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Analysis of shading periods caused by moving clouds

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ABSTRACT

Fast variability of solar radiation is the main cause of fluctuating photovoltaic power production. Shadows caused by moving clouds are the main reason of such variability. Irradiance transitions caused by edges of cloud shadows can be very steep and large and might lead to failures in maximum power point tracking causing extra losses. Further, fast fluctuations of the power fed to the electric grid can cause power balance and quality problems for the grid.

This paper presents a method to identify shading periods caused by moving clouds in measured irradiance data. A total of around 12,000 shading periods were identified in a measured data of 15 months around midsummer in 2011–2014 and their shading strength, duration, time of occurrence etc. were analysed. It was found that the duration of shading periods varies a lot from about four seconds up to almost 1.5 h with an average duration of around 60 s. Furthermore, the Linear Cloud Edge method was used to determine the velocity of shadows and their speed, direction of movement, length etc. were analysed. The determination of velocity was conducted by two different ways based directly on measured irradiance values and on the curve fits of a mathematical model of irradiance transitions. The use of curve fits mitigates the effects of irregularities present on shadow edges. The speed of shadows varies greatly with an average value of around 13 m/s.

1. Introduction

Fast variability of solar radiation is the prime cause of fluctuating photovoltaic (PV) power production and overpassing cloud shadows are the main reason of such variability. Fast irradiance transitions caused by edges of shadows can lead to failures in maximum power point tracking causing extra losses and to mismatch power losses due to partial shading of the PV generator. Furthermore, feeding fluctuating power to the electric grid can cause power balance and quality problems. The fast growth of PV power production sets technical requirements such as ramp rate control, reactive power capability and voltage ride-through capability to accommodate large amounts of PV production in the power systems (Woyte et al., 2006).

The operation of partially shaded PV systems have been studied in several papers, e.g. in Belhachat and Larbes (2015), Bidram et al. (2012), Mäki et al. (2012), Patel and Agarwal (2008), Psarros et al. (2015), Shams El-Dein et al. (2013), Wang and Hsu (2011), Woyte et al. (2003). The effects of overpassing cloud shadows have been studied e.g. in Kern et al. (1989), Lappalainen et al. (2013a,b), Mäki and Valkealahti (2014), Sánchez Reinoso et al. (2013). It has been noticed that cloud shadows can cause large and fast changes in PV power production which are problematic for the grid operation. Mismatch losses can be up to 25% during an irradiance transition caused by an overpassing cloud shadow depending on the PV system layout (Lappalainen et al., 2013a,b).

The actual variability of solar radiation due to overpassing cloud shadows has been studied e.g. in Lave and Kleissl (2010), Lave et al. (2015), Hinkelman (2013), Tomson and Hansen (2011) and the characteristics and identification of irradiance transitions caused by edges of cloud shadows in Lappalainen and Valkealahti (2015), Tomson (2010, 2013). In Lappalainen and Valkealahti (2015) a comprehensive analysis and a mathematical model of irradiance transitions caused by moving clouds have been presented. It has been found that irradiance transitions can be very steep and large. Irradiance can change over 300 W/m^2 in 0.1 s during an irradiance transition. The duration of irradiance transitions varies a lot from a few seconds up to several minutes. Determination of shadow velocity have been studied e.g. in Bosch and Kleissl (2013), Bosch et al. (2013), Fung et al. (2014). The Linear Cloud Edge (LCE) method has been presented in Bosch et al. (2013) to determine the speed and direction of movement of shadows from the time lags between shading of a set of three irradiance sensors.

In this paper, a method is presented to identify shading periods caused by moving clouds in measured irradiance data. 15 months of data measured during spring, summer and autumn in 2011,

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2012, 2013 and 2014 was analysed. A total of around 12,000 shading periods were identified and their shading strength, duration, time of occurrence etc. were analysed. Curve fitting of the mathematical model presented in Lappalainen and Valkealahti (2015) was conducted for all the identified shading periods and the obtained parameter values were analysed as well. Furthermore, the LCE method was used to determine the velocity of shadows. The most critical stages of using the LCE method, ensuring that the same shadow has been identified by all the three sensors and defining the time lags between shading of the sensors, were conducted by using two different methods based directly on measured irradiance values and on the curve fits of the mathematical model of irradiance transitions. The speed, direction of movement, length etc. of the identified shadows were analysed. Although the presented analyses are based on measurements of a particular location and the characteristics of shading periods differ slightly regionally, the presented results provide useful information of the magnitudes, ranges and correlations of the shading period characteristics. The developed methods are not regionally bounded. They can be exploited, for example, in short-term forecasting of PV production and in designing of PV array layouts.

2. Methods and data

2.1. Identification of shading periods

A shading period is defined as a combination of a decreasing and an increasing irradiance transition with steady shading between them. A decreasing irradiance transition is called a fall and an increasing transition is called a rise, similarly as in Lappalainen and Valkealahti (2015), Tomson (2013). The method to identify irradiance transitions in measured irradiance data presented in Lappalainen and Valkealahti (2015) was adapted to identify shading periods. It was found in Lappalainen and Valkealahti (2015) that while irradiance transitions can be extremely fast and even shorter than 1 s, a sampling frequency of 1 Hz is high enough to identify all relevant transitions. Thus, a sampling frequency of 1 Hz was used in identification to ensure reasonable computing time. In order to be resistant to small insignificant irradiance fluctuations, the method identifies rough starting and ending points of irradiance transitions from a moving average of five seconds. Transitions were identified when the moving average of irradiance changed more than 5 $\mathrm{W/m^2s}$. Thereafter, for the sake of accuracy, more exact points for the start and end of the irradiance transition were searched from the vicinity of rough points from the data measured with a sampling frequency of 10 Hz. The final point is the maximum (start of a fall or end of a rise) or minimum (end of a fall or start of a rise) irradiance within 0.5 s from the initial rough point. Furthermore, the irradiance before and after a transition was checked to be steady, to ensure that the transition is not occurring during other irradiance fluctuation or is not only a part of a larger transition. The identification of irradiance transitions has been presented in more detail in Lappalainen and Valkealahti (2015).

A shading period was identified when an irradiance fall was followed by steady shading and thereafter by an irradiance rise. To ensure that only appropriate shading periods were identified, irradiance during the steady shading period was required to differ less than 50% from the irradiance at the end of the fall and at the beginning of the rise. Also the irradiance difference between the end of the fall and the beginning of the rise had to be less than 30%. The three parts of shading periods are presented in Fig. 1, where an example of a typical shading period identified in the data of three irradiance sensors is shown.

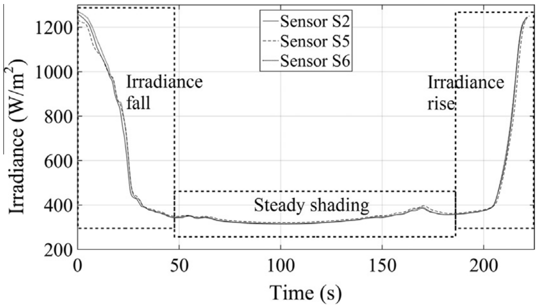

Fig. 1. Irradiance as a function of time during a shading period measured by irradiance sensors S2, S5 and S6 at a sampling frequency of 10 Hz. Shading periods measured by different sensors have been shifted to start at the same time.

Also the shading strength, i.e., the attenuation of irradiance due to shading, was checked to be high enough to identify only shading periods meaningful to the operation of PV generators. Shading strength (SS), can be written as

$$\mathrm{SS} = \frac{G_{\mathrm{us}} - G_{\mathrm{s}}}{G_{\mathrm{us}}}, \tag{1}$$

where G_{us} is the irradiance of an unshaded situation and G_{s} the irradiance under shading. The shading strength of a shading period is defined as the average of the shading strengths of the irradiance fall and rise. The 40% limit of minimum acknowledged shading strength was used because it has been shown in Lappalainen and Valkealahti (2015) that moving shadows with lower shading strength have no significant effect on the operation of series-connected PV strings, which are the most sensitive PV system layouts to partial shading. The 40% limit was applied to both the falls and rises of shading periods.

2.2. Determination of shadow velocity

The speed and direction of movement of shadows can be determined by using the LCE method presented by Bosch et al. (2013) by analysing the time lags between shading of a set of three irradiance sensors with known locations. In the LCE method, the following three assumptions have been made: the velocity of the shadow while passing over the sensors is constant, the shadow edge is linear across the irradiance sensor array and the shadow covers all the three sensors. For closely placed sensors these assumptions are generally satisfied. A scheme of the LCE method to determine shadow velocity from shading periods measured by sensors $\mathrm{S_o}$, $\mathrm{S_a}$ and $\mathrm{S_b}$ is presented in Fig. 2, where d_{a} and d_{b} are the distances between the sensors, v the shadow speed, α the angle between the direction of movement of the shadow and the line oa (line from sensor $\mathrm{S_o}$ to sensor $\mathrm{S_a}$), θ the angle between the lines oa and ob, δ

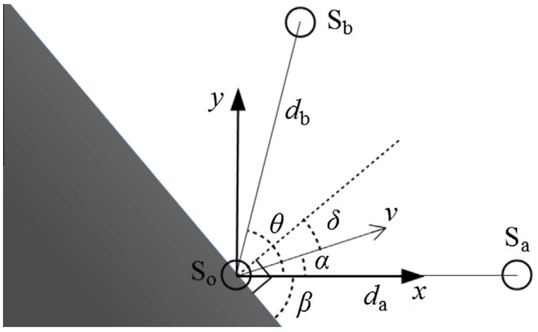

Fig. 2. Scheme of the Linear Cloud Edge method to determine the velocity of a shadow from shading periods measured by irradiance sensors $\mathrm{S_o}$, $\mathrm{S_a}$ and $\mathrm{S_b}$.