FlexPlan.jl – An open-source Julia tool for holistic transmission and distribution grid planning

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***Abstract*—In the ever complex world of the power systems, robust decision making in the context of investment planning becomes a difficult problem. In the decision making process, the costs and benefits of implementing complementary or competing technologies (AC versus DC or storage versus classical transmission expansion) need to be assessed. Additionally, the electrification of industrial demand and the integration of smart loads, such as heat pumps or electric vehicles, pave the way for demand flexibility provision on large scale. Considering that the majority of the demand flexibility is located in the distribution grid, there is a need for planning models and tools able to perform combined transmission and distribution grid planning. This paper introduces *FlexPlan.jl*, a Julia/JuMP-based open-source tool for holistic planning of transmission and distribution grids which includes a complete set of planning candidates for transmission and distribution networks and fully internalizes demand flexibility and storage usage. We use stochastic optimisation, in order to find robust decisions with respect to different climate conditions and operating hours within given climate years. To keep the optimisation problem tractable, we introduce a novel decomposition between the transmission and distribution grid planning problems. We demonstrate that using the proposed approach a speed improvement of up to 100 times can be achieved for cases with a large number of distribution grids, with negligible increase of the objective function value and a good solution quality in terms of power flow.**

***Index Terms*—Holistic planning, mixed-integer optimisation, transmission grid planning, distribution grid planning, demand flexibility, storage, hvdc.**

I. INTRODUCTION

The need for decarbonising the electricity system and the inherent increase in renewable generation requires massive investments into electricity transmission and distribution grids in the near future. According to the European Commission, $800\,\text{G€}$ worth of investments are needed for boosting the offshore renewable generation by 2050, of which two thirds are expected to be grid infrastructure investments [1]. Similarly, according to Eurelectric, distribution grid investments of $375 \div 475\,\text{G€}$ are required, in order to facilitate the utilisation of distributed generation, electrification of transport and domestic heat demand [2]. More importantly, ENTSO-E states that annual network investments of $1.3\,\text{G€}$ could facilitate the decrease of power generation costs by $4\,\text{G€}$ per year [3], demonstrating that grid expansion is inevitable for affordable energy supply in the future.

The use of flexibility in form of demand flexibility, storage, or power flow control through High Voltage Direct Current (HVDC) links can help to decrease the need for classical grid expansion and achieve significant cost savings considering the large investment volumes projected. Considering the difficulties for obtaining permissions for large infrastructure projects, making use of flexibility becomes even more important.

In order to find the necessary trade-offs between classical grid investment – into both transmission and distribution networks – and sources of flexibility, a holistic planning model is needed. Although many transmission expansion optimisation models exist in the literature, to the best of our knowledge there are no tractable implementations of the problem, which can consider all layers of the network, and a large uncertainty set to represent future operation conditions with respect to renewable generation and demand.

The aim of the *FlexPlan* project is to tackle this issue, by providing a comprehensive planning model [4]. Within the project, a chain of tools have been developed for creating realistic planning scenarios, for determining the location and size of expansion candidates, and to perform the planning optimisation. Within the tool-chain, *FlexPlan.jl* builds the rapid prototyping platform that has been developed to test different problem formulations, equipment and flexibility models, and solution approaches [5]. At the same time *FlexPlan.jl* provides a reference implementation to the cloud-based planning tool developed within *FlexPlan* [6]. *FlexPlan.jl* has been released as a registered open-source Julia package under BSD 3-Clause License.

The next section describes the design specifications of *FlexPlan.jl* as a rapid prototyping platform for grid planning. In Section III, the scope of the planning model is described, outlining the model structure, component and network models. Further, in Section IV, a novel approach to decompose transmission and distribution grid planning models is shown, which provides accurate results with significant improvement of computation time with respect to the combined model. Finally, Section V draws the main conclusions and provides directions for future work.

II. Design specifications of FlexPlan.jl

The aim of *FlexPlan.jl* is to perform holistic, sequential network planning considering a large number of uncertainties with respect to power generation and demand. Although stiff and dedicated implementations provide higher efficiency, for *FlexPlan.jl* our goal was to find a trade-off between code flexibility for easy extension and rapid prototyping on the one hand, and still being computationally efficient on the other. This has lead to the following design specifications:

1) Compatibility with different optimisation solvers: Considering that extensions of the model might result in different mathematical complexity classes, the implementation should allow to easily switch the used optimisation solver. As such, we have chosen a Julia/JuMP based implementation [7], [8].

2) Extendability towards new problem types, component models and power flow formulations: Although the provided implementation focuses currently on one dedicated problem type and a given set of equipment, in the future, planning models with different objectives and other types of technologies should be easily implementable within the model for rapid prototyping. Therefore we have chosen to use the *PowerModels.jl* [9] framework as basis for *FlexPlan.jl*.

3) Supporting sequential, stochastic planning models: This requires a number of auxiliary functions in order to keep track of different planning scenarios, planning years, e.g. sequences, and the renewable-based and demand resources time series defined within each planning year and scenario. The provided implementation allows to specify any number and combination of the above mentioned model dimensions, and thus allows to solve deterministic, stochastic or robust planning problems.

4) Allowing to use different power flow formulations for transmission and distribution grids in the same optimisation problem: The provided implementation offers the possibility to choose the power flow formulations separately for transmission and distribution grids, which allows to solve both planning problems separately or together, similarly as presented in [10]. Although to date all implemented models are linear, in the future these could be extended to combinations of different complexity classes such as quadratic or conic formulations as well.

III. Description of the generic planning model

The outline of the optimisation model implemented in *FlexPlan.jl* is provided in Fig. 1. In general, the optimisation model uses three sets of inputs. Firstly, the grid data for the existing transmission and distribution networks are required. The data models of [9] and [12] are used to represent AC and DC grids respectively. Secondly, a list of candidate grid expansion options need to be provided, namely candidate AC and DC grid extensions, demand flexibility and storage investments from which the optimal subset is determined. Lastly, as planning scenarios, a number of renewable generation and demand time series are required, defined per generator and per load. The length of the time series can be determined by the user. For sequential planning, the time series can be defined for multiple planning years. Further, multiple sets of time series

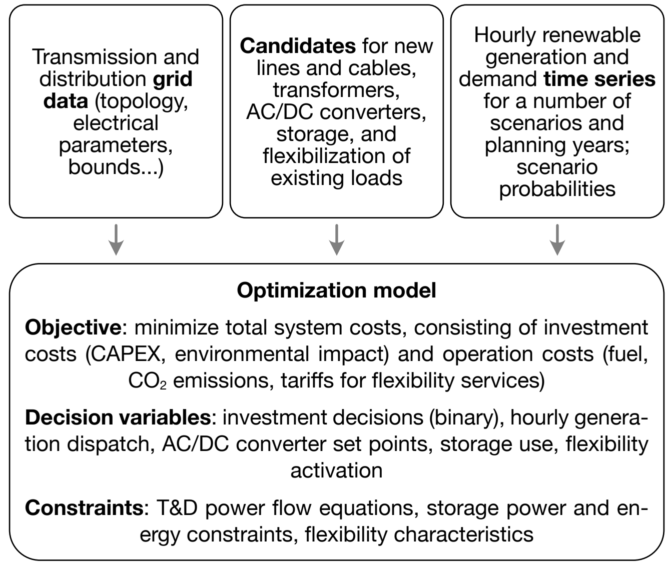

Fig. 1. The outline of the *FlexPlan* model based on [11].

can be defined for each planning year to represent climatic variations, allowing to perform stochastic optimisation. To that end, the probabilities for the different "climate years", which feature different possible profiles for demand and non-dispatchable power units, need to be defined. For the detailed description of the data model the readers are referred to the definitions in [13] and the examples available in [5].

A. Objective function

The objective function of the planning model considers the maximisation of the social welfare by formulating it as a cost minimisation problem. To that end, the cost of investments related to grid expansion (capital expenditure, CAPEX) and the cost related to operation such as generation and demand flexibility (operational expenditure, OPEX) are minimized:

$$\min \sum_{y \in \mathcal{Y}} \left([\text{CAPEX}]_y + \sum_{s \in \mathcal{S}} \pi_s \sum_{t \in \mathcal{T}} [\text{OPEX}]_{t,s,y} \right) \tag{1}$$

Here, $\mathcal{T}$ is the set of operation periods, whereas $\mathcal{Y}$ is the set of investment periods ("planning years"). The stochastic dimension is introduced by weighting the operation cost of each possible scenario $s \in \mathcal{S}$ with its probability π_s, such that the optimization process returns a unique set of investment decisions with the statistically highest benefits in terms of total costs containment.

Investment costs are computed as

$$\begin{aligned}[\text{CAPEX}]_y = & \sum_{c \in S^{cc}} C^{cc}_{c,y} \alpha^{cc}_{c,y} + \sum_{d \in S^{dc}} C^{dc}_{d,y} \alpha^{dc}_{d,y} + \\ & + \sum_{a \in S^{ac}} C^{ac}_{a,y} \alpha^{ac}_{a,y} + \sum_{b \in S^{bc}} C^{bc}_{b,y} \alpha^{bc}_{b,y} + \\ & + \sum_{l \in S^{lf}} C^{lf}_{l,y} \alpha^{lf}_{l,y}\end{aligned} \tag{2}$$

where $C^{*}_{\cdot,y}$ represent cost parameters and $\alpha^{*}_{\cdot,y}$ are binary investment decision variables. The model accounts for investments in grid expansion elements: DC converters (S^{cc}); DC branches (S^{dc}); AC branches (S^{ac}) such as lines, cables, and transformers; storage devices (S^{bc}); as well as for the flexibilization (S^{lf}) of existing loads.

Operation costs are defined by

$$
\begin{aligned}
[\text{OPEX}]_{t,s,y} = & \sum_{g\in S^{gd}} C^{g}_{g,t,s,y} P^{g}_{g,t,s,y} + \\
& + \sum_{g\in S^{gn}} C^{gcurt}_{g,t,s,y} P^{gcurt}_{g,t,s,y} + \sum_{l\in S^{l}\cup S^{lf}} C^{lcurt}_{l,t,s,y} P^{lcurt}_{l,t,s,y} + \\
& + \sum_{l\in S^{lf}} \left(C^{lred}_{l,t,s,y} P^{lred}_{l,t,s,y} + \frac{C^{lsh}_{l,t,s,y}}{2} \left(P^{lshup}_{l,t,s,y} + P^{lshdn}_{l,t,s,y} \right) \right)
\end{aligned}
\tag{3}
$$

where $C^{*}_{\cdot,t,s,y}$ are cost parameters and $P^{*}_{\cdot,t,s,y}$ are continuous decision variables representing per-unit power. Dispatchable generators $g \in S^{gd}$ are accounted for production (g), whereas non-dispatchable generators $g \in S^{gn}$ can be curtailed ($gcurt$). Loads $l \in S^{lf}$ can provide flexibility services – namely, up- ($lshup$) and downward ($lshdn$) demand shifting (lsh), and voluntary reduction ($lred$) – upon investment decision $\alpha^{lf}_{l,y}$. The set S^{l}, instead, represents loads that cannot provide flexibility services. Both types of load can be curtailed ($lcurt$).

In order to consider the environmental impact, the carbon footprint costs and the landscape impact can be included in the investment cost, whereas the CO_2 emission costs can be included in the power generation cost. Details for the calculation of the environmental costs can be found under [13]. To quantify landscape impact related costs, [14] provides an open-source tool based on the algorithm described in [15].

B. Component and network models

For the sake of brevity, in the following paragraphs we are only briefly describing the component and network models. References for the modelling details are provided at the appropriate locations.

1) HVDC lines, branches and converters: The HVDC substation and grid models are based on [12]. The substations and DC branches are modelled separately in order to allow the modelling of meshed DC grids. The substation model includes converter transformers, reactive and capacitive filters, and a lossy power electronic converter model. DC branches are defined to connect a pair of DC nodes. Although different power flow models have been proposed in [12], to keep the model linear, a network flow model is used for DC branches. As for the DC converter substations, the linearised "DC power flow" formulation is chosen. One of features of the model is the possibility to define candidate DC nodes for modelling DC connections between DC nodes that might not yet exist, and also to allow intermediate tappings within DC interconnectors, which is useful for modelling hybrid offshore assets.

2) AC lines, cables and transformers: A generic π-section model is used to represent AC branches in general as provided in [9]. For AC lines, cables and power transformers, the model allows the inclusion of phase angle and voltage taps as fixed parameters, whereas the voltage taps of on-load tap changers in distribution networks are modelled as continuous variables.

3) Generators modelling: The power produced by dispatchable generators $g \in S^{gd}$ is bounded by a parameter: $P^{g}_{g,t,s,y} \in [0, P^{g,max}_{g,t,s,y}]$. Non-dispatchable generators $g \in S^{gn}$, instead, have an input reference power $P^{gref}_{g,t,s,y}$ and can be curtailed, so their produced power is

$$
P^{g}_{g,t,s,y} = P^{gref}_{g,t,s,y} - P^{gcurt}_{g,t,s,y} \tag{4}
$$

where the curtailed power is bounded: $P^{gcurt}_{g,t,s,y} \in [0, P^{gref}_{g,t,s,y}]$.

4) Storage modelling: Existing ($b \in S^{b}$) and candidate ($b \in S^{bc}$) storage is modelled as a realistic lossy storage device. The state equation

$$
\begin{aligned}
E_{b,t,s,y} = & (1-\lambda_b)^{\Delta t} E_{b,t-1,s,y} + \\
& + \Delta t \left(\eta^{abs}_{b} P^{abs}_{b,t,s,y} - \frac{P^{inj}_{b,t,s,y}}{\eta^{inj}_{b}} + \xi_{b,t,s,y} \right)
\end{aligned}
\tag{5}
$$

computes the energy $E_{b,t,s,y} \in [0, E^{max}_{b}]$ at end of operation period t from the energy at the previous period depending on: the self-discharge rate $\lambda_b \in (0,1)$; the absorbed/injected power $P^{abs}_{b,t,s,y} \in [0, P^{abs,max}_{b,t,s,y}]$ and $P^{inj}_{b,t,s,y} \in [0, P^{inj,max}_{b,t,s,y}]$, which are optimization variables; the absorption/injection efficiencies $\eta^{abs}_{b} \in (0,1)$ and $\eta^{inj}_{b} \in (0,1)$; and the *external process* $\xi_{b,t,s,y}$, an input parameter representing changes in stored energy (e.g. rain flow and spillage for hydro reservoirs). Energy levels E^{init}_{b} and E^{final}_{b} at the boundaries of the optimization horizon are input parameters. Regardless of technology (synchronous machine or inverter-based), storage devices are assumed to be capable of providing reactive power support. Although only active power is modelled in the transmission system, the modelling of reactive power is essential in distribution grid planning problems as outlined in Section III-B6.

5) Demand flexibility modelling: The non-negative demand of loads, used in the nodal power balance equations as outlined in Section III-B6, is computed as

$$
P^{lflex}_{l,t,s,y} = P^{lref}_{l,t,s,y} + P^{lshup}_{l,t,s,y} - P^{lshdn}_{l,t,s,y} - P^{lred}_{l,t,s,y} - P^{lcurt}_{l,t,s,y} \tag{6}
$$

for loads $l \in S^{lf}$, and as

$$
P^{lflex}_{l,t,s,y} = P^{lref}_{l,t,s,y} - P^{lcurt}_{l,t,s,y} \tag{7}
$$

for loads $l \in S^{l}$. The reference demand parameter $P^{lref}_{l,t,s,y} \geq 0$ gives the base profile, which is time- and scenario-dependent. The flexibility variables introduced in (3) are all bounded by parameters that can be adapted by the user depending on the load characteristics: $P^{lshup}_{l,t,s,y} \in [0, P^{lshup,max}_{l,t,s,y}]$, $P^{lshdn}_{l,t,s,y} \in [0, P^{lshdn,max}_{l,t,s,y}]$, and $P^{lred}_{l,t,s,y} \in [0, P^{lred,max}_{l,t,s,y}]$.

It is assumed that demand shifting is re-balanced every T^{r} periods, that is, for every $\tau \in \mathcal{T}$ such that $\mod(\tau, T^{r}) = 0$:

$$
\sum_{t=\tau-T^{r}+1}^{\tau} \left(P^{lshup}_{l,t,s,y} - P^{lshdn}_{l,t,s,y} \right) = 0. \tag{8}
$$

6) Network power flow formulations: To represent meshed AC/DC transmission grids, the well known linearised "DC power flow" approach is used. Note that due to the choice of the linearised power flow model, the DC grid power flows transpose to a network flow model as stated in [12]. Although this introduces some inaccuracy, considering that meshed HVDC networks are not that wide-spread, the effect on the overall network will be rather limited. Separate binary investment decision variables have been used for AC branches, DC branches and DC converters, allowing to define a large variety of expansion candidates and thus different grid topologies. Concerning distribution networks, active power exchange of local demand and generation has a significant impact on the voltage because of the higher R/X ratio of lines and cables. This means that, in addition to power transport capacity, voltage limits can likely represent a bottleneck against load and generation increase. As such, the application of the "DC power flow" approach would not allow to investigate the effects of voltage congestion. To that end, we have chosen to use the *simplified DistFlow* model [16] to represent distribution networks. Under the assumptions that the grid is operated radially and active/reactive power losses are reasonably small, the selected linear formulation is demonstrated to be a good approximation of the exact power flow formulation. Furthermore, in order to consider power transfer capacity of distribution lines and transformers without neglecting the impact of reactive power flows, the apparent-power circular-constraint is linearized by means of a convex polygon (inscribed regular octagon).

Within the software implementation, both transmission and distribution grid expansion models can be used either independently, or as a combined model where both power flow formulations are accommodated at the same for the transmission and distribution grids respectively. Note that when the transmission and distribution grids are optimised together, due to the nature of the power flow models, the coupling between the networks will only be based on the active/reactive power injections, instead of through voltage magnitudes and/or angles as one would expect in a typical power flow model. Considering that typically a large number of distribution networks are connected to a single node of the meshed transmission grid (typically up to 8 medium voltage feeders per HV/MV substation), to keep the tractability of the model, a novel decomposition method relying on surrogate models has been developed, which is described in the next section.

IV. T&D DECOMPOSITION USING SURROGATE MODELS

Planning of Transmission and Distribution (T&D) networks can be accomplished in two ways using *FlexPlan.jl*. Using the *combined model*, introduced hereafter, the two grid levels are coupled and the model is solved in a "conventional way". The other method is the *decoupling heuristic*, explained in Section IV-B: it is a heuristic algorithm for decoupling the two network levels that exploits *surrogate models* of distribution networks to solve independent optimization problems for transmission and distribution networks. The two methods are compared in Section IV-C.

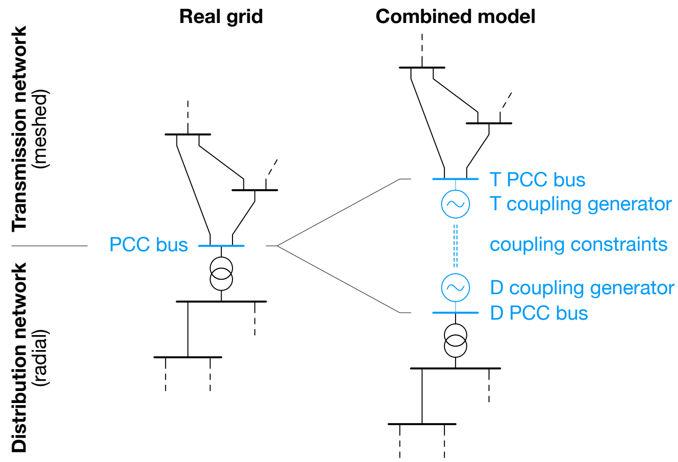

Fig. 2. Coupling of the transmission network and a distribution network using the combined model.

A. Combined model

In the combined model, coupling is implemented by splitting the network at the Points of Common Coupling (PCCs) of transmission and distribution as shown in Fig. 2. Firstly, PCC buses are duplicated, each copy retaining only connections to either transmission or distribution network components. Then, a *coupling generator*, having zero cost and a rectangular symmetric PQ capability sized according to the rated power of the connected HV/MV transformers, is attached to each PCC bus copy. Finally, coupling constraints are defined in the model to link the power exchanged by the two generators. Equality constraints are added for balancing active and reactive power, if applicable. If reactive power is only supported by distribution grid's power flow model, reactive power exchanged with transmission can be bounded in a given interval.

The approach for coupling the two grid levels through generators and coupling constraints has been chosen because of its versatility. As it only involves standard network components, the complexity classes of the power flow models for transmission and distribution can be changed at any time without requiring adaptations to the model itself. Coupling via a dedicated bus, on the other hand, would have required the user to write a custom bus power balance equation for the specific pair of power flow models they intended to use.

B. Decoupling heuristic

Based on the idea that a better computational performance can be expected by solving a number of small problems instead of a single, very large problem, a heuristic procedure that decouples the two network levels has been devised and implemented in order to reduce memory requirements and computation time of the combined transmission and distribution network expansion planning problem. The better computational performance is obtained at the expenses of the optimality guarantee on investment decisions, since the proposed heuristic relies on the definition of an approximated surrogate model for each distribution network, the purpose of which is

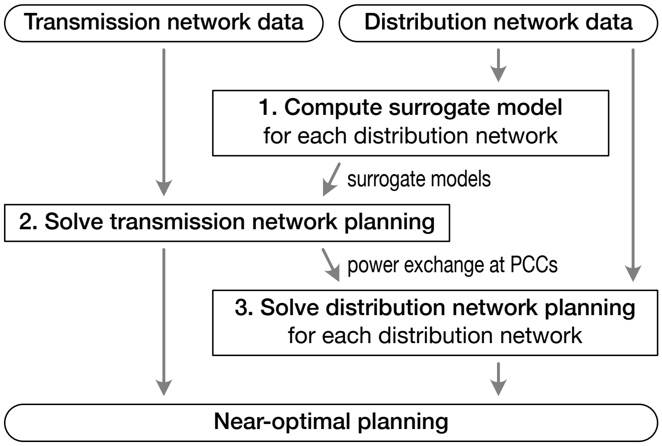

Fig. 3. Diagram of the decoupling heuristic.

to model the potential active power capabilities at the HV/MV substations with a limited amount of parameters. Nevertheless, this approximation can be considered a good representation of the limitations (and related sub-optimal solutions) imposed by the coordination challenges between transmission and distribution system operators in terms of information exchange. More detail on the motivation is provided in [17], which also describes a preliminary version of the heuristic.

The heuristic can be applied to any T&D network as an alternative to the combined model, provided that all generators at distribution level are non-dispatchable, which is largely the case for renewables.

1) Decoupling heuristic overview: The procedure is composed by three stages (Fig. 3).

In the first stage, a *surrogate model* is computed for each distribution network, which reduces the distribution network to a single bus representation consisting of one aggregated generator, one aggregated flexible load and one aggregated storage device. The surrogate model is aimed at capturing time- and scenario-dependent information about the feasible active power exchange between transmission and distribution networks, and the flexibility that the distribution network is able to provide to transmission. Details on how the surrogate model is computed are provided further below.

In the second stage, the surrogate models of distribution networks are attached to the respective transmission system buses; then, the transmission network expansion planning problem is solved. This returns the optimal solution from the perspective of the transmission grid and provides the expected power exchange between transmission and distribution networks.

In the third and last stage, after fixing the power exchange between transmission and distribution grids as resulting from previous stage, the optimal expansion plan of the distribution grid is determined using the full network model. This provides eventually the optimal solution from the distribution grid point of view.

2) Surrogate model construction: The surrogate model of a distribution network is itself the result of another heuristic

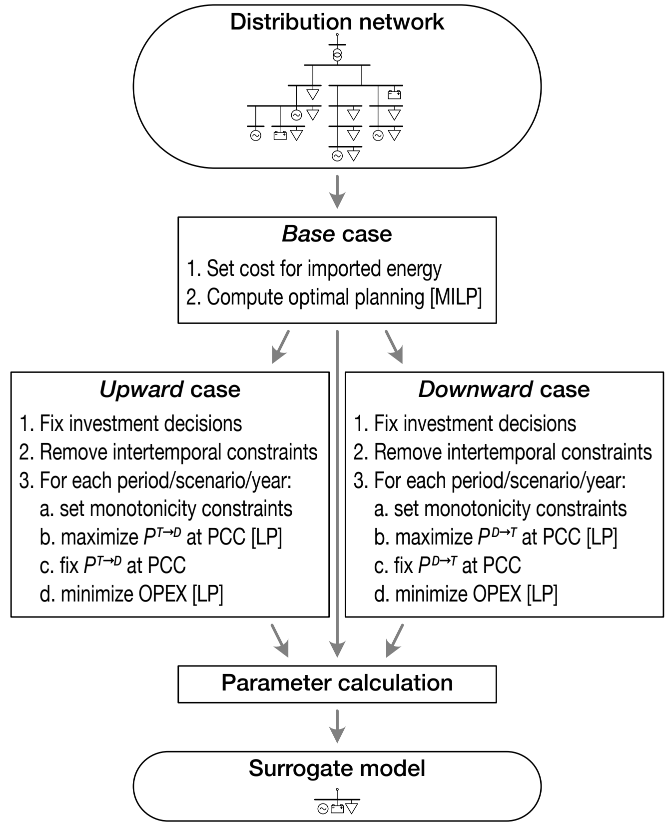

Fig. 4. Diagram summarizing the computation of the surrogate model of a distribution network.

procedure, outlined in Fig. 4, that compares the network under three different conditions – named *base case*, *upward case*, and *downward case* hereinafter – and perform simple algebraic calculations.

a) Base case: Starting from the observation that local congestion can only be solved by acting locally, the underlying idea is that the surrogate model should incorporate the investments needed to solve congestion in the distribution network – provided that enough investment candidates are supplied as input – while enabling transmission to exploit the distribution grid's residual flexibility. To that end, distribution network expansion planning is solved considering a constant cost for the energy exchanged with transmission. The optimal solution of this problem, referred to as the *base case*, provides an initial hypothesis for the utilization of distributed resources, the required investments to prevent network congestion, and a reference value $P_{t,s,y}^{pcc,base}$ for the power exchanged between transmission and distribution at PCC, with a positive value indicating power flow towards distribution). To simplify notation, we define $S_y^{b\cup bc,base} = S^b \cup \left\{ b \in S^{bc} : \alpha_{b,y}^{bc,base} = 1 \right\}$ (the set of existing and deployed candidate storage devices), $S_y^{lf,base} = \left\{ l \in S^{lf} : \alpha_{l,y}^{lf,base} = 1 \right\}$ (the set of deployed flexible loads), and $S_y^{l\cup lf,base} = S^l \cup S_y^{lf,base}$.

b) Upward case: The objective of the *upward case* is to evaluate the maximum amount of power that can be transferred from the transmission network to the distribution network in each operation period, independent of the others, using the same investments as in the *base case*. To compute the *upward case*, investment decisions are first fixed and intertemporal constraints are removed from the model. Then, the following steps are carried out for each $t \in \mathcal{T}$, $s \in \mathcal{S}$, and $y \in \mathcal{Y}$:

1) Additional monotonicity constraints are set on the power exchanged by each resource to prevent them from absorbing less or generating more than in the *base case*:

$$\forall g \in S^{gn} \qquad P^{g}_{g,t,s,y} \leq P^{g,base}_{g,t,s,y} \tag{9}$$

$$\forall b \in S^{b \cup bc,base}_{y} \qquad P^{abs}_{b,t,s,y} - P^{inj}_{b,t,s,y} \geq P^{abs,base}_{b,t,s,y} - P^{inj,base}_{b,t,s,y} \tag{10}$$

$$\forall l \in S^{l \cup lf,base}_{y} \qquad P^{flex}_{l,t,s,y} \geq P^{flex,base}_{l,t,s,y} \tag{11}$$

$$\forall l \in S^{lf,base}_{y} \qquad P^{lshup}_{l,t,s,y} \geq P^{lshup,base}_{l,t,s,y} \tag{12}$$

2) The power exchange at PCC from transmission to distribution ($P^{pcc,up}_{t,s,y}$) is maximized.

3) The power exchange at PCC is fixed to $P^{pcc,up}_{t,s,y}$.

4) The operation cost $[\mathrm{OPEX}]_{t,s,y}$ is minimized to identify a realistic operating point among those producing the maximum power exchange.

c) Downward case: The *downward case* is similar to the *upward case*, but the opposite direction is considered for the power exchange at PCC, i.e., from distribution to transmission ($P^{pcc,dn}_{t,s,y}$). The monotonicity constraints to be added are:

$$\forall g \in S^{gn} \qquad P^{g}_{g,t,s,y} \geq P^{g,base}_{g,t,s,y} \tag{13}$$

$$\forall b \in S^{b \cup bc,base}_{y} \qquad P^{abs}_{b,t,s,y} - P^{inj}_{b,t,s,y} \leq P^{abs,base}_{b,t,s,y} - P^{inj,base}_{b,t,s,y} \tag{14}$$

$$\forall l \in S^{l \cup lf,base}_{y} \qquad P^{flex}_{l,t,s,y} \leq P^{flex,base}_{l,t,s,y} \tag{15}$$

$$\forall l \in S^{lf,base}_{y} \qquad P^{lshdn}_{l,t,s,y} \geq P^{lshdn,base}_{l,t,s,y} \tag{16}$$

$$\forall l \in S^{lf,base}_{y} \qquad P^{lred}_{l,t,s,y} \geq P^{lred,base}_{l,t,s,y} \tag{17}$$

d) Parameter calculation: The surrogate model consists of one generator, one storage device and one flexible load, the parameters of which are computed – as detailed below – in such a way that if the power exchange between transmission and distribution networks is feasible according to the surrogate model, it is also feasible according to the full distribution network model. To ensure this, two assumptions are introduced. The first is the *independence assumption*, which requires that the three components are connected to the same transmission HV bus and are used independently of each other during the second stage of the decoupling heuristic (planning of transmission network). This may necessitate reducing their rated power in some optimization periods so that their combined use at full power results in a feasible power exchange according to the full distribution network model. The second assumption is the *monotonicity assumption*, which requires that the variations in injected/absorbed power of each component of the full distribution model have the same sign when maximising the power exchange at PCC. This assumption is enforced by the monotonicity constraints (9)–(17) added to the *upward* and *downward* cases, and is necessary to produce comparable

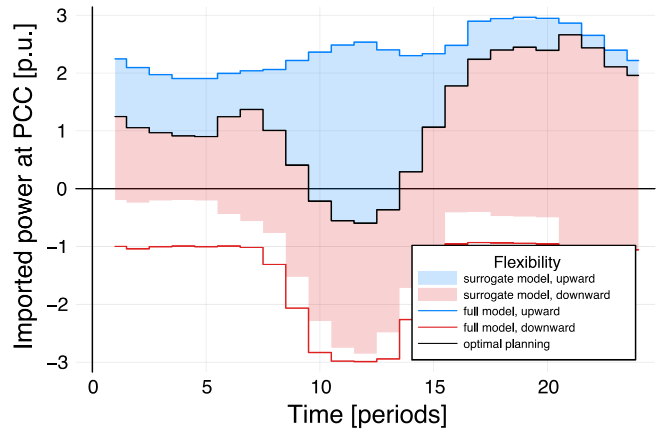

Fig. 5. A comparison of the single-period flexibility provided by a sample distribution network for a given scenario and year is presented in the figure. The single-period flexibility as resulting from the surrogate model is delimited by the filled areas, which represent the feasible combined power exchange of the generator, storage device and flexible load constituting the surrogate model. The single-period flexibility of the full distribution network model is given by the straight lines at top/bottom. The difference in the downward capability of the two models is mainly due to the independence assumption, whereas the barely noticeable difference in the upward capability (periods $18 \div 20$) is due to the monotonicity assumption.

results in the algebraic calculations reported below. Due to the above assumptions, the *single-period flexibility* – i.e., the flexibility that can be provided without considering the intertemporal constraints – of the surrogate model may not completely cover the one attainable with the full network model. As a result, the surrogate model provides a conservative approximation of the distribution grid's active power capability at PCC (Fig. 5).

The storage device's parameters are:

$$P^{abs,max}_{t,s,y} = \min \Bigg\{ \sum_{b \in S^{b \cup bc,base}_{y}} \Big(P^{abs,up}_{b,t,s,y} - P^{inj,up}_{b,t,s,y} + - P^{abs,base}_{b,t,s,y} + P^{inj,base}_{b,t,s,y} \Big), P^{pcc,up}_{t,s,y} \Bigg\} \tag{18}$$

$$P^{inj,max}_{t,s,y} = \min \Bigg\{ \sum_{b \in S^{b \cup bc,base}_{y}} \Big(P^{abs,base}_{b,t,s,y} - P^{inj,base}_{b,t,s,y} + - P^{abs,dn}_{b,t,s,y} + P^{inj,dn}_{b,t,s,y} \Big), -P^{pcc,dn}_{t,s,y} \Bigg\} \tag{19}$$

$$\eta^{abs} = \max_{b \in S^{b \cup bc,base}_{y}} \eta^{abs}_{b} \tag{20}$$

$$\eta^{inj} = \max_{b \in S^{b \cup bc,base}_{y}} \eta^{inj}_{b} \tag{21}$$

$$E^{max} = \sum_{b \in S^{b \cup bc,base}_{y}} E^{max}_{b} \tag{22}$$

$$E^{init} = \sum_{b \in S^{b \cup bc,base}_{y}} E^{init}_{b} \tag{23}$$

$$E^{final} = \sum_{b \in S^{b \cup bc,base}_{y}} E^{final}_{b} \tag{24}$$

$$\lambda = \min_{b \in S_y^{b\cup bc,base}} \lambda_b \tag{25}$$

$$\xi_{t,s,y} = \sum_{b \in S_y^{b\cup bc,base}} \Bigg(\eta_b^{abs} P_{b,t,s,y}^{abs,base} + - \frac{1}{\eta_b^{inj}} P_{b,t,s,y}^{inj,base} + \xi_{b,t,s,y} \Bigg) \tag{26}$$

Note that $P_{t,s,y}^{abs,max}$ and $P_{t,s,y}^{inj,max}$, representing the maximum power that can be simultaneously absorbed/injected by teh distribution network's storage devices, are computed from the optimal solution of the three cases, and not simply by summing the rated power values of the individual storage devices. This approach accounts for potential bottlenecks in the distribution grid. Additionally, the external process $\xi_{t,s,y}$ considers the expected usage of storage devices by the distribution network, enabling an estimation of the total energy that could be used to provide flexibility services to the transmission network.

The flexible load's parameters are:

$$P_{t,s,y}^{lshup,max} = \min \Bigg\{ \sum_{l \in S_y^{lf,base}} \Big(P_{l,t,s,y}^{lshup,up} + - P_{l,t,s,y}^{lshup,base} \Big), P_{t,s,y}^{pcc,up} - P_{t,s,y}^{abs,max} \Bigg\} \tag{27}$$

$$P_{t,s,y}^{lshdn,max} = \sum_{l \in S_y^{lf,base}} \Big(P_{l,t,s,y}^{lshdn,dn} - P_{l,t,s,y}^{lshdn,base} \Big) \tag{28}$$

$$P_{t,s,y}^{lred,max} = \sum_{l \in S_y^{lf,base}} \Big(P_{l,t,s,y}^{lred,dn} - P_{l,t,s,y}^{lred,base} \Big) \tag{29}$$

$$P_{t,s,y}^{lref} = \min \big\{ P_{t,s,y}^{pcc,up} - P_{t,s,y}^{abs,max} - P_{t,s,y}^{dshup,max}, P_{t,s,y}^{pcc,base} - P_{t,s,y}^{pcc,dn} - P_{t,s,y}^{inj,max} \big\} \tag{30}$$

$$C_{t,s,y}^{lsh} = \min_{l \in S_y^{lf,base}} C_{l,t,s,y}^{lsh} \tag{31}$$

$$C_{t,s,y}^{lred} = \min_{l \in S_y^{lf,base}} C_{l,t,s,y}^{lred} \tag{32}$$

$$C_{t,s,y}^{lcurt} = \min_{l \in S_y^{l\cup lf,base}} C_{l,t,s,y}^{lcurt} \tag{33}$$

The non-dispatchable generator's parameters are:

$$P_{t,s,y}^{gref} = P_{t,s,y}^{lref} - P_{t,s,y}^{pcc,base} \tag{34}$$

$$C_{t,s,y}^{gcurt} = \min_{g \in S^{gn}} C_{g,t,s,y}^{gcurt} \tag{35}$$

Note that the surrogate model derived here is solely utilized in the second stage of the decoupling heuristic (planning of transmission network). It only affects the usage of transmission resources and, consequently, the power exchange at PCCs (the output of second stage). In contrast, the planning of the distribution networks – including both investments and operation – is carried out using the full distribution model.

C. Experimental results

The decoupling heuristic offers two main benefits. Firstly, it significantly reduces the amount of memory required for the optimization process, which makes it possible to handle larger expansion planning problems on the same hardware. Secondly, it can provide a considerable speed-up, up to two orders of magnitude, depending on the relative size of the transmission and distribution parts of the grid.

TABLE I
PERFORMANCE COMPARISON OF COMBINED MODEL AND DECOUPLING HEURISTIC

N_d	binary variables	CPU time			relative cost increase
		combined model [s]	decoupling heuristic [s]	ratio	
case67 with N_d IEEE33 distribution networks					
1	83	38	21	**0.553**	$-1.1{\cdot}10^{-5}$
4	158	148	25	**0.169**	$6.0{\cdot}10^{-7}$
16	458	1139	41	**0.036**	$1.4{\cdot}10^{-6}$
64	1658	4228	87	**0.021**	$6.6{\cdot}10^{-5}$
case67 with N_d CIGRE MV distribution networks					
1	88	39	23	**0.590**	$-5.3{\cdot}10^{-15}$
4	178	79	20	**0.253**	$6.2{\cdot}10^{-5}$
16	538	210	30	**0.143**	$5.3{\cdot}10^{-15}$
64	1978	6479	59	**0.009**	$4.1{\cdot}10^{-4}$

To evaluate the effectiveness of the decoupling heuristic, we composed a T&D system by attaching a variable amount $N_d \in \{2^0, \dots, 2^6\}$ of distribution networks (either *IEEE33* or *CIGRE MV*) to a transmission network (specifically, *case67*, an AC/DC grid having 67 AC buses) on different buses.[1] We then solved a 48-period planning problem.[2]

The results presented in Table I demonstrate that the improvement in speed becomes more significant as the amount of distribution networks connected to the transmission system increases. Additionally, the achieved results are nearly optimal in terms of the optimality gap with respect to the combined model. In our tests, the relative increase in solution cost – that is, the error in comparison to the optimal solution of the combined model – returned by the decoupling heuristic never exceeded the solver's optimality tolerance setting by more than 5 times.

Finally, we further analyzed the quality of solution of the two test cases with the highest amount of distribution networks ($N_d = 64$). We recorded the power exchanged at PCCs for each period t and distribution network n and divided the values by the rated power of the respective primary substation, thus obtaining two series of values $p_{PCC}^{heuristic}(t,n)$ and $p_{PCC}^{combined}(t,n)$ ranging in $[-1,+1]$. Their difference $p_{PCC}^{heuristic}(t,n) - p_{PCC}^{combined}(t,n)$ is close to zero: the interquartile range of the distribution is well below $2\,\%$ (Fig. 6). This indicates that the decoupling heuristic provides solutions that are similar to those obtained with the combined model, even in terms of power flow.

[1] Network data and stochastic time series used in these tests are published in *FlexPlan.jl*'s repository.

[2] Solver: CPLEX, with an $1{\cdot}10^{-4}$ relative optimality tolerance. Hardware: desktop PC with an Intel Core i7-9700 (3 GHz, 8 cores) CPU and 64 GB RAM.

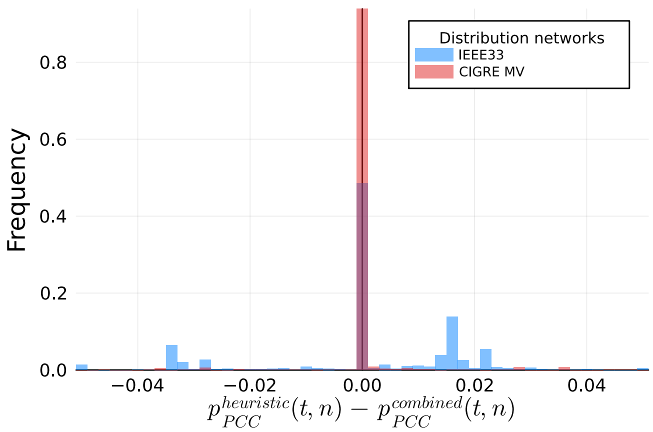

Fig. 6. Distribution of $p_{PCC}^{heuristic}(t,n) - p_{PCC}^{combined}(t,n)$ in $[-0.05, 0.05]$ (for CIGRE MV networks, $8\,\%$ of the samples are outside the represented interval). When using CIGRE MV as distribution networks, the interquartile range is 0.015 (0 with IEEE33 networks) and the $1\,\%$ trimmed range is 0.41 (0.08 with IEEE33 networks).

V. Conclusions

FlexPlan.jl provides an extendable, customizable and solver-independent software library for holistic planning of transmission and distribution grids, considering the trade-off between demand flexibility and traditional grid expansion. Transmission and distribution networks can be co-optimized using the combined model, and the planning problem for very large power systems can be solved efficiently by using the proposed decoupling heuristic.

Due to the flexible design of the library, *FlexPlan.jl* allows to experiment with different power flow and component models, as well as problem types, and as such *FlexPlan.jl* can be used for rapid prototyping of future grid planning tools. Included visualization capabilities (Fig. 7) enable easier interpretation of the planning outcomes.

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Fig. 7. Sample visualizations of planning results produced with *FlexPlan.jl*, using data from the repository.

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