MEDIUM VOLTAGE NETWORK PLANNING CONSIDERING DISTRIBUTED GENERATION AND DEMAND SIDE MANAGEMENT

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ABSTRACT

Curtailment of distributed generation and demand side management may be a feasible alternative to network expansions in future medium voltage networks. Hence both must be considered in network planning today to develop cost efficient networks. Different control strategies are possible and each will result in a distinct optimal network structure. Network and energy costs will also differ. So far network operators and regulators do not know what control strategy should be striven for.

Furthermore no planning algorithm exists that allows considering different control strategies. In this paper, a new algorithm is presented in this paper to solve the planning and control problem in an integrated manner. The distribution system operator of the city of Aachen (STAWAG) has decided to use this algorithm to evaluate different control strategies and derive an optimal long term network structure. The results of this study are also elaborated in the following.

INTRODUCTION

The European Union (EU) has agreed upon an energy strategy for 2020. The energy efficiency is to be increased by 20% and 20% of the final energy consumption are to be supplied by renewable energies. In Germany it is expected that distributed generation, especially from wind and photovoltaic energy sources, increases significantly till 2020 [1]. This has severe consequences for the operation and planning of distribution networks. Different consulting firms approximate that medium voltage (MV) networks will be affected strongly and investments of 5 to 6 billion € will be required for network expansion in this voltage level [2]. It is expected that demand side management (especially for electric vehicles) will contribute significantly to facilitate system balancing on a national level. As of today it is not yet obvious who will control these flexible loads and what control strategy will be used. Numerous regulating regimes are being discussed. Spot market based control strategies are one likely alternative that may be used for demand side management (DSM) in future. Often times this will lead to a reduction of distribution network loading, especially if solar generation is high. However, if renewable generation that is not distributed (i.e. offshore wind) causes a low system load (and thereby low prices), market based demand side management may be beneficial for system balancing but may also cause overloading in distribution networks.
For the reasons stated above, a direct relationship of long-term distribution network cost and demand side management exists. The municipality of Aachen (STAWAG) has decided to review its planning standards of medium voltage networks. STAWAG and the Institute for Power Systems and Power Economics (IAEW) at RWTH Aachen have been working together in the government funded project “E-Aix” to estimate the influence of distributed generation and demand side management (especially electric vehicle charging) on long term medium voltage network costs in Aachen.
Firstly a target network structure, which had been used to identify expansion planning projects so far, has been analyzed taking into account new expected growth rates for distributed generation based on the national renewable energy actions plan [1]. Thereafter a Greenfield approach has been used to plan new target networks for three different scenarios. The regulating regime and demand side management strategies have been varied in these scenarios and were evaluated based on total costs, which include both energy costs and network costs. Furthermore it has been evaluated whether or not demand side management may be able to mitigate network overloading. It is the purpose of this paper to present the conducted research.
No medium voltage network planning algorithm exists that allows considering trade-offs between network expansions and demand side management strategies [3, 4]. Therefore a new algorithm was developed to address these challenges. The following sections describe the problem formulation and present a possible solution.

SCOPE

Two types of medium voltage network planning algorithms exist. Short term planning is also called expansion planning. It takes into account present infrastructure and its objective is to identify the network expansions that are the most suitable reactions to connect new customers or address a change of load. In order to keep network costs low in the long run, target network planning identifies the network structure that has minimal costs disregarding present infrastructure. This network is called target network. Target networks provide information for the expansion planning process and help planners to select the most suitable projects. In order to identify the long term influences of distributed generation and demand side management, target network planning is an adequate tool and hence used for planning in the scope of this research.
All parameters that are relevant for a planning decision on medium voltage level are to be modelled. Medium voltage networks are operated electrically isolated and do transport energy from high voltage (HV) substation to high voltage substation. The same holds true for low voltage networks. Therefore medium voltage networks

can be planned disregarding the detailed structures of their surrounding high and low voltage networks.

TECHNICAL EVALUATION

Loading restrictions of circuits and transformers as well as requirements for the busbar voltages must be taken into account during network planning. The allowed voltage deviation at customer connections points is standardized for Europe in EN 50160. Due to the fact that medium voltage substations do not usually have tap-changing transformers, the voltage drop or raise that may occur on medium voltage circuits is smaller than the values given in EN 50160. Loading restrictions of circuits and transformers during normal operation ensure that the lifetime of these components is not unduly shortened. Load-flow calculations for three switching states (normal operation, switch opened at HV substation at either side of a ring) and 8760 hours throughout one year ensure that networks generated in the planning process are technically viable. The simplified algorithm [5] solves this problem efficiently in weakly meshed networks. Short circuit currents that may occur in a planned network must be within certain limits. Circuit breakers can only handle currents up to their switching capacity. In order to be detectable, the minimum short circuit current must be higher than the current at maximum load. Short circuit calculations are based on the simplified algorithm presented in EN 60909-0.

ECONOMIC EVALUATION

To evaluate the interdependencies of network planning and demand side management, energy costs as well as network costs have to be taken into account. Energy costs include the value of energy fed into the grid by distributed generators as well as the costs of energy for loads and that for primary energy supply of combined heat and power (CHP) generators. The medium voltage network, which is being planned, is modeled as price taker. A simulation of the future European electric energy system according to [6] is used to provide hourly spot market prices. Taxes and feed-in tariffs are not taken into account. Restrictions for the maximum market based simultaneity of flexible loads can also be obtained from this simulation. Network costs include costs for investments, maintenance and losses. The annuity method is used to derive average network costs per year.

DSM STRATEGIES

Three possible demand side management strategies are likely alternatives. An overview is given in Table 1 and described in the following.
Customer based control (CU): No demand side management is done. The customers control their loads to minimize discomfort and maximize utility. Heating is done whenever the outside temperature is low and electric vehicles are charged immediately after having been operated.
Market based control (MB): Demand side management is purely market based. No network restrictions are taken into account. Network operators have to enforce the network if overloading occurs. This strategy yields the smallest energy costs.
Control of Network Operators (NO): Demand side management is market based. However, if overloading occurs, network operators may interfere and reschedule loads controlled by demand side management. This process may not interfere gravely with customer comfort. Furthermore network operators may curtail feed-in of distributed generators. If feed-in is curtailed, network operators must compensate generators with the value of curtailed energy, which is evaluated based on the sport market price.

Strategy	*Market Based Control*	*Control considers Network Restrictions*
CU	No	No
MB	Yes	No
NO	Yes	Yes

Table 1: Overview Control Strategies

INTEGRATING PLANNING AND DSM

The network planning problem is a combinatorial problem with a finite but high number of possible solutions (candidate networks). A heuristic optimization algorithm may be used to limit the number of candidate networks that have to be taken into account. The developed algorithm uses the ant colony system [4] to do so. Demand Side Management, which takes into account network restrictions (strategy NO), has to be done for each candidate network. Network restrictions can be formulated as quadratic equations. Hence the demand side management problem is a quadratic problem. Figure 1 illustrates the integrated optimization approach.

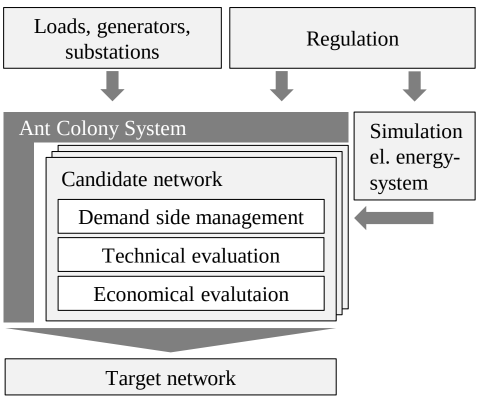

Figure 1: Integrated optimization approach

GENERATION OF NETWORKS

The objective of the target medium voltage network planning is to connect medium voltage substations as cost efficiently as possible to high voltage substations. Planners may choose which cables to use and where to put them. Usually only one type of cable is used to keep maintenance simple and reduce storage costs. Most medium voltage networks are planned as ring structures to ensure a decent reliability of supply. In theory, any medium voltage substation could be connected with any other substation. In practice it makes sense to limit the possible connections to neighbouring stations. This can be achieved by using the Delaunay-Triangulation. After it is applied, all substations are situated in the corners of triangles. The edges of the triangles are possible trenches where cables can be put. No edges intersect. The ring-planning problem can be formulated efficiently using the properties of this graph. An overlay structure that connects the centres of triangles is introduced. A radial structure within this overlay network, which starts at a high voltage substation and connects multiple triangles, is equivalent to a ring structure tracing the perimeters of all connected triangles. As a consequence, the medium voltage ring planning problem can be reformulated as a capacitated minimal spanning tree problem. Ant Colony Systems solve this problem efficiently [4]. Ants operate on the overlay structure. For this reason the connections of triangles are called ant paths. Their intersections are called ant network nodes. Approaches presented on network planning problems in literature so far do not present algorithms that are as efficient as this combination of Delaunay-Triangulation and Ant Colony System. Figure 2 depicts the duality of ant and ring network.

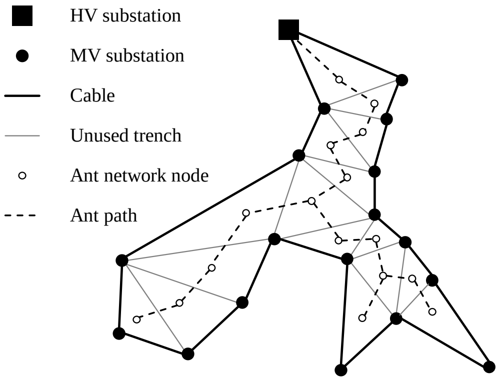

Figure 2: Duality of radial and ring structure

DEMAND SIDE MANAGEMENT

The demand side management problem that can be formulated as a quadratic problem is solved in two steps for reasons of computing time. Firstly all flexible loads and CHP generators are optimized disregarding network restrictions. The objective function depends on the control strategy. Dynamic programming solves this problem efficiently. A previous paper [6] describes the methodology for electric vehicles. Load flow calculations check whether overloading occurs. If overloading occurs and the network operator may not interfere (strategies CU, MB), a candidate network is invalid. Elsewise a second optimization step is applied. The network operator limits the power of flexible loads and distributed generators in that medium voltage network ring where the overloading occurs. He may also define a minimum power for flexible loads, which is preferable to curtailing distributed generators.

RESULTS

Firstly an existing medium voltage network plan is analyzed. This plan was derived in previous studies disregarding distributed generation and it was meant to be the strategic objective for network planning to reduce long term network costs. 20,600 household are situated in the analyzed area, which is the southern part of Aachen. Presently peak load is at 23 MW. The load and distributed generators (DG) were adapted to the most recent forcasts according to [1] for a post 2030 scenario. Photovoltaic generation is expected to increase to 32 MW, CHP plants have a combined rated power of 7 MW and three smaller wind power plants supply up to 9 MW. 944 heat pumps (4 MW) and 5678 electric vehicles (63 MW) are expected to be the most important flexible loads in 2030. For the reference case it is assumed that electric vehicles and heat pumps are controlled by consumers (CU) and the potential flexibility is not used. The network loading during peak generation without control of flexible loads is depicted in Figure 3. Many network components are highly loaded and n-1 security can no longer be guaranteed. Costly network expansion would be the consequence. In a second step, it was reviewed how network loading changes if market based control (MB) is applied. Firstly the European energy system was modeled using the methodology of [7] for the year 2030 based on public data of the European Union [1, 8] to obtain prices for 2030. This optimization also indicated that the simultaneity of electric vehicle charging may be very high. At fleet penetration of 10% the maximum simultaneity of electric vehicle charging may be as high as 75%. For this reason market based restrictions of simultaneity have not been taken into account in network planning.

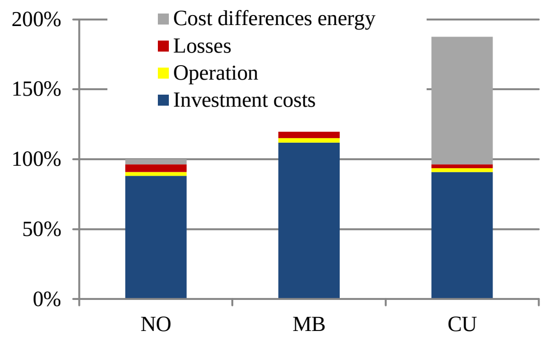

Figure 6: Total costs

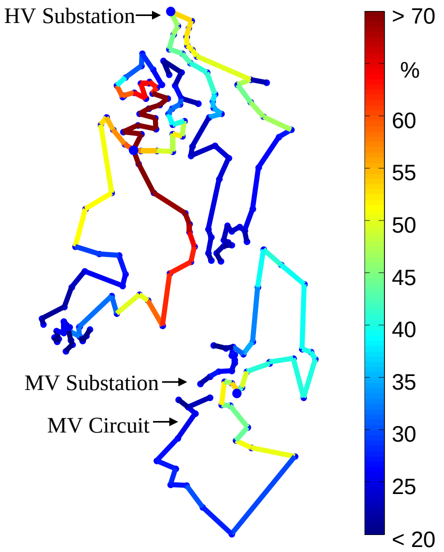

Figure 3: Loading of circuits during peak generation

Flexible loads are controlled centrally to achieve minimal energy costs. Average wholesale energy paid for by these loads decreases significantly by (0.0268 €/kWh). As depicted in Figure 4, a correlation of flexible loads and photovoltaic generation is given. However, strategy MB cannot reduce the critical feed-in at all times. Furthermore, purely market based charging (MB) leads to overloading during winter hours (Figure 5). Such high load situations could be avoided if the distribution system operator could limit the power of flexible loads. The resulting load curve of the strategy NO is also depicted in Figure 5.

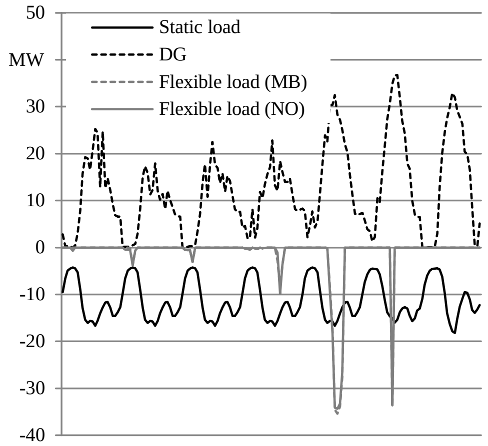

Figure 4: Load profile during summer week

In this case the wholesale energy costs flexible loads pay do also decrease significantly (0.0266 €/kWh), however not as much as it would be possible with a purely market based control strategy. Finally new optimal network structures for 2030 are calculated for all three control strategies. As depicted in Figure 6, the total costs increase significantly if market based control (MB) is not limited by distribution network operators (NO). Curtailment of DG is not feasible due to a high load density. Not using the flexibility of heat pumps and electric vehicles is unattractive due to high energy costs (CU). Therefore STAWAG will strive to control flexible loads (strategy NO) and network expansions will be planned accordingly.

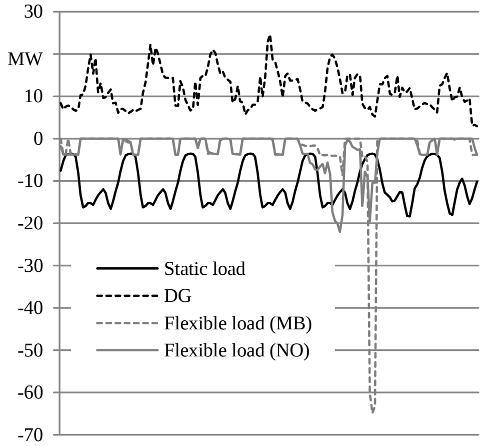

Figure 5: Load profile during winter week

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