11029 Session 2022
C1 Power System Development and Economics
PS2 – Energy sector integration and tackling the complexity of multi-faceted network projects

Storage and Demand Response inclusion in the network extension planning process

Raúl RODRÍGUEZ-SÁNCHEZ*
TECNALIA R&I (BRTA)
Spain
raul.rodriguez@tecnalia.com

Santiago GARCÍA-LÁZARO
TECNALIA R&I (BRTA)
Spain
santiago.garcialazaro@tecnalia.com

Gianluigi MIGLIAVACCA
RSE SpA
Italy
gianluigi.migliavacca@rse-web.it

Dario SIFACE
RSE SpA
Italy
dario.siface@rse-web.it

SUMMARY

The increasing participation of variable wind and solar energy production plants in the power system requires flexibility from other resources, such as fast reacting generation assets, storage and demand response. Storage, other than pumped-storage hydropower, and demand response have not been considered in traditional network planning procedures, but they are expected to play a bigger role in the operation of power systems in the future.
In the frame of the EU FlexPlan R&D project (https://flexplan-project.eu/) an innovative network planning methodology is proposed, where flexibility resources are presented as candidates for network planning, competing with conventional network assets. The candidate pre-selection is carried out by a specific software tool developed to interact automatically with the main planning tool.
The consideration of relatively small size flexibility resources in the planning process, along with other aspects such as the environmental impact, the reliability, various scenarios and the interaction between distribution and transmission network operation, makes challenging the formulation and solution of the optimization function. Therefore, a pre-section of network extension candidates contributes to reduce the dimension of the mathematical problem.
The flexibility resources analysis is performed by the candidate pre-processor through the following steps:

- Network lines and transformers potentially affected by congestion are identified after performing an optimal power flow (OPF) simulation in the non-expanded network. The network model is evaluated under several generation and load scenarios. A ranking of congested branches is proposed based on hourly Lagrange multipliers' (LM) values.

- The flexibility resources analysis tool (pre-processor) proposes a list of network expansion candidates for identified congested assets, including storage (Li-ion, NaS and flow batteries, hydrogen, CAES and LAES), demand response (DR), and lines/cables/transformers. This selection is performed based on congestion characteristics and on possible location-related constraints. Cost and size details are provided related to the technology of each selected candidate.
- Eventually, the proposed candidates for grid congestion support are provided to the planning tool as input, which, in turn, assesses the best planning option for the power system in the time frame of the study.

Before proposing the candidate technologies, locational constraints and bus characteristics are checked. The network information provided for relevant nodes is used to discard, or not, some of the candidate technologies: urban substations, restricted areas, or the inexistence of loads, for example, already make some of them unfeasible. The characteristics of the congestion, such as the number of congestion hours in one year or the number of consecutive congestion hours are also an input for the selection of candidate technologies. A set of rules is predefined at the pre-processor to perform the assessment.

Once the most suitable technologies have been selected, the pre-processor estimates and provides a size and cost for each of them.

KEYWORDS

Storage - Demand Response – Electricity Network - Planning - Flexibility

INTRODUCTION: THE FLEXPLAN PROJECT

The increasing participation of variable wind and solar energy production plants in the power system requires flexibility from other resources, such as fast reacting generation assets, storage and Demand Response (DR) actions [1]. Storage, other than pumped-storage hydropower, and DR have not been considered in traditional network planning procedures, but they are expected to play a bigger role in the operation of power systems in the future.

To address this, the FlexPlan R&D project (www.flexplan-project.eu) was launched in 2019, financed under the European Union Horizon 2020 programme [2]. Its main objective is to establish a new T&D grid planning methodology considering the opportunity to install new storage devices, as well as to perform a flexible exercise of some loads located in selected grid nodes as an alternative to building new lines.

The specifications of the methodology and software to be develop try to meet several challenges:

- Consider an integrated planning of distribution and transmission networks at country and multiple country level.
- Assess environmental impact, targeting at air quality, carbon footprint and landscape restrictions.
- Optimize simultaneously several time-horizons (2030-3040-2050).
- Consider different meteorological variants in the analysis to account for weather variability throughout the years (scenario variants).
- Consider distributed flexibility resources (storage and DR) as network expansion candidates, together with conventional assets.
- Include investment decisions (candidates) through binary variables in the optimization model.

The requirements above result in a big size optimization problem, which becomes complex to solve because of its computational burden (details on the optimization function can be found in [3]). To limit the latter, decomposition techniques are used to divide the global problem in smaller sub-problems.

To support the planning problem, a software module has been created to reduce the number of network expansion candidates: candidate pre-processor (pre-processor from now on). Instead of considering every node of the network and every technology as candidate, this software performs a pre-selection of locations and technologies, to restrict the number of related binary variables in the problem. A “short” list of locations and technologies helps keeping the optimization problem tractable.

METHODOLOGY FOR FLEXIBILITY CANDIDATE SELECTION

The pre-processor software has been coded following a specification that gives response to the following aspects:

- It must be integrated with the planning tool in an automated way: results are exchanged between both applications to permit an iterative process, which starts with the introduction of the inputs by the user (network model and scenarios) and ends with the optimal grid expansion solution provided by the planning tool.
- The congestions in the system must be identified using the results of an Optimal Power Flow (OPF).
- Storage, DR and conventional assets should be proposed as candidate for network expansion, but depending on the characteristics of location and congestions, a pre-selection of technologies needs to be done to reduce the size of the problem.
- An estimation of size and price needs to be provided for every selected candidate, as input for the planning tool.

The whole planning process, where the candidate pre-selection is integrated, is illustrated in the following Figure 1. Three loops are necessary to carry out the complete procedure, so as to cover all three target years. The first step is to run an OPF simulation on a non-expanded electricity network model plus scenario for the first year of study, 2030 (which represents the 2020-2030 decade). With the results from the OPF and the inputs from the user, the pre-processor provides a set of candidates for network expansion for year 2030. Then, the planning tool runs the optimization process and the resulting network becomes the non-expanded model for 2040 and it will be the input for the second loop. In the final step, the planning tool will provide the optimal network expansion for the whole period under study (2030 to 2050), choosing among all the candidates proposed by the pre-processor in the three loops.

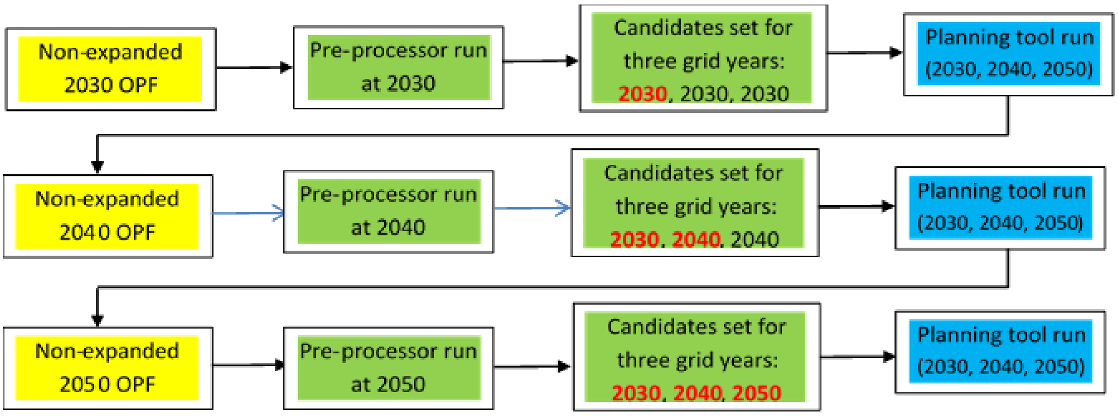

Figure 1 Integration of planning tool and pre-processor

To meet the rest of the points of the specification above, a methodology was defined for the pre-processor, consisting in four main steps: analysis of congestions, node and branch selection, check of constraints and characteristics, and selection of the set of candidates. These steps are detailed in the next two sections and are summarized graphically in the next Figure 2.

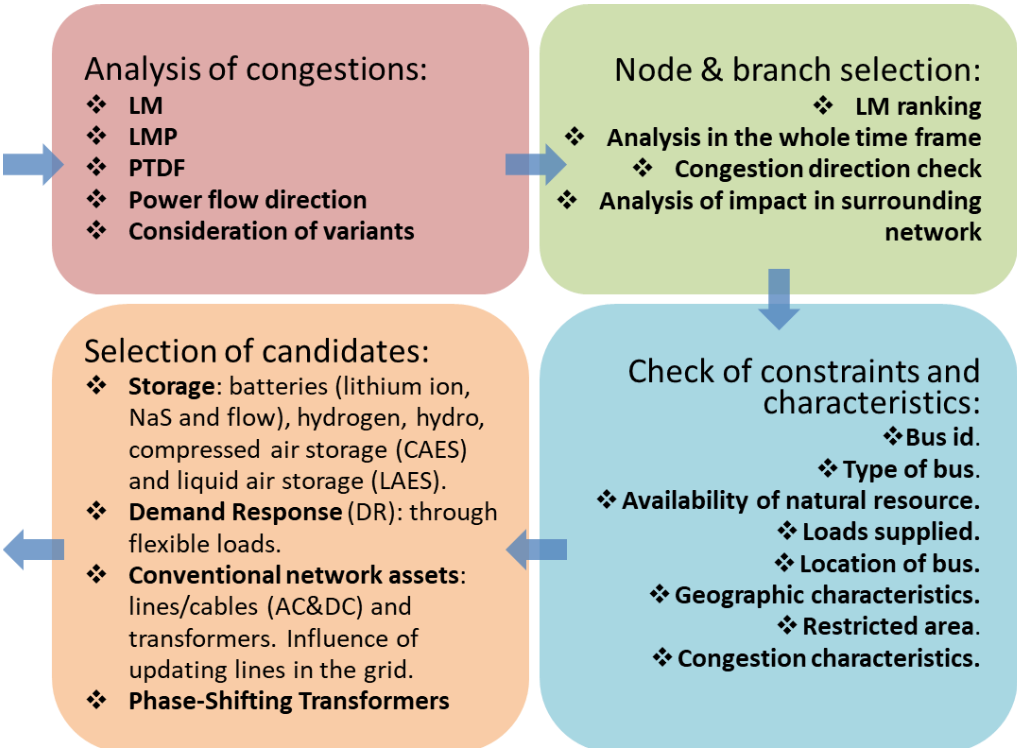

Figure 2 Main steps for pre-processor methodology

SELECTION OF CONGESTION SCENARIOS AND LOCATIONS

The main input source to perform the selection of congested scenarios is the planning software suite, which performs an OPF on the input grid and scenarios before calculating any optimum expansion (non-expanded OPF).

The OPF provides a constrained solution and, therefore, power flows result below or at the capacity limits of each network asset, i.e., they are not an indication of congestion (see Deliverable 2.1, at www.flexplan-project.eu). By contrast, four types of inputs are provided by the OPF solver which are used by the pre-processor:

- Lagrange Multipliers constraints (LM) of branches are a direct outcome of the solution of the optimization problem (OPF) [4]. They provide information about the dispatching cost reduction obtained by sending an additional MW of power through a branch. Therefore, they permit to identify congested lines: these lines will be characterized by non-zero LM values and such value will correspond to the objective function cost reduction deriving from one unit increase of the line transit limit.
- Locational Marginal Prices (LMP) show the dispatching cost variation to accommodate a unit increment of demand at a bus [5][6]. They provide useful information for the location of flexible resources (storage and DR).
- Power flow values of branches provide information about the direction of the flow of energy and about their saturation level, in relation to their rating.
- The Power Transfer Distribution Factors (PTDF) represent the change in the active power flow through network branches, as a consequence of transferring one extra power unit between two nodes at given grid [7].

In a year-long simulation, the OPF provides a value, for the first three parameters in the list above, for each of the 8760 hours and for each of the buses and/or branches, in form of matrices. The PTDF is dependent on the topology and, therefore, there is a unique value for the whole year (no topology changes are considered before the expansion).

In a first step, the pre-processor checks the LM matrix with the results of the OPF, for the grid model under study and various scenario variants for each year (3 to 5 meteorological variants). The LM value evolution along the year is analysed statistically, but two main values are considered to reflect the following:

- Congestion occurrence: number of hours in a year, when the LM value is different from zero.
- Congestion severity: average LM value considering all year hours (sum of LM values for a branch, along a year).

These two values are considered together in a factor that result from their multiplication, i.e., occurrence times severity. For each year under study, this is done for all scenario variants, and a common ranking is created for all the branches of the system. The probability assigned to each scenario variant is also used to provide a weight to the congestions identified in each of them.

Based on the ranking, branches are selected, starting from those with higher values (the number of candidates is a parameter for the software). These selected branches reflect the most congested lines in the system and, therefore, a possible location for network extension: either for a storage, for a flexible load (DR) or a conventional network asset (new line or cable).

For each of the selected congested lines, the characteristics of the congestion are analysed in a more detailed way:

- Power flow direction: it is studied for the whole period, to check whether the congestions occur in one or two directions and the probability of that occurrence.

- Number of congestion hours: the number of hours that a branch is congested throughout a year is counted.
- Consecutive congestion hours: the number of consecutive hours that a branch is congested within a year is calculated, this affects both sizing and performace of storage systems.

This information is used in the next steps of the methodology to help select the best flexibility options.

CHECK OF CONSTRAINTS AND SELECTION OF FLEXIBILITY CANDIDATES

The pre-processor aims to propose a set of network expansion flexibility candidates targeting at the resolution of the existing congestion at each of the selected branches in the previous step. The flexibility technologies considered by the pre-processor as candidates are the following:

- Storage: batteries (lithium-ion, NaS and flow), pumped-hydro, hydrogen, compressed air storage (CAES) and liquid air storage (LAES).
- Demand Response (DR): through flexible loads.
- Conventional network assets: lines/cables (AC, HVDC) and transformers.
- Phase-Shifting Transformers (PSTs).

All technologies above are considered as possible candidates for network extension, competing with conventional network assets. In the frame of FlexPlan, these technologies have been characterized and results of that characterization are available in Deliverable 2.2 (www.flexplan-project.eu).

Two ways are possible to propose candidates to the planning tool: forced by the user and automatically calculated by the candidate pre-processor module. In the first case, the user, based on the knowledge about the network, proposes network extension candidates. This is specially recommended when:

- The network needs to be extended between nodes that are not connected through lines or cables in the non-expanded scenario.
- Technologies require a dedicated study for their installation, e.g., HVDC, phase shifting transformers (PST) and pumped-hydro, which are designed specifically for a location.

Forced candidates have preference in the candidates' list that the pre-processor provides to the planning tool. Candidates calculated automatically by the pre-processor are added after them depending on their position in the ranking.

In the latter case, for all locations where a congestion is identified, the suitability of each technology is checked through the analysis of local constraints and the characteristics of the congestion. Congestions are characterized through the analysis of the non-expanded OPF results, as described before. In the case of the locational constraints, as part of the grid model definition, users can provide additional characteristics related to each network node. The selection of candidates at a specific location is screened according to this characterization: the network information provided for nodes and the congestion characteristics are used to discard, or not, some of the candidate technologies.

In the planning tool developed in FlexPlan, the user can assign the following characteristics, grouped in areas, to each of the nodes (buses) of the grid model:

- Type of bus: substation (air, air-compact, underground); Industrial load (metal, paper, textile, cement, water treatment, gas industry, mining, shipyard, high speed train, automotive, chemical, other); power plant (wind, PV, solar, thermal coal, CC, biomass, hydro, nuclear); commercial load (airport, other).

- Availability of natural resources (for substation type buses): water (river, reservoir); wind (area with wind parks near); sun (solar power plants near); cavern; biomass.
- Loads supplied (for substation type buses): residential (mainly); commercial (mainly); industrial (mainly); mixed (lower voltage level networks, sub-transmission/distribution); big industrial (as above).
- Location of bus: urban (populated city); industrial area; semi-rural (outskirts of populated city, small city); rural.
- Geographic characteristics (for rural buses): mountainous; plain
- Restricted area (not allowed to build new installations): for lines; for hydrogen; for batteries; for CAES/LAES; total restriction.

It is not mandatory to provide all this information, but it helps refining the candidate pre-selection, so it is recommended to include it, at least, for those the nodes affected by congestions (it is advised to include it in a second round, after congestions have been identified). When a node or branch is selected for the installation of a new flexibility resource or network asset, bus and congestion characteristics are checked, to assess the suitability of each of the candidate technologies. If one or more technologies are not suitable for a location, they are not included in the candidate list that the pre-processor provides to the planning tool. For example, if a congestion tends to last more than six hours, batteries or demand response strategies might not be the best flexibility candidates to relieve a congestion.

In order to perform this assessment automatically, a heuristic approach is assumed to check the constraints and characteristics of the model and scenario variants.

Once the most suitable technologies have been selected for a location, the pre-processor provides a size and cost for each of them. The estimation of the size and price of the candidates is based on literature and on the existing network characteristics, but it can be configured in the pre-processor.

The candidate selection process has aspects common to all technologies but also some differences related to them:

- Storage: from the congested branch, the node with higher LMP is preferred as location, because it indicates a higher cost avoided for the system to supply demand at that point. LMP values need to be checked for all the hours simulated. The power of the storage candidate is proposed in relation to the rated capacity of the congested branch and its energy capacity in relation to the maximum number of consecutive hours of congestion, or to the maximum yearly congestion hours, depending on the technology.
- Demand Response: the first action is to check if a load exists at any the congested branch nodes. If that is the case, it is checked if the load is already flexible, if not, we assume that it can be made flexible. If the load is characterised with a type and there exists a percentage of flexibility assigned to that type of load, this value is considered. If there is not, a general percentage is considered, which is lower than the previous. Then, the "size" of the DR is related to its flexibility. The cost of DR is a very difficult value to assess, so some estimation is provided, however, it is recommended to use this parameter to perform sensibility analyses.
- Line/cable: candidates are proposed with the same characteristics of those of the congested asset. The cost of the line, cable or transformer is proposed based on literature values.

In the case of lines, an additional check is carried out. Solving the congestion in one branch of the network, e.g., adding new capacity between two nodes, may cause new congestion in other surrounding branches, because of the new power flow. This is especially relevant for meshed networks. In order to avoid that an investment turns out ineffective, because congestion is just

moved from one branch to another, PTDFs are used to estimate how the increase of capacity in one line may affect the saturation in other lines.
Given a congested line *LC*, we consider an injection of power in node K_1 and the extraction of the same power in K_2. The line power constraints are relaxed so that line transits can go over the rated capacity of the line.

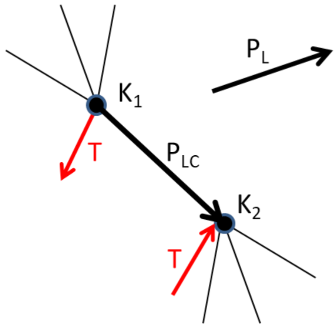

Figure 3 PTDF analysis approach

Following the definition of PTDFs, we calculate the power flow modification as result of this new power exchange (T), in both the congested line (*lc*) and a surrounding line *l*:

$$P_l - P_l^0 = T\left(PTDF_{K_2,l} - PTDF_{K_1,l}\right) \qquad (1)$$

$$P_{lc} - P_{lc}^{max} = T\left(PTDF_{K_2,lc} - PTDF_{K_1,lc}\right) \qquad (2)$$

Combining the previous equations, we obtain a relationship between them. We consider the case when the saturation of line *l* occurs ($P_l = P_l^{max}$; $Plc = Plc^*$).

$$P_{lc}^* - P_{lc}^{max} = \frac{\left(PTDF_{K_2,lc} - PTDF_{K_1,lc}\right)}{\left(PTDF_{K_2,l} - PTDF_{K_1,l}\right)}\left(P_l^{max} - P_l^0\right) \qquad (3)$$

We define the parameter $\alpha_{l,lc}$, which represents the oversaturation in line *lc* when line *l* gets saturated.

$$\alpha_{l,lc} = \frac{P_{lc}^* - P_{lc}^{max}}{P_{lc}^{max}} = \frac{\left(PTDF_{K_2,lc} - PTDF_{K_1,lc}\right)}{\left(PTDF_{K_2,l} - PTDF_{K_1,l}\right)}\frac{\left(P_l^{max} - P_l^0\right)}{P_{lc}^{max}} \qquad (4)$$

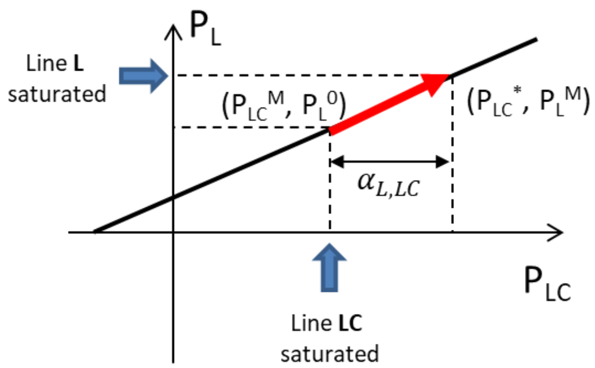

Figure 4 Relationship between the saturation of the congested line and of a line in the influence area

The lines with higher risk to become congested are those with lower values of $\alpha_{l,lc}$. To avoid congestion problems in other points of the network, they should be expanded alongside the congested line identified in the first place. In this way, an expansion corridor is created. To cope with this, the pre-processor calculates the saturation factors, α, of all branches and adds those with lower values, if any, as candidate for expansion.

FIRST VALIDATION OF RESULTS

One of the tests of the pre-processor was performed using the IEEE 6-bus system, as defined in [8]. The input files used by the pre-processor were the following:

- Grid and scenario input files for the planning tool: it is a grid with six AC buses, four AC branches and two DC branches.

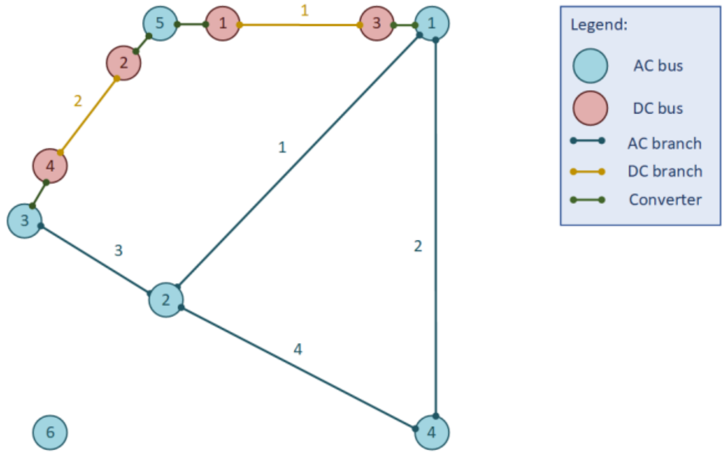

Figure 5 IEEE 6 bus system

- OPF Output file from the FlexPlan planning tool, including: AC power flows in branches, LM values for branches, LMP values for nodes and PTDF matrix. LM values were nonzero in branches 3 and 4 for certain hours, which means that they had some sort of congestion in that period. However branch 4 had very small values (under 10^{-10}). Branch 3 in the model shows high congestion and its LM values are represented in the following Figure 6.

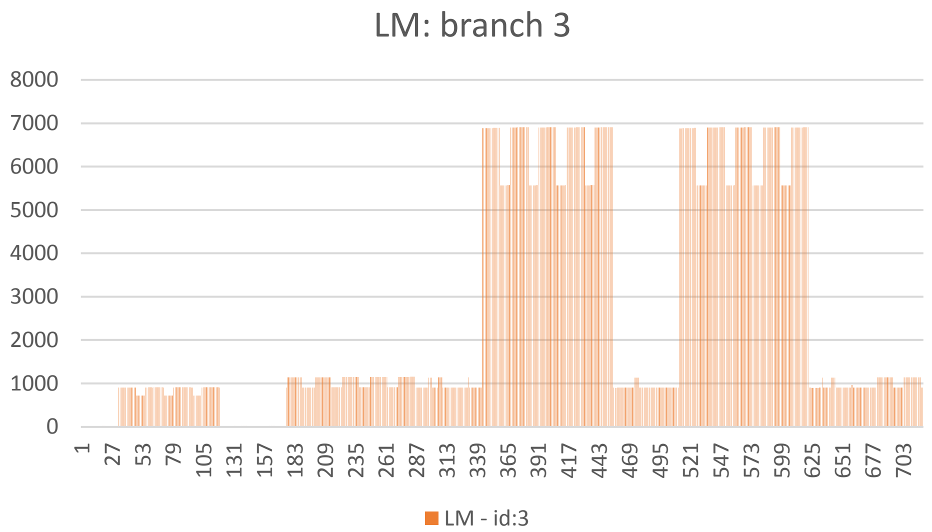

Figure 6 LM values of branch 3 of the IEEE 6 bus system (output from the FlexPlan planning tool)

Considering the previous inputs, the pre-processor provided the following candidates for network expansion:

- Lines AC and DC for branches 3 and 4. Even if the SW allows to establish a limit for LM value consideration, in this example, this was set to zero, so all nonzero values were considered as congestion. In addition, branch 1 was also selected as candidate due to the influence of one of the other branches.

- Two storages were proposed as candidate by the tool in node 2, one because of branch 3 and the other because of branch 4. Only one technology was selected, hydrogen, and this can be explained because of the duration of congestions, which makes not possible the use of batteries or LAES. Also, buses were not totally characterized, and, in this case, there was no information about cavern availability, so CAES was not a candidate.
- A flexible load was proposed in bus 2, because a load characteristic was introduced in that bus to test the tool.

The figure below shows an equivalent of Figure 6, calculated by the pre-processor tool..

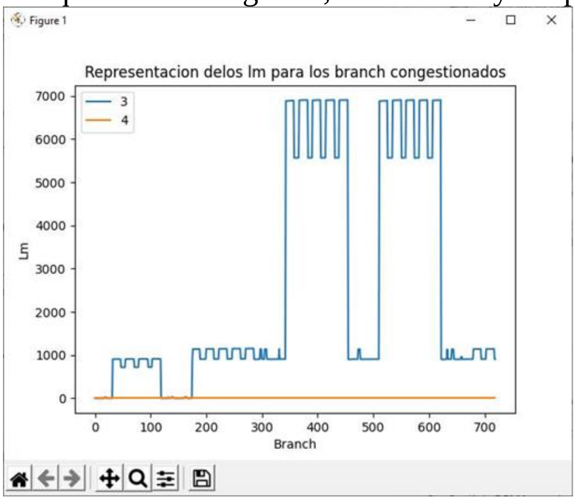

Figure 7 LM values of branch 3 of the IEEE 6 bus system (output from the pre-processor)

The following figure shows the congested lines in a map, considering that a location (longitude and latitude) was provided to each of the buses. The debug mode of the pre-processor permits such a graphical analysis.

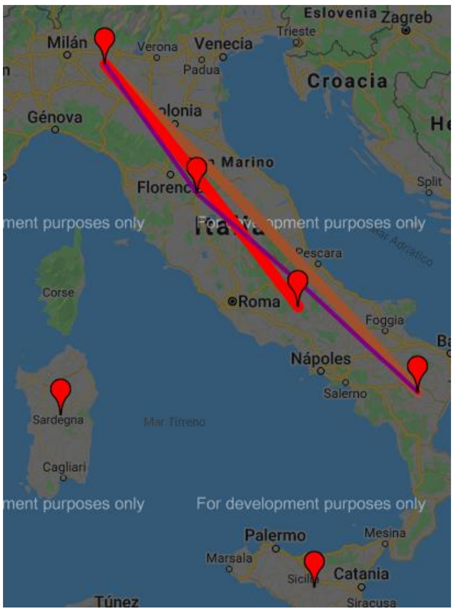

Figure 8 Map showing congested branches (red and orange)

CONCLUSIONS

Flexibility resources such as storage (big water reservoirs excluded) and demand response (DR) are expected to play a major role in the future, driven by the expected increase of the electrification of the energy system and of the high share of renewables in the energy mix. The need of flexibility will affect the short term operation of electricity networks and this should be reflected, in advance, during the planning process of future grids. Currently, distributed resources are not normally considered at the planning stage.

A methodology and a software have been developed in the frame of the FlexPlan project aiming to consider storage and DR as network extension candidates at the planning stage. The characterization of flexibility providing technologies, together with a standard OPF simulation, permits to conduct an automated assessment of expected congestions in the grid and a proposal of network extension candidates. The extended characterization of the network buses, including restrictions and additional data on the location, allows a better selection of technologies. However, the user is also permitted to input candidates based on its knowledge about the network.

To allow an automated assessment of candidates, technologies need to be characterized in a proper way, both from the technical and economical standpoints. Dealing with extensive areas of network involves many different realities (energy demand characteristics, energy mix, network infrastructure, regional policy and regulation, etc.), still, average values need to be considered for characterization, to make the problem tractable. Therefore, using sensibility analyses for some key performance indicators (KPI), is foreseen as a requirement. Some parameters are uncertain, either because they are linked to currently non-deployed technologies or markets, or just because the evolution of climate, raw materials, country politics is hard to foresee, specially, when we look at distant time horizons. Some of the parameters that we consider suitable for sensibility are, for example, the cost of the demand response, the availability of flexibility by demand response and the evolution in the cost of batteries.

The pre-processing of network expansion candidates turns out to be an adequate approach to help make extensive planning optimization problems tractable.

BIBLIOGRAPHY

[1] European Commission. “A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy” (COM(2018) 773 final, Brussels, 28.11.2018)

[2] European Commission. “Horizon 2020” [online: https://ec.europa.eu/programmes/horizon2020/en/home, last accessed: 12/01/2022]

[3] G. Migliavacca et al. “The Innovative FlexPlan Grid-Planning Methodology: How Storage and Flexible Resources Could Help in De-Bottlenecking the European System” (Energies, vol. 14, no. 4, doi: 10.3390/en14041194, February 2021, page 1194)

[4] H. Liu, L. Tesfatsion, A. Chowdhury. “Locational marginal pricing basics for restructured wholesale power markets” (Power & Energy Society (PES) General Meeting, 2009. IEEE, Calgary, 2009)

[5] L. Chen, H. Suzuki, T. Wachi, Y. Shimura. “Components of nodal prices for electric power systems” (IEEE Transactions on power systems, vol. 17, no. 1, 2002, pages 41-49)

[6] Q. Wang, G. Zhang, J. D. McCalley, T. Zheng, E. Litvinov. “Risk-based locational marginal pricing and congestion management” (IEEE transactions of power systems, vol. 29, no. 5, 2014, pages 2518-2528)

[7] D. Huang. “Dynamic PTDF implementation in the market model” (Delft: Delft University of Technology, Faculty of Electrical Engineering, Mathematics and Computer Science, 2001)

[8] L. Garver. “Transmission Network Estimation Using Linear Programming” (IEEE transactions on power apparatus and systems, vol. 89, no. 7, 1970, pages 1688-1697).