of DERs and is a source of power flexibility.

C. Modeling the Dispatchable/Stochastic Power Plants

The models of both DPPs and SPPs are shown in Fig. 4. DPPs are able not only to follow their (typically day-ahead) defined schedule but also to provide active power flexibility which is restricted just by the power limits. However, SPPs, such as wind and solar power plants, may deviate from their schedule because of predictions errors thereby are sources of uncertainties.

IV. Risk-Aware Flexibility Allocation Model

This section relies on the resource modeling framework presented in Section III and leverage a cost-benefit method [26] to construct a risk-aware flexibility allocation model for TSOs. More specifically, it follows the flexibility allocation procedure introduced in Section II and minimizes TSO's cost on the basis of a two-stage linear stochastic optimization model. The H&N stage models the flexibility market where the TSO's required size of flexibility is booked. Its decision variables, i.e., $\Psi^{\mathrm{H\&N}} = \{F^{\mathrm{G}+}_{g}, F^{\mathrm{G}-}_{g}, F^{\mathrm{P}+}_{k}, F^{\mathrm{P}-}_{k}, F^{\mathrm{PE}+}_{k}, F^{\mathrm{PE}-}_{k}\}$, do not depend on any particular scenario and these decisions are made prior to the real-time operation. Then, W&S stage models constraints of power system. Its decision variables, i.e., $\Psi^{\mathrm{W\&S}} = \{f^{\mathrm{G}+}_{gts}, f^{\mathrm{G}-}_{gts}, f^{\mathrm{P}+}_{kts}, f^{\mathrm{P}-}_{kts}, f^{\mathrm{PE}+}_{kts}, f^{\mathrm{PE}-}_{kts}, \delta_{its}, P^{\mathrm{SL}}_{kts}, P^{\mathrm{SL}}_{lts}\}$, pertain to the real-time operation thereby depending on each particular scenario. The mathematical formulation of the model is as follows:

A. Objective Function

The TSO objective is to minimize its total cost, i.e., C^{TSO}, which is formed of the cost associated with H&N stage and the expected cost associated with W&S stage

$$\min_{\Psi^{\text{H\&N}} \cup \Psi^{\text{W\&S}}} C^{\text{TSO}} = C^{\text{H\&N}} + \sum_{t\in\mathbb{T}} EC_t^{\text{W\&S}}. \quad (6)$$

1) $C^{\text{H\&N}}$ is the cost of TSO due to booking upward/downward active power flexibility from DPPs and AFENs (P-constrained/P&E-constrained resources) in H&N stage, i.e., prior to the real-time operation. Based on the approach introduced in the Appendix A, $C^{\text{H\&N}}$ can be linearly expressed as

$$C^{\text{H\&N}} = \sum_{g\in\mathbb{DP}} (\gamma_g^{\text{G}+} + \gamma_g^{\text{G}-}) + \sum_{k\in\mathbb{A}} (\gamma_k^{\text{P}+} + \gamma_k^{\text{P}-} + \gamma_k^{\text{PE}+} + \gamma_k^{\text{PE}-}) \quad (7)$$

$$\gamma_g^{\text{G}+} \geq \text{C}_g^{\text{G}+},\ \gamma_g^{\text{G}-} \geq \text{C}_g^{\text{G}-}, \quad \forall g \in \mathbb{DP} \quad (8)$$

$$\gamma_k^{\text{P}+} \geq C_k^{\text{P}+},\ \gamma_k^{\text{P}-} \geq C_k^{\text{P}-}, \quad \forall k \in \mathbb{A} \quad (9)$$

$$\gamma_k^{\text{PE}+} \geq C_k^{\text{PE}+},\ \gamma_k^{\text{PE}-} \geq C_k^{\text{PE}-}, \quad \forall k \in \mathbb{A} \quad (10)$$

where $\gamma_g^{\text{G}+}$, $\gamma_g^{\text{G}-}$, $\gamma_k^{\text{P}+}$, $\gamma_k^{\text{P}-}$, $\gamma_k^{\text{PE}+}$, and $\gamma_k^{\text{PE}-}$ are auxiliary variables and $\text{C}_g^{\text{G}+}$, $\text{C}_g^{\text{G}-}$, $C_k^{\text{P}+}$, $C_k^{\text{P}-}$, $C_k^{\text{PE}+}$, and $C_k^{\text{PE}-}$ can be calculated as detailed in the Appendix A.

2) $\text{EC}_t^{\text{W\&S}}$ is the expected cost of TSO in W&S (real-time operation) stage over time period t due to deploying upward/downward active power flexibility, i.e., $\text{EC}_t^{\text{Flexibility}}$, and load curtailment, i.e., $\text{EC}_t^{\text{Curtailment}}$

$$\text{EC}_t^{\text{W\&S}} = \text{EC}_t^{\text{Flexibility}} + \text{EC}_t^{\text{Curtailment}} \quad (11)$$

where $\text{EC}_t^{\text{Flexibility}}$ is the expected cost of TSO due to deploying upward/downward active power flexibility from DPPs and AFENs (P-constrained as well as P&E-constrained sources) during the real-time operation over time period t

$$\text{EC}_t^{\text{Flexibility}} = \sum_{s\in\mathbb{S}} \tau\rho_s\pi_t^{+} \left[\sum_{g\in\mathbb{DP}} f_{gts}^{\text{G}+} + \sum_{k\in\mathbb{A}} \left(f_{kts}^{\text{P}+} + f_{kts}^{\text{PE}+}\right)\right] + \sum_{s\in\mathbb{S}} \tau\rho_s\pi_t^{-} \left[\sum_{g\in\mathbb{DP}} f_{gts}^{\text{G}-} + \sum_{k\in\mathbb{A}} \left(f_{kts}^{\text{P}-} + f_{kts}^{\text{PE}-}\right)\right] \quad (12)$$

and $\text{EC}_t^{\text{Curtailment}}$ is the expected cost of TSO due to demand curtailment of AFENs and loads during the real-time operation over time period t

$$\text{EC}_t^{\text{Curtailment}} = \sum_{s\in\mathbb{S}} \sum_{i\in\mathbb{B}} \rho_s\tau\text{VOLL}_i \left[\sum_{l\in\mathbb{L}_i} P_{lts}^{\text{SL}} + \sum_{k\in\mathbb{A}_i} P_{kts}^{\text{SL}}\right]. \quad (13)$$

It is worth mentioning that the price of upward and downward deployed active power flexibility over time period t (i.e., π_t^{+} and π_t^{-}) are determined based on the day-ahead electricity price. Following the introduced sequential market structure (in Section II) where energy market is separately cleared before the flexibility market, the outcome of the energy market, i.e., the day-ahead electricity price, is known. Accordingly, the amount of π_t^{+} and π_t^{-} are known, thus, π_t^{+} and π_t^{-} are parameter.[5]

Note that expressions (7) and (12) characterize the cost of flexibility, while expression (13) relies on the value of lost load (VOLL) index to economically quantify the TSO's risk whose reduction characterizes the benefit of the flexibility. In other words, the objective function aims at booking flexibility while balancing the costs and benefits incurred by the flexibility. In this way, it prevents over-booking, which is uneconomic, and under-booking, which is unreliable.

B. Constraints of H&N Stage

The size of upward/downward active power flexibility that TSO books from DPPs and AFENs should respect the size of flexibility offered by providers

$$0 \leq F_g^{\text{G}+} \leq \sum_{n\in\mathbb{N}} \text{F}_{gn}^{\text{G}+,\ \max} \quad \forall g \in \mathbb{DP} \quad (14)$$

$$0 \leq F_g^{\text{G}-} \leq \sum_{n\in\mathbb{N}} \text{F}_{gn}^{\text{G}-,\max} \quad \forall g \in \mathbb{DP} \quad (15)$$

$$0 \leq F_k^{\text{P}+} \leq \sum_{n\in\mathbb{N}} \text{F}_{kn}^{\text{P}+,\max} \quad \forall k \in \mathbb{A} \quad (16)$$

$$0 \leq F_k^{\text{P}-} \leq \sum_{n\in\mathbb{N}} \text{F}_{kn}^{\text{P}-,\max} \quad \forall k \in \mathbb{A} \quad (17)$$

$$0 \leq F_k^{\text{PE}+} \leq \sum_{n\in\mathbb{N}} \text{F}_{kn}^{\text{PE}+,\max} \quad \forall k \in \mathbb{A} \quad (18)$$

$$0 \leq F_k^{\text{PE}-} \leq \sum_{n\in\mathbb{N}} \text{F}_{kn}^{\text{PE}-,\max} \quad \forall k \in \mathbb{A} \quad (19)$$

C. Constraints of W&S Stage

During the real-time operation, the amount of upward/downward active power flexibility that TSO is allowed to deploy from DPPs and AFENs is restricted by the booked size of active power flexibility in H&N stage

$$0 \leq f_{gts}^{\text{G}+} \leq \text{A}_{gts}^{\text{G}} F_g^{\text{G}+} \quad \forall g \in \mathbb{DP}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S} \quad (20)$$

$$0 \leq f_{gts}^{\text{G}-} \leq \text{A}_{gts}^{\text{G}} F_g^{\text{G}-} \quad \forall g \in \mathbb{DP}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S} \quad (21)$$

$$0 \leq f_{kts}^{\text{P}+} \leq F_k^{\text{P}+} \quad \forall k \in \mathbb{A}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S} \quad (22)$$

$$0 \leq f_{kts}^{\text{P}-} \leq F_k^{\text{P}-} \quad \forall k \in \mathbb{A}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S} \quad (23)$$

$$0 \leq f_{kts}^{\text{PE}+} \leq F_k^{\text{PE}+} \quad \forall k \in \mathbb{A}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S} \quad (24)$$

$$0 \leq f_{kts}^{\text{PE}-} \leq F_k^{\text{PE}-} \quad \forall k \in \mathbb{A}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S} \quad (25)$$

$$-\text{E}_k^{\text{PE}-,\max} \leq \sum_{t'=1}^{t} \left(f_{kt's}^{\text{PE}+} - f_{kt's}^{\text{PE}-}\right)\tau \leq \text{E}_k^{\text{PE}+,\max} \quad \forall k \in \mathbb{A}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S} \quad (26)$$

[5]For example, Swissgrid sets π_t^{+} equal to 120% of the day-ahead electricity price in time period t and sets of equal to 20% of the day-ahead electricity price in time period t.

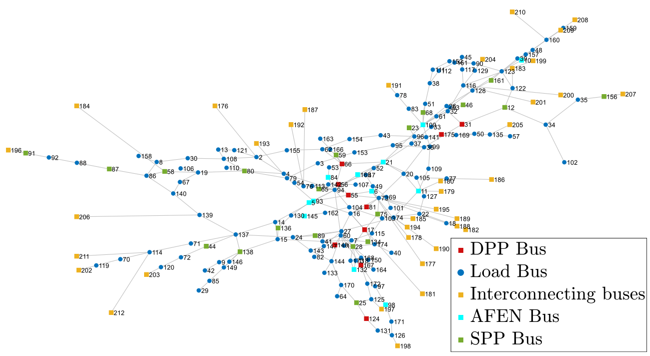

Fig. 5. Swissgrid network topology.

The transmission lines' flow limits as well as nodal active power balance in each time period are modeled based on the dc load-flow model

$$-\mathrm{P}_{ij}^{\max} \leq \mathrm{A}_{ijts}^{\mathrm{L}}\, \mathrm{B}_{ij}\left(\theta_{its}-\theta_{jts}\right) \leq \mathrm{P}_{ij}^{\max}, \quad \forall i,j \in \mathbb{B}, \forall t \in \mathbb{T},\ \forall s \in \mathbb{S} \tag{27}$$

$$\begin{aligned}&\sum_{k\in\mathbb{A}_i}\left[-\left(\mathrm{P}_{kt}-P_{kts}^{\mathrm{SL}}\right)+f_{kts}^{\mathrm{P}+}-f_{kts}^{\mathrm{P}-}+f_{kts}^{\mathrm{PE}+}-f_{kts}^{\mathrm{PE}-}\right]+\\&\sum_{g\in\mathbb{DP}_i}\left[\mathrm{A}_{gts}^{\mathrm{G}}\left(\mathrm{P}_{gt}+f_{gts}^{\mathrm{G}+}-f_{gts}^{\mathrm{G}-}\right)\right]+\\&+\sum_{g\in\mathbb{SP}_i}\left[\mathrm{A}_{gts}^{\mathrm{G}}\left(\mathrm{P}_{gt}+\Delta\mathrm{P}_{gts}\right)\right]+\\&+\sum_{l\in\mathbb{L}_i}\left[-\left(\mathrm{P}_{lt}+\Delta\mathrm{P}_{lts}-P_{lts}^{\mathrm{SL}}\right)\right]\\&=\sum_{j\in\mathbb{B}_i}\mathrm{A}_{ijts}^{\mathrm{L}}\,\mathrm{B}_{ij}\left(\theta_{its}-\theta_{jts}\right)\\&\qquad\forall i\in\mathbb{B},\forall t\in\mathbb{T},\ \forall s\in\mathbb{S}\end{aligned} \tag{28}$$

$$\theta_{1ts} = 0 \qquad \forall t \in \mathbb{T},\ \forall s \in \mathbb{S} \tag{29}$$

where bus 1 is considered as the reference bus for the voltage angle of buses.

The two-stage stochastic optimization model is composed of the objective function (6) along with constraints (7)–(29). This model can help TSOs to optimally book active power flexibility from not only DPPs but also AFENs while economically balancing the costs and benefits of the flexibility.

V. Case Study and Results

A. Case Study

The effectiveness of the proposed method is illustrated in the case of a real grid, i.e., Switzerland's transmission grid operated by Swissgrid. In this article, it is assumed that stochastic renewable generation is substituted for nuclear generation. The topology of this grid is shown in Fig. 5, it consists of 212 buses at 220 and 380 kV which are connected together via 25 transmission transformers and 284 transmission lines. This grid, located in the central part of Europe, is connected to Germany, France, Austria, and Italy via 37 buses. In this article, these 37 interconnecting buses are modeled as a constant positive/negative injection in each time period. All buses of the grid can be classified into five categories based on the entity connected to them:

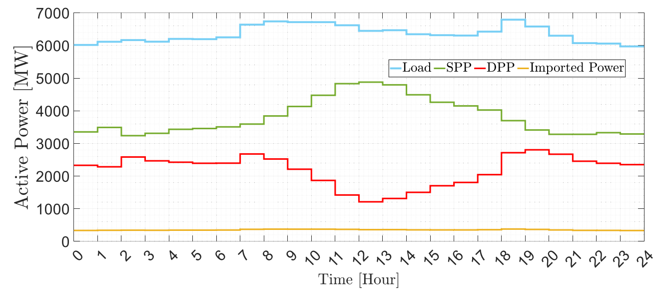

Fig. 6. Total active power generation, consumption, and import of the transmission network during 24 h of study.

TABLE I

Size of Upward/Downward Active Power Flexibility Offered by AFENs to the TSO

Bus Number of AFEN	5	6	10	11	21	84	93	98	100	132	145	165
$\sum_n \mathbf{F}_{kn}^{\mathbf{P+,max}}$(MW)	35	87	30	30	39	81	43	32	55	38	55	32
$\sum_n \mathbf{F}_{kn}^{\mathbf{P-,max}}$(MW)	35	87	30	30	39	81	43	32	55	38	55	32
$\sum_n \mathbf{F}_{kn}^{\mathbf{PE+,max}}$(MW)	18	43	16	15	19	41	21	16	27	19	37	16
$\sum_n \mathbf{F}_{kn}^{\mathbf{P-,max}}$(MW)	18	43	16	15	19	41	21	16	27	19	37	16
$\mathbf{E}_{k}^{\mathbf{PE+,max}}$(MWh)	72	45	90	45	37	95	45	35	94	95	94	35
$\mathbf{E}_{k}^{\mathbf{PE-,max}}$(MWh)	62	40	76	50	40	95	50	44	76	78	48	38

TABLE II

Size of Upward/Downward Active Power Flexibility Offered by DPPs to the TSO

Bus Number of DPP	17	31	55	56	66	81	124	148	167	175
$\sum_n \mathbf{F}_{gn}^{\mathbf{G+,max}}$(MW)	40	150	110	117	29	91	52	45	19	26
$\sum_n \mathbf{F}_{gn}^{\mathbf{G-,max}}$(MW)	78	123	195	150	110	124	58	60	105	130

1) DPP buses hosting DPPs.
2) SPP buses hosting SPPs.
3) Interconnecting buses, i.e., buses connecting the grid to neighboring countries.
4) AFENs buses hosting AFENs.
5) Load buses hosting aggregated consumers.

Based on the time-line of the problem described in Section II, the duration of $\mathcal{H}$ and τ are, respectively, considered 24 hours and 1 hour which models 24-hour of next day. Each 1-hour time period corresponds to a single scheduled operating point. All grid's parameters and scheduled operating points of the grid over the 24-hour of study are provided by Swissgrid. Fig. 6 shows the total active power generation of DPPs and SPPs along with the total imported power from neighboring networks and the total consumption of the loads throughout all 24 time periods. The total energy consumption of the network is 152.6 GWh throughout all 24 time periods and stochastic generation covers 60% of it. The size of active power flexibility offered by DPPs and AFENs are, respectively, reported in Tables I and II. As detailed in Appendix B, the prices of booked and deployed flexibility are extracted from the historical data of Swissgrid's flexibility market [27]. To model the grid's contingencies and uncertainties, twenty thousand scenarios are generated. In this respect, sequential Monte Carlo (SMC) simulation [28], [29] is used to generate twenty thousand scenarios modeling grid

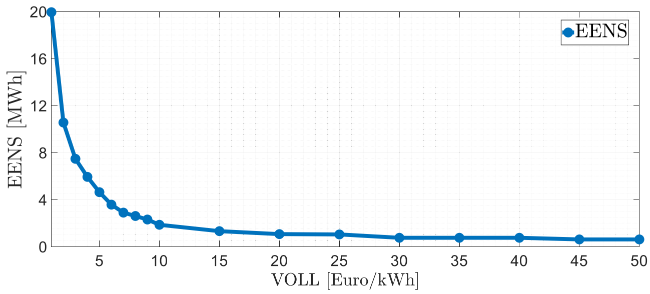

Fig. 7. Impact of the opted VOLL on the reliability of the grid.

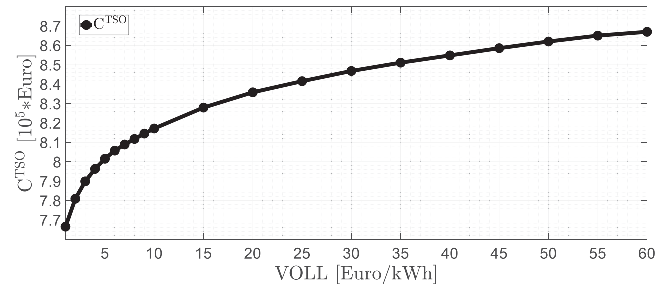

Fig. 8. Impact of the opted VOLL on the total cost of TSO.

contingencies over 24 hours of study. To this end, SMC simulation is carried out over $24 * 20\,000$ hours where each 24 hours corresponds to a single scenario. The grid contingencies, including power plant outages and line/transformer outages, are modeled as binary parameters. More specifically, the state of power plants and transmission lines/transformers are modeled as independent two-states 0, 1 Markov chains where 1 stands for availability and 0 stands for unavailability. Then, the following procedure is adopted to model the state of each component over $24 * 20\,000$ hours: 1) the initial state of component c is assumed available (i.e., 1); 2) a sample of time to failure (t') is drawn from the exponential distribution with average of $\mathrm{MTTF}_{\mathrm{c}}$, where $\mathrm{MTTF}_{\mathrm{c}}$ indicates the mean time to failure of component c; 3) the state of component c is set equal to 1 for $t = 1, 2, \ldots, t'$; 4) a sample of time to repair (t'') is drawn from the exponential distribution with average of $\mathrm{MTTR}_{\mathrm{c}}$, where $\mathrm{MTTR}_{\mathrm{c}}$ indicates the mean time to repair of component c; 5) the state of component c is set equal to 0 for $t = t' + 1, t'+2, \ldots, t' + t''$; and 6) steps 2–5 are followed to generate a series of 1 and 0 with length of $24 * 20\,000$ modeling the state of component c. Moreover, the uncertainties (day-ahead forecast errors) associated with active power consumption/generation of loads/SPPs are modeled based on the historical data. Then, k-medoids clustering algorithm [30] is used to reduce the number of scenarios to one thousand representative scenarios. Finally, the problem is modeled using YALMIP-MATLAB [31] and solved with GUROBI [32].

B. Estimating the Value of Lost Load (VOLL)

In the absence of a standardized methodology for computing VOLL [33], this section aims to pinpoint a reliable and credible value for VOLL, thereby preventing from over-estimating/under-estimating VOLL that causes TSO to operate its grid in an uneconomic/unreliable manner. In this respect, the impact of the opted VOLL on the reliability of the network (i.e., EENS) and the total cost of TSO (i.e., C^{TSO}) are shown in Figs. 7 and 8. It corroborates that the reliability of the network improves when VOLL increases. More specifically, EENS considerably falls when VOLL increases up to 20 Euro/kWh; however, above 20 Euro/kWh, EENS almost levels off while C^{TSO} constantly increases by increasing VOLL. Therefore, it can be concluded that the credible value for VOLL is 20 Euro/kWh where the TSO operates its grid both reliably and economically. Above all, opting VOLL = 20 Euro/kWh leads to EENS = 1.31 MWh/day that satisfies the reliability criterion used by some European TSOs, i.e., EENS remains less than 0.002% of the net demand.

TABLE III
COMPARISON BETWEEN THE PRESENTED METHOD AND TRADITIONAL METHODS

	Case A	Case B
C^{TSO} [CHF]	835698	3395432
ELNS (MWh/day)	1.310	132.246

C. Comparison With Traditional Methods

In order to achieve a clear perception about the advantage of the proposed method in comparison with the traditional methods that only take into account the active power flexibility of DPPs and completely neglect the potential active power flexibility available in the distribution networks (i.e., AFENs), two different cases are defined:

1) *Case A:* the presented method exploits the active power flexibility of both DPPs and AFENs. The size of active power flexibility offered by DPPs and AFENs are, respectively, reported in Tables I and II.
2) *Case B:* the presented method exploits only the active power flexibility of DPPs and completely ignores the power flexibility of AFENs. The size of active power flexibility offered by DPPs is reported in Table II.

Then, a comparison between case A and case B is reported in Table III. As it can be seen, the presented method outperforms the traditional methods by exploiting the power flexibility of AFENs. More specifically, this method significantly improves the reliability of the transmission network while decreasing the total cost of TSO in comparison with traditional methods that only rely on the active power flexibility of DPPs.

D. Economic and Technical Benefits of AFENs

To investigate the effectiveness of the proposed method in respect to the penetration rate of the DERs, the size of active power flexibility offered by AFENs are changed from 0% to 100% of the reported values in Table I. Then, both economic and technical impacts of the AFENs' flexibility are quantified. Fig. 9 shows the EENS and total cost of the TSO (i.e., C^{TSO}) as a function of the size of AFENs. As it can be seen, flexibility of AFENs significantly improves reliability of the network (i.e.,

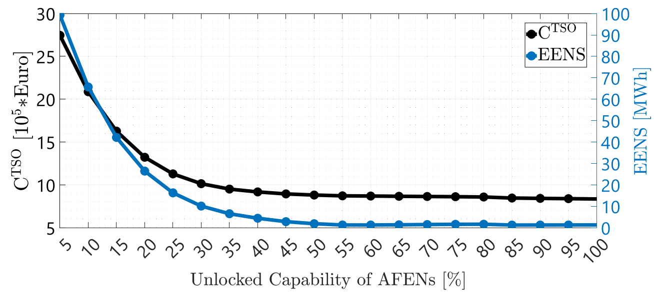

Fig. 9. Quantifying the benefit of AFENs on the TSO's cost and EENS.

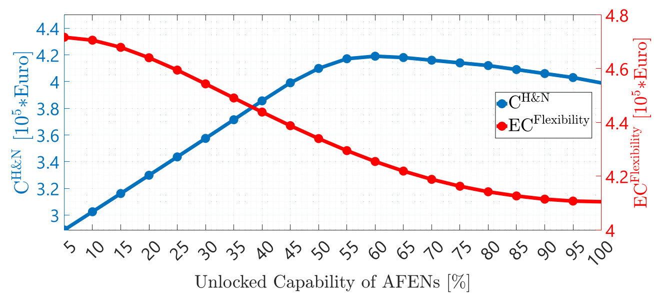

Fig. 10. Impact of the AFEN's flexibility on $\boldsymbol{C^{\mathrm{H\&N}}}$ and $\mathrm{EC}^{\mathrm{Flexibility}}$.

EENS) and reduces the total cost of the TSO (i.e., C^{TSO}). It upholds that the reliability of the network improves when AFENs flexibility increases. More specifically, EENS considerably falls when AFENs' flexibility increases up to 60%; however, above 60%, EENS does not significantly change. To figure out why EENS levels off when AFENs' flexibility goes beyond 60%, the impact of AFENs' flexibility on $C^{\mathrm{H\&N}}$ and $\mathrm{EC}^{\mathrm{Flexibility}}$ is examined. It should be noted that $\mathrm{EC}^{\mathrm{Flexibility}}$ represents the TSO's total expected cost due to deploying upward/downward active power flexibility over all 24 time periods as

$$\mathrm{EC}^{\mathrm{Flexibility}} = \sum_{t\in\mathbb{T}} \mathrm{EC}_t^{\mathrm{Flexibility}} \tag{30}$$

and $\mathrm{EC}^{\mathrm{Curtailment}}$ as the TSO's total expected cost due to demand curtailment over all 24 time periods as

$$\mathrm{EC}^{\mathrm{Curtailment}} = \sum_{t\in\mathbb{T}} \mathrm{EC}_t^{\mathrm{Curtailment}}. \tag{31}$$

As illustrated in Fig. 10, when AFENs' flexibility increases, $C^{\mathrm{H\&N}}$ constantly increases due to the fact that the TSO books greater deal of active power flexibility to decrease its EENS and accordingly $\mathrm{EC}^{\mathrm{Curtailment}}$ (TSO suffers from the shortage of power flexibility). However, when AFENs' flexibility goes beyond 60%, the TSO faces with the oversupply of power flexibility, thus, TSO starts replacing its high price booked flexibility with the low price one. Accordingly, $C^{\mathrm{H\&N}}$ starts falling. Moreover, it should be noted that when AFENs' flexibility increases, $\mathrm{EC}^{\mathrm{Flexibility}}$ constantly decreases thanks to the fact that the TSO can deploy its required power flexibility from more buses distributed throughout the grid, thereby more easily (by deploying less amount of power flexibility) mitigating the impact of uncertainties during the real-time grid operation.

Last but not the least, Figs. 9 and 10 bear testimony to the capability of the presented method in quantifying the economic and technical benefits of the AFENs, whereby TSO can define economic incentives to empower AFENs for flexibility provision. In sum, it can be concluded that the provision of active power flexibility by AFENs not only decreases the total cost of TSO, but it also improves the reliability of the transmission network.

VI. Conclusion

This article constructed a risk-aware active power flexibility allocation model for TSOs. This model follows a sequential market structure to suit the Switzerland's flexibility market that is separate from the energy market. The model is mathematically formulated as a two-stage linear stochastic optimization problem where a cost-benefit approach is exploited to realize a balance between cost and benefit of the flexibility. This model can help TSOs to take advantage of the flexibility of DERs located in distribution networks.

This article selected a real transmission grid, i.e., the Switzerland's transmission grid operated by Swissgrid as a case study. Then, it determines a credible value for VOLL to help Swissgrid to economically allocate its required active power flexibility while preserving the reliability of its network. Moreover, the economic and technical analysis carried out to concretely quantify the benefits of the AFENs' flexibility, i.e., flexibility of DERs located at distribution level. The numerical results indicate the improvement of the TSO's security in addition to the reduction of the TSO's costs. Therefore, this article succeeded to realize a twofold goal. First, it developed a novel approach to modernize the traditional top-to-down flexibility provision mechanism to a bidirectional flexibility provision structure. Second, it demonstrated the benefits of this novel TSO–DSO collaboration approach.

Appendix A

The cost of TSO due to booking active power flexibility in H&N stage, i.e., $C^{\mathrm{H\&N}}$, is formed of the sum of TSO's cost due to booking upward/downward active power flexibility from P-constrained ($C_k^{\mathrm{P}+}/\ C_k^{\mathrm{P}-}$) and P&E-constrained ($C_k^{\mathrm{PE}+}/\ C_k^{\mathrm{PE}-}$) resources of AFENs as well as DPPs ($\mathrm{C}_g^{\mathrm{G}+}/\mathrm{C}_g^{\mathrm{G}-}$)

$$C^{\mathrm{H\&N}} = \sum_{g\in\mathbb{DP}} (\,\mathrm{C}_g^{\mathrm{G}+} + \mathrm{C}_g^{\mathrm{G}-}) + \sum_{k\in\mathbb{A}} (C_k^{\mathrm{P}+} + C_k^{\mathrm{P}-} + C_k^{\mathrm{PE}+} + C_k^{\mathrm{PE}-}) \tag{A.1}$$

in which all terms are piecewise linear functions thanks to the piecewise constant offer curves of the flexibility providers. However, each term has a linear equivalent. For the sake of brevity, this appendix only extracts the linear equivalent for the term associated with TSO's cost due to booking upward active power flexibility from P&E-constrained resources of AFEN k in H&N stage, i.e., $C_k^{\mathrm{PE}+}$. To this end, let us consider the offer curve of AFEN k for its upward PE-constrained active power flexibility as shown in Fig. 11. The area under the offer curve

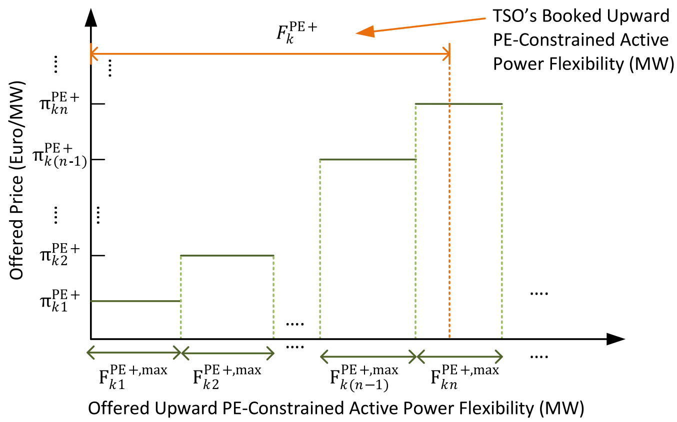

Fig. 11. Offer curve of AFEN k for its size of upward PE-constrained active power flexibility.

defines $C_k^{\mathrm{PE}+}$ which is a piecewise linear function of $F_k^{\mathrm{PE}+}$. $C_k^{\mathrm{PE}+}$ over the nth piece, i.e., $C_{kn}^{\mathrm{PE}+}$ can be calculated as

$$\begin{aligned}C_{kn}^{\mathrm{PE}+} &= \pi_{k1}^{\mathrm{PE}+}\,\mathrm{F}_{k1}^{\mathrm{PE}+,\max} + \pi_{k2}^{\mathrm{PE}+}\mathrm{F}_{k2}^{\mathrm{PE}+,\max} + \ldots\ldots + \\ &\quad + \pi_{k(n-1)}^{\mathrm{PE}+}\mathrm{F}_{k(n-1)}^{\mathrm{PE}+,\max} + \pi_{kn}^{\mathrm{PE}+}\left(F_k^{\mathrm{PE}+} - \sum_{n'=1}^{n-1}\mathrm{F}_{kn'}^{\mathrm{PE}+,\max}\right) \\ &= \left(\pi_{k1}^{\mathrm{PE}+} - \pi_{kn}^{\mathrm{PE}+}\right)\mathrm{F}_{k1}^{\mathrm{PE}+,\max} + \left(\pi_{k2}^{\mathrm{PE}+} - \pi_{kn}^{\mathrm{PE}+}\right)\mathrm{F}_{k2}^{\mathrm{PE}+,\max} + \\ &\quad + \ldots + \left(\pi_{k(n-1)}^{\mathrm{PE}+} - \pi_{kn}^{\mathrm{PE}+}\right)\mathrm{F}_{k(n-1)}^{\mathrm{PE}+,\max} + \pi_{kn}^{\mathrm{PE}+}F_k^{\mathrm{PE}+} \\ &= \pi_{kn}^{\mathrm{PE}+}\,F_k^{\mathrm{PE}+} + \sum_{n'=1}^{n-1}\left(\pi_{kn'}^{\mathrm{PE}+} - \pi_{kn}^{\mathrm{PE}+}\right)\mathrm{F}_{kn'}^{\mathrm{PE}+,\max} \\ &\sum_{n'=1}^{n-1}\mathrm{F}_{kn'}^{\mathrm{PE}+,\max} \le F_k^{\mathrm{PE}+} \le \sum_{n'=1}^{n}\mathrm{F}_{kn'}^{\mathrm{PE}+,\max}. \end{aligned} \tag{A.2}$$

$C_k^{\mathrm{PE}+}$ is an increasing piecewise linear function, thanks to the fact that the offer curves are increasing functions. Therefore, minimizing $C_k^{\mathrm{PE}+}$over all pieces is equivalent to

$$\min \gamma_k^{\mathrm{PE}+} \tag{A.3}$$

$$C_{kn}^{\mathrm{PE}+} = \pi_{kn}^{\mathrm{PE}+}\,F_k^{\mathrm{PE}+} + \sum_{n'=1}^{n-1}\left(\pi_{kn'}^{\mathrm{PE}+} - \pi_{kn}^{\mathrm{PE}+}\right)\mathrm{F}_{kn'}^{\mathrm{PE}+,\max} \le \gamma_k^{\mathrm{PE}+} \quad \forall n \in \mathbb{N} \tag{A.4}$$

where $\gamma_k^{\mathrm{PE}+}$is an auxiliary variable. In the same way, the linear counterparts of the other terms of (A.1) can be extracted by introducing auxiliary variables $\gamma_g^{\mathrm{G}+}$, $\gamma_g^{\mathrm{G}-}$, $\gamma_k^{\mathrm{P}+}$, $\gamma_k^{\mathrm{P}-}$, and $\gamma_k^{\mathrm{PE}-}$.

Appendix B

Swissgrid regularly publishes the outcomes of its flexibility market including the prices/volumes of deployed and booked active power flexibility [27], [34]. After processing this data, this article assumes the price of upward/downward deployed active power flexibility, i.e., π_t^+ and π_t^-, equal to the annual average price of the respective product over 2019. Thus, it supposes $\pi_t^+ = 102$ Euro/MWh and $\pi_t^- = 35$ Euro/MWh for all t in $\mathbb{T}$.

To determine the offer curves of DPPs and AFENs for their upward/downward active power flexibility (i.e., $\pi_{gn}^{\mathrm{G}+}$, $\pi_{gn}^{\mathrm{G}-}$, $\pi_{kn}^{\mathrm{P}+}$, $\pi_{kn}^{\mathrm{P}-}$, $\pi_{kn}^{\mathrm{PE}+}$, and $\pi_{kn}^{\mathrm{PE}-}$), the prices and volumes of upward/downward booked active power flexibility of the Swissgrid over 2019 are processed (separately for upward and downward booked active power flexibility) as follows.

1) Prices are first sorted in ascending order.
2) The sorted prices are segmented into 20 equivolume groups where the first group consists of the lowest prices, …, and the 20th group consists of the highest prices.
3) Weighted average price of each group is calculated considering the volume associated with each price. Accordingly, it results in 20 ascending prices.
4) An increasing piecewise constant function is constructed relying on the 20 prices achieved in the former step (i.e., step 3). It is assumed that this function has equilength pieces with length of 10 MW. This function is considered as the offer curve.

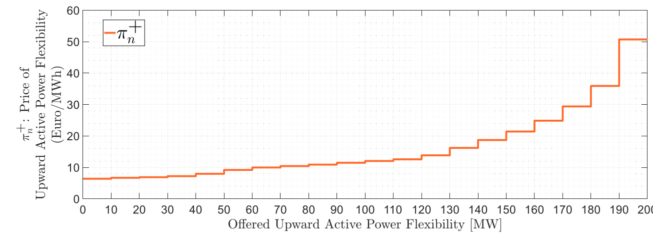

Fig. 12. Constructed offer curve for upward active power flexibility.

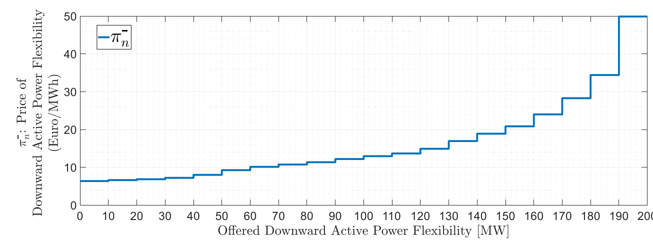

Fig. 13. Constructed offer curve for downward active power flexibility.

This procedure results in the offer curves for upward and downward active power flexibility represented in Figs. 12 and 13. To give the same priority to all power flexibility providers, it is assumed that all flexibility providers, respectively, offer their upward and downward active power flexibility following the offer curves illustrated in Figs. 12 and 13. However, it should be noted that each power flexibility provider can come up with its own size of offer (as reported in Tables I and II).

Disclaimer

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

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