Effects of Flicker in a Distribution Grid with high PV Penetration

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ABSTRACT: The quantity of installed photovoltaic (PV) systems in the German distribution grid is still increasing. In some areas the installed PV capacity exceeds 5 kW_p [SPR-13] per house connection (HC). Therefore the load flow changes its characteristics and leads to new requirements for the grid. In some areas the power feedback is higher than the delivery and the installed PV capacity becomes the decisive factor for grid planning. This paper discusses the impact of PV systems on the flicker level. The focus hereby is on the correlation between the flicker level and the grid voltage and the meteorological parameters. Different approaches to investigate if there is an influence of PV systems on the flicker are taken into account. Furthermore an investigation if the normative limit is exceeded will be shown.

Keywords: Grid integration, Stability, Photovoltaic

1 INTRODUCTION

Flicker is a subjective impression of the discontinuity of visual perception caused by a variation of voltage and therefore a volatile luminance. The flicker can be measured by a flickermeter (defined in [VDE-0847]) that based on a reproduction of a 60 W incandescent lamp, the sensitivity of the human eye and the corresponding brain reaction. For the evaluation of the emissions different flicker limit curves have been determined. The reasons for flickers are voltage fluctuations, whereby the curve form of this variability (sinusoidal, ramp, rectangle) and the frequency are essential.

Flickers can be characterized by [SCH-13]:

- short term flicker (index st) in a time period of 10 minutes and long term flicker (index lt) in a time period of 2 hours,
- the relative voltage changes $\Delta u(t)$,
- different correction factors.

Long term flicker (P_{lt}) is one relevant parameter for the power quality. The permissible value of P_{lt} in a low voltage grid, produced from the totality of all feeders and loads, is according to the German low voltage guide line [VDE-4105]

$$P_{lt} \leq 0.5 \qquad (1\text{-}1)$$

even at the weakest node. The value is calculated from twelve consecutive short term flicker (P_{st}) [SCH-08]. Flicker values are given dimensionless.

$$P_{lt} = \sqrt[3]{\frac{\sum_{i=1}^{12} P_{st,i}^3}{12}} \qquad (1\text{-}2)$$

The limiting value for the short term flicker is

$$P_{st} \leq 1.0. \qquad (1\text{-}3)$$

This value is decisive for product standardization but not for power quality. Nevertheless, due to the temporal resolution this short term flicker is used in the following to analyse the dependency of the flicker on the PV feed in. The long term flicker is only used to analyse exceedances of the normative limit.

Higher values leads to disturbing perceptions caused by voltage fluctuations and variations in the luminance by more than 50 % of the test persons. Formula (1-4) [SCH-08] describes the calculation instruction. Essential is the voltage variation in %, R and F are frequency and form factors, r is the repetition rate.

$$P_{st} = 0{,}365 * R * F * \left(\frac{r}{min^{-1}}\right)^{0{,}31} * \left|\left(\frac{\Delta U_{max}}{U}\right)/\%\right| \qquad (1\text{-}4)$$

Frequency and form factors for various repetition rates and relative voltages changes are given in [SCH-08]. The size of these factors is in the range of 0.2 and 1.4.

On days with a fluctuating cloudiness the ramp rate of the irradiation and thereby the irradiation changes are very high. The generated output power of PV systems is strongly volatile [WIR-12]. This has an intense effect on the grid voltage and thereby possibly on the flicker. In this article, the evaluation of the short and long term flickers depending on the relative grid voltage, the time of the day, date of the year, global irradiation gradients and the clear sky index in an area with a high PV penetration is shown.

2 DATABASE

To gain more knowledge of the changing grid requirements the E.ON Bayern AG initiated the project “Grid of the Future” (Netz der Zukunft) [EBY-10] in cooperation with the University of Applied Sciences Munich and the Technische Universität München. In this project a medium voltage grid in Lower Bavaria and the underlying low voltage (LV) grids are analysed. This area stands for high PV yields (for Germany) and an above average PV penetration (5 kW_p / HC). Around 560 smart meters are installed, mainly at house connections with PV systems. A database collects the 10 minutes average data from the measurement devices. The short term flicker is one electrical parameter that is recorded. All results refer to the period from January 2011 to December 2012. Thus the test series include two complete summers.

To get significant results, several evaluation steps are necessary. The low voltage grids have to be analysed separately because of the high data volume. Each smart meter calculates the 10 minutes average P_{st} value for three phases. This leads to 432 values per smart meter and day and therefore to nearly five Million data values per year for a grid with thirty smart meters.

All flicker values are real measurement data. Therefore it is not possible to match theses values bijective to PV systems or loads. Different approaches to allocate the flicker levels to loads or PV systems are realised. The assignment is done for the relative grid voltage, the date and time as well as the global irradiation gradients and the clear sky index.

The clear sky index is the quotient of the measured irradiation to the clear sky reference irradiance on the particular location and day [ZEH-12] (see formula (2-1)). The clear sky index from one irradiation sensor in the investigation area is calculated and used for this study. A clear sky index value equal to one describes clear sky conditions. Days with a fluctuating cloudiness cause clear sky index values different to one. Cloud shadowing cause clear sky index values lower than one, irradiance enhancements cause clear sky index values higher than one.

$$k_T = \frac{G_{measured}}{G_{clear\ sky}} \qquad (2\text{-}1)$$

The investigation of the flicker is made for several low voltage grids. The results, however, are similar for all investigated grids. Therefore the detailed results for only one low voltage grid in the year 2012 will be discussed and shown in the following evaluations.

This LV grid can be characterized by a high PV penetration of more than 1050 kW_p of installed power in June 2012. 13 of 144 house connections are equipped with smart meters. This leads to a PV penetration of 7.3 kW_p / HC.

3 RESULTS

DISTRIBUTION OF THE LONG TERM FLICKER

In this section the long term flicker, which is one relevant parameter for power quality, in an exemplary LV grid is analysed. The investigated village shows a totality of more than two Million data points in the period from January to December 2012 (Table 1). Only 0.20 % reach a flicker level higher than 0.5. To exclude unrepresentative outliers, the 95 % quantile is determined (Figure 1). The mean value is 0.135, the 95 % quantile 0.365. Both values a far below the normative limit. Nevertheless, around 60 values were measured with a level above one. This is twice the allowed maximum value.

Table 1: *Distribution of the long term flicker for one low voltage grid in the investigation area in 2012. 0.20 % of the P_{lt} values are higher than the normative limit.*

P_{lt}	Number of data points	Share of the totality in %
> 0.0	2 048 511	100
> 0.1	1 600 553	78.13
> 0.3	258 745	12.63
> 0.5	4 103	**0.20**
> 1.0	58	0.003
> 1.5	0	0

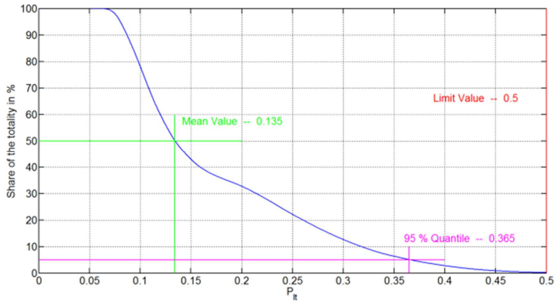

Figure 1: *Distribution of the long term flicker for an exemplary low voltage grid in the investigation area in 2012. The mean value and even the 95 % quantile are far below the normative limit.*

CORRELATION OF THE SHORT TERM FLICKER WITH THE RELATIVE GRID VOLTAGE

All following results refer to the measured short term flickers because of the higher temporal resolution compared to the long term flicker. The short term flicker is not relevant for power quality. It is only significant for product standardization. The evaluation of the dependency of the flicker on PV systems contains different approaches that will be shown in the following analyses.

To investigate the influence of PV systems on the short term flicker, the correlation between the P_{st} and the grid voltage is a useful indicator. Relative grid voltages higher than 100 % leads to a high power feed in. It can therefore be assumed that the corresponding flickers can be caused by PV systems and loads during days with a fluctuating cloudiness or only by loads on clear sky days. Voltages lower than 100 % occur during times with lower or even no PV power feed in and therefore without any noticeable irradiation. Thus flickers that appear on these lower voltages can be attributed to loads.

Figure 2 visualizes the short term flicker depending on the relative grid voltage. High densities of flicker values are red, low densities are blue. Most of the short term flickers are within a range below 0.15 and occur at voltages between 98 % and 101 % of the grid voltage. Many of the high short term flicker values of 0.15 up to 0.5 are detected at voltages higher than 100 %. These flicker values can be attributed to the power feedback situation. Most of the installed PV systems are connected to phase one [PAR-12]. Due to that, differences between the phases are expected. There is in fact a slight disparity but it is still marginal. In general there is a considerable scatter of the P_{st} values on each phase. Therefore only one phase is shown in most of the following evaluations.

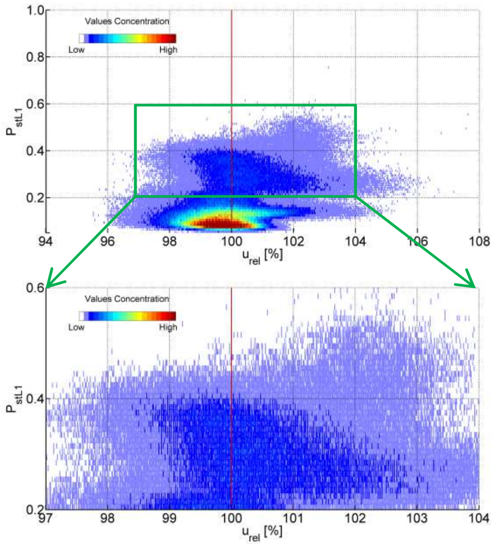

Figure 2: *Visualization of the short term flicker in dependency of the relative grid voltage. Higher flicker values occur mainly at voltages higher than 100 %.*

CORRELATION OF THE SHORT TERM FLICKER WITH THE TIME OF THE DAY

In this part of the investigation the short term flicker is assigned to the time of the day. Therefore all day courses of the P_{st} values are superimposed. Figure 3 shows the result for phase one of the exemplary grid.

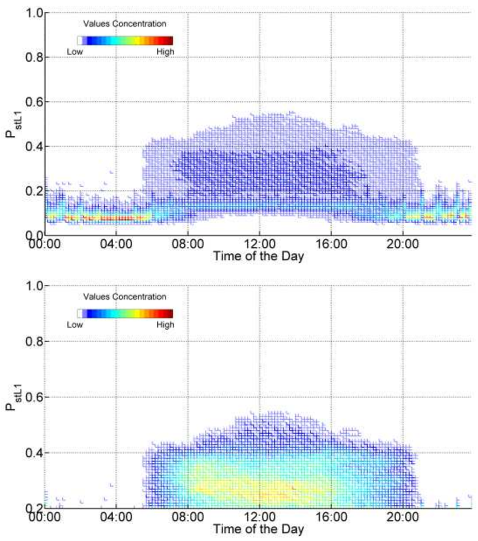

Figure 3: *Visualization of the short term flicker over the time of the day. Higher flicker levels can be seen during daytime with a slight peak at noon.*

The upper part of Figure 3 displays the short term flicker in the range from zero to one. In the night hours the level is low, at around 0.1. During daytime a bigger spread at a higher level occurs. Therefore the density of these levels is lower.

The lower part of the figure illustrates only the daytime levels. Besides the equal distribution between 06:00 and 20:00 o´clock is a slight peak at noon. This peak could be caused by PV systems. It is obvious that during daytime the flicker level is higher due to the living habits of the people. The connected loads, such as motors, consumer electronics or agricultural and industrial machines, consume higher loads and have therefore a higher impact on voltage fluctuations and on the flicker. During night much less machines or other devices are in use.

CORRELATION OF THE SHORT TERM FLICKER WITH THE DATE OF THE YEAR

After the correlation with the time of the day, the day of the year correlation is the logical next step. PV systems produce a large part of their yearly electricity in the months Mai, June, July and August. If PV systems have a noticeable impact on the flicker level the expected level in these time period should be higher than during the rest of the year.

Figure 4 shows the short term flicker on phase one for the whole year 2012. There are some data gaps, especially in June. The flicker level remains nearly constant over the complete year. Only a flimsy enhancement in June and July is visible. There is no obvious drop in the winter months. This leads to the conclusion that the flicker level caused by loads is as high as the level caused by PV systems. Even the few high levels in the summer month could be evoked by loads.

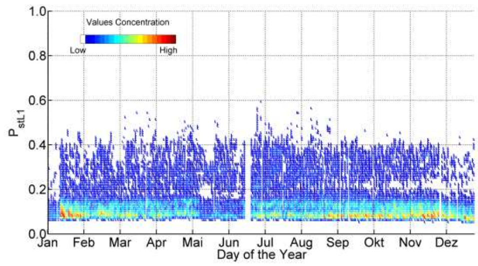

Figure 4: *Visualization of the short term flicker in dependency of the day of the year. Marginally higher flicker levels can be seen in June and July with a slight peak at the end of June.*

Figure 5 shows the behavior of the daily flickers throughout the year. The duration of higher flicker levels during the days is a function of the day of the year. Long summer days are an indicator for longer high flicker levels. This fits with the rhythm of the human routine as well as with the PV production.

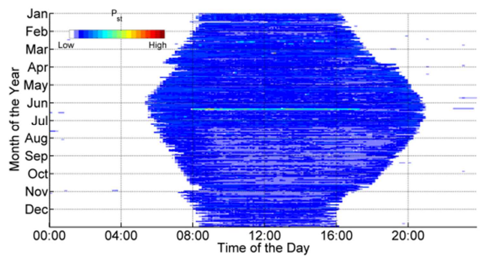

Figure 5: *Visualization of the short term flicker in dependency of the time of the day and the day of the year. The length of higher flicker levels during daytime varies during the year.*

CORRELATION OF THE SHORT TERM FLICKER WITH THE GLOBAL IRRADIATION

To investigate the influence of PV systems on the flicker it is essential to calculate the correlation to the global irradiation. In this paper that is done in two different ways:

- 10 Minute average values of the irradiation (G_{mean}).
- Difference between maximum and minimum irradiation in a 10 minute interval (G_{diff}).

The short term flicker refers to a 10 minute time slot. In comparison to that the global irradiation is available as a high precision one second value for ten different locations in the investigation area. To correlate the time series it is obvious to calculate 10 minute average irradiation values with the knowledge that all enhanced irradiation values are smoothed. The results of this examination refer to the time period 01.06.2012 to 10.10.2012 because of the data availability. In this period ten autarkic sensors located distributed in the investigation area deliver irradiation and ambient temperature on the horizontal plane. For each low voltage grid the irradiation of the nearest sensor is used.

Figure 6 outlines the result. Each flicker level correlates to one 10 minute average irradiation value. A small increase to higher flicker levels on high irradiation values can be seen. The 90 % and 99 % quantile make the coherences more apparent. The flicker level is nearly independent on the irradiation. Even at cloudy days with maximum irradiations around 300 W/m² the flickers reach the same level as on days with a bright sunshine.

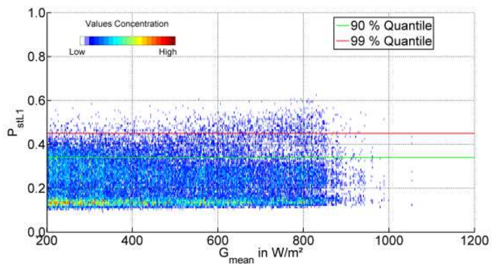

Figure 6: *Visualization of the short term flicker in dependency of the 10 minute average irradiation value. Considerably higher flicker levels can be seen with increasing irradiances.*

To separate the clear sky conditions from the fluctuating cloudiness with a possible impact on the flicker level, the "maximum difference" per 10 minute raster is calculated. This "maximum difference" is the difference between the absolute maximal to the absolute minimal irradiation in a 10 minute interval. On a clear sky day this value is low. On days with a highly volatile irradiation profile the "maximum difference" can reach values up to 1000 W/m².

The results are displayed in Figure 7. It is expected to receive excessive flicker levels at higher "maximum difference" irradiations. The 90 % and 99 % quantile makes the constant flicker level scattering evident.

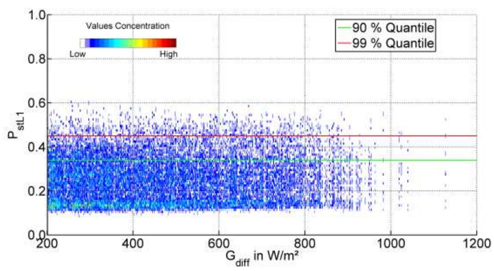

Figure 7: *Visualization of the short term flicker in dependency of the 10 minute "maximum difference" irradiation value. The flicker level remains constant.*

To sum up these two different approaches: Slightly higher flicker levels occur on higher mean irradiation values but not on higher "maximum difference" irradiations. This leads to the suggestion, that higher flicker levels are produced by loads during daytime. This is consistent with the evaluation of the flicker in dependency of the time of the day and the typical human behavior.

To eliminate the influence of the loads as effective as possible the same evaluation as shown in Figure 7 is done only for Sundays. Assuming that most of the loads are shut down on a Sunday, the effect of PV systems should be more apparent.

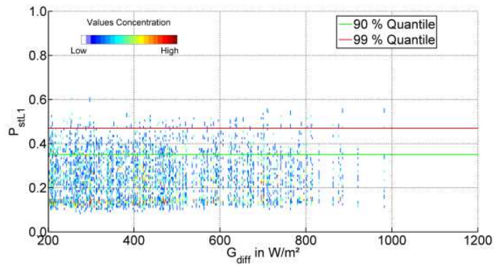

Figure 8: *Visualization of the short term flicker in dependency of the 10 minute "maximum difference" irradiation value on Sundays. The flicker level remains still constant.*

The flicker values on Sundays in dependency of the "maximum difference" irradiation are revealed in Figure 8. Again the distribution remains nearly constant.

Nevertheless, to exclude the influence of a fluctuating cloudiness on the flicker level the evaluation of the correlation with the clear sky index is done in the following section.

CORRELATION OF THE SHORT TERM FLICKER WITH THE CLEAR SKY INDEX

Days with a fluctuating cloudiness exhibit clear sky index values different to one. The values can be lower due to cloud shadowing or higher do to irradiation enhancements [ZEH-12]. Consequently influences of PV systems on the flicker value should occur on clear sky index values unequal to one.

The pictures of Figure 9 illustrate the flicker value in dependency of the clear sky index for all three phases. Despite obvious differences in the phases all of them do not show elevated flicker values at clear sky indexes unequal to one.

Phase one displays the highest flicker values at a clear sky index around one. This can again be attributed to the ordinary human behavior and due to that contributed to loads. Furthermore is the investigated low voltage grid a rural area with a high density of agricultural loads. These loads are mainly used outside on sunny days.

A similar behavior at least in the density of the flicker level shows the second picture of Figure 9. In the third one, the distribution of the flicker level is nearly constant. The most serious difference between the third and the other two pictures is the absolute level of the flicker. Phase three has a maximum level around 0.3, phase one and two of 0.4 up to 0.6. Due to that conspicuousness there are more and / or stronger loads connected to the phases one and two than to phase three. Once again no influence of PV systems on the flicker level can be obtained.

To eliminate the load as well as possible the following analysis on Sundays is taken out.

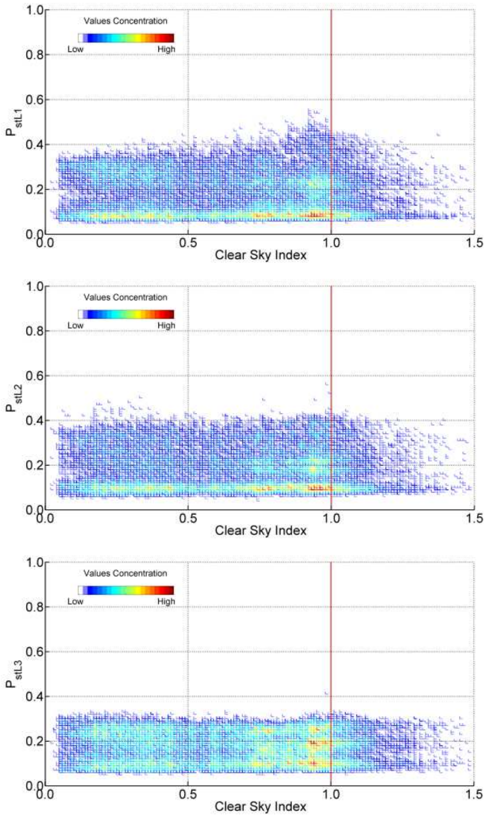

Figure 9: *Visualization of the short term flicker in dependency of the clear sky index for all three phases. Despite obvious differences in the phases all three do not show elevated flicker values at clear sky index values unlike one.*

COMPARISON OF THE FLICKER LEVEL ON A LONG FEEDER WITH PV SYSTEM ON A CLEAR SKY DAY WITH A FLUCTUATING DAY

A nearly entire elimination of the load is possible by considering only one long feeder with a huge PV system on Sundays. This evaluation is done in this part of the evaluation.

In this approach the irradiation profiles of all Sundays are analysed. The most fluctuating and clear sky irradiation profiles are taken into account. The measured house connection is at the end of a long feeder and a 16.7 kW_p PV system is installed.

Figure 10 and Figure 11 show the irradiation and flicker profiles for these two exemplary days on the chosen grid node. Blue represents the irradiation in W/m², red the flicker level. Slightly higher flicker values occur on the fluctuating day. There are high peak flicker values at times with no or very low irradiance. These values can again be attributed to the influence of loads. It should always be taken into account that the measured values are far below the normative limit of one. The peak values of this evaluation are below 0.2.

INVESTIGATION OF THE FLICKER LEVEL ON CLOUDY DAYS WITH ALMOST NO PV FEED IN AND ON CLEAR SKY DAYS WITH NO IMPACT OF PV SYSTEMS ON THE FLICKER LEVEL

The goal of this section, in contrast to the last analysis, is to eliminate the influence of PV systems on the flicker level. Therefore days with a thick cloud cover and clear sky days without any feed in fluctuations are examined.

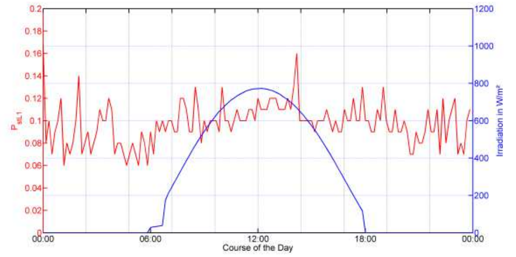

Figure 10: *Visualization of the short term flicker (red) and the irradiation (blue) at the end of a long feeder for a clear sky day.*

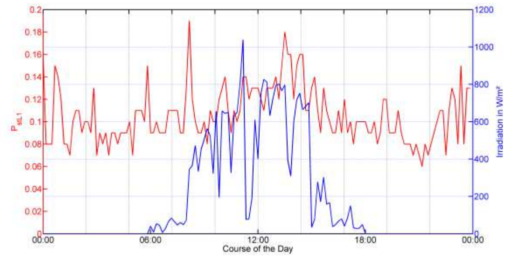

Figure 11: *Visualization of the short term flicker (red) and the irradiation (blue) at the end of a long feeder for a fluctuating day.*

In the first part only the cloudiest days in 2012 are analysed. The choice of the days was done by a Fast Fourier Transformation (FFT) and filtering algorithm [RAU-13]. This algorithm sorts the daily irradiation profiles in twelve categories in dependency of the irradiation gradients and the maximum irradiations. All analysed days do not reach irradiation values higher than 350 W/m². Figure 12 displays the daily irradiation profiles of the four cloudiest days in 2012.

The inherent flicker values of these four cloudy days are displayed in Figure 13. The comparison of Figure 13 with Figure 3 shows no differences in the maximum flicker level. There are higher flicker values during day time because of the human daily life. Summarising the flicker values evoked by loads are at least as high as the flicker values caused by PV systems. Nevertheless, there is the possibility of occasional high flicker values caused by PV systems despite all realised investigations.

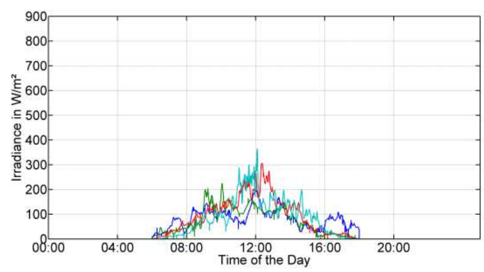

Figure 12: *Daily irradiation profiles of four days in 2012 with a thick cloud cover.*

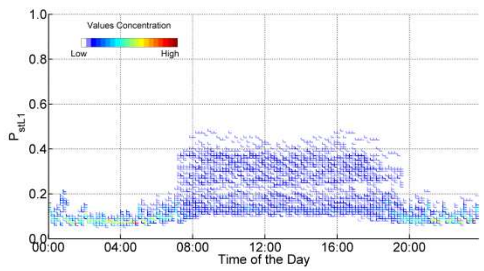

Figure 13: *Visualization of the short term flicker in dependency on the time of the day on days with a thick cloud cover. Again higher flicker levels can be seen during daytime.*

The maximum P_{st} value was measured on the 18^{th} January 2012. On this day the short term flickers on phase one reached a maximum value of 1.38, on phase two of 1.31 and on phase three of 1.17. This day was a sunny Wednesday without any irradiance fluctuations. Due to this awareness of the flicker Figure 14 displays the daily irradiation profiles of eight days in 2012 with no fluctuations in the irradiation. All these days are almost perfect clear sky days. The maximum irradiation depends on the day of the year.

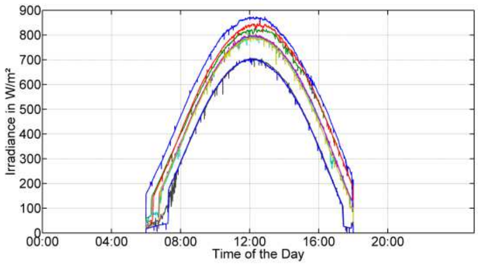

Figure 14: *Daily irradiation profiles of eight days in 2012 without any irradiance fluctuations.*

The inherent flicker values of these eight clear sky days are displayed in Figure 15. The comparison of Figure 15 with Figure 3 shows no differences in the maximum flicker level. There are higher flicker values during day time because of the human daily life. All flickers on these days have to be generated by loads.

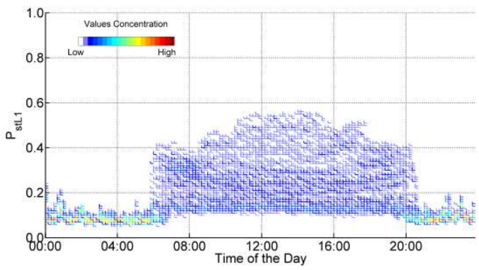

Figure 15: *Visualization of the short term flicker in dependency on the time of the day on days without any irradiance fluctuations. Again higher flicker levels can be seen during daytime.*

4 SUMMARY AND CONCLUSION

In this article the influence of PV systems on the flicker level in an area with a high PV penetration is analysed. Therefore measurement data from around 560 smart meters for two years are available. The survey is done for various low voltage grids with different supply structures.

The evaluation delivered the following results: The permissible value for power quality of the long term flicker ($P_{lt} \leq 0.5$) is not always respected. There are 0.20 % of the values that exceed the limit. Nevertheless these values are very rare.

Different approaches to determine the effects of the PV feed in on the flicker level and to isolate the effects of the load on the flicker level were taken into account. The evaluation of the short term flicker (P_{st}) in dependency on the relative grid voltage shows slightly above average flicker values at voltages higher than 100 % of the nominal grid voltage. These values can be caused by PV systems on days with a fluctuating cloudiness but also by loads at clear sky days with a high PV feed in. The investigation of the short term flicker in dependency on the time of the day and the day of the year leads to no knowledge of the influence of PV systems. By calculating the correlation between flicker value and global irradiation or clear sky index, no influence is obvious. The loads do have a more significant influence on the flicker. Only the investigation of a long feeder with a big PV system on Sundays (load is marginal) reveals a slight dependency of the flicker on PV systems. The evaluation of the flicker level on days with a thick cloud cover and on clear sky days show as high flicker levels as days with a fluctuating cloudiness. These values can be completely attributed to loads.

In conclusion it can be stated that no higher flicker levels are caused by PV systems. The determining factor remains still the load. This statement is only applicable under the current planning conditions. If these conditions change, for example the maximum voltage hub in low voltage grids of 3 % [VDE-4105], these statements lose their validity. If the PV penetration reaches higher values in the future this study has to be implemented again to investigate the influence of these new high penetrations on the flicker level. Nevertheless, there are no high deviations in the flicker level expected.

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