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Impact and modeling of topological action among sub-transmission grid units

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Abstract—The rise in renewable energy sources, storage, and flexibility means decentralizes power injection among the grid, and new congestions occur on the sub-transmission grid (60 to 150 kV, just below the extra-high voltage). It becomes pertinent to include, in EHV grid models for power flow studies, some of the sub-transmission units. However, congestions appearing on a static representation of the sub-transmission could in reality be solved with topological actions and shall not lead to curtailment. Moreover, the operation plan remains unknown when working with open data. This article analyses the impact of 1-move topological actions, and proposes a methodology to model sub-transmission with its incertitude on operation plan and potential 1-move topological actions.

Index Terms—congestion, sub-transmission, RES, topological action, operation plan, line switching, PST

I. INTRODUCTION

In the context of an energy transition, Renewable Energy Sources (RES) and new energy technologies such as storage systems, electric vehicles, and flexibility means are being incorporated into the grid. Apart from offshore wind farms which are typically connected directly to the Extra High Voltage (EHV) grid (220-400 kV), many are linked to lower voltage levels.

However, traditional grid models for European power flow studies only explicitly represent the Extra High Voltage (EHV) grid. Industrials use models based on Transmission System Operators (TSOs) released datasets, such as TYNDP [1] (ENTSO-E) and the Static Grid Model [2], while academics tend to work on participative open models like PyPSA-Eur [3]. The emergence of new power injectors below the EHV grid is altering the traditional model of vertical power flows from centralized synchronous power plants to passive loads, and thus the initial modeling of aggregated load to the geographically closest EHV node. In addition, the decentralization of power production toward lower voltage levels also induces a reinforcement of lower voltage grid levels, notably the sub-transmission level (60 - 150 kV depending on the country), as planned for example by the French TSO RTE [4].

In a previous work [5], it has been proposed to consider the sub-transmission, but to only represent the most impactful sub-transmission units. Several reasons lead to a need of modeling some sub-transmission meshes. A better understand-

ing of new power flow inversion due to power injection from sub-transmission and distribution grid. A visualization of congestions that can occur among the sub-transmission grid and generate curtailment. Finally, the impact of EHV power flow's part that transits through the sub-transmission grid. It represents a limited percentage of EHV power flow but, sub-transmission having a smaller transit capacity, this percentage of power can strongly load the sub-transmission lines.

Most of the time, Service Operators (SOs) do not share sub-transmission grid model. Rebuilding the sub-transmission grid thanks to geographical open data provides the base case of operation. Sub-transmission can be rebuilt from Open Street Map (OSM), with characteristic parameters, as made for the region of Schleswig Holstein in Germany in [6] and [7], for 3 regions including Schleswig Holstein [8] or for all Germany in [9] and [10]. A tool, OpenGridMap, is developed to extract grid models with OpenStreetMap and is shown in [11] to extract sub-transmission for Ireland (110kV), Denmark (132, 150 kV), and Great Britain (132k kV) notably.

From those rebuilt sub-transmission models, a potential simplification is to aggregate production and consumption of a sub-transmission unit to each EHV connection node, proportionally to their PTDF value, as also proposed in [9]. Under the direct-current hypothesis, PTDF matrix is obtained from electrical parameters and topology. However, the grid is not operated with a fixed topology. Some congestions that would appear within this static grid topology could be relieved by non-costly topological remedial actions. In addition, system operators can modify the grid topology for operation needs.

For research entities that are not system operators, working on open data and without knowledge on the specific operation plan of the grid, the following problematic can be raised: what representation of the grid could include the uncertainty due to the grid operation plan? Can we reach a better representation of sub-transmission grid units among the EHV grid than the actual one (production and consumption linked to the geographically closest EHV node), without raising excessive curtailment? What impact can topological actions have on EHV power flows? What flexibility potential is offered by topological actions on the sub-transmission to relieve congestion on the EHV grid?

In literature, the uncertainty or flexibility on power injection from a specific region of the grid can be viewed as a Feasible Operation Region (FOR). This representation can be used to communicate, in real-time operation, to estimate available flexibility from a flexibility providing unit (FPU) distribution to sub-transmission [12] or from sub-transmission to EHV [13]. Complexity is raised when the FPU is connected to several nodes, as it is the case for sub-transmission connected to several EHV nodes. An interdependence between FOR at EHV connection nodes of the same sub-transmission unit shall be modeled, as proposed in [13]. For DC load flow, the FOR only includes active power.

This article proposes in part II a review on topological action, and heuristics on their choices present in literature. The impact of some of them applied on two grid models including sub-transmission units, the *Nordics r32*, and *Pegase 89* grid models will be presented part III, as they show different but complementary information. A special focus on congestion among the sub-transmission and its mitigation will be given part IV. Finally, a model for sub-transmission with additional variable loads to account for operation plan uncertainty and 1-move topological actions will be proposed part V.

II. TOPOLOGICAL ACTIONS IN SUB-TRANSMISSION

A. Topological actions

Main remedial actions are the following: line switching, busbar switching, Phase Shift Transformers (PST) and Dynamic Line Rating (DLR). Line switching is the most treated in literature [14]–[20]. It conveys optimization complexity (binary process, often approximated by a continuous one). Busbar switching is a reconfiguration of a node with breakers ([14], [16], [17]), also non-linear [17]. PSTs allow shift steps on the transformer’s admittance ([18]). Finally, DLR uses meteorological parameters and operating condition to consider the actual thermal limits of lines instead of the worst case limits [20].

B. Hierarchy between topological actions

Few articles detail the remedial action strategy used by TSOs. [17] illustrates the strategy used by French dispatchers from RTE (TSO), spotting the parallel paths for power flows if a congested line was (theoretically) opened, then using remedial actions to redirect a part of the flow through its parallel paths.

Authors of [15] highlight that, for EHV grid, radial lines must not be proposed for off-switching lines, as it can induce grid isolation, transient stability issues, and power imbalance in multiple areas.

Finally, [17] shows that 1-move topological actions are quite efficient already, solving 40% of overloadings (on a realistic database describing historical snapshots, 4 per day between 2012 and 2014). More precisely, in looped grid topology around the congestion (the most frequent), 76% of congestions are solved with 1-move action, while only 3% for unmeshed grid topology around the congestion. They describe that 1-

move node reconfiguration and branch switching solve respectively 64% and 55% of looped topology cases.

In the end, there is a part of uncertainty on the choice of topological actions as it is still made by human hand, even though new tools are developed to support the dispatcher’s decision as French TSO RTE’s APOGEE project described in [17], and automatize several remedial actions such as the NAZA project from RTE [21] (automatizing battery storage and curtailment for congestion management).

III. IMPACT OF 1-MOVE ACTIONS AMONG SUB-TRANSMISSION UNITS OF NORDICS R32 AND PEGASE 89

The focus is set here on line switching and PST for simplicity, but node breaking can be seen, in a purely topological view, as opening lines with negligible impedance.

A. Nordics r32 modified grid model

The *Nordics r32 modified* test grid, enhanced by Sharon Müller in [22] presents 2 looped sub-transmission units, each connected to the EHV grid with 2 nodes, see fig. 1. The *Central* unit, studied here consumes 2210 MW from the grid.

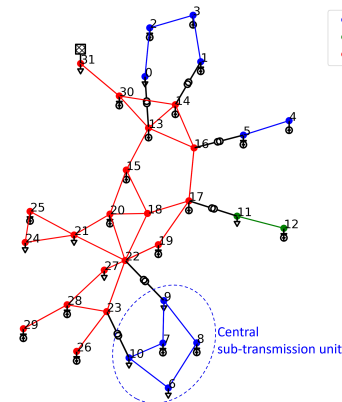


Fig. 1. Nordics test grid model

B. Pegase 89 grid model

Pegase 89 grid model [23] is an 89-nodes model, operating at 380, 220 and 150 kV, furnished as part of the European project Pegase (see fig. 2). The main sub-transmission unit is made of 35 nodes (150 kV), connected to 25 EHV nodes with 40 transformers. Some inconsistencies in the PandaPower available version have been manually modified. For this study, a wind power park have been added at node 37 (150 kV, the park could be connected at a lower voltage below this node).

Both models are at the same time incomplete and complementary. *Nordics’s* sub-transmission units are poorly meshed, with only two connection nodes that are in the same EHV loop. On the other hand, *Pegase 89’s* sub-transmission unit is much more meshed, with many EHV connection nodes. However, the sub-transmission represents a third of the complete grid nodes, thus it might strongly impact the rest of the grid.

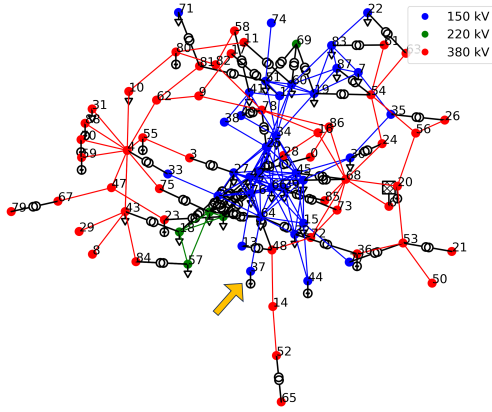


Fig. 2. Pegase 89 test grid model

C. DC-PTDF computation

PTDF computation are widely used for DC load flow [24]. Under the DC hypothesis, power flow on lines vector F can be obtained thanks to the nodal power vector P and the nodal PTDF matrix, which translate the electric parameters and topology of the grid, see eq. 1:

$$F = PTDF \tilde{P} \quad (1)$$

$$PTDF \triangleq B_L \tilde{A} \tilde{L}^{-1} = B_L \tilde{A} (\tilde{A}^\top B_L \tilde{A})^{-1}$$

with:

- M^\top , \tilde{M} respectively the transpose of vector or matrix M , and M reduced of its slack bus component(s)
- $B_L \triangleq \text{diag}(b_0, \dots, b_L)$ the diagonal susceptance matrix
- A the incidence matrix of the corresponding graph
- $L \triangleq A^\top B_L A$ the Laplacian matrix

Finally, it must be noted that DC approximation reaches its limits when voltage levels are getting lower than EHV (hypothesis $x \gg r$ less valid), thus for certain levels of sub-transmission. This is a limitation of this study, which remains in the scope of acceptable for European power flow studies. An approximated consideration of reactive power flow through lines is to block 5% of lines' capacity for reactive power [25]. On Pegase, the absolute difference of EHV lines' loading between a LFDC and AC is in average at 2%, standard deviation of 3.4%.

D. Impact on EHV lines power flow

When applying all the one-move topological changes, the power exchanged at the interconnections is modified, which impacts EHV power flows. The net power over the sub-transmission unit remains constant.

On the *Nordics 32* test grid, the impact of the one-move topological changes on EHV lines is close to zero (the strongest difference between min and max loading of a line is of 0.6 %). Indeed, connection nodes are in the same EHV loop, they are electrically very close. Consequently, the impact is locally compensated.

On the other hand, on *Pegase 89* test grid, there are many connection nodes that are more dispersed. Hence, the impact on EHV lines power flow is stronger, see fig. 3.

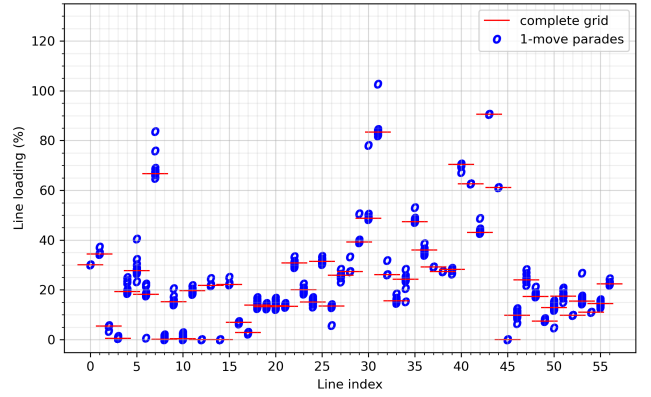


Fig. 3. Loading on EHV lines accessible with 1-move actions, Pegase

Each 1-move topological action does not have the same probability of occurrence, it should rather be seen as an available range for system operators.

E. Error between complete grid and EHV grid with injection from sub-transmission unit via PTDF

Considering the objective of an enhancement of European power flow modeling, adding explicit sub-transmission to large-scale EHV simulations would induce a significant rise in complexity. A first proposition would be to neglect EHV power flow transits through the sub-transmission unit, and only model the relative injection of the sub-transmission unit at each connection node using the PTDF values. Figures 4 and 5 are presented, for the initial grid topology (of respectively *Nordics* and *Pegase* test grids), the difference on EHV power flow line between the complete grid and aggregated sub-transmission cases. On both test grids, the impact is not negligible.

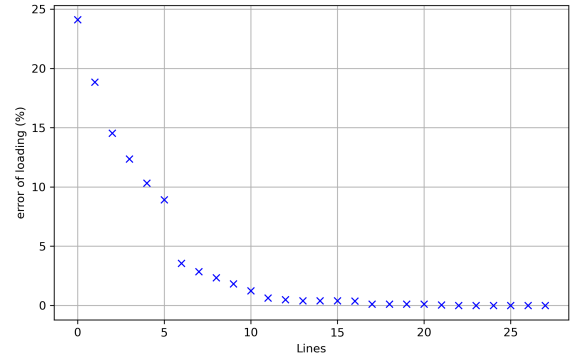


Fig. 4. Absolute difference between EHV lines' loading between the case with PTDF and the complete grid, *Nordics r32* test grid

This difference has been observed by authors of [9], but was not much explained. We can add to their supposition that this difference is due to the EHV power flows transiting through the sub-transmission grid.

For *Pegase 89* grid, the very strong difference is also due to the fact that 1/3 of nodes are in the sub-transmission mesh, hence it is not representative. However, that this difference is also visible on the *Nordics r32* grid suggests that EHV power flows transiting through the sub-transmission are not negligible for EHV power flow study.

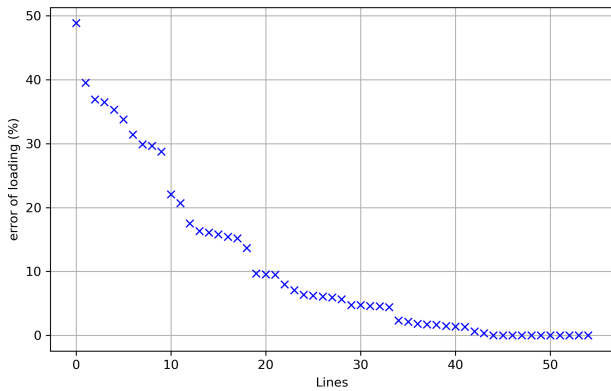


Fig. 5. Absolute difference between EHV lines' loading between the case with PTDF and the complete grid, Pegase 89 test grid

Finally, this impact is particularly notable here for sub-transmission lines with voltage levels close to the EHV (130 and 150 kV, compared to 110 kV in Germany, 90 or 63 kV in France). For lower voltage levels, with usually lower power capacity, the error would probably be smaller.

IV. MITIGATION OF CONGESTIONS IN SUB-TRANSMISSION

A. Mitigation of congestions in sub-transmission

Representing the sub-transmission grid statically can lead to excessive curtailment, as a part of the congestions could have been mitigated via costless topological actions. Fig. 6 are represented the range of loading for sub-transmission lines reached with 1-move topological actions. Line 5 presents a congestion at complete grid simulation (see fig. 6, congestion for loading above 90%), that could be solved with a 1-move action. Consequently, only some of the congestions appearing in the complete static grid modeling will truly lead to curtailment.

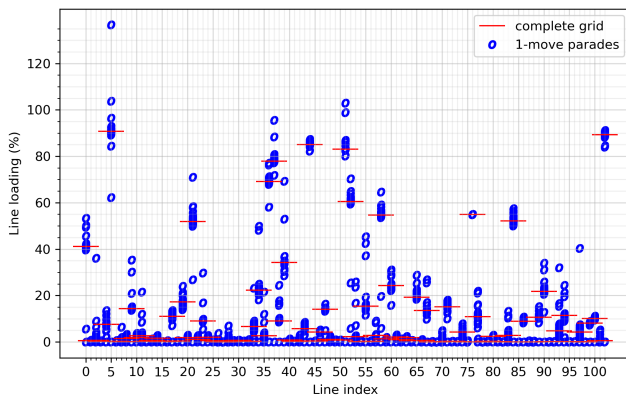


Fig. 6. Sub-transmission lines' loading values accessible with 1-move topological action, Pegase

It should be noted that opening a sub-transmission line does not always overload remaining sub-transmission lines, a congestion on a line can indeed be solved by opening another.

B. Scenario for one wind park production

For a better representation of the impact of sub-transmission and remedial action on EHV grid, a proposition of scenarios

of one wind park power production is given _ it does not represent the full grid operation. One year at hour step of operation of a wind turbine is taken from the open-source API *renewable.ninja* [26]. The dataset is approximated with a lognorm distribution, then, 200 random variates are generated from this distribution law. The rest of the grid production plan remains constant, except the slack bus that absorbs the variation.

In this configuration, some peaks of wind production generate a congestion on sub-transmission line, (congestion threshold à 90%), at static grid. However, as this test grid is strongly meshed, all of those congestion occurrences can be solved with 1-move topological action, see fig. 7. In a more realistic scenario, some production cases would eventually be curtailed.

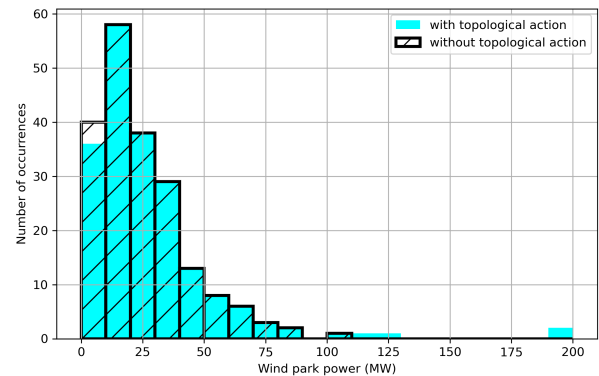


Fig. 7. Histogram of the 200 scenarios of power injection from the wind park, with and without topological action, Pegase

A more realistic representation would include scenario of other production means and consumption, allowing a visualization of several wind parks' combined impact on congestions.

V. MODELING THE UNCERTAINTY OF OPERATION PLAN

A. Model of a sub-transmission unit for EHV grid OPF

Working without a TSO knowledge of each initial operation plan requires this incertitude. A reasonable hypothesis would be to consider that the sub-transmission configuration contributes to the optimization of EHV power flow (valid for countries where the sub-transmission is managed by TSO like France and Italy. Maybe debatable when it is by the DSO as in Germany, as TSOs and DSOs have their own optimization objectives, even though TSO/DSO cooperation is rising [27]).

In addition, it has been shown part III-E that not representing the sub-transmission lines, just aggregating the sub-transmission injection (+/-) via PTDF leads to an error. But modeling an Optimal Transmission Switching for each sub-transmission unit in the European grid would rise unnecessarily the complexity, and add binary variables.

The model proposed in this article for sub-transmission unit among a European grid subject to an Optimal Power Flow (OPF) is the following:

- 1) Run one load flow with the complete grid. If a congestion occur, test all the 1-move actions until one solve it. If it doesn't, then the OPF will curtail.
- 2) If no congestion, compute with PTDF the injection (+/-) from sub-transmission at each connection node, it will be the reference injection value from the sub-transmission unit $P_{n_i, ref, PTDF}$.
- 3) For each potential 1-move topological change, compute with PTDF the new power injection at connection node P_{PTDF} . These values create a range of value around the reference injection from the sub-transmission unit calculated at step 2), see eq. 2.

$$\begin{aligned} P_{min, var n_i} &= \min(P_{n_i, PTDF} - P_{n_i, ref, PTDF}) \\ P_{max, var n_i} &= \max(P_{n_i, PTDF} - P_{n_i, ref, PTDF}) \end{aligned} \quad (2)$$

- 4) Shift this range of value around $P_{ref, PTDF}$. It gives the margin of operation available for optimization for new variable loads, added to the EHV connection nodes, initial value at 0 (see fig. 8). The sum of relative variation loads power around the complete sub-transmission unit shall remains equal null, see eq. 3.

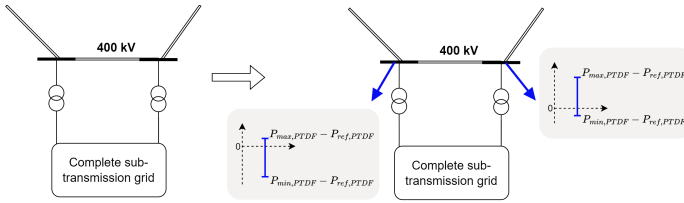


Fig. 8. Variable loads added at connection nodes with range obtained with PTDF computation

The OPF problem is then defined as:

$$\begin{aligned} &\min_x cost(x) \\ &\text{s.t.} \\ &\left\{ \begin{array}{l} \sum_{n_i} P_{gen, n_i} - \sum_{n_i} P_{load, n_i} = 0 \\ P_{gen} - P_{load} + B\theta = 0 \\ \theta_{slack} = 0 \\ P_{min, gen} \leq P_{gen} \leq P_{max, gen} \\ -F_{branch, max} \leq F_{branch} \leq F_{branch, max} \\ \sum_{n_i} P_{var, n_i} = 0 \\ P_{min, var n_i} \leq P_{var, n_i} \leq P_{max, var n_i} \end{array} \right. \end{aligned} \quad (3)$$

with:

- $x = (\theta, P_{gen})$, nodal angle and generation vectors
- P_{load} the nodal load vector, not including the variable loads
- P_{var} the nodal variable load vector as defined part. V
- B the susceptance matrix

Consequently, the optimization can use the flexibility provided by topological changes among the sub-transmission, while keeping an approximate representation of EHV power flow

transiting through the sub-transmission. This calculation artifice allows a relatively short calculation time as PTDFs can be computed in advance (depending only on topology and electrical parameters for DCLF calculation).

Furthermore, variable loads can be chosen in a continuous range. If one wants to strictly restrain the study to 1-move topological action, they can be discretized again toward the closest value (obtained with PTDF). However, wider combinations of action can occur, which would densify the panel of accessible values, notably within the range reached with 1-move action. On the other hand, the continuous property allows derivation and facilitates optimization.

B. Validation of OPF results with variable loads

For this calculation artifice to be valid, it must lead to coherent OPF results with the ones reachable with topological actions on the complete grid (without the variable loads). It is the case for all the EHV lines except a few that remain under reasonable deviation, see fig. 9. The wider range of line loading is due to the OPF calculation, with potential slight variation in dispatch.

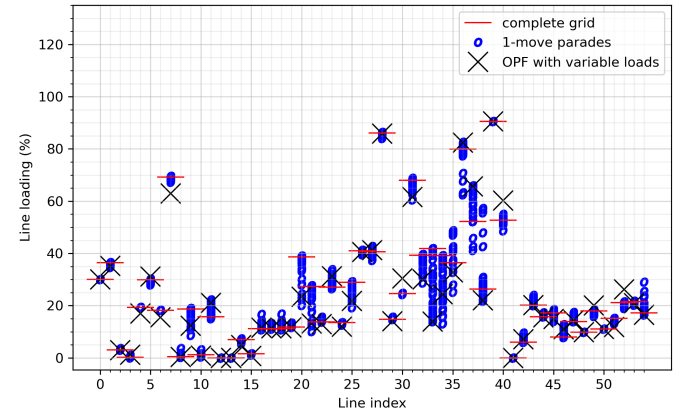


Fig. 9. EHV lines' loading for all the actions, OPF without variable load (blue and red), and OPF with variable loads (black cross), Pegase

The optimization of power flow on the complete grid (EHV + sub-transmission) with the variable loads enhances slightly the cost of the system (cf. fig 10), as the complete grid presented a congestion on a sub-transmission line (green line), but topological actions could mitigate it. It remains consistent with OPF applied to each topology.

VI. CONCLUSIONS AND PERSPECTIVES

To conclude, it has been shown that sub-transmission topology changes have a notable impact on EHV power flow in its vicinity when it is connected to EHV nodes that are dispersed (as in *Pegase*), while when the connection nodes are in the same EHV loop, there is no impact of those topological changes (as in *Nordics*).

It has been evidenced that modeling the sub-transmission as aggregated loads with PTDF values neglects the EHV power flow transiting through the sub-transmission. Even in the

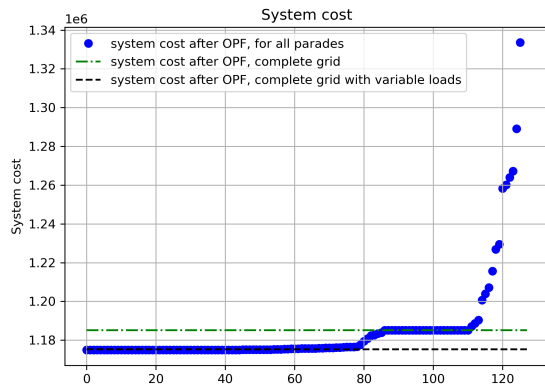


Fig. 10. System cost

Nordics test grid, where the sub-transmission unit is small and localized, 8% of EHV power flows through sub-transmission lines. Neglecting this generates a notable error on EHV flows.

This article proposes a methodology for modeling the sub-transmission units of interest including the uncertainty of the operation plan as additional variables for the OPF. It considers topological variations of 1 movement compared to the complete grid. This concept can be extended to k -movement variations, if keeping in mind that un-meshing a grid makes it less stable, and is thus not prioritised by system operators. Moreover, this analysis and model would be pertinent applied to a real grid model like [1], disaggregating locally one or several sub-transmission units using open data.

Several improvement perspectives can be considered. First, calculation time could be saved with a more efficient heuristic like [17]’s for congestion mitigation in the sub-transmission unit. Then, to include reactive power’s impact on congestions in sub-transmission, as it can worsen the situation. Finally, having more test grid representing the sub-transmission among the EHV in its diversity to improve research in this field.

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