

Methodological Approach for Integrated Grid and Market Simulation of Coherent Distribution and Transmission Systems

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Abstract

The analysis of distributed generation systems and their influence on the different voltage levels of the power grid involves a detailed modelling of all observed units and the connecting distribution and overlaying transmission networks. In return this generation has increasing effects on the European transmission system, whose entire simulation with the same detailing as single distributed generation systems is not feasible, because of the complexity of the therefor needed simulation system. Thus a concept has been developed to fulfil both a high level of detail in distribution networks for a multi-agent system based control algorithm and the analysis of the European transmission system. This was achieved by aggregating and transferring the information and behaviour of single distribution networks to the ultra-high voltage nodes of the transmission system in separated, but coordinated joint simulations.

1 Introduction

With the analysis of large, spatially extended systems as the European transmission system the complexity of the simulation model is a distinct constraint, if detailed models are required. This problem gets enhanced, if not only the transmission system, but also the underlying supply levels are considered.

The transformation of the energy supply system from classical design with large scale fossil power plants and top-down power flows to a generation mainly realised with renewable energy sources (RES) is contemporary high focused in research and political programs and outlines several research questions for both energy supply and market processes. Especially questions of overall system stability, in particular frequency stability and the compliance of voltage levels are widely discussed in current research projects². With this system transformation in all voltage levels many technical problems will and already do occur, thus a neglect of one voltage level is not acceptable in research analyses. Furthermore, these effects are closely tied to the current electrical power markets and grid codes, which specify the deployment of generation as well as the profitability of the system design. Thus market and grid must be modelled in congruent scenarios. This leads to several problems in the realisation of the required system model with permissible simplifications and sensible approaches for combining all requirements.

As presented, the analysis of the on-going transformation process needs detailed simulation models of both large scale transmission systems and the local constraints of single distribution grids. Comparable simulation methods, though focussed on the transmission system, are currently developed at several research facilities, e. g. (Gutschi et. al. 2012), (Moser 2012). Based on own preliminary work on an integrated grid and power market simulation (see chapter 4) for the European transmission system, the principal question of the overall system model was the integration of distribution networks and decentralised organised generation capacities (see chapter 4 and 5).

Primarily this merging affects questions of overall complexity, grid design and market functionality, considering two significant different systems, which are connected on both electrical and market layer, but are spatially entirely divergent.

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² For example www.kombikraftwerk.de

The analysis of the on-going transformation process is part of the research project Smart Nord³ (see chapter 2) as well as the approach of solving the shown problem of system complexity. This challenge was main focus during the last year of research at the Institute of Electric Power Systems (IEH) within this research project. This paper explains the main challenge of a complete, but not infinite detailed system model for grid simulation, as well as the therefor needed market design and describes the developed approach.

2 Project Smart Nord

This approach for an integrated grid and market simulation for coherent distribution and transmission systems (below system model) is the central system model to evaluate system-stabilising approaches and new market-design concepts in the interdisciplinary research project Smart Nord⁴. It has to be suitable to answer different research questions of this project as described in (Sonnenschein et. al. 2012). Main focus of this research project is the analysis of both influence and possibilities of multi-agent systems (MAS) which control consumers and RES in future energy systems. The MAS are developed by another subproject (Nieße et. al. 2012). Not only the benefits of these MAS but also the boundaries of further RES expansion will be examined.

The research project consists of several different sub-projects with different research objectives covering the disciplines electrical power engineering, informatics, economics and environmental planning. The focus encompasses first the self-coordinated, decentralised provision of active power, reactive power and balancing power by MAS in local distribution networks in which the control of single households and generation units in self-organised coalitions and the permissibility of these regional bounded system states are the main research questions. Second the analysis of the influences of this provision on the European transmission grid, the European market for electricity and the frequency stability of the electrical power system are realised with pan-European system models and simulations of the entire system. More extensive project descriptions are given in (Sonnenschein et. al. 2012) and (Nieße et. al. 2012).

Because a combined analysis with only a small number of distribution grids controlled by the MAS would yield non relevant impact on the German or European transmission system or electricity market, the following explained system model (see chapter 5) with two electrical separate grid areas has been developed, so both questions can be analysed in adequate accurateness. The introduced system model fulfils both requirements of local exactitude and overall coherent assumptions. Additionally an integrated market model (see chapter 4) has been developed to comply with the needs of all research questions in the overall project.

3 Methodology

Because of the introduced requirements the main questions in the research methodology were, how first the overall simulation system accuracy and second the transfer of system services contributed by local coalitions to the overall system stability could be realised and analysed without an extensive overall modelling from each ultra-high voltage (UHV)-node to its underlying low voltage (LV)-networks. To avoid this inadmissible complexity, only separate distribution networks are modelled in detail (see chapter 5).

With only a few parts of the grid controlled by the new algorithm and the rest of the grid being modelled with conventional design models the analyses of market, frequency stability or the provision of fur-

³ Acknowledgement: The Lower Saxony research network 'Smart Nord' acknowledges the support of the Lower Saxony Ministry of Science and Culture through the "Niedersächsisches Vorab" grant programme (grant ZN 2764).

⁴ <http://www.smartnord.de>

ther system services would have been non-significant in the simulation. Thus a reasonable and achievable transfer of the detailed modelled distribution networks to all UHV nodes is required to achieve a conclusive concept.

Hence a slight modification in the self-organisation algorithm of the MAS used for the distribution grids will be used to reproduce the coalition behaviour of these grids first at selected, later on at each transmission grid node (see Figure 1). The alteration of the MAS will be implemented by the subproject responsible for the regular MAS. As a first approach for the aggregated units the models for the single units are scaled with the nominal power. With increasing project progression they will gradually be improved by using first results of the MAS distribution system simulations.

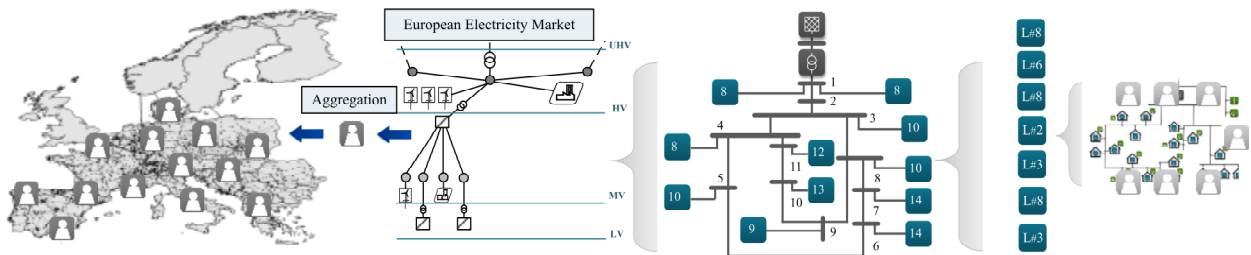


Figure 1 Transfer of distribution grid MAS to transmission grid MAS

Hereby these aggregated agents will control all underlying RES, such as wind power, photovoltaics and combined heat and power plants as well as flexible loads. With the knowledge from the detailed analysis of the single distribution grids these agents will bid with notably more generation power on the markets for active power and balancing power compared to the analysis in the local MV to LV grids. To gain results for all relevant research objectives the two grid areas are linked by coherent market prices and using the same simulation scenarios (Blank et. al. 2013) which have been developed interdisciplinary by all research partners.

Thus it is ensured to have significant impact of the self-organised units on market prices and power flows. Herewith analyses of various impacts caused by this new approach of system-control and market design can be realised (see chapter 6). With this simulation method a feasible abstraction is conceived and in the next project stage simulations of first stationary and second dynamic processes can be performed and analysed (see chapter 6).

4 Integrated Grid and Power Market Simulation

For analyses of the on-going changes in the European electric power system, e.g. the strong increase of renewable and decentralised generation and cross-border power flows caused by trading activities, the IEH in Hanover is developing an integrated grid and market simulation of the European electric power system. To ease enhancements the simulator is built modularly. Main elements are: power plant dispatch, reliability model, optimal power exchange calculation, UHV grid data of the Continental European Network of Transmission System Operators for Electricity (ENTSO-E) Interconnected System Grid, power flow calculation, short circuit calculation and several databases. As this paper is about the alteration of the simulation to regard market offers made by self-coordinated coalitions the focus of this chapter will only be on modules of the simulator that are affected by this alteration. For a full description of the integrated grid and market model refer to (Rendel et. al. 2012), (Breithaupt et. al. 2012) and (Rendel et. al. 2011).

The power plant data base contains most European thermal power plants with a nominal power larger than 50 MW with the attributes commissioning year, nominal power, combustion type, fuel, efficiency, location and the installed capacities of RES as well as the load for each ultra-high voltage node. As most of the RES in Germany are covered by the renewable energy law (EEG 2008) they can feed in their generation with priority and were therefore modelled with historic generation time series. The load was assumed to be temporal inflexible and price insensitive and was therefore also modelled with historic time series (Rendel et. al. 2012).

To implement a market-based approach for renewable generation and flexible loads the renewable generation and parts of the load in Germany will prospectively bid at the market as MAS-controlled self-organised coalitions of aggregated units (see chapter 3).

To integrate the bids of the aggregated units the existing power plant dispatch will be modified. In the first step the residual load (total load minus flexible load and renewable generation) in a certain price zone is split into several blocks as shown in Figure 2. From these blocks for every point in time and load level an expected operation time horizon can be derived. Based on the expected operation time horizon the plant operators compute their marginal costs for the currently treated load level and point in time. These marginal costs include start-up costs and expectation values for possible inaccuracies in the load and renewable generation forecast. As start-up costs are primarily relevant for large thermal power plants, only these units get dispatched in that way.

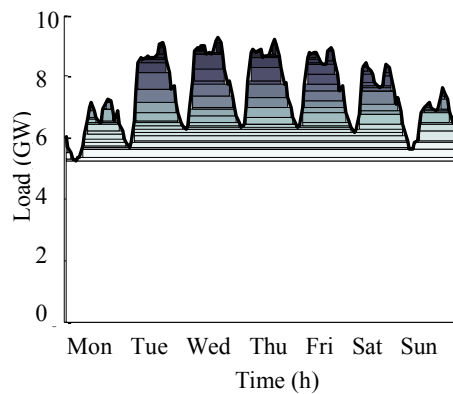


Figure 2 Load split in several load blocks

In the second step the merit-order of each hour is calculated using the marginal costs of all dispatched thermal power plants. The bids made by self-organised coalitions are integrated into this merit-order. The new intersection of merit-order and fixed load determines which coalition has been successful.

5 System Model

5.1 Cohesive Grid and Load Model

With the objective of a grid model covering UHV to LV grids and in consideration of the already developed detailed model of the European UHV grid (see chapter 4) a main aspect of the system modelling was the integration of newly developed grid models for the underlying voltage levels. Also part of the system model is the power market simulation described in chapter 4.

To extend the grid model, the given constraints of the 400-kV-model were used as input parameters for the modelling of single distribution networks, which are connected to selected UHV nodes and represent

the simulation environment for the self-organisation approach for single units of affiliated subprojects with focus on self-organised processes (see Figure 3).

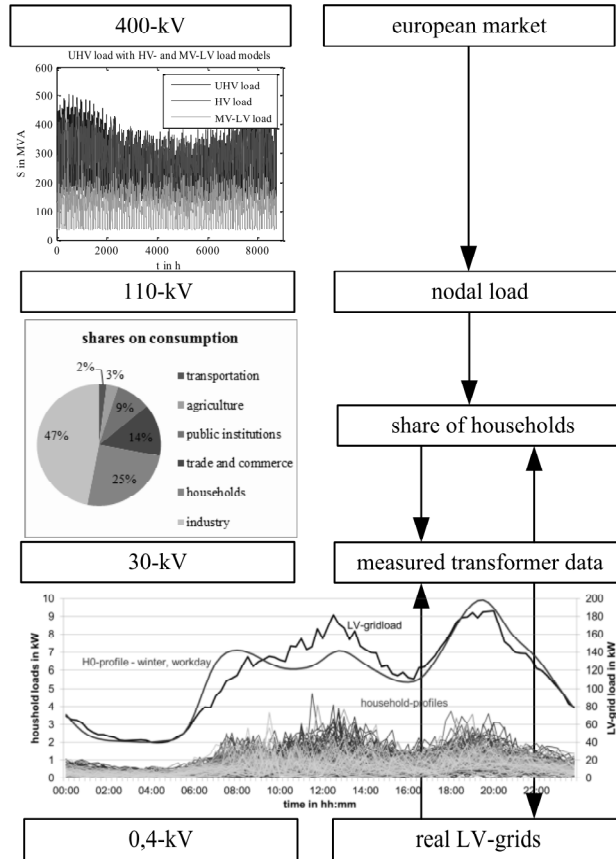


Figure 3 Development of the system model under given constraints

One challenge of this approach was the required combination of both, the UHV nodal load data and the real LV local distribution systems of smaller towns in Germany given by (Blank et. al. 2013) (see Figure 3). These LV-grids had to be used, since the gathered detailed information on the distribution networks could be used by other subprojects to build realistic evaluation scenarios (for the years 2011 and 2030) within the LV grids.

This combination of UHV and LV constraints was realised within a load distribution model (see Figure 3), which first divides the given time course of the UHV in the main consumption sectors according to (BDEW 2012). In the high-voltage (HV)-level this division is further subdivided into manually sized shares and allocated to the nodes of 110-kV-benchmark grids (Blank et. al. 2013)⁵. Beyond that the share of households on this various nodal time series is used to determine the required numbers of

⁵ These grids will later be replaced by synthetic 110-kV-grids based on approximated real grid data.

different LV-grids (8 rural and 2 urban characterised grid models are used) to represent the same network load as the 110-kV-data using a Monte Carlo method based algorithm.

Since the LV grid models use the BDEW H0⁶ profile, a standard load profile for German households, to reproduce measured data of the local distribution network transformer, whereas the UHV load curve is based on measured data published by the ENTSO-E⁷, a deviation of the network load occurs. Therefore the resulting divergence from the UHV load is merged with the shares of consumption parts besides households (e.g. industrial and agricultural large-scale consumers) in a residual load model for each HV node. This results in a cohesive grid model from single HV nodes to detailed modelled MV and LV areas (Blank et. al. 2013).

5.2 Grid Expansion

In the first stage of the project the main focus is the stationary analysis of the developed power system with different approaches of benchmark (sub-)grids and the implementation of the MAS-controlled units in two different main scenarios (Blank et. al. 2013). Within the upcoming power flow simulations the technical constraints of the grid data, e.g. transformer and transmission line capacities, will presumably not be sufficient in all case studies due to high amounts of distributed generation capacities used in the scenarios.

Although the expansion of the distribution grids is a widely politically discussed topic the grid models in this project will be plainly expanded according to common standards – as described e.g. in (dena 2012) – to ensure a functional simulation environment for the MAS without analyses of costs and timing of single grid expansion projects.

With the on-going development of the *Bundesbedarfsplangesetz* (BMWi 2012), based on the *Netzentwicklungsplan 2012* (BNetzA 2012), sufficient estimations of the expansion of the German transmission grid are available in detailed scenarios. To achieve a realistic overall scenario within this research project it was decided to adopt the designated expansion plans in the German UHV grid. For the European grid the ENTSO-E released the Ten Years Network Development Plan (TNYDP) (ENTSO-E 2012), which gives a good estimation of the pan-European demand of grid expansion in the next ten years.

6 Conclusion and Outlook

Based on a description and analyses of the requirements and research questions of the research project Smart Nord an evaluation concept with separated, but coordinated joint simulations was developed. The first simulation involves models of the whole Continental European transmission system with a detailed modelling of selected subordinate distribution networks covering UHV to MV as well as the European electricity market. Objective of this simulation is to gain global results about the alteration of e.g. power flows, voltages, electricity prices and frequency stability due to increasing decentralised generation. The second simulation involves detailed models of single distribution networks covering MV to LV. This simulation tends to get results about the ability of MAS self-organisation algorithms to control single generation or load units in order to make offers at active and balancing power markets or to provide additional system services.

Since both simulations are required to get results on the fundamental research question whether MAS controlled, self-organised, distributed units are able to provide all required system services, the simulations are coupled by the electricity price and by using the same scenarios. Furthermore, because single dis-

⁶ http://www.eon-bayern.com/pages/eby_de/Netz/Stromnetz/Netzzugang/Lastprofilverfahren/Standard_Lastprofile/index.htm.

⁷ Available on <https://www.entsoe.eu>.

tribution grids are neither able to distinctly influence power flows and voltages in the transmission system nor market prices, an adapted self-organisation approach applied in the MV to LV simulation is used to control the renewable generation and flexible loads in entire Germany. Therefor aggregated models of the renewable generation and flexible loads will be developed to realise a provision of active power, system services, esp. control power, and reliable market bids.

During the simulations of stationary processes the first focus will be the (re-)design and benchmarking of the grid and system model, e.g. needs of grid expansion and (n-1)-security of the overall system. Further the functionality and design of the overall market will be in focus, with the market being the central position for all agent coalitions' activities.

In the later following analysis of dynamic processes the frequency stability and contributions of the RES-coalitions for voltage stability in the local distribution networks will be discussed. As a result of the simulations of the stationary and dynamic behaviour, forecasts on grid expansion, electricity prices and possible boundaries for the share of decentralized generation will be given.

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