LOCAL FLEXIBILITY MARKETS: AN ECONOMIC SOLUTION FOR THE UPCOMING INFLUENCE OF ELECTRICAL CHARGING STATION PENETRATION

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ABSTRACT

The installation of decentralized renewable energies is still going on in low and medium voltage grids and will increase the frequency of congestions in the near future. Especially voltage range violations are issues caused by simultaneous power peaks of photovoltaic systems. The concept of local flexibility markets (LFM) provides a reasonable solution for the distribution system operators (DSO) preventive congestion management in an economic and ecological manner. Furthermore, local flexibility markets can support the rapidly advancing integration of electric vehicle charging stations in particular within urban grid structures, where the mentioned challenges will be at maximum. The process of optimizing the flexibility acquisition as a key component of local flexibility market solutions will be a key aspect in this paper. Individual procedures and the use of specific matching algorithm will be addressed in detail. For demonstrating how LFM can support the integration of electric vehicle charging stations, the results of an urban low voltage grid simulation will be highlighted.

INTRODUCTION

Due to the emerging development of the installed capacity of renewable energy systems, congestion problems will occur more often in the near future. Since this critical grid states occur only a few hours per year in most of the distribution grids, innovative smart grid solutions can reduce or postpone the conventional enhancement of the grid. However, the upcoming influence of electrical charging station penetration will also result in equipment overloads, because of large additional loads that will probably occur highly localized in some single strands and grid areas. Active grid users can support distribution system operators (DSO) to solve voltage range violations and overloads [1] by offering their power flexibility [2] via local flexibility markets (LFM). This concept provides a reasonable solution for the DSO's preventive congestion management in an economic and ecological manner. Furthermore, local flexibility markets can support the rapidly advancing integration of electric vehicle charging stations in particular within urban grid structures, where the mentioned challenges will be at maximum. This additional field of application is a highly potential benefit of designed local flexibility markets [3] and could avoid or postpone expensive intelligent charging management and other grid investments.

This paper describes the calculation of the optimal flexibility acquisition at the online trading platform managed by the LFM service provider that is one essential process in the LFM environment [3]. The optimization module matches offered standardized flexibility products with the flexibility demand based on forecasted grid states to prevent critical grid states by minimizing the total costs. Determining the necessary constraints and point out the challenges of combining the grid side restrictions and market concept in one optimization will be a key part. Also ecological aspects will be considered in the selection process. This paper presents the developed optimization module and its internal procedures as an important component within the implementation of local flexibility markets.

In recent discussions about smart grid and smart market solutions, the cost-saving potential is often a key aspect [4] [5]. To evaluate this theoretical potential this paper will demonstrate a future scenario with regard to the rising renewable energy and electrical charging station penetration. The simulation results will estimate the costs of LFM requests in an urban low voltage grid and compare the outcome with a conventional network planning as a benchmark. In addition, a network planning with innovative assets completes the cost comparison. The impact of increasing electrical charging stations on the grid capacity cannot be neglected [6] and this paper will give an outlook how local flexibility markets could provide a reasonable solution to deal with the arising challenges.

OPTIMIZED FLEXIBILITY ACQUISITION

Basic functionality of the optimization module

All procedures of the developed local flexibility market design [3] are classified in three traffic light phases based on the BDEW traffic light concept (TLC) [7]. In the green phase, flexibility providers can operate freely at all accessible markets. The specific LFM marketplaces are closed. The grid state forecast, as a component of the LFM environment, continuously calculates predicted grid states as an input parameter for the Traffic Light Module (TLM) [3]. After the TLM identifies a probable voltage boundary violation or asset overloads a three-stage regulation concept, using only the available DSO-measures, is simulated to determine the remaining flexibility demand for avoiding the predicted critical grid state. If there is an additional need for flexibility products, the change trigger to the yellow traffic light phase is initiated and the online trading platform opens the relevant marketplace for aggregators and private owners' offers [8]. The optimization process is a key task for the LFM service provider and determines the cost-optimized combination of offered flexibilities to prevent the predicted congestions. In consideration of different constraints like flexibility system data, grid connection points, variable and fixed price components as well as forecasted grid states and DSO grid parameters the optimization module generates optimal flexibility schedules. Notifications of contract awards or rejections complete the trading cycle at the LFM trading platform for one single time slice. Meanwhile, the next trading cycle has already started.

Optimal Power Flow formulation

The actual optimization algorithm is based on the AC optimal power flow (OPF) architecture implemented in MATPOWER, which is an open-source power system simulation framework for Matlab [9]. The standard AC OPF problem is a general non-linear constrained optimization problem, with non-linear costs and constraints. This version uses the following equations:

$$\min_{x} f(x) \tag{1}$$

subject to

$$g(x) = 0 \tag{2}$$

$$h(x) \leq 0 \tag{3}$$

$$x_{min} \leq x \leq x_{max} \tag{4}$$

In a system with n_b buses, n_g generators and n_l branches, the optimization variable x is defined by the $n_b \times 1$ vectors of Θ and V being the bus voltage angles and magnitudes. Additionally, x is defined by the n_g ×1 vectors of generator real and reactive power injections P and Q as follows [9].

$$x = \begin{bmatrix} \Theta \\ V \\ P \\ Q \end{bmatrix} \tag{5}$$

The resulting objective function (1) is a summation of polynomial cost functions f_P^i and f_Q^i of real and reactive power injections for each generator and looks like equation (6).

$$\min_{\Theta,V,P,Q} \sum_{i=1}^{n_g} f_P^i(p_i) + f_Q^i(q_i) \tag{6}$$

The equality constraints (2) consist of two sets of n_b nonlinear nodal power balance equations, where one is for real power and one for reactive power. On the other hand the inequality constraints (3) consist of two sets of n_l branch flow limits as non-linear functions of the bus voltage angles Θ and magnitudes V representing both power flow directions. The variable limits (4) include an equality limited reference bus angle and upper and lower limits on all bus voltage magnitudes and real and reactive generator injections [9].

LFM optimization module

As the solving of mixed-integer non-linear OPF problems is beyond the scope of the current framework, there are some challenges to deal with. Specific adjustments had to be realized so that constraints and parameters like fix cost components, discrete control stages of flexible systems and the objective of minimizing the renewable energy curtailment could be added. The fundamental adaptation is to model each flexible system, that participates at the market auction, as a generator with minimum and maximum real power injection under a specific cost function, which is determined by offering data that have been made at the online trading platform. The schematic overview of the optimization tool process shows Figure 1.

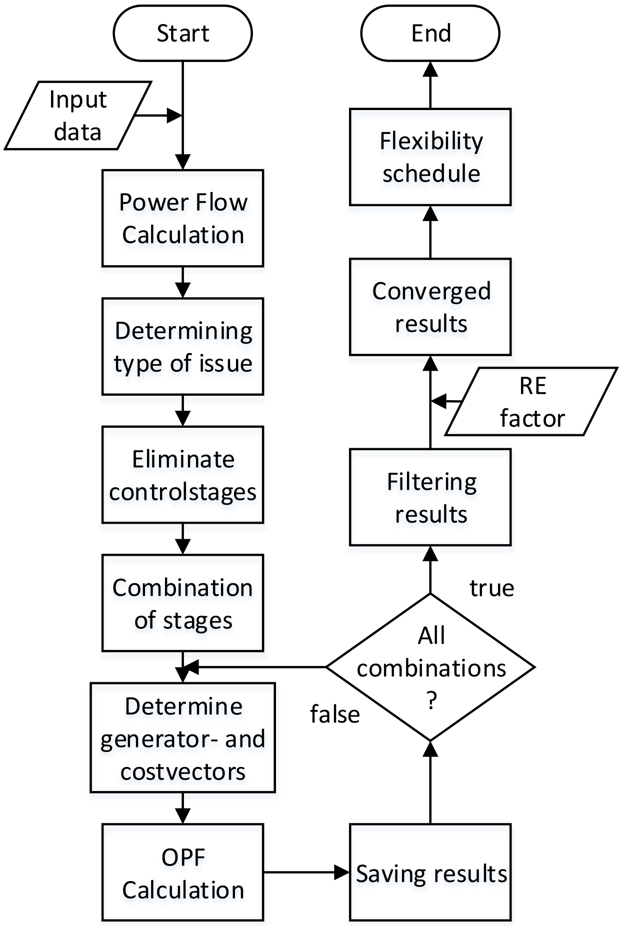

Figure 1: schematic Optimization Module process

Since all input parameters are converted in the necessary data format, one power flow calculation determines the type of issue for the current predicted time slice. The determination differentiates between upper and lower voltage boundary violations, asset overloads or in few cases a simultaneous upper and lower voltage boundary violation. Hereafter the type of issue and the predicted power injection of renewable energy systems define the relevant control stages for the current optimization.

If, for example, a battery storage system submits an offer to feed into the grid or charge and the congestion is based on a cable overload, the optimization module would eliminate all control stages of charging. The additional load caused by a possible charging of the battery storage system would just intensify the critical grid state. If the predicted power injection of a photovoltaic system is only at 30% peak power, the available control stages are reduced to stages below 30%. For a variable portfolio of flexibility systems, all remaining control stages of each system are combined in the next step. Subsequently, the matrices for generator data involving minimum and maximum power injection as well as for generator costs are determined (Figure 1). For systems with control stages, the minimum and maximum power injection is constrained to the same value defined by the first combination matrix, whereas continuously adjustable systems without fixed costs are modelled with their real minimum and maximum power values. This method provides the possibility to deal with fixed cost elements by dividing them by the constrained power value for the current control stage. The results are linear cost functions that meet the requirements of the used AC optimal power flow formulation. The OPF algorithm afterwards calculates the cost-optimal flexibility usage to prevent the predicted critical grid state under the grid restrictions and constraints defined by the DSO. This iterative process, whereby in each iteration the generator- and costmatrices are modified on the basis of the present combination matrix, ends with the abort criterion that all reasonable combinations have been calculated (Figure 1).

After filtering all OPF results based on a total cost limit for the cumulative flexibility demand, the so-called renewable energy curtailment factor (RECF) can optionally be considered. This factor is parameterizable by the DSO and describes the decrease of curtailed renewable energy in relation to the increase of total costs for the flexibility demand. Under the conditions of the RECF, the total cost limit and DSO specific constraints of individual system demand the optimization tool identifies the optimal converged solution of the result matrix. The flow of the optimization algorithm ends with the output of the flexibility schedule for the critical time slice.

LFM SIMULATION IN URBAN GRIDS

Structure of the simulation grid

Under the assumption that influencing factors like for example the purchase power and living structure, because of the possibility to charge at home, define the electric vehicle (EV) purchase decision [10,11], grids in suburban residential areas might be most affected by the penetration of EV-charging stations. To illustrate how LFMs could prevent critical grid states, which are mainly caused by load peak overlaps of EV-charging power, an appropriate low voltage (LV) grid has been simulated on the basis of a moderate EV-ramp-up curve for the year 2035. The LV-grid of a medium-sized German city consists of 277 nodes, which are arranged typically in single strands starting from the local power transformer sized with 1 MVA rated power. All connected flexible systems and loads as well as household connections without other flexibilities are listed in Table 1.

Table 1: Overview of connected flexible systems, loads and households in the simulated LV-grid

system/ load type	quantity	peak power in kW
photovoltaic	28	4 to 30
heatpump	27	15
EV-charging station	23	11 to 22
battery storage system	5	10 to 30
household	59	8

The EV penetration value of 22% in 2035 of all households, that are owing a private conventional car, is coming from self-generated EV-ramp-up curves based on data from EV-studies appeared between 2014 and 2018. In Figure 2 the generic load and injection profiles of flexible systems, loads and households are exemplary illustrated with per unit values for a time horizon of three days in 15-minute time steps. The time series simulation has been executed for typical weeks in spring, summer, autumn and winter to represent the seasonal influences in a logical manner. The simulation and optimization results have been upscaled to one year for purpose of comparison.

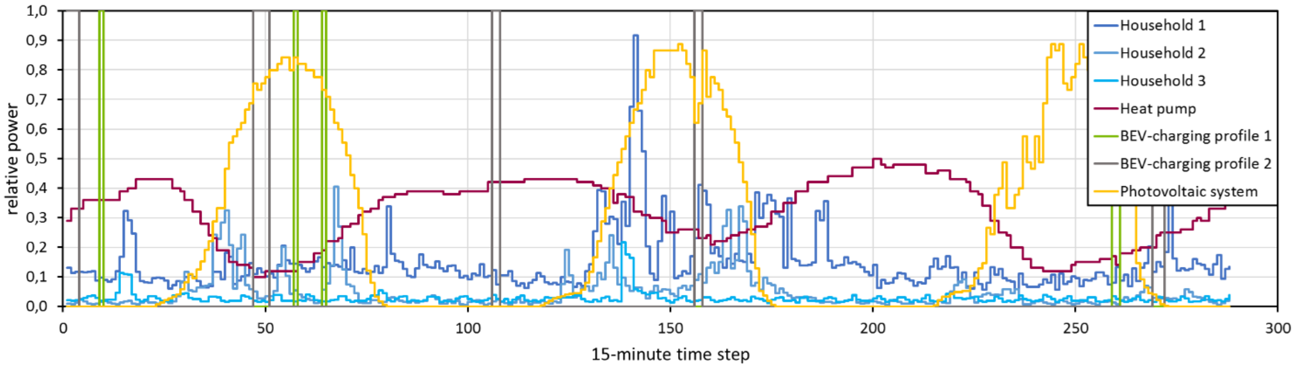

Figure 2: generic load and injection profiles of flexible systems in the urban grid

LFM optimization results

Since there are no practical experiences to what extent compensation payments have to be made on a LFM to attract participants and provide high enough incentives for prosumer and aggregators, the range of fixed price components of flexibility offers and the general liquidity at the online marketplace is varied. Overall, all identified critical grid states resulting from the time series based grid simulation for one year have been optimized several times with different offer data. The participating systems and the variable and fixed price ranges used are shown in Table 2.

Table 2: Used price ranges in the offer data

system/ load type	variable price in ct/kWh	fixed price in €
photovoltaic	11,87 to 30,00	1 to 50
heatpump	11,87 to 30,00	1 to 50
EV-charging station	11,87 to 30,00	1 to 50
battery storage system	11,87 to 30,00	1 to 50

The first optimization series has been progressed with a fixed price range between one and five euro. The liquidity, which means how many flexibility owners participate at the LFM relative to the theoretical available systems in the simulated grid, is considered at 10%. For each next optimization series, the fixed price range has been increased up to a maximum factor of ten while the liquidity has remained unchanged. This process has been repeated for liquidities of 20% and 30%, to find out whether the assumption of decreasing costs due to increasing market participation proves true.

The simulation and optimization results, presented as the yearly flexibility costs of all demands needed to prevent the forecasted critical grid states subject to the LFM liquidity, are shown in Figure 3. Cost range 1 (green line) represents a fixed cost range (CR) of one to five euro. The total costs in 2035 of 631€ for a liquidity of 10% result of an amount of 208 demands with a voltage boundary of 92% to 108% at the LFM. The total costs can be reduced by 17,1% to 523€ by increasing the LFM liquidity to 30%.

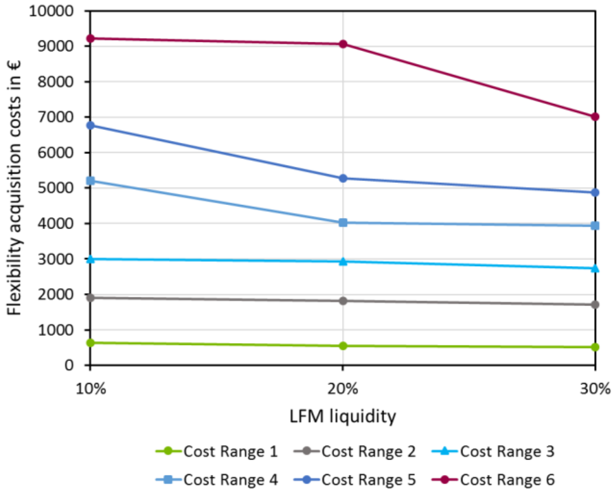

Figure 3: Flexibility costs per year subject to the market liquidity

Whereas the average of the total cost reduction by increasing the liquidity from 10% up to 30% of all cost ranges is 19,4%, the highest relative reduction of 28% shows cost range 5 (dark blue line) by decreasing the total costs from 6767€ to 4869€. Cost range 5 represents a fixed cost range of 20€ to 40€.

In order to assess the flexibility acquisition costs, the simulation grid has been planned by using conventional grid expansion measures and one additional planning with innovative assets. For the purposes of better comparability, all solution variations have been discounted and calculated as present values. The results are presented in Figure 4. The most significant cost saving of 93,2% can be identified with flexibility acquisitions by a fixed cost range of one to five euro (CR1) relative to the conventional enhancement (conventional) and a LFM liquidity of 30%. However, in this outcome the smart-grid-system (SGS) is already in place, so that the comparison considering the SGS investment costs seems more valid. Nevertheless, the cost saving potential in this case is at 67,6% with a present value of 35.454€ (CR1+SGS) instead of 109.542€ (conventional).

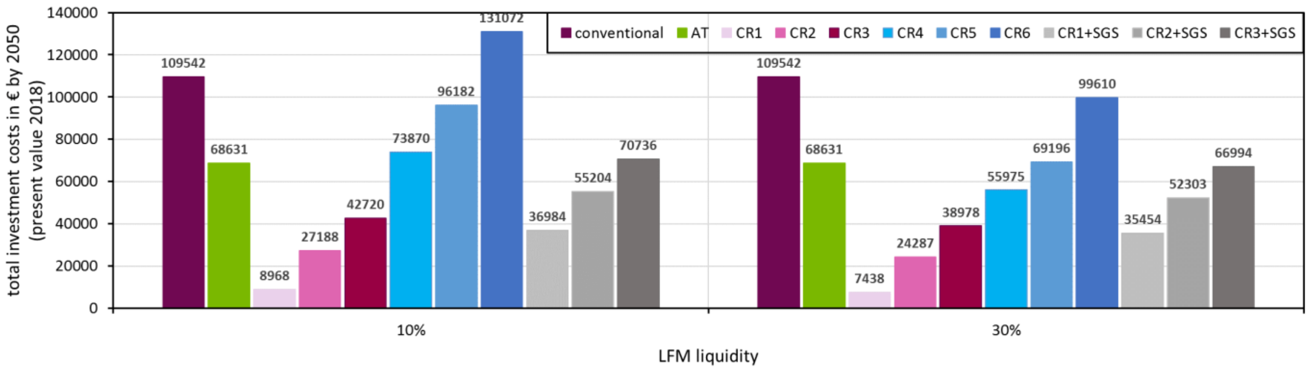

Figure 4: total investment costs as present value of acquisitions at the LFM compared to conventional and other innovative solutions

Even with a fixed cost range of 10€ to 20€ (CR3+SGS) and a liquidity of just 10%, the LFM solution has a cost saving potential of 35,4%, as other innovative planning solutions like adjustable transformers are at the same cost level with 68.631€ (AT) and 37,3%. Furthermore, the illustrated results point out that fixed cost ranges above 15€ to 30€ (CR4), even without considering the SGS investment costs, have any significant economic benefit compared to conventional solutions if the liquidity remains at 10% at the LFM.

CONCLUSION AND OUTLOOK

The basic functionality of the introduced optimization module, as a key component of designed local flexibility market solutions [3], has been stated and classified in the whole trading cycle of the LFM considering the defined phases of BDEW traffic light concept. On the basis of an AC optimal power flow formulation [9], that was originally developed for the power plant deployment planning, in this paper were challenges described to overcome and specific adjustments that have to be made for the successful and reasonable adaptation of the framework. This allows the possible consideration of parameters like fixed cost components, discrete control stages of flexible systems and inlcudes the objective of minimizing the renewable energy curtailment as an option determined by the DSO. The optimization module can handle all necessary cost components and flexible system data to identify the cost-optimized schedule based on stored offering data preventing forecasted critical grid states at the online trading platform.

The simulation of an suburban low voltage grid of a medium-sized German city illustrates how LFMs could prevent critical grid states, that are mainly caused by load peak overlaps of EV-charging power. It has been demonstrated that the integration of EVs with a value of 22% in 2035 of all households could be implemented via LFMs, which could avoid or postpone conventional grid investments and provide a preventive congestion management in an economic and ecological manner. A variety of cost ranges and different liquidities of the LFM marketplace have been simulated, with the result that considering the SGS investment in the best case the cost saving potential is at 67,6% relative to the conventional enhancement for the simulated grid and its constraints mentioned. Nevertheless, the lowest considered fixed cost range, that has still an economic benefit compared to conventional solutions, of 10 to 20 euros in this case seems sufficiently high and has a cost saving potential of 38,8%. The average of the total cost reduction by increasing the liquidity from 10% up to 30% of all cost ranges has been at 19,4%, whereas the highest relative reduction is 28%. Due to the fact that despite varying cost ranges and the LFM liquidity all results represent cost saving potentials of one suburban grid, additional cost simulations of other grids must be evaluated to validate the shown conclusions.

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REFERENCES

[1] T. Kornrumpf, J. Meese, M. Zdrallek, N. Neusel-Lange und M. Roch, 2016, "Economic Dispatch of Flexibility Options for Grid Services on Distribution Level", *Proceedings 19th Power Systems Computation Conference (PSCC)*, 1-7.

[2] B. Biegel, P. Andrersen, J. Stoustrup, K. S. Rasmussen, L. H. Hansen, S. Østberg, P. Cajar und H. Knudsen, 2014, "The Value of Flexibility in the Distribution Grid", *5th IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*, 1-6.

[3] K. Kotthaus, J. Hermanns, F. Paulat, S. Pack, J. Meese, M. Zdrallek, N. Neusel-Lange und F. Schweiger und R. Schweiger, 2018, "Concrete design of local flexibility markets using the traffic light approach", *Proceedings CIRED Workshop Ljubljana*, 1-4.

[4] P. Olivella-Rosell, P. Lloret-Gallego, I. Munné-Collado, R. Villafafila-Robles, A. Sumper, S. Ø. Ottessen, J. Rajasekharan und B. A. Bremdal, 2018, "Local Flexibility Market Design for Aggregators Providing Multiple Flexibility Services at Distribution Network Level", *Energies 2018* vol. 11(4), 822.

[5] T. Esterl, R. Schwalbe, D. Burnier de Castro, F. Kupzog und S. Kadam, 2016, "Impact of market-based flexibility on distribution grids", *Proceedings CIRED Workshop Helsinki*.

[6] S. Deb, K. Tammi, K. Kalita und P. Mahanta, 2018, "Impact of Electric Vehicle Charging Station Load on Distribution Network", *Energies 2018* vol. 11(1), 178.

[7] BDEW – German Association of Energy and Water Industries, 2015, "Smart Grid Traffic Light Concept", *BDEW Discussion Paper*, 1-14.

[8] ETG RegioFlex Task Force, 2015, "Regional Flexibility Markets", *VDE Study*, 50-55.

[9] R. D. Zimmerman, C. E. Murrilo-Sánchez, R. J. Thomas, 2009, "MATPOWER's Extensible Optimal Power Flow Architecture", *IEEE Xplore*, 1-2.

[10] X. Mosquet, H. Zablit, A. Dinger, G. Xu, M. Andersen and K. Tominaga, 2018, "The electric car tipping point", *BCG research report*, The Boston Consulting Group, 6-15.

[11] F. Liao, E. Molin, B. van Wee, 2017, "Consumer preferences for electric vehicles: a literature review", *Transport Reviews 2017*, 252-275.