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# Impact of a High Penetration of Electric Vehicles and Photovoltaic Inverters on Power Quality in an Urban Residential Grid
# Part I – Unbalance

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**Abstract.** This paper presents a measurement-based assessment of the impact of a high penetration of plug-in electric vehicles with on-board charger (EVC) and photovoltaic inverters (PVI) on Power Quality in a public low voltage (LV) network. The paper consists of two parts. This first part is focused on the impact on unbalance, the second part is related to harmonics. The results are based on extensive measurements in an urban residential grid with almost 100 households (HH), 43 PVIs and 36 EVCs. The impact of PVI and EVC on unbalance at different levels of aggregation is described in detail. At first the individual impact of a single PVI and EVC is discussed for different operating conditions. In particular, a sunny day, a cloudy day and hours during the night are used for PVI, while periods of charging and periods of no charging are considered for EVC. Next sections analyse the interaction between PVI, EVC and residual load at household level as well as the overall impact of PVIs and EVCs in the low voltage grid. The analysis considers current unbalance and voltage unbalance.

## Key words
Photovoltaic inverter, electric vehicle charger, power quality, voltage unbalance, current unbalance

## 1. Introduction
Due to the political framework the number of EVCs and PVIs increases continuously. At present most electric vehicles have a single-phase on-board charger. PVIs with a rated power ($\boldsymbol{S}_{\mathrm{rPV}}$) less or equal to 4.6 kVA usually have a single-phase connection as well. Due to its operation at high currents and for long time periods, a considerable impact on voltage unbalance is expected [1]-[4].

In order to simulate the impact of increasing penetration of PVIs and EVCs on unbalance in residential grids comprehensively, realistic models for both PVI, EVC as well as the residual household are required. A generic model of EVC for unbalanced load flow studies is described e.g. in [5]. In order to validate the models, detailed measurements have been carried out in an urban residential grid with a high penetration of PVIs and EVCs.

After the description of the measured grid including the measuring locations, the first section of the paper presents the characteristic of an individual PVI and EVC. Next the results at household level are discussed, which show that PVIs and EVCs can have a significant impact on unbalance. Finally, the impact on the unbalance at the end of a feeder as well as the low voltage busbar is presented. The paper concludes with recommendations how unbalance levels can be efficiently managed in presence of high EVC and/or PVI penetration.

## 2. Measurement Framework

*A. Grid Details*

For the field study the urban LV grid of the "Smart Grids Model Community Köstendorf" in Austria has been selected. It is characterized by a high penetration of distributed PVIs (45% of customers) and EVs (38% of customers). The total power of installed PVIs corresponds to more than 75% of the MV/LV transformer rated power. Most PVIs are from the same manufacturer and only two different types of EVs are used. Network details are listed in Table I.

The single line diagram of the network is shown in Figure 1. A triangle symbolizes a group of households. The amount of households, EVCs and PVIs per group is also provided in the figure. The blue triangles indicate that in the respective group a single household including EVC and PVI has been measured. The blue circles show locations where an aggregate of multiple households has been measured.

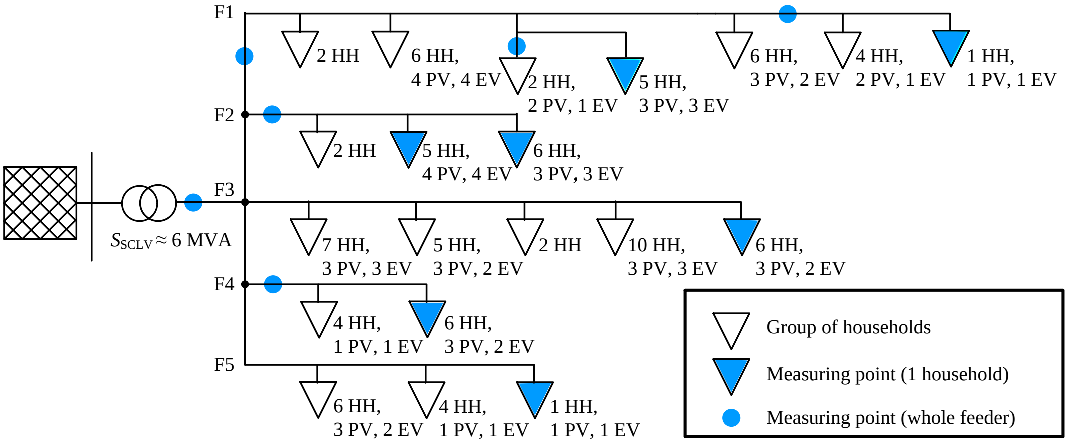


Fig. 1. Single line diagram of the network, EV: electric vehicle, HH: household, PV: photovoltaic, F*x*: feeder number

Table I. Characteristic parameter

| | |
|---|---|
| $S_{rT}$ | 250 kVA Dyn5 |
| $u_k$ | 4 % |
| | |
| Cable type | NAYY 4x150mm$^2$ |
| Longest feeder | 550 m |
| | |
| No. of households | 90 |
| No. of EVs | 36 |
| Max. EVC charging current | 10 A single-phase |
| No. of PVIs | 43 PVs (~192 kVA) |
| Power of PVIs | 2 x 10 kVA 3~ (14.4 A); all others 1~ between 3 kVA (13 A) and 5 kVA (21.7 A) |

Based on a specific installation rule the PVIs are equally distributed to the three phases as best as possible. In case a household has both a PVI and an EVC, both are connected to different phases.

### B. Measurement Details

Measurements have been carried out for three weeks with PQ instruments complying with the requirements of IEC 61000-4-30 class A. An one minute averaging interval has been selected and magnitude and phase angle of voltages and currents were recorded. Harmonic voltages and currents have been recorded as well, but are discussed in more detail in the second part of the paper. Measurement duration was about three weeks from which one week has been selected for the analyses in this paper.

## 3. Assessment indices

Unbalance distinguishes voltage and current unbalance (e.g. [6]). As only unbalance at fundamental frequency is considered, a negative and a zero sequence unbalance are defined as ratio of the absolute values of negative or zero sequence to the absolute value of the positive sequence of voltage or current. For voltages the respective equations are:

$$k_{U2} = \frac{|\underline{U}_2|}{|\underline{U}_1|} \quad ; \quad k_{U0} = \frac{|\underline{U}_0|}{|\underline{U}_1|} \qquad (1; 2)$$

The negative sequence voltage has unfavourable influence on electric rotating machines, transformers and three phase connected rectifiers [7]-[9]. Consequently, the negative sequence unbalance is limited e.g. in IEC 61000-2-2. The zero sequence unbalance has impact on the grounding system and the neutral wire loading. As standards consider negative unbalance only, this paper limits the analysis to negative sequence unbalance which will be simply referred to as unbalance in the further text.

The voltage unbalance level at a particular location is always determined by the contribution of the upstream grid and the customers connected to the considered point. To characterize the unbalance contribution of a particular customer or device, two methods should be used:

- Absolute negative sequence current $|\underline{I}_2|$
- (Equivalent) unbalance (apparent) power $S_{un}$ as introduced in IEC 61000-3-14

The relative current unbalance can be calculated similar to (1). However, particularly in grids with distributed generation in case of a balance between generation and consumption the positive sequence current can become very low. This would result in a misleading high value of $I_2/I_1$ and should therefore be used very carefully or better avoided at all.

In this paper the unbalance power $S_{un}$ is applied for the assessment of unbalance contribution. It is calculated using the complex apparent powers of the individual phases assuming that the phase angles of the line to neutral voltages are approximately 0°, 240° and 120° and is given by:

$$S_{un} = \left|\underline{S}_{L1} + \underline{a} \cdot \underline{S}_{L2} + \underline{a}^2 \cdot \underline{S}_{L3}\right|$$
$$\text{with} \quad \underline{a} = -\frac{1}{2} + \mathrm{j} \cdot \frac{\sqrt{3}}{2} \qquad (3)$$

If short circuit power $S_{sc}$ at the connection point and unbalance power $S_{un}$ of a customer installation or device are known, the contribution to voltage unbalance $\boldsymbol{k}_{U2}$ can be estimated (e.g. [6]) as:

$$k_{U2} = \frac{S_{un}}{S_{sc}} \qquad (4)$$

## 4. Characterisation of individual devices

### A. PV inverter

Figure 2 shows the active power of an individual measured PVI for a sunny and a cloudy day. During the night the inverter is disconnected from the grid and neither draws nor generates power. The plot for the sunny day shows the typical behaviour of a roof-top PV installation with an increasing power generation during the morning hours, the maximum generation around noon

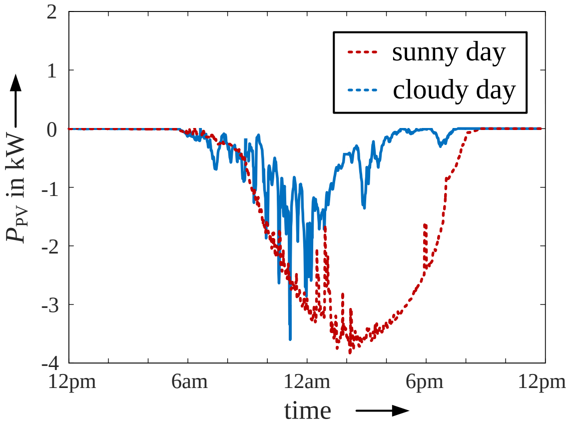


Fig. 2. Generated power of a PVI for a sunny/cloudy day

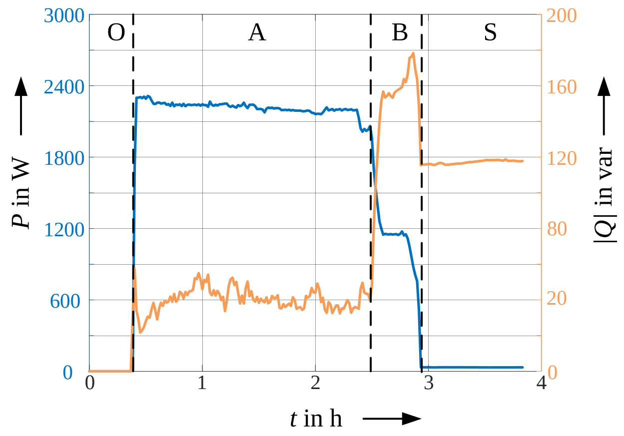


Fig. 3. Charging characteristic of an EVC

and the decreasing power generation during the afternoon. The sudden changes indicate individual clouds even during the sunny day. The cloudy day shows a much higher variation but significantly less power generation than on the sunny day.

*B. EV charger*

Figure 3 shows the charging cycle for one of the EVC types. According to the classification of the charging cycle in [5], the charging behaviour is separated in four states:

- O Off, EVC is disconnected from the grid
- A Constant charging current
- B Decrease of charging current
- S Standby mode

The ranges of active and reactive power for the charging states A, B and S are listed in Table II.

Table II. Parameters of different charging states

| State | A | B | S |
|---|---|---|---|
| *P* in kW | 2.0 .. 2.3 | 0.5 .. 2.0 | 0.03 |
| *Q* in var | 22 .. 57 | 48 .. 178 | 116 .. 119 |
| Power Factor (PF) | > 0.99 | 0.96 .. 0.99 | 0.28 |

The charging current in state A is almost constant for long periods (Constant Current mode – CC mode) and the reactive power is low. At the end of the charging cycle (state B) the charging power decreases very fast and no dedicated CV mode (Constant Voltage mode) is observed. The reactive power increases in this state. The active power in standby mode is very low and the reactive power has a value between state A and B. Active and reactive power are almost constant for the standby mode. The reactive power is always capacitive.

State B lasts for each charging cycle almost 20 minutes. The duration of charging state A depends on the EVC's state of charge (SoC) and the duration of state S depends on the time period that the owner has his EVC plugged into the socket.

*C. Households*

All measured households were equipped with a PVI and an EVC. While for one household PVI and EVC current have been measured individually, the measurement devices for all other households were installed at the junction box outside the house measuring the sum of PVI, EVC and residual household load. To study the behaviour of household loads separately, only times are considered, where no EVC was connected and PVI does not generate power. The EVC connection periods are taken from a respective log file, while the periods without PVI generation have been selected by analysing the individually measured PVI.

Figure 4 shows the cumulative distribution function of the unbalance power of single households as well as the aggregate of 6, 12 and 27 households. It is shown that the unbalance power of household loads without EVC charging and PV generation is lower than 4 kVA. A considerable unbalance cancellation exists, as the unbalance power of 27 households is clearly lower than the sum of the unbalance power of 27 single households. This is further confirmed as the unbalance power of 6 households is almost equal to the unbalance power of 12 households.

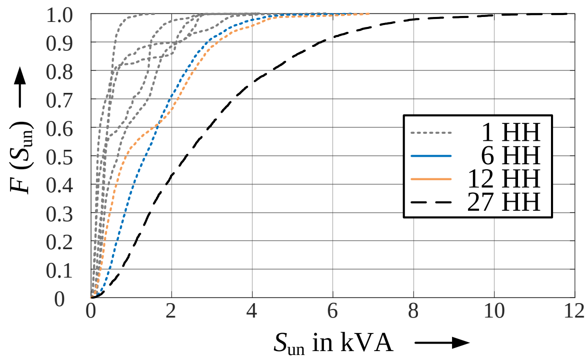


Fig. 4. Cumulative distribution function of unbalance power for different aggregates of households

## 5. Interaction at household level

This section discusses the unbalance caused by different combinations of PVI, EVC and residual household load. In order to ensure the representativeness of the analysis, only households with a sufficient number of data points at parallel operation of HH/EVC, HH/PVI and HH/EVC/PVI are considered.

*A. Household and PVI (HH/PVI)*

To study the load unbalance for combinations of households and PVIs only data between 12am and 3pm are considered. Time periods with parallel EV charging have been excluded from the analysis. The remaining data are classified in cloudy or sunny. As weather data with high resolution were not available, the classification is based on the power characteristic of the individual measured PVI. If the measured power ($P_{PV}$) of the individual PVI is higher or equal to $0.8{\cdot}P_{\mathrm{rPV}}$, the respective data are assigned to the category "sunny". If the measured power is lower than $0.3{\cdot}P_{\mathrm{rPV}}$, it is treated as "cloudy" respectively. All measurement data for which the measured power of the individual PVI is between $0.3{\cdot}P_{\mathrm{rPV}}$ and $0.8{\cdot}P_{\mathrm{rPV}}$ are not used.

Results are presented in Figure 5. The cumulative distribution function of unbalance power for the category "sunny" is almost a parallel shift of the cumulative distribution function of the category "cloudy". The value of the shift is about 0.6 .. $0.7{\cdot}P_{\mathrm{rPV}}$ of the installed PVIs and corresponds very well to the difference in power generation between the categories "sunny" and "cloudy".

Without PV generation the household is almost balanced and the PVIs contribute almost exclusively to the unbalance power. Consequently, virtually no cancellation between households and PVI can be expected. For simplified studies the household load could even be neglected.

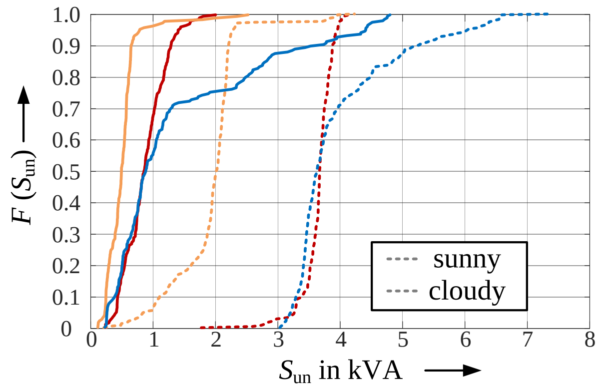


Fig. 5. Cumulative distribution function of unbalance power for households with PVI for sunny and cloudy weather (195 .. 405 data points per c.d.f.)

## B. *Household and EVC (HH/EVC)*

To study the impact of a combination of household and EVC only, time periods when an EVC was charging and no PV power was generated (preferably at night) are selected. Figure 6 compares the unbalance power of households during periods without EVC charging and times with EVC charging.

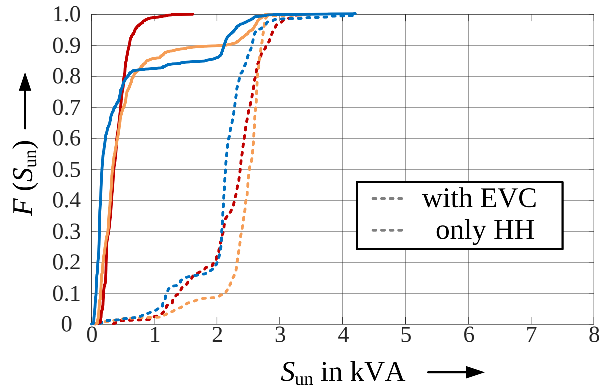


Fig. 6. Cumulative distribution function of unbalance power for households with EVC charging (with EVC: 463 .. 709 data points per c.d.f.)

The difference between the two curves for each household is around 2.3 kVA. This equals to the charging power of the EVCs which are charging at almost 10 A. Similar to the finding in section 4.A virtually no potential for cancellation exists between the remaining household load and the EVC charging. The cumulative distribution functions with EVC charging show clearly the two states (A and B) of the charging cycle, which were explained in section 3.B. For the two households indicated by the red and the blue dottet line charging state B contributes with about 15%, charging state A with around 85 %. For the remaining household (yellow doted line) the shares are with around 10 % for state B and around 90 % for state A slightly different.

## C. *Household and EVC and PVI (HH/EVC/PVI)*

To study the impact of the parallel operation of household, EVC and PVI, only data between 12am and 3pm are selected when an EVC is charging. Similar to section 4.A it is distinguished between the categories "sunny" and "cloudy" for PV generation.

Figure 7 shows the results, presented as cumulative distribution functions. Sufficient data for the required characteristics is only available for two households. Particularly for the red indicated household only 4 data points are available for "cloudy" conditions with EVC charging. Even though this number is not representative, the difference corresponding to the reduced PVI power generation is clearly visible.

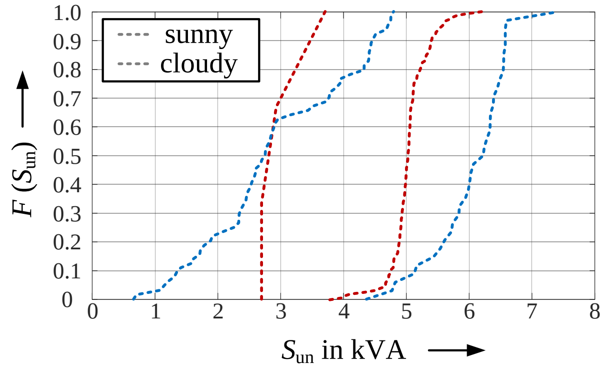


Fig. 7. Cumulative distribution function of unbalance power for households with PVI and EVC for sunny and cloudy weather (sunny: 93/154 data points; cloudy: 65/4 data points per c.d.f.)

The unbalance power of both households increases significantly during the periods with PV generation (sunny periods). Compared to Figure 4 a single household with EVC and PVI can contribute to the load unbalance as much as about 30 households without EVC and PVI. Therefore, particular attention should be paid to the minimization of the unbalance power caused by EVCs and PVIs. Solutions could be the connection of single-phase PVI and EVC in one household to the same phase, the reduction of the maximum charging/generated current or the use of three-phase devices. Furthermore, the results show that a coordinated phase distribution of PVIs and EVCs in the whole grid is necessary to avoid high load unbalance and consequently increasing voltage unbalance. However, this is only possible if the Distribution System Operator (DSO) has documented the assignment of the phases at the connection terminals of the customers, which is usually not the case yet.

## 6. Impact on Unbalance Levels in the Grid

This section discusses the cumulative effect of the collective operation of PVIs and/or EVCs on the unbalance in the network. Voltage unbalance is discussed for a particular feeder end because highest levels are usually observed at these locations. Current unbalance is discussed for the total current at the LV busbar with respect to the transfer to the upstream grid.

### *A. Voltage unbalance at the feeder end*

To study the impact of PVIs on the voltage unbalance, the measurement of a whole week is divided in periods with PV generation (almost 5:30am to 8.30pm) and periods without PV generation. For both data groups the 10 minute RMS value of voltage unbalance is analysed. Figure 8 shows the 5th and 95th percentile for both data groups. While the 5th percentiles are very similar, the 95th percentile with PV generation is with $k_{U2} = 0.8\ \%$ almost two times higher than the same percentile without PV generation. In addition to the percentiles, the 1 minute RMS values of the PV generation are shown as ratio $\boldsymbol{P}_{\mathrm{PV}}/\boldsymbol{P}_{\mathrm{rPV}}$ for reference.
A considerable higher unbalance is observed for times with a higher level of power generation.

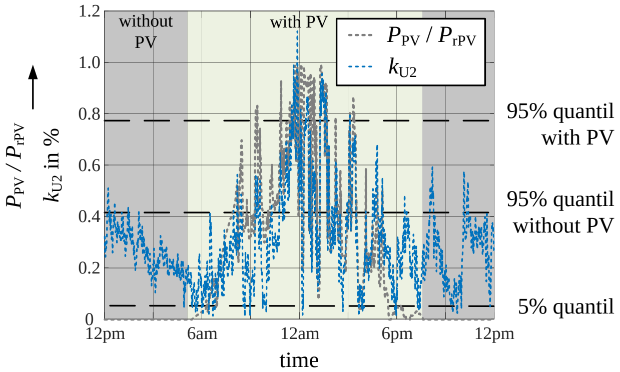


Fig. 8. Voltage Unbalance at household level for a day with cloudy and sunny periods

Due to an almost uniform distribution of the single-phase PVIs to the phases and the reduction of the maximum charging current of the EVCs to 10 A, the voltage unbalance at high solar radiation is with about 1 % well below the limit according to IEC 61000-2-2 (2%).
However, a direct relation between the generated power of the PVIs and the voltage unbalance can be observed. If the solar radiation decreases, the voltage unbalance decreases too. Figure 9 shows this effect by a box plot for different ranges of the amount of generated power. The red line symbolizes the median, the blue boxes the interquartile range (25th percentile to the 75th percentile), the grey lines the whiskers covering a variance of 2.5 times the median and the red crosses single data points that are likely outliers. It should be noted that the number of values per power range differs significantly and decreases with increasing power generation. While about 32 % (1650 data points) of the data points are located at the lowest power ($P_{PV}/P_{rPV} = 0\ ..\ 10\ \%$), only 2 % (111 data points) are allocated to the highest power.

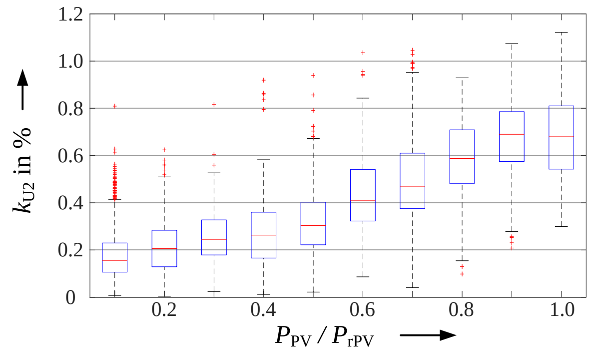


Fig. 9. Voltage Unbalance depending on the PV generation

To study the impact of EVCs on the voltage unbalance for feeder F1 (cf. to Figure 1), time periods where EVCs are connected to the grid are compared with time periods without any EVC charging. To reduce the unwanted impact of PVIs, only times during evening and night are chosen, for which the probability of EV charging is higher anyway. Figure 10 shows that the unbalance levels increase only slightly (around 0.1 %) with increasing number of EVCs. The limit of 2 % is not exceeded. To interpret this result it should be noted that due to the naturally lower probability of simultaneous EVC charging, the maximum number of parallel charging EVCs is only 6.

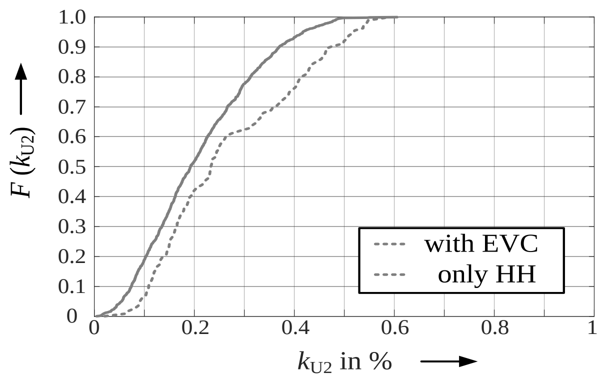


Fig. 10. Cumulative distribution function of voltage unbalance at the end of feeder F1 for periods with and without EV charging and no PV generation

The comparison of the results in Figure 9 and 10 shows that the PVIs impact voltage unbalance clearly higher than EVCs, although both have a comparable penetration. One reason is that PVIs have a coincidence factor of almost 1 as the weather conditions in the area and the tilt angle of the roofs are very similar for all PVIs. That means during sunny periods all installed PVIs generate maximum power at the same time. For EVCs the coincidence factor is lower, as the charging behaviour and travelled distances vary strongly among the customers. This variation is directly linked to the charging duration and frequency. During the whole measurement interval not more than 6 of the 36 EVCs have been charged simultaneously. This corresponds to a coincidence factor of 0.17. In Addition, the installed power of a single PVI (4 kVA) is almost two times higher than the charging power of an EVC (almost 2.3 kVA) and the total installed PV power (~185 kVA) is higher than the total installed EV power (~83kVA) as well.

The results confirm that a careful distribution of single-phase PVIs to the phases together with an intentionally limitation of the rated power of the devices (in this case reduced maximum charging current of the EVCs of 10 A/ 2.3 kVA) are effective countermeasures to avoid high voltage unbalance levels in this network. Additional studies have shown that in case of less careful coordination of single phase EVCs and PVIs the unbalance levels can quickly exceed the compatibility level [1].

*B. Unbalance power at the transformer*

To study the impact of all households, PVIs and EVCs on the unbalance power, the unbalance power at the LV transformer busbar is analysed.

Figure 11 presents the unbalance power of the LV network vs. the total active power. Time periods with PV generation and periods without PV generation are presented in different colours. A negative active power means that total generation of all PVIs is higher than the consumption at the considered time instant. The unbalance power, which directly influences the voltage unbalance, increases with increasing PV generation. This fact is an evidence for the dominating impact of PVI on the unbalance. In fact that the increase of voltage unbalance during sunny days compared to times with a low solar radiation is lower than 0.5 % (see Figure 9), the PVIs have a good balanced distribution in this network.

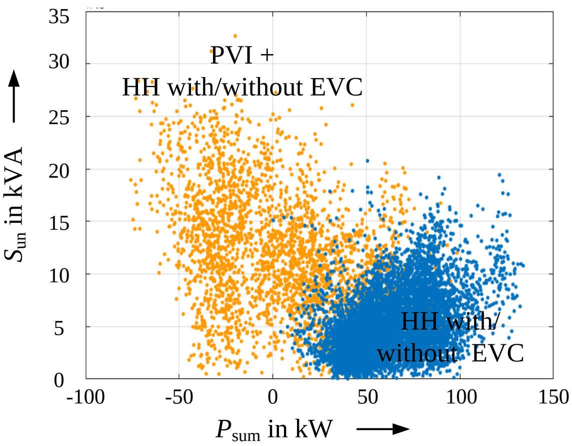


Fig. 11. Unbalance power at transformer busbar depending on the total active power of the LV network

## 7. Conclusion

The paper presents the impact of a high penetration of single-phase connected PVIs and EVCs on the voltage and unbalance power in a residential LV grid based on measurements. It discusses the unbalance contribution of households, PVIs and EVCs individually and the interaction between them. Finally, the unbalance of the whole LV grid is analysed. Although the DSO distributed the PVIs as best as possible to the three phases, the major contribution to unbalance is still caused by the PVIs. This is mainly due to its high coincidence factor of virtually 1 in combination with different sizes and locations in the network. The impact of EVCs is significantly smaller as their coincidence factor is significantly lower than for PVIs and the DSO has additionally limited the maximum possible charging current. Furthermore, the operation period of EVCs is usually much smaller than for the PVIs. The study has also shown that the remaining household load does not provide any potential for unbalance cancellation, neither with PVIs nor EVCs.

The results of the study confirm that efficient unbalance management in public LV grids in presence of high power devices with long operation periods does not necessarily need additional mitigation devices (e.g. PQ conditioning devices). By following some basic rules, the unbalance levels can be maintained well within the limits given by IEC 61000-2-2 and EN 50160. This includes the coordinated connection of PVI and EVC within one household to the same phase, the careful distribution of the PVIs to different phases (considering their sizes and locations) together with the reduction of maximum allowable single phase current for PV generation as well as EVC charging. In case the DSO does not have information about the assignment of the phase conductors, at least an allocation to the phases based on the measurement of phase to ground voltages at the connection point (for PVI phase conductor with lowest voltage during sunny weather) is recommended.

## Acknowledgement

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