Impact of Considering 110 kV Grid Structures on the Congestion Management in the German Transmission Grid

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Abstract. The structural changes in the European energy system lead to an increase of renewable energy sources that are primarily connected to the distribution grid. Hence the stationary analysis of the transmission grid and the regionalization of generation capacities are strongly influenced by subordinate grid structures. To quantify the impact on the congestion management in the German transmission grid, a 110 kV grid model is derived using publicly available data delivered by Open Street Map and integrated into an existing model of the European transmission grid. Power flow and redispatch simulations are performed for three different regionalization methods and grid configurations. The results show a significant impact of the 110 kV system and prove an overestimation of power flows in the transmission grid when neglecting subordinate grids. Thus, the redispatch volume in Germany to dissolve bottlenecks in case of N-1 contingencies decreases by 38 % when considering the 110 kV grid.

1. Introduction
The massive integration of renewable energy sources (RES) and the energy market liberalization have led to strong structural changes in the European power system, which are expected to continue. Already today 76% of the installed capacity of RES in Germany is connected to the low-, medium- and high-voltage level with an increasing tendency [1]. Thus, reversing power flows from the distribution into the transmission grid can be observed. In addition, the concentration of RES far from load centers, e.g. wind power in northern Germany, involves very long transmission distances. Both developments change the typical power flow patterns within the power system and hence require a comprehensive analysis of the utilization patterns of the future power system.

Existing grid models for power flow simulations or tools for network expansion planning usually just focus on a detailed representation of the extra high voltage level (EHV) [2][3][4]. However, subordinate high voltage grids, e.g. the 110 kV level in Germany, are totally neglected or not modelled in detail. Instead grid equivalents representing the residual power flows are applied [5][6]. This however stands in clear contradiction to the described structural changes. As a consequence, pursuing methods for an adequate modelling of subordinate high voltage grids are required, which allow an analysis of the impact of subordinate grid structures on the transmission grid. In addition to an accurate representation of substations and lines, a suitable regionalization method is required to map the generation capacities and loads to the nodes of the derived grid model. Based on the resulting grid model a recommendation for the consideration of subordinate high voltage grids in future studies, e.g. power flow or redispatch simulations, may be given.
2. Methodology

2.1. Grid data basis
Due to the comprehensive data and its suitable format, data delivered by Open Street Map (OSM) is used to develop a model of the German 110 kV network. OSM is a geographic information system that, among others, contains geographical information of the electrical infrastructure. In addition, this data mostly contains information regarding voltage level, frequency and number of circuits, which allows an artificial determination of the electrical parameters [7]. OSM data is categorized in nodes, ways and relations with each type having a unique numeric identifier. In addition every node has a unique geographical identifier indicating if it represents, for example, an electrical tower or an arbitrary point on the fence of a substation. Ways are comprised of more than one node and can be classified as a closed-way which represents a substation, generation plant or other electrical infrastructure facilities. An open-way however represents a route comprising of one or more systems of an overhead line (OHL) or an underground cable. This differentiation is directly provided in each way as an attribute-tag with the type of infrastructure it represents. Every relation is comprised of one or more ways and nodes and may represent a substation, generation plant or route.

2.2. Modelling of 110 kV grid structures
Since OSM is an open source project and available information is maintained by volunteers, methods are required to process and supplement data as well as check its plausibility. Therefore, an iterative process is established that successively adjusts existing and complements missing information to derive a node-branch model of the 110 kV grid in Germany. The methodology is implemented in Matlab® and classified into the steps pre-processing, main-processing and post-processing. Since ways and relations not only connect substations, but instead are connected to each other on nodes (towers), the main aspect of the process is to identify how different routes are connected to each other and handle them accordingly. Connections of different routes on towers are classified into connection types based on the number of routes meeting on a tower. Rulesets are defined for each connection type to enable the handling of such multiple routes on towers. The rulesets contain instructions to handle routes by splitting them into individual circuits or generate tripod structures. Figure 1 exemplarily shows three connection types of different routes that have various number of conductors of the three-phase system and associated rulesets to handle them. In total, nearly 350 different connection types are identified within the German 110 kV grid and nearly 20 rulesets are developed to define the galvanic connection of the conductors. The rulesets are used in the pre-processing and main-processing steps to validate and modify the topology.

The defined ruleset is used to handle missing or (rare occurring) implausible electrical information of routes in the pre-processing step. Missing information of routes is assumed after analysing the information of all other routes associated with it. This procedure is performed iteratively for voltage, frequency and number of conductor information of all routes in the entire grid. Implausible routes (e.g. connections of lines of different voltage levels or connections of routes where, due to the number of conductors, no technically valid connection can be defined for) are identified and their information is
changed depending on the connection type and its associated rule. Subsequently, routes that do not carry any relevant information for the 110 kV network are deleted, i.e. network elements with a voltage that is not 110 kV (e.g. EHV lines) or a frequency that is not 50 Hz (e.g. 16.7 Hz railway grid). The first stage of main-processing involves converting routes with multiple voltages and frequencies (e.g. routes carrying 380 kV and 110 kV systems) into unique voltage and unique frequency routes. Again, the connections are analysed to consider changes caused by deleted routes. Towers with implausible combinations of circuits are identified with the help of the pre-defined ruleset. All routes with implausible combinations are checked regarding their voltage and frequency information. The implausibility is attributable to routes with extra circuits which belong to non-110 kV voltage levels and non-50 Hz frequency. Therefore, the electrical information of such routes is modified iteratively for all towers to obtain a system consisting of routes with only 110 kV and 50 Hz.

The second stage of main-processing converts multi-circuit routes into single-circuit routes, since an electrical node-branch model has to consist of three phase circuits with three conductors. This is achieved by analysing the connection types and identifying all plausible combinations of circuits according to the pre-defined ruleset. Iteratively, towers with more than one circuit are processed until all multi-circuit routes are converted and a plausible node-branch model can be constructed. The π branch model is used to parameterize all branches of the developed network with characteristic series impedance and charging susceptance for sub-transmission lines and cables [8]. In the post-processing step the developed model consisting of 110 kV grid structures in Germany is integrated into a detailed model of the Continental European EHV grid and coupled via 380/110 kV and 220/110 kV transformers [9]. Again the parameters of the transformers are derived from typical electrical parameters based on their nominal power [10]. Finally, remaining electrical islands within the 110 kV system are eliminated by connecting them to the synchronous grid via synthetic lines.

2.3. Regionalization

The simulation of power flows requires detailed information about the generation capacities and loads at each grid node. The determination of these capacities based on overall installed capacities for each generation technology and demand is subject of the regionalization. The regionalization can be divided into two steps. The first one consists of the spatial allocation of generation and load capacities. The assignment of these capacities to grid nodes is subject of the second step. The allocation of renewable generation capacities, such as wind and photovoltaic, is done based on detailed meteorological and topological information for Europe [11]. Conventional power plants are allocated according to their location and connected voltage level [12]. The load is distributed based on detailed regional socio-economical information taking electric, heat and gas demand of private households, industry and commerce, trade & services (CTS) into account [13][14]. In Germany, the regionalization is done at postal code (ZIP) level. For this purpose two approaches are applied for the assignment of distributed generation units and loads to grid nodes (second step). The first approach assigns the information at ZIP level to each grid node proportional to the inverse of the distance between the center of the postal code region and the grid node. The number of nodes considered for the distribution has to be defined a priori. Here, the three nearest stations are considered for the distribution of capacities as shown in Figure 2, left, which also describes the share of capacities in a ZIP zone assigned to a station. This regionalization approach can be applied to both grid structures, with and without the 110 kV network.

\[
P_{S1, ZIP} = \frac{d_1^{-1}}{d_1^{-1} + d_2^{-1} + d_3^{-1}} \cdot P_{ZIP}
\]

\[
P_{TS1,S1} = \frac{PTD_{F1}^{S1}}{\sum_t PTD_{F1}^t} \cdot P_{S1}
\]

**Figure 2.** Assignment of capacities in ZIP zones to grid stations.
The second regionalization approach is applied for power flow simulations without consideration of the 110 kV network. However, the structure of the 110 kV network is used in order to derive installed capacities at each station of the transmission grid (220 kV or 380 kV). First, the regionalization is done considering all stations of the 110 kV network. Power Flow Distribution Factors (PTDF) are applied in order to distribute the regionalized capacities in subordinate grids to stations in the transmission grid. Figure 2, right, shows schematically the distribution of load and generation capacities connected to a 110 kV station, which is distributed among three stations in the transmission grid. PTDF\textsubscript{T1S1} defines the change in power flow on transformer T1 in station TS1 for a power injection at the 110 kV station S1. The share of capacity assigned to TS1 is done proportional to PTDF values of the network coupling transformers. This approach uses PTDF values as a metric to define the electrical proximity between the stations and allows a more accurate regionalization for the transmission network model (voltage level above 220 kV).

3. Model verification

The derived 110 kV grid model based on OSM data consists of 7,689 nodes (3,760 substations assumed to have coupled busbars and 3,529 connections outside substations, i.e. tripods) and 11,838 branches (OHL and cables) with a total circuit length of 77,156 km. This corresponds to 80.1% of the total circuit length according to official sources [15]. 148 of those branches are synthetic lines that connect 67 electrical islands consisting of 248 nodes. The generated network has been visually compared with published grid maps of German Distribution System Operators (DSO), e.g. Westfalen Weser Netz, LEW Verteilnetz, E.DIS, Stromnetz Berlin, Stromnetz Hamburg, inetz, TEN Thüringer Energienetze or Infrawest. The analysis exposed a close match in suburban and rural regions. Due to the high density of underground cables in urban regions and insufficient mapping in OSM, primarily the representation of those regions is more inaccurate and requires additional modelling in future work. Figure 3, left, shows the derived 110 kV system in Germany integrated in the European transmission grid [9]. Figure 3, right, visualizes the regionalization of generation according to subsection 2.3 and shows the installed capacities of renewable and conventional generation at each extra high voltage and high voltage grid node in Germany.

![Figure 3: 110 kV grid model in Germany integrated into the European transmission system (left) and regionalization of conventional and renewable generation capacities (right).](image-url)
4. Results

4.1. Approach and scenario framework

The impact of 110 kV grid structures on the congestion management in Germany is quantified by comparing different grid models and methods for regionalization of demand and renewable as well as conventional generation (cf. subsection 2.3). Demand time series are created taking standard electric load profiles and ENTSO-E data into account. Time series of renewable generators are generated based on the allocation of generation capacities (regionalization), meteorological data of the weather year 2012 and standard generation unit models [11]. To identify the power plant dispatch for 8760 hours, a simulation of the European electricity market is performed [16]. Using a Newton-Raphson based AC power flow algorithm, loadings of all transmission lines and transformers in the European transmission grid as well as in the German 110 kV grid are calculated. Subsequently, redispatch simulations are performed to quantify congestion management efforts.

The redispatch model is a linear optimization that minimizes total redispatch costs while dissolving all bottlenecks in the transmission grid including potential N-1 contingencies. The network topology is represented by linear sensitivities that indicate changes of power flows on branches in case of changes of injected power at nodes as well as in case of line outages. To keep the power system in balance, it has to be ensured that the increased and decreased power is equal when adjusting power of generation. The redispatch simulation includes conventional power plants, renewables and cross-border units. The parametrization is done according to the current regulatory framework in Germany (e.g. prioritized infed from renewables) [17].

Since the 110 kV grid model generated by OSM data does not contain future grid expansion measures, a contemporary scenario for the year 2018 is chosen. The scenario framework regarding the installed generation capacities applied in this paper is based on officially published power plant lists, the Mid-term Adequacy Forecast by ENTSO-E and forecasts regarding the development of renewable energy sources in Germany [12][18][19].

The comparison of power flow as well as redispatch simulations is done on the basis of three grid models. The first transmission grid model includes the derived 110 kV grid structure, called here ‘110kV’. The second model only considers the transmission grid with line voltage levels equal to 220 kV and 380 kV. This model is called ‘EHV DIST’. The third variant only considers the transmission grid as well, but the regionalization method presented in Figure 2, right, is applied, which considers the subordinate 110 kV grid structure for a more accurate regionalization. This model is labelled as ‘EHV PTDF’. For the ‘110kV’ and the ‘EHV DIST’ model the regionalization is done based on the distance between ZIP and grid stations (Figure 2, left).

4.2. Power flow results

The difference of power flows on transmission grid lines between both EHV grid models and the transmission grid model including the 110 kV grid structures is analysed and quantified. Besides power flows in the pre-contingency state (Figure 4), maximal power flows in case of N-1 contingencies are considered (Figure 5). For both cases, the mean difference between the absolute power flows on transmission grid line $l$ is calculated as follows:

$$\Delta S_{l,mean}^{EHV} = \frac{1}{H} \sum_{h=1}^{H} \left( |S_{l,h}^{110kV}| - |S_{l,h}^{EHV}| \right)$$

$S_{l,h}^{110kV}$ is the apparent power flow on line $l$ in hour $h$ for the model including 110 kV lines. $S_{l,h}^{EHV}$ corresponds to the same line in the same hour for the model ‘EHV DIST’ or ‘EHV PTDF’. $H$ is the number of hours considered, here equal to 8760.
Figure 4. Distribution of the mean difference on power flows in the N-0 case for each line.

Figure 5. Distribution of the mean difference on power flows in the N-1 case for each line.

The results show an overall reduction of power flows in the transmission grid, most notably in the N-1 case, when considering the 110 kV grid structures. The 110 kV voltage level takes over a part of the power transfer and thus relieves the transmission grid. A visualization of this comparison is also shown in Figure 6. Positive values (green lines) represent a lower flow on the line due to the consideration of the 110 kV grid. This emphasizes the overall relief of the transmission grid, but also proves increasing power flows in some specific cases.

Figure 6. Line specific mean difference in power flows on the transmission grid lines.

Furthermore, the vertical load, i.e. the power exchange between the high and extra high voltage levels over the coupling transformers, is quantified. Figure 7 shows a comparison of the vertical load for each hour of the year. The vertical load is systematically higher when neglecting the 110 kV grid. This evidences that a consideration of the 110 kV grid structure leads to a lower energy flow between the transmission grid and the subordinate voltage levels. The loads at the 110 kV level can be supplied by generation located at the same voltage level such that power flows on transmission grid lines are partially superseded.
The analysis of power flow patterns proves the necessity for considering the 110 kV grid system in future network analysis. Otherwise, the resulting power flows within the transmission grid might be overestimated. Furthermore, the results show also a lower overestimation and therefore a more accurate modelling when applying regionalization for the EHV based on the 110 kV grid structure compared to the regionalization based solely on the distance between ZIP and grid nodes.

4.3. Redispatch results

Based on the market results and power flow calculations redispatch simulations are performed to quantify and compare the congestion management effort to relieve bottlenecks. Due to the large number of renewable units connected to the 110 kV network, wind onshore and photovoltaic units are aggregated to 300 groups per technology to reduce the complexity of the optimization when considering subordinate grid structures. A k-means clustering is applied to form these groups according to their node-branch sensitivity on all lines in the network.

Figure 8 shows the sum of power increases and decreases for all considered technologies for the three different grid models defined in section 4.2. The redispatch results confirm the results from chapter 4.2 and show a significant impact of 110 kV structures on the congestion management in Germany. Due to reduced power flows, especially for N-1 contingencies, the required redispatch volumes are smaller when considering subordinate grids. The total redispatch volume is 28.23 TWh (sum of increased and decreased power) when considering the 110 kV grid. The choice of the regionalization method for transmission grid models without the 110 kV level has a lower impact, but regionalization based on PTDF leads to a slightly smaller redispatch volume (43.08 TWh) in comparison to the regionalization based on the distance (45.61 TWh).
The regional distribution of the required redispatch is visualized in Figure 9. The comparison of all simulations shows similar redispatch patterns, but reduced power adjustments when considering subordinate grid structures. The 110 kV grid increases the transfer capacity within the system and allows the application of more detailed regionalization methods. This influences redispatch measures especially in weakly meshed regions dominated by 220 kV lines (e.g. in north-western part of Germany near Emden), which have notably lower thermal ratings than 380 kV lines.

Figure 9. Geographical visualization of power increases (upward triangle) and decreases (downward triangle) for 110 kV (left), EHV$_{PTDF}$ (middle), EHV$_{DIST}$ (right).

5. Conclusion and outlook
The simulation of redispatch measures in Germany is significantly impacted by the modelling of 110 kV grid structures. Since power flows in the transmission grid, especially in case of N-1 contingencies, are systematically lower when considering 110 kV grid structures, fewer adjustments are required to relieve overloads. Since OSM includes partially insufficient data, future work will focus on further development of methods to process or complement grid information, e.g. the representation of cable-dominated urban regions. Additionally, the methods will be applied to derive models of subordinate grid structures of further European countries and quantify the impact on power flow as well as redispatch simulations for the whole European power system.

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