Power Fluctuations in Micro-grids Introduced by Photovoltaics: Analysis and Solutions

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Abstract:

In minigrids with a high fraction of photovoltaics, short time fluctuations of solar irradiance have a decisive impact on the availability of power and thus the steady-state grid stability. Voltage and frequency controllers in the minigrid have to react on these fluctuations and appropriate energy buffers need to be installed. Buffers that might be applied in minigrids are for example conventional batteries, redox flow batteries, and supercapacitors. The choice and sizing of the storage device depends on the amplitude of the expectable fluctuations, their duration, and their frequency of occurrence.

An analysis method has been developed that serves for assessing the solar radiation pattern at a specific location. The method is based on time scale decomposition of the solar irradiance by means of orthonormal wavelet bases. A wavelet power spectrum is calculated that shows the power content for different characteristic durations of fluctuations of the instantaneous clearness index. The 'squared fluctuation index' is defined as a measure for the occurrence of fluctuations with particular duration on an annual basis. The squared fluctuation index is calculated for measured radiation data from different locations with moderate maritime, moderate continental, and dry tropical climate.

Based on values for the squared fluctuation index for the specific region, a suitable strategy can be determined for grid control and storage. The values of the squared fluctuation index for the different characteristic time scales indicate the necessary bridging times that a storage device must be able to cover and also the necessary capacity. The frequency of occurrence is a measure for the number of charge cycles per year.

Results show that the squared fluctuation index depends on the daily average clearness index. For very low average clearness index (overcast sky) and very high average clearness index (clear sky), the squared fluctuation index is generally low. It takes maximum values for partly clouded sky conditions. With regard to the duration of fluctuations, the squared fluctuation index takes a local maximum in the range of 600 s up to 1800 s, indicating that fluctuations are most significant with regard to steady state stability and storage of PV power in this order of magnitude.

The most significant fluctuations persist from several minutes up to an hour. For bridging fluctuations of this durations with a high frequency of occurrence, conventional batteries might be less suited since they cannot provide the high number of charge cycles. The most interesting option for bridging these fluctuations are supercapacitors. They can bridge fluctuations of 30 minutes and more and their capacity doubles every couple of years. In the conference paper, a sample application of super capacitors for bridging power fluctuations in minigrids introduced by photovoltaic will be presented.

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Introduction and Literature Review

In minigrids with a high fraction of photovoltaics, short time fluctuations of solar irradiance have a decisive impact on the availability of power and thus the steady-state grid stability. In order to qualify the short term variability of power from photovoltaic (PV) systems, a number of studies have already been carried out. The advantages and drawbacks of these studies are discussed, especially with regard to the approach that is proposed here.

The approach proposed in this paper can combine advantages of several preceding studies by using a wavelet filter bank for the frequency decomposition. Unlike in most of the preceding studies, a mathematically consistent model is applied which allows further generalization of the model and broader conclusions. Furthermore, in the present study, exemplary conclusions are drawn on the necessary storage in a hybrid minigrid with PV under different climatic conditions.

Modelling Approach

In this study a tool is provided for assessing meteorologically induced irradiance fluctuations and draw conclusions for PV application in hybrid minigrids. Global solar irradiance has been recorded with very high time resolution (1 s^{-1} to 1 min^{-1}) at different climatic locations. From this irradiance data, time series of clearness index (k_T) have been computed on 362 sample days. The clearness index is defined as solar irradiance normalized on extraterrestrial irradiance. As the clearness index is a measure for the cloud coverage of the sky, being independent from any astronomically induced seasonal or day time variations, the time series of clearness index may be applied as short term irradiance pattern at an arbitrary day and time by scaling them by extraterrestrial irradiance on that very day and time.

Inter-hourly fluctuations induced by passing clouds occur randomly distributed in time and their shape is rather bi-modal than sinusoidal. Nevertheless, a kind of frequency domain representation of the recorded fluctuation patterns can still be derived by applying a wavelet transform. Analogous 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. In the present case, a time-invariant, so-called 'stationary' wavelet transformation is applied.

Due to its similarity with the bi-modal 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. The *haar* wavelet is a simple function that is scaled by the factor 2^j and shifted along the t-axis by θ (Fig. 1).

Based on the stationary wavelet transform, wavelet periodograms are calculated from the clearness index time series'. 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 spectrum.

The wavelet periodogram is a measure for the power content of a signal for different dyadic time scales, similarly to frequencies with a Fourier transformation. Fig. 2 shows a typical two-hour clearness index signal and its wavelet periodogram for a number of significant scales. Fluctuations of the clearness index (upper graph) correspond with local maxima on the very time scale that corresponds with the length of the particular fluctuation.

The mean value for a particular time scale *j* of all wavelet periodograms for a high number of sample days will be referred to as the 'squared fluctuation index' (cf^2). The squared fluctuation index represents the mean square value of all fluctuations in clearness index on the particular time scale. It can therefore serve as a measure for the necessary storage capacity on each time scale when PV systems are densely connected to a network.

Results

The squared fluctuation index has been calculated for different locations. Fig. 3 shows the cf^2 values for Leuven as a function of time scale of fluctuation for different daily mean values of the clearness index.

For short fluctuations cf^2 is generally lower than for longer-ones. With linearly increasing time scale, cf^2 increases slightly faster than linearly up to a local maximum. For very low K_T (overcast sky) and very high K_T (clear sky), cf^2 is generally low. The squared fluctuation index takes maximum values for partly clouded sky conditions. Partly, a slight local maximum is visible around a duration between 600 s up to 1800 s, indicating that this range of fluctuations is significant for network planning and storage of PV power. The local maxima that are visible at 10^4 s indicate global changes of the weather conditions during several hours like e.g. from clear sky in the morning to cloudy in the afternoon. Obviously, these maxima have no significant meaning with regard to short time fluctuations of the available solar irradiance.

For bridging fluctuations of this durations with a high frequency of occurrence, conventional batteries might be less suited since they cannot provide the high number of charge cycles. The most interesting option for bridging these fluctuations are currently supercapacitors. They can bridge fluctuations of 30 minutes and more and their capacity is rapidly increasing. A sample application of super capacitors for bridging power fluctuations originating from PV in a minigrid will be provided in the conference paper.

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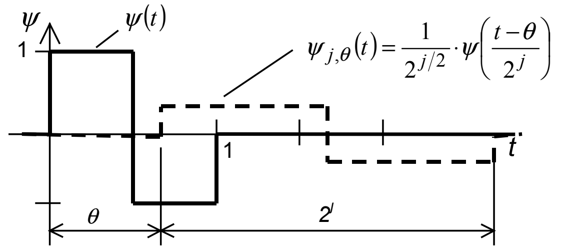

Figure 1: Haar wavelet $\psi(t)$ and scaled and shifted wavelet $\psi_{j,\theta}(t)$

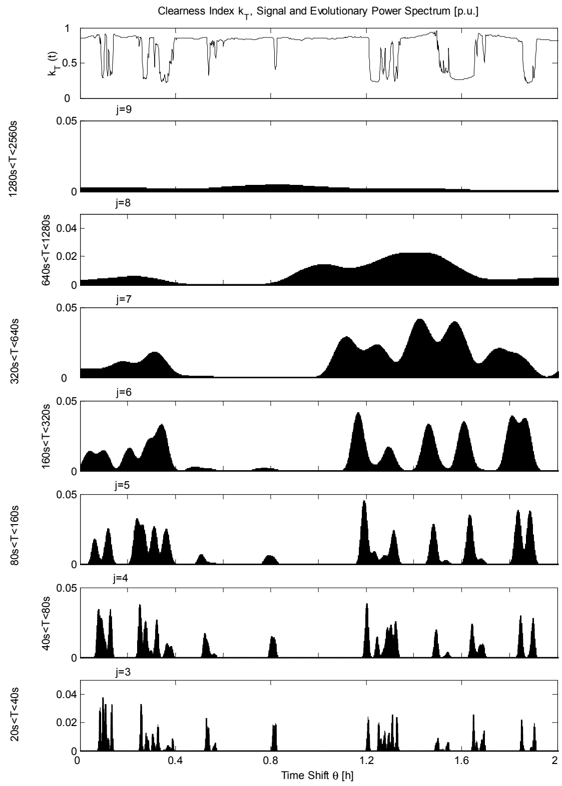

Figure 2: Wavelet periodogram of a 2-h-time series of the clearness index. The sum over all wavelet scales *j* equals the power content of the clearness index signal $k_T(t)$ (orthonormality); wavelet: *haar*, $\Delta T = 5$ s, decomposition with $j = 1$ up to 12 with only $j = 3$ up to 9 shown

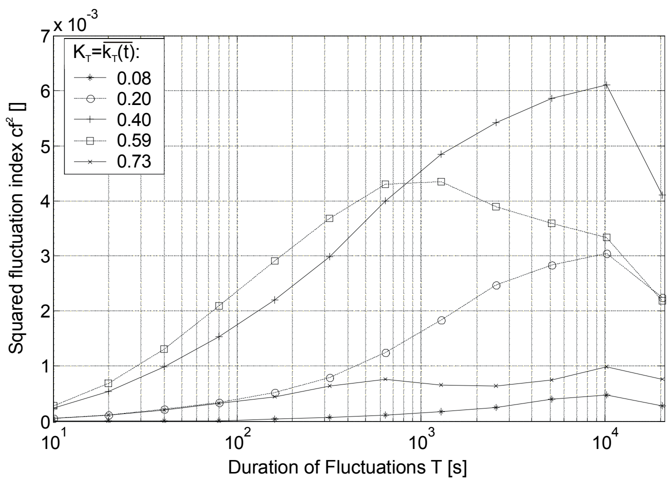

Figure 3: Squared fluctuation index as a function of the time scale (duration) of the fluctuations; different curves for different average values of daily clearness index K_T; T=5s·2^j