DEGRADATION AND RESILIENCE OF PRE-CRACKED PV-MODULES

AGCS Expert Days 2017, November 2nd, 2017, München

Dr.-Ing. Claudia Buerhop
PV-inspection
Performance study of pre-cracked modules

Visualization of cracks using imaging techniques

Electroluminescence EL-imaging

EL-images visualize e. g.

- **cracks** in solar cells $\rightarrow$ normally no impact on electrical power output
- Electrically **inactive cell area** by differing shades of grey and black $\rightarrow$ impact on electrical power output

Nominal module power $P_0 = 232.2$ W

Actual module power $P = 228.8$ W
Study of crack evolution in PV-modules at real operating conditions

1. EL-imaging – visualization of cracks in PV-modules, and now?
2. Experimental study – field test, lab study and FEM-simulations
3. Case study I – cleaning procedure
4. Case study II – severe storm event
Performance study of pre-cracked modules

How does the module look like after one year of field exposure?

At the beginning

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Option A: unchanged

Option B: Low impact

Option C: Strong impact

P0/P0 = 100%
P/P0 = 99%
P/P0 = 98%
P/P0 = 97%
Performance study of pre-cracked modules

Approach

Field study

• 54 modules pre-cracked
• 1 year → continuous monitoring of weather data, string power, module temp.
• → 3 times: IR-, EL- imaging, module power

Load testing in the lab

• 20 modules pre-cracked
• Static loading – over- and underpressure – simulating snow and wind loads
• EL-imaging, IV-curves, strain measurements

FEM-simulations

• Abaqus
• Stress distribution
Field exposure

PV-plant and weather conditions (in Bavaria, Oct. 2015 - Dec. 2016)

Test facility

- Module mounting system
- Over- and underpressure
- EL-imaging (InGaAs-camera, 100 Hz)
- Strain gauges
- „Mobile flasher“
Lab testing

EL-images with increasing loading and unloading

- At loading → crack opening
- At unloading → crack closure
Lab testing

Power outcome at loading and unloading

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Lab testing

Wind and snow loads

- **V\text{\scriptsize max} = 137 \text{ km/h}**
- **V\text{\scriptsize mean} = 32 \text{ km/h}**

Lab testing

EL-images at loaded (400 Pa + 5000 Pa) and unloaded state

EL-images at ex-post loaded state simulating normal operating conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Image 1</th>
<th>Image 2</th>
<th>Image 3</th>
<th>Image 4</th>
<th>Image 5</th>
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</thead>
<tbody>
<tr>
<td>initial</td>
<td>P/P0 = 100%</td>
<td>P/P0 = 98%</td>
<td>P/P0 = 89%</td>
<td>P/P0 = 98%</td>
<td>P/P0 = 99%</td>
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<tr>
<td>at p = 0 Pa</td>
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<td>p = 400 Pa</td>
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<td>at p = 5000 Pa</td>
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<td>After p = 5000 Pa</td>
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<td>at p = 0 Pa</td>
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<td>Ex-post</td>
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<td>p = 300 Pa</td>
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<tr>
<td>p = 400 Pa</td>
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</table>

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FEM-simulations

Stress distribution across the material layers

Simulation assumptions:
- Static, planar loads
- No busbars, no gridfingers
- No cracks
- Linear, elastic material properties
FEM-simulations

Stress distribution on cell level

Quarter model, $p = 1000 \, \text{Pa}$

FEM-Simulation vs. EL-images

Crack orientation

loaded state

FEM-simulation

Difference image between EL-images of loaded and intial state

Unloaded state

Module 744, 3600 Pa
EL-image – crack distribution

Difference image between EL (4600 Pa) and EL (0 Pa)

Field exposure

PV-plant and weather conditions (in Bavaria, Oct. 2015 - Dec. 2016)

Max. wind speed

Field data

EL-imaging

Oct 2015

May 2016 / Oct 2016

- No newly cracked cells
- Changes in intensity distribution possible
Field data

Module power measurement

module power in W

module ID with description

INV 1
moderate + few cracks

INV 2
good + few cracks

INV 3
bad + cracks

INV 4
moderate + cracks

INV 5
mixed

INV 6
mixed

Oct 2015  May 2016  August 2016

Performance study of pre-cracked modules

Conclusion – static planar loading = simulating snow or wind loads

At the beginning

Option A: unchanged

- Cracks open and close
- Open cracks → power loss possible
- Moderate weather conditions including several severe wind scenarios → no detectable / measurable changes

• Existing cracks do not necessarily impact the performance negatively at real operating conditions.
Case study I - Cleaning of PV-systems
Case study I - Cleaning of PV-systems
Case study I - Cleaning of PV-systems

BEFORE loading procedure = cleaning

P = 228W

AFTER loading procedure = cleaning

P = 227W

Walking over modules
Case study I - Cleaning of PV-systems

Simulating subsequent „normal“ operating conditions

\( v_{\text{wind}} = 55 \text{ km/h} \)
\( h_{\text{snow}} = 5 \text{ cm (wet snow)} \)
\( - 20 \text{ cm (fresh snow)} \)

\( v_{\text{wind}} = 96 \text{ km/h, storm} \)
\( h_{\text{snow}} = 15 \text{ cm (wet snow)} \)
\( - 60 \text{ cm (fresh snow)} \)

\( v_{\text{wind}} = 124 \text{ km/h} \)

\( p = 0 \text{ Pa} \)
\( p = 200 \text{ Pa} \)
\( p = 600 \text{ Pa} \)
\( p = 1000 \text{ Pa} \)
\( p = 0 \text{ Pa} \)

\( \frac{P}{P_0} = 100\% \)
\( \frac{P}{P_0} = 99\% \)
\( \frac{P}{P_0} = 91\% \)
\( \frac{P}{P_0} = 89\% \)
\( \frac{P}{P_0} = 99\% \)
Case study II - Extreme weather events

Hurricanes or hail storms

Cadolzburg, Germany,
18th August 2017
Max. wind speed = 91 km/h
source: www.wetteronline.de
Case study II - hail storm

Simulating subsequent „normal“ operating conditions

\[ p = 0 \text{ Pa} \quad \quad p = 200 \text{ Pa} \quad \quad p = 400 \text{ Pa} \quad \quad p = 1000 \text{ Pa} \quad \quad p = 0 \text{ Pa} \]

\[ v_{\text{wind}} = 55 \text{ km/h, high wind} \]
\[ h_{\text{snow}} = 5 \text{ cm (wet snow)} \quad - 20 \text{ cm (fresh snow)} \]

\[ v_{\text{wind}} = 78 \text{ km/h, strong gale} \]
\[ h_{\text{snow}} = 10 \text{ cm (wet snow)} \quad - 40 \text{ cm (fresh snow)} \]

\[ v_{\text{wind}} = 124 \text{ km/h, hurricane force} \]

\[ \frac{P}{P_0} = 100\% \quad \quad \frac{P}{P_0} = 100\% \quad \quad \frac{P}{P_0} = 100\% \quad \quad \frac{P}{P_0} = 97\% \quad \quad \frac{P}{P_0} = 99\% \]
Degradation of pre-cracked PV-modules

Cell cracks – only half as bad?
Degradation of pre-cracked PV-modules

• loading tests in the lab
  → At low loads – existing cracks open
  → At high loads – new cracks are initiated
    -- power reduction due to open cracks

• field measurements
  → At moderate weather – no measurable/visible changes

• „Long-term performance of cracked PV-modules?“
  → First answers: Resilience and mechanical stability of pre-cracked PV-modules
THANK YOU FOR YOUR ATTENTION!

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