A Fractal Based Cumulus Cloud Shadow Model For Power System Analysis With High Penetration Photovoltaics (PV)

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Introduction

Outline

- Introduction to photovoltaics
- Motivation
- Literature review
- Cloud shadow model
- Future work
Types of solar energy

Concentrating solar power (CSP)

Photovoltaics (PV)
PV development in US

US Photovoltaics Capacity

<table>
<thead>
<tr>
<th>Country</th>
<th>Capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>32,509</td>
</tr>
<tr>
<td>Italy</td>
<td>16,987</td>
</tr>
<tr>
<td>China</td>
<td>8,043</td>
</tr>
<tr>
<td>US</td>
<td>7,383</td>
</tr>
<tr>
<td>Japan</td>
<td>6,704</td>
</tr>
<tr>
<td>Spain</td>
<td>4,543</td>
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</tbody>
</table>
PV potential in US v.s. Germany and Spain
Motivation

- Impact of PV: variability and uncertainty
- Modeling PV generation considering cloud shadows
- Point measurement v.s. areal average
- No high resolution data (power or irradiance)
Problem definition

Develop a package of solar irradiance models that can realistically generate solar irradiance time series for an area of interest under different weather conditions.

- Sunlight: clear, partially cloudy or overcast.
- Cloud coverage ratio: fixed or changing.
- Wind: speed and direction.
Literature review

- Measurement grid: very expensive.
- Satellite images: no sequential images with good spatial resolution.
- Numerically generate cloud patterns.
Literature review

W. T. Jewell et al. (1987 to 1990)
Literature review

D. L. Garrett et al. (1989)
Literature review

H. G. Beyer et al. (1994)
Literature review

W. T. Jewel and D. L. Garrett:
- Simple and rigid shape of clouds.
- No consideration of cloud coverage ratios.

H. G. Beyer
- Single frame of cloud pattern.
- Fixed meteorology conditions, e.g. wind speed and cloud coverage.
Contribution

Extend Beyer’s work in:

- Arbitrary number of frames of cloud pattern to enable longer-term simulation studies.
- The global irradiance is modeled by two separate components, e.g. beam and diffuse irradiance.
- The effect of variable cloud thickness is reproduced;
- Statistics from measured data are qualitatively applied in the synthesis of the solar irradiance to obtain a realistic variation.
- The model can represent variable wind speed and cloud coverage ratio.
Overview

Irradiance Model During Days with Cumulus Clouds:

- Solar irradiance characteristics.
- Basics of fractal-based cloud generation.
- Meteorological and geographic parameters.
- Cloud pattern Generation.
- Synthesis of the irradiance pattern.
Solar irradiance characteristics

Experimental station at Iowa State University.

- 270 Wp DC-off grid PV station.
- MPPT.
- NI ENET 9205 sampling card.
- Logging data at 1-sec interval.
Solar irradiance characteristics

Key questions:

- How to model the beam and diffuse component in the cloud-based irradiance model?

- What is the duration of shading?

- How severe is the shading?
Solar irradiance characteristics

(a) Global horizontal irradiance (solid) and the estimated diffuse horizontal irradiance (dotted).
(b) Zenith angle.
(c) Beam normal irradiance (solid) and the digitization threshold (dotted).
(d) Digitized shading condition.
Solar irradiance characteristics

Answers:

- The beam irradiance will be directly affected by the cloud shadow.

- A constant value or a slowly changing profile is used for the diffuse irradiance.

- Apply this process to all data collected to get the statistics of the beam irradiance.
Basics of fractal-based cloud generation

What is a fractal?

Mandelbrot:
A fractal is defined as a rough or fragmented geometric shape that can be split into parts, each of which is, at least approximately, a reduced-size copy of the whole.
Basics of fractal-based cloud generation

Midpoint displacement algorithm.

Takes \( \log_2^N \) stages to generate a \((N + 1) \times (N + 1)\) fractal surface.

2 steps in each stage.

Added noise \( \varepsilon \sim \mathcal{N}(0, \sigma^2) \).

In each step \( \sigma \) is reduced.

5x5 grid example \((N = 4)\)
Basics of fractal-based cloud generation

Generate a 33 x 33 fractal surface:

Stage 0 (Initialization)
Basics of fractal-based cloud generation

Generate a 33 x 33 fractal surface:

Stage 1
Basics of fractal-based cloud generation

Generate a 33 x 33 fractal surface:

Stage 2
Basics of fractal-based cloud generation

Generate a 33 x 33 fractal surface:

Stage 3
Basics of fractal-based cloud generation

Generate a 33 x 33 fractal surface:

Stage 4
Basics of fractal-based cloud generation

Generate a 33 x 33 fractal surface:

Stage 5
Basics of fractal-based cloud shadow generation

From the fractal surface to the cloud pattern.

513-by-513 fractal surface

Cloud shadow pattern obtained with $R = 33.4\%$
Relationship between the cutting surface height \((h)\) and the cloud coverage ratio \((R)\)
Meteorological and geographic parameters

(a) Cloud coverage ratio.
(b) Wind speed at cloud height.
Geographic layout of measurement points.
Cloud pattern Generation

Steps to generate the cloud pattern:

- Determine the number of frames to generate, based on the wind speed and simulation time.

- Calculate the cutting surface, based on the cloud coverage ratio.

- Represent the change of thickness of clouds by a multi-layer technique.
Cloud pattern Generation

Determine the number of frames:

\[ F = \text{ceil} \left( \frac{\sum_{k=k_s}^{k_e-1} v_w(t_k) \Delta t}{(N + 1)s} \right) + 1 \]  

(1)

where:

- \( F \) is the number of frames to generate.
- \( k_s \) and \( k_e \) are the start and end index of the simulation time step.
- \( v_w \) is the wind speed.
- \( \Delta t \) is the step size, here 1 second.
- \( s \) is the scale.
Cloud pattern Generation

Calculate the cutting surface:

--- frames of fractal surface

--- 1st window at time $t_s$

--- 2nd window at time $t_s + 60\Delta t$

•••• 3rd window at time $t_s + 120\Delta t$
Interpolate the cutting surface value:

Comparison of the cutting surface height before and after interpolation.
Cloud pattern Generation

Represent the change of the thickness of cloud (multi-layer technique):

- Create $K-1$ more cutting surface below the original one.
- Each cutting surface is lowered by a factor $l = \frac{h_{\text{max}} - h_{\text{min}}}{\alpha}$.
- Assign clouded pixels in $k$-th layer values using a uniform distribution $\mathcal{U}(a, b)$, where $a = \frac{(k - 1)}{K}$, $b = \frac{k}{K}$, and $k = 1, 2, ..., K$. 
Cloud pattern Generation

Result of generated cloud shadow pattern.

(Top) Generated binary cloud shadow pattern for time period between 2:00 and 3:00 PM. The wind direction is SW. A is the study area.
(Bottom) Final cloud shadow pattern, using a multi-layer rendering technique. The pixels of the hatched area on the right were not needed in this simulation.
Cloud pattern Generation

Magnified cloud shadow pattern.
Synthesis of the irradiance pattern

(a) Cloud transparency level.
(b) Beam horizontal irradiance under clear sky condition.
(c) Synthesized global horizontal irradiance pattern.
(d) Averaged irradiance pattern.
Future work

- Complete the solar irradiance package for three major conditions:
  - Fully clear day.
  - Partially cloudy day.
  - Overcast day.

- Establish a PV panels model library.

- Improve the test feeder model by adding location of each house.

- Perform simulation studies to investigate the impact of high penetration PV.

- Test the performance of control methods under different weather conditions.
Thank you!

Questions?

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