Live Testing of Flexibilities on Distribution Grid Level – Simulation Setup and Lessons Learned

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***Abstract*—In the DESIGNETZ project real flexibility units were connected to a distribution grid simulation to investigate the integration of decentralized flexibilities for different use-cases. The simulation determines the demand for unit flexibility and communicates the demand to the flexibilities. In return, the response of the flexibilities is integrated back into the simulation to consider not-simulated effects, too. This paper presents the simulation setup and discusses lessons learnt from deploying the simulation into operation.**

Keywords—flexibility, real-world application, active distribution grids, congestion management, energy system simulation

I. Introduction and Literature Review

The increasing number of renewable energy resources (RES) and the coupling with other energy sectors through new electricity applications such as the mobility sector through electric vehicles or the heating sector through heat pumps leads to an increased need for expansion in the distribution grids in the future [1]. Yet, these developments allow the coordination of these flexibilities to offset imbalances in the power system as well as for congestion management [2]. To investigate this not only theoretically, different studies with real world applications have been carried out. References [3]-[5] investigate flexibility usage from demand response. Further studies widen the scope and integrate feeders and storage depended technologies [6]-[11]. In [12] a framework for local flexibility market was developed, which was taken into practical investigation for example in [7]. These projects use flexibility to resolve congestions in present transmission and distribution grids. Future challenges and opportunities arising from energy systems with a high share of decentralized flexibilities require the projection and simulation of future energy systems.

In the Designetz project 14 flexible pilot projects were developed and connected via an information and communications technology (ICT) platform [13]-[15]. These pilot projects offered flexibility from 5 kW up to 22 MW, connected to low, medium and high voltage. In order to encounter grid extension challenges, adapted planning and operating principles for the distribution grid were examined. Following this assumption, distribution grid models were created with respect to scenarios for the year 2035. In order to investigate the operation of distribution grids with the use of flexibility, the grid control software *System-Cockpit* was developed. It allows for the simulation of a future distribution grid, where real flexibilities are connected to selected nodes. In operation, the pilot projects provide forecasts of their intended electricity consumption or generation and the corresponding flexibility potential as schedules for 6 hours in 15 min time step resolution. In a two-phase process, the simulation integrates those power values and determines the use of the available flexibility potential first in regards to power-system-global demand (hereinafter referred to as market-driven) and secondly to respect to distribution-grid-local constraints (hereinafter referred to as grid-relieving). The results of these optimizations are communicated to the flexibility providing pilot projects in the field as calls for flexibility. Afterwards, the actual power change of these real flexibilities is taken into account by the simulation, resulting in a changed power flow and thus to a changed utilization of the simulated distribution grid. Fig. 1 portrays the main interconnections and objectives of the project.

In this paper, the final setup of the *System-Cockpit* and the methodology to determine the use of flexibility is described and the results of the operation of such a grid with real flexibilities are discussed. Finally we present the lessons learned from

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operating this system in cooperation with 14 flexibility providing pilot projects.

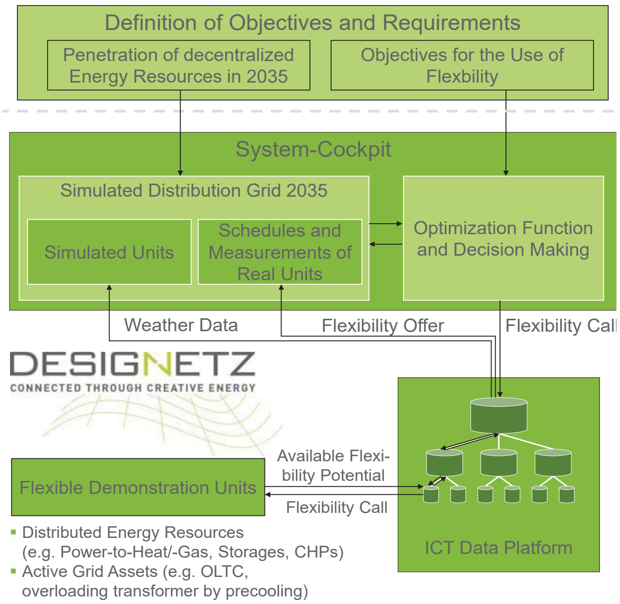

Fig. 1 Interconnections and objectives of the DESIGNETZ project [15]

II. Methodology and Simulation Setup

The simulation of the *System-Cockpit* consists of individual software components, the so-called *simulators*, which are orchestrated by the co-simulation framework *mosaik* [16]. The methodology to determine the use of flexibility is depicted in Fig. 2.

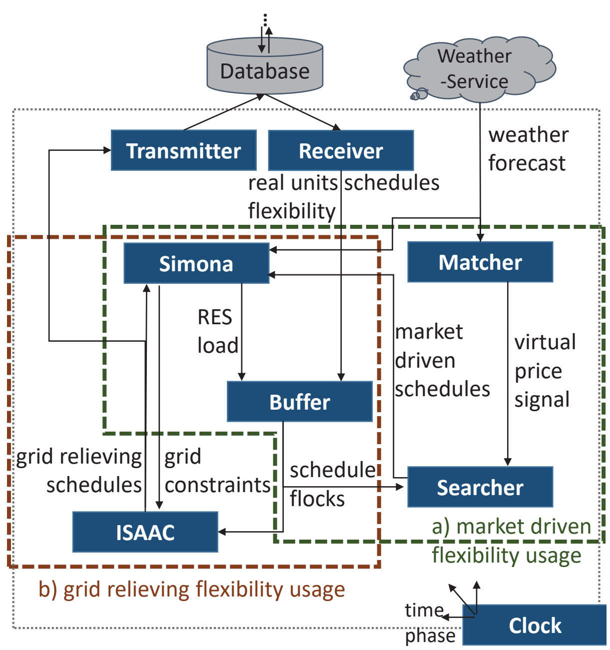

Fig. 2. Complete Simulation Setup of the System-Cockpit

The functional scope of the System-Cockpit can be divided into the selection of the market driven flexibility and the determination of the restriction of this due to grid constraint violations in the distribution grid, hereinafter referred to as grid-relieving flexibility utilization. The *Receiver* and the *Transmitter* represent the interface of these functions with the other systems within the project system, including the pilot projects. The weather service provides weather forecasts to the *System-Cockpit*. To determine the market driven use of the available flexibility, the simulators *Matcher*, SIMONA, *Buffer* and *Searcher* are used in the System-Cockpit, as highlighted in Fig. 2. First, the residual load in Germany is determined on the basis of the Germany-wide weather forecast, which is transferred to the *Searcher* as a virtual price signal. With SIMONA, this weather forecast is used to determine the feed-in of RES and electrical demand in the examined distribution grids. In the *Buffer*, all possible flexibility schedules are generated as schedule flocks. In the *Searcher*, those schedules that reduce the residual load in Germany are selected from the schedule flocks. This is based on the assumption that a positive residual load always provides market incentives to increase electricity production (or reduce demand) of decentralized flexibility options and a negative residual load provides a reduction in electricity production (or an increase in generation). If the market driven use of the flexibility leads to grid constraint violations in the distribution grid at certain points in time, the *Buffer*, SIMONA and ISAAC simulators, as highlighted in Fig. 2, determine the grid-relieving flexibility.

First, using load flow calculation, the simulated distribution grid is checked for possible grid constraint violations when flexibility is fully serving the market. In case of grid constraint violations, the optimizer ISAAC is used to determine the necessary curtailment of the schedules based on the available flexibility calculated with the *Buffer*. The selected schedules are checked again using load flow calculation and, if grid constraint violations exist, are passed to the optimizer again. As soon as there are no more grid constraint violations, the coordinated use of flexibility between the market and the grid is completed. If the grid constraint violations cannot be resolved with the available flexibility, this is an indicator of a further need for expansion of the affected grid section.

In addition to the market driven use of the available flexibility, the use of flexibilities is also possible to offset a power imbalance in the electric power system. The assumption is made that control energy management in periods of quarter hours occurs according to mechanisms similar to those of market driven operation. However, a further safety margin is taken into account when calculating the grid constraint violations in the distribution grid, which means that no critical grid states occur in the event of an unpredictable change in the use of the flexibilities. In this way, the system-serving use of the flexibility options is implicitly taken into account in the operational planning.

Hereafter, the function and structure of every simulator is described in detail.

A. Clock

The *Clock* simulator determines the coordinated universal time and derives from it the current as well as the next six-hour planning interval of the *System-Cockpit's* simulation. A planning interval denotes the time interval for which the *System-Cockpit* plans the use of available flexibility. The first planning interval starts at 00:00 and the next intervals follow accordingly in 15-minute time steps. The start time is generic and can be configured, provided that appropriate knowledge is available. For example, for making test calls that are supervised by responsible employees, it makes sense to coordinate them with the usual working hours. In addition, planning times in practice should be adapted to the established processes of the flexibility providing units. For example, the increased demand for control power during the morning hour should be taken into account when selecting a simulation start time. Since some simulators are called several times and perform different tasks, the *Clock* keeps track of the current phase of the *System-Cockpit*, communicates this to the other simulators and thus controls the simulation run on a high level.

B. Receiver and Transmitter

The *Receiver* is used to incorporate the available flexibility of the pilot projects into the *System-Cockpit* simulation. It receives HTTPS POST requests from the ICT platform, which provide new forecast schedules and operating values in JSON format, parses this data and converts it according to the *System-Cockpit*-internal data model. The available forecast schedules and operating values are then provided to all other interested mosaik simulators. The *Receiver* thus represents the egress interface to the ICT platform and also the ingress interface to the simulation defined as a mosaik scenario and thus to the other simulators contained within.

In software-architectural symmetry with the *Receiver*, the *Transmitter* receives the selected flexibility schedules from the *mosaik* scenario in the *System-Cockpit* internal data model, converts them into the data model of the database and transmits them as calls for flexibility to the ICT platform. Since the ICT platform provides an REST API to make such calls, the *Transmitter* sends them as HTTPS POST requests.

C. Matcher

In the overarching project, fundamental market simulations have been carried out to determine the favorable usage of available flexibility by means of overall costs. The findings were incorporated into a catalog of measures for different energy system situations. These measures, described as use cases, propose a demand for flexibility in predefined situations of the energy system. They create the link between residual load of the model region and the (aggregated) residual load in Germany. The *Matcher* is used to select the appropriate measure for the prevailing situation at any time step of the *System-Cockpit*'s live operation.

Without external constraints, it can be assumed that flexibility providers behave in a revenue-optimizing manner as rationally-deciding actors. Depending on the prevailing regulations and possible market entry barriers, self-consumption optimization or participating in the energy markets takes place. In order to map this behavior - also referred to as "market-driven flexibility" - a virtual price signal is determined based on the residual load in Germany, which is used to determine the behavior of the flexibility. Accordingly, it is assumed that if the residual load is negative, there is no incentive for additional power generation by the flexibility providers and that a positive residual load always leads to increased feed-in.

As shown in [17], feed-in from wind generators and photovoltaic plants (PV) is correlated to the extent that grouping similar feeders into 78 regions for wind and 21 regions for PV yields similar behavior in terms of power fed into the grid in Germany. Analogous to the number of regions used in [17], zip code regions are used to determine feed-in for the System-Cockpit. For this purpose, the state-specific results of the regionalization from the Designetz project are used and the future installed capacity is distributed to the 2-digit zip code regions using a distribution key (existing plants in 2019). For each 2-digit zip code region, weather data is transmitted at one-hour resolution during live operation. Based on this weather data, the Germany-wide feed-in for the respective planning interval of the *System-Cockpit* is approximated by an integrated PV model and a wind turbine model. Subsequently, the electrical demand in Germany is determined using a stored time series for the year 2035 and the residual load is derived from it. Consequently, the calculated residual load serves the other simulators as an indicator for the market price. In this respect, the use of technologies that cannot be assigned to self-consumption optimization of a connected load (e.g. large battery storage) is determined as minimization of the residual load in Germany.

D. Buffer

In order to specify the use of the available flexibility according to different criteria later, the determination of the available flexibility is carried out in the *Buffer* first. The *Buffer* uses the forecast schedules of simulated and physical units in conjunction with their technical master data to derive a flock of potential schedules for each of these electrical units. The resulting schedule flock describes the technically possible flexibility by giving a set of concrete examples of potential unit behavior in the next planning interval.

Pilot projects in the field report their forecasted operating schedule for the planning interval, as well as the available flexibility potential in positive and negative directions, and a total amount of energy that can be provided before the potential is exhausted, if applicable. Based on these parameters, valid schedules are randomly generated in the *Buffer* until the sample size N is reached. To limit larger gradients within a schedule, the interval I from which a value is randomly selected by the *Buffer* for a time t is limited as follows:

$$I = [P_{t-1} - \Delta P_{t=0}\, ;\, P_{t-1} + \Delta P_{t=0}] \text{ with } \Delta P_{t=0} = |P^{+} - P^{-}| \times \alpha \quad (1)$$

Where P^{+} and P^{-} represent the maximum and minimum possible operating values within the flexibility offer at time t, and α is a modifiable weighting parameter. In Fig. 3 a resulting schedule flock is shown for sample size of N=100 and α=0.1. For the simulated flexibility units, a possible schedule flock is determined analogously based on their (e.g. chemical, thermal or kinetic) buffer state of the last planning interval and the associated models.

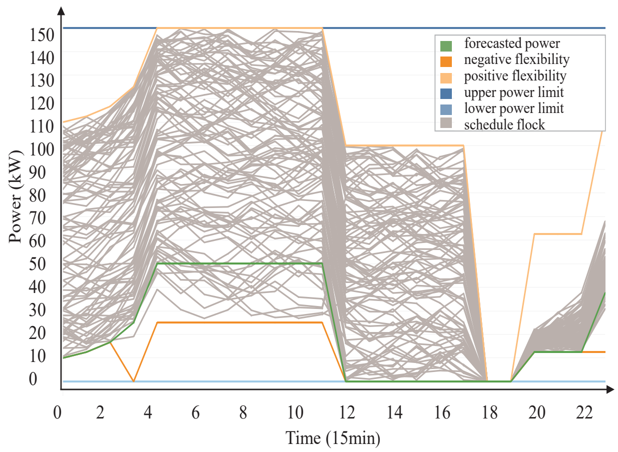

Fig. 3. Resulting schedule flock for sample size N=100 and α=0.1

For the supply-dependent plants from the SIMONA simulator, the current feed-in is defined as the upper bound and zero as the lower bound, which corresponds to a complete curtailment. In addition, models for other simulated flexibility options are stored in the *Buffer* and are used to create schedules for technologies that are dependent on their buffer storage. In the *System-Cockpit*, these are power-to-heat and power-to-gas units, battery storage and electric vehicles. An initial buffer state is assumed for simulation start, carried forward for all planning intervals, and updated according to the selected schedules.

E. SIMONA

In order to use the available flexibility, it must be ensured that the use in the affected distribution grid does not cause any grid constraint violations. For this investigation, the SIMONA simulator is used in the *System-Cockpit* [18]. On the one hand, a distribution grid operation is simulated and on the other hand, both the feed-in from RES and the electrical and thermal demand of household and industrial consumers are calculated based of live weather data.

In a first step, the market driven schedules of the pilot projects and simulated units for the current planning interval are integrated into the distribution grid operation simulation. After a load flow calculation has been performed, the flows on all lines and transformers and the node voltages are checked with respect to possible grid constraint violations. In the case of voltage band violations, it is first checked to what extent the grid constraint violation can be relieved by reconfiguration of on-load tap changing transformers. If this is not possible, the power flow or voltage sensitivities are calculated analytically for the corresponding resources or the affected nodes, respectively [15]. These sensitivities serve the ISAAC simulator as input values for determining the grid-relieving flexibility utilization.

In a second step, these schedules created under grid restrictions are checked again. If grid constraint violations occur again, sensitivities are calculated and transferred once more. If no new grid constraint violations are detected, the optimization process has converged and the schedules can be processed further. However, if grid constraint violations remain after a certain number of iterations between the grid calculation and the scheduling optimizer, the market driven use of flexibility is not considered possible without further upgrading the affected distribution grid. In a last step, SIMONA checks to what extent possible deviations of the pilot projects in operation from the specific flexibility product of the *System-Cockpit* lead to grid constraint violations. The actually provided powers of the simulated units are assumed to be identical to the ones listed in their schedules predetermined in planning. On the one hand, repeated grid constraint violations during operation allow conclusions to be drawn about further safety margins being necessary when determining the grid-relieving use of flexibility. On the other hand, the forecast quality of the pilot projects can be investigated.

F. Searcher

The use of available flexibility in line with market requirements is determined on the basis of Germany's residual load. One exception to this are the renewable energies, which are not market-driven but initially feed in the maximum amount of their supply. The *Searcher* simulator selects for each unit the schedule from the schedule flock that minimizes the residual load from the *Matcher* and thus maximizes the expected revenues of the decentralized flexibilities.

G. ISAAC

The resolution of possible grid constraint violations due to the market driven flexibility utilization is an optimization problem, for which the multi-agent system *ISAAC* is used [19]. The impact of each flexibility on grid constraint violation is formulated to yield the following objective function for power limit violations:

$$P_{max} > \sum_{i=1}^{N} s_{k,i}^{b}(t) \times P_i(t) \;\; \forall \;\; s_{l,i}^{b}(t) \in [0;1], b \in B \;, t \in T \tag{2}$$

Here, N denotes the number of units, $s_{k,i}^{b}$ the influence of unit i, at grid node k on asset b from the set of all resources B at time t in the planning interval T. The sensitivities $s_{k,i}^{b}$ are normalized to the unit with the largest influence on the constraint violation, as a consequence of which the left-hand side of the equation results in a power P_{max} to be undercut by changing $P_i(t)$ or P_{min} depending on the grid constraint violation. For voltage band violations, the result is analogous:

$$P_{max} > \sum_{i=1}^{N} s_{k,i}(t) \times P_i(t) > P_{min} \;\; \forall \;\; s_{l,i}(t) \in [0;1], \;\; t \in T \tag{3}$$

In the case of voltage band violations, an upper (P_{max}) or lower bound (P_{min}) is obtained after the violation is formed, with the respective non-active bound set to zero.

In addition to the grid constraint violations and the voltage band violations, ISAAC obtains the catalog of measures to use flexibilities (as described in C), which specify a qualitative order of the technologies.

All optimization targets are considered in the context of a lexicographic optimization. Primarily, the scheduling of the units is optimized with respect to the bound violation and remaining flexibility is used to enable those unit types that are at the back of the catalog of measures to select their cost-optimal schedule. For this purpose, a penalty value is determined for each possible solution, which indicates to what extent the catalog is taken into account in the solution. This value is calculated from the sum of all individual penalty values. An individual penalty value is 0 if a unit chooses its cost-optimal schedule. In all other cases, the value equals the position-number of the unit type in the catalog. Thus, the penalty value of a unit is larger the lower the associated unit type is in the catalog order, i.e., the higher its penalty value, the later or less frequently the unit is chosen.

To solve this optimization problem, ISAAC uses the distributed COHDA heuristic [20]. Each agent primarily selects the schedule of its unit that reduces the distance of the aggregate solution of all agents to the required goal the furthest. Each agent communicates the current observed system state, as well as the current best solution, to its immediate neighbors. If an agent receives a message, all information is integrated in the local working memory of an agent. The agent then optimizes the scheduling of its unit regarding its current knowledge. In case it has received new information or it has changed its planned schedule, the agent communicates its current knowledge to its neighbors. Once an intermediate solution exists at all agents that contains information from all other agents, it is considered complete. This completes the first phase of the algorithm, while in the second phase the solutions circulate in the agent system and are iteratively improved by the same mechanism using local information. This algorithm is known to converge after a certain amount of time. If it takes longer than a given time limit, the algorithm is stopped and the best possible existing solution is chosen. This means that after a complete solution has been found, there always is one, steadily improving solution available. Finally, the currently selected schedules of all agents are given to SIMONA simulator for re-examination.

III. Application and Results

The grid model used in the *System-Cockpit* was derived from grid data of distribution grid operators from the German federal states of North Rhine-Westphalia, Rhineland-Palatinate and Saarland. After defining nationwide scenarios for the composition of energy sources in 2035, these were transformed into discrete flexibility units based on socio-economic structural parameters and located in the distribution grid models. The chosen scenario represents a progressive estimation of renewable energies and flexibilities for the year 2035. The expansion status of the grid is selected in such a way that flexibility is required for a secure and stable operation. The grid model includes two high voltage, three medium voltage and two low voltage grids, whereas the rest of the grid is not modeled in detail. Instead equivalent loads are attached to the nodes. The pilot projects were connected to the grid model by means of technical and geographic data. The remaining grid users from the scenario were represented by corresponding models in the *System-Cockpit*. For this purpose, models of the following technologies were integrated: PV, wind power, biogas, power-to-heat and power-to-gas units, electric storage, electric vehicles (EV), residential and industrial loads, thermal storage, and cogeneration units. In addition to 14 pilot projects, 3,755 simulated entities were taken into account. In some cases models for aggregating units were also used.

Exemplary, Fig. 4 depicts the resulting flexibility use that results in a selected sub grid if flexibilities are used in a market-driven way. Note that there is a positive residual load for the selected period.

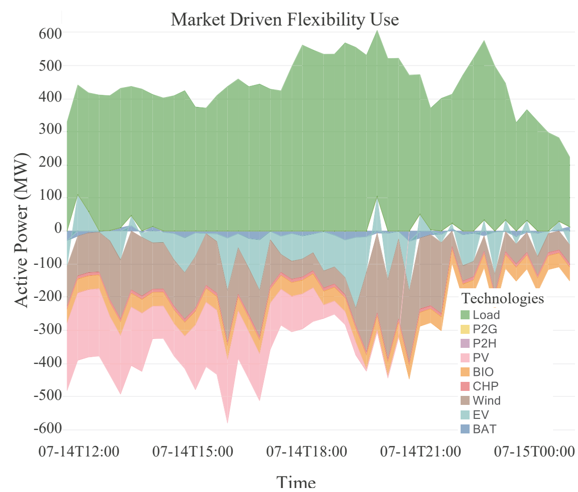

Fig. 4. Market driven flexibility use for positive resdidual load

The flexibilities are used, according to their technical restrictions, in a way that maximizes the energy input in this planning interval. At the start of the simulation, all flexibilities that have some kind of storage are initialized with a storage level of 50%. Due to weak heat demand, the power-to-heat units are not activated and the remaining heat demand can be covered by the heat storages. The EV behave accordingly, since the batteries start with an initial storage level and there is only weak mobility demand during the night hours, a large part of the energy can be fed into the grid. These effects due to the initial storage level, decrease in longer simulation periods due to mixing effects and this does not occur at times with a strong heat demand or a strong mobility demand, since the demand exceeds the capacity of the storage. Fig. 5 depicts two planning

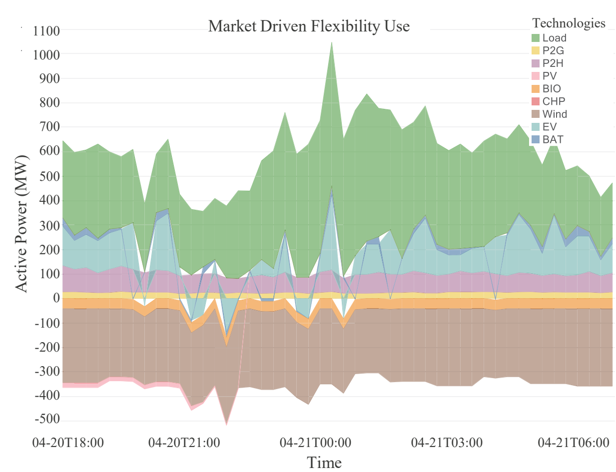

Fig. 5. Market driven flexibility use for low and negative residual load

intervals for the market driven use of flexibility with an increased heat demand and a low and partly negative residual load. The market-driven use of flexibilities leads to increased simultaneity in the distribution grids under investigation. In particular, this occurs when the residual load of the overall system behaves contrary to the residual load in the observed grid area. In addition, the presented methodology is used to determine the grid-relieving use of flexibilities in the event of grid constraint violations. Fig. 6 depicts the line utilization before (top) and after (bottom) the grid-relieving use of flexibility for a selected high voltage grid area.

The data-driven approach and the high number of flexibilities leads to the fact that the generation of valid schedule variants of the *Buffer* simulator was limited to five schedules per flexibility unit in order to control the computing time. This limited solution space in turn leads to the fact that schedules are available to the optimization process for solving the grid constraint violation, which at other times of the planning interval differ significantly from the previously determined schedules and lead to a change in the previously determined load flow results. By implementing an iteration process between the grid calculation and the optimization process, these possible new grid constraint violations are solved together with the older ones. However, due to the limited number of schedule variants and with an acceptable number of iterations, not all grid constraint violations could be resolved at every point in time. This should be taken into account in future work. Furthermore, grid constraint violations of the modeled sub-grids are solved exclusively with flexibilities from this sub grid, even if the power flows of the under- or overlaid grid levels are considered. This leads to a change in all other connected sub-grids in case of a change due to grid constraint violations of one sub-grid. Even if this circumstance is addressed by the iterations between grid calculation and optimization, this influence should be considered more comprehensively in future work.

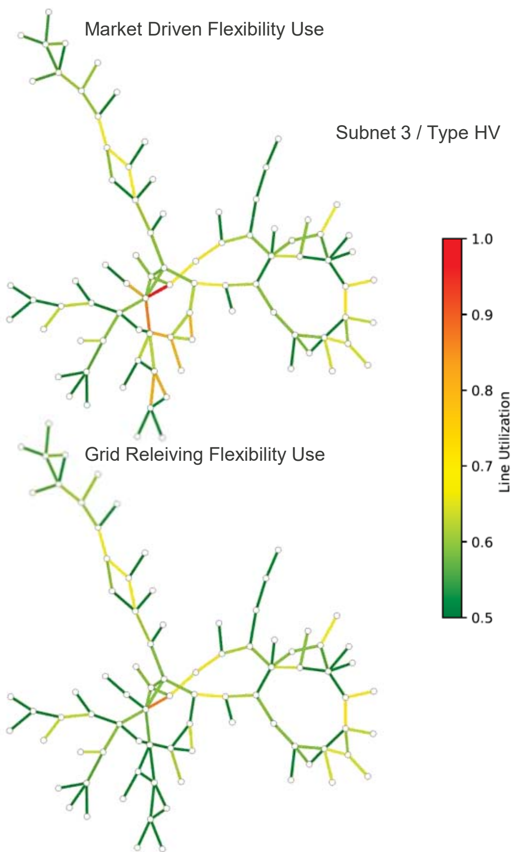

Fig. 6. Line utilization for examplary 110kV distribution grid, before grid-relieving flexibility use (top) and after (bottom)

IV. Lessons Learnt From Live Testing

In the DESIGNETZ project, 14 flexibility providers from different industries with different original energy technical processes were connected to the *System-Cockpit*. This variety requires high level of accuracy and comprehensibility of the interface definitions and the process descriptions. For later mass suitability, the interface should be standardized and concentrated on the absolutely necessary data traffic; high reliability and remote maintainability. Data consistency, i.e. the constancy of a date across different simulation and communication steps - as long as no intentional changes are made - is of high relevance. Standards with regard to security, interfaces and data formats must be defined in an agile but clear manner to enable rapid and secure connection of participants from a heterogeneous playing field. Live operation has also highlighted the high future demand for data exchange. In some cases large amounts of data and many handshakes between the systems led to increased response times or even crashes of subsystems. The scalability in the development of further units is questionable and supports the introduction of a digital twin of the plant models to reduce the data volume [21]. Transferring the implemented system into practical operation requires further investigation in regards to information availability due to the regulatory framework of liberalized energy markets. Even if the developed simulators could support the grid operator in the future for decision support in grid operation, role issues and information transparency must be taken into account. With an increasing amount of flexibilities, aspects of mass suitability and swarm behavior will come to the fore and the deviation from planning of individual providers will be less important. This applies to a lesser extent in the case of grid-relieving use, the greater the impact of this flexibility is on the grid bottleneck. On the low voltage level, the forecast of individual units is crucial and challenging, due to the high spacial resolution requirements. Therefore, the demand of intelligent grid assets for congestion management is likewise important. The central decision for grid-relieving use was determined by the *System-Cockpit* in a non-discriminatory manner on the basis of the greatest influence of the flexibility on the grid constraint violation. In order to implement this in practice, the creation of a financial incentive for providers of flexibilities and the integration of the regulatory and procedural framework would be necessary. Both adjustments are not further considered in the *System-Cockpit*.

Based on the simulations, it could be shown that the market-driven use of flexibility efficiently contributes to minimizing the residual load in Germany and, accordingly, to compensating the fluctuating generation of RES. The feedback effect of the market-driven use of units under consideration on the residual load of the overall system was not investigated. During operation, the market-driven use of flexibility led to an increased simultaneity in the distribution grids. For the lower voltage levels, most of the resulting voltage band violations was solved by using on-load tap changing transformers. In this context, it should be noted that the financial incentive could decrease accordingly and thus the observed high simultaneity occurs less strongly when considering the overall system. By assuming a constant power factor, the potential of reactive power control to resolve voltage band violations was not exploited. This could further reduce the need to adjust market solutions. In contrast, due to the lack of feedback and the different time resolution, flexibility use as control power was neglected, which in turn could lead to increased simultaneity in the distribution grids. As a critical infrastructure, the distribution grid is subject to increased security requirements. In this respect, further safety margins and emergency concepts have to be taken into account when this methodology is put into practice. Furthermore, the grid-relieving flexibility use was determined based on the complete knowledge of all node voltages and power flows of the considered distribution grid. In practice, this approach would require upgrading the distribution grids with respect to monitoring of all voltage levels. In addition, no forecast inaccuracies or unforeseen failures were considered for the simulated units.

Collectively, the integration of flexibilities is both a challenge and a solution. The market- and system-driven use of flexibility - for the operation of an energy supply system with a high penetration of renewable energies - can result in a high degree of simultaneity in the distribution grids. If, however, the development takes place in such a way that the coordinated use also enables a grid-relieving use of flexibility, the grid infrastructure can be optimally utilized and an economically inefficient grid expansion for rare extreme scenarios can be avoided.

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