A MODEL CORRECTING THE EFFECT OF SUB-HOURLY IRRADIANCE FLUCTUATIONS ON OVERLOAD CLIPPING LOSSES IN HOURLY SIMULATIONS

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ABSTRACT: Simulations of PV systems that proceed in hourly steps can underestimate overload losses arising from sub-hourly irradiance fluctuations. The aim of this study is to estimate and address these additional overload clipping losses to improve the accuracy of the simulations in PVsyst.

The current trend for designing PV systems is to increase the DC/AC ratio. This trend is mainly due to PV modules plummeting in price and PV plants being constrained by grid limitations. The increase in DC/AC ratio allows PV systems to maximize production for the same AC capacity, by having the inverters operating at full output power for more hours during the day. When the inverter is operating close to maximal power, it can happen that irradiance spikes drive it into clipping conditions. This behavior is not captured by a simulation that proceeds in hourly steps, which leads to a systematic underestimation of the clipping losses (1-5% or more over a year).

The purpose of this study is to find a way to estimate from sub-hourly irradiance fluctuations a correction that can be applied in a general way to the clipping losses of an hourly simulation. In a first step, an analysis of hourly average irradiation data and sub-hourly data was done, to identify a way to calculate the behavior of overload clipping losses when applying a threshold. The analysis then went on using the same irradiation data for complete simulations in four climates and covering multiple cases of orientations of PV modules and DC/AC ratios.

The goal of the study, to improve simulations in PVsyst that are done in hourly steps, was achieved by using coefficients extracted from the sub-hourly data, applied on a simple geometrical model. This model corrects the error on overload losses significantly and thereby reduces the average difference of minute- and hourly-based AC generation below 1% for each DC/AC ratio.
Keywords: Clipping, Modelling, Simulation, System Performance

1 MOTIVATION

Sub-hourly clipping losses are a well-known phenomenon. If the simulation of the PV performance is performed in hourly steps, then the calculations will be based on hourly average values. If the hourly average irradiance value is close to the clipping level, the irradiance fluctuations will cause clipping losses that are missed in the hourly simulation. Several studies suggest that this effect may amount in up to 5% overestimates of the yearly generation for high DC/AC ratios, and a few percent for more regular systems. A non-exhaustive list of such studies can be found in [1, 2, 3, 4, 5, 6, 7, 8, 9, 10].

To visualize how this comes about, we take the irradiance evolution in one-minute steps for one hour and compare it to its mean hourly value and the level at which clipping sets in.

We have four distinct cases, which are depicted in Fig. 1. The first two on the top, are when the clipping level is above the highest or below the lowest irradiance value within the hour. Then the hourly average will not miss any additional clipping, since we are always either in non-clipping mode or permanently clipping, making the hourly average equivalent to the minute level treatment.

The third case on the bottom left is when the clipping level is in between the highest and the mean irradiance. The hourly treatment will detect no clipping at all, which means that the orange area above the clipping level will be missed.

Finally, if the clipping level is in between the lowest and the mean value, we get to a situation that is harder to grasp. The hourly treatment will detect clipping and remove all the area in between the mean and the clipping level. This will miss entirely the area above the mean, but it will contain also a part of the non-clipping portion towards the lower irradiance values. This second part will never fully compensate the missed part above the mean, since in total the areas above and below the mean are the same. Therefore, also this situation leads to under-estimated clipping losses.

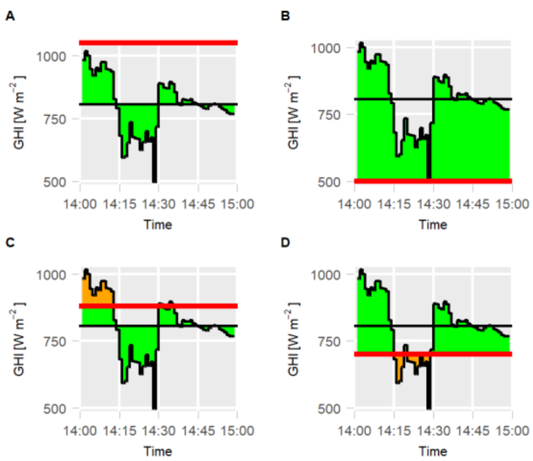

Figure 1: Irradiance evolution within one hour. On the left (cases A and C) the clipping threshold is above the hourly average, on the right (B and D) it is below. In the top row (A and B) the hourly averaging will capture correctly the clipping losses, while in the lower row (C and D) the clipping losses will be underestimated by an amount proportional to the orange surfaces.

In conclusion we can say that the clipping losses that are calculated with the help of hourly averages will either be correct, or underestimate the clipping losses, they will never overestimate them. The missed clipping losses are highest in hours where the clipping threshold coincides with the average irradiance value. As result, the hourly simulations will be biased towards a higher PV generation. The exact amount will depend on the specific weather as well as on the DC/AC ratio of the system. Studies have shown that this bias can reach a few percent, which is a non-negligible amount, and that calls for a correction. This is the subject of the present study.

2 APPROACH FOR THE SUB-HOURLY CLIPPING CORRECTION

One way to handle the sub-hourly irradiance fluctuations would be to move to a minute-level simulation. However, this can become extremely time consuming for large PV systems or PV systems with complex shading situations. Other approaches aim at finding corrections for hourly simulation values, based on the DC/AC ratio and general features of the weather files used in the simulations, like weather variability or climate category [4, 5, 11, 12, 13, 14, 15, 16, 17].

In this study, we choose an approach that is a combination of both, and which is schematically shown in Fig. 2. In a first step, the minute-level weather data is analyzed in order to extract coefficients that are stored together with the hourly values. These coefficients will allow to correct for the sub-hourly fluctuations at the stage when the clipping losses in the inverter are calculated.

The key idea is based on a reordering and linearization of the irradiance values and will be explained in the following.

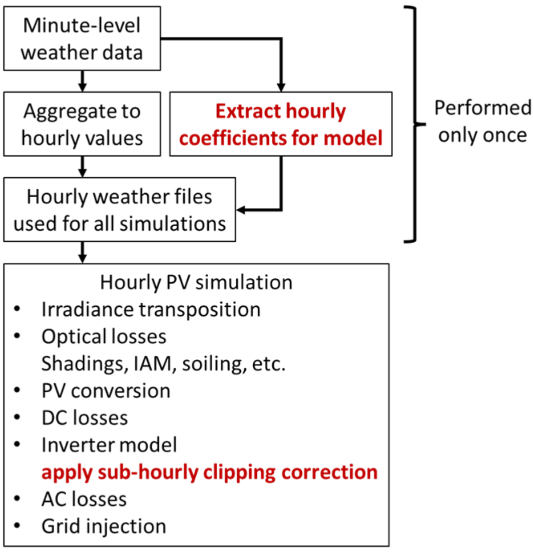

Figure 2: Approach for correcting the sub-hourly clipping losses. When aggregating the minute-level weather data to hourly values, additional coefficients are stored together with the hourly values, and which are used in the inverter modeling to estimate the sub-hourly clipping losses.

2.1 Reordering irradiance values

The performance of a PV system is in first order a linear function of the effective irradiance reaching the PV modules. Other conditions like temperature or spectral corrections affect the output only in second order. The PV system reacts almost instantaneously to the irradiance level, which, in a minute-level simulation, would in principle allow us to reorder the minute-values within each hour, without affecting the simulation result. Therefore, we can sort the minute irradiance values in ascending order and get a simplified irradiance evolution over one hour. This is shown in Fig. 3.

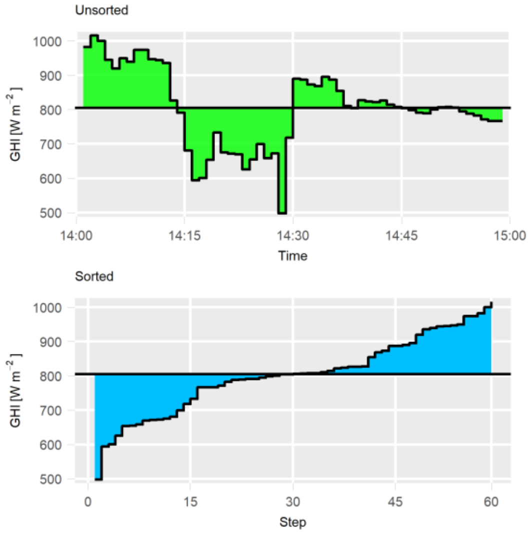

Figure 3: Re-ordering the minute values within an hour does not affect the simulation results. Sorting the values in ascending irradiance values allows to describe the irradiance value distribution with a simple approximation.

The reordering simplifies considerably the shape of the irradiance evolution, which can now be described with a few parameters only. This will allow to reconstruct this irradiance evolution at the stage where the clipping of the inverters is treated. In this way the amount of irradiance that will lead to clipping can be estimated allowing to correct the hourly clipping losses.

2.2 Linearized irradiance evolution

We approximate the ordered irradiance evolution by two stretches of straight lines, as shown in figure 4. The lines are limited by the lowest and highest irradiance and touch at the point where the irradiance evolution crosses the mean value. This can be described by a total of three parameters.

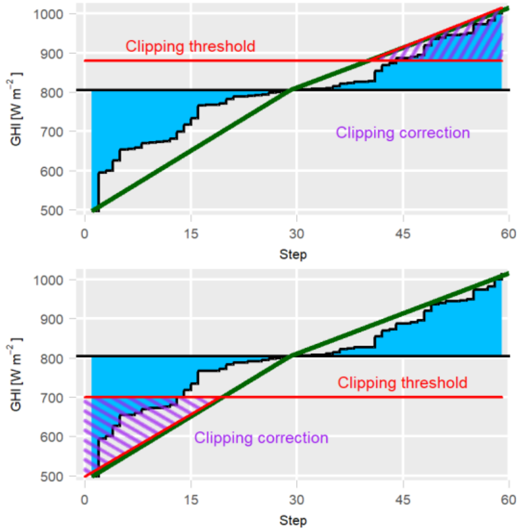

Figure 4: Approximation of the ordered irradiance values by two stretches of straight lines. The lines are delimited by minimal and maximal irradiance, and touch at the point where the values cross the mean. The clipping correction is approximated by the area of the textured triangle.

In the example shown in Fig. 4, one can see that this approximation is not always perfect. The values above the mean are quite well approximated by the triangle, whereas the values below the mean are only grossly described by the triangle.

We chose to start with this simple approach, but it is possible to use other parametrizations with more parameters in order to optimize the fitting to the minute-level data.

2.3 From horizontal irradiance to AC power

The minute level input data contains the irradiance on a horizontal plane. In our approach we derive the additional coefficients from this data, and store them together with the hourly irradiance averages, in order to be able to reproduce the irradiance distribution within the hour, when we perform the hourly simulation steps.

This horizontal irradiance is subject to several transformations before the final effective irradiance on the PV modules is obtained. These include the transposition to the plane of incidence, the incidence angle losses, shading losses and soiling losses. After this, follows the PV conversion, the losses in the DC part of the system and the inverter model, before the AC power on which the clipping will be applied is known. Since not all these effects are linear, the shape of the horizontal irradiance evolution will suffer modifications, as shown in Fig. 5. In our approach we neglected these non-linearities and converted the linear description at the irradiance level directly to AC power by applying the ratio of the mean values. This is a simplification that can easily be improved in further sophistications of the model.

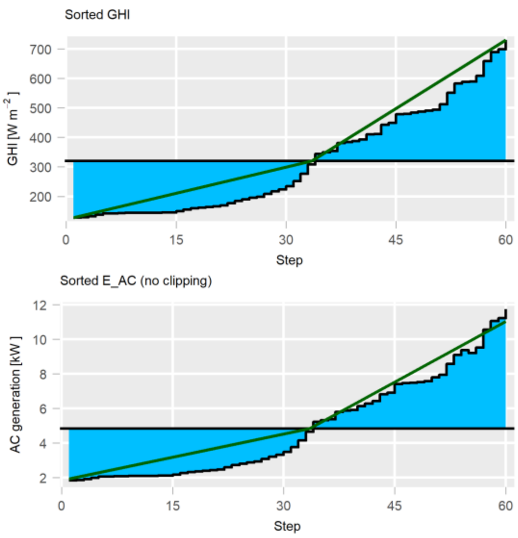

Figure 5: When going from global horizontal irradiance to generated AC power, the shape and ordering of the minute-level values changes. The simple linear approach uses just a linear rescaling of the two straight lines.

3 SIMULATIONS WITH ONE-MINUTE DATA

In order to check the effectiveness of the clipping loss correction, we performed simulations of a PV system in one-minute steps. Since the PVsyst simulation that was used in this study only allows to simulate in hourly steps, a special handling was necessary to obtain the one-minute simulation data.

The minute-level weather data can be sliced into 60 sets, one for each minute in the hour, as indicated in Fig. 6. Introducing a corresponding time shift to each of the slices, it is possible to run the hourly simulation on them and re-assemble the results in order to get effectively the results of a one-minute level simulation.

Since the hourly simulation uses a stationary thermal model, these results would correspond to the hypothesis of PV modules without any thermal inertia. This is an extreme case that will bias the results. The true temperature of the PV modules will not follow instantaneously the irradiance fluctuations but have a time constant in the order of 10 minutes. Therefore, we performed the set of simulations with the PV module temperature fixed during every hour at the value obtained by the hourly simulation using the averaged weather input data. This represents the case where the PV modules have a rather high thermal inertia. We chose these results as reference to which we compare the hour-level simulations, with and without the clipping loss correction.

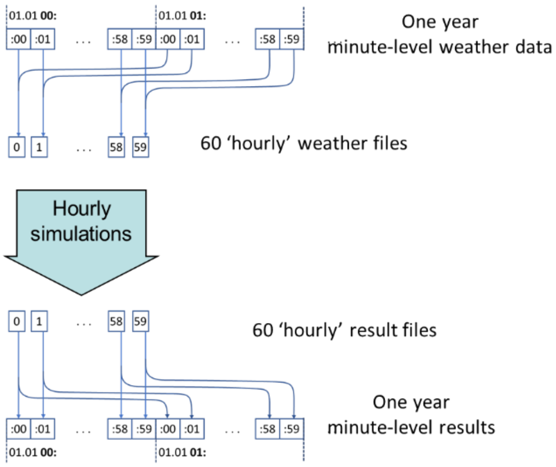

Figure 6: Decomposition of one-minute weather data into 60 'hourly' files. Each of the files is used as input for one hourly simulation and the results are re-assembled to give an effective one-minute simulation.

3.1 Data considered

The minute simulation approach was applied on four weather datasets, and we considered several PV system scenarios.

The data was obtained from four stations in the U.S. listed by the NREL Measurement and Instrumentation Data Center (MIDC): the NREL SRRL Baseline Measurement System [18], in Golden, Colorado; the University of Oregon [19], in Eugene, Oregon; the Natural Energy Laboratory of Hawaii Authority [20], in Kailua-Kona, Hawaii; and the University of Louisiana at Lafayette [21], in Lafayette, Louisiana. The four listed sites belong to four different climates under the Köppen climate classification, respectively, semi-arid continental (BSk), warm-summer Mediterranean (Csb), tropical semi-arid (BSh), and humid subtropical (Cfa). Temporally, the data subset used is that of year 2020.

As PV system scenarios, we considered four different DC/AC ratios and seventeen orientations. The DC/AC ratios are, 1, 1.33, 1.67, and 2, and are obtained using a 9kW inverter AC nominal power, and a variable number of strings in parallel, for systems amounting to 9, 12, 15, and 18 kWp DC. The orientations cover azimuths among [-135°, -90°, -45°, 0°, 45°, 90°, 135°], with the south as azimuth 0° and east at -90°, and tilts among [0°, 30°, 60°, 90°] with additional conditions: tilt 90° combined only to full E and full W azimuths, and tilt 0° computed only once. When accumulating multiple scenarios or climates, we have given the same weight to all cases.

4 HOURLY RESULT COMPARISON

Our correction modifies the resulting AC power at the level of the hourly steps of a simulation. As explained in section 2, the missing clipping loss at each hourly step is estimated based on the three coefficients extracted from the irradiance minute-data. In order to corroborate the model, the first step is therefore to investigate whether the correction effectively improves the hourly level clipping losses.

In Fig. 7, we compare the hourly clipping losses to the sum of the clipping losses found in the minute simulations for the corresponding hours. The points represent only the hours that have non-negligible clipping in the minute simulation. The data used for the plot covers only one site (Lafayette) and one orientation (South 30° Tilt), but the results are representative of all other cases. In the plot at the top, the clipping losses from the hourly simulation are not corrected, while the values of plot at the bottom have been corrected using our model.

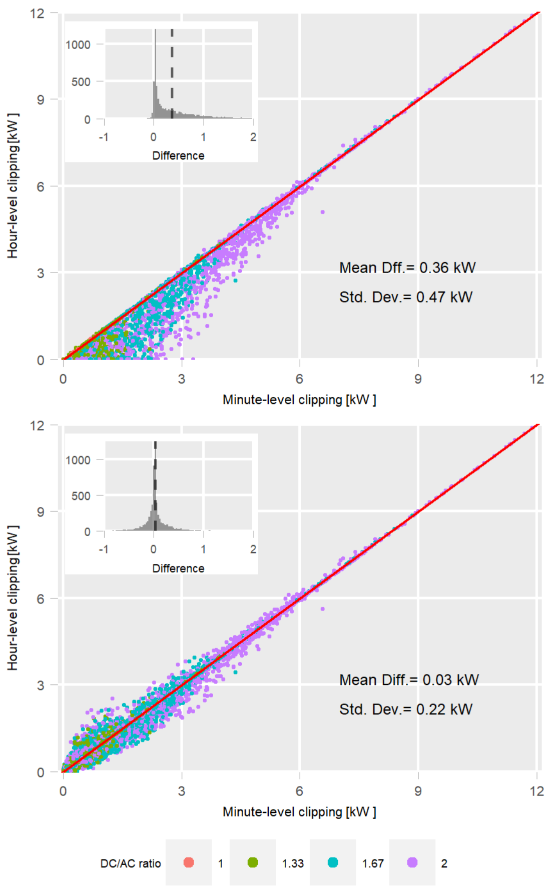

Figure 7: Comparison of the clipping losses of the hourly simulation with the hourly sums of the minute simulation for a 9kWAC PV system and four different DC/AC ratios. The first plot uses values without correction, while the second plot uses the corrected values.

As expected from the discussion in section 1, the non-corrected hourly data clipping is always smaller than the minute-data clipping. In other words, the distribution of the clipping losses from the hourly simulation exhibits a non-negligible bias towards lower values. The mean difference is 0.36 kW, to be put into perspective with the fixed system AC nominal power, 9 kW. The standard deviation is 0.47 kW. The clipping losses correction brings all points back towards the diagonal. Using corrected hourly clipping losses, the mean difference is 0.03 kW, and the standard deviation is 0.22 kW. The model therefore improves both the accuracy and the precision of the hourly simulation which thus becomes more consistent with the minute-level simulation.

5 IMPACT ON YEARLY RESULTS

In the previous section, we have shown that both the spread and bias of the distribution of the clipping loss errors for each hourly step did significantly improve with our model. In this section we will look at the impact of the correction on the yearly AC power output.

In Fig. 8, we show a histogram of the distribution of the difference in AC generation between hourly simulation and minute simulation. All cases under study have been considered, each count thus representing the yearly simulation for a given site, DC/AC ratio, and orientation. The lower side (negative counts) of the histogram denotes the results without correction, while the upper side (positive counts) denotes the results with the clipping correction. For both sides, we show the different DC/AC ratios with different colors, to highlight that the improvement spans all DC/AC ratios.

In Fig. 9, the same data is presented in a different fashion: the data is split according to different DC/AC ratios, and the distributions are represented using violin plots, with the non-corrected and corrected results shown side-by-side and in different colors (red and blue respectively). The central points denote the median of the distribution, and the error bars show the 25% and 75% quantiles. This second plot allows us to better quantify the improvement that is achieved by the clipping correction.

It can be noted again that both the spread and the bias of the distributions are improved. The mean and the standard deviation for the different DC/AC ratios are presented in Table I.

Table I: Mean and standard deviation of the distribution of the errors among the yearly AC generation results, comparing the hourly simulation with an without correction, to the minute simulation.

AC power error	Mean [%]		Standard Deviation [%]	
	Uncorr.	Corr.	Uncorr.	Corr.
Global	-2.61	-0.77	1.5	0.72
DC/AC = 1	-1.04	-0.92	0.73	0.72
DC/AC = 1.33	-2.1	-0.61	0.84	0.64
DC/AC = 1.67	-3.34	-0.64	1.09	0.67
DC/AC = 2	-3.96	-0.88	1.24	0.81

The improvement in the AC generation result distribution is negligible for the DC/AC ratio 1 but is important for the higher DC/AC ratios, with the most improvement for the highest ratio. Still there remains an overall bias around 0.6%, which is not removed by the correction. As explained before, the differences in AC generation also include other sources of bias. Our preliminary studies point towards a bias introduced by the transposition from the horizontal to the tilted plane.

In summary, we can say that the model captures most of the error, as the AC generation bias can be reduced below the 1% level for all DC/AC ratios. The correction of the remaining bias will be the subject of a subsequent study.

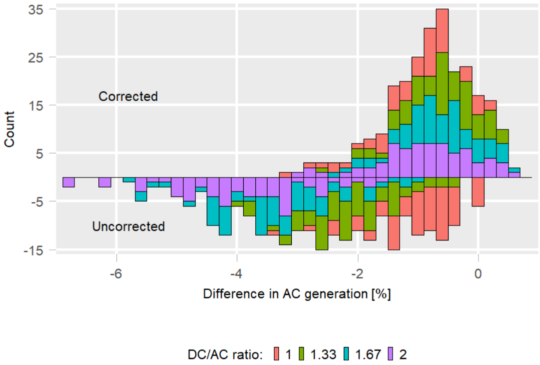

Figure 8: Histogram of the distribution of errors comparing the yearly AC generation from the hourly simulations with that of the minute simulations. All cases (site, orientation, and DC/AC ratio) have been considered. The distribution of errors without correction is shown as negative counts, the one with correction as positive counts. Different DC/AC ratios are shown in different colors.

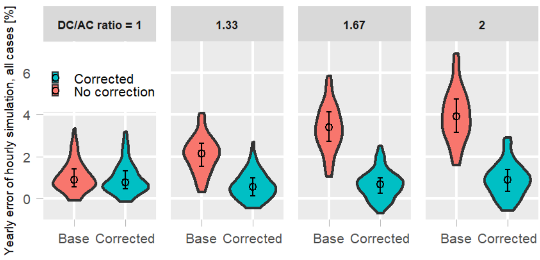

Figure 9: Violin plot of the distribution of errors, comparing comparing the yearly AC generation from the hourly simulations with that of the minute simulations. The different DC/AC ratios have been separated and corrected vs. uncorrected results are shown side by side. Central points denote the median of the distribution and and the error bars show the 25% and 75% quantiles.

6 CONCLUSION

When simulating PV systems with an hourly resolution, some effects with a shorter time scale may be missed, potentially causing a bias in the simulation results. One of the most important higher resolution effects that may cause such a bias is the clipping losses due to sub-hourly clipping, which generally leads to overestimates in the simulated generation of PV systems. Several studies have found that this effect may lead to up to about 5% overestimates of the yearly generation for high DC/AC ratios, and a few percent for more regular systems.

Since performing higher-resolution simulation comes at a greater cost in terms of performance, we propose an approach to correct the hourly resolution clipping by means of few coefficients extracted from minute-resolution irradiance data. We utilize the near linearity of the PV generation in terms of irradiance to reorder the minute-data without affecting the results significantly. This allows us to estimate the distribution of irradiance values within each hourly step using a simple linear approximation with three coefficients, and ultimately model the missed clipping loss using this linear estimate.

We applied the model to four sites with minute-level data and scenarios spanning different orientations and DC/AC ratios. To analyze the results, we compared both the uncorrected and corrected results to a minute-resolution simulation. The results show that our approach corrects both the spread and the bias of the hourly clipping loss distribution, by a factor of two and ten respectively. We also compared the yearly results, showing that the bias error on the AC generation is on average reduced to the sub-percent level.

Further investigation suggests that the remaining bias may be related to effects other than the missing sub-hourly clipping. Such other effects have been shown to exist [22, 23, 24], for example the shadings and transposition evaluation. A bias comparable to the remaining error at AC generation is already observed after application of the transposition model. Correcting this will need further study. In parallel to this, our model still has room for improvement. Furthermore, we would like to validate the model for tracking systems as well as more climates and weather data sources.

The model presented in this publication will be made available in a future PVsyst version and be improved further.

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