

# Voltage Fluctuations on Distribution Level Introduced by Photovoltaic Systems

Achim Woyte, Vu Van Thong, *Student Member, IEEE*, Ronnie Belmans, *Senior Member, IEEE*, and Johan Nijs, *Senior Member, IEEE*

**Abstract**—In moderate climates, short fluctuations in solar irradiance and their impact on the distribution grid will become an important issue with regard to the future large-scale application of embedded photovoltaic systems. Several related studies from the past are recalled. The approach that is presented here applies a localized spectral analysis to the solar irradiance and derived quantities in order to determine the power content of fluctuations, depending on their characteristic persistence. Pseudorandom time series of solar irradiance, based on measured values of the instantaneous clearness index, are applied as input data. Power-flow calculations are carried out in order to assess the impact of fluctuating solar irradiance on the grid voltage. The “fluctuation power index” is defined as a measure for the mean-square value of fluctuations of a specific persistence. A typical scenario is simulated, and the results are interpreted.

**Index Terms**—Dispersed storage and generation, Monte Carlo methods, random number generation, signal analysis, solar energy, solar radiation, wavelet transforms.

## I. INTRODUCTION

SOLAR irradiance in moderate climates is mostly characterized by short-time fluctuations. With high-connection densities of photovoltaics (PVs) in the distribution low-voltage grid, this can lead to unpredictable variations of node voltages and power, mainly in weak residential and rural grids. In small grids and micro-grids as they exist (e.g., on islands), such fluctuations could even cause instabilities in case of intermediate power shortages with insufficient storage.

### A. Problem Description

The severity of grid voltage and power flow fluctuations at the point of common coupling as a consequence of fluctuations in solar irradiance is difficult to determine. Currently, capacity limits for auto-producers, as they are specified in the respective grid connection guidelines, are usually based on worst-case assumptions as, for the most part, is the network planning of the

distribution system operator. If the effect of such irradiance fluctuations could be estimated more realistically, adequate measures, such as grid reinforcement or the installation of storage capacity, could be taken when necessary while too-cautious and cost-intensive measures would be avoided.

Power variations from different embedded generation resources differ regarding their impact on voltage profile and power. Since heat-driven micro-CHP and domestic fuel cells are weather dependent only on a seasonal down to diurnal basis and wind power today is mainly connected to medium or high voltage, studies with regard to short-term fluctuations on low voltage must focus especially on residential photovoltaic systems in the range of 1 to 50 kVA. The time-dependent generation of these systems is mainly determined by the solar irradiance and its variation.

### B. Preceding Studies

Regarding the availability of PV-generated power over very large areas, studies have been carried out in Japan and Germany with the time resolution being  $1 \text{ h}^{-1}$  and  $0.2 \text{ min}^{-1}$ , respectively [1], [2]. Conclusions toward spatially limited low-voltage grids are difficult to be drawn from these studies due to the large size of the area under examination.

Two studies that focus on the situation in smaller distribution grids are described in [3]–[7]. These studies look at medium-voltage distribution grids with spatial extensions of 10 and  $0.2 \text{ km}^2$ , respectively. Corresponding to the situation in the U.S. where very small groups of consumers are supplied from medium voltage by pole-mounted transformers, voltage fluctuations on long distribution lines are not an issue in these studies. They mainly focus on fluctuations in power and their impact on economic dispatch. The installation of storage capacity is not taken into account. Time resolution in these studies is  $1 \text{ min}^{-1}$ .

The models applied in the aforementioned studies [3]–[7] are based on the modeling of clouds moving over the area under examination. They apply predefined values for wind speed and wind direction for the given site and a given network topology. Conclusions on the statistical frequency and persistence of fluctuations in irradiance and power flow have not been drawn. In order to allow general conclusions on the influence of such fluctuations on low-voltage power flow and its variation in time, a more generic model is needed.

In [8], the contours of clouds in inhomogeneous skies are modeled as fractals, taking into account the irregular shape and spatial distribution of clouds. With this approach, the fractal dimension is a measure for the cloud-induced variability of solar radiation. Synthetic cloud patterns derived from [8] formed the

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A. Woyte is with 3E sa, Bruxelles 1000, Belgium (e-mail: Achim.Woyte@3E.be).

V. V. Thong and R. Belmans are with the Department of Electrical Engineering, Katholieke Universiteit Leuven, Leuven 3001, Belgium.

J. Nijs is with Photovoltech sa, Tienen 3300, Belgium.

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input for in-depth studies of the grid voltage behavior in distribution grids with high PV connection density [9]. According to [9], in typical European distribution networks, PV-induced voltage fluctuations are generally not an issue. However, in weak grids or micro-grids, the situation has to be examined depending on the particular case.

A set of specifications for the description of fluctuations has been proposed in [10]. Based on high-resolution measurements of PV output, fluctuations in power are described by three parameters: magnitude, duration of a transition between clear and cloudy, and speed of the transition, defined as the ratio of magnitude and duration. Based on these definitions, cumulative frequency distributions of these parameters can be determined from measured data. The sampling period in this study is 1.2 s.

A statistical approach is applied in [11]. There, irradiance data are described by their fluctuation factor which is the root mean square (RMS) value of the highpass-filtered time series of solar irradiance. The fluctuation factor of a superposition of irradiance time series from spatially distributed locations has been determined for an area of  $4 \times 4$ -km size. Further conclusions on the statistics of power and voltage profile in the grid apparently have not yet been published by these authors.

An approach that can combine advantages from [8], [10], and [11] is the analysis of short fluctuations in solar irradiance and derived signals such as node voltage, by means of a wavelet-based localized spectral analysis [12]–[14]. On the one hand, the wavelet approach allows splitting the fluctuating signal according to significant time scales of the fluctuation, similar to the highpass filtering in [11]. On the other hand, similar to fractal cloud patterns [8], the approach allows analysis of all scales of fluctuation from very short variations as they appear close to the edge of a cloud up to long fluctuations between clouds. Finally, unlike the parameters as they are defined in [10], the wavelet approach is based on a thorough mathematical base [15], [16].

## II. MODELING APPROACH

In this study, a simulation tool is provided for estimating the impact of meteorologically induced irradiance fluctuations on distribution networks with PV power generation. The flow of the calculation is sketched in Fig. 1. The different sections in the flowchart are described in the following subsections.

### A. Meteorological Sample Data

As a sample input, global solar irradiance has been recorded during one year by means of a silicon reference cell with  $0.2 \text{ s}^{-1}$  time resolution. The sensor is situated 30 m above sea level at  $4.7^\circ$  eastern longitude and  $50.9^\circ$  northern latitude in a moderate maritime climate. Its tilt angle is  $30^\circ$ , which is close to optimum for a grid-connected PV array under the given climate.

From these irradiance data, time series of the instantaneous clearness index  $k_T$  has been computed for  $2^{12} = 4096$  time steps around solar noon ( $\approx 6$  h) on 362 sample days. The instantaneous clearness index is defined as solar irradiance normalized on extraterrestrial irradiance. It is a measure for the transparency of the atmosphere, independent from any astronomically induced seasonal or daytime variations. As a good approx-

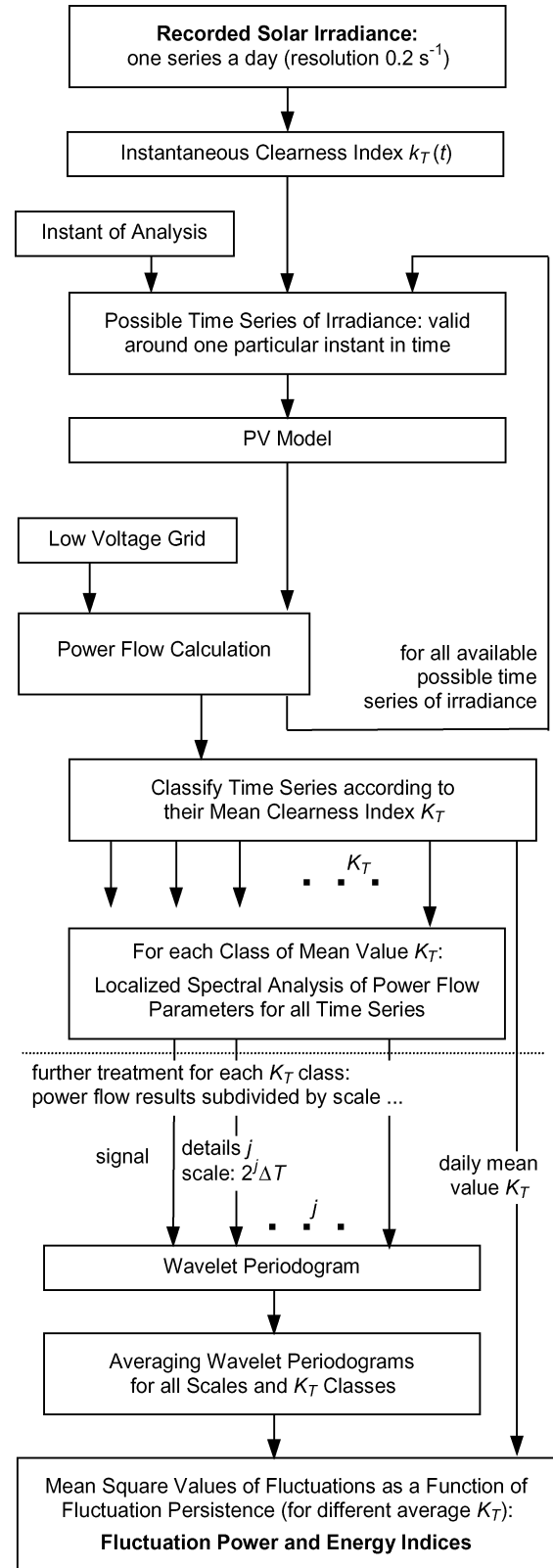


Fig. 1. Flowchart of the calculation process.

imation, the statistic frequency distribution of the instantaneous clearness index  $k_T$  during a period of time depends solely on the mean clearness index  $K_T$  and, thus, the average cloud coverage during that period [17], [18].

Since the short-time behavior of solar irradiance around a certain instant in time is mainly determined by the cloud movement, it can be interpreted as a stochastic process. Possible realizations of this stochastic process under a given characteristic cloud coverage can be obtained by multiplying any measured time series of  $k_T$  for a given mean value  $K_T$  by the extraterrestrial irradiance at the desired instant in time.

This way, the measured time series of the instantaneous clearness index from one year or longer serves as pseudorandom input data, for a kind of Monte Carlo simulation. Multiplied by extraterrestrial irradiance on a specific time and day, they may be applied as short-term irradiance patterns at that time and day with their frequency distribution and sequence characteristic for a specific  $K_T$ .

### B. Photovoltaic System Model

The PV system is simulated as a generic crystalline silicon PV array connected to an inverter with an ideal maximum power point (MPP) tracker. The PV array is represented by a simplified model for its efficiency at MPP as a function of solar irradiance and PV cell temperature [19]. The PV cell temperature is assumed to be linearly dependent on solar irradiance while neglecting thermal inertia and assuming a fix ambient temperature at the considered instant in time.

The inverter is represented by its conversion efficiency as a function of power for a generic state-of-the-art device. It is assumed to have a dc rating equal to PV peak power at standard test conditions (STCs) with a conversion efficiency at a rated power of 0.9. When the available PV power is higher than the inverter's dc rating, the inverter must limit the power in order to prevent overload.

While the active front end of a PV inverter for grid connection usually works at unity power factor, reactive power is supplied to the grid by the inverter's grid filter. For the present study, the reactive power is modeled by a constant component due to the filter's capacitance plus a linear component proportional to active power, hence

$$q_{AC} = d_0 + d_1 p_{AC} \quad (1)$$

where  $q_{AC}$  and  $p_{AC}$  are normalized reactive and active output power of the inverter, respectively. From power factor measurements on existing PV inverters, the polynomial coefficients in (1) have been determined to  $(d_0, d_1) = (7.2 \cdot 10^{-2}, 3.4 \cdot 10^{-2})$ .

It is also possible to vary reactive power of a PV inverter in order to stabilize the grid; however, in most countries today, such control schemes are not permitted for inverters connected to the public mains. In the present example of a distribution grid with high series resistance, the impact of reactive power on the voltage profile is virtually negligible. However, in inductive grids, locally injected reactive power has a significant influence and may be applied by purpose in order to mitigate fluctuations from PV [20].

This way, the PV model transforms the time series of short-time irradiance around a given instant in time and ambient temperature at that time into possible realizations of short-time active and reactive power of a PV system of a given rating.

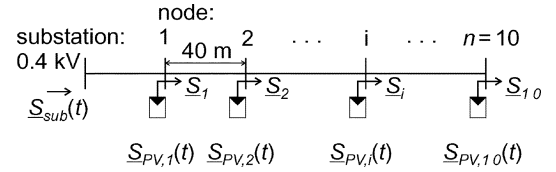


Fig. 2. Simulated distribution feeder with ten equally distributed consumer loads and PV supplies; cable 50 mm<sup>2</sup> with  $X' = 86 \cdot 10^{-6} \Omega/\text{m}$ ,  $r/x = 4.5$ , loads  $\underline{S}_i = 0.6 \text{ kW} + j0.3 \text{ kvar}$ , PV inverter rated power  $\underline{S}_{PV,r} = 9 \text{ kW} + j1.03 \text{ kvar}$ , substation voltage 1.0 p.u.

### C. Power-Flow Calculation

The simulation tool can be applied to all types of power distribution networks. As an example, here a three-phase low-voltage distribution feeder is assessed. The configuration shown in Fig. 2 is typical for a residential distribution system in Belgium. The nodes 1 to 10 represent switchgear cabins where usually one residential house is connected per phase. For the power-flow calculation, the voltage drop method has been applied [21].

In order to isolate the influence of irradiance fluctuations from short-time load fluctuations at individual nodes, the loads are assumed to be constant. By applying the derived time series of active and reactive PV output power around one instant in time, the fluctuation of the grid parameters introduced by PV can be assessed for representative moments of the year. Representative scenarios are, for example, minimum and maximum load during daytime as they are characteristic for the different seasons of the year.

In the present example, load and PV power have been assumed to be equally distributed over all nodes. The assumed 10-kW-installed PV peak power per three houses is realistic for future high-density PV scenarios like, for example, a residential building area with all houses equipped with PV. The load of 0.6 kW per three houses corresponds with a low-load period on a summer afternoon when the residential load is considerably low while PV power may peak. This low-load scenario is typical for Central and Western Europe where the load is generally low in summer and high in winter. While, even in summer only, little air conditioning is applied, the load typically peaks in winter due to the increased demand for lighting and heating. With different climatic conditions and load profiles, comparable scenarios of low load and high PV generation may occur during other seasons, for example, on a mild autumn afternoon or a cold winter morning.

It is assumed that for such a high-density embedded-generation network, the substation voltage is adjusted to 1.0 p.u., anticipating increased voltages as a consequence of reverse power flow.

### D. Localized Spectral Analysis of Time Series

A mathematically consistent approach is needed for the description of fluctuations and their persistence in time. The fluctuation factor, as it is introduced in [11], is a good measure for the power content of fast fluctuating signals but it provides no information on their persistence.

Inter-hourly fluctuations induced by passing clouds occur randomly distributed in time and their shape is rather bimodal

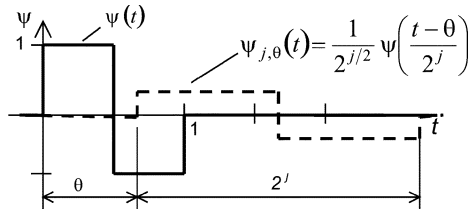


Fig. 3. Haar wavelet  $\psi(t)$  and scaled and shifted wavelet  $\psi_{j,\theta}(t)$ .

than sinusoidal [6], [18], [22]. This is why stochastic methods for harmonic spectral analysis have been found to be not suitable for analyzing these types of fluctuations.

Frequency-domain properties of the recorded fluctuation patterns can still be derived by applying a wavelet transform. In analogy to the Fourier transform, the wavelet transform of a function is defined by the inner product of this function and a set of orthonormal basis functions. However, unlike for Fourier decomposition, the basis functions for wavelet decomposition are localized in time, and they are not necessarily sinusoidal [15]. In the present case, a time-invariant, so-called “stationary” wavelet transform [23] is applied.

The approach is well suited for the analysis of cloud-induced irradiance fluctuations and all derived quantities including the possibly fluctuating voltages and power flows in a distribution grid as a consequence of fluctuating PV generation.

The stationary wavelet transform  $W$  of a signal  $x(t)$  is calculated as the inner product of  $x(t)$  and the scaled and shifted wavelet base  $\psi_{j,\theta}(t)$

$$W_{2^j}^\theta(x(t)) = \int_{-\infty}^{\infty} x(t) \frac{1}{2^{j/2}} \psi^* \left( \frac{t-\theta}{2^j} \right) dt \quad (2)$$

with  $j \in \mathbf{Z}$ ,  $\theta$ , and  $t \in \mathbf{R}$ .

Due to its similarity with the bimodal steps in clearness index and its orthogonality, the Haar wavelet has been chosen as a basis function for analysis of the time series of the clearness index and derived quantities. The Haar wavelet is a simple function that is scaled by the factor  $2^j$  and shifted along the  $t$ -axis by  $\theta$  (Fig. 3).

Based on the stationary wavelet transform, wavelet periodograms, as proposed by [24]–[26], are calculated from the time series of the node voltages. As an estimator for the wavelet periodogram,  $I$  is obtained in analogy with the Fourier periodogram by calculating the square of the coefficients of the stationary wavelet transform

$$I_{2^j}^\theta = |W_{2^j}^\theta|^2. \quad (3)$$

The wavelet periodogram is a measure for the power content of a signal for all dyadic time scales as defined by  $j$ , and it is variable in time with the time shift  $\theta$ . Fig. 4 shows a typical 2-h node voltage signal and its wavelet periodogram for a number of significant scales. Fluctuations of the node voltage (upper graph) correspond to local maxima on the time scale that corresponds to the length of the particular fluctuation.

For example, the voltage dip of approximately 200-s persistence, occurring around  $\theta = 1.9$  h, causes a maximum on the scale with  $j = 6$  as well as some side effects on the neighboring scales. Conversely, the much shorter voltage dip shortly

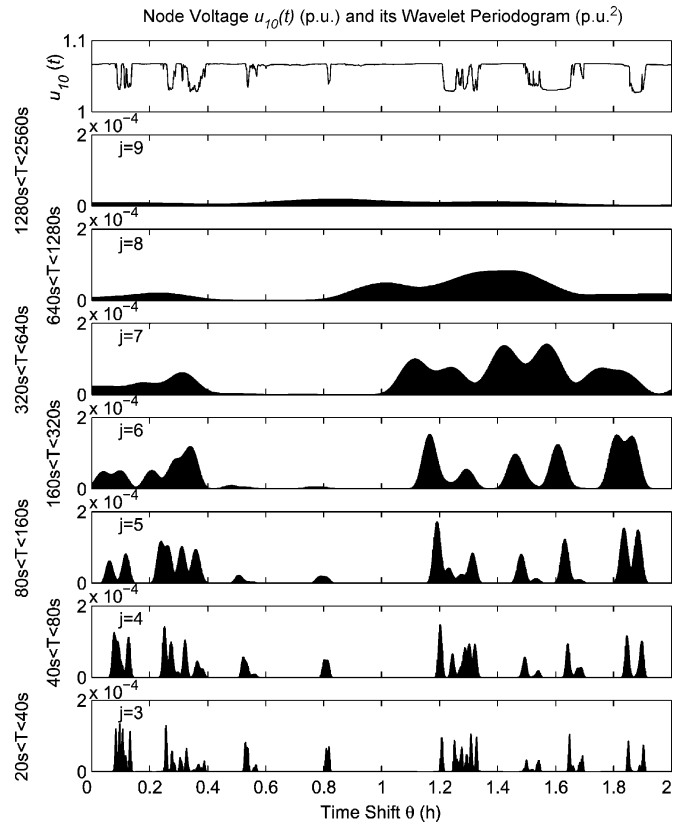


Fig. 4. Wavelet periodogram of a 2-h time series of the node voltage at node 10. The sum over all wavelet scales  $j$  equals the power content of the node voltage signal  $u_{10}(t)$  (orthonormality);  $K_T = 0.73$ , wavelet: Haar,  $\Delta T = 5$  s, decomposition with  $j = 1$  up to 12 with only  $j = 3$  up to 9 shown.

after  $\theta = 0.8$  h mainly affects the scales with  $j = 3$  and 4. According to Parseval’s theorem, the sum over all time-integrated scales  $j$  of the periodogram  $I$  equals the square of the analyzed voltage signal.

To newcomers in signal processing, the localized spectral analysis may seem like a relatively complex tool. However, the algorithms for the stationary wavelet transform are publicly available as software libraries and, therefore, the analysis can be implemented with little effort also by a power system engineer. After an initial learning period, running such an analysis that has once been implemented is not significantly more complex than other established tools such as, for example, harmonic analyses or reliability calculations.

### E. Fluctuation Indices

The wavelet decomposition leads to wavelet periodograms of node voltages or other grid parameters for a high number of time series. Each periodogram represents one possible fluctuating sequence as it is introduced by a corresponding possible sequence of solar irradiance around the regarded instant in time. In order to extrapolate the occurrence and magnitude of fluctuations of different characteristic persistence, mean values are calculated from all available realizations of the stochastic process.

The mean value of all wavelet periodograms for a high number of sample days on each time scale  $j$  will be referred to as the “fluctuation power index” ( $c_{f_p}$ ). The fluctuation power index represents the mean square value, or average power

in mathematical terms, of all fluctuations in the respective signal on the particular time scale. For node voltage,  $cf_p$  also physically corresponds to power, indicating the average variations in the demand of a hypothetical parallel linear load as a consequence of voltage fluctuations of a given persistence.

The product of the fluctuation power index for each time scale times half the respective time scale will be referred to as the “fluctuation energy index” ( $cf_e$ ). For a specified time scale with  $j$ , this relationship reads

$$cf_{e,j} = 2^{j-1} \Delta T cf_{p,j}. \quad (4)$$

Again applied to the node voltage,  $cf_e$  is a measure for the energy that is typically bound and freed again during a voltage variation of the persistence  $T_j$  with

$$T_j = 2^{j-1} \Delta T. \quad (5)$$

Therefore, fluctuation power index and fluctuation energy index can serve as the assessment of the persistence and severity of voltage fluctuations induced by densely connected PV generation. Moreover, when introducing storage devices, these indices also form a measure for the necessary storage capacity for different significant characteristic bridging times.

### III. SIMULATION RESULTS

Wavelet periodograms and the fluctuation power index have been calculated from 5-s average irradiance data measured during one year in Leuven, Belgium. The analysis following Fig. 1 was carried out for a summer day in the early afternoon with low load as specified in the previous section. The characteristic time series of solar irradiance input as they could occur around solar noon in summer are derived from rescaling the time series of the clearness index by the extraterrestrial irradiance on the  $30^\circ$  tilted plane at solar noon on the summer solstice (i.e., local time 13:42 h on June 21).

#### A. Irradiance and Voltage Fluctuations

The exemplary periodogram in Fig. 4 shows a possible variation of the voltage at node 10 under a slightly clouded summer sky. When no clouds cover the sun, the PV generation is limited by the inverter’s rated power. The node voltage during these periods is flat. At times when clouds cover the sun, the solar irradiance can quickly drop down to 30% of its previous value, causing sudden variations in node voltage in the range of 0.03 to 0.04 p.u. The generally high voltage values of 1.03 to 1.07 p.u. at the end of the feeder with the substation voltage set to 1 p.u. are characteristic for the low load of 0.2 kW per house that was assumed. On an afternoon with slight cloud cover, in a residential neighborhood with high PV density, the node voltage may behave like this.

These voltage variations are still within the limits of international grid voltage standards like IEC 60038 [27]. However, in practice, these variations add up to the voltage variations already present without distributed generation. This is why national or regional network operators’ guidelines for the grid connection of distributed generation level often introduce additional limits for the voltage increase due to distributed generation only. For instance, the respective guidelines of German

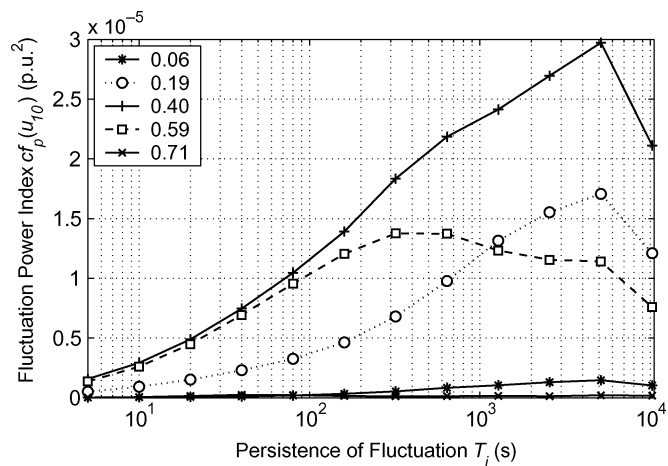


Fig. 5. Fluctuation power index  $cf_p$  of the node voltage  $v_{10}$  as a function of persistence  $T_j$  of the fluctuations ( $T_j = 5 \text{ s} \cdot 2^j$ ); different curves for different mean values of daily clearness index  $K_T$ .

power system operators [28] limit the permissible voltage increase on the low-voltage level due to distributed generation to 0.02 p.u. Hence, without grid reinforcement or additional measures for voltage control, the presented scenario would not be permitted in Germany.

In a period with more scattered clouds ( $K_T = 0.2 - 0.6$ ), the voltage would fluctuate more often and persist shorter periods in the “up state”; however, the amplitude of the voltage fluctuations at this node would remain the same.

With higher load demand, as might occur in a residential grid around noon during weekends, the voltage also becomes lower than 1 p.u., however, with the amplitude of the fluctuations unchanged. Aside from the installed PV peak power, the amplitude of the fluctuations mainly depends on astronomical parameters, such as the time of the day and season, reflecting the variable angle of incidence on a fixed PV array.

#### B. Fluctuation Indices of Node Voltage

Power-flow calculations based on pseudorandom time series of solar irradiance already allow for the assessment of node voltage and the amplitude of its fluctuations under typical meteorological and load scenarios. However, such case studies do not provide any information about the typical frequency of occurrence and persistence of voltage variations induced by PV. Therefore, average values of the fluctuating variables’ power content for a high number of sample cases are necessary.

Fig. 5 shows the  $cf_p$  values as a function of persistence  $T_j$  of fluctuation for different daily mean values  $K_T$  of the clearness index, specifying different classes of days with regard to cloudiness at that day.

For shorter persistence, the fluctuation power index is generally lower than for higher values. With a linearly increasing time scale  $j$ , the fluctuation index increases slightly faster than linearly up to a local maximum.

Clearly, for very low  $K_T$  (overcast sky) and very high  $K_T$  (slightly clouded to clear sky), the fluctuation power index is low. As expected, it takes maximum values for sky conditions with scattered clouds with  $K_T$  between 0.2 and 0.6. A slight local maximum is visible around a persistence between 300 to

700 s, indicating that this range of fluctuations is especially significant for network planning and storage of PV power. The local maxima that are visible at 5000 s indicate global changes of the weather conditions during several hours such as from a clear sky in the morning to cloudy in the afternoon. Obviously, these maxima have no significant meaning in regards to short-time fluctuations of the solar irradiance.

### C. Necessary Storage and Impact on the Network

For bridging fluctuations of several dozens of seconds up to an hour with a high frequency of occurrence, conventional batteries might be less suited since they cannot provide the necessary high number of charge cycles. From [29] and [30], which are two comparative studies of storage devices, it can be seen that only a few years ago, electrical and magnetic storage devices, such as supercapacitors and inductors (SMES), still had rather low bridging times with roughly up to 1 or 2 min. Today, supercapacitors can already bridge fluctuations of 30 min and more, and their capacity is rapidly increasing [14], [31]. Since the most significant fluctuations are situated between several minutes up to 1 h, they are one of the most interesting options for buffering power fluctuations introduced by PV.

Based on the same time series of the clearness index as above, supercapacitors for the mitigation of power fluctuations have been sized in [14] for a comparable scenario of high PV-connection density at a distribution feeder and in [32] for a stand-alone PV hybrid system. The necessary buffer capacity for mitigating fluctuations of up to 1-h persistence has been determined to 86 kJ/kW PV peak power for the distribution feeder and 257 kJ/kW PV peak power for the hybrid system. In case of the distribution feeder, the amplitude of voltage fluctuations shorter than 1 h is reduced from 9.9% to 6.4% of rated voltage. The costs for the necessary amount of supercapacitors in 2003 were around 1400 Euros (U.S.\$ 1700) per kilowatt PV peak power, which is 18% of the average system price of grid-connected PV in Belgium.

Other and often less expensive options for mitigating PV-induced voltage fluctuations in future distribution grids might be applying PV inverters that can inject variable reactive power or medium-to-low-voltage transformers with electronic tap changers.

The effect of reactive power injection on low voltage very much depends on the  $r/x$  ratio of the line, and it raises some questions with regard to protection from unintended islanding [33], [34]. Nevertheless, the application of embedded generation units for grid support has been discussed in the literature [20], [35], [36].

Medium-to-low-voltage transformers with electronic tap changers have the drawback of high investment costs which makes them unlikely to be installed in the near future in a free electricity market. Yet, the concept of electronic tap changers has already been studied and respective patents are pending [37].

## IV. CONCLUSIONS AND OUTLOOK

In low-voltage distribution grids with high penetration by PV, special attention needs to be paid to the voltage profile and the power flow on the lines. While long-term variations of PV generation may be handled by forecasting methods, especially short

fluctuations as they are introduced by moving clouds may lead to inadmissible voltage fluctuations at the endpoints of long distribution feeders.

The treatment of a measured time series of the instantaneous clearness index as pseudorandom data allows the distinction between stochastic fluctuations, induced by meteorological conditions, and deterministic variations, originating from astronomical circumstances. Through a combination of the stochastic model for the clearness index with a steady-state power-flow calculation, the impact of a fast fluctuating solar irradiance can be assessed around an arbitrary instant in time.

The tool of wavelet-based localized spectral analysis provides a solid mathematical basis for the analysis of fluctuations in solar irradiance and derived quantities. Due to the orthonormality of the applied wavelet basis, the wavelet periodogram of the stationary wavelet transform represents the total power content of a fluctuating signal that is decomposed per characteristic scale of persistence.

The fluctuation power index and fluctuation energy index have been defined as parameters for the assessment of stochastic fluctuations decomposed per scale of persistence. The fluctuation power index is a measure for the amplitude and frequency of occurrence of fluctuations of a specific persistence. The fluctuation energy index moreover permits conclusions on the capacity and bridging times of storage devices that would be necessary for mitigating voltage and power fluctuations introduced by photovoltaics.

Exemplary results have been calculated for a residential distribution feeder assuming low load on a summer afternoon. Results show that the frequency of occurrence of voltage fluctuations is highest for scattered cloud cover and lower for clear sky and overcast sky conditions. In the regarded sample case, the most significant fluctuations occurred under partly overcast sky conditions persisting 5 to 12 min; however, fluctuations may also be expected to persist only several seconds or more than 1 h.

Unless for fully overcast sky conditions, the amplitude of PV-induced voltage fluctuations is independent from the cloud cover and, thus, the weather conditions.

If power-flow fluctuations introduced by PV are to be mitigated, storage devices may be an option especially in cable grids with a high series resistance. In mainly inductive grids, such as overhead lines, the injection of reactive power by the PV inverter may be another promising option.

The additional costs for mitigating the amplitude of short PV-induced fluctuations from 9.9 to 6.4% of rated voltage by means of supercapacitors are 18% of the PV system price. While this example is based on a very high PV connection density, in many cases, PV-induced fluctuations will lead to much lower voltage variations. Depending on PV connection density, load profile, and network topology, the distribution system operator may be able to avoid such an investment without compromising the voltage quality. Therefore, the presented localized spectral analysis is a valuable tool for estimating the expected fluctuations, enabling the distribution system operator to make realistic decisions with regards to such high investments.

In the future, parametric studies will be performed in order to assess the fluctuating behavior for different situations under

characteristic load demand and astronomical boundary conditions. The interrelationship between fluctuation indices and storage demand will be examined on a theoretical basis. Applications for the thus refined simulation tool are, for example, in the field of network planning with nonutility-owned embedded generation units and in the design of autonomous energy islands powered by fluctuating resources.

Moreover, the approach should be applied to existing power systems with dense PV generation in order to validate the presented algorithms based on empirical data. A necessary condition for such a validation is the availability of power-flow data from such a distribution grid with the appropriate time resolution. Up to now, such data have not been available.

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**Achim Woyte** received the Electrical Engineering degree from the University of Hannover, Hannover, Germany, in 1997 and the Ph.D. degree in engineering from the Katholieke Universiteit Leuven, Leuven, Belgium, in 2003.

At the beginning of 2004, he joined the Policy Studies department of the Brussels-based consultant 3E. There, he coordinates policy-related projects in renewable energy technology. He also performs research and engineering regarding the grid integration of renewable energy technologies. He is co-author of many scientific publications.



**Vu Van Thong** (S'02) was born in 1976 in NgheAn, Vietnam. He received the B.E. and M.E. degrees in electrical power systems from Hanoi University of Technology, Hanoi, Vietnam, in 1997 and the Asian Institute of Technology, Bangkok, Thailand, in 2001, respectively. He is currently pursuing the Ph.D. degree with the Electrical Energy Research Group, Department of Electrical Engineering, Katholieke Universiteit (K.U.) Leuven, Leuven, Belgium.

He was an Electrical Engineer with Electricity of Vietnam for nearly three years. His interests are distributed generation, voltage stability, power quality, reliability, and optimal power flow.



**Ronnie Belmans** (S'77–M'84–SM'89) received the M.S. degree in electrical engineering and the Ph.D. and the Special Doctorate degrees from the Katholieke Universiteit (K.U.) Leuven, Leuven, Belgium, in 1979, 1984, and 1989, respectively. He received the Habilitation from the RWTH, Aachen, Germany, in 1993.

Currently, he is Full Professor with K.U. Leuven, teaching electrical machines and variable-speed drives. He is an Appointed Visiting Professor at Imperial College, London, U.K. and is President of UIE. He was with the Laboratory for Electrical Machines of the RWTH. From 1989 to 1990, he was Visiting Associate Professor, McMaster University, Hamilton, ON, Canada. He was the Chair of the Anglo-Belgian Society at London University, London, U.K.

Dr. Belmans is Chairman of the Board of Directors of ELIA: the Belgian transmission grid operator. He is a member of the Institute of Electrical Engineers (U.K.). He was a Von Humboldt Fellow from 1988 to 1989.



**Johan Nijs** (SM'97) received the Electrical Engineering University degree, the Ph.D. degree in applied sciences, and the degree of Master of Business Administration degree from the Katholieke Universiteit (K.U.) Leuven, Leuven, Belgium in 1977, 1982, and 1994, respectively.

He was with Philips, Leuven; K.U. Leuven; and IBM Thomas J. Watson Research Center, Yorktown Heights, NY. In 1984, he joined the Interuniversity Micro-Electronics Center (IMEC), Leuven, where he was Group Leader of the silicon materials and solar-cell activities and, in 2000, became Associate Vice-President and Department Director of the Packaging, MEMS, and Photovoltaics Department. In 1990, he was also appointed Part-Time Associate Professor and later Guest Professor at the Katholieke Universiteit (K.U.) Leuven. Since 2002, his main activity has been the setup of a new spinoff company of IMEC, named Photovoltech, for the production of solar cells and modules based on IMEC's technology.