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Distributed Flexibility Estimation for TSO-DSO Interactions

Corentin Jacquier, Rémy Rigo-Mariani, Vincent Debusschere, *Senior Member, IEEE*, Jean-Nicolas Louis, Silvana Mima

Abstract— The transmission system operator (TSO) and the distribution system operator (DSO) need to plan and operate together to cope with the increasing penetration of distributed energy resources (DERs). Optimization of both systems is required to reduce the global cost. But direct co-optimization of distribution and transmission grids for large systems is still computationally out of reach, especially when long-term prospective studies are carried out. Also, decomposition-based methods are either long or imprecise. This paper presents a tractable method based on the estimation of the distributed flexibility potential that captures the distribution grid characteristics. This method requires a fine definition of the flexibility the DSO could offer to the TSO. In radial distribution grids, the amount of available flexibility for the transmission grid is thus determined, which results in bounds for the TSO-DSO power exchanges over a given time horizon.

Index Terms—Energy system planning, flexibility, optimal power flow, radial grid, TSO-DSO interaction.

NOMENCLATURE

Sets

$t \in T$	Set of time steps
$n \in N$	Set of nodes
$l \in L$	Set of lines
$lu(n) \in L_u(n)$	Set of lines upstream of node n
$ld(n) \in L_d(n)$	Set of lines downstream of node n
$nd(n) \in N_d(n)$	Set of nodes directly connected downstream of node n
$X = \{bat, VRES\}$	Set of producing units
$Y = \{bat, load\}$	Set of consuming units
$Z = \{bat+, bat-, DSM, curt\}$	Set of flexibility

Variables

$g_{t,n}^x$	Power produced by x (MW)
$d_{t,n}^y$	Power consumed by y (MW)
$P_{t,l}, Q_{t,l}$	Active, reactive flow in line l (MW)
$v_{t,n}$	Voltage magnitude (kV)
$e_{t,n}$	Amount of energy in storage (MWh)
$f_{t,n}^z$	Flexibility potential of type z (MW)
$F_{t,n}^+ / F_{t,n}^-$	Up/downward usable flexibility (MW)
P_t^{DT}	Power transfer from DSO to TSO at the interface (MW)

Parameters

π_x	Generation price for x (€/MWh)
π_t^{TSO}	TSO energy price (€/MWh)
dt	Interval between two timesteps (h)
r_l, x_l	Line resistance, reactance (Ω)
η	Generic storage efficiency
$\underline{\cdot}, \overline{\cdot}$	Lower / upper bounds of the variable ‘ \cdot ’

I. INTRODUCTION

THE increasing penetration of distributed energy resources in distribution grids raises new issues for Distribution System Operators (DSO). Therefore, models are required to thoroughly operate and plan those grids, to notably provide a forecast of available flexibilities to the Transmission System Operator (TSO) over a range of time horizons. Indeed, TSOs are usually in charge of the higher scale point of view, to develop national energy strategies for example – i.e. simulations of long-term prospective scenarios. Those strategies may no longer be relevant if they oversimplify the distribution grid behavior and misestimate underlying costs and feasibility, notably misrepresenting the operation of potential distributed flexibilities.

Distribution grids in energy prospective studies are rarely considered due to the high computational cost. When they are considered, they are usually highly oversimplified. To decrease the computation time, [1] and [2] consider a reduced number of nodes. There are only 3 distribution grids in the whole of Europe in [1] and 16 in Germany in [2] for instance. Another solution is to simply simulate distribution and transmission grids independently [3]. In either case, interactions between grids are oversimplified if not simply ignored which leads to suboptimal results with potential TSO-DSO interactions not represented.

Adapted from previous works [1], a long-term international economic model of the European energy system, named POLES [4], has been coupled with a technical model, named Backbone [5], representing the daily operation of grids. POLES is a partial equilibrium economic model used for prospective scenarios at the country level and long-term time horizon (up to 2100). Backbone is a multi-energy and multi-market unit commitment model relying on stochastic optimization, that will be used to jointly optimize distribution and transmission grids.

Two main classes of methodology are traditionally employed in the literature to mitigate heavy computational time when co-optimizing transmission and distribution systems. Iterative

processes were proposed to overcome this issue [6]–[9]. These processes converge to the global solution [6], and are faster than the standalone problem [7]. Iterative processes can then solve large system problems in a reasonable time [8]. The idea is to optimize distribution and transmission grids separately. In order to converge, electric quantities at the point of connection between TSO and DSO should be close, with iterations based on an error threshold. However, the number of iterations is not fixed by default, as the convergence criteria can be reached rapidly or not. Limiting the number of iterations is efficient to cap the computation time but the optimality is no longer guaranteed [10]. The alternating direction multiplier method (ADMM) [11] is also an iterative method to couple distribution and transmission systems operation. But its complexity makes it intractable for energy prospective scenarios for which several decades need to be simulated.

Another possibility, named the capability area method, computes the range of possible values for the quantities at the TSO-DSO interface [12]. Building a capability area requires several simulations to build a list of possible interactions of the systems, which creates an area of reachable active and reactive powers. The TSO then determines power profiles within this area. As defining the capability area requires a significant number of simulations, it is not suited for time series in the context of prospective scenarios.

To provide an answer to the aforementioned issue, a three-step method using the DSO flexibility characterization is being developed. The idea is to go back and forth from the DSO flexibility to the TSO needs, as presented in Fig. 1, but while controlling the number of iterations (unlike conventional iterative methods).

The first steps consist of an optimal power flow (OPF) at the scale of the DSO. This typical OPF accounts for the energy import from the TSO, local generation assets, and variable and renewable energy sources (VRES). Then, along the given simulation horizon, the potential flexibility (upward/downward) that the DSO can provide to the TSO is evaluated around the OPF results. Note that in the paper flexibilities are provided by storage systems (upward/downward), renewable curtailment (downward), and load shedding (upward). In the second step, the TSO determines its optimal behavior within the flexibility range provided by the DSO. In the last step, the DSO reoptimizes its grid with the input of the TSO. With this process, DSO and TSO agree on the power they exchange, P_t^{DT} .

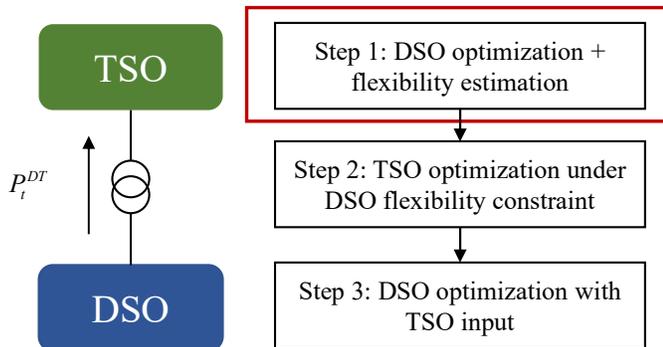


Fig. 1: Proposed DSO-TSO coupling method and scope of the paper in red (first step of the method)

The scope of this paper is strictly focused on the first step, which consists in optimizing the distribution grid and estimating the flexibility around this optimal point.

The proposed method presents the advantage of requiring only three steps, so a fixed number of iterations, and also of representing more precisely the potential that TSO and DSO could extract from distributed flexibilities. This will impact prospective scenarios in the context of the massive integration of renewable energy and non-conventional loads, highlighting the relevance of its modeling.

II. DISTRIBUTION GRID OPTIMIZATION

In the POLES/Backbone coupled model, a unit commitment with grid constraints is processed in Backbone. It optimizes the behavior of generation and flexibility units. The role of this section is to describe this optimal power flow which provides material to estimate the amount of distributed flexibility later available for the TSO.

A. Objective function

The objective of this optimal power flow (OPF) is to reduce the cost of electricity in the grid. The first type of cost for the DSO is local energy production on the n nodes of the grid. The second is the import from the TSO. This minimization problem is stated in (1):

$$obj = \min \sum_{t \in T} \left(-P_t^{DT} \times \pi_t^{TSO} + \sum_{n \in N} \sum_{x \in X} g_{t,n}^x \times \pi_x \right) \times dt \quad (1)$$

Where $-P_t^{DT}$ is the power imported from the transmission grid, $g_{t,n}^x$ the power generated at node n by unit x , π_x the generation price of this unit, and π_t^{TSO} the market price.

B. Constraints

The constraints of this OPF, based on the linearized DistFlow model for radial grids [13], are listed below:

$$\forall n, m \in N, \forall l \in L(n) \cup L(m), \forall t \quad 2 \times (r_l \times p_{t,l} + x_l \times q_{t,l}) = v_{t,n}^2 - v_{t,m}^2 \quad (2)$$

Node voltage, $v_{t,n}$, is updated with the successive voltage drop along lines depending on the real power, $p_{t,l}$, and reactive power, $q_{t,l}$, with the line of resistance r_l and reactance x_l (2). The next constraints are presented only for real power for the sake of simplicity but equivalent constraints for reactive power are implemented.

$$\sum_{l \in L(n)} p_{t,l} + \sum_{x \in X} g_{t,n}^x - \sum_{y \in Y} d_{t,n}^y = 0 \quad (3)$$

$$e_{t,n} = e_{t-1,n} + (\eta \times d_{t,n}^{bat} - g_{t,n}^{bat} / \eta) \times dt \quad (4)$$

$$\underline{e}_n \leq e_{t,n} \leq \bar{e}_n \quad (5) \quad -\bar{p}_l \leq p_{t,l} \leq \bar{p}_l \quad (6)$$

$$\underline{v}_n^2 \leq v_{t,n}^2 \leq \bar{v}_n^2 \quad (7) \quad 0 \leq g_{t,n}^x \leq \bar{g}_n^x \quad (8)$$

Active power balance (3) states that a flow through a line is the contribution of the bus power (generation, $g_{t,n}^x$, and demand,

$d_{t,n}^Y$) for all the nodes downstream the branch. The battery charge and discharge with the efficiency of the storage unit, η , determine the amount of energy stored, $e_{t,n}$ (4) at every time step that shall remain within limits (5). Line flows (6), voltage (7), and generation (8) are also bounded.

For development/validation purposes, the optimization problem is solved over one day with 24 timesteps. In an iterative distribution and transmission grid coordination process, only the optimal value of the power flow at the DSO-TSO interface, P_t^{DT} , would have been useful for the TSO. The method explained in the next session uses the other results of the distribution grid optimization to improve the speed of convergence of the global co-optimization. Each value resulting from the DSO optimization is noted with a “*” in the following. $g_{t,n}^{VRES*}$ is then the optimal power generated by VRES for node n at time t .

III. DETERMINATION OF THE DISTRIBUTED FLEXIBILITY

This section aims to explain the methodology to estimate the flexibility at the distribution grid level that will later be available for the TSO (step 2 in Fig.1 which is outside the scope of this paper).

Flexibility is defined as the capability to increase or decrease power. We consider as upward flexibility the capability to increase the power flowing from DSO to TSO (P_t^{DT}) – i.e. increase the DSO generation or reduce its load. On the contrary, downward flexibility increases the power injected by the transmission grid.

A. Flexibility Characterization

Three types of flexibility are considered in this study.

First source of flexibility (downward only) is the power curtailment of VRES. The amount of flexibility offered by curtailment, noted $f_{t,n}^{curt}$, corresponds to the quantity of power from VRES that can be switched off. The optimal production of VRES ($g_{t,n}^{VRES*}$) gives then the quantity of flexibility provided by curtailment (9).

$$f_{t,n}^{curt} = g_{t,n}^{VRES*} \quad (9)$$

DSM represents the ability of the grid operator to shift or reduce the load during a period in exchange for monetary compensation. As such, it is upward flexibility. In this model, DSM has only been expressed as a load shedding. DSM can offer to the TSO a quantity of flexibility $f_{t,n}^{DSM}$ corresponding to the installed capacity (10).

$$f_{t,n}^{DSM} = \overline{g_n^{DSM}} \quad (10)$$

The last type of flexibility considered is provided by installed battery storage systems - both upward and downward flexibility. Here, upward and downward flexibilities are linked as the possibility to discharge the battery is connected to the amount of energy charged.

The amount of downward flexibility provided by the battery charge $f_{t,n}^{bat-}$ is limited by both the power and the energy usage of the battery (11). Its energy limitation comes from the fact

that, if the DSO already reached full capacity, the TSO cannot use the battery to store. Power limitation also depends on the DSO optimal as the battery usage is divided between TSO and DSO. So, the sum of the usages cannot go beyond limits.

$$f_{t,n}^{bat-} = \min \left(\frac{\overline{e_n^{bat}} - e_{n,t}^{bat*}}{dt}, \overline{g_n^{bat}} - d_{n,t}^{bat*} \right) \quad (11)$$

For battery discharge offering upward flexibility $f_{t,n}^{bat+}$ similar limitations exist (12). This discharge is bounded by the optimal power predicted by the DSO optimization and by the energy the TSO has already charged.

$$f_{t,n}^{bat+} = \min \left(\frac{e_n^{bat} - \overline{e_{n,t-1}^{bat}}}{dt}, \overline{g_n^{bat}} - g_{n,t}^{bat*} \right) \quad (12)$$

Note that it is possible to model other flexibility means, such as electric vehicles or small hydraulic plants. However, the characterization of flexibility for these other types is not truly different from the three presented cases and is easily added to the global method.

B. Grid constraints consideration

The flexibility characterization provides the total amount of flexibility available for the TSO once the DSO optimization is performed if distribution grids were not constrained. In the case of a constrained network, flexibilities may not be able to be fully used. This is due to a potential violation of line flow limits. Thus, this paper proposes a heuristic and explainable approach to simply account for those constraints when defining DSO flexibilities capabilities.

Note that line power flows are bidirectional, meaning that there is a limit to the power flowing up as well as flowing down. For each limit, we define a variable representing the amount of flexibility that can be transmitted through the line. The first variable is $F_{t,n}^+$, which is the possible increase of the DSO generation. It allows the estimation of the maximal power that could flow up to node n if the upward flexibilities are activated at a given time step t . The maximal flexibility that can be activated is defined based on the DSO's optimal power consumption and production for this node, to which upward flexibilities from batteries and DSM are added as well as the maximum power flowing from the directly downstream nodes (13).

$$F_{t,n}^+ = \min \left(\sum_{m \in N_{down}(n)} F_{t,m}^+ + \sum_{x \in X} g_{t,n}^{x*} - \sum_{y \in Y} d_{t,n}^{y*} + f_{t,n}^{bat+} + f_{t,n}^{DSM}, \overline{P_{lu}} \right) \quad (13)$$

$\forall n \in N, \forall lu \in L_u(n), \forall t$

The second variable, $F_{t,n}^-$, is the minimal power the TSO can transmit to node n if the downward flexibilities are activated (14). As this is a minimal power, downward flexibilities from batteries and curtailment are subtracted from the optimal power. Moreover, with the convention of counting negatively the power flowing from the TSO to the DSO, this minimal value can be negative and is therefore bounded by the lower side of the flow constraint (6).

$$F_{t,n}^- = \max \left(\sum_{m \in N_{\text{down}}(n)} F_{t,m}^- + \sum_{x \in X} g_{t,n}^{x*} - \sum_{y \in Y} d_{t,n}^{y*} - f_{t,n}^{\text{bat}^-} - f_{t,n}^{\text{curt}}, -p_{lu} \right)$$

$$\forall n \in N, \forall lu \in L_u(n), \forall t \quad (14)$$

These two variables are then built through an iterative process in radial distribution grids up to the point of interface with the TSO - from downstream nodes where are computed $F_{t,n}^+$ or $F_{t,n}^-$ as described in Algorithm 1. In this algorithm, only $F_{t,n}^+$ is shown but the process is similar for $F_{t,n}^-$.

Algorithm 1: Order of computation for $F_{t,n}^+$

- 1: **For** all $n \in N$:
 - 2: $N_d^{\text{var}}(n) \leftarrow N_d(n)$
 - 3: **For** all $n \in N, N_d^{\text{var}}(n) = \emptyset$:
 - 4: Calculate $F_{t,n}^+$
 - 5: **For** all l in $L_u(n)$:
 - 6: **If** $\exists m \in N, l \in L_d(m)$:
 - 7: $N_d^{\text{var}}(m) \leftarrow N_d(m) \setminus \{n\}$
-

This method finally results in limits for the flexibility exported by the DSO. The power flowing from the DSO to the TSO is then limited by $F_{t,n}^+$ and $F_{t,n}^-$ as stated in (15). This equation is for node n_0 which corresponds to the node at the interface between DSO and TSO.

$$F_{t,n_0}^- < P_t^{\text{DT}} < F_{t,n_0}^+ \quad n_0 \in N, L_u(n_0) = \emptyset, \forall t \quad (15)$$

To illustrate Algorithm 1 and the calculation made in (13) and (14) an exemplary grid is provided in Fig. 2 and Fig. 3.

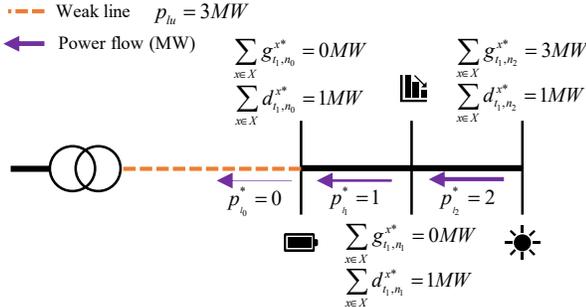


Fig. 2: Optimal flows on the distribution grid

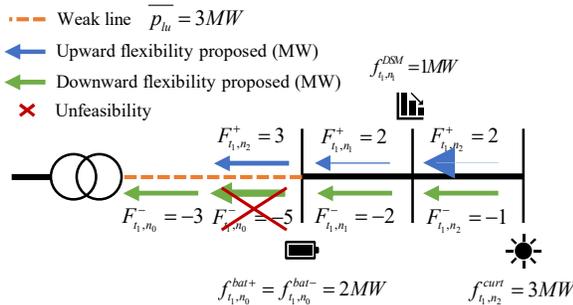


Fig. 3: Flexibility proposed by the distribution grid

The optimal behavior of the distribution grid is displayed in Fig. 2. As the total production and demand of the grid are balanced, the DSO has no interest to provide or be provided in power by the TSO. However, the TSO may be motivated to exchange power with the DSO, hence the flexibility definition around the optimal point. Fig. 3 shows the amount of power the

DSO can propose to the TSO which is made available by the flexibility. The upward flexibility proposed to the TSO is in blue. Its value increases each time an upward flexibility is available. Downward flexibility follows the opposite behavior, its value decreases when going upstream. In this grid, the orange line is weak and its power is limited to 3MW. As F_{t_1,n_0}^+ is not above, all the available flexibility can be proposed to the TSO. However, F_{t_1,n_0}^- does not respect (14) and is therefore limited to the line maximal power.

IV. RESULTS

This section gathers and discusses the main results obtained with the application of the first step of the discussed method on a benchmark distribution grid. The studied ten-bus distribution grid contains the three types of flexibility modeled in this article.

A. Initial Scenario

The first scenario provides a visual representation of (15), displayed in Fig. 4.

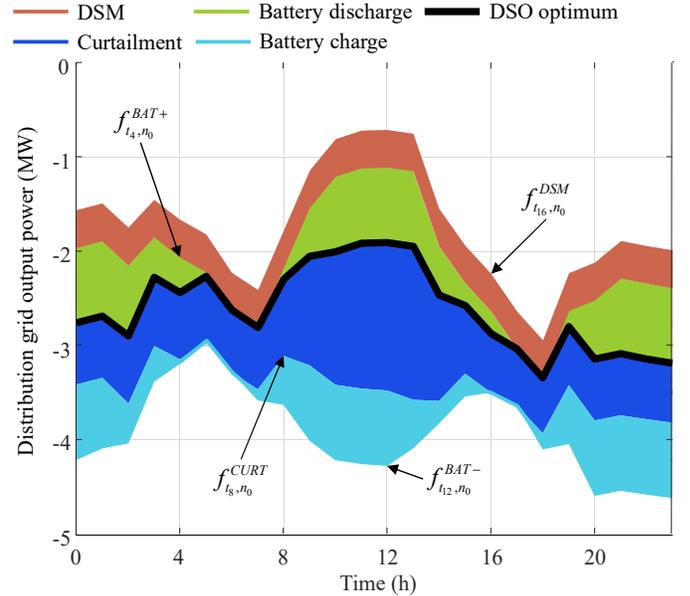


Fig. 4: DSO flexibility for the initial scenario

In Fig. 4, F_{t,n_0}^+ is the part above the DSO optimum. It is composed of the DSM and the battery discharge. The part below the DSO optimum, $F_{t,n}^-$, combines the downward flexibilities. Fig. 4 shows that the flexibility proposed to the TSO varies significantly during the day. This variability is due to the weather dependence of VRE and load curve dynamics but also to the choices made by the DSO to find its optimum. For instance, during morning and evening consumption peaks the batteries are fully used by the DSO optimization, which prevents the TSO to access them. When the consumption is lower (i.e. outside of the peak moments), the amount of available flexibility is higher. This is due to the higher solar production at noon that can be curtailed and the fact the DSO is not using the battery. DSM is not activated by the DSO as it is more expensive than buying energy from the TSO. DSM is always proposed to the DSO, hence the constant thickness of the brown shape.

B. Constrained Scenario

In the initial scenario, the grid is not limiting the provision of flexibility to the TSO. In this second scenario, a weaker grid is considered, where the line capacity between nodes has been reduced. It results in a decrease in the available flexibility for the TSO at some timesteps, as shown in Fig. 5.

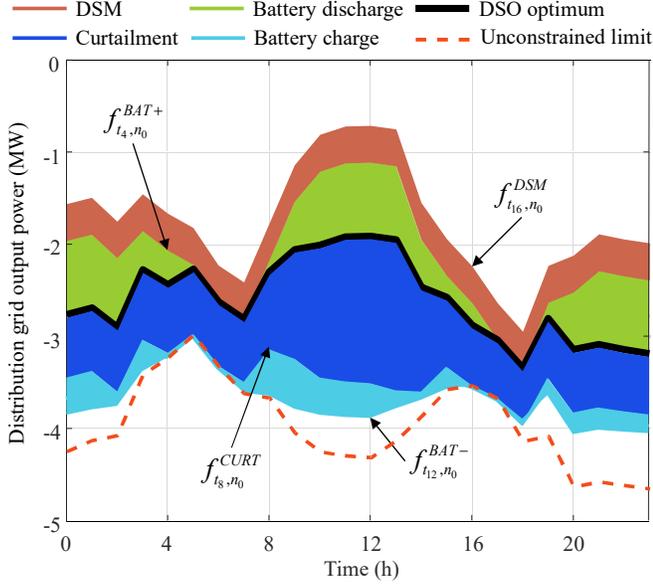


Fig. 5: DSO flexibility for the constrained scenario

As the distribution grid output power is always negative, the upward flexibility is not affected by the stronger line constraints – i.e. no positive line flows through the constrained lines. However, this constraint reduces the amount of downward flexibility available for the TSO specifically when a large quantity was available in the initial scenario. The importance of jointly sizing lines and the flexibilities at the distribution level is emphasized here. In this case, increasing the line capacity is more effective than adding flexibility.

V. CONCLUSION

This paper discusses the first step of a method evaluating the distributed flexibility for a TSO-DSO interaction, which consists in modeling distributed flexibilities and providing them to the TSO. This method is designed in the larger context of prospective studies, where pathways creation for the European power system toward the next decades would benefit from considering the distribution grid constraints, assuming that computation would remain tractable given the complexity of the considered system. It also enables a better understanding of the role of flexibility that could be used both by the DSO and the TSO (with a limited sharing mechanism in this study).

This work presents the first step to provide a complete, fast, and accurate enough TSO-DSO coordination algorithm. Thereafter, the question of the transmission grid utilization of the DSO flexibility will be addressed, especially with the consideration of the price of flexibility use, and energy constraints related to the various sources of flexibility. A last iteration is then necessary to provide the distribution grid with the needs on the transmission side. Requiring only three steps,

the coordination process will be a considerable advantage when integrating this method in the study of very large power systems compared to the literature.

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