MODELLING OF SYNTHETIC POWER DISTRIBUTION SYSTEMS IN CONSIDERATION OF THE LOCAL ELECTRICITY SUPPLY TASK

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ABSTRACT

With the increasing integration of renewable energy sources into the electricity supply system, planning and operation of power distribution systems has become more complex and challenging. As a consequence of this progress, new and innovative concepts for distribution system operation are in research. Therefore, detailed grid models are required. Due to different power demand and generation according to the region, these grids show a very heterogenous structure. Thus, this paper proposes an approach to synthesize grid models based on the real supply task of German grids.

Publicly available data of geoinformation systems, demography, and power generations in combination with a probabilistic approach based on evaluations of real grid data is used to identify the electricity supply task in high spatial resolution. Considering the local supply task, the grid topology is simulated in a two-step heuristic, including a capacitated vehicle routing problem to determine the basic grid topology.

The resulting model is able to generate German MV grids in high spatial resolution. Further, it is possible to identify and reproduce local characteristics.

INTRODUCTION

The energy transition in Germany has led to a significant restructuring of the energy supply system. This change is particularly evident on the generation side, where there is an increased expansion of renewable energies at the distribution grid level. In the future, however, consumer behavior will also change significantly, e.g. due to the electrification of mobility and an increased amount of home battery storage facilities. The generations and loads installed in the distribution system show a wide range of local variations. These differences are reflected in the energy supply task and result in varying grid structures.

Considering these developments, planning and operation of power distribution systems are becoming more complex and challenging in the future. The development of new concepts and methodologies for improving planning and operation of power distribution system needs performance evaluation with realistic grid topologies. However, even though several small-scale grid data sets are publicly available, access to diverse and large-scale distribution power systems is limited. In addition, there is a risk that locally specific grid characteristics are neglected due to the lack of representativity of real grid samples. Synthetic grids can offer an alternative for this problem. Modelling synthetic grid aims to generate test systems that are completely fictitious but capable of representing local characteristics of actual real power grids. Hence, this paper presents an approach to generate models of present and future synthetic medium voltage (MV) grids based on both statistical evaluation analysis of real grid data and spatial high-resolution land cover and land usage data. This paper focuses on modelling MV grids of Germany. The Low Voltage (LV) grid is neglected and represented as aggregated load and generation at the MV-LV substation.

MODELLING APPROACH

Model Overview

Based on a given MV grid area the presented model determines the grid topology according to the specific electricity supply task and the positions of the grid customers in the area. As data basis, the model uses multiple high-resolution spatial data, which contain information about land cover and use, power generations and loads, and population density. These data sources are aggregated in a so-called input database. In addition, the model also includes a scenario database as an input. The scenario database enables the integration of forecasts for future developments of renewable energy sources (RES) and loads into the procedure. Forecast data is often broken down into different spatial resolutions. For example, forecasts for numbers of grid customers or their installed capacities are usually related to a certain spatial area in the form of state or administrative boundaries. The model dissolves the forecast data and allocates the grid customers into the grid areas by using suitable distribution functions. After a preprocessing of the database, the first step of the model is to define a MV grid area. This represents the spatial boundaries of one MV grid. Using land cover and usage data as well as population density information the area is then spatially classified in order to determine possible locations for loads and generations. Next, the supply task is being defined. Using publicly available data for renewable generation and the previously determined spatial classification, the exact position, capacity and type of power plant are defined and assigned to MV nodes. The specific household-, as well as retail and industrial loads are determined and assigned to MV-LV substations by a combination of public sources regarding locally dispersed population, distribution functions based on statistic evaluation analysis, and the spatial classification. In a last step, the previously determined nodes are connected with a capacitated vehicle routing problem (CVRP) and topology-improvement heuristics. A general overview of the procedure can be seen in Figure 1.

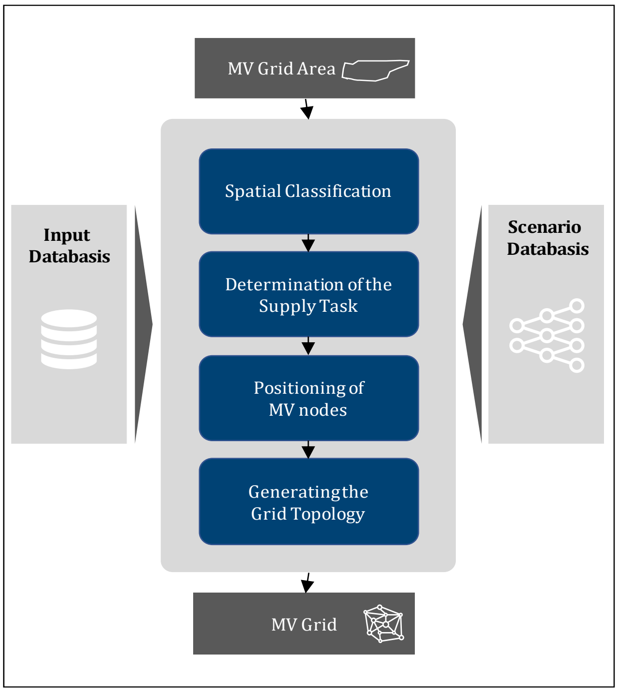

Figure 1 General Procedure of the Model

Medium Voltage Grid Areas

There are about 4.500 MV-grids in Germany [1]. However, there is no publicly available geographical information regarding the boundaries of the various grid areas. Therefore, the location and the size of a grid area is determined with the help of the position of the HV-MV substation – this can be taken from Open Street Map – and a Voronoi decomposition [2]. A Voronoi diagram decomposes an area (Germany) by assigning each given point (substation) all points which are closer to this point than to another of the given points. The resulting Voronoi areas are used as an approximation for the MV grid areas. All loads and power generations in an area are assigned to one MV grid.

Spatial classification

Historically, MV grids were built with the objective to distribute the power from the upper voltage level to the customers at the MV and LV level. Additionally, todays grid is responsible for the connection of decentral power plants mainly based on RES. Thus, the specific MV grid topology is derived from the individual position of all loads and power generation units.

Therefore, positioning requires spatial data that is as accurate as possible. For example, geoinformation systems (GIS) can be used to classify land areas in high resolution. In particular, the land cover and land use classes of the Corine Land Cover (CLC) data set derived from satellite data offer information for better classification of the supply task and for determining realistic positions of loads and generations [3]. With CLC it is possible to identify urban, suburban and industrial areas in order to respectively assign the household-, business and industrial customers. These data sets can be improved by combining them with population grid data of the Federal Statistical Office from the census [4]. It contains the population data in a 100 m² resolved grid structure. With this data source it is possible to assign population and therefore household customers in a highly spatial resolution. Rural, suburban and urban areas can thus be even more precisely identified and geographically located than merely with the CLC data. An exemplary result of the spatial classification of an MV-area can be seen in Figure 2 (the number of different classifications has been reduced for an improved overview).

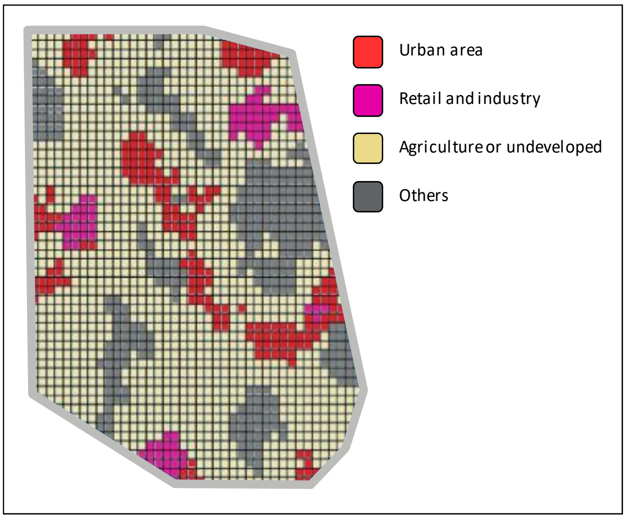

Figure 2 Spatial Classification of an MV Grid in 100 m² Resolution

Determination of the Electricity Supply Task

In order to create a synthetic grid topology based on the local supply task, the electricity demand and their geographic position need to be identified. The model distinguishes between four different grid customers: household loads, retail loads, industrial loads and power generations (mainly RES).

Deriving from the census information, the positions of household customers have been already locally identified in the previous step. However, it is also important to determine the household sizes in order to define the electricity demand of the loads. For this, the number and dimensioning of households for a house is drawn as a

function of the population density. Based on the size of the household, a further distribution function is used to determine the annual energy consumption and peak load of the household [5].
There are almost no precise data sets on retail and industrial customers available. However, the spatial extension of the retail and industrial area of Germany and their energy consumption is publicly available [6][7]. They have been divided into postal code areas. According to the shares of the postal code areas located in the MV grid area, the total retail and industrial area as well as the energy consumption can be estimated. With an existing model according to [8], the numbers and capacity of the customers can be defined by using specific distribution functions [5]. By considering the spatial classification of the MV grid area, the customers are then assigned to possible positions in the grid area.
Data on renewable power generations are publicly available [9][10][11]. In addition to information on the power plant type and the installed capacity, it also contains the spatial position. However, for some power plants there is no information about the exact spatial position. These power plants are therefore assigned to possible positions in the grid area according to the spatial classification and in correlation to the position of other power plants.

Positioning of the MV-LV substations and MV customers

Prior to the generation of the grid topology, it is necessary to assign all customers to a MV node. In case of household customers, realistic connections to a MV-LV substation must be identified. For this purpose, household customers are clustered by a hierarchical agglomerative algorithm to represent realistic low-voltage grids in terms of expansion and load. Due to the usual cable lengths and extensions of LV grids a distance of 1.5 km must not be exceeded [12][13]. In addition, power plants connected at the LV level are also assigned to the cluster. Based on a probabilistic approach, typical types of transformer sizes – depending on the local supply task (rural, suburban, and urban) – are determined as a substation. The basis of the probabilistic approach can be seen in Figure 3.

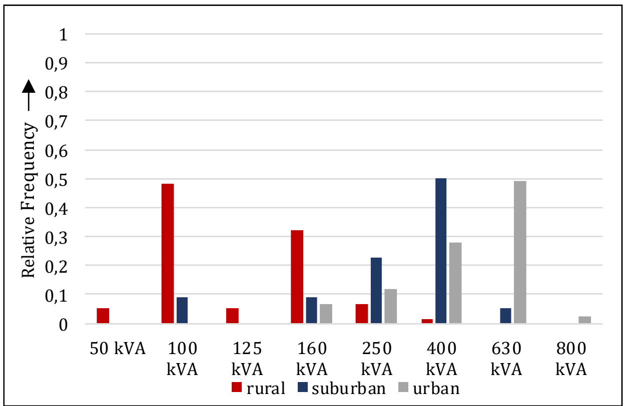

Figure 3 Relative frequency of transformer sizes in dependency

The position of the MV-LV substation is determined considering the geographical center and the spatial density of the households.
An analysis of real grid data shows that not every retail and industrial customer or power plant connected at the MV level has its own grid connection point, but often several grid customers share one connection point. For this reason, MS nodes contain different generation and load combinations. The node combinations derived from an analysis of real grids are shown in Table 1.

Table 1 Possible Combinations of Customers at a Node

	LV-Grid/Wind/ Retail&Industry /PV	LV-Grid/Wind/ Retail&Industry /PV	LV-Grid/Wind/ Retail&Industry /PV
Combination 0	LV-Grid/Wind/ Retail&Industry/P V	-	-
Combination 1	LV-Grid	Retail&Industry	-
Combination 2	LV-Grid	PV	-
Combination 3	LV-Grid	Retail&Industry	PV
Combination 4	Retail&Industry	PV	-
Combination 5	Wind	Wind	-
Combination 6	Wind	Wind	Wind

A discrete distribution function was derived from the frequency with which these nodes occur in real grids. The combinations are drawn from the pool of customers on the basis of this function. As soon as a certain customer type is no longer available, a combination containing this type can no longer be used. If the node corresponds to a LV grid or contains a LV grid, the position of the node is defined by the MV-LV substation. Otherwise, the nodes are assigned to a specific position in the grid area. In order to position these nodes realistically, this allocation is based on a local classification (CLC) described above. The routine for the determination of MV nodes is visualized in Figure 4.

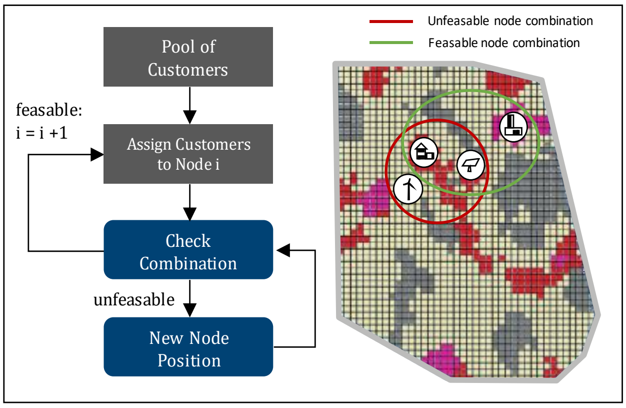

Figure 4 Routine of Assigning MV customers to a node

Generation of the Medium-Voltage Grid Topology

Historically, the structure of MV grids in Germany has grown primarily based on the supply task and can only be subsequently adapted to a limited extent or at high financial expense. Therefore, the grid structure is selected on the basis of various technical and economic criteria. In general, there are three basic structures which can be used by DSOs to build up the grid: meshed, ring and radial. The decisions always focus on the trade-off between cost and reliability of supply. As a result of this trade-off, 85% of the German MV grids consists of ring topologies. Thus, this model focuses solely on this topology [1].

The generation of MV grids with ring topology can be treated as an optimization problem in form of a CVRP. The objective of the CVRP is to identify a set of minimum cost routes for a fleet of vehicles, from a depot, and in consideration of a specific vehicle capacity. This optimization problem can be adjusted to generate MS grid topologies. The routes can be regarded as ring lines, the thermal capacities of lines are interpreted as vehicle capacity, the customer demands are then equivalent to the loads and generations connected to the nodes, and the depot corresponds to the HV-MV substation.

The initial topology is generated using the parallel savings heuristic of Clarke and Wright [14]. In order to determine the maximum possible demand of a node, loads and generations are summed up separately. The higher value is used as the maximum demand of the node. In reality, this represents the critical scenario of high load and low generation or respectively low load and high generation. The total capacity of the vehicle results from the technical boundary conditions of the line types. For this, the model uses a standard type of a MV cable and an overhead line. Cables are used for urban and suburban areas, while rural areas are partly supplied with overhead lines.

The resulting initial grid is capable of fulfilling the supply task by complying with the restrictions formulated in the CVRP. However, a comparison of the initial grid with real grids shows, that in reality some MV generations and remote loads are often connected with a stub. This leads to a significantly shorter total length of the grid. Thus, the initial grid topology is subsequently modified in a post processing. Therefore, a heuristic was implemented in order to reduce the total length of the rings by connecting specific nodes with a stub to the ring.

First, a node is separated from the ring and then connect via a stub to the altered ring. The reduction of line length compared to the initial topology is calculated. This is successively carried through for each node connected to the ring. This process represents one iteration. The final topology is determined by a heuristic, that implements the stub with the highest reduction in line length in each iteration. After each iteration the line length reduction for each possible stub is recalculated. This process is continued until no more reduction is possible. An example of the routine is visualized in Figure 5.

For reasons of the reliability of supply, a stub connecting a node, which includes a load must not exceed a length of 2-4 km – the specific length depends on the maximum demand of the node. The possible range of stub lengths has been determined within an evaluation of real grids. Since the supply of a power generation is not as critical as a load, there is no restriction to the length of a stub connecting a generation plant.

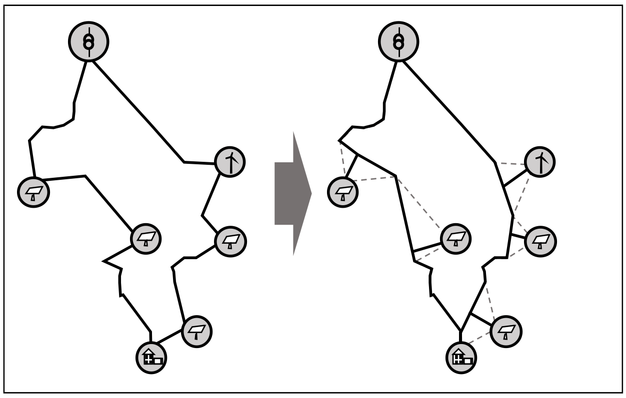

Figure 5 Exemplary Improvement of the Grid Topology with Stubs

EXEMPLARY RESULTS

First, we want to analysis the identified supply task. Therefore, an exemplary synthetic MV grid is shown in Figure 6.

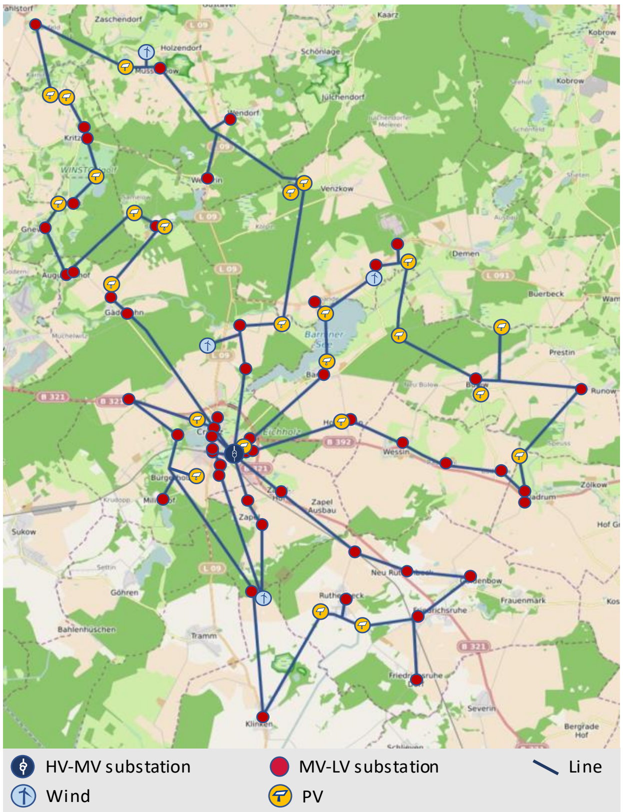

Figure 6 Exemplary MV grid (Source: Open Street Map)

The synthetic grid represents a mainly suburban and rural area with high share of RES – in particular PV. The resulting positions of the MV-LV substations are marked as red spots. Obviously, inhabited areas according to the displayed map have been considered by the model. MV-LV substations are geographically positioned inside or close to a city. Thus, a realistic population and substation distribution has been modelled. Due to the limited maximum capacity of the transformers, local accumulations of substations occur in areas with high density of population.

A comparison with multiple real grid data shows, that the basic structure of real grids can be reproduced with the model. In general, the number of MV nodes and MV-LV substations deviate only slightly. In terms of ring numbers and line length, disparities can occur in a few cases. Two reasons for this issue have been identified. First, an analysis of the results has shown, that the capacity of the line has a major impact on the topology. Real grids have developed historically and therefore consist of different types of lines with different capacities. However, the model considers only one type of cable and overhead line. Second, even though the majority of MV grids consist of rings, neglecting meshed and radial structure can also lead to a deviation from real topologies.

CONCLUSION

By combining probabilistic approaches with publicly available data on real geographic properties, demography, and power generations, it could be shown that the resulting synthetically generated grids are highly suitable as a representation of the according real electricity supply task. Furthermore, it is possible to generate a realistic grid structure as well as to reproduce local grid features.

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