Coincidence Definitions of Photovoltaic Systems for the Purpose of Grid Planning

The steadily increasing installation of photovoltaic systems (PV) in the low-voltage grid makes it urgently necessary to analyse the potential repercussions on the grid. Repercussions are in particular the feed-in-related voltage increase and the thermal utilisation of electrical components. These are usually analysed with the help of a grid simulation program. There are various approaches to taking generation units into account in the simulation.

The most commonly used approach is the assumption of a worst-case scenario, i.e. all generation units feed in at their rated power and there is a minimum load to be assumed, which can also be 0 kW. This assumption is used to calculate on the safe side, but the repercussions are also significantly overestimated in some cases. There is a particular feature with regard to PV in the low-voltage grid: Due to the predominance of rooftop systems, the PV are not all installed with the same sky orientation or tilt angle, but always as the conditions on the roof allow. This results in a clear coincidence effect, which ensures that the simultaneous output of systems can be assumed to be smaller in grid planning. In addition, there are other factors such as partial shading, soiling, damage, different module types and ages, which also reduce the maximum expected simultaneous active power feed-in.

PowerFactory offers the possibility to account for this coincidence effect with its low voltage load flow calculations. The general advantages of the low voltage load flow calculation using coincidence curves over other analysis methods are discussed in a future paper. This paper describes the fundamentals and derivation of the coincidence definitions for photovoltaics provided in the DIgSILENT library.

1 LV Load Flow Calculation

In *PowerFactory* 2025, DIgSILENT extended the existing coincidence calculation functionality that is used with the low-voltage load flow calculation to include generation units and PV in particular.

This means that coincidence definitions can now be assigned to generation units as well as loads, and the coupling definition of coincidence definitions has also been made more flexible. This allows the calculation for PV to be optimised and enables the calculation of realistic maximum utilisation of lines and transformers as well as maximum voltages at all nodes in a grid. As with the low-voltage loads, the available connection capacity can also be determined using a penetration factor.

The low-voltage load flow calculation can be used in both radial and meshed grids [4]. A sensitivity analysis is used to decide which units affect a specific branch flow (in meshed grids) or node voltages (in meshed and radial grids).

Compared with the loads, which are usually identical in terms of their grid connection power (e.g. typical household 30 kVA), the power of generation systems is very different. These usually have different individual power settings $S_{\text{max},i}$. In this case, the calculation is carried out using a customised procedure. For this purpose, the power of all relevant units is sorted in descending order and a $(n+1)$th power of zero is added so that the last power difference can be calculated:

$$S_{\text{max,total}} = \sum_{i=1}^{N} [i \cdot g(i) \cdot (S_{\text{max},i} - S_{\text{max},i+1})] \quad (1)$$

where g is the coincidence factor.

2 Coincidence Effects

Module orientation

As an introductory example, Figure 1 shows the simulation result of a model with three PV systems at the same location, but with different orientations and tilt angle. The PV systems have a connected load of 10 kW and a module output of 12 kW according to the so-called Standard Test Condition (STC). The module output is therefore oversized by 20 % and the degree of dimensioning is 120 %. The simulation was carried out assuming a clear sky and neglecting a temperature profile.

It can be seen that the systems reach their peak output at different times. The maximum power fed-in by all three systems is arround 21 kW. In relation to the sum of the system outputs, this results in a maximum coincidence factor of 70 %, which does not take into account any other factors apart from the orientation.

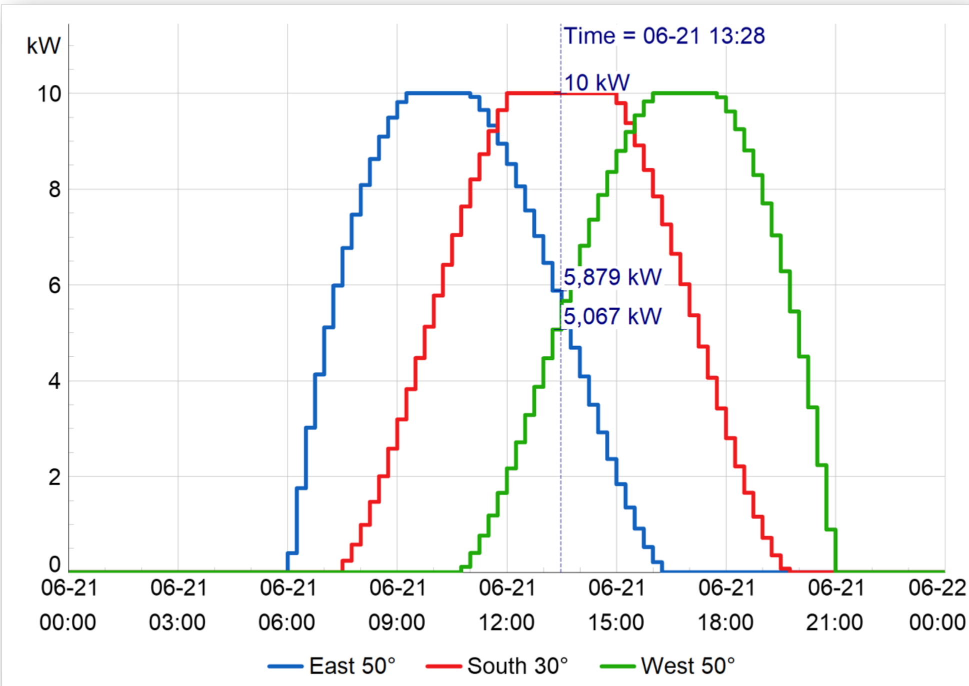

Figure 1: Quasi-Dynamic Simulation - solar irradiance with different orientations

This result shows a clear coincidence effect with PV. By carrying out a quasi-dynamic simulation (time series calculation in discrete time steps) while varying the solar irradiation and parameterising the PV accordingly, this coincidence effect can already be taken into account in grid planning today. However, this is time-consuming and requires precise parameterisation of the alignment.

It is also important which time range is used to determine the coincidence. A coincidence factor based on 1 s measured values will be higher than one based on 10 min average values. However, the 10 min average values are the relevant data for the evaluation.

Further coincidence effects

Again, there is a clear coincidence effect due to the different orientations and tilt angle. In addition, there are other aspects that further reduce the assumed summarised peak power. For example, different module types are usually installed (mono-crystalline modules, poly-crystalline modules, thin-film modules), which provide different feed-in behaviour under different meteorological conditions and this can be taken into account in grid planning (see [1]).

In addition, as the number of systems increases, the likelihood of individual systems being shaded, for example by chimneys, roof gables or trees, increases. An example is shown in this article later. Furthermore, efficiency losses due to ageing, soiling (see [2]) and locally broken module cells (see [3]) are additional aspects that can be statistically taken into account with a larger number of systems.

However, these effects cannot be derived deterministically as with the orientations/tilt angle, but can only be determined statistically using many measurements. It is expected that the coincidence factors for $n \to \infty$ in particular will be reduced if these additional effects are taken into account.

3 PV Coincidence Definitions

Approach for determination

The important part of a coincidence definition in *PowerFactory* is the coincidence curve, which takes into account the stochastic use of multiple units. The larger the number of units considered, the smaller the coincidence factor with which the peak power is reduced.

DIgSILENT has determined coincidence curves for PV using a series of probabilistic simulations. For many different configurations of PV (number and type of orientation), a quasi-dynamic simulation (QDS) was carried out over a time range with high feed-in. The highest instantaneous peak power is stored for each configuration. For X configurations, this results in X peak values, from which the 95%-quantile is taken to determine the coincidence value in relation to the cumulative rated power of all active systems. For a better understanding, the configuration of the example in Figure 1 is used again: there, the peak value was 21 kW, the cumulative rated power was 30 kW and thus the coincidence value was 0.7.

The decisive factor in this procedure is which calculation model is used for the solar irradiation and which total module output is assumed in relation to the inverter output (degree of dimensioning). When creating the coincidence curves shown here, the calculation models that produce the highest outputs were used (Haurwitz model for global radiation and Liu-Jordan model for diffuse radiation). This means that the calculations are on the safe side because the coincidence factor tend to be overestimated.

Coincidence curves were also determined for different degrees of dimensioning. The higher the degree of dimensioning, the greater the number of full load hours and the more likely a high coincidence factor. While a degree of dimensioning of 120% is not unusual for larger systems, the picture is far more inhomogeneous for house-roof systems, as the area of the roof and the discrete sizes of the inverters are the decisive factors. In order to take this into account, coincidence curves have been drawn up for the dimensioning levels 100%, 110% and 120%.

Results and evaluation

Figure 2 shows the results of the determination for the different degrees of dimensioning. It can be seen that the curves from the probabilistic simulation converge to one value in each case.

In addition to the different convergence values g_∞ $(n \to \infty)$, it can be seen that the gradient is significantly greater with smaller degrees of dimensioning and the coincidence factor quickly flattens out even with just a few systems taken into account.

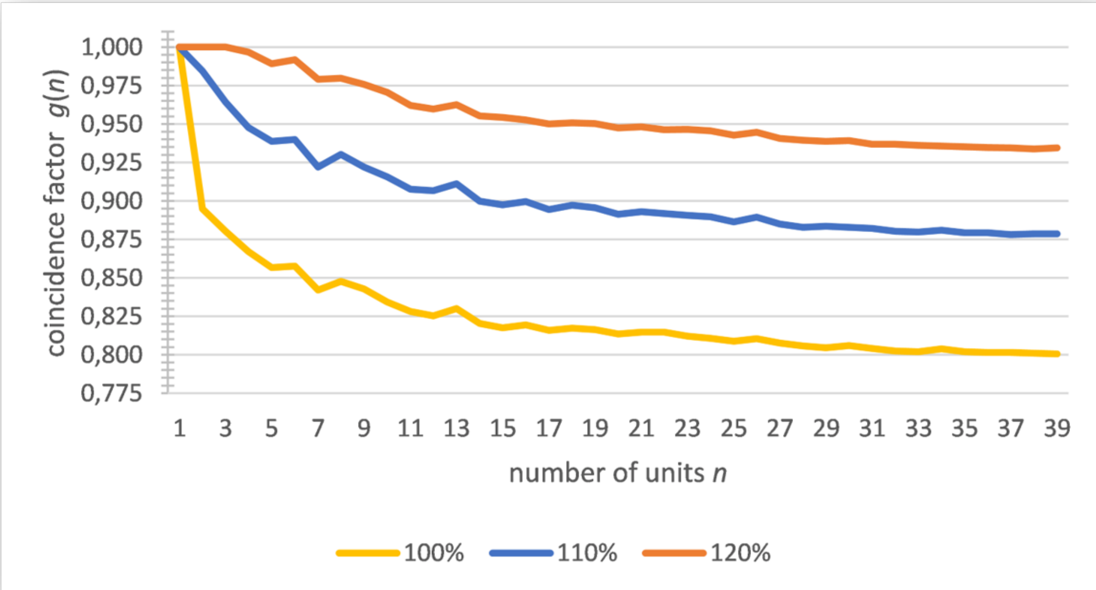

Figure 2: Illustration of the curves from the probabilistic simulation

The resulting values are approximated using a function and thus smoothed, resulting in the coincidence curves (CCs) for the different degrees of dimensioning. The function can generally be expressed using equation (2). The coefficients for the different degrees of dimensioning were determined according to the following table.

$$g(n) = g_\infty + (1 - g_\infty) \cdot a^{-(b \cdot (n-c))} \quad (2)$$

curve	CC120%	CC110%	CC100%
g_∞	0.930	0.875	0.800
a	3	5	2
b	0.075	0.08	0.255
c	3	1	-2
valid for	n > 3	n > 1	n > 1

The resulting curves are shown in Figure 3 in direct comparison with the probabilistic simulation results from Figure 2.

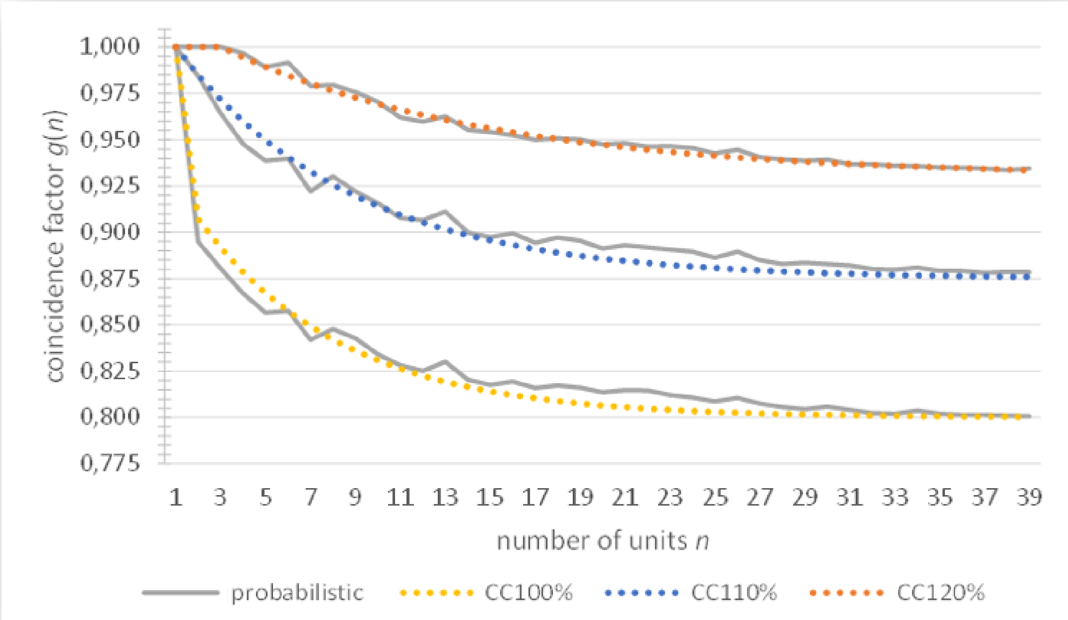

Figure 3: Illustration of the CCs compared to the probabilistic simulation results

Validation

In [5], the influence of the spatial distribution of generators on their coincidence effect was analysed on the basis of a measurement campaign with 286 measured PV. It was determined that the highest coincidence of the neighbouring units can be assumed to be the same as the coincidence of the unit at a distance of 12 km. The reason for this was identified as the fact that the maximum values occur under a cloudless sky and thus comparable weather conditions exist in the neighbourhood. From this, [5] derived the hypothesis that the influence of the spatial distance between the systems in low-voltage grids is negligible when analysing coincidence.

This hypothesis is also adopted in this paper. For the validation, real measured values (in short: real) from units located within a 12 km radius and collected as part of this work are used. These are 15-minute mean values. A total of 16 units were analysed for which the feed-in data is publicly available and the unit configurations can be determined. The system configurations were also transferred to *PowerFactory* in order to generate comparative results based on the solar irradiation model and a QDS. The median value of the degree of dimensioning of all systems is 114%.

Both data sources (real and QDS) are compared with the determined coincidence curve CC100% in Figure 4. For this purpose, all possible combinations of the systems were calculated or simulated and the highest coincidence value (feed-in power divided by inverter power) was determined over the measurement period under consideration. The result is a point cloud whose sample size decreases with increasing number of units. All results are shown in a scatter plot in Figure 4.

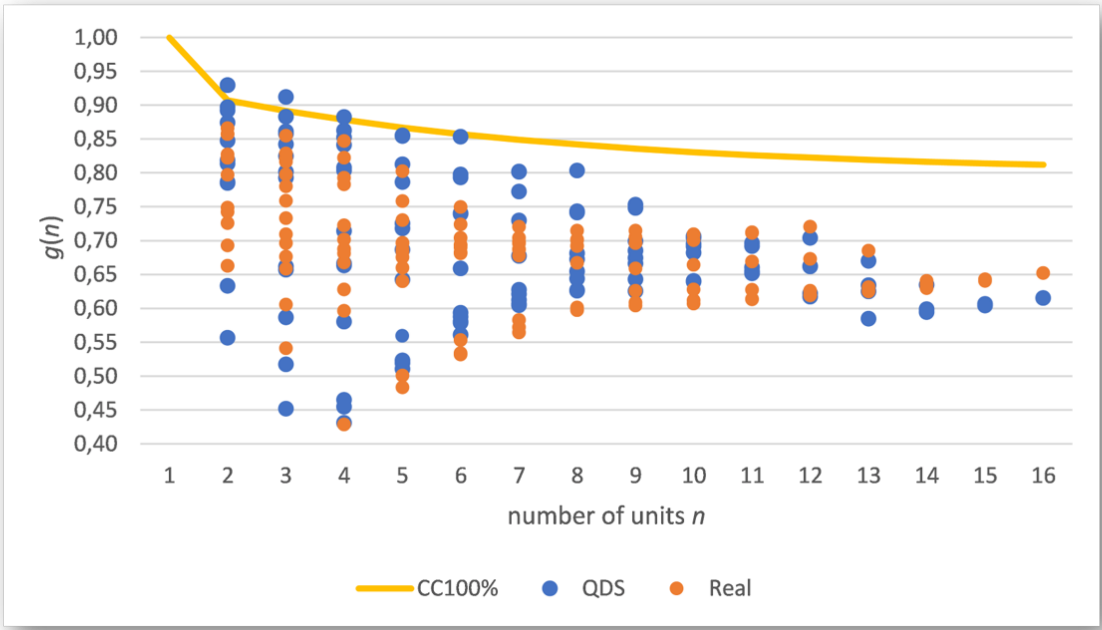

Figure 4: Comparison of CC100% to QDS and real measurement data

It can be seen that the coincidence values of the real database are always below the CC100% and in the simulation using QDS only a few combinations with a small number of units are above the characteristic curve. In both cases, the $g(16)$ is far below that of the CC100%. Particularly with a small number of units (n < 10), the real values are primarily significantly below the QDS values, which is attributed to further coincidence effects.

This comparison confirms the applicability of the 95% quantile of the QDS simulations for the creation of coincidence curves, as all real values are below the CC determined. Ultimately, the CC100% still appears to be a conservative estimate compared to the results of the QDS and the real data set, despite the median of the degree of dimensioning of 114 % for the systems under consideration.

The curves in Figure 5 illustrate the differences between the QDS and the measurement. On the one hand, the system configuration in the model is based on publicly available data (market master data register and Google Maps) and is therefore partially inaccurate. In addition, the diffuse radiation that actually occurs is also difficult to model accurately. Furthermore, a series of measurements shows a clear kink in the time curve, which results from the shading by a tree when the sun shines from the south-east (see PV2 in Figure 5).

4 Discussion and Outlook

The coincidence curves were determined under certain framework conditions (e.g. STC conditions). Other studies ([6],[7]) assume different framework conditions, but arrive at comparable curves. In some cases, these studies allow a smaller convergence value g_∞ than the CC presented here, especially if other coincidence effects were taken into account in these studies. The CCs presented here therefore represent a conservative approach that allows calculations to be made on the safe side, but still allows coincidence effects to be taken into account. Future work will investigate the advantages of taking coincidence definitions into account in grid planning.

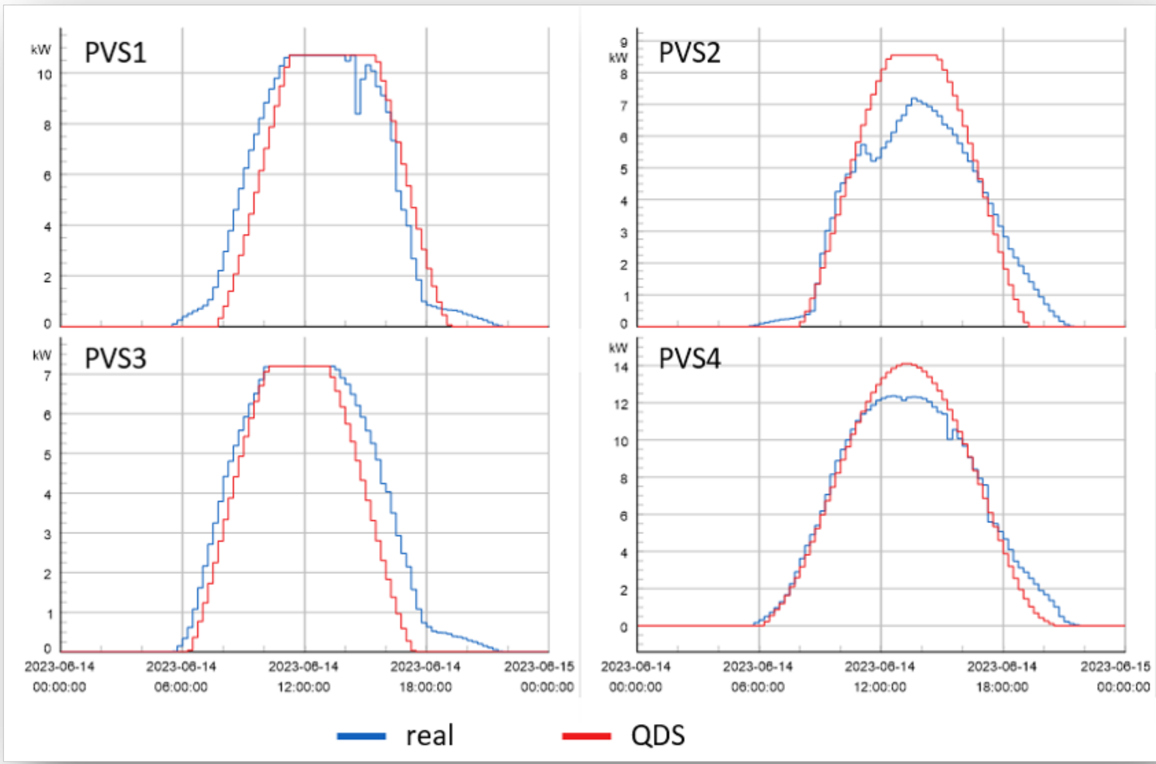

Figure 5: Comparison of feed-in curves of different PV with QDS and real measurement data

5 Executive Summary

The coincidence definitions of photovoltaic systems shown here can be easily applied with the LV load flow analysis. This is significantly faster and more robust against failures than preparing a model for a quasi-dynamic simulation. It still a calculation on the safe side and tend to overestimates the actual power, but not nearly as much as in the classic worst-case approaches.

6 Licence Configuration

Depending on the methods to be used, additional licence modules are required:

- ✓ Distribution Network Tools (for Low Voltage Load Flow)
- ✓ Quasi-Dynamic Simulation (for Time Series Analysis)

For more information, visit
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7 Literature

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