HOW MUCH PHOTOVOLTAIC CAPACITY CAN HANDLE DISTRIBUTION GRIDS WITH REGARD TO THE LONG TERM FLICKER?

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ABSTRACT

The purpose of this article is the identification of the maximum installable photovoltaic power with respect to the power quality criterion long term flicker. Based on today´s maximum photovoltaic penetrations a validated model with variations of photovoltaic power gradients and grid parameters is rendered. It is shown that in compliance with electrical and thermal operational limit values no violations of the long term flicker limits occur.

INTRODUCTION

The generated power of photovoltaic (PV) systems represents a rising part of the electrical energy supply in Germany. In summer 2014 more than 36.7 GW are installed [1] most of them in the low voltage level. In comparison to big, centralized coal and nuclear power systems, PV systems are a decentralized electrical energy source. Additionally, the feed-in is carried out via inverters instead of synchronous generators. Therefore, a large number of power electronic devices have to be integrated in the existing grid infrastructure. This leads to new challenges to guarantee the required power quality. The fast built-up of PV systems leads to unknown grid conditions, especially in the low voltage network.

One essential parameter of the power quality is the long term flicker P_{lt} (lt = long term). For ensuring a secure and reliable grid operation the long term flickers have to stay within specified limit values. These values depend on the voltage level and are standardized in DIN EN 50160 [2], VDE-AR-N-4105 [3] and BDEW-MV [4]. DIN EN 50160 defines voltage characteristics of electricity supplied by public distribution networks. VDE-AR-N 4105 and BDEW-MV define the technical requirements for the connection of generators with the low-voltage (VDE-AR-N 4105) and medium-voltage (BDEW-MV) grid.

The gradient of the global irradiation on days with a fluctuating cloudiness is very high. Also the feed-in power of PV systems is strongly volatile and has therefore an intense influence on the grid voltage and potentially on the flicker level.

This article introduces a simulation model for the determination of the long term flicker in dependency of the global irradiation, ambient temperature, PV system power and the grid parameters at the point of common coupling. The model is validated based on measurement values. With the help of this model the long term flickers evoked by PV systems for arbitrary grid structures and sizes, changes in the global irradiation and PV penetrations are simulated and limit values for the installation of PV systems with regard to the long term flicker are identified. Consequently, it is possible to claim if there is a limitation of the PV built-up concerning this power quality parameter.

BASICS OF THE SIMULATION

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 [5]) that is based on a reproduction of a 60 W incandescent lamp, the sensitivity of the human eye and the corresponding brain reaction. The normative value of the short term flicker P_{st} (st = short term) is standardized for voltage fluctuations that lead to disturbing perceptions caused by variations in the luminance by more than 50% of the test persons.
This normative value is defined as $P_{st} = 1$ [6].

There are two types of flicker [7]. The short term flicker that refers to a time interval of ten minutes is decisive for product standardization. The long term flicker that refers to a time interval of two hours is decisive for power quality. The long term flicker can be calculated from twelve consecutive short term flickers via Equation (1).

$$P_{lt} = \sqrt[3]{\frac{\sum_{i=1}^{12} P_{st}^3}{12}} \tag{1}$$

Essential for the warranty of the power quality is the long term flicker. The normative value in low voltage grids, produced from the totality of all feeders, is according to VDE-AR-N 4105 [3] $P_{lt} = 0.5$. According to DIN EN 50160 [2] should the long term flicker stay within $P_{lt} \leq 1$ in 95% of a random week interval. The evoked flickers of PV systems will be compared with these normative values. The comparison with VDE-AR-N 4105 shows the maximum installable PV power without prohibited interference emissions. The comparison with the DIN EN 50160 is done on the theoretical supposition that only the PV systems (and no loads and other generators) do have an influence on the voltage characteristics.

Relevant for the short term flicker is the voltage variation $(\frac{\Delta U_{max}}{U})$ in %, the shape of these variations, that is described by the form factor F, the repetition rate r of the relative voltage changes and the inherent frequency factor R [6]. The coherence shows Equation (2).

$$P_{st} = 0{,}365 * R * F * \left(\frac{r}{min^{-1}}\right)^{0{,}31} * |(\frac{\Delta U_{max}}{U})/\%| \qquad (2)$$

There are models to predict the feed-in power of PV systems based on measured global irradiation I and ambient temperature T_A [8]. The efficiency η in the maximum power point (MPP) depends on the global irradiation and the module temperature. The efficiency at STC (Standard Test Conditions - $I_{Global} = 1000W/m^2$, $T_{Module} = 25°C,\ AirMass = 1.5$) temperature can be calculated with the assistance of the model parameters a1, a2 und a3 [9] according to Equation (3).

$$\eta_{MPP}(I, 25°C) = a_1 + a_2 * I/\frac{W}{m^2} + a_3 * \ln(I/\frac{W}{m^2}). \qquad (3)$$

During times of an irradiation of 1000 W/m² and module temperature of 25 °C the STC efficiency η_{STC} is reached. Normally these high irradiations lead to higher module temperatures up to 70 °C. Crystalline modules exhibit a reduction of their efficiency of 0.5 %/°C. This leads to losses up to 20% compared to STC conditions. The temperature rise of PV systems is described by the parameter γ. Typical values are in the range of $\gamma = 0.020°C\frac{m^2}{W}$ for back-ventilated ground-mounted systems and $\gamma = 0.056°C\frac{m^2}{W}$ for roof-mounted applications. The module temperature T_M can be calculated with the help of the ambient temperature and Equation (4).

$$T_M = T_A + \gamma * I \qquad (4)$$

The efficiency of the PV modules can be calculated based on the current irradiation, the module temperature and the temperature coefficient α of the module material ($\alpha = -0{,}0035/°C$ for monocrystalline silicon) according to Equation (5).

$$\eta_{MPP}(I, T_M) = \eta_{MPP}(I, 25°C) * (1 + \alpha(T_M - 25°C)) \qquad (5)$$

The efficiency based AC power of a PV system is composed of the DC power and the efficiency of the inverter η_{Inv} according to Equation (6). The term $P_{r,PV}$ represents the rated power of the simulated PV system.

$$P_{AC}(t) = P_{DC}(t) * \eta_{Inv} = = \eta_{MPP}(I, T_M, t) * \frac{I(t)}{1000\frac{W}{m^2}} * P_{r,PV} * \eta_{Inv} \qquad (6)$$

The feed-in power is a time-varying variable because the irradiation and module temperature depend on the time. The maximum feed-in power on a clear sky day is lower than 80% of the rated power due to the influence of the module temperature on the efficiency. Maximum feed-in power higher than 80% of the rated power can be reached on days with a fluctuating cloudiness and therefor due to a cooling effect of the cloud shadows, irradiance enhancements and forward scattering [10][11]. The results of the PV power simulation show these coherences.

The voltage on arbitrary grid nodes can be simulated by load flow programs. For this work the software PSS®SINCAL is used. The input parameter is the simulated PV power. Finally, the long term flicker is simulated out of these voltages with an algorithm based on Equation (1) and (2).

SIMULATION OF THE LONG TERM FLICKER

Previous investigations of measurement data in areas with an over-average PV penetration of up to 10 kW/HC (HC = house connection) deliver that the load-occasioned flickers exceed the PV-occasioned flickers [12]. Based on these evaluations, a theoretical estimation of the flicker potential of PV systems in low voltage grids should be carried out. Irradiation and temperature profiles are the input parameters of the PV power simulation according to the Equations (3) to (6). The power profiles are on the other hand the input parameters of the network simulation that calculates the voltage profile on arbitrary grid nodes. No deferment of the PV power for several distributed systems in a low voltage grid takes place. This can be expected in reality because of the movement of the clouds. For a worst case simulation simultaneity of one is assumed. The validity of this approach will be shown below. After all, the calculation of the flicker level according to Equation (1) and (2) is carried out. The results of the model are the short and long term flickers evoked by PV systems.

The algorithm for calculating the PV power and short and long term flickers are implemented and validated based on measurement data. Figure 1 shows the relative error of the simulation. The deviations are in % and normalized to the normative value of 0.5. These deviations are only valid for days with a strong fluctuating cloudiness. This irradiation profiles are the worst case scenarios for the flicker level. The evoked deviation for clear sky days and days with a strong cloud cover are significantly lower.

A maximum error of 12% on the safe side arose. Also the median of 2.5% is on the safe side. This means the simulated flicker are more often overestimated than underestimated. This was carried out by the help of an exponential correction function. Nevertheless there are also simulated flicker values that are below the measured ones. The maximum deviations on the insecure side are in the range of 7%. This corresponds to an absolute value of 0.035.

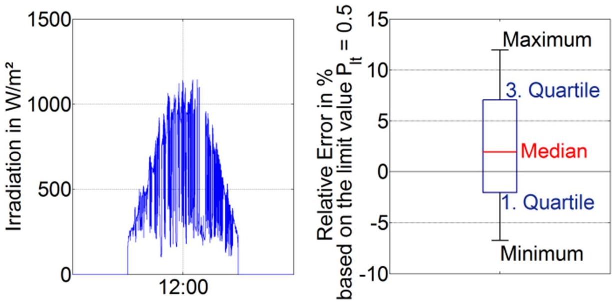

Figure 1: Validation of the flicker simulation model for days with a fluctuating irradiation. The maximum (12%) and also the median (2.5%) deviations are on the safe side.

The most critical two hour irradiation time interval with the highest gradients is chosen out of irradiation data sets of two years. The irradiation and ambient temperature was measured in Lower Bavaria with a resolution of one second. This two hour interval is used for the worst case simulation of the long term flicker in dependency of the number of installed PV systems (penetration), the length of the cables and therefore the R and X of the grid and the PV system power.

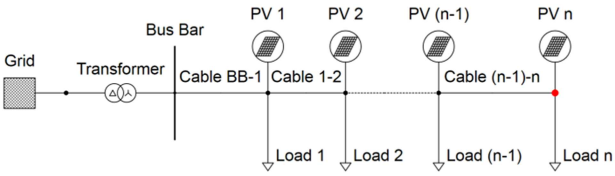

Figure 2: Low voltage feeder with high PV penetration. The long term flicker is calculated on the red grid node with the lowest short circuit power.

An exemplary grid configuration for the calculation of the flickers shows Figure 2. The number n of installed PV systems is $n = 20$ for the presented, exemplary grid. The penetration is 100%. This means a PV system is installed on every house connection node. The PV system power varies between 5 kW and 50 kW. The inclination of the systems is consistently 0°. Hence, deviations from the optimal orientation but also system losses due to mismatch, wiring losses and soiling and the damping of the gradients due to cloud-drift are neglected. The length of the cable between each PV system varies between 20 m and 200 m. The cables are of the type NAYY 4x150mm² with a $R' = 0{,}206\ \frac{\Omega}{\text{km}}$ and $X' = 0{,}091\ \frac{\Omega}{\text{km}}$. Capacitive line coverings are neglected for low voltage cables. The installed transformer has a rated apparent power of 1 MVA and a relative short circuit voltage of 5%. All loads are assumed as constant. So there is no influence of the loads on the flicker level. The absolute height of the grid voltage has no influence on the flicker level. The long term flicker is simulated on the red grid node. This is the node with the lowest short circuit power. Consequently, the influence of the PV feed-in on the grid voltage is conspicuous.

Figure 3 and Figure 4 depict the results of the flicker simulation algorithm. Additionally the normative values of the VDE-AR-N 4105 [3] and DIN EN 50160 [2] are visualized.

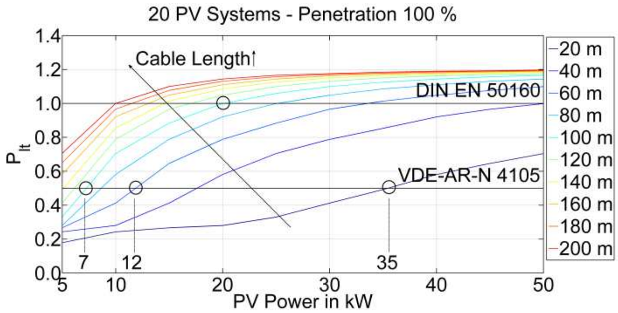

Figure 3: Simulated long term flickers for various cable lengths and PV system sizes.

Typical cable lengths of villages and small towns are in the range below 60 m (upper part of Figure 5). For a feeder with 20 installed PV systems it is possible to integrate 12 kW/HC of PV power without a violation of the VDE-AR-N 4105. This is equal to a total power of 240 kW. The resulting voltage rise at the end of cable reaches 13% according to Figure 6. This is much higher than the normative value of the VDE-AR-N 4105 and even higher than the limit value of the DIN EN 50160. The resulting current from the first PV system to the bus bar is equal to 128% of the cable thermal limit current of $I_{th} = 275$ A - Figure 7.

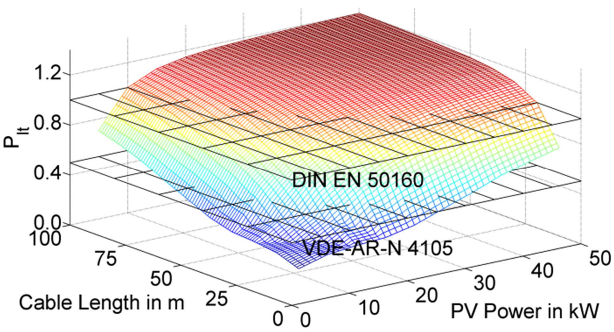

Figure 4: Simulated long term flickers for various cable lengths and PV system sizes in a 3D view.

In suburban low voltage grids the cable lengths are in the range of 20 m. In such a grid with 20 systems an installed PV capacity of 35 kW/HC fulfils the long term flicker limit value of the VDE-AR-N 4105. The total installed power sums up to 700 kW. The utilization rate of the cables is 374%. This means four cables are used to guarantee the thermal limits. The limit value of the relative voltage hub is also exceeded.

In rural grids cable lengths up to 100 m are common. For those grids a built-up of 7 kW/HC is permitted. The total power of 140 kW does not exceed the thermal limit but the correlated voltage rise is much higher than the normative limit values. This is avoided in the grid planning process. Consequently, grid enforcement will take place before such a constellation can arise. Furthermore it is substantially over-average to install 20 systems on one rural feeder. A statistic of the PV system size and number of installed PV systems per transformer in an area with an over-average high PV penetration show the middle and lower part of Figure 5.

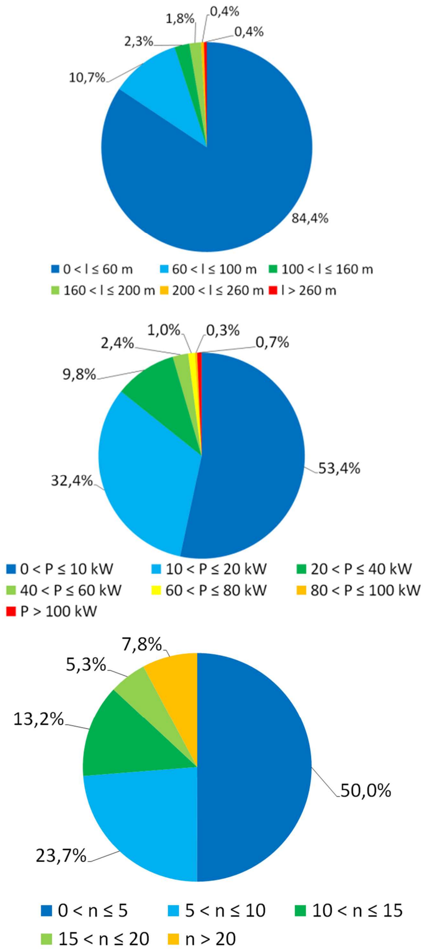

Figure 5: Statistic of the cable lengths, PV system power and PV penetration for the low voltage grids of a comprehensive research project that is called "Grid of the Future" [13].

By applying the normative value of DIN EN 50160, an even higher PV capacity with regard to the long term flicker is possible. 85% of the installed PV systems are in the power range below 20 kW. 95% of the low voltage cables are shorter than 100 m. Therefore an integration of 20 kW/HC fulfils the guide line. The total power (400 kW) exceeds again the electrical voltage and thermal cable current boundaries.

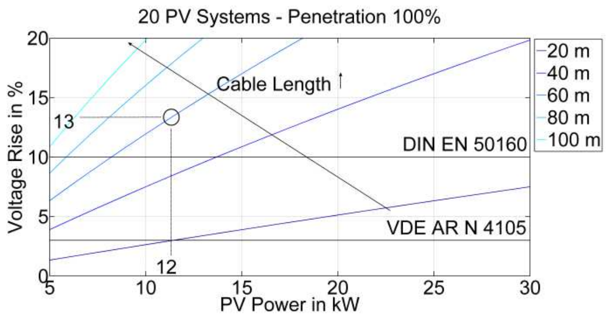

Figure 6: Resulting voltage rise on the red grid node of Figure 2. The rise for an installed PV power of 12 kW/HC exceeds the normative values.

In urban grids with short cables in the range of 20 m a PV system capacity of 100 kW/HC is permissible. The total power of 2000 kW does not only exceed the voltage range and thermal current boundaries of the cables but also the utilization rate of the transformer. The 1 MVA-transformer is working at 200% capacity. This means new cables and a bigger transformer have to be installed.

Even in rural grids with long cable lengths of 200 m a PV capacity of 10 kW/HC for 20 systems is permitted. The correlated voltage rise is extremely high.

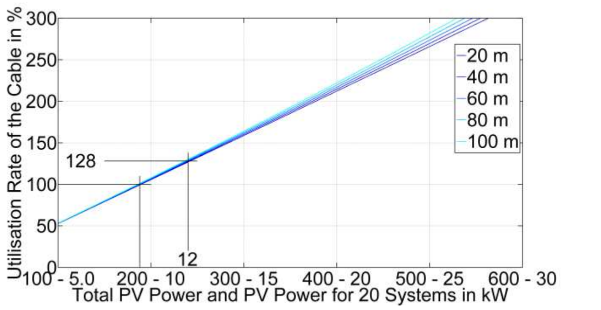

Figure 7: Resulting current over the cable from the first PV system to the bus bar according to Figure 2. The current for a PV power of 12 kW/HC exceeds the thermal limit.

In conclusion, it is permitted to claim that there is a huge PV built-up potential regarding the compliance of the power quality parameter long term flicker.

There are no limit value violations of the long term flicker for cable lengths below 60 m (probability 84.4%), PV powers below 10 kW (probability 53.4%) and a PV penetration ≤ 20 systems per low voltage local network area (probability 92.2%). There are also no limit value violations of the long term flicker for cable lengths below 60 m (probability 84.4%), PV powers below 20 kW (probability 85.8%) and a PV penetration ≤ 10 systems per low voltage local network area (probability 73.7%). These are typical constellations for the built-up of decentralized roof-mounted PV systems.

INFLUENCE OF THE ORIENTATION, SYSTEM LOSSES AND CLOUD-DRIFT

The optimal inclination of PV systems in Southern Germany is 30° with an azimuth angle of 0° (south). Typical system losses of PV systems are in the range of 9.5% [8]. These losses consist of module-inverter-mismatch, wiring losses and soiling of the PV modules. The cloud-drift velocity is in the range of 10m/s to 20m/s [14]. These three parameters do have an influence on the flicker simulation algorithm. The absolute difference between the evoked flicker levels compared to the 0° basic scenario depicts Figure 8.

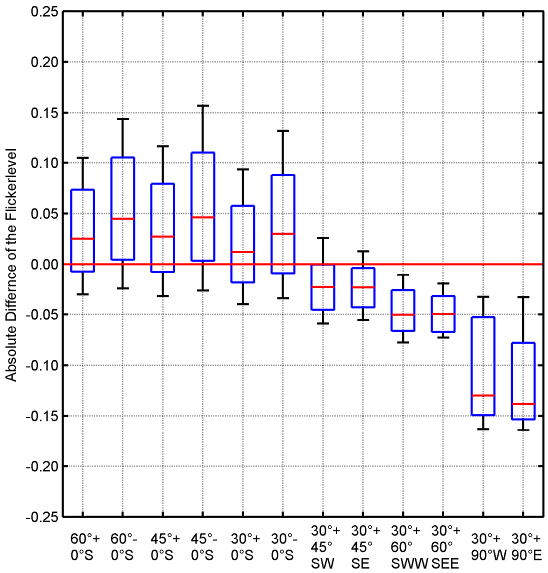

Figure 8: Resulting flickers for different inclination and azimuth angles. An additional cloud-drift of 10m/s is assumed.

The six boxplots on the left side of Figure 8 show the influence due to different inclination angles with (+) and without (-) system losses. If an additional deviation of the azimuth from 0° takes place (six boxplots on the right) the corresponding flickers are lower than the flickers of the 0° basic scenario despite the optimal inclination.

SUMMARY AND CONCLUSION

The simulation of the long term flicker shows clearly, that this power quality limit is not exceeded by compliance of the thermal current limits of the cables and transformers and normative voltage rises. If the thermal current limitations and voltage rises are within the normative limits the feed-in PV power gradients and repetition rates lead to long term flickers lower than 0.5.

The developed simulation model can be used for an arbitrary number of PV systems, PV penetrations and grid parameters (R', X', and l). It is therefore an effective method for the validation of the power quality concerning the long term flicker. Furthermore, it is a helpful tool for distribution grid operators for a reliable and efficient grid integration of PV systems.

In real grids there are load-occasioned and PV-occasioned flickers. The aggregate of all these flickers is the essential total-flicker. For today´s PV penetrations, these total-flickers can exceed the normative value and violate this power quality criterion. However, the analysis of the influence of this combined total-flicker was not the purpose of the considerations introduced in this article.

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