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CLOUD PASSING FORECASTING FOR PV POWER PLANT OUTPUT POWER SMOOTHING

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Abstract: The output power of photovoltaic power plants can change rapidly due to fast moving clouds. That could lead to voltage fluctuations and stability problems in the connected electricity distribution network. These effects can be reduced effectively by electricity network reinforcements or by battery energy storage systems that smooth out the output power fluctuations. These two solutions are effective but very costly. For house scale photovoltaic power plants of several kWp, both solutions represent a considerable percentage of investment. However, similar results can be achieved by a programed smooth reduction of the photovoltaic power plant output power, based on cloud passing forecasting. Low cost hardware Internet of Things (IoT) modules incorporated in a cloud passing forecast system could be a much cheaper alternative compared to a battery storage system or network reinforcement. This paper proposes a low-cost IoT based solution for intra-minute cloud passing forecasting. The low-cost hardware used is Raspberry PI Model B 3, an Omni Vision OV5647 camera, an optical circular polarizing (CPL) filter and a natural density (ND) filter. All of the used hardware costs less than 70 €.

Keywords: photovoltaic power plant, cloud passing forecasting, Raspberry Pi, camera.

1 Introduction

Clouds moving at a high speed can cover the sun, which leads to dynamic changes in the solar irradiance. The photovoltaic (PV) power plant active output power depends directly on the solar irradiance. That can cause high dynamics in the PV power plant output power. These changes can cause voltage fluctuations and stability problems in the connected electricity networks [1], [2], [3]. Electricity network reinforcement and the introduction of energy storage systems are two effective, but very costly solutions, that can be applied to solve these problems [3], [4], [5], [6], [7]. Another possibility is the predictive reduction of the PV power plant output power, based on a prediction of moving clouds that will cover the sun. This approach is much cheaper than the two previously mentioned ones, but requires an intra-minute forecast of clouds passing the sun. Photos of the sky are taken in predefined and constant time intervals. In the photos, the clouds and sun have to be identified. Some approaches for identification of clouds and cloud passing forecasting are described in [8], [9], [10], [11]. This paper deals with a low-cost IoT based solution for intra-minute cloud passing forecasting. A detailed description of the applied algorithm is already given in [12]. When the system detects that a cloud will cover the sun in the predefined time interval, it starts to smoothly reduce the PV power plant output power.

2 System hardware selection

The system for cloud passing forecasting was designed considering several criteria. The system must be able to take photos of the sky without any sunshades and to recognize clouds near the sun, when the sun is located perpendicularly to a camera. No moving parts are allowed and only low-cost and widely available hardware can be used. The total cost of all applied components should not exceed the price of a single normal size PV module.

The existing professional systems for solar irradiance and cloud passing forecasting can provide accurate forecasts but only at high costs. Their price can easily exceed the price of a small house-scale PV power plant [13]. The low-cost hardware used in our system consists of Raspberry PI Model B 3, an Omni Vision OV5647 camera, an optical circular polarizing (CPL) filter and a natural density (ND) filter (Figure 1). The cost for all of the hardware is less than 70 €.

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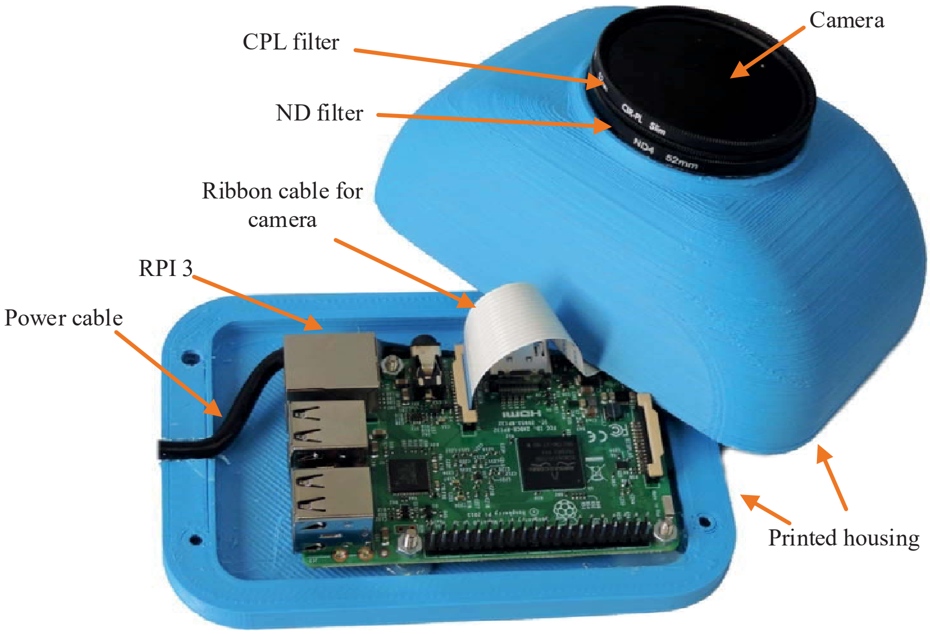

Figure 1: Used hardware

The ND filter reduces the density of the light that falls on the sensor and prevents its saturation and overheating whilst the CPL filter reduces the flare.

3 Cloud detection

The prediction of cloud movement is required only during the part of the day when the moving clouds could influence the output power of a PV power plant substantially. For the prediction of cloud movement within one minute, the photo is cropped down to a relatively small area around the sun where the cloud recognition is performed as shown in 2 and 3. In order to make the executive code for the prediction of cloud movement suitable for its implementations on low-cost IoT modules, the applied algorithms are minimized regarding the required computational effort.

The algorithm applied in the proposed cloud passing forecasting system differs from the existing ones. It uses the green and the blue colours for the cloud recognition and for the reduction of flare problems in red colour (Figure 2). The image processing is limited to a narrow area around the sun, which is sufficient for intra-minute cloud passing forecasting and can be performed with a low computational effort.

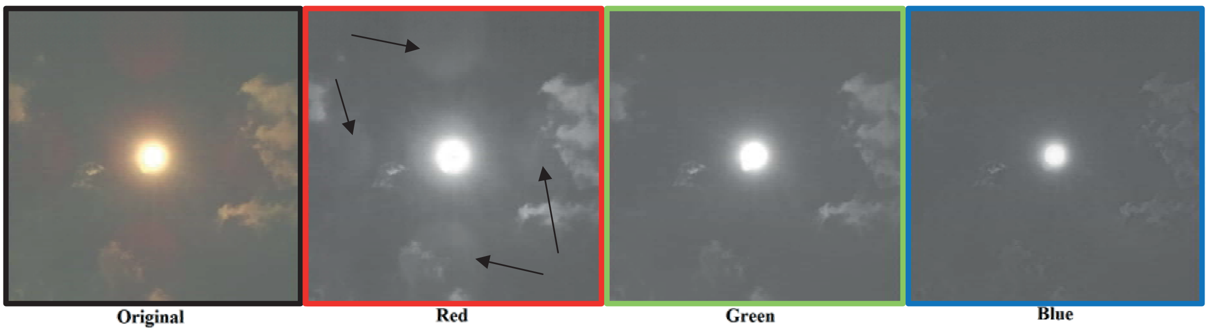

Figure 2: Decomposition of the photo with flare visible in the red colour

The recognition of clouds is based on the ratio between the green and the blue colours GBR (Green Blue Ratio) digital filter (1) instead of well-known RBR (Red Blue Ratio) filter [8], [12], [14].

$$\frac{Green}{Blue} > GBR_{\lim} \tag{1}$$

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The ratio between the $Green$ and $Blue$ colours is compared for each pixel around the sun with the experimentally determined threshold value GBR_{lim}. For the pixels that fulfil (1), the logical value in the cloud recognition matrix is set to the logical value 1, which means that these pixels belong to a cloud. The light passing through the atmosphere causes scattering very close to the sun. These effects influence the cloud recognition. Therefore, the logical values in the cloud recognition matrix in the radius around the sun's centre are set to the logical value 0 as shown Figure 3.

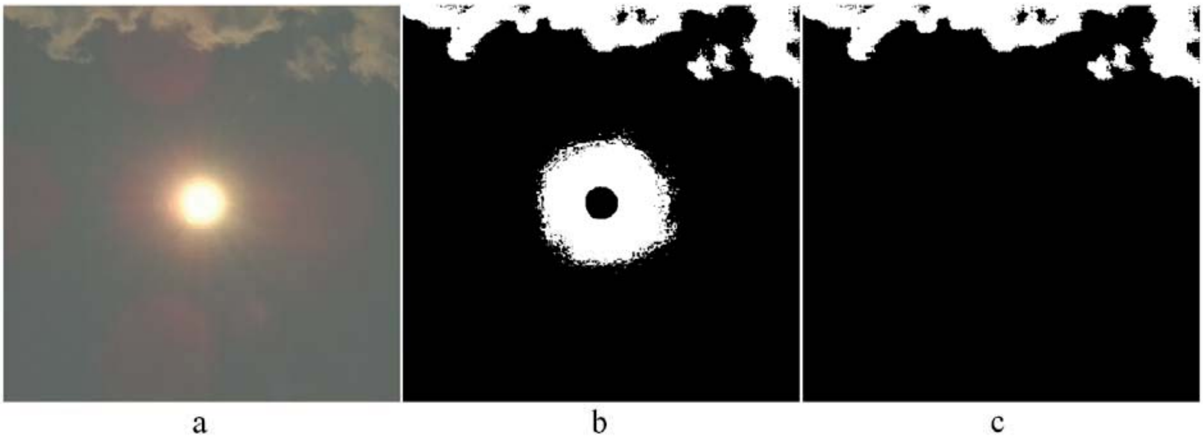

Figure 3: Cloud recognition: a) photo of the sun, b) clouds and area around the sun's centre, c) clouds without the sun

In order to detect the presence of clouds in the vicinity of the sun in a photo, checkpoints are arranged around the sun's centre (x_{sun}, y_{sun}). The checkpoints are organized in the form of a checkpoint matrix, the indices of which are marked in Figure 4. The checkpoint matrix is defined. It contains 128 checkpoints. Its elements are distributed in 4 radially equidistant layers, measured from the centre of the sun (Figure 4). Each layer contains 32 angularly equidistant points. The pixels representing the cloud in the cloud recognition matrix shown in Figure 3.c) are checked at the locations defined with the elements of the checkpoint matrix (Figure 4). The checking procedure starts with the checkpoints closest to the sun's centre, with the row index 1 and the column index 1 (Figure 4). When a cloud is detected at the given checkpoint, the checkpoint coordinates $(x_{\text{posit}}, x_{\text{posit}})$ are stored. The area of interest, with the centre at the detected point and with a surface of $(2m \times 2m)$ pixels is defined. It is marked with the square in Figure 5. The number of pixels m is selected in such a way, that the area of interest includes at least three checkpoints at the external checkpoint layer as show Figure 5. This area is confined by the points (x_{start}, y_{start}) and (x_{end}, y_{end}).

Inside area of interests the centre of gravity is determined only for those pixels with coordinates x_{p}, xy_{p} that are marked as a cloud in the cloud recognition matrix. The centre of gravity is given by the coordinates (x_{ave_p}, y_{ave_p}) defined by (2) and (3), where n_{p} is the number of pixel in the area of interests. With the time delay t_p the new photo is taken. For the already defined area of interest the centre of gravity is determined in the new photo. The difference in the centres of gravity in the two subsequently taken photos is used to determine the cloud movement vector, which describes the cloud movement.

$$x_{\text{ave\_p}} = \frac{\sum_{x_{\text{start}}}^{x_{\text{end}}} x_{\text{p}}}{n_{\text{p}}} \tag{2}$$

$$y_{\text{ave\_p}} = \frac{\sum_{y_{\text{start}}}^{y_{\text{end}}} y_{\text{p}}}{n_{\text{p}}} \tag{3}$$

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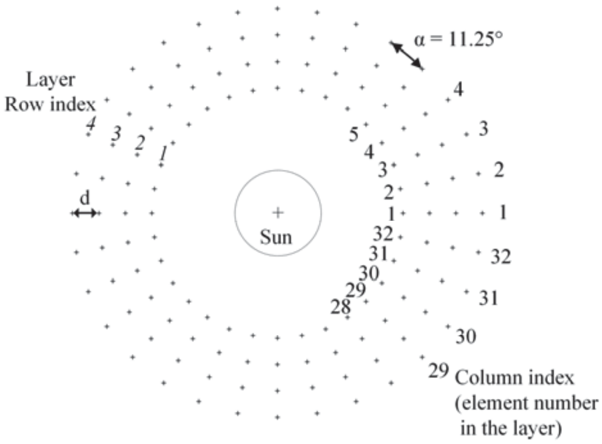

Figure 4: Checkpoints around the sun and checkpoint matrix indices

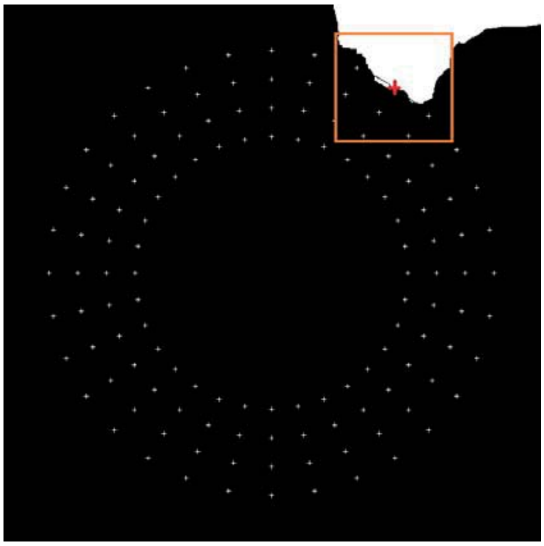

Figure 5: Defined area of interest

Based on the known cloud movement vector, the direction angle γ is determined that describes the direction of the cloud's movement. To distinct between the clouds passing by and the clouds that will cover the sun, the angle γ is used to draw a straight line from the sun's centre (x_{sun}, y_{sun}). The distance to the cloud d_{cloud} is measured by increasing the distance D for one pixel, starting from the internal layer of checkpoints placed around the sun's centre at the radius r_{ignore} (Figure 4). Based on (4) the coordinates along the aforementioned straight line (x_{cloud}, y_{cloud}) are defined. At these coordinates it is checked if the corresponding pixel in the cloud recognition is matrix is marked with the logical value 1, which means that it belongs to a cloud. When the first point that satisfies this condition is found, the distance to the cloud d_{cloud} (5) is set.

$$\begin{aligned} x_{\text{cloud}} &= x_{\text{sun}} + \left\| D \cdot \cos(\gamma) \right\| \\ y_{\text{cloud}} &= y_{\text{sun}} + \left\| D \cdot \sin(\gamma) \right\| \end{aligned} \qquad \left(D = r_{\text{ignore}},\ r_{\text{ignore}} + 1,\ \ldots,\ r_{\text{lim}} \right) \tag{4}$$

$$d_{\text{cloud}} = D\,,\ \left(x_{\text{cloud}}, x_{\text{cloud}} \right) > 0 \tag{5}$$

After that a new photo of the sky is taken and the described procedure is repeated for the step i. Considering the distances between the sun's centre and the cloud in the steps $i-1$ and i that are denoted by $d_{\text{cloud}}(i-1)$ and $d_{\text{cloud}}(1)$, and the time between the two taken photos t_{p}, the predicted time t_{prd} in which the cloud will cover the sun is calculated by (6).

$$t_{prd} = \frac{t_p \cdot d_{\text{cloud}}(i-1)}{d_{\text{cloud}}(i-1) - d_{\text{cloud}}(i)} \tag{6}$$

To smooth out fast changes in the output power of a PV power plant, caused by the clouds moving in front of the sun, a proper prediction of the cloud's movement is required 30 to 60 seconds before the cloud reaches the sun.

4 Results

The sequences of the processed images of the sky, shown in Figure 6, are used to demonstrate the operation of the proposed cloud passing forecasting system. When the developed system detects that a cloud will cover the sun in a predefined time or before, the logical value on its output changes from the logical value 0 to the logical value 1 (red colour). This signal is afterwards used to start the procedure for the reduction of the PV power plant output power.

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Figure 7 shows the output signal generated by the proposed cloud passing forecasting system, together with the measured PV power plant output power. The output power of the PV power plant is presented in the per unit system. The presented results clearly show that the proposed system properly generates the output signal each time before the output power of the PV power plant is reduced due to the clouds passing in front of the sun,

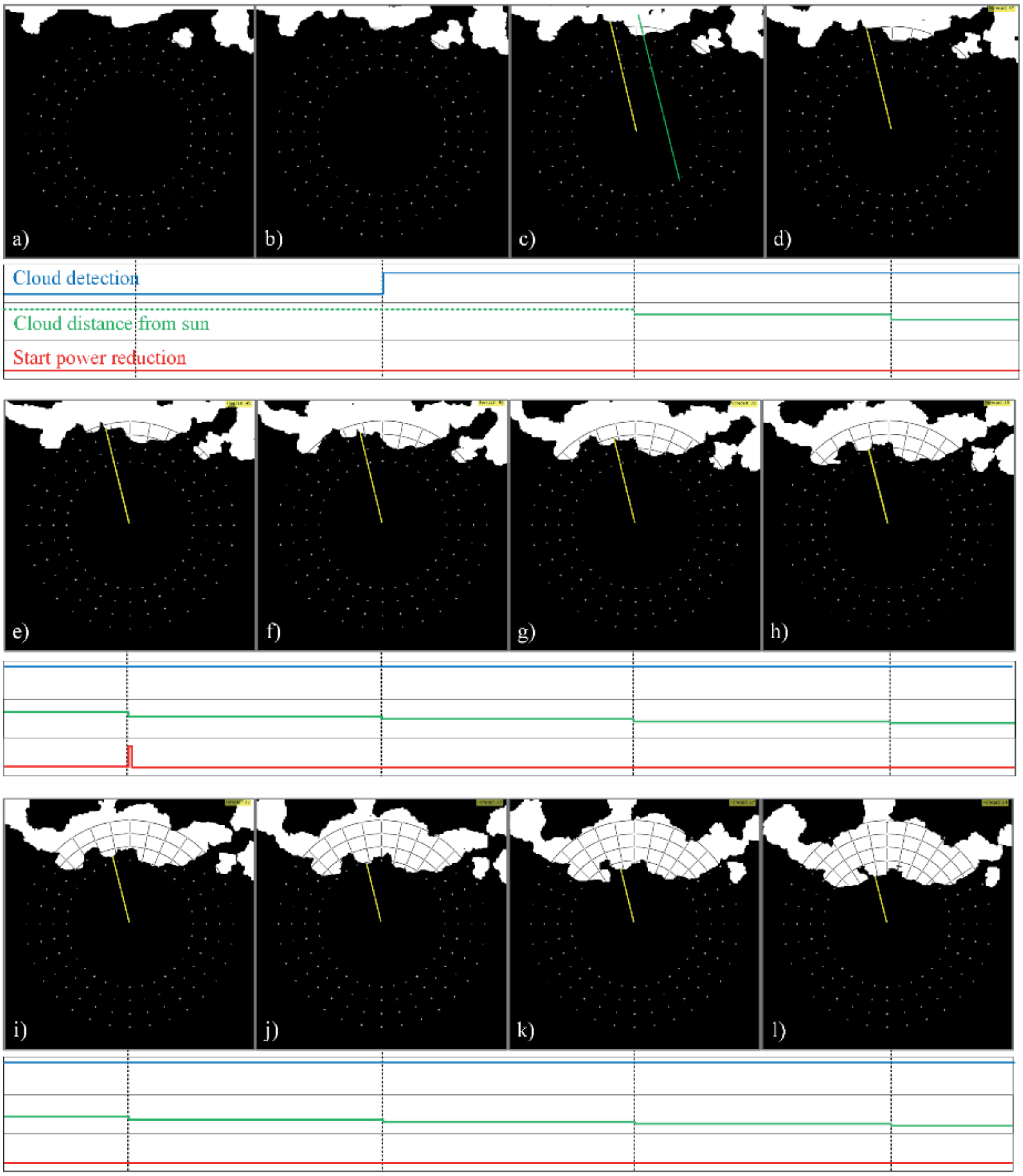

Figure 6: Moving clouds that cover the sun: a time sequence of processed cloud movement.

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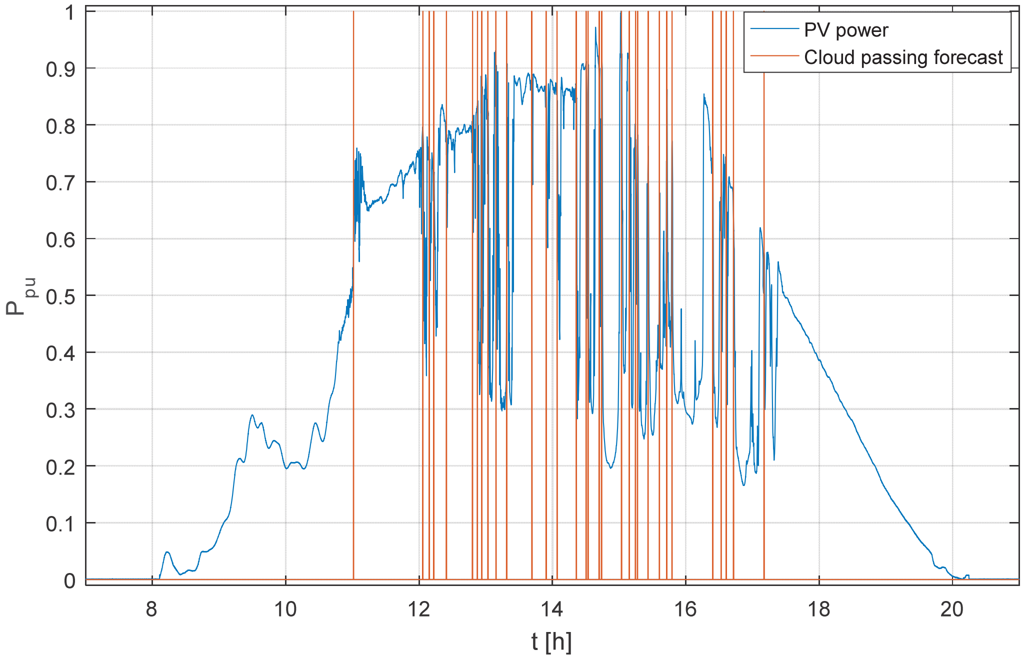

Figure 7: Output power measured on the test PV power plant and the output signal of the proposed cloud passing forecasting system

5 Conclusion

This paper presents a low-cost solution for intra-minute cloud passing forecasting. The applied algorithm is simple and requires low computational effort. The proposed system is applied to eliminate fast changes in the output power of PV power plants, which could cause voltage fluctuations in electricity networks with a high share of PV power plants. The developed prototype reliably estimates the time in which a cloud will cover the sun within the next minute.

References

[1] E. H. Thomas and P. Richard, "Quantifying PV power Output Variability," *Solar Energy* , pp. 1782-1793, 10/2010.

[2] S. Sayeef, S. Heslop, D. Cornforth, T. Moore, P. S., J. Ward and A. Berry, "Solar Intermittency: Australia's Clean Energy Challenge:Characterising the Effect of High Penetration Solar Intermittency onAustralian Electricity Networks," CSIRO, 2012.

[3] S. Shivashankar, S. Mekhilef, H. Mokhlis and M. Karimi, "Mitigating methods of power fluctuation of photovoltaic (PV) sources – A review," *Renewable and Sustainable Energy Reviews,* vol. 59, pp. 1170-1184, 2016.

[4] F. Cheng, S. Willard, j. Hawkins, B. Arellano and A. Mammoli, "Applying battery energy storage to enhance the benefits of photovoltaics," in *Energytech, 2012*, Cleveland, 2012.

[5] A. Ellis, D. Schoenwald, J. Hawkins, S. Willard and B. Arellano, "PV output smoothing with energy storage," in *Photovoltaic Specialists Conference*, Austin, 2012.

[6] A. Puri, "Optimally smoothing output of PV farms," in *PES General Meeting* , Harbor, 2014.

[7] A. Puri, "Bounds on the smoothing of renewable sources," in *Power & Energy Society General Meeting*, Denver, 2015.

[8] C. W. Chow, B. Urquhart, M. Lave, A. Dominguez and B. Washom, "Intra-hour forecasting with a total sky imager at the UC San Diego solar energy testbed," *Solar Energy,* vol. 11, pp. 2881-2893, 2011.

[9] J. Alonso-Montesinos and F. Batlles, "The use of a sky camera for solar radiation estimation based on digital image processing," *Energy,* vol. 90, pp. 377-386, 2015.

[10] A. Hammer, D. Heinemann, E. Lorenz and B. Lückehe, "Short-term forecasting of solar radiation: a statistical approach using satellite data," *Solar Energy,* vol. 67, pp. 139-150, 1999.

ISBN 978-3-85125-586-7 DOI 10.3217/978-3-85125-586-7

[11] R. W. Johnson, W. Hering and J. Shields, "Automated Visibility and Cloud Cover Measurements with a Solid State Imaging System," University of California, San Diego, 1989.

[12] P. Sukič and G. Štumberger, "Intra-Minute Cloud Passing Forecasting Based on a Low Cost IoT Sensor-A Solution for Smoothing the Output Power of PV Power Plants," *Sensors,* vol. 5, no. 1116, 2017.

[13] B. Urquhart, K. B and J. Kleissl, "Development of a sky imaging system for short-term solar power forecasting," *Atmospheric Measurement Techniques,* vol. 8, p. 875–890, 2015.

[14] G. Pfister, R. L. McKenzie, J. B. Liley, W. Thomas, B. W. Forgan and C. N. Long, "Cloud coverage based on all-sky imaging and its impact on surface solar irradiance," *American Meteorological Society,* pp. 1421-1434, 2003.

[15] R. Marquez and C. Coimbra, "Intra-hour DNI forecasting based on cloud tracking image analysis," *Solar Energy,* vol. Volume 91, pp. 327-336, 2012.

[16] M. S. Ghonima, B. Urquhart, C. W. Chow, J. E. Shields, A. Cazorla and J. Kleissl, "A method for cloud detection and opacity classification based on ground based sky imagery," *Atmospheric Measurement Techniques,* vol. 5, 2012.