Generation Management in Distributed Networks

Martin Ostermann
University of Kaiserslautern
Chair for Energy Systems and Energy Management
Kaiserslautern, Germany
ostermann@eit.uni-kl.de

***Abstract*—Due to the increase in electricity production from renewable energy sources, the share of volatile electricity supply rises in German distribution networks. Since these networks are, for historical reasons, not designed for the supply of distributed generation, this already leads to an overloading of the network resources, today. In this work, different distributed generation management concepts are presented, which should avoid this overloading by temporarily reducing the power supply. To simulate these methods, the supply from solar, wind, biomass and cogeneration power plants is modeled. The implementation of these distributed generation management concepts depends on the available information from measurement points. Finally, an evaluation of the different generation management methods is made, taking the implementing costs and the benefit of avoiding overloads into account.**

Keywords-generation management; distributed generation; cogeneration; measurement points; costs; overload

I. INTRODUCTION

In recent years, based on new insights into global climate change, a new environmental awareness has arisen in the European Union (EU) and especially in Germany. This has led to massive energy and climate policy changes within the entire EU region, in terms of new targets for the reduction of greenhouse gas emissions for the community of states. On the other hand, every country in the international community received its own targets, which have to be achieved through individual strategies. As a result the new energy concept forced a social and political supported departure from conventional energy generation towards a greater support for renewable energies. The Renewable Energy Law (Erneuerbare-Energien-Gesetz = EEG) specifies the target to increase the share of renewable electricity generation to at least 80% until 2050 [1]. Because of the associated promotion of renewable generation facilities, a massive expansion of decentralized renewable generation facilities has launched.

Particularly in medium- and low-voltage grids, the increased supply of distributed generation already leads to problems of network security, because of overloads. These overloads result mostly through changed network topologies due to maintenance but can also occur at normal switching states, favored by certain load and weather conditions [2]. To avoid these problems, the distributed generation management is used in Germany allowing a temporary reduction of the power from decentralized generation units connected to the network. The idea is to maintain security of supply and optimal absorption of the energy generated by renewable energies in the grids. Currently used forms of generation management have great potential to minimize the reduction of power, because all generation units, behind the detected overload, have to reduce their power supply equally. Hence, a procedure to bring the power reduction to a minimum, is required to avoid unnecessary costs. The complexity to maintain these goals increases due to the limited observability in medium- and low-voltage levels, because of missing measurement devices to examine the condition of the network.

This paper will discuss different concepts for distributed generation management to avoid overloads in the grid at lines or transformers. The design of these concepts is based on information from measurement devices. Thus, concepts of generation management for different dimensions of observability will be developed. In addition, an optimization to minimize the reduced power and therefore the compensation costs will be created.

For low–voltage grids the supply of solar power plants on roofs and combined heat and power plants (CHPP) are modelled. Additionally, In case of medium–voltage networks solar farms are modelled next to wind and biomass power plants. These concepts are simulated on medium- and low-voltage test-grids, developed by the Chair for Energy Systems and Energy Management (ESEM).

Finally, an evaluation is made, taking the total costs and benefits into account.

II. CONCEPT DEVELOPMENT

A. *Overloading of network operating ressources*

Due to the strong expansion of distributed generation, as a result of the promotion of renewable energies by the EEG, the supply in medium- and low-voltage networks has changed in recent years. This situation will be intensified by the expected further increase in distributed generation.

So far, current distribution networks, in particular the low-voltage grids, typically distinguish themselves through an orderly flow of power from the transformer to the connected consumers. Accordingly, the highest network load was usually at the entry point to the higher voltage level. The dimensioning of the network, therefore followed the maximum load on the substation, voltage stability and thermal fatigue loading of the lines. Hence, the existing distribution networks are not designed for the new emerging power flow situations, resulting from the increasing supply of decentralized generation units and new power-intensive consumers [3].

By reversing the direction of power flow due to a decentralized supply and increasing consumption in the future, power flows may occur which may exceed the load capacity at lines or transformers. If these overloads appear undetected in an unmonitored network, damages to the network infrastructure can emerge and would cause high costs to repair.

Overloading the lines means, the exceeding of the thermal current limit, by the power flow. Therefore, the thermal current limit is crucial for the load capacity. The acceptable load capacity of transformers is, for a short time, significantly higher than the rated power. Thus, in this paper transformers are assumed as overloaded, if the load exceeds a limit of 120% of the rated power of the transformer.

As a result of overloading lines or transformers a temperature limit is exceeded, which causes damages as mentioned above.

B. Observability of distribution networks

In contrast to high-voltage grids in German distribution networks, sensors providing information about the current network conditions are very rare to find. This is the case, because the assumption of a one directional power flow was made, during the initial planning of the network design. In addition, the share of distributed generation was negligible, so that area-wide coverage with measurements was not necessary and the costs for implementing measurement devices could be saved [3]. Only the transformers of the substations medium-voltage grids next to busbar feeders are monitored. Currently, low-voltage grids are not monitored at any point. However, to intervene in the context of a distributed generation management, information about the network condition are prerequisite. Without information, existing overloads cannot be monitored and no generation management can take place. Furthermore, in this paper medium- and low-voltage grids are equipped with different amounts of measuring devices to get these information according to the used generation management concept and the voltage level.

III. MODELLING DECENTRALIZED GENERATION UNITS AND THE LOAD OF HOUSEHOLDS

A. Modelling of solar power plants

In this paper, two types of solar power plants are modelled. In low-voltage networks, the supply of solar energy through photovoltaic systems on rooftops is determined. Solar power plants in medium-voltage networks are a model of significantly bigger solar parks. The power supply of a PV-system to a network is fixed to the radiation of the sun and the size and efficiency of the solar module. The energy of the solar radiation impinging on the surface of the PV-module depends strongly on the following factors: longitude/latitude, orientation to cardinal direction, inclination of the PV-module and most important, the weather condition. Thereafter, the resulting power supplied to the connected network is influenced by the size of the PV-module and the efficiency of the solar cells and the converter as well as the pollution degree of the module. In low-voltage grids the size of the PV-modules depend on the size and surface of the rooftops. For medium-voltage grids the total size of the PV-modules is identified based on the average installed capacity over several rural grid operators.

B. Modelling of wind turbines

The power contained in the wind is determined by the air density, the flown through area and most important the wind velocity. The wind velocity primarily depends on the three factors: location, height and roughness of the ground. The factor location means, that by moving from the coast to the interior the mean wind velocity decreases. According to the Rayleigh-distribution the frequency of high wind speeds declines. Besides, with increasing height the wind velocity rises according to the logarithmic wind profile, which involves the roughness of the ground as a component.

Because wind turbines are incapable to convert the whole power contained in the wind into electrical power, it is necessary to determine a total efficiency factor. The main factor of the total efficiency is represented by the power coefficient of the rotor. The power coefficient itself depends on the pitch angle of the rotor blades and the tip-speed-ratio. The power coefficient has its overall maximum at a pitch angle of zero. As a result a wind turbine will operate with a pitch of 0° until the nominal power is reached. After that, the rotor blades will be adjusted, bounding the power output to the nominal power for changing wind speeds. The modelled wind turbines are only considered for the medium-voltage grids and have been set to a nominal power of 1.5 MW, which corresponds approximately to the average installed capacity of the considered grid operators.

C. Modelling of cogeneration units

The cogeneration units in this paper are modelled as heat led CHPP. In a heat-controlled operation mode, the thermal power output of the plant follows the total heat demand of a building. Beneath the heat demand for room heating, the energy demand for hot water has also to be taken into account. The demand for hot water depends on the weekday and the number of people living in the considered household. Both heat demands form the total heat demand required to scale the CHPP.

The required heat demand, to heat up the building, has been calculated according to DIN 4108-6 and 4701. Therefore, losses like transmission heat losses due to the outer shell of the building, heat bridges and additional windage losses are considered. Profits as a result of solar gains on transparent and opaque surfaces next to internal profits, like heat gains generated by people or electrical devices, are considered as well. To calculate the gains, the same solar radiation time row as for solar power plants has been used. This leads to a heat demand of 21 MWh per year for a one family household in an averagely existing building.

To dimension the nominal thermal power of the CHPP, often a percentage of the thermal peak load is chosen. The lower limit of the thermal load of the motor is assumed as half the nominal thermal power to avoid damages. For the same reason, once activated, the CHPP has to work for at least 1.5 hours each cycle in order to prevent frequent on - off switching. The production of electrical power corresponds to a share of the generated thermal power. This share decreases by the declining efficiency of the CHPP with lower heat demands. To guarantee an optimal economic operation, a buffer reservoir, with a capacity to absorb the nominal thermal power of the plant for at least 1.5 hours, has to be added [4]. Because of using a buffer reservoir the efficiency to produce electrical power of the cogeneration unit increases. Since, the efficiency is highest by operating the CHPP with nominal thermal power, the buffer has to absorb heat to enable an operation at maximum power during moments with heat demands below the nominal thermal power. Additionally the operating time of the CHPP can by extended due to the buffer by absorbing heat at times with a heat demand below the lower thermal limit. In addition, heat from a peak boiler to support high demands can be saved by releasing stored energy.

The modelled CHPP is dimensioned to 2.2 kW nominal thermal power with approximately 1.1 kW electrical power. The operation time of the CHPP reaches around 6000 full-load hours over a year by using a buffer reservoir.

D. Modelling of biomass power plants

Biomass power plants are also regenerative decentralized generation units like wind turbines and solar power plants. However, biomass power plants do not depend on fluctuating environmental conditions, so the supply of biomass can be assumed as constant [5]. Biomass plants are only considered for medium-voltage grids and like the other plant models, their nominal power is calculated by the average of the installed capacity of several rural grid operators.

E. Loads of the households

For different types of electrical devices used in households, such as washing-machines or electrical water conditioning, the daily load profiles have been determined. This has been done by identifying the moment of their activation with certain probabilities, the typical load profile under operation and their power demand. Thereafter, this electrical equipment has been distributed to the households of the considered network with a certain probability.

IV. TECHNICAL AND REGULATORY PROVISIONS

The technical and regulatory provisions are forming the framework around the developed generation management concepts. Both, regulatory or technical provisions determine the obligations of grid or plant operators.

A. Regulatory Specifications

Grid operators are according to § 12 EEG obliged to purchase, transfer and distribute the generated energy of decentralized generation units by reinforcing or expanding the network. However, if network congestion problems occur, the grid operators are eligible to reduce the power of renewable generating and cogeneration units connected to the grid, as laid down in § 14 EEG. But only power plants which can be controlled remotely are able to respond to a generation management.

For renewable energy power plant operators as well as for operators of CHPP only nominal capacities of more than 100 kW are obligated to be equipped with technical devices to reduce the supply remotely, according to § 9 EEG. In addition, grid operators need to have online information of the actual power supply for such plants. For solar power plants, installed capacities of more than 30 kW require technical facilities that enable remote control. Plants with an installed capacity of less than 30 kW either comply with the requirement under § 9 EEG or the maximum active power must be limited to 70% of the installed capacity. Additionally, the grid operator has to compensate 95% of the reduced supply of the power plants, according to § 15 EEG.

Corresponding to these regulations, all power plants of the simulated medium-voltage grids are equipped with such technical devices, since all of them are larger than 100 kW. Additionally, only for low-voltage grids concepts to limit the supply to 70% of the installed capacity can be provided. In this paper only CHPPs cannot be remotely controlled due to generation management, because their nominal power is too small to have a significant impact.

B. Technical Specifications

For reducing the active power by a distributed generation management, set points of 100%, 60%, 30% and 0% related to the maximum active power output have been proven as efficient for low-voltage grids, according to VDE-AR-N 4105. For medium–voltage grids these set points are related to the agreed power at the connection point, which is equated with the nominal power in this paper.

If the supply of a generating plant exceeds the set point related to the maximum active power, it has to be reduced. This must be achieved by the plant operator, since the network operator only defines the signal. Since biomass power plants are similar to CHPPs, these levels cannot be applied, because usually the technical minimum power is >50% of the nominal power. For lower set points than 60% only a full deactivation is possible. Also the delaying reaction to power reduction measures and the slow ramp-up afterwards have to be considered [6].

V. CONCEPTS OF DISTRIBUTED GENERATIONS MANAGEMENT SYSTEMS

The generation management provides, if necessary, a temporary power reduction of the supplying renewable energy generating plants. These interventions at generating facilities take place by using a remote control signal for power reduction.

For reducing the power, three different approaches will be presented in this paper. At first, a concept limiting the power output of all units in the network. Second, a power reduction of all units behind the network congestion with the same set point by using individual measurement points or smart meter. Third, a method using a genetic algorithm, to optimize the reduction of power to a minimum in order to reduce the compensatory costs under the usage of smart meter.

A. *Fixed power limitation to 70% of the installed capacity*

This concept can only be considered for low–voltage grids, because just solar power plants smaller than 30 kW have the opportunity to choose a limitation to 70% of the installed power. Thus, in this concept no remote control or any measurement points are necessary, so no costs for additional technical devices arise. However, for an economical assessment the opportunity costs have to be considered.

B. *A scheme of setting individual measurement points*

In this approach, the detection of an overload bases solely on the information from the measurement points distributed in the network. These measurement points can be placed at the lines of the network or at the transformers. Accordingly, only the detected overload at the placed measurement point can be used as an indicator of congestion. Hence, there is no information about the rest of the network.

If an overload is detected, the power of all generation units behind the measurement point will be reduced equally on the basis of the set points mentioned in Chapter IV/B. For example after detecting an overload at the transformer all generation units of the network will be reduced. After detecting an overload the power reduction takes place gradually, starting at 60% as the first reduction step and ending at 0%. This procedure is performed until the overload is eliminated due to the supply of decentralized generation units. To simulate this approach, for low voltage-grids two different spots for measurement points have been selected. First, a generation management by placing a measurement point only at the transformer. For the second concept the individual measurement points have been placed at the outgoing feeders of the transformer station. Due to this concept for each of these feeders a measurement point has to be placed. These network position were selected because without any further information these points can be seen as most critical.

Since in medium voltage networks measurement points at the transformer and the busbar feeders typically already exist no measurement devices are necessary to calculate the costs of these grids.

C. *A concept with extensive use of measurement points and uniform power reduction*

In case of a widespread penetration of smart meters on all connection points of households a state estimation of the network to determine overloads at all lines and the transformers is possible. After an overload of one or more lines, all generation units contributing to the overload are determined by a sensitivity analysis. To eliminate network congestions, overloads of the lines will be considered first, because often after eliminating overloads at the lines, also a transgression of the transformer capacity limit is prevented. Additionally the elimination of overloads starts at the line with the greatest overload, since usually smaller overloads at other lines are often prevented, too. Like with the previous concept, the power reduction will be the same for all contributing generation units.

Besides the costs to install smart meters at all households, no additional costs for individual measurement points occur because the considered. Moreover, in contrast to the concepts mentioned before, all overloads can be detected and only the power of plants contributing to the overload have to be reduced.

D. *Concept to optimize the power reduction*

This concept corresponds to the previous, but optimizes the power reduction of the generation units by trying to find the best set point for each unit. For concepts with few individual measurement points, an optimization associated with the following procedure is not possible, because the network state is not known. The optimized reduction of active power of decentralized generation units, in order to avoid overloads, is an optimization problem with a large set of possible solutions. Finding the optimal solution for such complex problems requires full enumerating algorithms, with the disadvantage of a prohibitive computation time for complex tasks. To find a solution in an acceptable time often meta-heuristics are used. These methods can be characterized as a mixture of heuristics and exact algorithms. As one of the most frequently used meta-heuristics a genetic algorithm is selected in this paper.

The main goal of the developed algorithm is to avoid all overloads by reducing the power of the generation units as little as possible to minimize the compensatory costs. In order to meet this objective, at first generation units contributing to an overload have to be determined by a sensitivity analysis. Thereafter the power limits of the overloaded transformers or lines have to be specified. In case of overloading the transformer, this limit is set to 1.2 times of its rated power. For overloads at lines, the limit is set to their thermal power limits. The genetic algorithm is programmed to find for each generation unit the optimal set point, to get the power flow as close as possible to the considered power limit.

At first a starting population of individuals, corresponding to a vector of different set points with the length of all contributing plants, has to be established. These individuals consist of genes, illustrated as boxes in the following figure, which are corresponding to a contributing generation unit and its assigned set point. Such an individual is exemplarily shown in Figure 1.

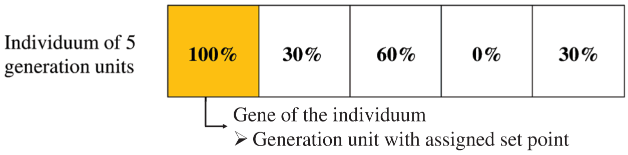

Figure 1. Exemplarily indiviuum of the genetic algorithm

The set points (100%, 60%, 30% and 0%) are given to the units with uniformly distributed probability. Each individual corresponds to a possible placing of set points to all generation units contributing to the overload. By reducing the power of the plants according to their assigned set points of the individual a certain power flow results at the overloaded network resource. The resulting power flow corresponds to the quality of an individual as a possible solution and is called the “fitness” of this individual. The closer the power flow due to the set points of an individual can get to the described power limit the better is the fitness of this individual. Figure 2 shows the basic procedure of the developed algorithm with dots as the previously described individuals.

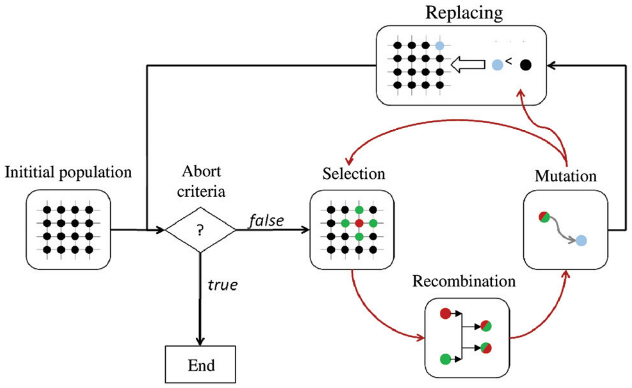

Figure 2. General procedure of the genetic algorithm [7]

In order to find solutions with a sufficiently high quality an abortion criteria as a range of an acceptable quality of the possible solutions has to be set. In this paper, only individuals with a fitness of more than 95% of the capacity limit are accepted. The genetic algorithm will be aborted only if five individuals of the population fulfill the mentioned abortion criterion. Thereafter, the end result of the genetic algorithm corresponds to the best of these five acceptable solutions. If the starting population does not contain enough individuals matching the abortion criterion, individuals with a better fitness have to be generated. Thus, two individuals (parents) must be recombined in order to generate new possibilities to assign set points to all generation units. Recombination means the generation of new individuals by interchanging the set points from a parent individual to another for all generation units behind a randomly determined position. The mentioned recombination process is exemplarily shown in Figure 3.

parent 1	**100%**	**30%**	**60%**	**0%**	**30%**
parent 2	60%	0%	30%	100%	100%
child 1	**100%**	**30%**	**60%**	100%	100%
child 2	60%	0%	30%	**0%**	**30%**

Figure 3. Recombination process of two individuals

To prevent the elimination of many set point combination possibilities an individual has to find its recombination partner solely in its nearby neighborhood in the population. This neighborhood is illustrated as the green points in Figure 2. As a result, the pool of combination possibilities can be maintained as big as possible because also individuals with a lower fitness are considered. Thereafter, each gene (box) of the resulting individuals (children) can mutate with a certain probability. This probability corresponds to the reciprocal of the amount of contributing generation units. In this context, a mutation means a random alteration of the set point of the element. Subsequently, the fitness for the children has to be determined by identifying their proximity to the limit. Thereafter, the children are compared to the individuals in the population with the worst fitness. If the children are closer to the capacity limit, these individuals in the population will be replaced by them. This process continues until enough individuals in the population meet the abortion criteria. To restrict the computation time, if a certain limit of iterations is reached, the abortion criteria of 95% of the capacity limit will be set down stepwise to extend the range for acceptable solutions.

VI. SIMULATION ENVIRONMENT

The developed generation management systems were simulated for medium- and low-voltage grids. The simulation of generation management for low-voltage grids used rural and suburban test grids. Figure 4 shows a suburban test-grid as an example.

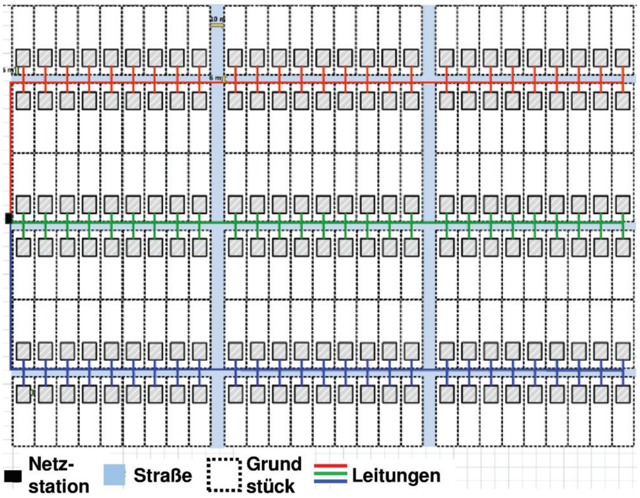

Figure 4. Suburban low-voltage test-grid [6]

All simulated low-voltage grids were built as radial networks. Each home stands for a house containing different types of households. For the various test grids these houses also differ in the numbers of households. Therefore the energy consumption of the houses varies between each other for every grid. Additionally each house is simulated as a load. For houses with installed PV-systems on the roof or a CHPP the load can therefore be negative in the case of supply due to high solar radiation or low loads of the households [8].

For medium-voltage grids rural networks with high or low population densities were simulated. Each low-voltage grid connected is modelled as a load with changing signs in case of energy supply or consumption. For modelling villages or small cities, different numbers and types of low-voltage grids were grouped together. The installed decentralized generation units of the medium-voltage grids were also modelled as loads. These grids were built as ring networks divided to radial networks by an open disconnecting switch [9].

VII. RESULTS

A. *Determining the benefit and the costs*

To evaluate the concepts, the benefit in terms of avoiding overloads, has to be calculated for each concept. Hence, a reference scenario has been identified. For this scenario no power reduction takes place and all occurring overloads at the lines or transformers have been recorded. The benefit of the concept is therefore equivalent to the avoided hours of overloads at transformers or lines, related to the reference scenario with a weighting factor for each type of overload. To compare the concepts economically, the annuity costs for implementing the different concepts have been considered with an assumed interest rate of 6%. Therefore, the depreciation of the investment costs for a duration of 20 years, fixed operating costs, opportunity costs and the compensatory costs have to be taken into account. The investment costs of concepts with individual measurement points aggregate to the costs of the devices to monitor transformers or lines at the corresponding location in the network. For concepts requiring extensive use of measurement points, the investment costs arise from each house connection, equipped with a smart meter.

B. *Cost-benefit assessment*

In Figure 5 the developed concepts are represented for a suburban, radial, low-voltage network with 162 detached one-family houses. This network corresponds also to the network shown in Figure 4. For simulating the concepts, a penetration of 75% of the households with PV-systems and a uniform weighting factor for overloads at transformers or lines is assumed.

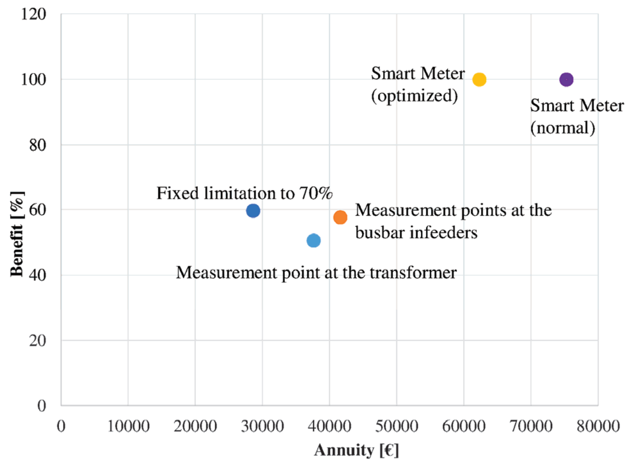

Figure 5. Evaluation of the concepts

As it is shown in Figure 5, all concepts are able to reduce the amount of overloads in the network, but only concepts using smart meters are capable to avoid all arising overloads. By comparing both approaches of the individual measurement concept, it can be seen, that with a higher level of observability due to more measurement points the benefit of the concepts increases. The simulation of the developed concepts for all test grids has shown, that placing measurement point at positions considered as most critical has not been sufficient to detect all overloads in the majority of the simulated networks. Only for small networks with just few households these concepts were able to detect every occurring overload.

By evaluating the costs, the concepts with an extensive use of measurement points are obviously the most expensive. But by optimizing the reduction of active power, a large part of the costs can be saved due minimizing the compensatory costs. For all simulated low-voltage grids, the concept with a fixed limitation of the power output always requires the lowest costs due to only considering opportunity costs. For medium-voltage grids the cost benefit ratio is significantly lower as in low-voltage grids for concepts with individual placed measurement points. That is the case because of already existing measuring devices at network positions considered as most critical in terms of overloads.

VIII. CONCLUSION

As long as only individual measurement points are placed, not all overloads due to the supply of the modelled power plants and loads of the households might be detected. Therefore, the observability determines the benefit of the generation management. Only concepts with an extensively usage of measurement points, by smart meter are capable to avoid all overloads in the network just by using generation management systems. Every increase of observability causes much higher costs but with a genetic algorithm optimizing the power reduction much of the arising costs can be saved.

A closer analysis of the cost benefit ratio has not been made, since repairing operating resources of the grid because of an overload has not been taken into consideration. Hence, a comparison of the concepts in terms of the cost-benefit ratio is not sufficient because the concepts detect different quantities of overloads at the simulated test-grids.

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