FLEXIBILITY OPTIONS FOR MEDIUM VOLTAGE GRID PLANNING

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ABSTRACT

The ascending relevance of flexibility in power systems, meaning a temporal modulation of the power consumption or production, needs to be considered adequately in future distribution grid planning. This paper presents a simulation approach, which allows to quantify the flexibility demands in order to prevent local limit value violations in the grid and to determine the remaining grid capacity during permissible operation. The methodology is explained along a case study for a real medium voltage grid with a special focus on wastewater treatment plants as a possible and useful source of flexibility in distribution grids. The results highlight the advantages of the approach and implications on the grid planning process are derived and discussed.

INTRODUCTION

The development of the installed capacity of Renewable Energy Sources (RES) during the last decade in Germany is an impressive example of the rapid changes of the requirements for distribution grid planning and operation. Further technical developments such as electric vehicles, storages and heat pumps as well as market developments (e.g. dynamic tariffs) and political decisions will affect the future requirements for the electrical infrastructure. Overall, the level of uncertainty for Distribution System Operators (DSO) will continue to rise and consequently increase the risk of misdirected investments.

Flexibility is the ability of a technical unit to temporary modulate its electrical power consumption or production due to an external signal. If this external signal is driven by the local grid state, flexibility can be used for the avoidance of limit value violations. Several publications and research projects (e.g. [1-3]) show the high potential of flexibility offered by demand side and infeed management in order to reduce or postpone the need for conventional enhancement of the grid. Therefore, the adequate consideration of flexibility in short-term to mid-term distribution grid planning will play a key role in order to exploit this potential.

This paper will present the analysis of the flexibility demand of a medium voltage grid and the comparison with sources of flexibility. In particular, the focus will be on the flexibility of wastewater treatment plants (WWTP). WWTPs usually contain energy-intensive processes (e.g. water aeration) as well as their own power production (combined heat and power plants with gas storages). Accordingly, they are a significant source of both: Positive and negative flexibility. The available flexibility during different operating states and optimization strategies will be determined using simplified models of the relevant processes of a WWTP, parametrized with real plant data.

An existing characterization method of system-wide operational flexibility consisting of metrics power, energy and power gradient [4] will be adapted to match demand and supply of flexibility on local distribution level. The range of the remaining grid capacity as well as the flexibility demand will be calculated by an adapted Optimal Power Flow method. Furthermore, the paper will present multiple graphical approaches for illustration and interpretation of the flexibility demand. The results of a case study based on real grid data of a German DSO will show how the demand of flexibility on distribution level can be assessed and compared with the flexibility offered by different technical units.

FLEXIBILITY IN DISTRIBUTION GRIDS

Sources and demand

Flexibility is a generic term for a bundle of different topics such as demand-side-, infeed- and storage-management for system, market and grid condition purposes. Flexibility can be provided by all grid-connected technical units, which are able to temporary modulate their power consumption or production. This ability is usually the result of a certain energy storage capacity, which may be a physical storage (e.g. gas storage) or an inherent storage capacity of a process (e.g. thermal inertia). Furthermore, flexibility can be provided by curtailment of RES or processes with alternative energy supplies (e.g. combined electrical and gas heating). Enabling and coordinating flexibility of existing and new participants is a major task in order to successfully and efficiently transfer the German electricity system towards a sustainable future.

An important distinction between the demands of different flexibility purposes is the dependence or independence on the location of the supply within the system. While ancillary services such as frequency control or wholesale-market signals can be provided from any connection point within the system (i.e. global signals), other purposes such as infeed management due to temporary equipment overload have a clear local restriction for possible suppliers (i.e. local signals). Either way, the flexibility supply due to local or global signals always influences the local power flow. Therefore, it is essential to characterize and analyse flexibility, provided by various technical units and for different purposes, in a generic way. Furthermore, the effects of global flexibility application on the distribution grid (e.g. higher simultaneity due to market signals) and the opportunities of distribution grid services as a replacement for conventional grid enhancement need to be considered in distribution grid planning.

Flexibility Metrics

In order to take account of flexibility in the planning process of distribution grids, flexibility needs to be characterized and quantified. A helpful method of characterizing flexibility with a simple set of metrics is presented in [4]. The paper focus on the assessment of operational flexibility during the operational planning on system level. In order to describe the available and needed operational flexibility the inter-temporal linked metrics power-gradient G, power P and energy E are used (1).

$$G \underset{\frac{d}{dt}}{\overset{\int dt}{\rightleftarrows}} P \underset{\frac{d}{dt}}{\overset{\int dt}{\rightleftarrows}} E \qquad (1)$$

Rather than just considering the available flexible power modulation, this set of parameters also takes account of the ramping and storage capabilities of different technologies and processes. Furthermore, it allows handling of aggregated flexibilities (for detailed information see [4]). Considering a certain time-interval, these metrics for the maximum offered and demanded operational flexibility are determined in positive and negative direction. All parameters of the offered flexibility are required to exceed the demanded flexibility for a sufficiently covered operational period (Eq. (2)-(4)) [4].

$$G^{+}_{demand} \le G^{+}_{offer}; \qquad G^{-}_{demand} \le G^{-}_{offer} \qquad (2)$$

$$P^{+}_{demand} \le P^{+}_{offer}; \qquad P^{-}_{demand} \le P^{-}_{offer} \qquad (3)$$

$$E^{+}_{demand} \le E^{+}_{offer}; \qquad E^{-}_{demand} \le E^{-}_{offer} \qquad (4)$$

To apply this approach for flexibility options and demands on distribution level, further aspects need to be considered. Local flexibility demands and offers depend on their position within the grid. In order to compare offer and demand according Eq. (2)-(4) they need to refer to the same node. Moreover, the supply of flexibility for a global demand may cause local limit value violations. The local grid capacity restrictions for flexibility options serving global demands are taken into account by adding a grid capacity term P_{GC} to restrict the possible active power modulation (Eq.(5)).

$$P^{+}_{demand} \le P^{+}_{offer} \le P^{+}_{GC}; \qquad P^{-}_{demand} \le P^{-}_{offer} \le P^{-}_{GC} \qquad (5)$$

The flexibility demand and flexibility offer as well as the grid capacity are quantified by a coupled time-series simulation model.

MODELLING AND SIMULATION

Due to the inter-temporal dependencies of the relevant parameters, it is necessary to set up a time-series simulation for further analyses of the flexibility demand, flexibility offer and grid capacity. Furthermore, the operation states of the different technical units connected to the grid section directly influence the power-flow. A closed simulation of the nonlinear AC power-flow and several detailed process models would be mathematically of high complexity and does not guarantee an optimal solution. Therefore, separate models for the grid and the technical units are set up and coupled by a so-called grid capacity corridor (GCC). Figure 1 illustrates this setup.

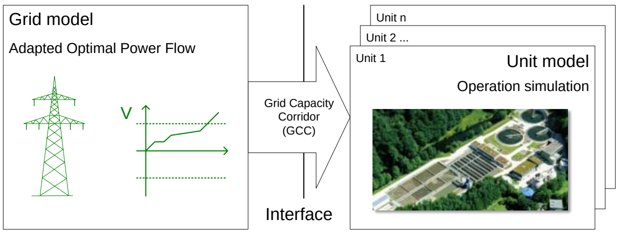

Figure 1: Simulation model setup

Further explanation of the simulation methodology will follow directly along a case study for a 10 kV medium voltage grid section in Germany with a high penetration of photovoltaics and a WWTP as an exemplary flexibility option.

Grid Model

The modelled grid section consists of 17 MV/LV-stations in a rural area with a total load of 1.3 MVA. The cable length adds up to 13 km. The topology is shown in Figure 2. A future scenario for the penetration of RES is applied, consisting of 2.1 MW installed power PV (incl. 1.8 MW MV-infeed directly at node 4), 500 kW biogas and 300 kW hydropower. The WWTP is connected at node 9.

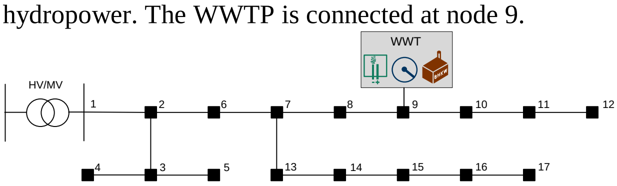

Figure 2: Grid topology of exemplary case

In order to calculate the flexibility demand and the remaining grid capacity at the connection point of the WWTP, active and reactive power time-series for load and infeed of all connected costumers ($\boldsymbol{P_{fixed}}$, $\boldsymbol{Q_{fixed}}$) are determined in 15 min resolution for a period of one year, except for the WWTP.

By using an Optimal-Power-flow algorithm based on [5], the maximum additional infeed (positive sign) (Eq.(6)) and the minimum additional outfeed (negative sign) (Eq.(7)) at the position of the WWTP are calculated in two runs. Using this method, all node voltage and thermal equipment constraints in this grid section are considered.

$$\max_{V,\Theta,P_{flex},Q_{flex}} P_{flex} \quad (6)$$

$$\min_{V,\Theta,P_{flex},Q_{flex}} P_{flex} \quad (7)$$

s.t.

$$\boldsymbol{P}_{node}(\boldsymbol{V},\Theta)+\boldsymbol{P}_{fixed}-\boldsymbol{P}_{flex}=\boldsymbol{0} \qquad \boldsymbol{V}^{\min}\leq\boldsymbol{V}\leq\boldsymbol{V}^{\max}$$

$$\boldsymbol{Q}_{node}(\boldsymbol{V},\Theta)+\boldsymbol{Q}_{fixed}-\boldsymbol{Q}_{flex}=\boldsymbol{0} \qquad -\infty\leq\boldsymbol{P}_{flex}\leq\infty$$

$$|\boldsymbol{I}(\boldsymbol{V},\Theta)|-\boldsymbol{I}_{max}\leq\boldsymbol{0} \qquad -\infty\leq\boldsymbol{Q}_{flex}\leq\infty$$

The result of the optimization is the tolerable operation range for the WWTP. In case of an already existing limit value violation in the grid section, the result is the local flexibility demand in order to solve the problem. The GCC corridor is the result of the sequential execution of this calculation (schematically illustrated in Figure 3).

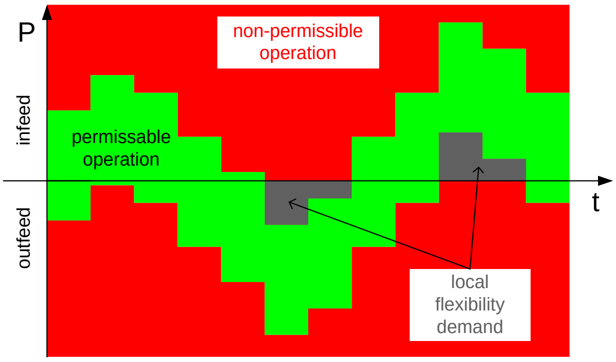

Figure 3: Grid capacity corridor

The GCC is the basis for the analyses of the time-variant grid capacity and the flexibility demand. Furthermore, it is used as input data for the WWTP simulation. By simulating the WWTP operation with and without the grid capacity restrictions, the impact of providing local flexibilities services on the plant operation is analysed.

Unit Model

In Germany, around 10.000 WWTPs exist, purifying wastewater for a population equivalent (PE) of 120 million. In order to test the flexibility of WWTPs, a mathematical model of the existing WWTP Radevormwald (mean PE: 58,000) is designed, using the simulation software Simba, version 6.4. The model contains sewage purification (primary settling tank → activated sludge tank → secondary settling tank), sludge treatment (initial drainage → digestion → final drainage) and digester gas utilization (gas storage → combined heat and power units (CHP)). The biological processes of sewage purification are described by the model ASM1 [6]. For anaerobic digestion, the model Siegrist [7] is used.

The electrical power demands of electric loads that are part of the model (aerators, pumps, etc.) are calculated using the measured real world efficiencies of those aggregates. The power demands of electrical loads, which are not part of the model (for example chemical feeder, stirrer, etc.), are integrated with constant values deduced from the actual power consumption at the WWTP Radevormwald.

The mean power demand of the WWTP sums up to 180 kW. Since 44 % of the energy demand is covered by the on-site CHP production, the mean consumption from the grid is reduced to 100 kW.

Negative flexibility (additional load) is provided by turning off the CHP units (2 x 80 kW). To turn off the CHP units, all of the following restrictions must be complied:

- runtime > minimal runtime (min. 30 minutes)
- switching cycles per day < maximal switching cycles per day (max. 5 cycles)
- gas storage level < maximal gas storage level (max. 700 m^3)

Additional negative flexibility can be provide by control interventions on the aeration system (max. 170 kW).

QUANTITATIVE RESULTS

Grid capacity

The calculation of the GCC for one year in 15 min resolution (35040 time-steps) without the impact of the WWTP exhibits, that the limit values for the upper voltage range would be exceeded in 587 time steps (~ 147 h/a or 1,7% of the year). The points in time with limit value violations (Figure 4) occur between spring and fall during the daytime mostly around noon and therefore show a clear PV driven characteristic. Overall limit value violation occur fairly rare and only during certain daytimes. During the rest of the day, the grid capacity is sufficient.

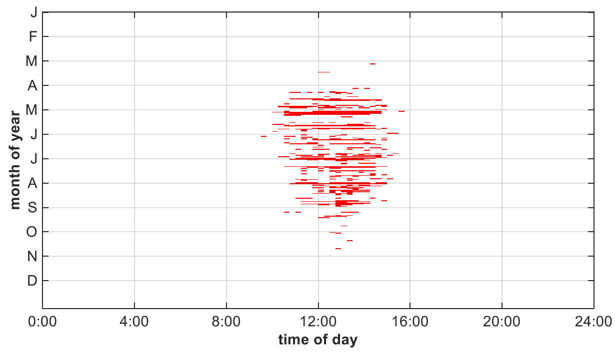

Figure 4: Points of time with local limit value violation

The magnitude of the time-variant grid capacity is displayed in Figure 5. The Figure shows the upper and lower bound for additional active power infeed and outfeed during the time of the day, aggregated for all 365 days of the year. Since the grid capacity at the same time of the day differs from day to day, an additional yellow range appears, compared to the schematic illustration in Figure 3. This yellow range indicates the fluctuation of the grid capacity at the same time of day during the year. If a limit value violation occurs, the capacity limits cut the abscissa (grey range). The median and the quartiles for each yellow range, which do not cut the abscissa, emphasize, that this happens only very infrequently. The maximum demand for negative flexibility is 230 kW while the average is 60 kW.

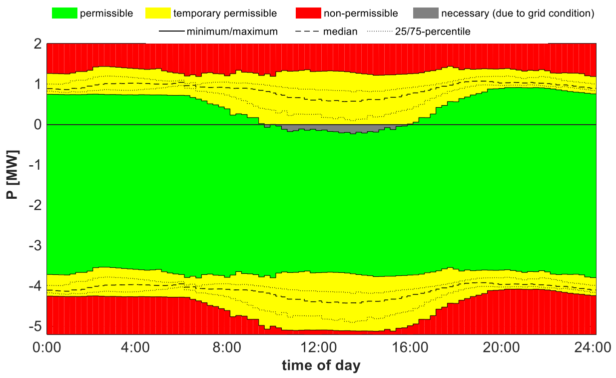

Figure 5: Aggregated GCC for 365 days

Local flexibility services by WWTP

So far, the results of the grid capacity and the flexibility demand do not consider the influence of the power consumption and production of the WWTP. In order to prevent any limit value violation in the grid section, the resulting load profile of the WWTP must remain within the green range at all times. Since the mean grid consumption of the WWTP sums up to 100 kW, it is likely that some of the limit value violation will be coincidentally prevented by the normal operation mode of the WWTP. Nevertheless, for some flexibility demands, it will be necessary to run down the CHP production actively and to temporary increase the load by turning on additional compressors of the aeration system.

In order to distinguish between coincidentally solved problems and active intervention in the WWTP operation, three simulation runs are executed:

1. Normal operation without consideration of GCC
2. GCC consideration in the CHP control
3. GCC consideration in the CHP and the aeration system control

In the normal operation mode, driven by the primary process, 84 time steps with limit value violations remain. By just influencing the CHP production according to the grid state, this number can be reduced by 94% down to five time steps. By additionally controlling the aeration system, all local grid problems can be solved, without negative backlashes on the purification performance of the WWTP. The duration of the local flexibility demand varies between 15 min and 2 h and therefore the amount of energy that needs to be taken out of the system. Figure 6 shows the total energy and the maximum power of each demand sequence and how it is covered. As for most flexibility options in distribution grids, the CHP and aeration allow very fast ramping (on/off-flexibilities). Therefore, the power gradient criterion (2) can neglected for the analyses of the technical potential. The modulation of the CHP production is the primary choice in order to provide flexibility, since it is only restricted by the gas storage level. Only if the available flexibility is not sufficient, additional power consumption is provided by the aeration system.

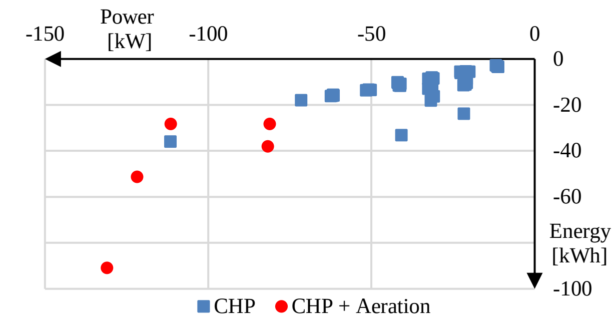

Figure 6: Coverage of local flexibility demand by WWTP

Restrictions on global flexibility services

The time-series of the calculated grid capacity shows, that local flexibility demands only occurs between 9 am and 4 pm. At a few days a year, it is necessary to activate negative flexibility for local demands and to restrict offers of positive flexibility for global demands during this time of the day. Nevertheless, during most of the time, the WTTP may offer its flexibility towards global demands (e.g. frequency control or wholesale-market optimisation).

Figure 7 displays the worst-case grid capacity for each time step and the maximum and mean potential flexibility of the WWTP in positive and negative direction according to the simulated operation points. The supply of negative flexibility is possible without any restrictions during the year. Unrestricted provision of positive flexibility is possible between 5 pm and 8 am and with possible temporary restrictions during the rest of the day.

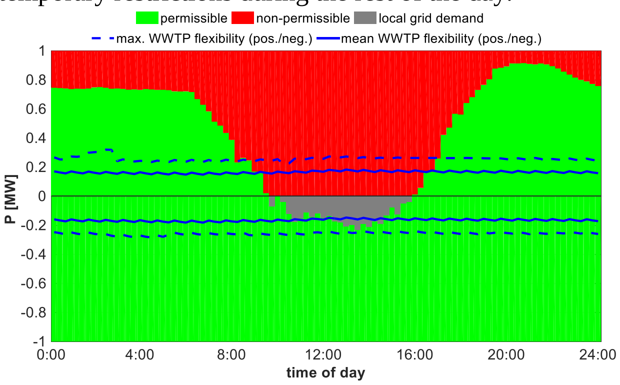

Figure 7: Potential WTTP flexibility vs. worst-case grid capacity

IMPLICATIONS ON GRID PLANNING

The presented simulation results highlight the relevance and the advantages of time-series calculation approaches in order to analyse flexibility adequately. Nevertheless, in order to consider local flexibility in the planning process, the analyses of the flexibility potential is a necessary but not a sufficient condition. Further conditions and requirements need to be fulfilled, including:

Technical feasibility: The relevant grid section requires monitoring and control signals based on the local grid state need to be calculated, transmitted and executed. Smart-Grid systems for the distribution level exist and are further developed towards the control of generic flexibility options [8].

Reliability: The access of the distribution system operator (DSO) on a costumer's flexibility option needs to reliable for an acceptable period. This may be solved by declarations of obligation in return to grid fee discounts or payments. As long as alternatives exist (e.g. curtailment of RES), the risks for the DSO due to non-availability of the flexibility options are low.

Cost-advantage: The investment and operation costs of local flexibility application need to be lower than alternative grid enhancement options (e.g. cable reinforcement or line-voltage regulator). Many studies show the cost advantages of RES curtailment over conventional grid enhancement [1-3]. The costs for RES curtailment can be reduced by including further flexibility options into the control concept. It is thinkable that different flexibility options (incl. RES) compete on an automatized local flexibility market in order to solve the temporary grid problem [9].

Beyond the application of flexibility for local purposes, the presented approach is helpful to analyse the impact of different global flexibility signals (e.g. synchronous dynamic tariff signals for all customers) on local, temporary bottlenecks in the grid capacity. These future developments may have a relevant impact on the existing simultaneity factors for grid planning. Grid monitoring and temporary constraints for activities on global markets are likely to be more cost-efficient than the conventional enhancement of the grid.

CONCLUSION AND OUTLOOK

The increasing importance of flexibility in the power system needs to be considered in the future grid-planning process. On one hand, the application of flexibility for local demands can prevent limit violations in the grid and therefore replace or postpone the necessary conventional grid enhancement. On the other hand, the application of flexibility on global demands may cause local problems in the grid. In order to avoid these problems without expensive reinforcement of the grid, market activities need to be temporary restrictable by the local grid state.

The presented approach is useful to analyse both aspects and derive implications on grid planning. Furthermore, the grid capacity corridor can be used as an interface for different unit models and the grid model. By considering the GCC in the unit simulation, the impact of flexibility supply and grid constraints on the process and different operation modes can be analysed comprehensively.

The methodology was explained along a case study for a real medium voltage grid and a flexible wastewater treatment plant. The flexibility demand and the grid capacity were calculated and analysed for a future scenario (2035) of the penetration with RES. Limit value violations only occurred rarely and the flexibility offer of the WWTP was sufficient to cover all demands without negative backlashes on the water purification performance.

The results show, that flexibility can significantly help to avoid critical grid conditions and therefore replace or postpone grid enhancement. By including demand processes like wastewater treatment into a smart grid system, the amount of curtailed energy of RES can be reduced considerably and the existing grid capacity can be utilized more efficiently. Beyond further technical developments, it is necessary to introduce a legal basis and market roles that allow the elaboration of local flexibility applications and coordinate local and global flexibility purposes.

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