Feature- and Structure-Preserving Network Reduction for Large-Scale Transmission Grids

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Abstract—Many countries are currently challenged with the extensive integration of renewable energy sources, which necessitates vast capacity expansion measures. These expansion measures in turn require comprehensive power flow studies which are often computationally highly demanding due to the extensive model complexity. In this work a reduction strategy for large-scale grid models is introduced which does not only reduce the model complexity but also preserves the structure and designated features of the grid. The objective is to ensure that areas crucial to the grid behavior remain unchanged and that all elements in the reduced model relate to uniquely identifiable physical components within the detailed model. This is accomplished through a specifically designed reduction method in conjunction with a collection of topological, electrical and market-based approaches to identify suitable areas for the reduction. We show that the proposed reduction strategy can adapt to various grid models and accomplishes a strong reduction in the number of buses and branches while retaining a low dispatch and branch flow deviation. Furthermore, the reduction method solely depends on the information of a (peak load) reference scenario and generalizes well to other scenarios, rendering it especially suited for comprehensive expansion studies. We also provide an open-source implementation of the presented method.

Index Terms—Network reduction, power system modeling, capacity expansion planning, optimal power flow.

I. INTRODUCTION

In several countries, power system operators face the challenges of an extensive integration of renewable energy sources (RES). This involves a decentralization and geographical dispersion of energy production that generally necessitates capacity expansion measures in the transmission grid [1], [2]. The decision making for capacity expansion measures relies on comprehensive power flow studies under projected scenarios [1], [3]. For large-scale transmission grids such power flow studies involve substantial and potentially prohibitive computational efforts, which require the utilization of network reduction techniques to reduce model complexity while retaining adequate accuracy [4]. The existing (static) network reduction techniques may be categorized as electrical equivalencing and market-based reduction.

Electrical equivalencing methods divide the system into two subsystems, the internal and external subsystem, where the former remains unmodified while the latter is reduced to a small number of buses (the essential buses) that replicate the electrical behavior of the external subsystem [4]–[7]. A widely employed method for electrical equivalencing is the Ward equivalent [8] (see also [9]–[13]), where all non-essential buses in the external system are reduced via Gaussian elimination on the system of linear equations that relates the nodal voltages and injection currents [4], [8]. As a consequence of this reduction of the bus admittance matrix, the boundary buses between the internal and external subsystem are interconnected by artificial branches in the reduced model. Another popular equivalencing method is the REI equivalent introduced by Dimo [14] (see also [4], [15]–[18]), where the external subsystem is replaced by artificial radial equivalent independent (REI) nodes. To this end, related buses in the external system are grouped and replaced by an REI node using the principle of zero power balance, i.e., the injection into the REI node equals the aggregated injection into the respective group of buses. The REI nodes are then connected to the internal subsystem via a radial network of artificial branches that replicate the electrical behavior at the considered system state [4], [14].

Market-based reduction methods implement zonal aggregations based on results of the optimal power flow (OPF), targeting a reduced model with almost identical power flow among the retained buses. For example, Singh and Srivastava [19] proposed an approach that aggregates clusters of buses with almost identical local marginal prices (LMPs), as the latter suggests that their aggregation may have a negligible impact on the power flow [4], [19]. While the LMPs are the means to select a subsystem, the reduction thereof utilizes the REI equivalent. Another approach based on power transfer distribution factors (PTDFs) was proposed by Shi and Tylavsky [20], where buses with a similar contribution to designated interzonal power flows are grouped in zones. Each of these zones are aggregated to a single bus and, subsequently, the interzonal flows are modeled using artificial branches between zones.

In the context of capacity expansion planning, the introduction of artificial branches and buses in the reduced model by the aforementioned methods constitutes a significant drawback. For example, consider that a certain branch in the reduced model is identified, whose capacity should be uprated by adding an additional circuit to that transmission corridor. If the branch is artificial, there is no relation to a physical corridor and the expansion measure cannot be directly realized within the real system. Furthermore, these methods...
do not explicitly separate the different voltage levels, which potentially leads to the physically unreasonable aggregation of different voltage levels that may incentivize invalid candidate expansion measures. To address these issues, this work proposes a network reduction approach that preserves features as well as the structure of the grid. By preserving features, like transformers, physically invalid or application-adverse reduction measures are avoided, while preserving the structure ensures that every element in the reduced model possesses a physical counterpart.

In the following, Section II defines the system model and reduction accuracy measure. Section III introduces the notion of features and Section IV presents the reduction method. Its application is illustrated in Section V while its robustness with respect to different scenarios and grid models is shown in Section VI. Section VII concludes the paper. An open-source implementation of the proposed reduction method is provided as a toolbox in hynet, an OPF framework for hybrid AC/DC power systems, which is available at [21].

II. SYSTEM MODEL AND REDUCTION ACCURACY

This work is based on the system model of hynet [22], [21] which includes a bus model with shunt compensation, a universal branch model (AC and DC lines and cables, transformers, phase shifters), and a converter model (inverters, rectifiers, voltage source converters). For the sake of simplicity, only those model details that are essential to this work are introduced here. The set of buses is $\mathcal{V}$, the set of branches is $\mathcal{E}$, the set of generators $\mathcal{I}$ is $\mathcal{I}$, and the series impedance of branch $k \in \mathcal{E}$ is $\bar{z}_k = 1/jy_k$. For a given OPF solution, the active power dispatch of generator $i \in \mathcal{I}$ is $P_i$, and the active power flow on branch $k \in \mathcal{E}$ is $p_k$, where the latter is considered as the maximum of the absolute active power flow at its two terminals. Furthermore, the dual variable of the active power balance equation of bus $n \in \mathcal{V}$ is $\lambda_n$, which corresponds to the LMP in case of a zero duality gap of the OPF problem [23].

According to the application in capacity expansion planning, the accuracy of the network reduction is considered in terms of the similarity of the generator dispatch and branch flows produced by an OPF calculation. To this end, let $P_i^{\text{org}}$ and $P_i^{\text{red}}$ be the active power dispatch of generator $i \in \mathcal{I}$ and $p_k^{\text{org}}$ and $p_k^{\text{red}}$ the active power flow on branch $k \in \mathcal{E}^{\text{org}} \subset \mathcal{E}^{\text{red}}$ in the original and reduced model, respectively, where $\mathcal{E}^{\text{red}}$ is the set of branches in the reduced model. Therewith, the contribution-weighted mean relative dispatch error $\varepsilon_{\text{disp}}$ and mean relative flow error $\varepsilon_{\text{flow}}$ reads

$$
\varepsilon_{\text{disp}} = \frac{1}{\sum_{i \in \mathcal{I}} P_i^{\text{org}}} \sum_{i \in \mathcal{I}} |P_i^{\text{red}} - P_i^{\text{org}}| \tag{1}
$$

$$
\varepsilon_{\text{flow}} = \frac{1}{\sum_{k \in \mathcal{E}^{\text{org}}} p_k^{\text{org}}} \sum_{k \in \mathcal{E}^{\text{org}}} |p_k^{\text{red}} - p_k^{\text{org}}| \tag{2}
$$

1 In hynet [22], [21] the set of injectors, also denoted by $\mathcal{I}$, includes conventional and RES-based generation as well as dispatchable and fixed loads. Due to the scope of this work, we focus on the subset of generators.

2 With hynet’s branch model in [22] Fig. 1b, the active power flow $p_k$ as considered here is given by $p_k = \max(|\text{Re}(V_{i(k)}I_{k}^*)|, |\text{Re}(V_{i(k)}I_{k}^*)|).

III. THE NOTION OF FEATURES

Features are defined as entities in the model which are essential to the application-relevant accuracy and validity of the derived results and conclusions. With regard to capacity expansion planning, the following features can be identified:

(a) Transformers, as their reduction may result in the aggregation of different voltage levels.

(b) Converters, as their reduction may result in the aggregation of AC and DC grids.

(c) Selected branches with a particular relevance to capacity expansion decisions, namely

- highly loaded and congested branches, i.e., their flow is observed to be close to or at the capacity rating, and
- branches of long transmission lines, e.g., longer than 50 km, as they are typically associated with bulk transmission.

(d) Terminal buses of conventional generators, as their power dispatch impacts the power flow significantly. This includes the reference bus.

By preserving such features during the reduction process, application-specific requirements on the reduced model can be incorporated. Furthermore, as illustrated later on, empirically determined features may be introduced to control and improve the accuracy of the model reduction.

IV. FEATURE- AND STRUCTURE-PRESERVING NETWORK REDUCTION

In order to arrive at a feature- and structure-preserving network reduction, the reduction process must be (a) aware of features and (b) retain the relation of every entity in the reduced model to its physical counterpart. To this end, the proposed method aims at the identification of a multitude of small subgrids within the transmission grid that are suited for reduction. These subgrids are then filtered based on features, i.e., if a subgrid contains a feature it is excluded from the reduction process. Subsequently, the remaining subgrids are aggregated in a fashion that avoids the introduction of artificial entities. The following description of the proposed method starts with the subgrid reduction and, subsequently, introduces three approaches to select suitable subgrids.

A. Subgrid Reduction

As the avoidance of artificial entities in the reduced model is considered essential, it is assumed that the subgrid can be reduced to a single bus, where the latter is the representative bus selected among the buses of the subgrid. Compared to the Ward and REI equivalent, this is a very restricted reduction process in terms of modeling the subgrid’s impact on the surrounding grid. In the proposed method, this limitation is compensated by the selection of comparably small subgrids, whose impact on the electrical behavior of the overall system is negligible.

In case that the considered subgrid does not contain any features, the following steps are performed to reduce the subgrid to its representative bus:
(a) The terminal bus of any generators and loads within the subgrid is set to the representative bus.
(b) All reactive power compensation (shunts) within the subgrid is moved to the representative bus.
(c) All branches or converters that connect a bus of the surrounding grid to a bus within the subgrid are connected to the representative bus instead.
(d) All remaining buses and branches of the subgrid are removed. The line charging of the removed branches is modeled as a shunt at the representative bus.

Due to this comparably coarse subgrid reduction, a careful selection of subgrids is essential. To this end, we utilize insights into the system behavior to identify subgrids with a potentially negligible impact on the electrical behavior of the overall system. Hereafter, three approaches are presented, which are based on topological, electrical, and market insights.

**B. Topology-Based Subgrid Selection**

Transmission grids often exhibit small subgrids at the boundary of the grid which are only connected by a single corridor, i.e., one branch or several parallel branches. These subgrids include single buses, lines of buses and small “islands”, i.e., small groups of buses which are connected to the main grid via a single corridor. Such structures may contain several branches and be meshed, but often their internal power flow is not crucial to the overall grid behavior.

Consequently, such a subgrid is a suitable candidate for reduction, using the shared bus with the main grid as the subgrid’s representative bus as illustrated in Fig. 1.

![Fig. 1. Reduction of single buses, lines of buses and small “islands” at the boundary of the grid.](image1)

**C. Electrical Coupling-Based Subgrid Selection**

When two buses are connected via a branch with a very low series impedance, their electrical states are strongly coupled compared to buses linked by medium to high impedance branches. Therefore their aggregation may not affect the overall system behavior significantly and subsequently they are potentially suited for reduction.

Such branches \( k \in \mathcal{E} \) are identified by comparing their series admittance in Ohms to a threshold parametrized by \( \tau \in [0, 1] \) which is relative to the maximum series impedance in the grid\(^3\)

\[
|z_k| \leq \tau \cdot \max_{k' \in \mathcal{E}} |z_{k'}|.
\]  

\(^3\)In case of parallel branches, the equivalent series impedance must be considered. For the sake of a simple presentation this is not elaborated here.

The subgrid associated with such a branch consists of the branch itself as well as its terminal buses. It is reduced to its representative bus, which is either one of the terminals, see Fig. 2.

**D. Market-Based Subgrid Selection**

Similar to the market-based reduction of Singh and Srivastava\(^4\) the following approach utilizes LMPs to identify candidate subgrids. However, here the focus is on other insights gained from similar LMPs, namely the following two valuable implications: Firstly, a connected group of buses with almost identical LMPs indicates an area with low electrical losses. Secondly, if congestion occurs in the grid, the LMPs in the vicinity of the congested branches usually diverge. As the overall system behavior is sensitive to areas with high losses and congestion, these should be preserved. On the contrary, the internal power flow in areas with similar LMPs is potentially negligible, rendering them candidates for reduction.

Such subgrids are identified through a breadth first search approach starting from candidate buses with two or more connected corridors. In this clustering process, the reference is always the LMP of the candidate bus where the search started.

If a cluster is identified, this candidate will be chosen as the respective representative bus. A bus \( n \) that is connected to a representative bus \( r \) is included in the respective subgrid if the deviation of their LMPs is below the threshold \( \delta > 0 \), i.e.,

\[
|\lambda_n - \lambda_r| \leq \delta.
\]  

The process is repeated iteratively for all buses that are connected to a subgrid until all boundary buses of the subgrids connect to buses of the main grid that exhibit an LMP deviation beyond \( \delta \) to the respective representative bus. After the clustering process, any overlapping subgrids are combined, using one of their representative buses as the representative bus of the union. All subgrids are then subject to the reduction process in Section IV-A.

![Fig. 2. Reduction of branches with a very low series impedance.](image2)

![Fig. 3. Reduction of a connected group of buses with similar LMPs.](image3)

\(^4\)Note that the dual variables \( \lambda_n \) only equal the LMPs if the associated primal solution is globally optimal and if the OPF exhibits a zero duality gap, cf. e.g.\( \text{[23]} \). However, with respect to the subgrid identification, this issue is of minor relevance and, thus, not considered to simplify the discussion.
V. REDUCTION PARAMETER SELECTION

The proposed reduction method depends on a set of tuning parameters. To better illustrate their impact on the result and to show how to arrive at a proper parametrization for a desired accuracy, the proposed method is demonstrated in detail for an exemplary grid. This example can also be found as a tutorial in the open-source implementation provided in [21]. To this end, the German high voltage transmission grid for the year 2030 as proposed in the network development plan [24], [3] is considered. The model consists of a total of 1524 buses and 2208 branches. With the criteria defined in Section III 856 features are identified.

A. Modular Principle of the Reduction Strategy

The proposed method provides three different subgrid selection approaches and follows a modular principle: Each approach can be used individually and tuned to the grid model. The parametrization process also offers valuable insights into the grid that can be used to refine the reduction process.

By applying a combined reduction strategy, the degrees of freedom can be used to target a certain accuracy, e.g. a dispatch error $\varepsilon_{\text{disp}} < 2\%$. We identified the following sequences as the most appropriate ordering:

(i) Topology-based reduction
(ii.a) Electrical coupling-based reduction with threshold $\tau$
(ii.b) Feature refinement and repetition of (ii.a)
(iii) Market-based reduction with parameter $\delta$

To start with the topology-based reduction is obvious as it does not impact the other reduction steps, is basically independent of parameter adjustments, and introduces only a small error. The ordering of the next steps is not as intuitive, but several experiments have shown that the market-based reduction profits from the electrical model-based reduction and its feature addition, while in the reversed ordering the feature addition is less effective.

B. Parametrization

The parametrization of the combined strategy is performed consecutively with each reduction step continuing on the result of the previous step.

The topology-based reduction depends on a definition of a “small” group of buses. Here 1% of the total number of buses were considered small. In several studies we found that above a certain threshold, the precise definition of “small” has little impact as the boundary structures themselves are small, e.g. for the considered model the choice of 20 or 800 buses leads to the same result. Even though the subgrids are small, the reduction potential is considerable: 13.4% of all buses and 10.8% of all branches are reduced by this approach, while the induced error is very small with $\varepsilon_{\text{disp}} = 0.11\%$ and $\varepsilon_{\text{flow}} = 0.07\%$.

In contrast, the electrical coupling-based reduction depends heavily on its parameter $\tau \in [0, 1]$. When performing a reduction for different $\tau$, it becomes evident that this method offers a trade-off between the reduction and the error: A higher value for $\tau$ enables a more extensive reduction, but usually increases the error for both the dispatch and branch flows, see Fig. [4] Besides this trade-off, we observed that the error caused by large values of $\tau$ is usually due to a comparably small number of generators which we will refer to as critical generators. This indicates that the reduced model does not represent the environment around these generators sufficiently accurate. As mentioned earlier, the notion of features provides the means to include this knowledge and improve the accuracy.
This feature refinement requires two parameters: an absolute limit of the dispatch error in MW to define when a generator is considered critical (here fixed as 10 MW) and the depth $\vartheta \in \mathbb{N}$. All buses which can be reached from critical generators by traversing a maximum of $\vartheta$ branches are added to the set of features. As shown in Fig. 5, the error decreases significantly faster than the achieved reduction. This feature refinement allows for large values of $\tau$ with a considerable reduction potential while retaining small dispatch and branch flow errors.

The market-based reduction offers the parameter $\delta > 0$. As with the electrical coupling-based reduction, it provides a trade-off between the reduction and the error: A higher $\delta$ enables a more extensive reduction but typically invites a higher error. The results for different $\delta$ are shown in Fig. 6.

To achieve the targeted dispatch error of $\varepsilon_{\text{disp}} < 2\%$, the parameters are set to $\tau = 0.05$, $\vartheta = 4$, and $\delta = 0.08$ which leads to a reduced model with 729 buses (52.1% reduced), 1234 branches (44.1% reduced) and 292 cycles (35.8% reduced). The error evolution over the reduction steps is shown in Fig. 7 and results in $\varepsilon_{\text{disp}} = 1.5\%$ and $\varepsilon_{\text{flow}} = 9.4\%$.

VI. Application Examples

In this section, the proposed reduction strategy is applied to three different transmission grids, targeting a reduced model with approximately half the number of buses. This is an exemplary choice – for a higher accuracy, a lower reduction may be targeted. Furthermore, it is illustrated how the reduction accuracy under the reference scenario for the reduction decisions transfers to different load scenarios. In the following, the German grid (380 and 220 kV, 455 cycles) of the previous section as well as the Polish and French grid are considered. The Polish grid model represents the Polish grid 400, 220 and 110 kV networks during winter peak conditions (2383 buses, 2896 branches and 504 cycles)\footnote{The number of cycles is relevant in certain expansion strategies, e.g. the hybrid architecture \cite{23,25,26}.}. The French grid model represents the French 380, 225 and 150 kV networks (2848 buses, 3776 branches and 595 cycles)\footnote{Parameters: $\tau = 0.05$, $\vartheta = 4$ and $\delta = 0.8$.}.

As documented in Table I reduced models with a similar reduction extent and accuracy to that of the German grid discussed in Section V-A can be constructed for the Polish and French system. This is a consequence of the fact that the reduction strategy can be adapted to different grids by adjusting the reduction parameters. On account of the different approaches, there is an inherent adaptability: if one reduction approach is less effective for a certain grid, the other approaches can be applied more radically to achieve a similar reduction.

A. Reduction and Results for the Reference Scenario

As documented in Table I reduced models with a similar reduction extent and accuracy to that of the German grid discussed in Section V-A can be constructed for the Polish and French system. This is a consequence of the fact that the reduction strategy can be adapted to different grids by adjusting the reduction parameters. On account of the different approaches, there is an inherent adaptability: if one reduction approach is less effective for a certain grid, the other approaches can be applied more radically to achieve a similar reduction.

B. Verification for Different Load Scenarios

The reduction strategy is solely based on a reference scenario of the grid. However, for conversion planning it is necessary that the reduced model offers also sufficient accuracy under different load scenarios. In the following, this is examined for all three grids. The different load scenarios are generated by scaling the loads of the reference scenario according to the 96 hours of the exemplary winter and summer weekday and weekend presented by the IEEE Reliability Test System Task Force\footnote{Parameters: $\tau = 0.03$, $\vartheta = 7$ and $\delta = 0.1$.} Table 4.

As shown in Fig. 8 the generalization is particular to a model: the French grid, which is the most strongly meshed.
among these examples, exhibits an especially consistent behavior. The German and Polish grid fluctuate somewhat more and, depending on the application, a slightly more conservative reduction may be necessary. Still, all reduced models exhibit an adequate accuracy for all scenarios, which can be attributed to the exclusive reduction of subgrids with a limited impact on the overall system behavior.

VII. CONCLUSION

The proposed reduction strategy combines a topology-based, electrical coupling-based, and market-based subgrid selection with a specifically designed reduction method to produce a reduced grid model which preserves designated features and the structure of the original grid. This approach avoids the addition of artificial entities and the implementation of physically invalid or application-adverse reduction measures by being aware of and preserving features and the relation of every entity to its physical counterpart.

Inherently, on account of its adjustable parameters, the reduction strategy offers a trade-off between the reduced model’s complexity and accuracy, enabling the construction of a reduced model with a specific accuracy. The combination of the different approaches also allows the strategy to adapt to different grids: if one reduction approach proves to be less effective for a certain grid, the targeted reduction can be achieved by applying the others more drastically. The reduction strategy offers considerable reduction potential, e.g. to half of the number of buses at a very moderate error, which enables power flow studies at substantially lower computational costs.

Due to the careful selection of subgrids for the reduction and the preservation of features, the accuracy for the reference scenario generalizes well to different load scenarios: An appropriate parametrization under the reference scenario leads to a reduced model which adequately represents the original grid model for various load scenarios.

Especially in the context of comprehensive power flow studies for capacity expansion it is of the essence that conclusions drawn from the reduced grid model transfer to all load cases in order to arrive at reasonable capacity expansion measures. Moreover, the objective of these studies is to identify areas of the grid which require capacity expansion. The proposed reduction strategy is especially qualified in this case as it is designed to preserve such structures within the reduced model and thereby draws the focus to areas that are crucial to the overall grid behavior.

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