Grid Integration of Electric Vehicle Fleets Using a Traffic Light Concept

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Distribution systems face increasing challenges due to the energy transition, for which innovative approaches are needed. One such challenge relates to finding an unbundling-compliant alternative to the increasingly used curtailment measures by using the flexibility of distributed energy resources such as the batteries of electric vehicles. In this context, a widely discussed approach is the traffic light concept, which envisages an unbundling-compliant definition of the interaction between the grid and the market, in case of expected local grid congestions. In this paper, a configuration proposal for the traffic light concept is described as well as a simulation framework to determine the potential of electric vehicle fleets to provide grid-oriented flexibility to distribution system operators.

Keywords: Traffic light concept, electric vehicle fleets, grid-oriented flexibility, virtual power plants

I. INTRODUCTION

The increasing share of distributed energy resources (DER), such as renewable energy sources (RES), has induced disruptive effects on power systems. Due to local bottlenecks in the grid, the number of feed-in management measures has continuously increased [1]. Besides the distributed generation, the increasing number of electric vehicles (EV) and other electrical loads due to cross-sector electrification may also lead to bottlenecks and load shedding measures. To maintain a high level of power supply quality in distribution grids and to avoid grid expansion measures that meet rare worst-case grid situations, concepts for the integration of further DER and new electrical loads are required, i.e. a spatiotemporal coordination of flexible DER [2]. Significant potential is associated with DER that offer a high degree of predictability and flexibility, such as EV fleets with significant standing times. The fleets' flexibility can be used for market- and system-oriented purposes, but also for the provision of grid-oriented flexibility as discussed in the context of the BDEW traffic light concept [3]. The key idea of the traffic light concept is adding an interactive "amber phase" to the existing green (normal operation) and red (*ultima ratio* curtailment) phases. In the new phase, the interaction between grid and markets is clearly regulated as it envisages the timely procurement of flexibility by distribution system operators (DSO) as a preventive measure for forecasted bottlenecks.

II. GOAL AND SCOPE

There is neither conclusive agreement on a standardized configuration for the traffic light concept nor a regulatory framework precise enough for setting the formal boundaries of the market-grid-interaction. Furthermore, the type of and the implications for flexibility providers are yet to be assessed [4]. Therefore, the paper addresses the following questions:

- How can a traffic light concept be configured and embedded into the current / future legal-regulatory framework?
- How can the potential of electric vehicle fleets as providers of grid-oriented flexibility be assessed?

The proposed refinement takes into account the specifications of the research project 3connect, which aims, among other things, at a market- and grid-oriented coupling of the sectors energy and mobility. Within the project, a clear assignment of the roles and interfaces is assumed for the trader, aggregator and the DER operators including an electric vehicle fleet operator, mainly based on the technical capabilities of each actor. This serves as an input both for the configuration proposal of a traffic light concept and for the simulative assessment of the fleet's potential to provide grid-oriented flexibility. In 3connect, the DSO does not have an active participation but it represents a key component of the simulation framework.

III. TRAFFIC LIGHT CONCEPT

For the development of approaches for the efficient management of local bottlenecks, an analysis of the technical (feasibility), legal-regulatory and institutional (roles and interactions) framework should be considered. Therefore, the key concept of flexibility will be introduced, followed by a brief analysis of the traffic light concept and the framework it could be embedded in, considering the regulatory framework as well as the abovementioned project-specific requirements.

A. Flexibility

A broadly accepted definition describes flexibility as "the modification of generation injection and/or consumption patterns in reaction to an external signal (price signal or activation) in order to provide a service within the energy system" [5]. DER have a technology-specific capability of controlling their supply or demand (flexibility potential) and can sustain three main goals. First, a market-oriented control of their supply or demand can impact their profit. Second, a system-oriented control can support transmission system operators (TSOs) with regard to frequency stability and redispatch measures. Finally, the DER could control their supply or demand and provide gird-oriented flexibility for grid-oriented purposes that would support distribution system operators (DSOs) in their task of managing local grid bottlenecks.

In contrast to the market- and system-oriented flexibility use, the grid-oriented flexibility is currently not subject to a market- or regulatory-based mechanism and is thus not an established option [4]. However, the need is evident due to the increasing fall back to last resort measures such as feed-in management. In the year 2015, the curtailed energy amounted to 4.722 GWh, which corresponds to about a threefold increase compared to the previous year [1].

B. *Legal-regulatory framework*

Against this background, an increasingly relevant discussion topic revolves around the question of how to efficiently manage local bottlenecks in distribution grids. Both feed-in management and incentive-based approaches envisage the interference of the regulated DSO in the market-oriented behavior of the competitive actors such as DER operators. Therefore, the discussion raises complex regulatory questions. A first recommendation by the German Association of Energy and Water Industries (BDEW) is referred to as the traffic light concept. The key idea is to differentiate between three phases [3]. These phases represent the delimitation and interaction between the market and grid as well as a ranking for the operational measures available to transmission system operators (TSO) (Tab. 1) [4].

TABLE I. LEGAL CLASSIFICATION OF THE TRAFFIC LIGHT CONCEPT

Phase	***Operational measure***	***Legal reference***
Green	Competitive actors can fulfill their schedules; system operators can take grid-oriented measures if need be	§ 13 Par.1 Nr.1 EnWG
Amber	System operators fall back to market-oriented measures (e.g. balancing power, controllable loads)	§ 13 Par.1 Nr.3 EnWG
Red	System operators fall back to *ultima ratio* measures	§ 13 Par.2 EnWG; § 14 EEG

The legal classification in Tab. 1 applies to DSOs as well according to § 14 EnWG (Energiewirtschaftsgesetz, eng. Energy Industry Act). At distribution level, the green and red phases are integral and almost exclusive components of the current grid operation. While TSOs can procure system-oriented flexibility for frequency stability on the control power market, provision and the incentives to procure flexibility are scarce for DSOs. Currently, §14a EnWG enables DSOs to charge grid users connected to the low voltage grid reduced network charges should they provide a grid-oriented remote control of a load (e.g. EVs) to the DSO. However, an efficient grid operation also needs controllable generation [6]. Currently, feed-in management is just possible as an ultima ratio measure which in the concept of the traffic light concept corresponds to the red phase. Alternatives are being discussed in the course of the network charges taxonomy's reform (Anreizregulierungsverordnung) and are possible due to the smart meter rollout envisaged by the law regarding the metering point operation (Messstellenbetriebsgesetz). These include among other things a stronger weighting of the kilowatt hour rates in comparison to the unit prices. With regard to electric fleets as grid-oriented flexibility providers, this would represent a suitable approach considering that as a rule their peak loads are disproportionally high compared to their relatively low yearly consumption [6]. The difficulty of deciding upon a remuneration mechanism for grid-oriented flexibility also influences the DSOs' incentive to explore their options within the amber phase. Furthermore, the lack of incentives for DSOs to procure grid-oriented flexibility has been a recurrent topic in the discussions regarding a reform of the incentive regulation [4]. The key issue addresses the fact that DSOs should choose the economically most efficient alternative between conventional grid expansion and innovative smart grid operation and that both options should have equivalent financial incentives.

In the last few years, several configuration options for the amber phase have been proposed. Three prominent examples have been described in [3, 7, 8]. Similarities between all three proposals are mainly the requirement of a non-discriminatory treatment of all flexibility providers as well as the prerequisite of an advanced level of automation at distribution level. One difference relates to the configuration of areas assigned to one traffic light respectively. While the bne (Association of Energy Market Innovators) and the VDE (Association for Electrical, Electronic & Information Technologies) agree on a manageable number of delimited areas, the BDEW proposes an area demarcation within distribution grids. The latter is motivated by the fact that the exchange of grid-oriented flexibility is set to take place between one DSO and the flexibility providers within his distribution grid. The prevailing uncertainties relate to the standardization of flexibility products as well as of transactions and thus to the concrete description of procedures and timeframes for the exchange of grid-oriented flexibility.

C. *Configuration proposal*

One of the goals of the research project 3connect is to provide a configuration proposal suitable for the project-specific context substantiated by a simulative analysis of its effects on the involved actors. Fig. 1 shows the involved actors as well as the information exchange and instructions delivery. The involved DER are willing or bound to trade their feed-in in the electricity and/or balancing markets. For this purpose, they are connected by information and communication technology in order to avoid an individual trading strategy, which, as a rule, is less profitable than an aggregated one [9].

The trading strategy is determined by a trader, which may be but is not necessarily the same actor carrying out the function of an aggregator. In the former case, the trading-aggregating-agent (e.g. a virtual power plant) is an established role. Based on price forecasts, the measurement and forecasting data of the DER and the subsequent pre-analysis of the aggregator, the trader determines the economically optimal trading schedule for the DER-network. The operational scheduling process may be preceded by an optimization of the DER-network's self-consumption, depending on the capabilities and operational targets of the aggregator.

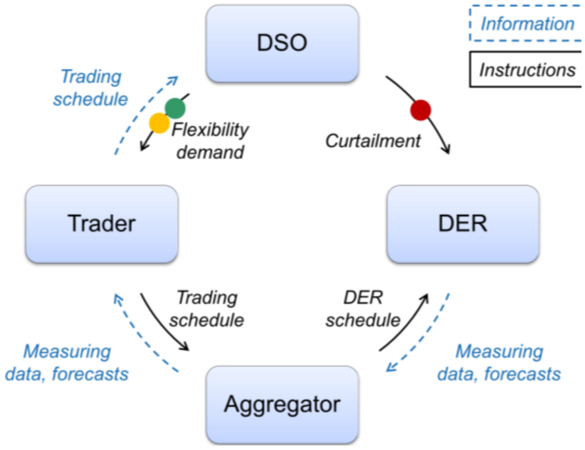

Figure 1. Information and inctructions exchange between the actors involved in the proposed traffic light concept

As soon as the trading schedule for the DER-network is determined, it is provided to the DSO. The DSO then uses the information for the estimation of the future grid state, also considering non-flexible consumption and generation in the grid. If the DSO expects a bottleneck, he will determine the time- and location-specific flexibility needed to avoid the bottleneck. The flexibility demand is then communicated to the trader. Taking these constraints into account, the trader carries out a new operational scheduling process. The difference between the profits of both trading schedules, before and after the flexibility demand, represents the minimum price that the trader expects from the DSO as a compensation for his grid-oriented flexibility offer. Once the scheduling process is concluded, the aggregated schedule is forwarded to the aggregator, who in turn carries out a disaggregation for determining DER-specific schedules, i.e. the control signals for the real time operation. During real-time operation, bottlenecks may occur due to insufficient flexibility provision, a significant deviation from the grid state estimation or due to unpredictable circumstances, e.g. an asset malfunction. As during real-time the DSO lacks the opportunity to procure gird-oriented flexibility in a timely manner, he must resort to the *ultima ratio* measure of curtailing the DER feed-in or load consumption.

IV. SIMULATION FRAMEWORK

The described traffic light concept offers several levels of freedom regarding for instance the threshold between the green and the amber phases or the time period in which the procurement of grid-oriented flexibility is permitted. In order to assess these configuration options, a simulation framework was developed (Fig. 2). It consists of two main model components, which contain the simulation of the trading decision and the determination of the grid-oriented flexibility demand.

Model components

The initial assumption envisages a day-ahead operational scheduling process (OSP) and thus the day-ahead provision of the trading schedule for the DER-network to the DSO. The major trading decisions still take place on the day-ahead spot market in Germany rather than on the intraday market thus conveying a relatively high level of reliability to the day-ahead schedule [10]. With regard to methodology, the operational scheduling process is formulated as a mixed-integer linear problem (MILP) within a stochastic programming framework [11]. The objective of profit maximization is restricted by technical and market constraints and dependent on price and generation forecasts for the renewable generation units. The OSP provides a market-oriented, optimal schedule for the DER-network.

The electric vehicle fleet is modelled as a single DER in the OSP that implicitly contains all information and restrictions of the individual vehicles. The technical restrictions of the fleet for the next day are determined in a preliminary simulation, which takes the following aspects into account:

- synthetic driving profiles
- vehicles' state of charge (S.O.C.) at arrival
- vehicles' targeted S.O.C. before departure
- charging energy demand
- uni- vs. bidirectional charging
- capacity restrictions
- power restrictions

This information is used to calculate the fleet's flexibility potential for the next day. Thereby, the minimum and maximum aggregated charging power for each time step of the next day is determined, which meets the technical and driver-specific restrictions of each vehicle. The resulting flexibility range is then translated into restrictions for the optimization problem of the OSP. Analogously to the other DER, the OSP uses the fleet's flexibility to maximize the profit at the electricity and balancing energy markets by shifting the power supply and demand according to the price signals.

Based on the information contained in the day-ahead schedule provided by the OSP as well as on further information relating to the generation and demand situation on the next day, the DSO carries out an optimal power flow. The approach used is a probabilistic power flow that takes the stochastic nature of household loads as well as uncertainties of wind and photovoltaic generation forecasts into account [11]. The curtailment measures suggested by the optimal power flow represent the minimum flexibility demand needed to avoid grid congestions (voltage range deviations or overloads) during the next day. This demand is time- and location-specific and can thus only be provided by specific DER. The DSO communicates the flexibility demand to the trader, who translates the demand into restrictions in his OSP. Thereby, the trader is able to determine whether it would be technically possible for its DER to provide the requested amount and how high the opportunity costs would be. This monetary indication serves as a reference value for the remuneration expected by DER owners to provide gird-oriented flexibility.

After the second OSP, the planning process is over and the operation phase begins. Hereby, the DSO continually monitors the grid state (i.e. carries out a power flow calculation every 15 minutes). In case of grid congestions, the DSO acts according to the measures permitted during the red phase. During the red phase, the DER owners are not remunerated for curtailment measures because they would otherwise not have the incentive to provide grid-oriented flexibility during the amber phase.

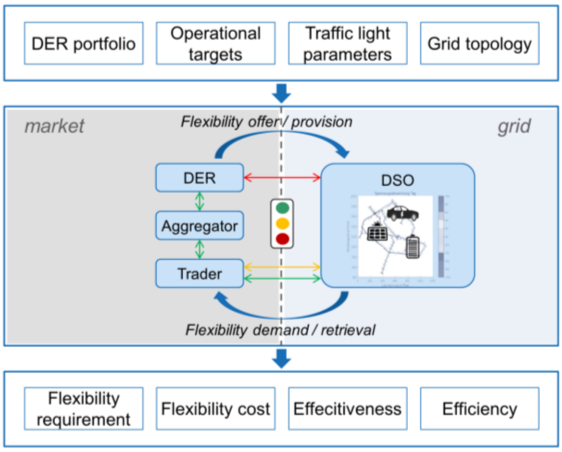

Figure 2. Simulation framework for the traffic light concept

Parametrization

Besides defining when the phase switch can take place, the threshold values must be determined. The first option would be to consider the permitted boundaries required by the technical regulations both for the switch to the amber and the red phase. However, the potential phase switch between the green and the amber phase occurs during the planning phase, which is characterized by uncertainty with regards to the input parameters for the power flow calculation. Therefore, setting stricter threshold values could be a suitable safeguarding measure against planning uncertainties as forecast deviations can be the reason for grid congestions during real-time operation. On the other hand, a switch to the amber phase always entails remuneration for the provided grid-oriented flexibility. DSOs must therefore determine the trade-off between low remuneration costs and planning robustness. In order to assess the effects of different threshold values, these are kept variable in the simulation framework and must be varied in an iterative manner in order to assess the trade-off for the specific use cases. The result can differ according to the examined grid topology, generation and load situation.

V. EXEMPLARY RESULTS

The results of the simulation for one exemplary day are described in the following chapter. A medium voltage grid is regarded which comprises loads, uncontrollable DER as well as a virtual power plant consisting of the DER listed in Table 2.

TABLE II. DER OF THE VIRTUAL POWER PLANT

DER	***Number***	***Total installed power [kW]***
Photovoltaic units (PV)	2	394
Wind energy units (WEU)	1	2.000
Combined heat and power units (CHP)	4	1.718
Storage units	1	300 (360 kWh)
Load bank	1	150
Genset	1	80
Electric vehicle fleet	1	15 vehicles; 100 kW each (50 kWh)

The OSP is carried out for a day in August 2017, in which the daily feed-in amounted to around 280 MWh and the daily demand amounted to 720 MWh. Without flexibility, voltage boundaries violations would occur (fig. 3). For voltage boundaries of ±10 % the DSO would switch to the amber phase after the OSP and request grid-oriented flexibility amounting to 22 MWh. 3 % thereof would ideally be provided by the grid node to which the electric vehicle fleet is connected, together with a PV and a CHP.

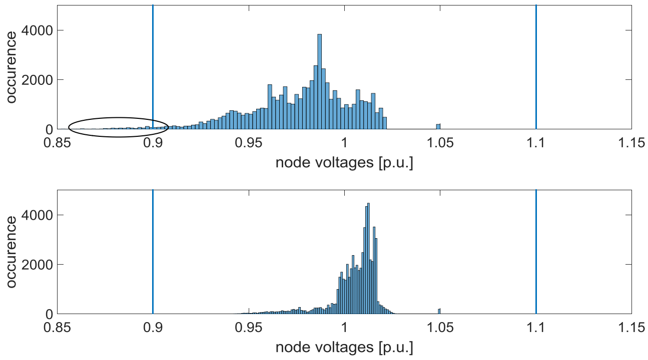

Figure 3. Node voltages for the exemplary day after the pf (top) and opf (bottom)

According to the OPF results, the curtailment would amount to 619 kWh for the PV, 43 kWh for the CHP and 65 kWh for the electric vehicle fleet. The flexibility range of the electric vehicle fleet is determined before the OSP based on synthetic driving and charging profiles, initial S.O.C. as well as further technical restrictions of the vehicles' batteries. For each time step of the optimization period, the minimum (Pmin) and maximum (Pmax) charging power is determined that guarantees a timely and complete charging process for each individual vehicle while taking the technical restrictions of the batteries and of course the number of parked vehicles into account (fig. 4). The area between both curves therefore represents the flexibility range, within which a shift of the charging process is permitted.

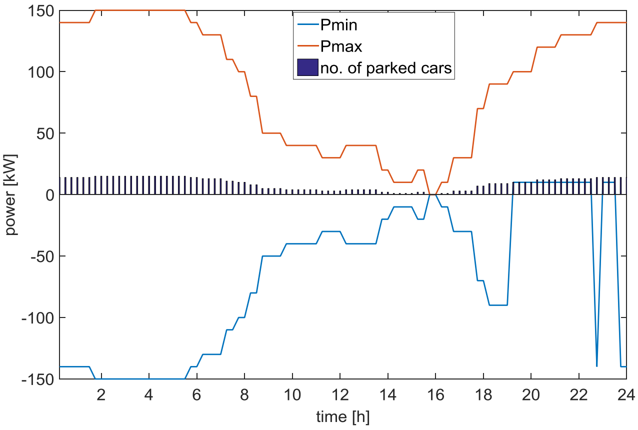

Figure 4. Flexibility range of the electric vehicle fleet

The decision, whether and to which extent the DER are curtailed in order to provide grid-oriented flexibility is only possible if the curtailment does not violate the OSP's restrictions and is motivated by economic considerations. In the described example, the grid-oriented flexibility requested by the DSO could be provided by the DER, as the technical restrictions of the fleet would be fulfilled and the renewable energy units are assumed to be remotely controllable. Besides the technical restrictions, different unit-specific costs could be assumed that would have an impact on the amount of flexibility offered by DER connected to the same grid node. In this example, the same costs are assumed for PV, CHP and the electrical vehicle fleet because they are offering grid-oriented flexibility as part of the same DER-network and not as concurring providers. Therefore, the distribution of the grid-oriented flexibility retrieval between the PV, the CHP and the electric vehicle fleet connected to the same node represents one possible but not exclusive solution.

VI. SUMMARY AND OUTLOOK

The proposed traffic light configuration aims at minimizing the fall back of DSOs to the ultima ratio measure of curtailing DER at distribution level. It envisages an unbundling-compliant interaction between the grid and market processes by entailing an exchange of grid-oriented flexibility. However, it presupposes a high level of information and software functionalities from DSO, which as a rule is not yet state of the art in Germany.

The developed simulation framework based on the proposed configuration is suitable for assessing different traffic light concepts as well as the potential of electric vehicle fleets to provide grid-oriented flexibility. In order to obtain representative results for specific use cases (e.g. grid topologies) however, extensive sensitivity analyses are necessary that enable determining the effect of parameter variations on the suitability of the traffic light concepts. Furthermore, longer time periods (e.g. a year) should be examined in order to provide results that are robust with respect to seasonal influences and stochastic input parameters such as loads and renewable energy sources. For this purpose, an extensive data basis is needed, on the basis of which a representative scenario framework can be developed.

VII. FUNDING REFERENCE

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