# THE FUTURE ROLE OF A DSO IN DISTRIBUTION NETWORKS WITH HIGH PENETRATION OF FLEXIBLE PROSUMERS

Uros MARKOVIC
ETH – Switzerland
markovic@eeh.ee.ethz.ch

Evdokia KAFFE
ewz – Switzerland
evdokia.kaffe@ewz.ch

Dona MOUNTOURI
ewz – Switzerland
dona.mountouri@ewz.ch

Dr. Florian KIENZLE
ewz – Switzerland
florian.kienzle@ewz.ch

Stavros KARAGIANNOPOULOS
ETH – Switzerland
karagiannopoulos@eeh.ee.ethz.ch

Dr. Andreas ULBIG
ETH – Switzerland
ulbig@eeh.ee.ethz.ch

## ABSTRACT

*In this work the extended future role of a DSO in networks with high PV infeed and active prosumers is examined. The resulting challenges for the distribution grid are tackled both through innovative tariff incentives and operational real-time interventions in critical situations. The prosumers and the grid are modelled based on real data and projections for a low-voltage grid in the city of Zurich. The prosumers and the DSO can interact with each other and the final nodal dispatch is defined after a three-step multi-objective optimization. Our results show that a certain level of operational real-time interventions by DSOs is always required. This can be significantly reduced with suitable incentives via bidirectional grid tariffs.*

## INTRODUCTION

In 2008, the citizens of Zurich voted in favour of the implementation of the “2000-Watt society” concept [1]. This concept refers both to the reduction of the overall continuous energy usage to no more than 2000 Watts per person, as well as to the reduction of the carbon footprint to less than 1 ton CO2 equivalent per person by 2050 [2].
Therefore, the penetration of renewable energy sources and new loads, such as electric vehicles, is expected to grow significantly in low-voltage (LV) distribution grids in the city of Zurich. Large shares of such units pose new challenges to distribution system operators (DSOs) which may need to confront line/transformer over-loadings and voltage violations. Previous studies have shown that grid integration measures solely based on traditional grid reinforcements and battery installations for pure grid usage require high investment costs by DSOs. Therefore, questions arise regarding the role a DSO should take in order to solve these challenges. In this paper, we examine additional options that DSOs may use apart from the conventionally used methods, in order to efficiently manage the grid and maximize the integration of distributed generation. The focus is set on the combination of suitable grid tariffs with grid monitoring and control during critical situations.
An existing grid in the city of Zurich is used for the simulations. Two actors are modelled: the DSO and the prosumers. Through a three step optimization we test the effectivity of the incentives given through tariffs and the resulting level of required intervention. An important aspect of our approach is that in this setting, the DSO defines the level of required adjustment for each node but the prosumer decides which actions are required in order to comply.

## MODELLING FRAMEWORK

While the goal of each individual prosumer is to satisfy its electricity demand with minimal costs, the DSO’s task is to maintain the grid within the allowed operational limits and secure the financial reimbursement of its investments. These two interests can temporarily be conflicting and invoke the need for a real-time monitoring and control.

### Prosumers

Each prosumer is fully equipped with photovoltaic (PV) panels, a battery unit and an electric vehicle (EV). The solar potential of the respective roof area is estimated through “Solarkataster”, a GIS application of the city of Zurich, while the provided storage system is modelled with the same installed capacity as the PV system. Each household is assigned with a single electric vehicle, rated at a 3kW power level. It is also assumed that 10% of the prosumer’s load is actively manageable through a demand side management system (DSM), whereas the availability of this controllable load share is estimated based on the generated seasonal heat demand profiles. Additionally, active power curtailment (APC) of the PV production is possible. Due to computational reasons, each prosumer is modelled as an aggregation of households supplied from a single grid connection point.
The connection of distributed generation (DG) to the receiving end of a distribution line can result in unacceptable voltage rises, as well as the occurrence of reversed power flows that can exceed the rated loading of lines and MV/LV transformers.

### DSO

In order to cope with the above mentioned challenges, e.g. to comply with the European Norm EN 50160 [3] for the voltage levels and with the thermal limits of the grid components, the DSO can take several actions. On the one hand, the DSO can provide the prosumers with incentives for a grid friendly behaviour through suitable grid tariffs. A suitable tariff design facilitates the grid integration of a growing amount of distributed generation (DG) and storage units, mostly by replacing the standard volumetric (based on kWh) concepts with the more appropriate capacity-based (kW) pricing approaches.
On the other hand, when the impact of the new tariffs is not

enough, the DSO needs to intervene and require the adjustment of the nodal injection to guarantee the safe operation of the grid. In order to implement such a control algorithm, a bidirectional real-time communication interface between the energy management system (EMS) of the prosumers and the grid monitoring and control system of the DSO is required.

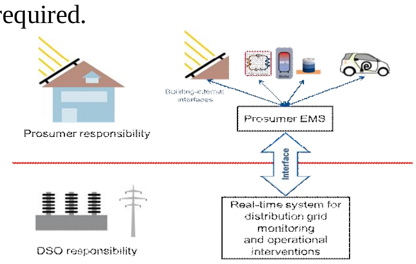



**Figure 1:** Basic concept for the interface between DSO and prosumers.

## Optimization algorithm

To address the problem of the conflicting interests between the prosumers and the DSO, a set of three consecutive optimization sequences is used, aiming to simultaneously maximize the benefits of both sides, as depicted in Figure 2.

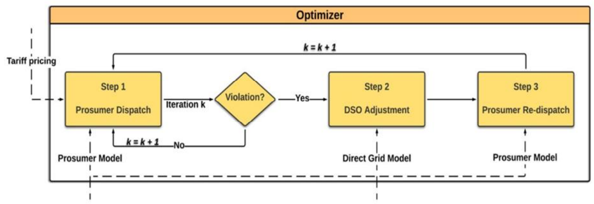



**Figure 2.** Block diagram of the employed optimization algorithm.

**Step 1: Prosumer dispatch**

The first step focuses on the individual prosumer aggregation and minimizes the respective annual electricity costs by determining the optimal unit dispatch. This problem can be formulated for the prosumer with index *i* as follows:

$$\vartheta_1 = \min_{\mathbf{P}_{PV},\mathbf{P}_{DL},\mathbf{P}_{EV},\mathbf{P}_{BS},\Delta\mathbf{P}_{APC},\Delta\mathbf{P}_{DSM}} \left\{ \kappa_E(i) + \kappa_G(i) \right\} \quad (1)$$

$$\kappa_E(i) = \sum_{t=1}^{N_t} \left\{ C_{E,t} P_{imp,t}(i) - C_{R,t} P_{exp,t}(i) \right\} \Delta t$$

$$\kappa_G(i) = \Psi_{N_t} \left\{ \mathbf{C}_G, \mathbf{P}_{imp}(i), \mathbf{P}_{exp}(i), S_{HC}(i) \right\}$$

where $N_t$ is the number of time steps per year; $C_E$, $C_G$ and $C_R$ are the tariffs for consumed energy, grid usage and produced surplus reimbursement respectively; $P_{imp,t}$ and $P_{exp,t}$ denote the power import and export during the time step *t*; $\Psi_{N_t}$ represents the grid cost function, while $S_{HC}$ stands for the installed capacity of the house connection cable. The set of constraints refers to fulfilling the nodal balance and respecting the technical limitations of prosumer components such as batteries or EV charging stations. No grid constraints are considered in this step. For the purpose of an efficient resource management, a model predictive control based on a 24-hour time horizon and machine-learning forecast techniques is integrated in this segment of the optimizer.

**Step 2: DSO adjustment**

Since none of the network's limitations are considered in the initial prosumer dispatch, the DSO is required at the same time step to investigate the system parameters and promptly react to any potential violations. If the critical voltage and loading levels are breached, the subsequent optimization procedure computes the minimal level of nodal injection readjustment that provides full mitigation of the problem at hand, as presented in (2).

$$\vartheta_2 = \min_{\mathbf{P}_{inj}^{adj}} \sum_{i=1}^{N_p} \left\{ P_{inj}^{adj}(i) - P_{inj}(i) \right\} \quad (2)$$

The symbol $N_p$ denotes the total number of prosumers, whereas the $P_{inj}^{adj}$ symbols the final adjustment signals enforced on the customers by the DSO.

**Step 3: Final re-dispatch**

In the final step of the algorithm, the prosumers are obliged to alter their dispatch schedules according to the signals sent by the DSO. The set of constraints remains the same as for the initial step, but the main objective is to comply with the adaption of nodal injections required by the DSO while considering a set of weighting factors for different prosumer actions:

$$\vartheta_3 = \min_{\mathbf{P}_{PV},\mathbf{P}_{DL},\mathbf{P}_{EV},\mathbf{P}_{BS},\Delta\mathbf{P}_{APC},\Delta\mathbf{P}_{DSM}} \sum_{f=1}^{4} \lambda_f \left| P_f(i) - P_f(i) \right| \quad (3)$$

with $f \in \{PV, DL, EV, BS\}$ describing four different unit types and their respective weighting factors $\lambda_f$. The utilization of the batteries is preferred over all other options, while PV curtailment is considered the least favourable from the prosumer perspective as it leads to direct monetary losses.

## Tariff design

The standard tariff schemes consist of two components, reflecting the consumed electricity and the utilization of the network's infrastructure respectively. Moreover, a financial reimbursement for any export of excessive energy is introduced in the form of a feed-in tariff (FIT). All energy-related costs are based on the volumetric time-of-use (ToU) principles. Beside the current high/low (HT/LT) tariff concept, the constant (Uniform) and the spot market kWh rates have also been investigated.

The constantly increasing self-consumption challenges current grid tariff schemes, which are usually primarily designed around volumetric charges. Hence, capacity-based methodologies addressing the critical peak pricing (CPP) are introduced and examined [4], as listed in Table 1. *Cap1D* only penalizes the monthly maximum of the grid import, whereas for *Cap2D* tariffs both import and export are relevant. *Cap2Da* is asymmetric with imports being higher penalized, while in *Cap2Ds* only the maximum of import or export is charged with a symmetric price. A flat rate based on the installed cable capacity of the prosumer's connection to the grid is also included.

| *Grid Tariff* | *Type* | *Pricing Method* | *Index* |
|---|---|---|---|
| HT/LT | ToU | $C_{HT} \cdot E_{imp}^{06-22} + C_{LT} \cdot E_{imp}^{22-06}$ | g1 |
| Cap1D | CPP | $C_{imp}^{1D} \cdot P_{imp}^{max}$ | g2 |
| Cap2Da | CPP | $C_{imp}^{2D-a} \cdot P_{imp}^{max} + C_{exp}^{2D-a} \cdot P_{exp}^{max}$ | g3 |
| Cap2Ds | CPP | $C_{imp/exp}^{2D-s} \cdot \max\left\{P_{imp}^{max}, P_{exp}^{max}\right\}$ | g4 |
| Flat | ~ | $C_{flat} \cdot S_{HC}$ | g5 |

**Table 1**. Proposed grid tariff pricing models.

## TEST ENVIRONMENT

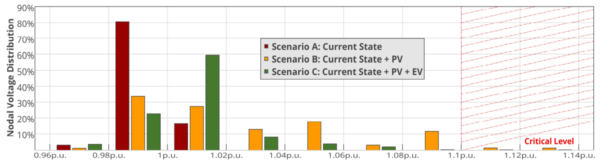
As test area for the above described methodology, Leimbach, a mainly residential district in the southern periphery of the city of Zurich, was chosen [5]. Its relatively low load density in combination with large available roof areas makes it an ideal case study for the demonstration of the impact of PV penetration on LV grids. In this paper, the "Hüslibachstrasse" LV area fed by two 630 kVA MV/LV transformers, is chosen as a case study. A total of 254 nodes are modelled, out of which 111 refer to house connection meters of ewz.

The load profiles used in the simulations are generated from yearly transformer loading measurements, while the PV potential corresponds to a value 2.8 times higher than the respective peak load. However, the maximum PV infeed, which appears in summer, does not coincide with the peak load demand occurring in winter. The maximum value of the total PV infeed to peak load ratio is 5.4, and it is observed at the maximum PV infeed time point on May 18th. Approximately 500 hours of transformer overloading and 120 hours of voltage violations can be identified in 2013, if the whole PV potential of the area is considered. The total battery installation potential, which depends on the installed PV capacity per node, could cover 55% of the maximum daily PV production.

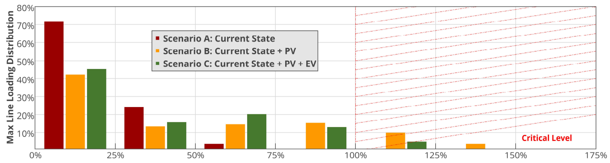
## RESULTS

The first set of simulation scenarios analyses the current state in the LV network of Leimbach and the overall hosting capabilities in case of large PV and EV penetrations. Neither storage units, nor real-time optimization control are included in these case studies.

The results depicted in Figure 3 show that, despite having a properly dimensioned grid for the current load demand, a significant amount of PV production would lead to an unacceptable voltage rise in almost 5% of the time. Furthermore, the lines and transformers face even greater and more frequent challenges, as their respective loading limits are exceeded by approximately 50% and 80%. While the integration of additional consumption in the form of electromobility reduces the existing stresses, it is insufficient for completely mitigating the problems.




(a)




(b)

**Figure 3.** Annual distribution of stresses for three basic scenarios regarding: (a) Nodal voltages. b) Line loading.

After employing the proposed optimization algorithm, the prosumers are capable of reducing the electricity costs by managing their resources more efficiently. The nodal balance profiles presented in Figure 4 depict the prosumer behaviour under the high and low rates of the presently employed tariff scheme in Zurich. The combination of incentives to export power and insufficient storage capacities during the high PV in-feed hours explains the need for frequent DSO regulation in the spring and summer seasons, reflected as the enforced PV curtailment.

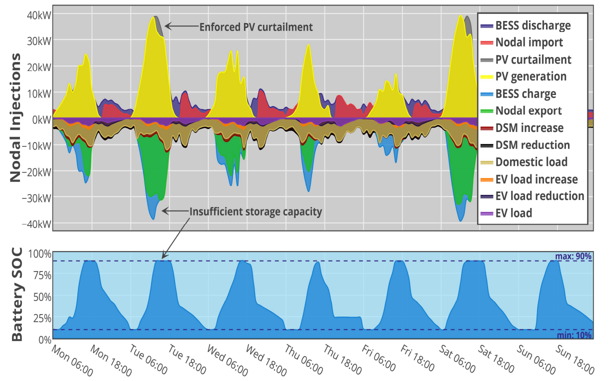



**Figure 4.** Final nodal balance profile during spring week.

Unlike the ToU model, the capacity-based grid cost tariffs provide different incentives, mostly based on the respective nodal injection monthly peak. While the import limitations imposed by the *Cap1D* approach do not address the most critical time instances of the year, the bidirectional concepts significantly aid the grid during these intervals (Figure 5). This is achieved by motivating the prosumers to independently reduce their own production within the initial dispatch as a trade-off against the higher grid costs. On the other hand, the flat grid tariff has an adverse effect on the LV system, as it facilitates an environment for prosumer arbitrage, which can further lead to excessive nodal injections over the day.

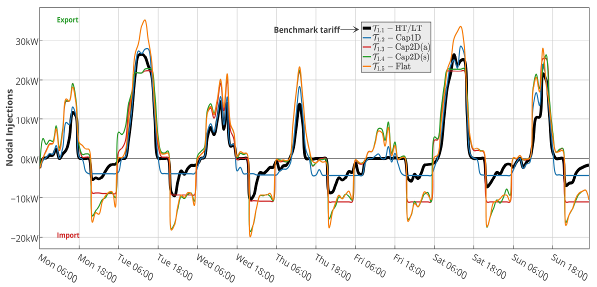



**Figure 5.** Nodal injections for different grid tariff designs.

The previous conclusions are confirmed by observing the DSO adjustments in case of various network tariff designs, as shown in Figure 6. The grid-friendly nature of *Cap2D* concepts comes to the fore, as the annual nodal injection adjustments (in kWh) are reduced more than 50% compared to the other pricing schemes. Nevertheless, this beneficial property is characteristic only for the spring season, whereas slightly lower PV/load ratio during summer provides insufficient incentive for APC activation by the prosumer himself.

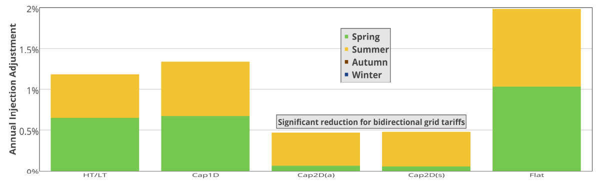
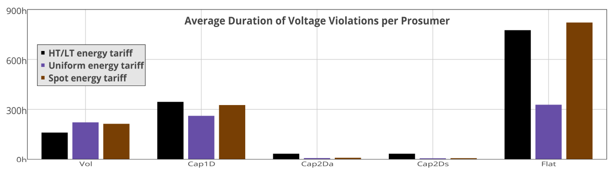
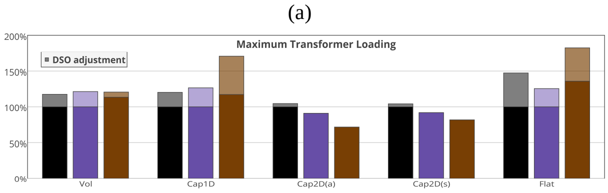



**Figure 6.** Required operational real-time adjustments of the DSO for different grid tariff designs.

The analysis of LV system's properties under combination of different energy and grid tariff models is presented in Figure 7. The volatile nature of the spot price is often a downside and can lead to extreme voltage and transformer loading levels. On the other hand, both *Uniform* and *Spot* energy concepts enhance the efficiency of bidirectional CPP network tariffs, leading to only negligible share of critical voltage hours over the year. Hence, a need for a real-time DSO regulation and the installation of a complex communication interface could be avoided.




(a)




(b)

**Figure 7.** Critical system parameters for all tariff models (a) Nodal voltages. b) Maximum transformer loading.

Due to a simpler pricing structure for the customer, as well as the more appropriate battery usage patterns, the combinations of *Uniform* (energy) and *Cap2D* (grid) tariff models can be considered the most favourable for the examined grid regarding minimizing the overall level of DSO readjustments.

## CONCLUSION AND OUTLOOK

This study shows that line and transformer overloading, as well as voltage violations, are expected in the future under the current network tariff design in grids with a high amount of flexible prosumers. The expected challenges due to high penetration of renewable generation and integration of new technologies require an extension of today's role of DSOs in two dimensions:

Firstly, grid tariffs should be proactively designed in such a way that they provide incentives for grid-friendly behaviour of active prosumers. Our results show that bidirectional capacity-based grid tariffs are suitable for this purpose. On the contrary, the flat rate tariff based on the installed grid connection capacity of the prosumer results in the highest peaks in grid usage.

Secondly, a real-time grid monitoring and control will be required in the future. The extent of this measure will differ depending on the specific grid topology and grid characteristics such as load density.

In the end, an optimal balance between suitable grid tariff design and real-time monitoring and control is required in order to guarantee cost-efficient distribution grids.

The focus of this paper was mainly on the future role of DSOs and on cost efficiency of the grid. In future work, the role of other players such as aggregators or flexibility providers should also be analysed in more detail. In this context, the optimal balance between grid and electricity market efficiency and the impact of grid tariff design and real-time operational interventions on this balance has to be taken into account.

## REFERENCES

[1] Municipal Code of the City of Zurich. Status March 2013

[2] 2000-Watt-Gesellschaft. http://www.2000watt.ch/. (accessed April 2015)

[3] CENELEC, 1999, "European Norm EN 50160: Voltage characteristics of electricity supplied by public distribution systems".

[4] Mountouri D., Kienzle F., Poulios V., 2015, "Suitable network tariff design for the grid integration of decentralized generation and storage", CIRED.

[5] V. Poulios, 2015, „Optimal placement and sizing of battery storage to increase the PV hosting capacity of low voltage grids.", ETG Kongress, Bonn