CHALLENGES WITH PV GRID INTEGRATION IN URBAN DISTRIBUTION SYSTEMS: A CASE STUDY IN THE CITY OF ZURICH

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ABSTRACT

In this paper, the impact of a high penetration of photovoltaic plants on the low voltage network of a residential area in the city of Zurich is investigated. The full utilization of the available roof area for photovoltaic plants in districts with a relatively low load density can lead to transformer and line overloading as well as to voltage rise problems. Potential remedies to these problems are examined and the optimal combination of individual measures is identified for a concrete case study. The intention of this paper is to show challenges and corresponding solutions for a cost-efficient integration of extensive distributed generation in urban distribution grids.

INTRODUCTION

In Switzerland, the promotion of renewable energy technologies by the federal government has been increasing over the last years. Specifically, the majority of the citizens of the city of Zurich voted in 2008 in favor of the implementation of the 2000-Watt society concept [1], an environmental vision introduced by ETH. The 2000-Watt society 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 no more than 1 tone CO_2 equivalent per person by 2050 [2].

Therefore, a significant amount of distributed generation (DG) and more specifically photovoltaic (PV) production is expected to be installed in the distribution system of the city of Zurich over the next years. A high PV penetration in the low voltage level (LV) can bring challenges for the existing electricity grid infrastructure, possibly leading to the violation of several technical constraints. More specifically, the arbitrary DG installation may cause unacceptable voltage rises in the network as well as an increase in the cable and transformer loadings.

In light of the above situation, this paper investigates the effect of a large DG penetration in an urban LV grid in the city of Zurich. The distribution grid of Leimbach, a mainly residential district in the periphery of the city was chosen for the case study.

The paper is structured as follows. After a description of the Leimbach LV network characteristics, the results of a load flow analysis for different scenarios are presented. Subsequently all the examined PV integration measures are analysed and the costs per measure are assessed. Furthermore, the results of a time series analysis based on real measurement data for PV production and demand are presented. Finally, conclusions will be drawn and an outlook to further analyses will be given.

LEIMBACH NETWORK AS A CASE STUDY

Leimbach is a mainly residential district in the southern periphery of the city of Zurich. Its relatively low load density in comparison with relatively large available roof areas makes it an ideal case study for the demonstration of the potential impact of PV on the low voltage grid.

Existing situation

The medium voltage (MV) system of ewz is designed with ring structures. The MV ring under investigation comprises 5 MV/LV substations with a total simultaneous maximum load of 4.5 MVA. 437 different house connection points with an inductive power factor of 0.95, as well as 1138 different line segments with a total length of 31 km were modeled.

Solar potential of Leimbach

In the examined area, about 1.5 km^2 of roof area is available for the installation of PV panels. The PV potential of Leimbach was assessed through "Solarkataster", a GIS application of the city of Zurich. The identified solar potential of Leimbach corresponds to a total installed PV capacity of 10.2 MW$_p$. Today's maximum transformer loading and the identified PV potential per substation is depicted in Figure 1. The ratio between PV potential and maximum transformer loading varies from 1.1 in Sihlweid, where some high residential buildings are located, to 3.3 in Bruderwies.

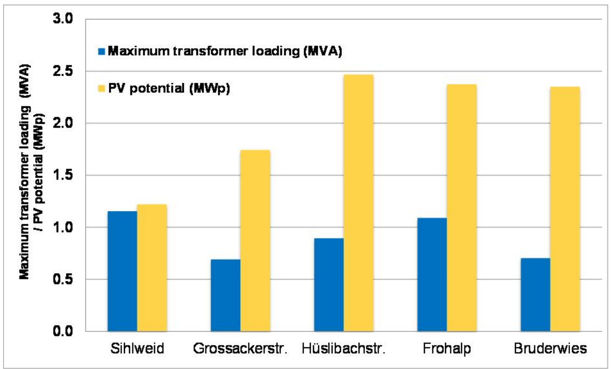

Figure 1: Maximum transformer loading and PV potential per transformer station.

LOAD FLOW SCENARIO ANALYSIS

Scenarios

In this paper three different combinations of load and PV infeed are investigated. Each scenario is characterized by the abbreviation Lx% / PVy%. x refers to the percentage of the maximum load considered in each scenario, while y corresponds to the installed PV capacity as a percentage of the total identified PV potential of Leimbach.

Winter evening (L100% / PV0%)
LV networks are designed such that the maximum electricity load can be reliably supplied. This scenario corresponds to a winter evening. In Zurich this is the time when electricity demand typically reaches its maximum, which means that this scenario represents the worst case loading of the network without any PV penetration.

Summer noon (L30% / PV100%)
This scenario corresponds to the maximum PV production. A demand equal to 30% of the yearly maximum load is used in this case as a minimum empirical summer noon load. This scenario represents the worst case PV infeed situation.

Summer noon - PV curtailment (L30% / PV70%)
PV curtailment is a measure that is already applied in some countries in order to reduce the strain on the network when a big PV infeed occurs. In Germany, e.g., PV plants with an installed capacity smaller than 30 kW are obliged to be able to limit their production to 70% of their installed capacity if necessary [3]. Therefore, in this scenario a potential 30% PV curtailment during a summer noon is examined.

Technical constraints

As a result of the DG penetration in the LV level, distribution systems are no longer merely supplying loads, but are confronted with power flows and voltages determined by the generation to load ratio at each point of time. When the energy produced by photovoltaic panels during solar peak radiation hours exceeds the locally demanded load, reverse power flows towards the medium voltage network and voltage rises occur. This can pose new challenges to the electric power systems, where traditionally only large central plants supplied electricity through the transmission and distribution grid to the end user.

Voltage
The connection of DG to the receiving end of a distribution line results in voltage rises at the connection points. The evaluation of the network's voltage profile is done according to the European Norm EN 50160 [4] along with the DACHCZ group guidelines [5]. EN 50160 specifies a band of ±10% around the nominal voltage $U_N=400_{ph\text{-}ph}$ for the low voltage network. Respectively, the DACHCZ guideline defines that the relative voltage rise incurred by the totality of all generating plants must not exceed 3% at any point of common coupling in the LV network.

Line loading
As mentioned above, another result of the DG penetration in the LV level may be the appearance of reverse power flows. If at a specific time PV production is much higher than the demand, the reverse power flows towards the MV/LV transformer might be higher than the maximum loading for which the lines were designed for. In this paper, a 100% loading of a line corresponds to the setting of the line protection (e.g. fuses).

Transformer loading
As with cables, the existing transformer stations are designed so as to be able to reliably supply the maximum load. Moreover, in every transformer station two transformers are installed (e.g. 2x630kVA), allowing in that way the system to be n-1 secure. For the transformer loading constraint, the rated power is considered.

Simulation results

The three aforementioned constraints were examined per scenario through load flow calculations.
Voltage
The Leimbach network voltage distribution for all the three scenarios under investigation is shown in Figure 2. In the winter evening scenario (green colour), voltage drops appear in the network with the highest one amounting to 7%. The EN50160 limits are respected in this case. The penetration of the full PV potential in the network (red colour), however, results to unacceptable voltage rises during the summer noon scenario. In this case, the highest voltage rise of 21% occurs in a remote farm. The PV curtailment to 70% of the installed capacity (blue coloured bars) improves considerably the

voltage profile of the network as in this case only few individual nodes exceed the EN50160 constraint. The highest voltage rise in this case is limited to 16%.

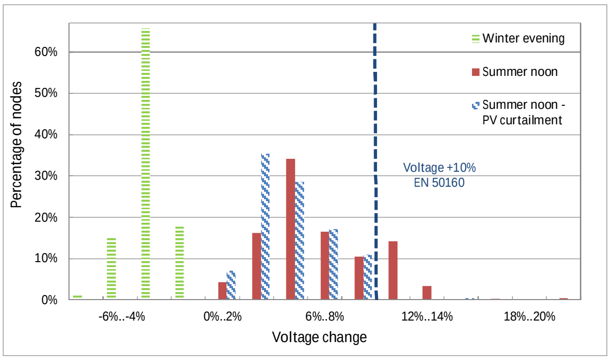

Figure 2: Voltage distribution per scenario.

The DACHCZ voltage constraint poses far stricter limits to the integration of PV in comparison to the EN50160 norm (see Table 1 in the following). On the other hand with a PV curtailment of 70%, the EN50160 constraint is violated only in few individual nodes of the "Grossackerstrasse" and the "Bruderwies" LV areas.

Line loading

The line loading distribution profile of all the modeled 1138 different line segments is depicted in Figure 3 for all three examined scenarios. The maximum line loading during the winter evening scenario is 64%. In the summer noon scenario, although the majority of the line segments are loaded within the acceptable limits, there are some overloaded lines with loadings up to 248% (not illustrated in the figure for the sake of readability). The PV curtailment results to a considerable decrease of the overloaded line segments. In this case, the maximum line loading amounts to 180%, with only 3 out of 1138 overloaded line segments.

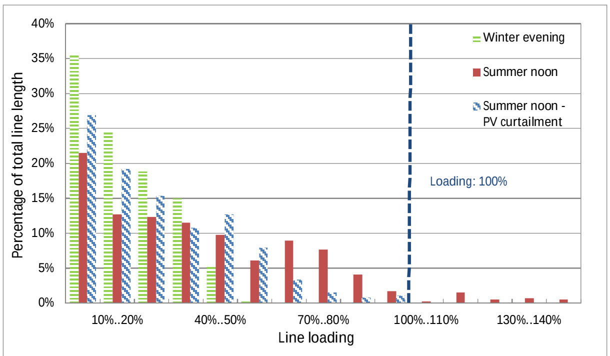

Figure 3: Line loading distribution per scenario.

Transformer loading

In Figure 4 the transformer loading of the 5 transformer stations of Leimbach is presented. The transformer stations are dimensioned in such a way that they can supply the areas, fulfilling at the same time the n-1 security principle. Therefore the loading for the maximum load case is around 50%. The PV penetration leads to an increase of the transformer loading in 4 out of the 5 transformer stations, while in "Sihlweid" the transformer loading is reduced due to the relatively low ratio between PV potential and maximum loading. The highest transformer loading is 161% and can be observed in the LV network "Hüslibachstrasse". A curtailment to 70% results in a reduction of the transformer loading in all the transformer stations. However, the transformer loading constraint is still violated in "Hüslibachstrasse" and "Bruderwies".

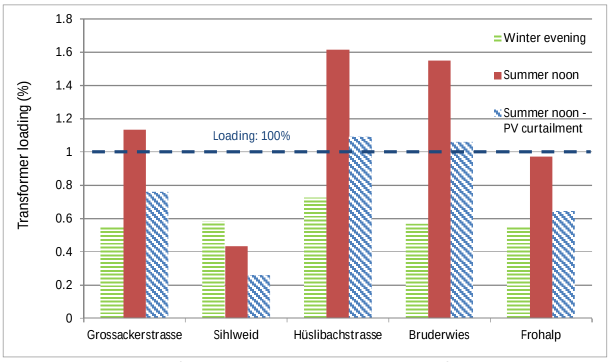

Figure 4: Transformer loading per transformer and per scenario.

Maximum allowable PV penetration

In addition to the scenario analysis, the maximum allowable PV penetration per constraint and per substation, assuming a minimum load of 30% of the yearly maximum load, was examined. The results are presented in Table 1. The green colored "ok" indicates that even with a 100% PV penetration, the specific constraint is not violated, while the substation with the lowest allowable PV penetration is highlighted in red for each constraint. From Table 1, it is obvious that the PV hosting capacity of the existing Leimbach network differs per substation and per constraint. At the substations "Sihlweid" and "Frohalp" only the relatively conservative DACHCZ constraint is violated, while "Hüslibachstrasse", "Grossackerstrasse" and "Bruderwies" appear to be the most problematic areas in terms of PV integration. The main reasons for this are the high ratios between PV potential and maximum transformer loading as well as the existence of some remote farms with big roof areas.

Constraints/Substation	Grossackerstr.	Sihlweid	Hüslibachstr.	Frohalp	Bruderwies
DACHCZ voltage rise	19%	78%	35%	55%	24%
EN50160 voltage band	42%	ok	77%	ok	52%
Line loading	50%	ok	ok	ok	37%
Transformer loading	90%	ok	65%	ok	67%

Table 1: Maximum allowable PV penetration per constraint and per substation.

EXAMINED MEASURES AND COSTS

In this chapter a set of potential solutions to the above-mentioned problems is examined. The analysis is done for the LV network of "Hüslibachstrasse" which is chosen as a characteristic illustrative case.

Conventional network expansion

All measures that a DSO traditionally takes for the reinforcement of the network are called conventional network expansion measures. Such measures are the upgrade of existing transformers or cables, the laying of new cables, the switching of cable connections to nearby feeders, etc.

Active power curtailment of PV plants

As it can be seen in Table 1, a permanent active PV power curtailment (APC) to 65% would be required for the three main constraints (EN50160, line and transformer loading) not to be violated in the LV network of Hüslibachstrasse. The energy losses in such a case would amount to 2.4% of the total yearly energy yield of the PV plants. By correlating the curtailed energy with the SwissIX electricity hourly prices, the yearly cost of the curtailed energy would be 2'230 CHF. If a typical grid assets depreciation period of 40 years is assumed, the total cost of APC as a PV integration measure amounts to about 90'000 CHF (no discount factor considered).

Load management

Assuming an additional load shifting potential of 10% of today's maximum load, the summer noon scenario is formulated as L40% / PV100%. In this case the maximum transformer loading of the Hüslibachstrasse substation would be 156% instead of 161%, while the maximum voltage rise now amounts to 12% instead of 13%. This shows that load management has a noticeable but limited effect.

Reactive power control

Reactive power control (RPC) of the PV inverters is another potential mitigating measure. A power factor of 0.9 (inductive) is needed in the six most problematic nodes of "Hüslibachstrasse" (total 111 nodes) to bring the voltage profile of the network within acceptable limits.

Although Hüslibachstrasse has no line overloading problems, the RPC increases the power flows and brings the currents of some lines out of the acceptable limits. Therefore, conventional network reinforcement is still needed. An additional cost of 200 CHF/kVA is needed for the dimensioning of the six PV inverters so that they are able to provide reactive power control without limiting the active power production [4].

On-load tap changing MV/LV transformers

The installation of on-load tap changing (OLTC) transformers on the MV/LV level is another potential PV integration measure. The voltage problem can be solved, but some individual conventional measures are still needed. The cost of the OLTC transformers is assumed to be double the cost of the conventional ones.

Cost comparison

In Figure 5, the investment costs per examined measure are presented. It is important to note that the cost estimates are based on general unit costs and not on detailed project engineering. The cost component "Further substation adaptions" comprises e.g. measures for electromagnetic shielding and upgrade of low-voltage switches. Being the most expensive solution, the "conventional network expansion" measure is used as a benchmark and the costs of all measures are given relative to this benchmark. The cheapest examined measure is the APC followed by the reactive power control combined with individual conventional measures. The cost estimates in Figure 5 are based on a general static view. If the timing of concrete investments is considered, the resulting costs might differ significantly from these estimates. For instance, the actual costs for conventional network expansion measures are much lower if the corresponding assets are close to the end of their lifetime and must be replaced anyway in the near future.

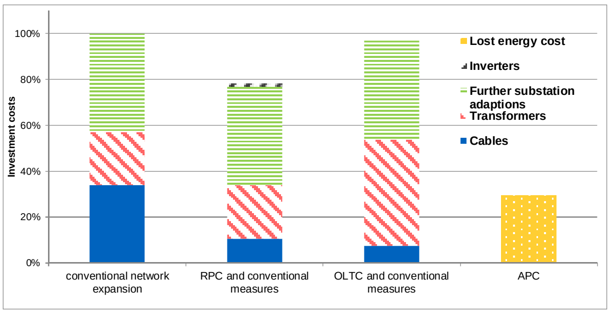

Figure 5: Investment costs per examined measure.

The implementation of APC would necessitate interventions with plants that are not owned by the DSO. This measure would therefore require special contracts between the DSO and the PV producers or a legal basis on a national level, which does not yet exist in Switzerland. Therefore, the RPC measure is presented in a more detailed way in the following as it can already be implemented by a DSO without any interventions with the producers. All actions that would need to be taken in the RPC measure in order not to violate any constraint in the Hüslibachstrasse LV network are depicted in Figure 6. The upgrade of the transformer station, the two new line segments as well as the reactive power control in six different nodes are highlighted in blue.

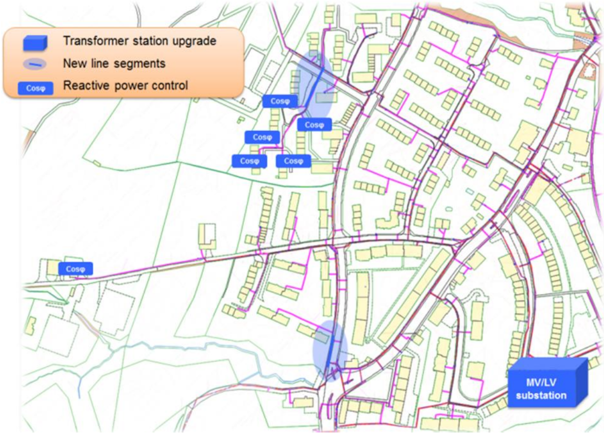

Figure 6: Necessary adaptions for the “RPC and conventional measures” solution.

TIME SERIES ANALYSIS

In addition to the investigations based on the empirical minimum load of 30%, a time series analysis with quarter-hourly measurement data for the transformer loading and the PV production in the year 2013 has been conducted. The PV production curve was generated using real PV production data from about 300 PV plants in the city of Zurich. The production of this sample was scaled according to the PV potential within the Hüslibachstrasse LV network area. The worst-case situation in terms of transformer loading can be observed at 13:45 on 18th May when the transformer loading amounts to 150%. The loading conditions at that time would correspond to an L51% / PV100% scenario. The maximum voltage rise amounts to 11% and appears at 15:15 on 5th June when the loading conditions correspond to an L40% / PV95% scenario. No cable overloading is observed throughout the year. The transformer loading of “Hüslibachstrasse” for 18th May both with and without PV penetration is presented in Figure 7. The PV penetration results in a decrease of the transformer loading during the early morning and the early evening hours while loadings above the limit can be observed from 11:00 until 17:00.

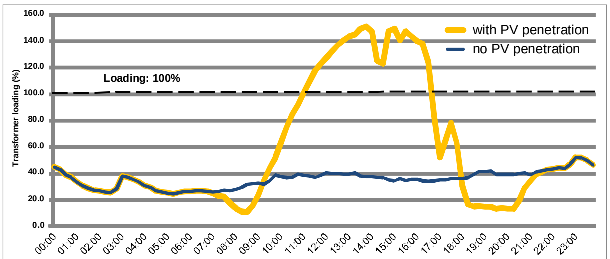

Figure 7: Transformer loading of “Hüslibachstrasse” on 18th May with and without PV penetration.

SUMMARY AND OUTLOOK

The purpose of this paper was to investigate the impacts of a large PV penetration in an urban distribution system as well as to examine the potential PV integration measures. Power flow analyses were carried out for three different load / PV production scenarios focusing on voltage, cable and transformer loading constraints.

The PV hosting capacity of the existing Leimbach network differs per substation and per constraint and it depends mainly on the ratio between the PV potential and the maximum demand. The EN50160 voltage constraint as well as the transformer loading constraint is violated in three out of five LV networks, while the cable loading constraint is violated only in two. The more conservative DACHCZ voltage constraint poses limits to the installable PV capacity in all five LV networks.

The cost of four different potential PV integration measures for the LV network of “Hüslibachstrasse” was assessed. The PV curtailment proves to be the most cost-efficient solution from a pure distribution grid perspective. However, a legal basis for the implementation of this measure is still missing in Switzerland.

Finally, a time series analysis for the year 2013 was carried out and the worst-case points in time per constraint were identified.

As a next step, it is planned to extend the presented analysis with a study of the potential contribution of decentralized storage to PV grid integration. More specifically the cost-optimal placement and sizing of battery storage will be examined considering also the potential future demand induced by the charging of electric vehicles.

REFERENCES

[1] 2013, "Municipal Code of the City of Zurich", status March 2013.
[2] http://www.2000watt.ch/ (accessed March 2014).
[3] 2008, "Gesetz für den Vorrang Erneuerbarer Energien (Erneuerbare-Energien-Gesetz - EEG)".
[4] CENELEC, 1999, "European Norm EN 50160: Voltage characteristics of electricity supplied by public distribution systems".
[5] DACHCZ, 2007, "Technical rules for the assessment of network disturbances. ".
[6] D. U. Sauer, 2013, "Kurzgutachten Marktanreizprogramm für dezentrale Speicher insbesondere für PV-Strom".