PV integration with flexible generation and consumption units

Evaluation of a quota-based grid traffic light approach in a field test

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Abstract—The increase in renewable power generation in Germany leads to the need for new concepts for the coordination and utilization of flexibility provided by decentralized units for congestion management in distribution grids. One approach is the grid traffic light concept. This paper introduces the quota model as an implementation of the yellow traffic light phase. Within this model, quotas represent the share of flexible units in a grid cluster that can be activated at the same time without causing congestion. Based on results of a field test in a rural low voltage grid, it is shown that grid congestion caused by PV feed-in can be successfully avoided by the applied quota based approach. For this, the flexibility of battery storage units is used. By storing feed-in peaks, the curtailment of PV generation can be avoided and a higher share of renewable power generation can be integrated into the grid. In addition, the application of the quota model puts the distribution system operator in a position to bridge the time gap until grid expansion is carried out or to possibly postpone or avoid grid expansion if congestion occurs only in a few hours per year.

Keywords - grid traffic light concept, quota model, congestion management, distribution grids, flexibility

I. BACKGROUND AND MOTIVATION

The increase in renewable power generation in Germany up to 80% till 2050 will cause a fundamental change in power supply infrastructure [1]. The closure of conventional power plants at transmission system level and the installation of wind turbines, mainly at high and medium voltage level, and PV generators, mainly at medium and low voltage level, lead to a gradual shift of generation capacity to the distribution system level. Therefore, the importance of distribution systems to ensure overall system stability will increase. An increasing number of battery storage units and electric vehicles will further complicate the operation and planning of distribution systems. In particular, high feed-in or high demand situations due to simultaneous operation of these flexible units are a serious challenge for distribution system operators (DSOs). At the same time, an inefficient grid expansion should be avoided. Hence, new methods for coordination of flexible units aiming at utilizing their flexibility for grid operation are required.

A. The Grid Traffic Light Concept

One approach for the coordination of flexible units in distribution grids is the grid traffic light concept. The idea behind this concept is that for a particular period of time and a particular grid segment, the grid status can be described using one of the colors “green”, “yellow” and “red”. Depending on the relevant traffic light color, certain rules apply in the respective grid segment for the interaction of all relevant market roles such as generators, suppliers, storage facility operators, balance responsible parties, and the statutory regulated role of the DSO [2].

The concept describes the interaction between the different market roles. Therefore, it lays the foundation for the development of a flexibility market at distribution grid level and thus differs from other traffic light concepts such as that of ENTSO-E, which describes the grid status and the capacity to act of transmission system operators (TSOs) [2].

The green traffic light phase, also called the market phase, is characterized by time intervals when there are no critical grid conditions predicted for the relevant grid segment or if the DSO can prevent these with its own, purely grid-related measures. There is no interaction between the DSO and market players. The existing flexibility options are used by market players solely to provide flexibility for the market or the system. The green traffic light phase is the standard phase [3].

In the yellow traffic light phase, the interaction phase, the DSO utilizes contracted flexibility to prevent expected grid congestion. Therefore, the DSO specifies restrictions for the market players regarding the operation of their flexible units [3]. For the exact design of the yellow traffic light phase, there are different proposals, which differ in particular with regard to the control, the aggregation level, the type of contracting flexibility options and the duration of the lead time [4].

In the red traffic light phase, the grid phase, a critical grid state occurs, which can not be remedied by grid-related measures or the use of market-based flexibility and would thus endanger or disrupt secure grid operation. In order to remedy grid congestion, the grid operator uses the existing...
regulations of the Renewable Energy Act (EEG) and the German Energy Industry Act (EnWG) directly and without any contractual basis to intervene in the operation of units [3].

B. Project grid-control

The research project “grid-control – advanced decentral grid-control” started in July 2015 to develop and evaluate new concepts and innovative system solutions in sustainable distribution grids. Besides some other aspects, the implementation and testing of the above introduced grid traffic light concept is particularly addressed.

II. THE QUOTA MODEL AS IMPLEMENTATION OF THE YELLOW GRID TRAFFIC LIGHT PHASE

A. Basic principles of the quota model

Grid congestion can generally be caused due to high feed-in or high consumption. In both situations, the DSO is, in principle, indifferent whether the generation or the consumption side changes its behavior during the yellow traffic light phase to relieve the grid at the time of forecasted congestion. In order to restrict market participants as little as possible and to be non-discriminatory, the quota model includes the declaration of an opportunity range within which market participants can freely optimize themselves. The notification of this opportunity range to market participants takes place day-ahead in form of non-discriminatory quotas for every 15-minute interval of the following day. Within the provided restrictions, market participants may optimize among themselves, e.g. by trading quota in a secondary market. Furthermore, the DSO does not act as a market participant and does not specify precise requirements for individual units [5].

For the determination of the grid traffic light phases, four grid-oriented, regional cluster levels are introduced [5].

- HV/MV transformer
- MV feeder
- MV/LV transformer
- LV feeder

Fig. 1 shows schematically these cluster levels. The levels reflect possible grid restrictions, such as capacity limits of transformers or lines, that affect all flexible units in subordinate levels. Hence, depending on the different cluster levels, the DSO may provide several constraints (quotas / opportunity ranges) for each grid connection point (e.g. a grid connection point of a single flexible unit or a house with several flexible units and a local Building Energy Management System (BEMS) that provides the flexibility). For this, the DSO carries out the mapping of the meter point numbers to the connection point and grid clusters.

B. Calculation of quotas

For each point in time, quotas represent the share of flexible units per grid cluster that can be activated without causing grid congestion. The ratio is calculated on a quarter-hourly basis according to the opportunity limits and the installed capacity of flexible units in each cluster.

At first, the prognosis time series for inflexible loads \( P_{L,\text{inflex,}\,\,t} \) and generators \( P_{G,\text{inflex,}\,\,t} \) in cluster \( c \), which have to be provided by the DSO, and the capacity limits \( C_{L,\,c} \) and \( C_{G,\,c} \) of the power flow restricting asset, e.g. voltage limits or maximum transmittable apparent power of a transformer or line, are used to calculate the load opportunity limit \( O_{L,\,c,t} \) and the feed-in opportunity limit \( O_{L,\,c,t} \) for each 15 minute time interval \( t \) of the following day (see (1) and (2)). In this context, load is defined as positive value and generation as negative value.

\[
O_{L,\,c,t} = C_{L,\,c} - P_{L,\text{inflex,}\,\,t} - P_{G,\text{inflex,}\,\,t} \tag{1}
\]

\[
O_{L,\,c,t} = C_{G,\,c} - P_{G,\text{inflex,}\,\,t} - P_{L,\text{inflex,}\,\,t} \tag{2}
\]

These load and feed-in opportunity limits for cluster \( c \) represent the maximum allowable load or feed-in of all flexible generation and consumption units in total without causing grid congestion in this cluster. The range between these two limits is the so-called opportunity range. Within this range, market participants can freely optimize the operation of their flexible units.

Next, the compliance of the planned schedule \( P_{\text{flex,}\,\,c,t} \), which is composed of the planned schedule of all flexible load and generation units in total (see (3)), with the calculated opportunity limits is checked. For this, market participants have to submit a planned schedule for all individual flexible units prior to this.

\[
P_{\text{flex,}\,\,c,t} = P_{L,\text{flex,}\,\,c,t} + P_{G,\text{flex,}\,\,c,t} \tag{3}
\]

In Fig. 2, it is illustratively shown that the planned schedule of the flexible units may temporarily exceed the calculated opportunity ranges. These periods are then defined as yellow grid traffic light phases.
The opportunity ranges are declared to market participants by quotas that set the opportunity limits in relation to the installed capacity of flexible units in the cluster (load: $P_{L,flex,inst}$; generation: $P_{G,flex,inst}$). These percentages are non-discriminatory for all active market participants in the respective cluster and are determined individually for each cluster.

$$q_{L,c,t} = \frac{o_{L,c,t}}{P_{L,flex,inst}}$$  \hspace{1cm} (4)

$$q_{G,c,t} = \frac{o_{G,c,t}}{P_{G,flex,inst}}$$  \hspace{1cm} (5)

In case of compliance with the opportunity limits (see (6)), the result is a green traffic light signal. Nevertheless, the market participants are informed based on the quotas by how many percent they may deviate with their flexible units on the load side and generation side from the submitted planned schedules.

$$\frac{P_{flex,c,t}}{P_{L,flex,inst}} \leq q_{L,c,t} \wedge \frac{P_{flex,c,t}}{P_{G,flex,inst}} \leq q_{G,c,t}$$  \hspace{1cm} (6)

If an opportunity limit is not met at time $t$, i.e. the planned schedule is outside of the opportunity range, the market participants are notified of the quotas which have to be met and a yellow traffic light signal is generated. The quotas are valid for all flexible units in the relevant cluster and are non-discriminatory, i.e. similar in size for all market participants with flexible units in the cluster.

III. PROCESS AND SYSTEM SOLUTIONS

A. Process and system overview

In the project grid-control, several system components are developed for the DSO, market participants and prosumers. The developed systems and the process of prediction and avoidance of congestion is presented in Fig. 3.

The smart home systems (Building Energy Management Systems (BEMS)) of prosumers with flexibility forecast the generation and consumption of the decentral systems behind the grid connection point (e.g. household, PV-system, battery storage unit, electric vehicle, power-to-heat system, etc.) and create an initial schedule and flexibility ranges for the next day. The market participants gather this information, optimize the schedules market-oriented and provide the planned schedules for the flexible units to the DSO. For this, the market participants run e.g. a Flexibility Management System (FMS). Afterwards, the DSO calculates the grid constraints and provides them to the market participants. To calculate these capacity constraints a Grid Load Management System (GLMS) is developed. In case of predicted congestion the market participants consider the given constraints in a new, market-oriented optimization and send the final schedules to the systems (BEMS) at the prosumer side.

Besides the systems for congestion management in the yellow traffic light phase, the grid state is monitored by e.g. a Regional Energy Management System (REMS). On the basis of real time measurements and a state estimation, the REMS executes emergency measures (e.g. curtailing the feed-in of PV-systems or stopping the charging process of a battery storage unit) in case of a red phase [5].

In the following, the central system for the yellow traffic light phase, the GLMS, with its functionalities which include in particular the implementation of a load flow prognosis and the quota calculation are described in more detail.

B. Grid Load Management System (GLMS)

The GLMS is the interface between market participants and DSO and calculates the power flow prognosis in the grid as well as quotas for the yellow traffic light phase. As input data, the planned day-ahead schedules for all flexible units, which are provided by the market participants, as well as prognosis time series for unflexible load and generation, which are prepared by the DSO, are used.

For the calculation of the power flow different methods can be applied. An “advanced” GLMS (Fig. 4, bottom) uses complex power flow calculation tools. Project grid-control focuses on the low-voltage level where the grid topology is mostly a radial structure. Therefore, as a first step, a more „simple“ GLMS for an estimation of the active power flow is realized (Fig. 4, top).

![Figure 2. Opportunity range and traffic light phases](image)

![Figure 3. Process and system overview](image)
With a radial grid topology the grid connection points and their connections can be depicted as a hierarchy/tree structure. An example is shown in Fig. 5.

On this basis the active power flow in each connection point can be calculated through an (hierarchical) aggregation of the power feed-in and consumption of the downstream grid connection points. For example, the active power flow at grid connection point 1 in Fig. 5 is calculated as

$$P_{1,t} = \sum_{i=2}^{10} P_{GCP,i,t}$$  \hspace{1cm} (7)

The power aggregation can be realized in a database and no elaborate power flow calculation tools are necessary. In addition, less input data e.g. concerning the grid topology are necessary and no interim results need to be saved. As a further development, planned topology changes can be taken into account by means of a time-based storing of the tree structure.

With the “simple” GLMS and a consideration of active power flow only, the quota calculation is also simplified. Only the maximum transmittable active power of transformers and lines is used as criteria restricting the power flow, voltage limits and apparent power limits are not considered.

IV. FIELD TEST RESULTS

The developed quota model as well as the corresponding system solutions are tested and evaluated in a field test in the gridlab (NETZlabor) Freiamt of Netze BW GmbH. The gridlab Freiamt is a rural MV-section (approx. 4,000 inhabitants), where the maximum generation, mainly due to PV generation, is more than three times higher than the maximum load. These conditions form a perfect environment to practically test the future integration of large shares of PV generation in today’s grid environment by applying the grid traffic light concept.

A. Field test setup

The field test is run in one low voltage grid which is shown in Fig. 6.

The grid is characterized by a high number of PV generators, which are all considered to be unflexible units, and 4 flexible battery storage units which can be used to avoid congestion due to high feed-in from the PV generators. Table 1 shows the main facts about the field test setup.

<table>
<thead>
<tr>
<th>low voltage feeders</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>grid connection points</td>
<td>44</td>
</tr>
<tr>
<td>meter points (inflexible loads / inflexible generation)</td>
<td>54 (48/12)</td>
</tr>
<tr>
<td>installed generation capacity</td>
<td>approx. 200 kWp (12 PV generation units)</td>
</tr>
<tr>
<td>flexible units (battery storage units)</td>
<td>1x 120 kW/20 kWh, 1x 19 kW/19 kWh, 2x 4.6 kW/9 kWh</td>
</tr>
<tr>
<td>transformer rated power</td>
<td>250 kVA</td>
</tr>
</tbody>
</table>

B. Examination and results

In order to test congestion management in the yellow traffic light phase, lower restrictions for single assets regarding maximum power are virtually introduced for the field test. Thus, the security of supply in the grid is not actually endangered due to the field test.

In the examination described in the following, the maximum transmittable active power of the MV/LV-transformer is virtually reduced to 50 kW in LV to MV direction (and 100 kW in MV to LV direction – which is however not a relevant restriction). As shown in Fig. 7, the active power flow across the transformer predicted by the GLMS, which is composed by both the prognosis for unflexible units and the planned schedule for flexible units, exceeds the virtually introduced limit of the transformer during the morning, due to high market prices resulting in a planned discharging of the batteries, and during the afternoon,
due to high feed-in from PV generators. Hence, a yellow traffic light is announced for both periods and quotas are calculated that affect the flexible battery storage units in the grid.

The initial schedule for the batteries, which is planned only according to price signals from the market, is shown in Fig. 8 (green color). The opportunity limits, which are calculated based on the virtual transformer limits and the predicted unflexible load and feed-in, are not met by this schedule for the two periods specified in the passage before. Hence, the schedule for the batteries must be adjusted by the market participants in order to stick to the calculated quotas. The resulting adjusted schedule (blue color) then lies within the opportunity range, thus congestion can be managed by deploying the flexibility of the battery storage units instead of curtailing feed-in from PV generators. As consequence, the predicted power flow across the transformer (orange color in Fig. 7) does not exceed the transformer limits anymore. In this way, more electrical energy from PV generators can be integrated into the grid as curtailment of PV generators can be avoided.

Fig. 9 shows once again the predicted active power flow across the transformer and in addition the realized active power flow which was measured. Whereas the predicted active power flow does not exceed the virtual limit of the transformer after the battery schedule is adjusted in the yellow traffic light phase, the realized active power flow still does a few times. The reason is the error of the day-ahead prognosis for the unflexible load and feed-in. In such a situation, when the prognosis error leads to congestion, a red traffic light phase would occur and the REMS system would be required. The state estimation would have to recognize the violation of the transformer limit and would then have to directly curtail feed-in from PV generators. However, the yellow and red traffic light phase in combination is still to be tested in further works.

In general, there are several options to avoid or reduce this curtailment of PV generators in the red traffic light phase. First, the prognosis error could be reduced by an improved prognosis quality for loads and renewable generation. Second, the process could be enhanced so that the prognosis and the calculation of quotas could be updated several times, i.e. the quota model would have to be adapted from a day-ahead approach only to an intraday approach. Third, an additional buffer could be considered when calculating the quotas. However, this would also mean that quotas would be more restricting for the operation of the flexible units in times when the buffer is not required.

V. SUMMARY AND CONCLUSION

This paper introduces the quota model which is a simple and lean implementation of the yellow traffic light phase. The yellow traffic light phase is part of the grid traffic light concept and defines situations when congestion management in distribution grids is conducted by utilizing flexibility provided by market participants. Within this model, quotas represent the share of flexible units in a grid cluster that can be activated at the same time without causing congestion. Market participants may freely optimize themselves and the operation of their units within these quotas or opportunity ranges respectively.

The model was tested in a field test in a rural low voltage grid. The grid section is characterized by a high number of PV generators, which cause congestion at times with high simultaneous feed-in, and several battery storage units, which are deployed for the provision of flexibility.

The results from the field test show that congestion can efficiently be managed through the application of the quota model. Despite the relatively simple process to calculate quotas, the predicted congestion can be avoided. Instead of curtailing feed-in from PV generators, the operation of battery storage units is adjusted. Likewise, other flexible units such as heat pumps, electric vehicles or flexible generation units could also be utilized for the provision of flexibility. In this way, more electrical energy from PV generation can be integrated into the grid as the curtailment is reduced.
Nevertheless, a curtailment of PV generators during the red traffic light phase is still necessary if prognosis errors for the unflexible load and feed-in occur. Thus, the curtailment of PV generators could be further reduced if prognosis quality would be improved. Another possibility would be the introduction of an additional buffer when calculating the opportunity limits. Also, the possibility to update the prognosis and adjust quotas intraday instead of day-ahead only would be helpful to optimize the approach.

Furthermore, the application of the quota model puts the DSO in a position to bridge the time gap until grid expansion is carried out. Moreover, if congestion only occurs a few hours per year, the utilization of flexibility is possibly a more efficient solution than grid expansion. Thus, grid expansion could possibly be postponed or avoided in certain applicable cases through the application of the quota model. For that matter, an interesting investigation would be if the level of the quotas as well as the frequency of yellow traffic light phases could be a useful indicator to decide about the execution of grid expansion.

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