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C6–ACTIVE DISTRIBUTION SYSTEMS AND DISTRIBUTED ENERGY RESOURCES

PS1 – Flexibility management in distribution networks

**The impact of sub-transmission levels' modeling on congestions' visualization
for European transmission grid calculations – a CIGRE benchmark models'
study**

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SUMMARY

European-scale power flow studies are usually made with models representing the extra high voltage (EHV) grid, ranging from 220 to 400 kV, like the TYNDP [1] or PyPSA-Eur [2]. In those models, sub-transmission grid (63 to 150 kV) and distribution grid are fully aggregated to the EHV grid (“**Simplified grid**”). However, the current energy transition requires a sharp rise in renewable energy sources (RES), often connected to sub-transmission and below. Due to the expansion of RES, new congestions are being observed by system operators (SO), notably on sub-transmission. A comparative study of sub-transmission grids in Germany, Italy, and France is given in the first part for a more detailed context, with a focus on France.

Hence, adapting the modeling of European grids to better reproduce RES behavior and their impact on power flows is a new challenge. However, for long term studies (5 to 10 years prospective) with many scenarios, a complete modeling of sub-transmission as made in [3] would induce a consequent rise in complexity (“**fully disaggregated grid**”). An intermediary proposition would be to apply a **selective spatial disaggregation**, e.g. modeling explicitly the sub-transmission on a geographically limited area among the main EHV grid model (creating a “**partially disaggregated grid**”). Only two types of zones would be targeted:

- Sub-transmission grids at risk of congestion,
- Sub-transmission grids directly connected to nodes that have the strongest influence on regularly congested EHV lines.

In the first case, it would disclose sub-transmission congestions and the potential curtailment induced, which remains invisible in the “simplified grid” model. In the second case, it would verify if a more precise model of the congestion’s surrounding tempers or increases the congestion. This type of “partially disaggregated grid” models selectively captures new grid constraints while containing complexity increase. It can help RES producers to position new assets and guide the development of flexibility means.

The article proposes a frame to calculate the benefits and costs of enhancing EHV grid models through a selective spatial grid disaggregation. The indicators proposed are valid for EHV models across countries, with different voltage levels, considering their respective weights. They enable a comparison between several local disaggregation possibilities to identify those with the strongest impact. A combination of local disaggregations forms a “partially disaggregated grid”. These indicators are calculated on an example grid, illustrating impacts of a local disaggregation through a sub-transmission mesh with a congested line.

KEYWORDS

Sub-transmission, congestions, European grid models, renewable sources of energy

I. Introduction

1. A growing need for cross-voltage representation of transmission and sub-transmission electrical grids

The necessary energy transition requires a sharp increase in RES penetration. According to TYNDP transition scenarios *Global Ambition* and *Distributed Energy*, in 2040, renewable and nuclear production should represent 95% of the EU27 electricity generation [1]. The renewable production must be connected to the electrical grid, mostly on voltage levels below the EHV.

However, electricity transmission through the grid is limited, notably in current intensity. Accordingly, congestions are defined as the limitations induced by maximum intensity thermal constraints on a network element.

In some European countries, congestions are observed on sub-transmission voltage levels, ranging from 63 to 150 kV. In Germany in 2021, 27% of congestion management measures were taken by distribution system operators (DSOs) for congestions on the distribution grid which includes the 110 kV [4]. A study from MIT and KIT [5] highlights that, for the year 2015, 70% of the curtailment was made on production among the Schleswig Holstein distribution grid and shows that an explicit model of the 110 kV of this region allows most of the curtailment to be displayed (for 2015 at least). Schleswig Holstein is a crucial connection point between the wind production on the North and Baltic seas and the German main grid, whereas consumption is mainly in the south.

In Italy, in 2015, the transmission system operator (TSO) registered more than 3000 h/year of congestion on some grid elements of the high voltage distribution (HVD) network, [6] which ranges from 132 to 150 kV. In France, TSO RTE announces, in its Forecast for 2050 [7], a growth of the sub-transmission grid between +10 and +40 % in length (subject to social and political acceptance) and insists on its optimal (economical) dimensioning principle. It is still difficult to compare countries on a standard basis regarding sub-transmission indicators. A development of common and homogeneous indicators for sub-transmission grid appears necessary in the long run to ensure observability and comparability between countries.

2. Observed lack of sub-transmission explicit description among main European grid models

Meanwhile, classical European grid models for international load flow studies like TYNDP [1] and PyPSA-Eur [2] only present an explicit model of the EHV grid (from 220 to 400 kV). Sub-transmission and distribution voltage levels are fully simplified, with aggregated consumption and production connected to EHV nodes. In the TYNDP, this aggregation is given by TSOs, thanks to their view on regional charge. In PyPSA-Eur, production and consumption are geographically estimated from open data and gathered to the closest EHV node [2].

Two concomitant issues are linked to the rise of RES and new objects (connected to sub-transmission and distribution) concerning the EHV national or European grid models:

- (Q1) What's the impact of sub-transmission congestions on EHV power flows? (Especially as their amount is growing with the rise of RES connection and new objects).
- (Q2) What's the impact of an explicit modeling of sub-transmission grid on congestion on EHV grid?

In the first case (Q1, congestions on the sub-transmission grid), the aggregated model of the sub-transmission can "hide" congestions and thus miss its impact on EHV power flows and power dispatch. In the second case (Q2, congestions on the EHV grid), the sub-transmission grid nearby might, in reality, relieve a part of the congestion by providing an alternative path, which can, however, lead to new congestion on the sub-transmission grid. Those two questions require a sub-transmission modeling to be answered.

The H2020 project FlexPlan deplores, in particular, the lack of sub-transmission models and tends to reproduce it with open data [8] to better take into account RES production, flexibility, and storage in their grid expansion planning. The study on Schleswig Holstein mentioned above shows the pertinence of modeling the 110 kV grid on the visualization of congestions (at least for that year and region) [5], also highlighted by the authors of [3]. The German project eGo [9] underlines the necessity of realistic transverse voltage models to explore grid expansion considering alternative flexibility options and

proposes model generation tools that balance complexity and accuracy. More generally, the joint declaration of intent between ENTSO-E and DSOE on the settling of a common digital twin for transmission and distribution together [10] illustrates this growing need.

3. Proposition and initial hypothesis concerning sub-transmission grids

Congestions on the sub-transmission grid are not visible on TYNDP or PyPSA-Eur (so far). On the other hand, no explicit model of sub-transmission grids is furnished by SO, and the additional rise in complexity would be consequent anyway. In France for example, the 225-400 kV grid counts 1170 nodes [11]. Adding the 3682 sub-transmission nodes [11] would increase by +315 % the grid size grid.

An intermediary solution between no representation (“simplified grid”) and a complete explicit representation of the sub-transmission networks (“fully disaggregated grid”) could be a “partially disaggregated grid”, e.g to **only represent explicitly**:

- sub-transmission zones at risk of congestion among the sub-transmission (cf **Q1**),
- sub-transmission grid connected to the EHV nodes that present the strongest impact on EHV congested grid elements (cf **Q2**).

This proposition of selective spatial disaggregation is based on the following hypothesis:

- **(H1)**: The sub-transmission grid is composed of sub-transmission grid units that are not connected unless passing by at least one node of the EHV grid. Therefore, each sub-transmission grid unit can be extended in its regional vicinity by a finite number of lines until all its ends reach the EHV network, allowing to represent them separately.
- **(H2)**: the sub-transmission grid has an impact area at the scale of a region (in a same way that it can be considered that, for an EHV grid, the scale of impact, that is to say the area containing grid elements and causes of the elements’ behavior, is of national or European size)
- **(H3)**: Enhancing an EHV model locally with the explicit model of a sub-transmission mesh or section, selected on congestion criteria (congestion on the sub-transmission grid or linked to nodes with a strong impact on the congested elements), can improve the flow calculations on EHV lines and better represent curtailment.

H1 will not be demonstrated in this article; H2 will be, and while H3 will be shown on an example, it requires a proper validation on a real national or European grid.

4. Problematic and objectives of work

The objective of this article is to provide a frame for an evaluation of national or European EHV models enhancement through a selective spatial disaggregation on sub-transmission zones at risk of congestions (H3).

A comparison between subtransmission grids in France, Germany, and Italy, as well as a focus on France, are given in part II for a better understanding of the topic.

Criteria of benefits and costs of the explicit addition of a sub-transmission mesh are defined in part III and illustrated in part II.

II. Sub-transmission grids in France and some European countries

1. Comparison of sub-transmission grids between France, Germany, and Italy

It can be observed among European countries an intermediary voltage, sometimes referred to as “sub-transmission grid” among other designations (cf Table 1 Table 1), which has a double role:

- Connection of RES production to the main grid, with a linear or looped structure and often 1 or a very few connection nodes with the main transmission grid
- repartition of power, flowing from the EHV to the lower voltage levels, with a meshed structure and mostly more than 1 connection node to the main transmission grid

In addition, it can support the EHV grid as it gives a secondary path for power flows.

It shall be noted that some publications, mainly from the US, refer to the 20-50 kV range as “sub-transmission” (notably publications on the 14-node IEEE grid where “sub-transmission” describes the 33 kV grid). In this article, it refers to the 60-150 kV voltage range in European countries.

TABLE 11: COMPARISON OF SUB-TRANSMISSION GRIDS BETWEEN FRANCE, GERMANY AND ITALY

Country > Indicator	France	Germany	Italy
Voltage levels (kV)	63, 90, 150	110	60, 132, 150
Names	-Repartition grid, [7] -Regional transmission grid [7]	-High Voltage Distribution [5]	-High Voltage Distribution [6] -Sub-transmission grid [12]
SO	TSO	DSO	TSO
Approximate length (km)	49 500 (calculated on GIS data from [11]. RTE also gives 70 000 km for the “sub-transmission” grid that includes some 225 kV lines [7])	81 000[13]	48 527 [14]
Density (km/km ²)	0,147	0,227	0,161
Direct congestions indicator	-Power not transmitted [15] -Number of constraints occurrence [15] -Energy not transmitted [15]	-Number of hours of constraints per grid element [4]	-Volume of non-distributed energy [14] -Number of hours of “inadequation” between production and charge [14]
Indirect congestions indicator	-Curtailment volume [7]	- Volume of congestion management solutions [4]	-
Limit of congestions today	-	-	-limit of 3h/year of “inadequation” in 2021 [14]
Congestions in the future	-average 0,3% curtailment limit in volume of RES energy for 2035 [16], 1% for 2050 [7]	- planned average 5.3% curtailment in volume of RES for 2045 [17]	-

2. Focus on France: congestions on sub-transmission and area of influence

In France in particular, 37% of installed total capacity is connected to sub-transmission grid (63, 90, 150 kV) or distribution grid (below), it represents 84% of RES capacity (cf Figure 1Figure 1). It generates new congestions on sub-transmission grid, which implies notably more curtailment. French TSO RTE provides regional data on energy volumes of congestions on its lines for 2022 [15] as part of the Regional Scheme for RES connection to the grid (S3REnR) (cf Figure 2Figure 2).

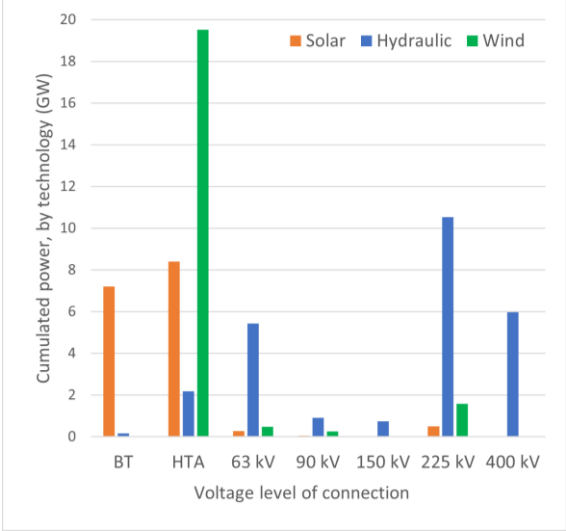


FIGURE 111 : CUMULATED INSTALLED RES POWER, BY VOLTAGE LEVEL OF CONNECTION, IN FRANCE (TOTAL POWER, INCLUDING NON-RES, = 149 GW)

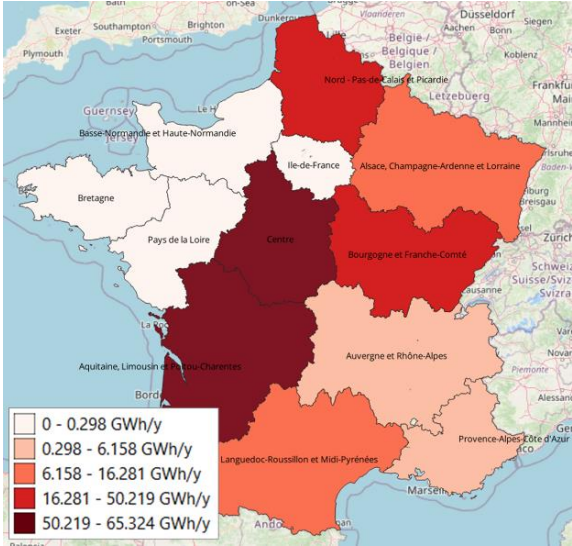


FIGURE 222: VOLUMES OF NOT TRANSMITTED ENERGY PER ADMINISTRATIVE REGION

Furthermore, TSO RTE shares a prospective dataset for the following 3 to 5 years in France [18], with grid elements expected to be congested at least once. 76% of them (in number) belong to 63 or 90 kV voltage levels. In addition, the maximum of not-transmitted power that can be reached is given for each element. Summing those local maximums gives a maximum need of local flexibility of 6.350 GW, with 70% (in power) on the sub-transmission.

Nonetheless, those numbers shall be put into context. In 2022, non-transmitted energy volume was of 255.78 GWh [15]. Compared to the 116 TWh of renewable electricity production in 2022 [19], it only represents 0.22%.

Finally, regarding the area of influence, RTE dataset on constraints for the 3 to 5 coming years [18] points to the 3 most influential electrical posts on branch constraints. Compiling, for 63 and 90 kV lines, the geographical distance between each congested line's centroid and its influent posts gives an overview of the geographical area of impact (cf Figure 3Figure 3). (The same exercise can be done on cables and posts). With a maximal distance between a congested line's centroid and its 3rd most influent post, of 60km, this shows an area of impact for sub-transmission grids with an approximate size between administrative department and region area. **This tends to validate (H2) for France.** (The maximal distance to 3rd influent post for 225 kV-lines is of 102 km, and there is no 400 kV lines in [18]).

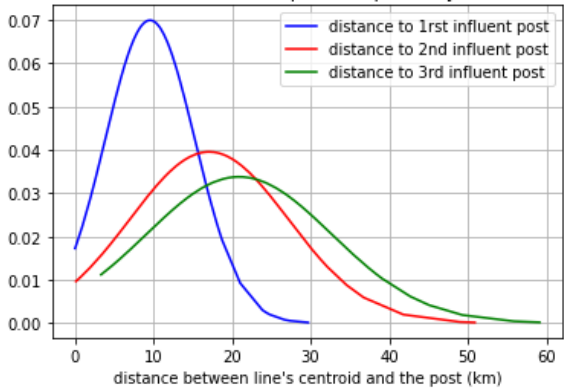


FIGURE 33 : NORMAL DISTRIBUTION OF DISTANCES FROM 63 AND 90 kV LINES' CENTROID TO THEIR 1ST, 2ND AND 3RD MOST INFLUENT POSTS

III. Methodology

1. Objectives

Aiming at better representing EHV power flows, a selective spatial disaggregation on chosen locations can be an alternative to the heavy, explicit representation of the sub-transmission grid. The proposed methodology frames the evaluation of the enhancement of real national or European EHV grids by applying selective disaggregations. Two sub-cases can lead to the use of this study:

- Representing a sub-transmission grid where congestions are expected,
- Representing a sub-transmission grid connected to a node that has a strong coefficient of impact on an EHV congested grid element (like the ones given in the 3-5 years prospective dataset, RTE [18])

Some other bricks are mentioned for further work but will not be explored in this study, namely:

- The demonstrations to validate or invalidate (H1),
- The methodology to choose the zone where to apply a local disaggregation,
- The methodology for the selective disaggregation itself, using open data to model the sub-transmission lines, production, and consumption.

2. Methodology for the impact study of a local grid disaggregation with cost and benefits indicators calculation

Supposing the data is fully available for modeling a chosen sub-transmission mesh, 2 cases can be defined:

- *simpl*: the simplified case, with production and consumption aggregated to the EHV grid
- *disagg*: the local disaggregation of the chosen sub-transmission grid zone

The indicators presented below are calculated via a DC optimal power flow (DCOPF). They are valid in the case of an additional sub-transmission mesh connected to more than one node of the main transmission network, as well as in the case of more than one additional sub-transmission mesh.

For the following calculations, the following references can be fixed:

- $\langle \rangle$: *The mean calculator*
- *A*: *the selected area on which the impact study is made. It gathers a group of EHV branches and transformers.*

a) Benefits indicators

Two benefit indicators are defined in this article: ***Impact*** and ***Δcurtailment***.

On DIgSILENT PowerFactory©, loading of a branch (line or cable) i , connected to buses k and p , is defined as on:

$$loading_i = \max\left(\frac{|I_{bus\ k}|}{I_{nom, bus\ k}}; \frac{|I_{bus\ p}|}{I_{nom, bus\ p}}\right) * 100 \quad (1)$$

An equivalent definition can be given for transformers.

Impact of the scenario *disagg* compared to the *base* scenario on grid elements i (branches and transformer) in A a part of the EHV grid can be calculated as follows:

$$Impact_{A,disagg\ vs\ simpl} = \frac{1}{\sum_{i \in A} S_{rated}} * \sum_{i \in A} |loading_{i,disagg} - loading_{i,simpl}| * S_{rated,i} \quad (2)$$

This indicator gathers loading variations on different voltage levels (225 or 400 kV, but also 380 kV in Germany for example) considering their respective impact, giving an overview of the variation induced on the observed zone A of the complete grid. In the case of available data concerning branches' length, a variant of this indicator would include a ponderation by branches' length to fully account for countries' and regions' specificities. (TYNDP, for example, does not provide lines' length).

$\Delta curt_{explicit\ vs\ simpl}$ shows the variation of total RES curtailed power between the *disaggregated* and the *simplified* cases. RES curtailment can be obtained in PowerFactory as the difference of total RES production with and without the branch flow limitation activated running the DCOPF:

$$curtailment = \sum_{g \in RES\ generators,} P_{g,no\ branch\ thermal\ limit} - P_{g,branch\ thermal\ limit} \quad (3)$$

In the *simplified* case, the definition remains the same, but among aggregated RES generators.

The curtailment variation is thus calculated:

$$\Delta curt_{disagg\ vs\ simpl} = curtailment_{disagg} - curtailment_{simpl} \quad [in\ MW] \quad (4)$$

b) Cost indicators

Supplementary cost induced by the additional grid model can be calculated with 2 indicators as well.

$\Delta complex$ reflects the structural additional complexity. It seems that computation time for DC load flow, considering the sparsity of the Jacobian matrix, is between a $O(nnz)$ and a $O(n^2)$ with n the size of the matrix and nnz the number of non-zero elements [20]. The number of non-zero elements for the Jacobian matrix in DC load flow can be obtained as follows:

$$nnz = 2 * Nb_{lines} + Nb_{nodes} \quad (5)$$

(using notably [22], counting the number of nnz element in the admittance matrix of the system). Considering a complexity of $O(n*nnz)$ for the resolution of the network equation system with the Jacobian matrix [20], [23], the variation of complexity can be counted as:

$$\Delta complex_{disagg\ vs\ simpl,\%} = \frac{Nb_{nodes,disagg} * nnz_{disagg} - Nb_{nodes,simpl} * nnz_{simpl}}{Nb_{nodes,simpl} * nnz_{simpl}} * 100 \quad [in\ \%] \quad (6)$$

Variation of calculation time counts the rise in calculation time:

$$\Delta t_{calc,\%} = \frac{t_{calc,disagg} - t_{calc,simpl}}{t_{calc,simpl}} * 100 \quad [in\ \%] \quad (7)$$

With $t_{calc,scen}$ the calculation time for the *scen* scenario grid (*disagg* or *simplified*)

IV. Illustration of indicators calculation on an example grid model

1. Existing grid test models

To illustrate the calculation of indicators, a grid test with EHV and sub-transmission is needed, with the possibility to easily aggregate the sub-transmission, to compare a plausible aggregation to the disaggregated case, the easier being a sub-transmission grid connected to a unique EHV node. Classical grid models like combination of CIGRE HV and MV [24] or IEEE 39-nodes [25] only present 1 node in sub-transmission, not a mesh. [26] inserts a 110 kV German grid benchmark model between the CIGRE HV and MV benchmark models, but data is not shared. Modified Nordics32 [27] shows a sub-transmission mesh, but, this time, its aggregation is not eased because of its multiple connection nodes to EHV.

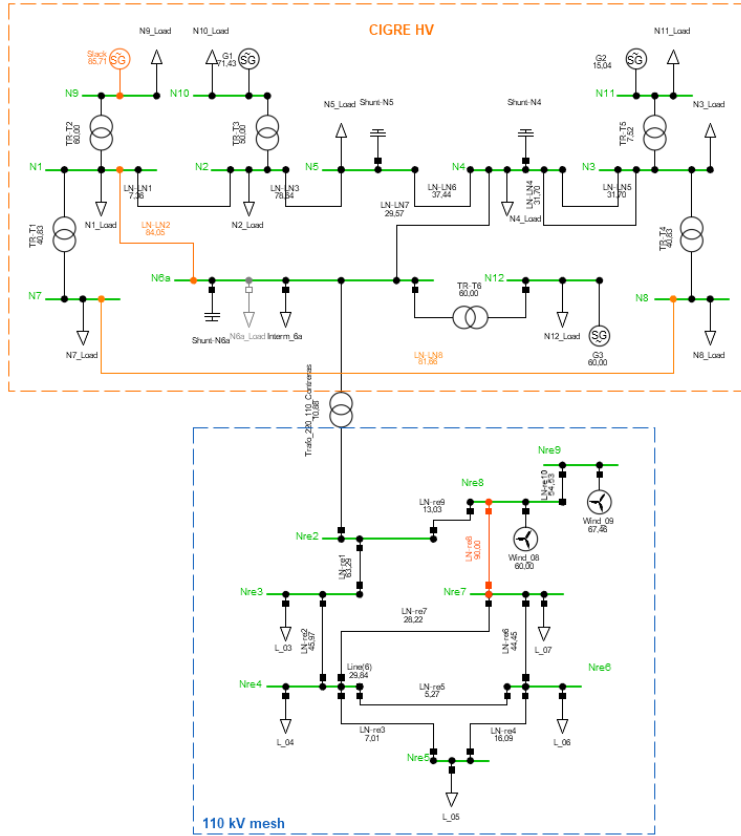


TABLE 222 : LOAD AND WIND PRODUCTION AT 110 kV MESH NODES

Node sub-t°	Load (MW)	Wind (MW)
<i>Nre3</i>	15	-
<i>Nre4</i>	18	-
<i>Nre5</i>	20	-
<i>Nre6</i>	20	-
<i>Nre7</i>	15	-
<i>Nre8</i>	-	42
<i>Nre9</i>	-	50

FIGURE 44: JOINED CIGRE HV GRID AND 110 kV MESH

2. Proposition of adapted test grid

A study from D. Contreras, S. Müller and K. Rudion [28] proposes the use of MV flexibility to solve sub-transmission congestions. The grid model contains a 110 kV mesh, to which are connected three 20 kV flexibility-providing grids. Average parameters are given but not exact values per line.

To illustrate the calculation of indicators introduced earlier, a proposition of reconstitution of this 110 kV mesh is given in this article, connected to the CIGRE HV benchmark test model [24]. Missing values are chosen arbitrarily and thus do not represent the real urban grid of [28]. The interest lies in comparing indicators between our simulation cases, not in their absolute values. Therefore, conclusions on German urban grids cannot be taken from the absolute indicator values calculated here.

110 kV lines' lengths have been chosen while keeping an average length of 3.2 km, an impedance of $0.001 + j0.003$ p.u./km, and rated power of 86.6 MVA, as in [28]. 2 wind parks have been added at node 8 and 9. A congestion threshold of 90% of charge is taken for 110 kV lines, supposing an equivalent margin to the 10% taken on EHV grids in Europe [29]. 110 kV mesh is connected to CIGRE HV benchmark test grid thanks to [28]'s 110/220 kV transformer, with a capacity of 400 MVA, using the connection method described in [24].

The calculation methodology for marginal cost is described in [30] and can be combined with ENTSO-E 2023 ERAA values of gas price (15,04 €/Net GJ) and CO2 price (77,73 €/ton CO2) for November 2022 to February 2023 [31]. It gives, for gas power plants, a marginal cost of 130.73€/MWh (high price due to the context in Ukraine for that period), applied for generators G1, G2, and G3 of CIGRE HV grid. Marginal cost is taken as null for wind power plants. The load shedding price is taken at 1000€/MWh.

Disaggregated case gathers CIGRE HV grid joint to the 110 kV mesh as described above (Figure 4Figure 4)

Simplified case is obtained by aggregating all the loads of 110 kV mesh in a unique load at node N6a and connecting the 2 wind generators at N6a (Figure 5Figure 5)

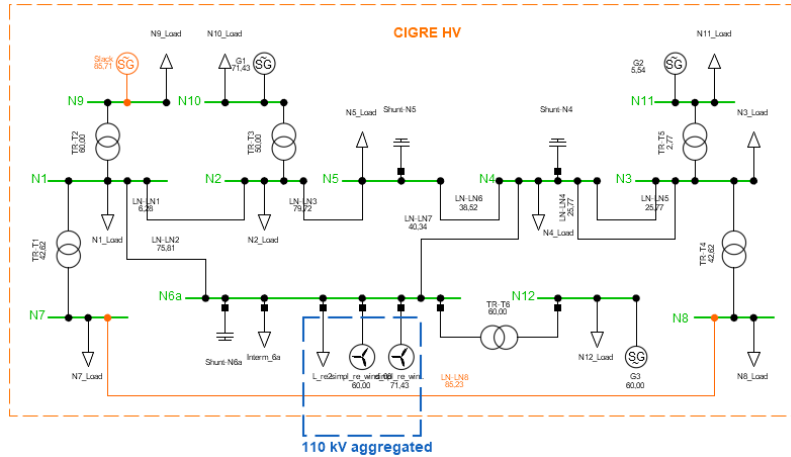


FIGURE 55 : SIMPLIFIED GRID - MODIFIED CIGRE HV GRID WITH AGGREGATED WIND PRODUCTION AND LOAD

3. Indicators results for the disclosure of a congestion on the sub-transmission grid

TABLE 33: CALCULATED INDICATORS

$\Delta curt_{disagg vs simpl}$	2.78 MW
$Impact_{A,disagg vs simpl}$	3.27 %
$\Delta complex_{disagg vs simpl, \%}$	+233%
$\Delta t_{calc, \%}$	+ 5.6%

Although this 110 kV grid is not representative of a real network as [28] is, it nevertheless shows, in the *disaggregated* case, wind production separated away from consumption, which induces a congestion between nodes 7 and 8 (cf Figure 4Figure 4). Indicators are presented Table 33Table 3. If the congestion is solved in the *disaggregated* case through curtailment on wind power plant on node 9 of 2.78 MW (5.56 % of this wind plant's initial production), this does not appear in the *simplified* case. Moreover, branches and transformers witness an overall rise of loading. In case of an already loaded grid, this can potentially bring some EHV grid elements to additional congestions. Finally, curtailment brings a modification of the power dispatch, and thus a deoptimization, which presents a cost for the system.

The main interest of these indicators does not lay on their absolute value but rather in their comparative analysis across multiple cases. Enhancing a “simplified” grid with an explicit representation of various sub-transmission parts requires a methodology for selecting these parts, while maintaining an acceptable calculation time. Employing these indicators to quantify the benefits and costs associated with each local disaggregation facilitates the establishment of a hierarchy among them. The computation of these indicators across a range of scenarios would add reliability to the selection process of the most impactful local disaggregation.

V. Conclusion

The RES rising penetration encourages grid stakeholders to a better representation of sub-transmission grid on national and European power flow studies. The methodology developed can be used to evaluate the costs and benefits for a local disaggregation regarding the enhancement of flow calculations on the EHV grid and curtailment observation, balanced with additional complexity and calculation time. It can be applied on local disaggregations on multiple areas, across countries and voltage levels. It is recommended for 2 specific use-cases:

- Local disaggregation on areas at risk of congestion on the sub-transmission grid
- Local disaggregation on sub-transmission grids connected to EHV nodes that are influent on EHV lines at risk of congestions.

The proposed indicators allow the comparison of multiple local disaggregations over an EHV grid to choose the optimal ones. Comparing several local disaggregations among real national or European grid models like PyPSA-Eur would be interesting. A reference of impactful sub-transmission area in Germany would probably be Schleswig Holstein [5]

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