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REEL Demo – Romande Energie ELectric network in local balance Demonstrator

Deliverable: 4f2 System-wide modelling and optimization of ancillary services provision and system impact

Demo site: Aigle

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1. Table of Contents

Nomenclature

Indices and sets

l	Index for loads.
h	Index for ARADSs.
i, j	Index for buses of the transmission system.
k	Index for power plants including both DBPPs and SPPs.
s	Index for scenario.
t, t'	Index for time slots.
$\mathbb{B}$	Set of buses of the transmission system.
$\mathbb{B}_i$	Set of adjacent buses connected through transmission lines to bus i.
$\mathbb{A}$	Set of ARADSs connected to the transmission system.
$\mathbb{A}_i$	Set of ARADSs connected to bus i.
$\mathbb{DP}$	Set of DBPPs connected to the transmission system.
$\mathbb{DP}_i$	Set of DBPPs connected to bus i.
$\mathbb{L}_i$	Set of loads connected to bus i.
$\mathbb{SP}_i$	Set of SPPs connected to bus i.
$\mathbb{S}$	Set of scenarios.
$\mathbb{T}$	Set of time slots of the scheduling time horizon.

Auxiliary Variables (at Distribution level)

$r_{hts}^{\mathrm{DDG+}}, r_{hts}^{\mathrm{DDG-}}$	Upward/downward active power reserve that TSO deploys from aggregated dispatchable DG of ARADS h during time slot t for scenario s [p.u.1].
$r_{hts}^{\mathrm{EES+}}, r_{hts}^{\mathrm{ESS-}}$	Upward/downward active power reserve that TSO deploys from aggregated ESS of ARADS h during time slot t for scenario s [p.u.1].
$r_{hts}^{\mathrm{FL+}}, r_{hts}^{\mathrm{FL-}}$	Upward/downward active power reserve that TSO deploys from aggregated flexible load of ARADS h during time slot t for scenario s [p.u.1].

Auxiliary Parameters (at Distribution level)

$\mathrm{P}_{ht}^{\mathrm{DDG}}$	Active power schedule for aggregated dispatchable DG of ARADS h during time slot t [p.u.1].
$\mathrm{P}_{ht}^{\mathrm{ESS}}$	Active power schedule for aggregated ESS of ARADS h during time slot t [p.u.1].
$\mathrm{P}_{ht}^{\mathrm{L}}$	Active power schedule for aggregated load (including firm and flexible loads and non-dispatchable DGs) of ARADS h during time slot t [p.u.1].

Variables (at Transmission level)

$P_{hts}^{\mathrm{SL}}, P_{lts}^{\mathrm{SL}}$	Shed load of ARADS h/load l during time slot t for scenario s [p.u.[1]].
$r_{kts}^{\mathrm{G+}}, r_{kts}^{\mathrm{G-}}$	Upward/downward active power reserve that TSO deploys from DBPP k during time slot t for scenario s [p.u.[1]].
$r_{hts}^{\mathrm{P+}}, r_{hts}^{\mathrm{P-}}$	Upward/downward P-constrained active power reserve that TSO deploys from ARADS h during time slot t for scenario s [p.u.[1]].
$r_{hts}^{\mathrm{PE+}}, r_{hts}^{\mathrm{PE-}}$	Upward/downward P&E-constrained active power reserve that TSO deploys from ARADS h during time slot t for scenario s [p.u.[1]].
$R_k^{\mathrm{G+}}, R_k^{\mathrm{G-}}$	Upward/downward active power reserve capacity that TSO books from DBPP k [p.u.[1]].
R_h^{P+}, R_h^{P-}	Upward/downward active power reserve capacity that TSO books from P-constrained active power reserve of ARADS h [p.u. [1]].

[1] The unit of p.u. refers to Watt.

R_h^{PE+}, R_h^{PE}	Upward/downward active power reserve capacity that TSO books from P&E-constrained active power reserve of ARADS h [p.u. [1]].
δ_{its}	Voltage angle of bus i during time slot t for scenario s [rad].

Parameters (at Transmission level)

$\mathrm{A}_{kts}^{\mathrm{G}}$	Binary 0,1 parameter denoting the availability-unavailability of power plant k during time slot t for scenario s.
$\mathrm{A}_{ijts}^{\mathrm{L}}$	Binary 0,1 parameter denoting the availability-unavailability of the transmission line between bus i and bus j during time slot t for scenario s.
B_{ij}	Longitudinal susceptance of the transmission line between bus i and bus j [p.u.].
$\mathrm{C}_k^{\mathrm{G+}}, \mathrm{C}_k^{\mathrm{G-}}$	Price that DBPP k offers to the TSO for its upward/downward active power reserve capacity [CHF[2]/(hour*p.u.[1])].
$\mathrm{C}_h^{\mathrm{P+}}, \mathrm{C}_h^{\mathrm{P-}}$	Price that ARADS h offers to the TSO for its upward/downward power capacity of P-constrained active power reserve [CHF/(hour*p.u.[1])].
$\mathrm{C}_h^{\mathrm{PE+}}, \mathrm{C}_h^{\mathrm{PE-}}$	Price that ARADS h offers to the TSO for its upward/downward power capacity of P&E-constrained active power reserve [CHF/(hour*p.u.[1])].
$\mathrm{E}_h^{\mathrm{PE+,max}}, \mathrm{E}_h^{\mathrm{PE-,max}}$	Upward/downward energy capacity of P&E-constrained active power reserve that ARADS h offers to the TSO [hour*p.u.[1]].
$\mathrm{F}_{ij}^{\mathrm{max}}$	Maximum power flow limit of the transmission line between buses i and j [p.u.[1]].
P_{ht}, $\mathrm{P}_{kt}, \mathrm{P}_{lt}$	Active power schedule for ARADS h/power plant k /load l during time slot t [p.u.[1]].
$\mathrm{R}_k^{\mathrm{G+,max}}, \mathrm{R}_k^{\mathrm{G-,max}}$	Upward/downward active power reserve capacity that DBPP k offers to the TSO [p.u.[1]].
$\mathrm{R}_h^{\mathrm{P+,max}}, \mathrm{R}_h^{\mathrm{P-,max}}$	Upward/downward power capacity of P-constrained active power reserve that ARADS h offers to the TSO [p.u.[1]].
$\mathrm{R}_h^{\mathrm{PE+,max}}, \mathrm{R}_h^{\mathrm{PE-,max}}$	Upward/downward power capacity of P&E-constrained active power reserve that ARADS h offers to the TSO [p.u.[1]].
$\mathrm{T}_h, \mathrm{T}_k$	Rated power of the substation connecting ARADS h /power plant k to the transmission system [p.u.[1]].
VOLL_i	Value of lost load for energy not served at bus i [CHF/(hour*p.u.[1])].
$\Delta\mathrm{P}_{kts}, \Delta\mathrm{P}_{lts}$	Deviation from scheduled active power for SPP k/load l during time slot t and scenario s [p.u.[1]].
π_t^+, π_t^-	Price that TSO pays for its deployed upward/ downward active power reserve from all providers including DBPPs and ARADSs during time slot t [CHF/(hour*p.u.[1])].
ρ_s	Probability of occurrence of scenario s.
τ	Duration of each time slot [hour].
$\mathcal{H}$	Duration of the scheduling time.

[2] Confederation Helvetica (Swiss) Franc.

1. Description of deliverable and goal

1.1. Executive summary

The flexibility of distributed energy resources (DERs) accommodated in active distribution networks (ADNs) can be aggregated and used to provide ancillary services to the transmission system operator (TSO). In this context, this report first establishes a framework for modeling aggregated resources installed in active distribution systems (ARADSs) as seen from TSO's perspective. Then, it presents a linear optimization model to optimally book the required active power reserve capacity of a TSO from ARADSs and dispatchable bulk power plants (DBPPs). It leverages a DC power flow model and a cost-benefit approach to formulate the problem as a linear optimization problem that minimizes the total cost of TSO, namely the sum of 1-expected cost of allocated active power reserve (i.e. booked and deployed reserve) from ARADSs and DBPPs, and 2-expected cost of energy not served over a desired time horizon. The value of lost load (VOLL) index is used as a criterion to realize an economical balance between the expected cost of allocated reserve and expected cost of energy not served. The method considers credible contingencies and forecast errors of loads/renewable generation as scenarios. Finally, the method is applied to the transmission network of Switzerland, operated by Swissgrid, to illustrate its effectiveness.

1.2. Research question

Environmental concerns and recent developments in renewable energy technologies are leading towards replacing conventional generation in favor of production from renewables [1]. For instance, in Switzerland, governmental goals have set to phase out nuclear generation by 2050, thus opening the way to produce energy from renewable energy sources (RESs) [2]. The main challenge of this transition is the increasing demand for controllable resources that need to be deployed to compensate the intermittent characteristic of renewable generation and guarantee the frequency stability, voltage regulation, power quality, and congestion management [2]-[5].

The number of distributed energy resources (DERs) like dispatchable distributed generators (DGs, e.g., gas turbines, micro turbines, combined heat and power units) and energy storage systems (ESSs, e.g., batteries, fuel-cells), in existing distribution networks is expected to increase steeply in the near future [5]. A promising solution to preserve the quality/security of supply is aggregating the DERs located in active distribution networks (ADNs) to provide ancillary services to the transmission system [6]. In this emerging architecture, further cooperation between operators of different levels of electric power systems, e.g., transmission system operators (TSOs) and distribution system operators (DSOs), is required to exchange ancillary services [7]. **The main question** that arises is **how much are the active power reserves that a TSO should book from all reserve providers (including ADNs) to minimize its total cost consisting of the expected cost of energy not served and allocated reserve (booked as well as deployed reserve) over a desired scheduling time horizon (e.g., 1 day or 1 week)?**

1.3. Novelty of the proposed solutions compared to the state-of-art

Traditional practices for allocating reserve consist in booking the active power reserve capacity required by the TSO while considering only dispatchable bulk power plants (DBPPs, e.g., gas, hydro, thermal power plants) and do not generally consider the potential of ADNs, see for instance [8]-[16]. Traditional methods can be categorized into deterministic and probabilistic approaches. A deterministic approach sets the amount of booked active power reserve capacity larger than or equal to the capacity of the largest online unit [9]. As far as the probabilistic approach is concerned, two mainstream methodologies can be traced in the existing literature: statistic-based and optimization-based. The statistic-based approach relies on a statistical assessment to characterize the contingencies and uncertainties which might happen in the system (including power plants/transmission lines outages, loads forecast errors, and forecast errors of renewable generation) leading to imbalance between generation and consumption, whereby they determine the booked reserve capacity so that a target risk level is satisfied (e.g., [10]-[12]). The optimization-based approach incorporates a risk index into an optimization problem, and then the optimum amount of required booked active power reserve capacity is achieved by solving that problem (e.g., [13]-[16]). Methods proposed in [15] and [16] minimize the total cost of TSO by making a balance between the cost of reserve allocation and cost of energy not serve, whereas methods proposed in [13] and [14] aim at either minimizing only the cost of reserve allocation or satisfying only a risk index like LOLP (lost of load probability), EENS (expected energy not served), etc.

All the above-mentioned methods may lead to excessive or deficient amount of reserve capacity so they are suboptimal since:

- they do not account for the capability of ADNs for provision of active power reserve;
- all of them except [15] and [16] don’t make a balance between the cost of reserve allocation and cost of energy not served.

In other words, the amount of booked reserve capacity through these methods are not economically justifiable. The above-mentioned limitations found in [8]-[16] paved the way to the method developed in this report. This report introduces the concept of aggregated resources of active distribution systems (ARADSs) with the aim of active power reserve provision to the transmission system. It first establishes a framework for modeling ARADSs as seen from TSO. Then, it leverages the proposed ARADS modeling framework and a cost-benefit

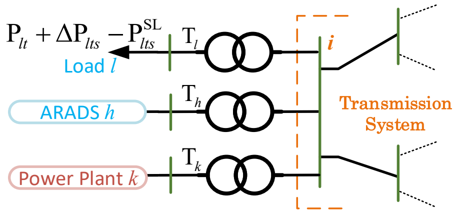

Fig. 1. The General structure of a bus of the transmission system.

approach [17] to develop a method for booking the required active power reserve capacity of TSO from both DBPPs and ARADSs. It considers line/generation outages as well as forecast errors of the loads and renewable generation as scenarios. This method minimizes the total cost of TSO throughout the scheduling time horizon by using a multi-period and multi-scenario optimization method. Thus, it can trade the expected energy not served of the network among time slots of the scheduling horizon, i.e. it may book less reserve and accept a higher energy not served at some time slots in such a way that the total cost of TSO over the total scheduling time horizon is minimized. The proposed formulation is generic and can accommodate any scheduling time horizon. To the best knowledge of the authors, this problem and its treatment have not been reported in the literature.

1.4. Description

1.4.1. Power System Modeling

This section models the power system as seen from a TSO's perspective with reliance on the following modelling assumptions:

- only active power and active power reserve are taken into consideration;
- the transmission system is loss-less and modeled by DC power flow equations;
- The scheduling time horizon ($\mathcal{H}$) consists of a number of time slots, each with duration of τ;
- for each time slot t of the scheduling time horizon, the active power schedule of the power plants/ARADSs and loads are known ($\mathrm{P}_{kt}, \mathrm{P}_{ht}, \mathrm{P}_{lt}$);
- the uncertainties of stochastic power plants (SPPs)/loads are modeled as stochastic positive/negative injections connected to the transmission system ($\Delta\mathrm{P}_{lts}, \Delta\mathrm{P}_{kts}$).

The general structure of a bus of the transmission system is illustrated in Fig. 1. It shows ARADS h, power plant k, and load l connected to the transmission system through 3 substations. In the rest of this section, the models of ARADSs and power plants are introduced.

1.4.2. ARADS Modeling

In the emerging ADNs, the number of DERs including DGs, ESSs and flexible loads is progressively increasing. DGs accommodated in ADNs can be categorized into dispatchable and non-dispatchable DGs. Dispatchable DGs (e.g., gas turbines, micro turbines, combined heat and

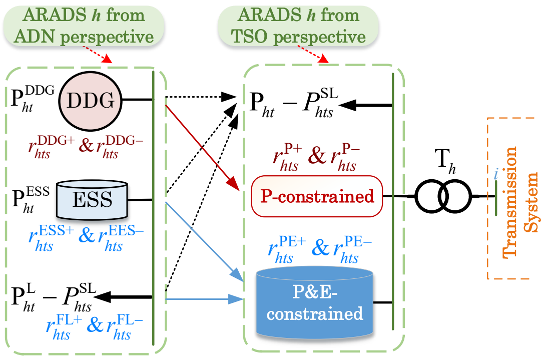

Fig. 2. The general structure of ARADS h connected to bus i. The notation refers to time slot t and scenario s.

power units) can provide flexibility to the grid, while non-dispatchable DGs (e.g., solar and wind generators) whose generated active power is associated with uncertainties raise the need for flexibility. In addition to the dispatchable DGs, ESSs and flexible loads are also able to provide flexibility to the grid. Flexibility can be perceived as a service, like active/reactive power reserves, that a resource provides to the grid by adjusting its operating point [19]. In this context, the flexibility of DERs including dispatchable DGs, EESs and flexible loads, installed in ADNs, can be exploited for provision of active power reserve to the transmission system. However, there are several obstacles in the way to achieve this goal as:

- DERs usually have small capacities;
- DERs typically belong to different owners;
- neither TSO nor DSO generally has access to the DERs' data and resources.

All of these obstacles can be resolved by aggregating DERs under the management of a third market player called aggregator. In order to utilize all capability of DERs a novel entity entitled ARADS can be defined with the aim of providing active power reserve to the transmission system. The general structure of an ARADS as seen from ADN and TSO perspectives are illustrated in Fig. 2.

1-**From ADN perspective:** ARADS comprises an aggregated dispatchable DG, an aggregated ESS as well as an aggregated load, as show in Fig. 2. In addition to the flexible loads, which are sources of flexibility, the aggregated load embraces the non-dispatchable DGs (negative loads) and firm loads, which are sources of uncertainties. It is assumed that deviations from scheduled active power of non-dispatchable DGs and loads are compensated by exploiting the local flexibilities of ARADS. The corresponding flexibilities of these aggregated resources (i.e. $r_{hts}^{\mathrm{DDG+}}, r_{hts}^{\mathrm{DDG-}}, r_{hts}^{\mathrm{ESS+}}, r_{hts}^{\mathrm{ESS-}}, r_{hts}^{\mathrm{FL+}}, r_{hts}^{\mathrm{FL-}}$) are defined as auxiliary variables. These variables are only accessible and controllable by the aggregator and not by TSO. Therefore, they cannot be directly involved in the mathematical formulation presented in Section **Error! Reference source not found.**. Actually, in that formulation we rely on variables translating how the auxiliary ones are perceived by TSO (i.e. $r_{hts}^{\mathrm{P+}}, r_{hts}^{\mathrm{P-}}, r_{hts}^{\mathrm{PE+}}, r_{hts}^{\mathrm{PE-}}$). The relationships between both sets of variables are:

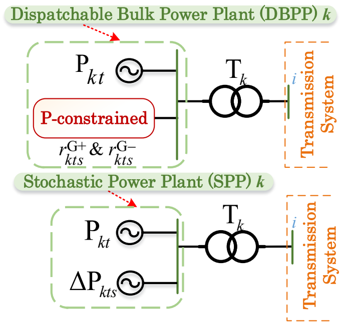

Fig. 3. The model of power plant k connected to bus i, from TSO point of view. The notation refers to time slot t and scenario s.

$$r_{hts}^{\mathrm{P+}} = r_{hts}^{\mathrm{DDG+}} \qquad \forall h \in \mathbb{A}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S}, \tag{1}$$

$$r_{hts}^{\mathrm{P-}} = r_{hts}^{\mathrm{DDG-}} \qquad \forall h \in \mathbb{A}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S}, \tag{2}$$

$$r_{hts}^{\mathrm{PE+}} = r_{hts}^{\mathrm{EES+}} + r_{hts}^{\mathrm{FL+}} \qquad \forall h \in \mathbb{A}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S}, \tag{3}$$

$$r_{hts}^{\mathrm{PE-}} = r_{hts}^{\mathrm{EES-}} + r_{hts}^{\mathrm{FL-}} \qquad \forall h \in \mathbb{A}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S}. \tag{4}$$

2-**From TSO perspective**: each ARADS can be modeled as an equivalent load along with a P-constrained (i.e. power constrained) and a P&E-constrained (i.e. power and energy constrained) resources of active power reserve, as shown in Fig. 2. The equivalent load represents the net active power schedule for the ARADS and can be expressed as:

$$\mathrm{P}_{ht} = -\mathrm{P}_{ht}^{\mathrm{DDG}} - \mathrm{P}_{ht}^{\mathrm{ESS}} + \mathrm{P}_{ht}^{\mathrm{L}} \qquad \forall h \in \mathbb{A}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S}. \tag{5}$$

P-constrained resources $(r_{hts}^{\mathrm{P+}}, r_{hts}^{\mathrm{P-}})$ are restricted only by the active power capacity $(\mathrm{R}_h^{\mathrm{P+,max}}, \mathrm{R}_h^{\mathrm{P-,max}})$ as in the case of dispatchable DGs. The P&E-constrained resources $(r_{hts}^{\mathrm{PE+}}, r_{hts}^{\mathrm{PE-}})$ are restricted by both active power capacity $(\mathrm{R}_h^{\mathrm{PE+,max}}, \mathrm{R}_h^{\mathrm{PE-,max}})$ and energy capacity $(\mathrm{E}_h^{\mathrm{PE+,max}}, \mathrm{E}_h^{\mathrm{PE-,max}})$ as in the case of ESSs and flexible loads. The variables located at the left-hand side of (1)-(4) indicate the active power reserve that TSO deploys from ARADS h during time slot t and scenario s. The boundaries of these variables throughout the scheduling time horizon $(\mathrm{R}_h^{\mathrm{P+,max}}, \mathrm{R}_h^{\mathrm{P-,max}}, \mathrm{R}_h^{\mathrm{PE+,max}}, \mathrm{R}_h^{\mathrm{PE-,max}}, \mathrm{E}_h^{\mathrm{PE+,max}}, \mathrm{E}_h^{\mathrm{PE-,max}})$ are offered by ARADS h to the TSO. Then, TSO solves the optimal reserve allocation problem defined in Section 1.3. The output of this problem determines the optimal active power reserve capacities $(R_h^{\mathrm{P+}}, R_h^{\mathrm{P-}}, R_h^{\mathrm{PE+}}, R_h^{\mathrm{PE-}})$ that TSO should book from each ARADS throughout the scheduling time horizon to minimize its total cost.

1.4.3. Power plant Modeling

The power plants are categorized into dispatchable and stochastic (i.e., non-dispatchable). During the real time operation, DBPPs follow their pre-defined (typically day-ahead) schedule plan and also can provide reserve to the TSO, while SPPs, like solar and wind power plants, may not follow their forecasted schedules due to predictions errors and they are sources of uncertainties. In line with the classification of the active power reserve resources presented in 1.4.2, the power plants can be modeled as illustrated in Fig. 3.

1.4.4. Method

Based on the models for ARADSs and power plants described in the previous section and exploiting the DC power flow model [9] along with a cost-benefit approach [17], the TSO's optimal allocation of active power reserve from DBPPs and ARADSs is formulated as the following linear programming problem:

$$\min_{\Psi} C^{\text{Interruption}}(\Psi) + C^{\text{Reserve}}(\Psi), \quad (6)$$

subject to:

$$0 \le r_{kts}^{\text{G}+} \le \text{A}_{kts}^{\text{G}} R_k^{\text{G}+} \qquad \forall k \in \mathbb{DP}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S}, \quad (7)$$

$$0 \le r_{kts}^{\text{G}-} \le \text{A}_{kts}^{\text{G}} R_k^{\text{G}-} \qquad \forall k \in \mathbb{DP}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S}, \quad (8)$$

$$0 \le R_k^{\text{G}+} \le \text{R}_k^{\text{G}+,\text{max}} \qquad \forall k \in \mathbb{DP}, \quad (9)$$

$$0 \le R_k^{\text{G}-} \le \text{R}_k^{\text{G}-,\text{max}} \qquad \forall k \in \mathbb{DP}, \quad (10)$$

$$0 \le r_{hts}^{\text{P}+} \le R_h^{\text{P}+} \qquad \forall h \in \mathbb{A}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S}, \quad (11)$$

$$0 \le r_{hts}^{\text{P}-} \le R_h^{\text{P}-} \qquad \forall h \in \mathbb{A}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S}, \quad (12)$$

$$0 \le r_{hts}^{\text{PE}+} \le R_h^{\text{PE}+} \qquad \forall h \in \mathbb{A}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S}, \quad (13)$$

$$0 \le r_{hts}^{\text{PE}-} \le R_h^{\text{PE}-} \qquad \forall h \in \mathbb{A}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S}, \quad (14)$$

$$-\text{E}_h^{\text{PE}-,\text{max}} \le \sum_{t'=1}^{t} \left(r_{ht's}^{\text{PE}+} - r_{ht's}^{\text{PE}-}\right)\tau \le \text{E}_h^{\text{PE}+,\text{max}} \qquad \forall h \in \mathbb{A}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S}, \quad (15)$$

$$0 \le R_h^{\text{P}+} \le \text{R}_h^{\text{P}+,\text{max}} \qquad \forall h \in \mathbb{A}, \quad (16)$$

$$0 \le R_h^{\text{P}-} \le \text{R}_h^{\text{P}-,\text{max}} \qquad \forall h \in \mathbb{A}, \quad (17)$$

$$0 \le R_h^{\text{PE}+} \le \text{R}_h^{\text{PE}+,\text{max}} \qquad \forall h \in \mathbb{A}, \quad (18)$$

$$0 \le R_h^{\text{PE}-} \le \text{R}_h^{\text{PE}-,\text{max}} \qquad \forall h \in \mathbb{A}, \quad (19)$$

$$-\text{T}_h \le -\left(\text{P}_{ht} - P_{hts}^{\text{SL}}\right) + r_{hts}^{\text{P}+} - r_{hts}^{\text{P}-} + r_{hts}^{\text{PE}+} - r_{hts}^{\text{PE}-} \le \text{T}_h \qquad \forall h \in \mathbb{A}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S}, \quad (20)$$

$$-\text{T}_k \le \text{A}_{kts}^{\text{G}}\left(\text{P}_{kt} + r_{kts}^{\text{G}+} - r_{kts}^{\text{G}-}\right) \le \text{T}_k \qquad \forall k \in \mathbb{DP}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S}, \quad (21)$$

$$-\text{F}_{ij}^{\text{max}} \le \text{A}_{ijts}^{\text{L}} \text{B}_{ij}\left(\delta_{its} - \delta_{jts}\right) \le \text{F}_{ij}^{\text{max}}, \qquad \forall i,j \in \mathbb{B}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S}, \quad (22)$$

$$\sum_{h\in\mathbb{A}_i}\left[-\left(\text{P}_{ht} - P_{hts}^{\text{SL}}\right) + r_{hts}^{\text{P}+} - r_{hts}^{\text{P}-} + r_{hts}^{\text{PE}+} - r_{hts}^{\text{PE}-}\right] + \sum_{k\in\mathbb{DP}_i}\left[\text{A}_{kts}^{\text{G}}\left(\text{P}_{kt} + r_{kts}^{\text{G}+} - r_{kts}^{\text{G}-}\right)\right] + \sum_{k\in\mathbb{SP}_i}\left[\text{A}_{kts}^{\text{G}}(\text{P}_{kt} + \Delta\text{P}_{kts})\right] + \sum_{l\in\mathbb{L}_i}\left[-\left(\text{P}_{lt} + \Delta\text{P}_{lts} - P_{lts}^{\text{SL}}\right)\right] = \sum_{j\in\mathbb{B}_i} \text{A}_{ijts}^{\text{L}} \text{B}_{ij}\left(\delta_{its} - \delta_{jts}\right)$$

$$\forall i \in \mathbb{B}, \forall t \in \mathbb{T}, \forall s \in \mathbb{S}, \quad (23)$$

$$\delta_{1ts} = 0 \qquad \forall t \in \mathbb{T}, \forall s \in \mathbb{S}. \quad (24)$$

The optimization variables of the problem are defined as:

$$\psi = \{r_{kts}^{\text{G}+}, r_{kts}^{\text{G}-}, r_{hts}^{\text{P}+}, r_{hts}^{\text{P}-}, r_{hts}^{\text{PE}+}, r_{hts}^{\text{PE}-}, R_k^{\text{G}+}, R_k^{\text{G}-}, R_h^{\text{P}+}, R_h^{\text{P}-}, R_h^{\text{PE}+}, R_h^{\text{PE}-}, \delta_{its}, P_{hts}^{\text{SL}}, P_{lts}^{\text{SL}}\}, \quad (25)$$

this set of variables comprises the deployed reserves and booked reserve capacities from all DBPPs and ARADSs, as well as the state of the transmission system.

The objective function (6) aims at minimizing:

- $C^{\text{Interruption}}(\Psi)$: the expected cost of energy not served with respect to the realization of the set of credible scenarios which can be expressed as:

$$C^{\text{Interruption}}(\Psi) = \sum_{i\in\mathbb{B}}\sum_{t\in\mathbb{T}}\sum_{s\in\mathbb{S}} \rho_s \tau \text{VOLL}_i \left[\sum_{l\in\mathbb{L}_i} P_{lts}^{\text{SL}} + \sum_{h\in\mathbb{A}_i} P_{hts}^{\text{SL}}\right]. \quad (26)$$

It measures the benefit of reserve in terms of the reduction in the expected cost of energy not served, i.e. it characterizes the benefit.

- $C^{\text{Reserve}}(\Psi)$: the expected cost of booked reserve capacities as well as the expected cost of deployed reserves from all providers including ARADSs and DBPPs throughout the scheduling time horizon over a set of credible scenarios. It characterize the cost of reserve. It can be expressed as:

$$C^{\text{Reserve}}(\Psi) = \sum_{s\in\mathbb{S}}\sum_{t\in\mathbb{T}} \tau\rho_s\pi_t^{+}[\sum_{k\in\mathbb{DP}} r_{kts}^{\text{G}+} + \sum_{h\in\mathbb{A}}(r_{hts}^{\text{P}+} + r_{hts}^{\text{PE}+})]$$
$$+\sum_{s\in\mathbb{S}}\sum_{t\in\mathbb{T}} \tau\rho_s\pi_t^{-}[\sum_{k\in\mathbb{DP}} r_{kts}^{\text{G}-} + \sum_{h\in\mathbb{A}}(r_{hts}^{\text{P}-} + r_{hts}^{\text{PE}-})] +$$
$$+\mathcal{H}\sum_{h\in\mathbb{A}}(\text{C}_h^{\text{P}+}R_h^{\text{P}+} + \text{C}_h^{\text{P}-}R_h^{\text{P}-} + \text{C}_h^{\text{PE}+}R_h^{\text{PE}+} + \text{C}_h^{\text{PE}-}R_h^{\text{PE}-})$$
$$+\mathcal{H}\sum_{k\in\mathbb{DP}}(\text{C}_k^{\text{G}+}R_k^{\text{G}+} + \text{C}_k^{\text{G}-}R_k^{\text{G}-}), \quad (27)$$

where the first term is the expected (with respect to the realization of the set of scenarios) cost of the upward deployed reserve from all DBPPs, P-constrained and P&E-constrained resources of ARADSs. The second term is the expected cost of the downward deployed reserve from all DBPPs, P-constrained and P&E-constrained resources of ARADSs. The third term consists in two parts, the first part represents the cost of upward/downward booked reserve capacity from P-constrained resources of ARADSs, while the second part represents the cost of upward/downward booked reserve capacity from P&E-constrained resources of ARADSs. The fourth term represents the cost of upward/downward booked reserve capacity from all DBPPs.

The set of constraints (7)-(24) binds the objective function (6). Constraints (7) and (8) respectively model the power capacity limits of the upward and downward P-constrained reserve deployed from DBPPs. The set of constraints (9) and (10) respectively enforces the upward and downward booked active power reserve capacities from DBPPs to respect the maximum active power reserve capacities that DBPPs offered to the TSO. Constraints (11) and (12) respectively model the power capacity limits of the upward and downward P-constrained reserve deployed from ARADSs. Constraints (13) and (14) respectively model the power capacity limits of the upward and downward P&E-constrained reserve deployed from ARADSs. The constraint (15) models the energy capacity limits of the upward and downward P&E-constrained reserve deployed from ARADSs. The set of constraints (16)-(19) enforces the booked upward/downward P-constrained and P&E-constrained reserve capacities from ARADSs to respect the maximum reserve capacities that ARADSs offered to the TSO. The set of constraints (20) and (21) models the power limits of the substations connecting the ARADSs and

DBPPs to the transmission system, respectively.

As the transmission system is assumed loss-less and modeled with the DC power flow model, the power flow in a transmission line is proportional to the difference of the voltage angles of the terminal buses of that line; so constraint (22) represents the power flow limits of the transmission lines. The constraint (23) enforces the power balance for all buses of the transmission system. The constraint (24) considers bus number 1 as the reference for the voltage angle of buses.

The above-mentioned objective function along with the defined constraints build a scenario-based stochastic linear optimization formulation for the problem of TSO's optimal allocation of active power reserve from ARADSs and BPPs. The outcome of this optimization problem determines the required optimal reserve capacities from ARADSs and DBPPs throughout the scheduling time horizon such that the total cost of TSO is minimized.

2. Achievement of deliverable:

2.1. Date

February 2020

2.2. Demonstration of the deliverable

2.2.1. Case Study: Swissgrid Network

The high-voltage transmission network of Switzerland (Swissgrid network) is considered as the case study. The grid is operated by Swissgrid and is an important electricity pathway due to its location in central Europe. It includes 212 buses at 380 kV and 220 kV connected through 284 transmission lines and 25 high-voltage transformers. It is connected to France, Germany, Italy and Austria through 37 buses. In this work, the interconnections to the neighboring countries are modeled as a constant positive or negative injection at the connecting nodes during each time slot. Fig. 4 shows the network configuration. Its buses can be categorized into 6 types:

- DBPP buses, which interface DBPPs;
- Load buses, which interface aggregated consumers;
- Neighboring buses, which connect the network to neighboring TSOs;
- ARADS buses, which interface ARADSs;
- SPP buses, which interface SPPs;
- SPP + load buses: where both SPPs and loads are connected.

In line with the general reserve allocation procedure introduced in Section 1.4.4, it is considered here that:

- the scheduling time horizon is 24 hours of the next day;

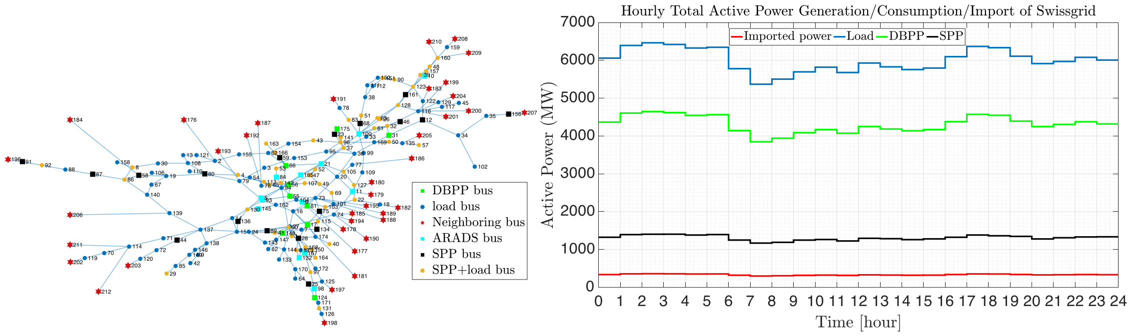

Fig. 4. Swissgrid network.

- the next day consists of 24 time slots, each with duration of 1-hour;
- Each 1-hour time slot represents a single scheduled grid operating point;
- TSO books reserve capacities, for the whole 24 hours of the next day, one hour before beginning of the next day;
- The amount of booked reserve capacity form each provider is constant throughout the next day.

The topology, technical parameters and profile of the nodal generation/consumption of this network are directly provided by Swissgrid. Fig. 4 shows the total active power generation of DBPPs and SPPs along with the total imported power from neighboring networks and the total consumption of the loads of TSO throughout all 24 time slots. The total energy consumption of the network is 144.2 GWh throughout all 24 time slots. The share of stochastic generation is assumed 30% of the total generation. The offered upward/downward power and energy reserve capacities of all active power reserve providers are assumed as reported in Table I and Table II. The prices of booked reserve capacities and deployed reserves are extracted from the Swissgrid reserve market clearing prices [20] and the statistics available in [21]. To address the correlation between the price and demand for reserve capacity, the prices of booked reserve capacities are modeled as staircase (piece-wise constant) functions of the amount of booked reserve. During 24-hour scheduling time horizon, the state (availability/unavailability) of power plants and transmission lines/transformers are modeled as independent two-states 0, 1 Markov chains. Then, sequential Monte Carlo simulation is used to provide scenarios that represent outages of generators, transmission lines and transformers. Moreover, the day-ahead forecast errors of loads and SPPs are modeled as independent Gaussian distributions. The forecast error of each load(/SPP) is sampled from a normal distribution with 0 mean and such that the standard deviation of the total load (/stochastic generation) forecast error is 3% (/8%) of the whole grid forecasted load (/stochastic generation) [22]. These forecast errors model the deviation of the net active power injection at each bus of the transmission system from its day-ahead scheduled value. This approach is utilized to model the contingencies and uncertainties by generating 20’000 scenarios. Finally, the k-medoids clustering method [23] is applied to reduce the number of scenarios to 200 representative scenarios.

Table I

OFFERED UPWARD/DOWNWARD POWER AND ENERGY RESERVE CAPACITIES OF ARADSS TO THE TSO.

Bus Number of ARADS	5	6	10	11	21	84	93	98	100	132	145	165	167
$\mathbf{R}_h^{\mathbf{P+,max}}$(MW)	10	14	4	6	4	5	11	15	8	5	13	9	16
$\mathbf{R}_h^{\mathbf{P-,max}}$(MW)	5	17	16	12	9	7	12	17	9	7	10	6	12
$\mathbf{R}_h^{\mathbf{PE+,max}}$(MW)	33	16	39	27	19	14	24	20	16	14	37	29	34
$\mathbf{R}_h^{\mathbf{PE-,max}}$(MW)	21	18	40	31	24	18	21	26	19	18	21	38	31
$\mathbf{E}_h^{\mathbf{PE+,max}}$(MWh)	72	45	90	45	37	50	70	65	45	35	94	95	100
$\mathbf{E}_h^{\mathbf{PE-,max}}$(MWh)	62	39	70	100	57	55	60	50	53	50	48	94	87

Table II

OFFERED UPWARD/DOWNWARD POWER RESERVE CAPACITIES OF DBPPS TO THE TSO.

Bus Number of DBPP	17	31	55	56	66	81	124	148	167	175
$\mathbf{R}_h^{\mathbf{G+,max}}$(MW)	110	180	190	120	130	200	125	140	160	120
$\mathbf{R}_h^{\mathbf{G-,max}}$(MW)	14	200	200	10	10	250	10	10	29	10

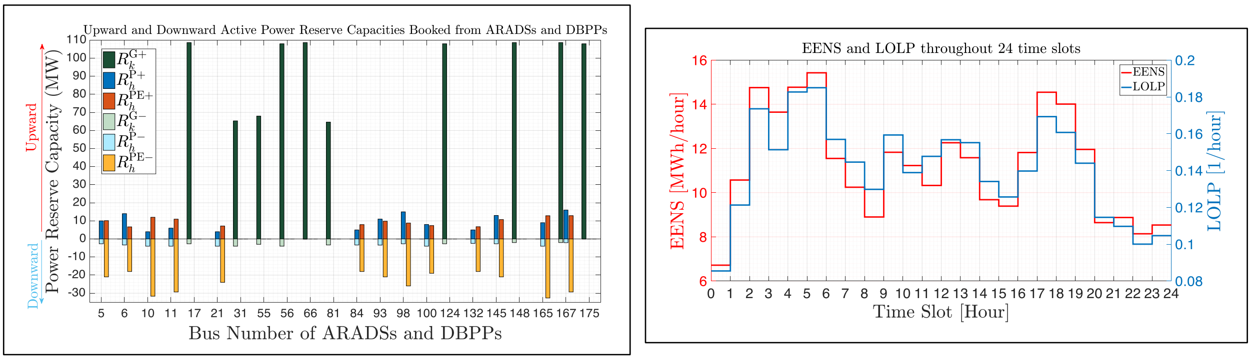

Fig. 5. A) Booked power reserve capacities from ARADSs and DBPPs. B)EENS and LOLP of TSO throughout all 24 time slots.

2.2.2. Optimal Allocation of active power reserve

The problem is modelled using YALMIP-MATLAB [24] and solved with GUROBI [25] on a PC with Windows equipped with a 2.8 GHz Xeon CPU and 32 GB of RAM. Then, the optimal reserve allocation problem (6)-(24) is solved for the developed case study by choosing value of lost load (VOLL) equal to 1000 CHF/MWh. The booked upward/downward active power reserve capacities from each individual provider are shown in Fig. 5. A. Moreover, the EENS and LOLP of the TSO during each time slot are represented in Fig. 5. B. It illustrates that the method accepts a higher EENS and LOLP at some time slots in such a way that the total cost of TSO over the total scheduling time horizon is minimized. The execution time of the problem is less than 600 seconds, while a real large-scale transmission network is used as the case study. It illustrates one of the most privileged features of the proposed method, namely its low computation burden.

2.2.3. Technical and Economical benefits of the ARADS

In order to achieve a clear perception about the technical and economical benefits of ARADSs, 2 different cases are defined. In case 1, both DBPPs and ARADSs provide active power reserve,

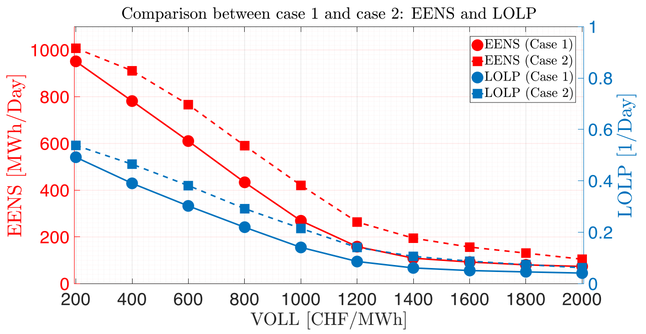

Fig. 6. Impact of the ARADSs on the reliability of the transmission network.

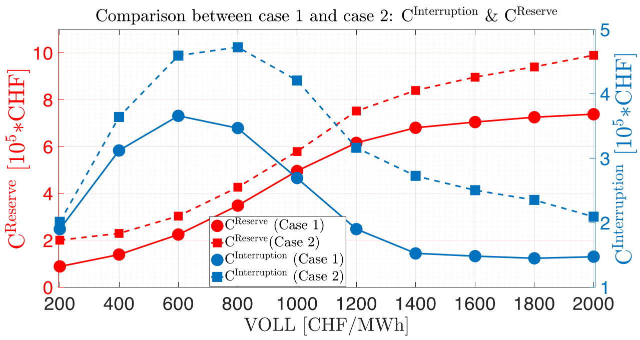

Fig. 7. Impact of the ARADS on the TSO's cost of interruption and reserve.

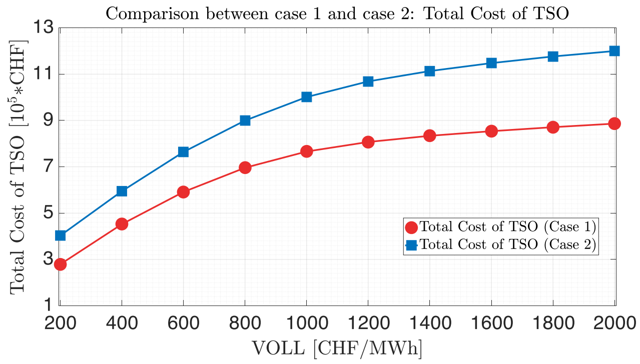

Fig. 8. Impact of ARADSs on the total cost of TSO.

while in case 2, only DBPPs provide active power reserve. Then, a comparison between cases 1 and 2 is reported in Fig. 6- Fig. 8. For different VOLLs, Fig. 6 illustrates that in case 1, the reliability of the network throughout the 24-hour scheduling time horizon is considerably better than in case 2. LOLP index just indicates the expected rate of load shedding without considering the duration and amount of shed load, while EENS index takes into account the duration and amount of shed load. Thus, EENS reflects the reliability of the network better than LOLP. For different VOLLs, Fig. 7 illustrates that the expected cost of both reserve and interruption, in case 1, is lower than in case 2. Consequently, the total expected cost of TSO comprising the cost of reserve and cost of interruption, in case 1, is lower than in case 2, as illustrated in Fig. 8. Finally, it can be concluded that the provision of active power reserve by ARADSs not only decreases the total expected cost of TSO, but it also improves the reliability of the transmission network.

3. Impact

This deliverable introduced a method to support TSOs to identify their needs for active power reserve capacity from all DBPPs and ARADSs. In this respect, a method of this kind can facilitate a tighter and more reliable cooperation between TSOs and lower-grid level operators and enable the transition from the current top-down mechanism for ancillary services provision to a bi-directional approach. It was also illustrated that this transition improves the electric power system security of supply against contingencies and reduces the cost of TSOs for procuring ancillary services.

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