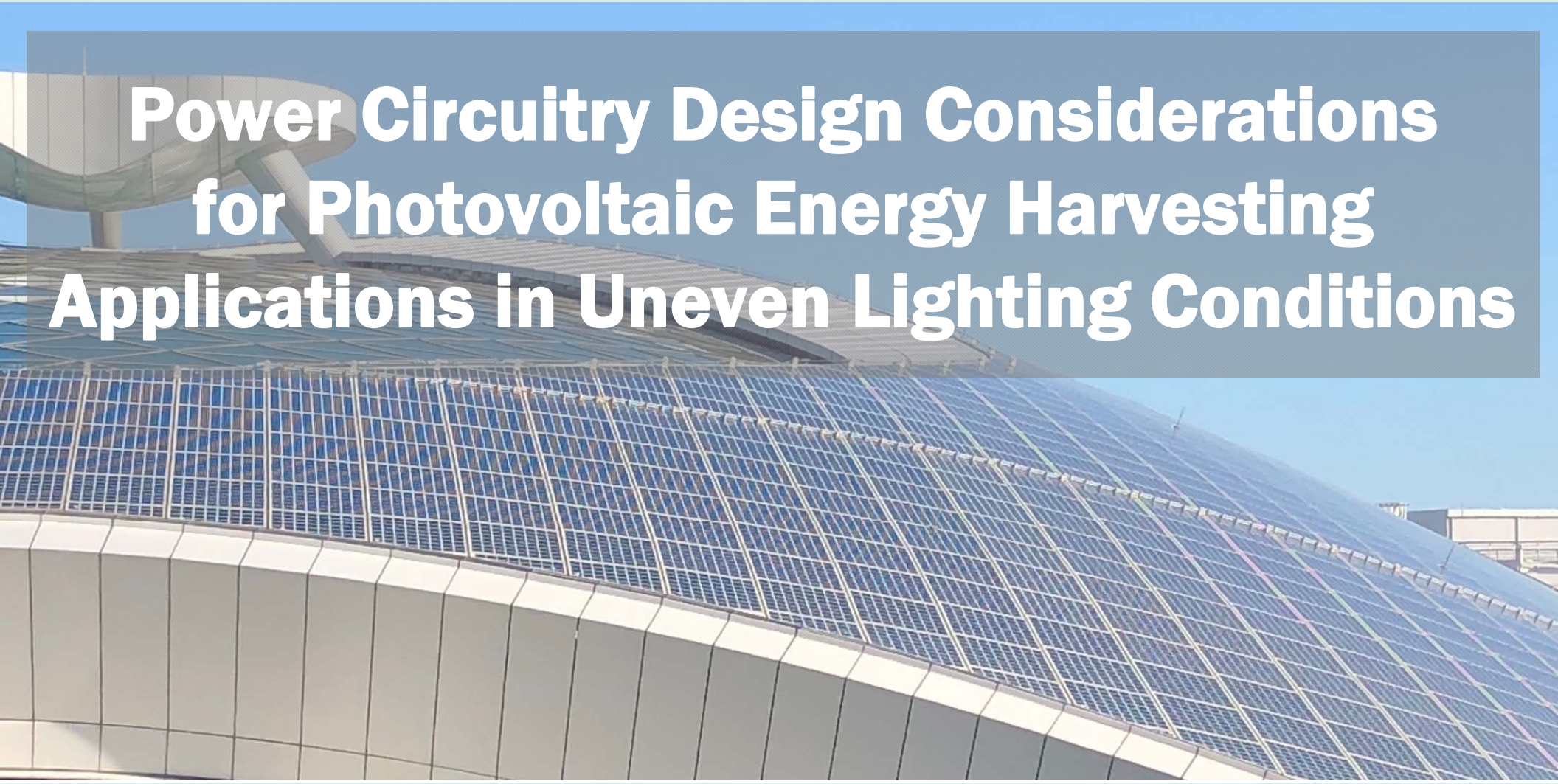
Power Circuitry Design Considerations for Photovoltaic Energy Harvesting Applications in Uneven Lighting Conditions



Katherine A. Kim

F. Selin Bagci, Franklin Bien, Yu-Chen Liu

May 30, 2018

ULSAN NATIONAL INSTITUTE OF SCIENCE AND TECHNOLOGY

정보통신기술진흥센터 IITP

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Selin Bagci

Prof. Franklin Bien, UNIST

SMTRC

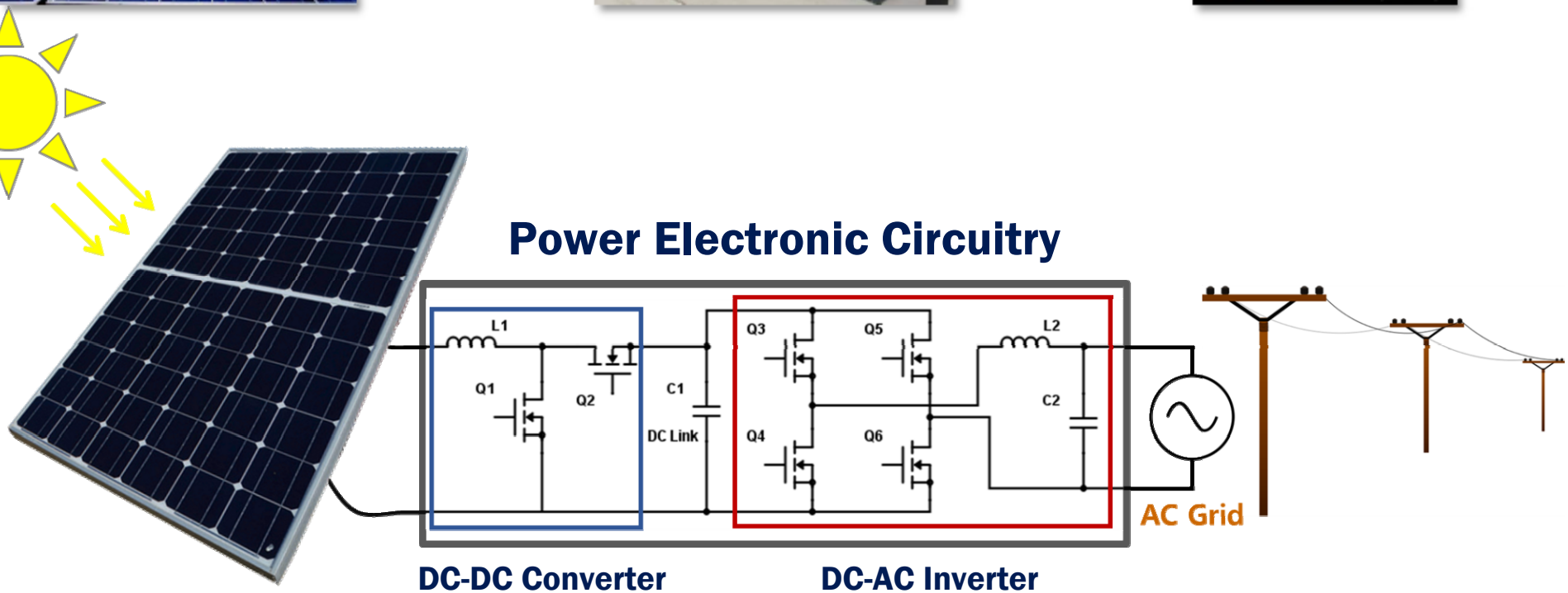
Self-Powered Mobile Tracker Research Center

Prof. Yu-Chen Liu, National Ilan Univ.
Collaborator, Power Electronics

Outline

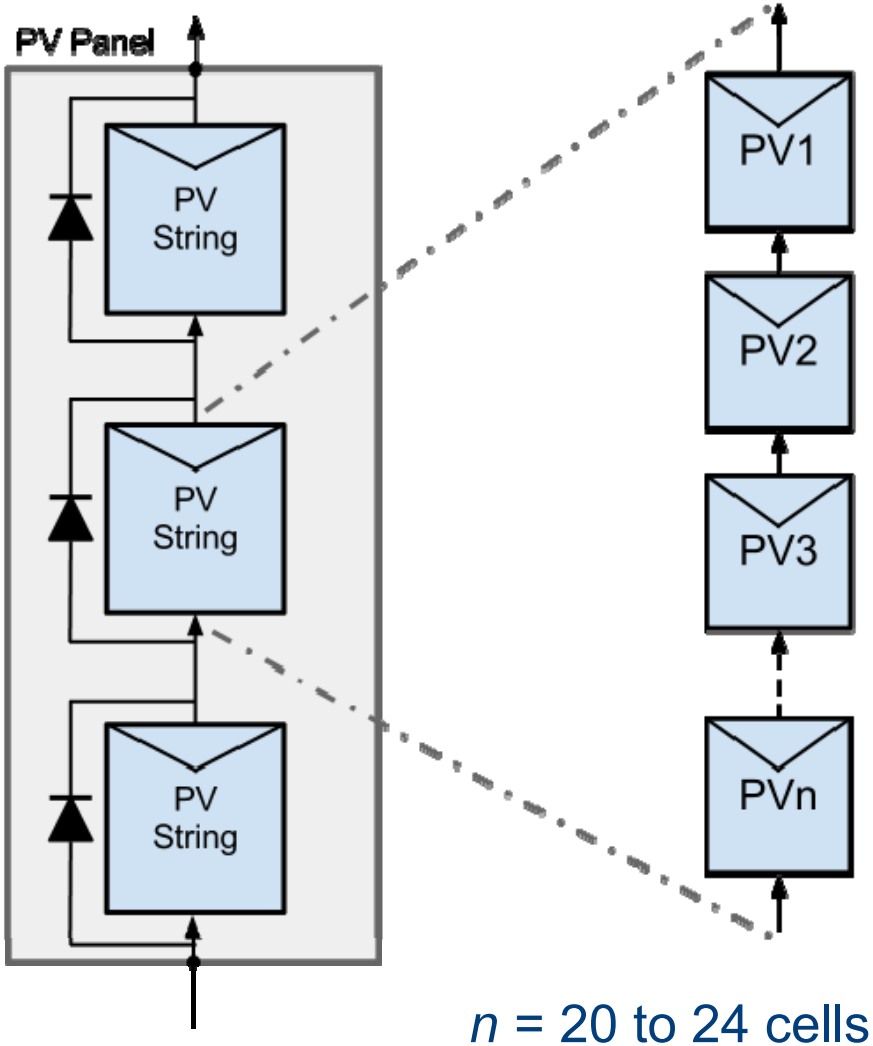
1. Emerging Photovoltaic (PV) Applications
2. PV Differential Power Processing Applications
    1. Series DPP PV Applications
    2. Parallel DPP for PV-powered wearable applications
3. Conclusion

Grid-Connected PV Systems



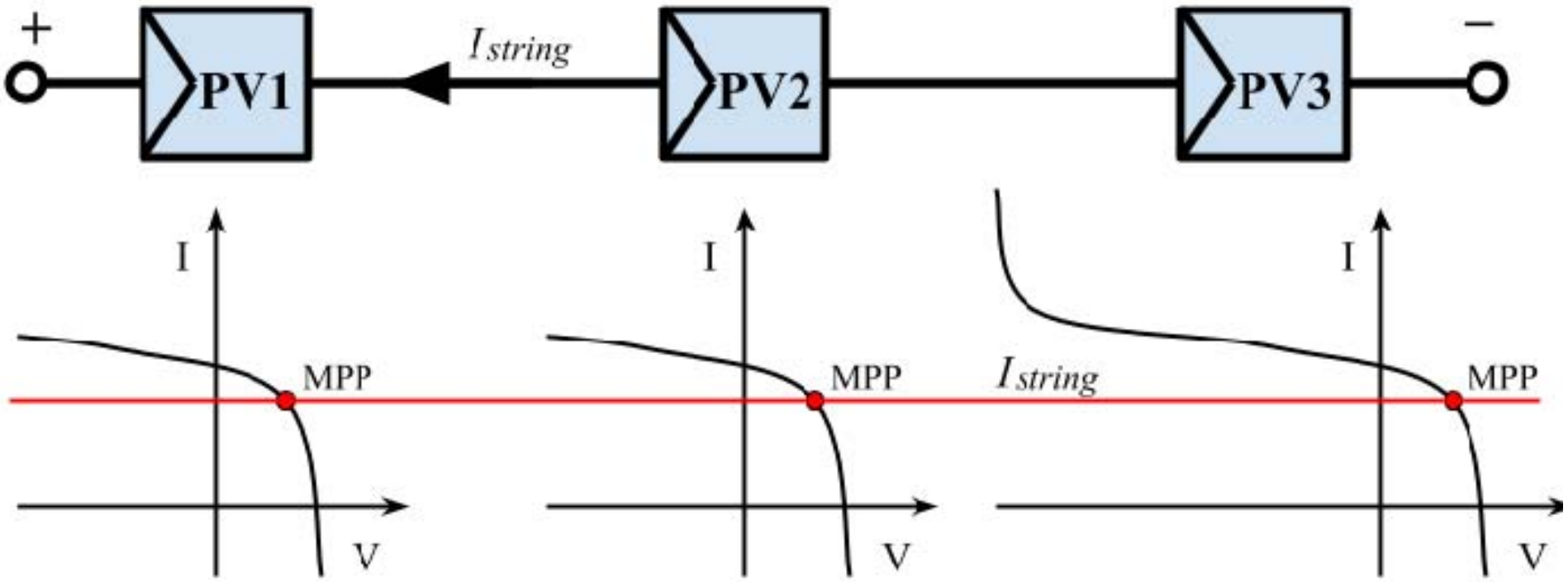
PV Cells Connected in Series

[Image Source: GreenSourceGS.com]



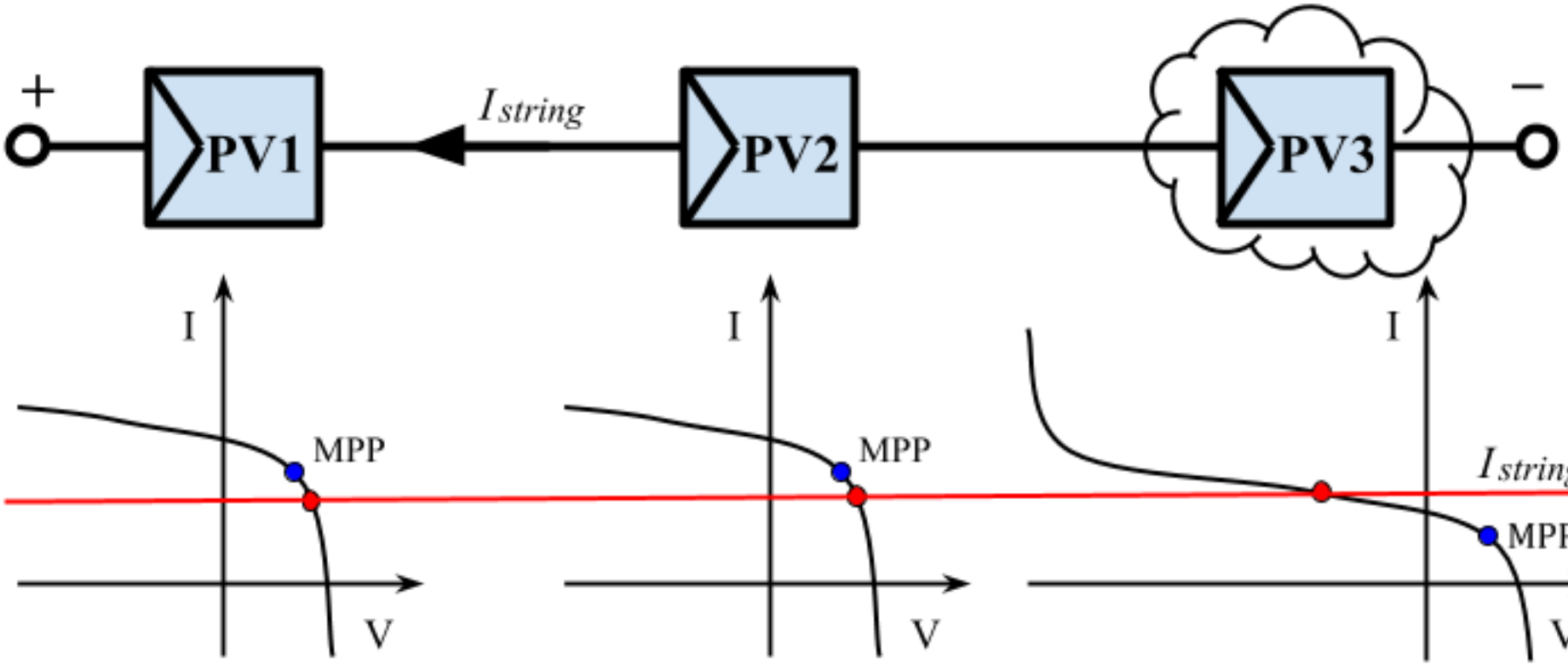
n = 20 to 24 cells

PVs in Series – Even Illumination



K. A. Kim and P. T. Krein, “Reexamination of Photovoltaic Hot Spotting to Show Inadequacy of the Bypass Diode,” IEEE J. Photovoltaic., 2015.

PVs in Series – Uneven Illumination

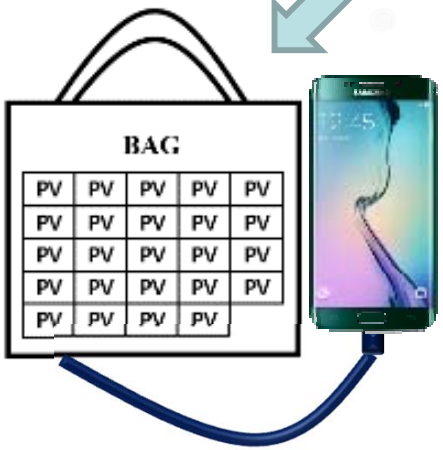


Series connection is not effective for uneven lighting

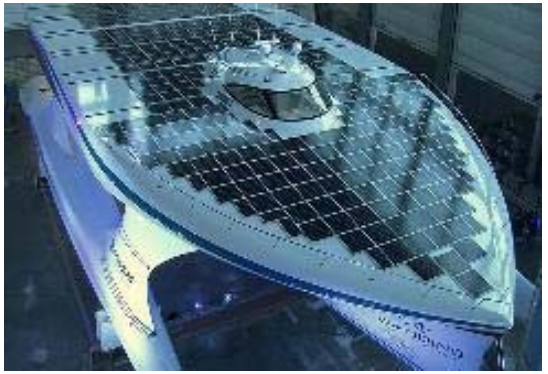
Emerging Photovoltaic Applications with Uneven Lighting Conditions

Roof-Top Installations

Electric Vehicles



Wearables and Internet of Things



Ships

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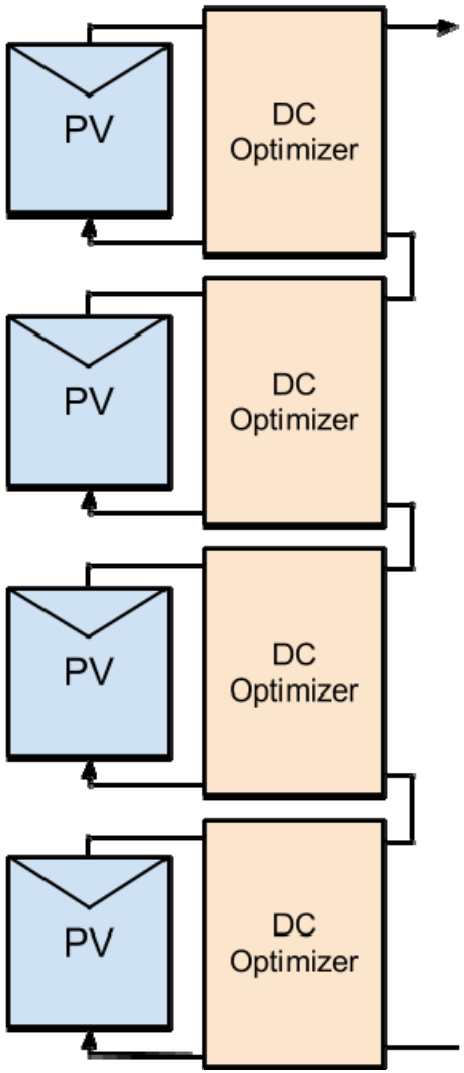
PV Series Differential Power Processing (DPP) Applications

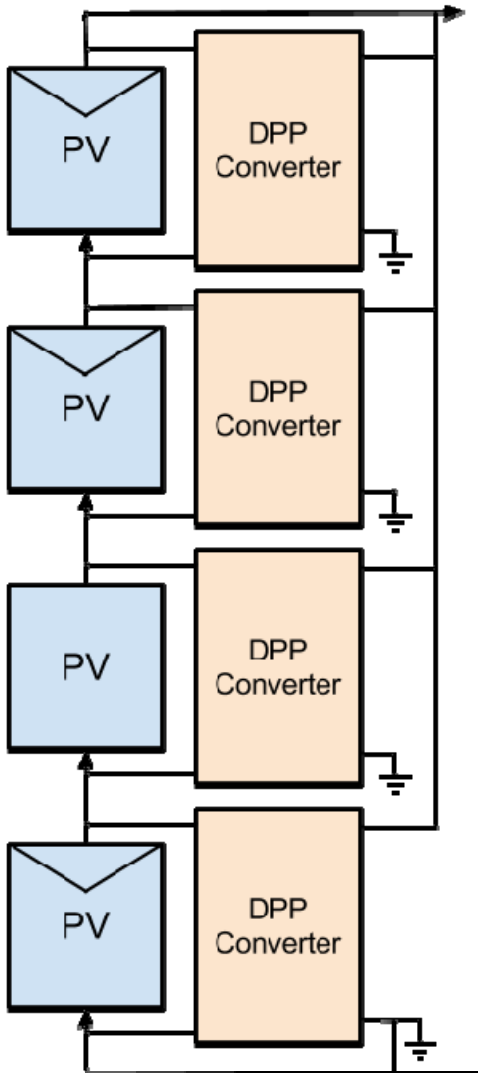
Overcoming Mismatch – DC Optimizer



- Panel-level
- Independent MPP control of each panel
- Processes 100% power
- Power rated for panel
- Maximum output is proportional to efficiency

G. R. Walker and P. C. Sernia, "Cascaded DC-DC converter connection of photovoltaic modules," *IEEE Trans. Power Electronics*, 2004.

Overcoming Mismatch – Differential Power Processing (DPP)

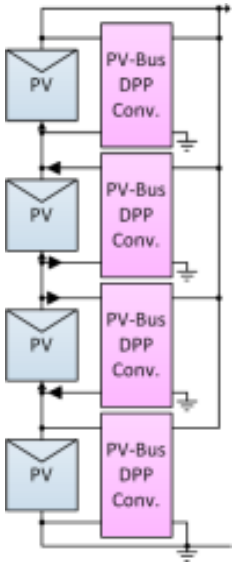


- Subpanel-level
- Independent MPP control of each string
- Lower power processed
- Lower power rating
- Higher output than dc optimizers

P. S. Shenoy, K. A. Kim, B. B. Johnson and P. T. Krein, "Differential Power Processing for Increased Energy Production and Reliability of Photovoltaic Systems," *IEEE Trans. Power Electronics*, 2013.

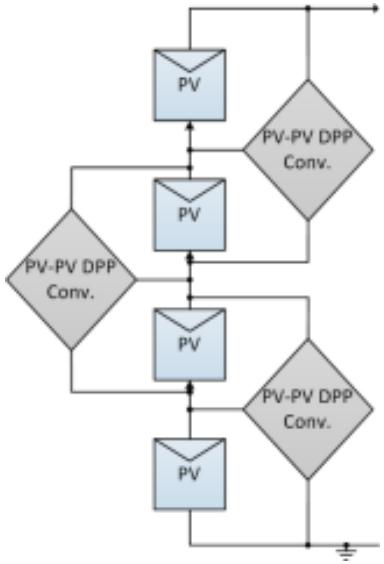
DPP Architecture Comparison

PV-to-Bus



- Advantages
  - Power draw from bus
  - Lower power processed
- Disadvantages
  - Not scalable
  - High output voltage rating

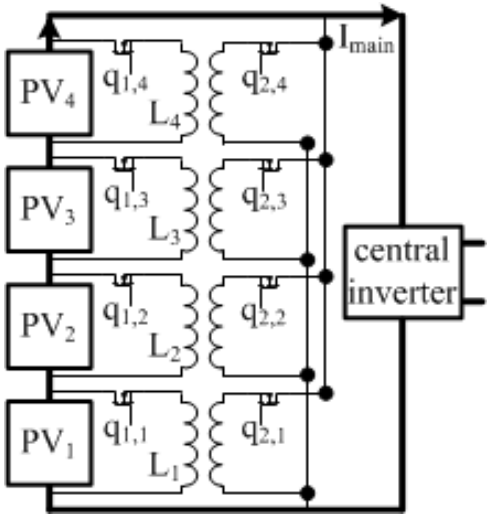
PV-to-PV



- Advantages
  - Scalable
  - PV-level Voltage rating
- Disadvantages
  - Power draw from neighbors
  - Higher power processed

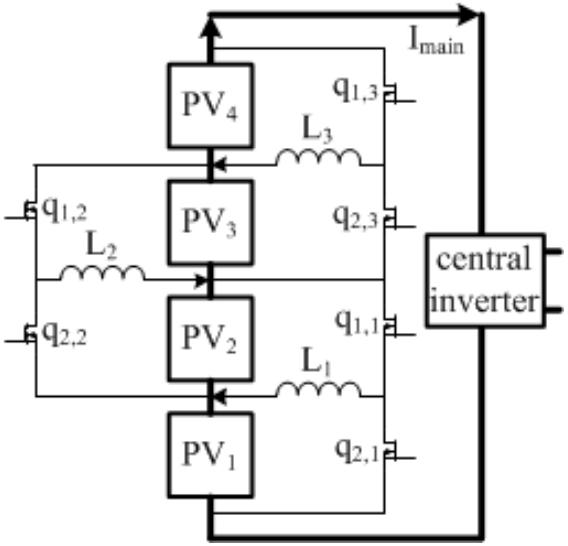
DPP Converter Topologies

PV-to-Bus Flyback



Bell and Pilawa-Podgurski, IEEE J. Emerging Selected Topics in Power Electronics, 2015.

PV-to-PV Buck-Boost



Qin, Barth and Pilawa-Podgurski, IEEE Trans. Power Electronics, 2016.

Series DPP Converter Findings

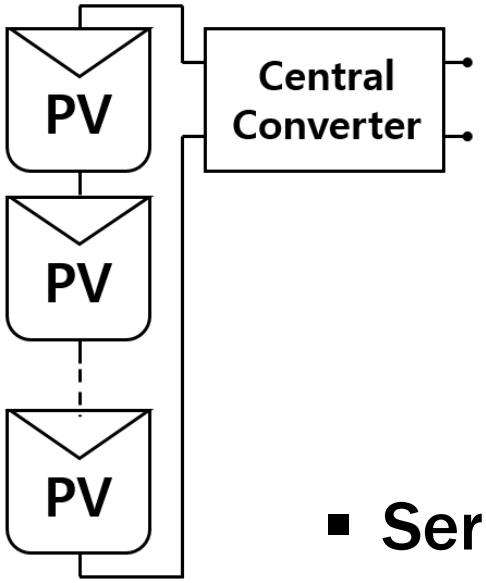
1. Superior performance over dc optimizers
2. Appropriate for higher-voltage applications
3. Best at mild mismatch conditions
4. Not as effective for long strings of PV cells

K. A. Kim, P. S. Shenoy, and P. T. Krein. “Converter rating analysis for photovoltaic differential power processing systems.” *IEEE Trans. Power Electron.*, 2014.

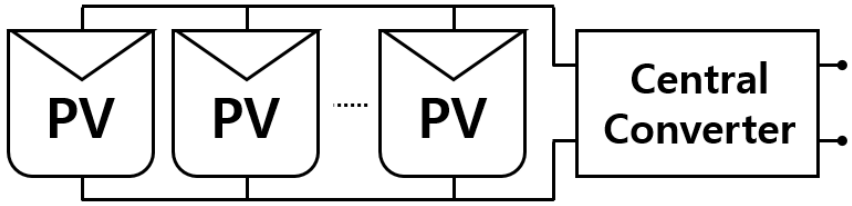
PV Parallel Differential Power Processing (DPP) Applications

Parallel vs. Series Connections

Series

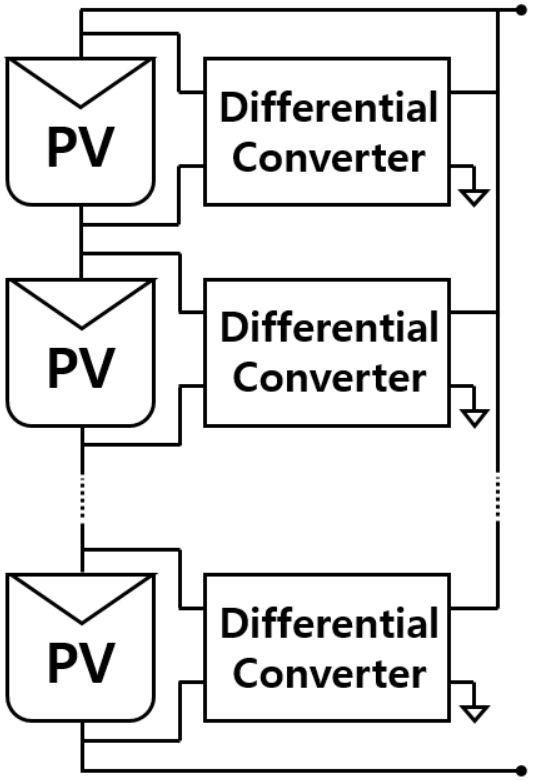


Parallel

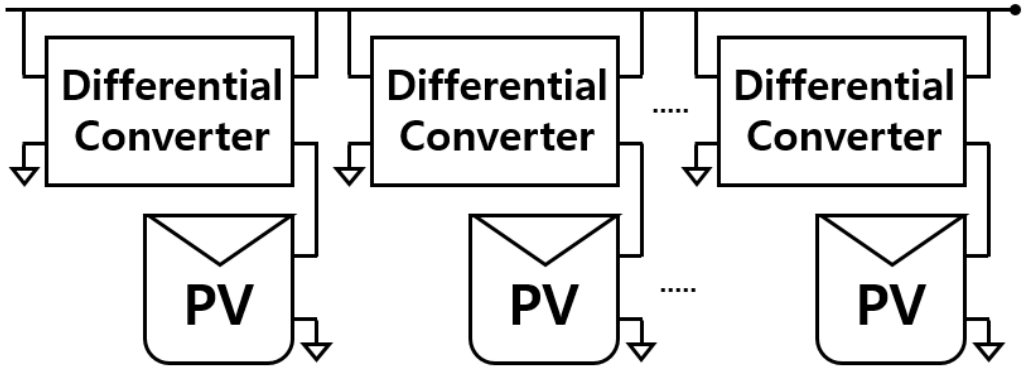


- Series
  - Higher voltage, lower current
  - Output power severely suffers from mismatch
- Parallel
  - Lower voltage, higher current
  - Output power less affected by my match

Differential Power Processing



DPP Series

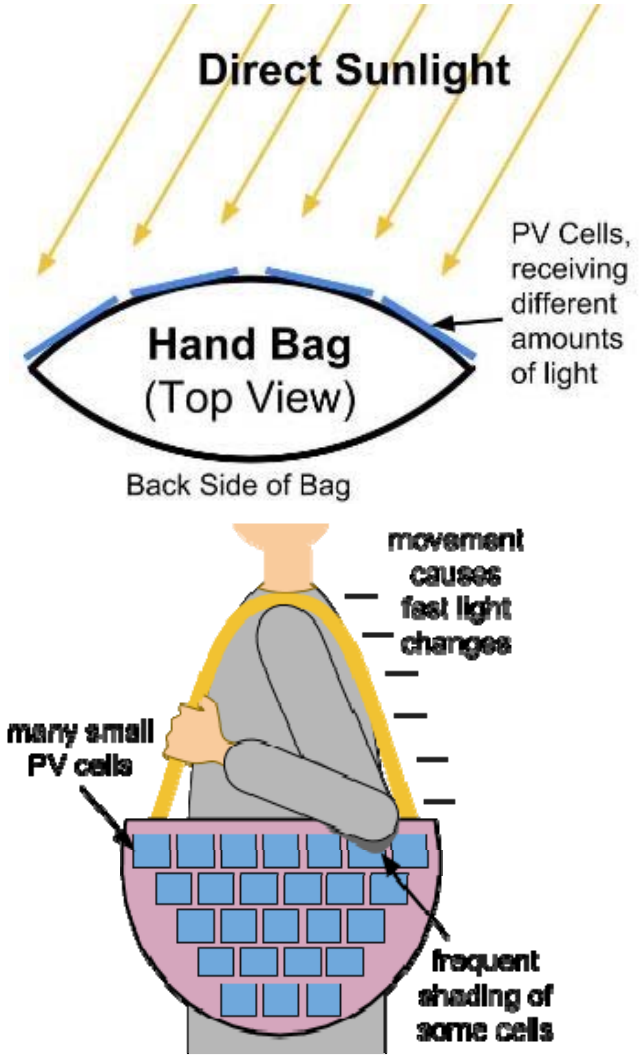


DPP Parallel

H. Zhou, J. Zhao and Y. Han, "PV Balancers: Concept, Architectures, and Realization," *IEEE Trans. Power Electronics*, 2015.

PV-Powered Wearable Application

Up to 5 W

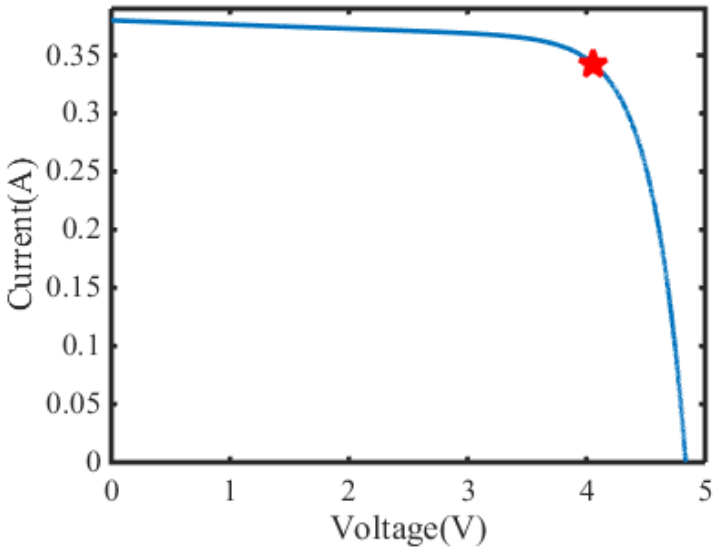


Goal: Charge mobile devices with ambient solar energy

Hyunji Lee and Katherine A. Kim, “Comparison of Photovoltaic Converter Configurations for Wearable Applications,” in Proc. IEEE Workshop on Control and Modeling for Power Electron., July 2015.

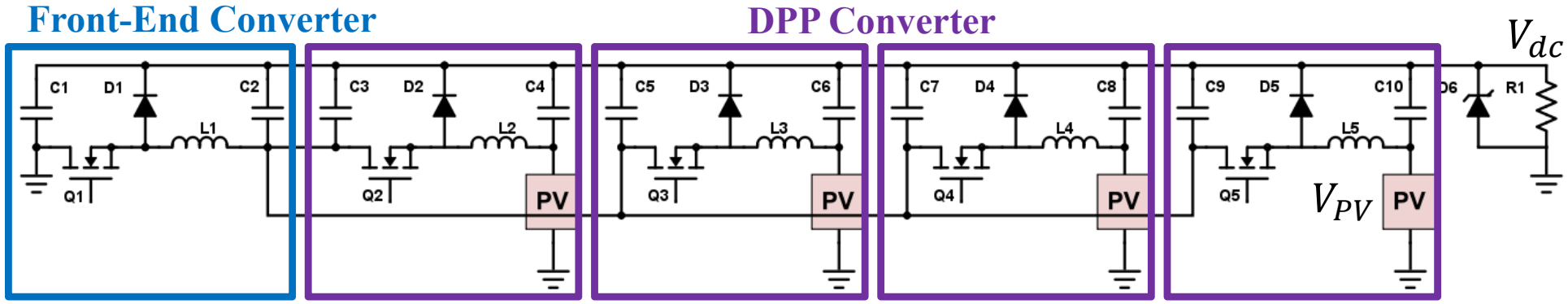
PV-Powered Charging Bag

I-V Characteristics



- I_{sc} : 0.37 A
- V_{oc} : 4.9 V
- I_{mpp} : 0.34 A
- V_{mpp} : 4.06 V
- P_{mpp} : 1.39 W

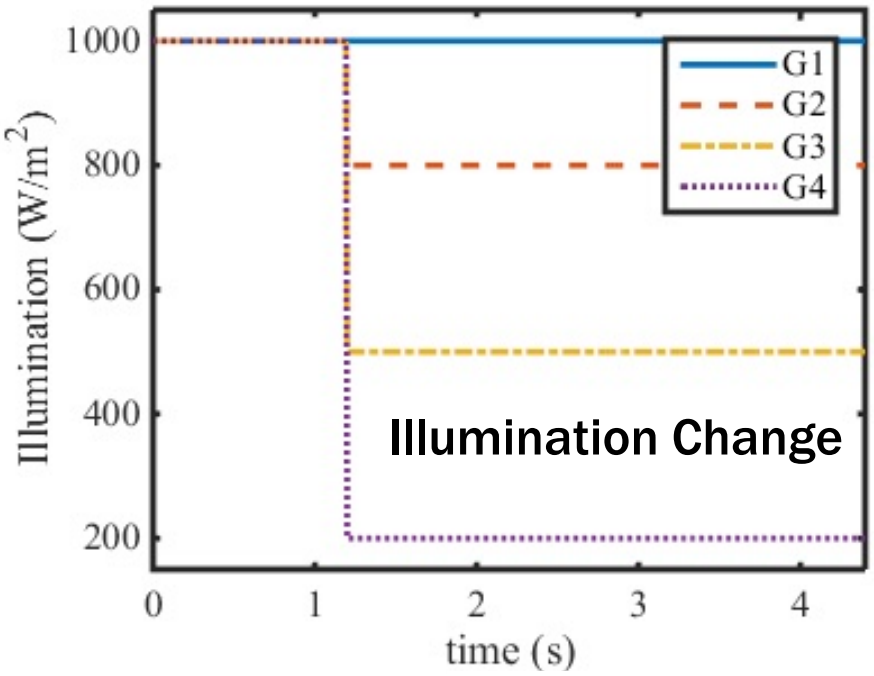
Parallel DPP System

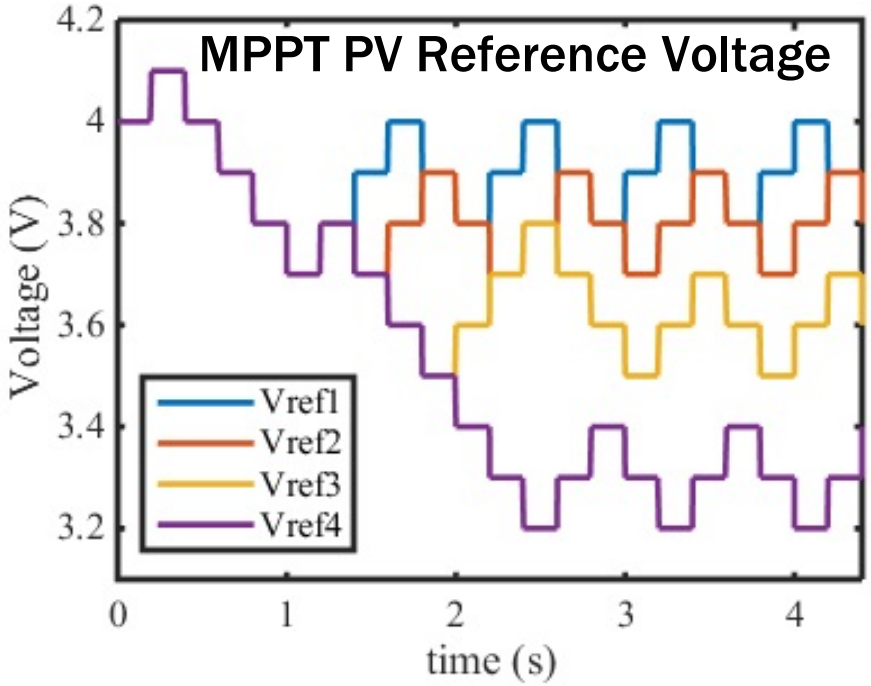


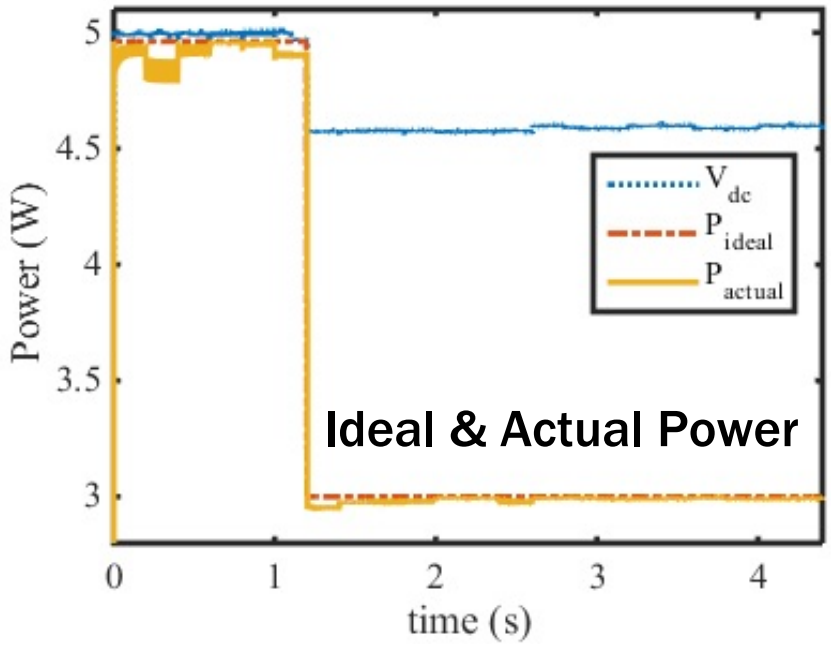
- A front-end converter + Four DPP converters
- Zener diode: clamp the dc voltage below 5.25 V
- Front-end converter: step down dc voltage 5 V → 2 V
- DPP converter input voltage: 2 V
- DPP converter output voltage: $V_{dc} - V_{PV,MPP}$

Hyunji Lee and Katherine A. Kim, "Differential Power Processing Converter Design for Photovoltaic Wearable Application," in Proc. Int. Power Electronics and Motion Control Conf., May 2016.

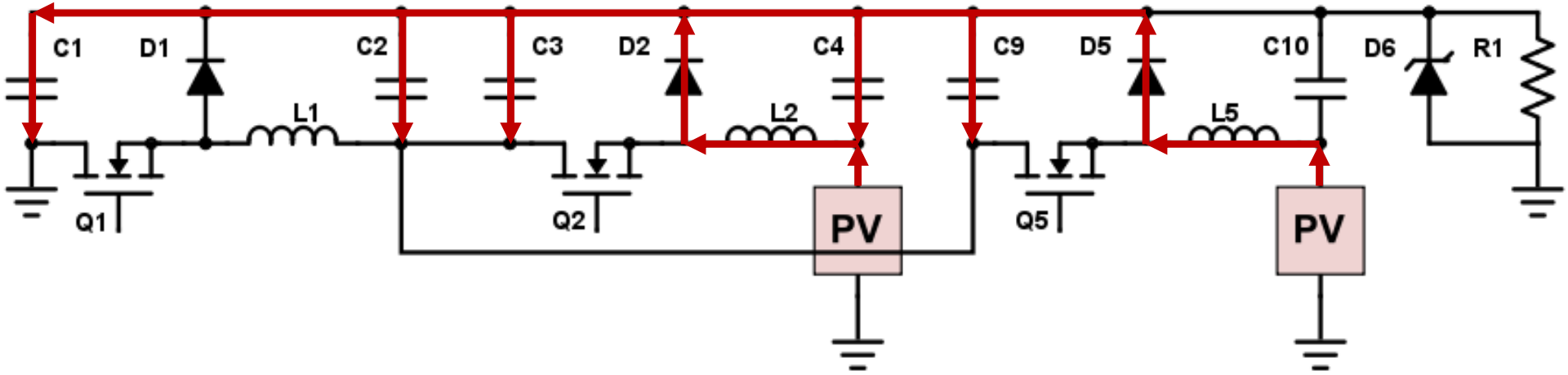
Simulation Results







Startup Operation

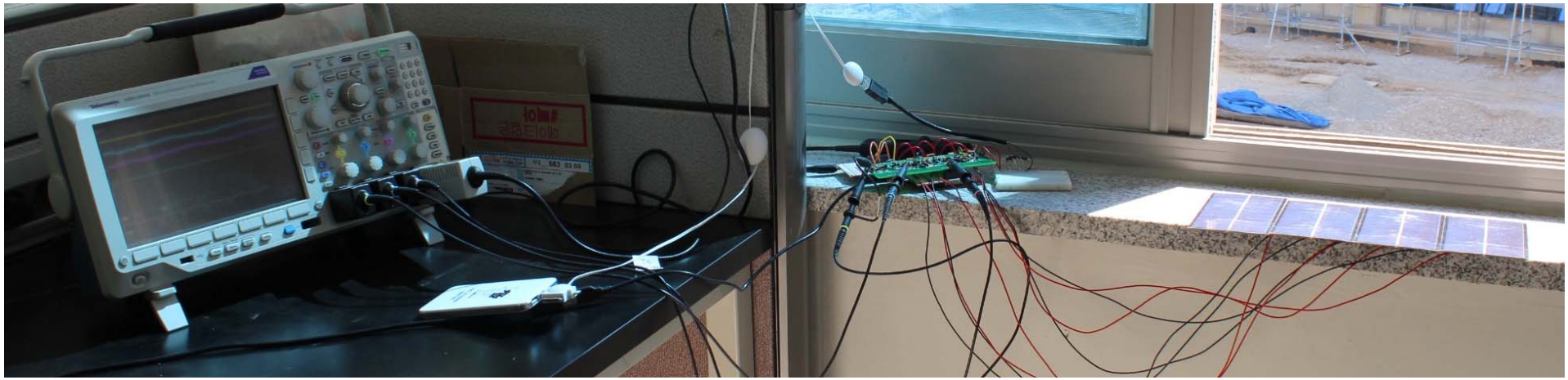


- Before the converters turn on, PV power will charge the bus capacitor through freewheeling diode
- After bus capacitor charged, controllers turn on
- Each DPP converter operates PV at its MPP

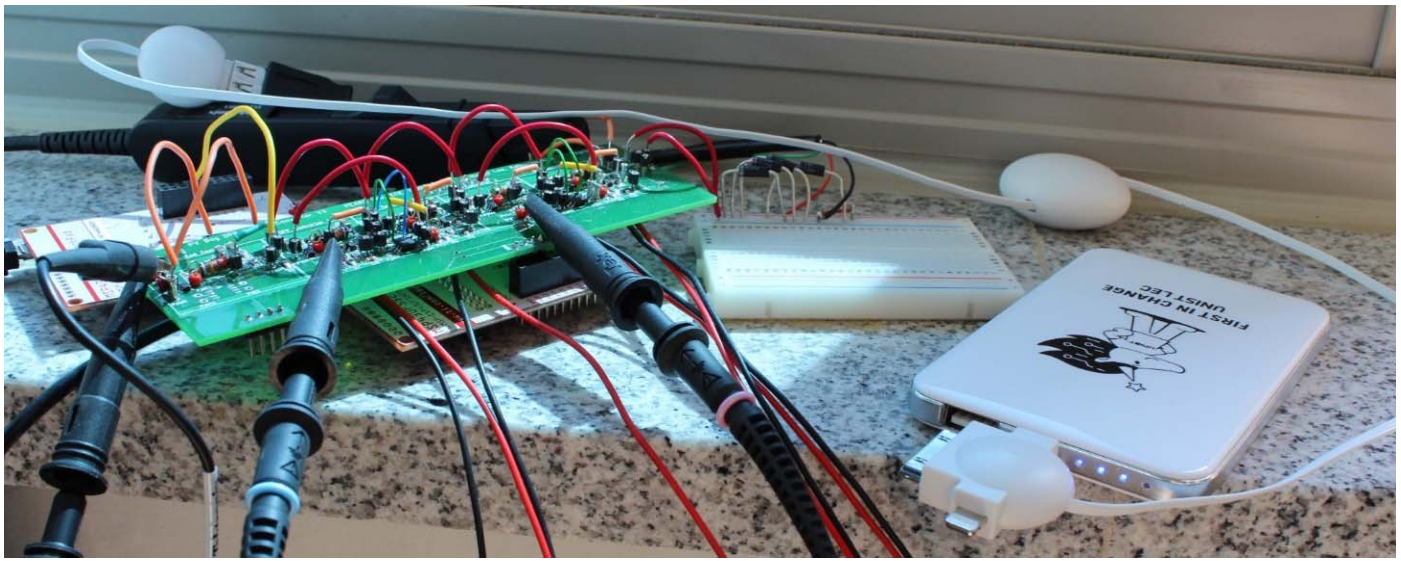
Experiment Setup

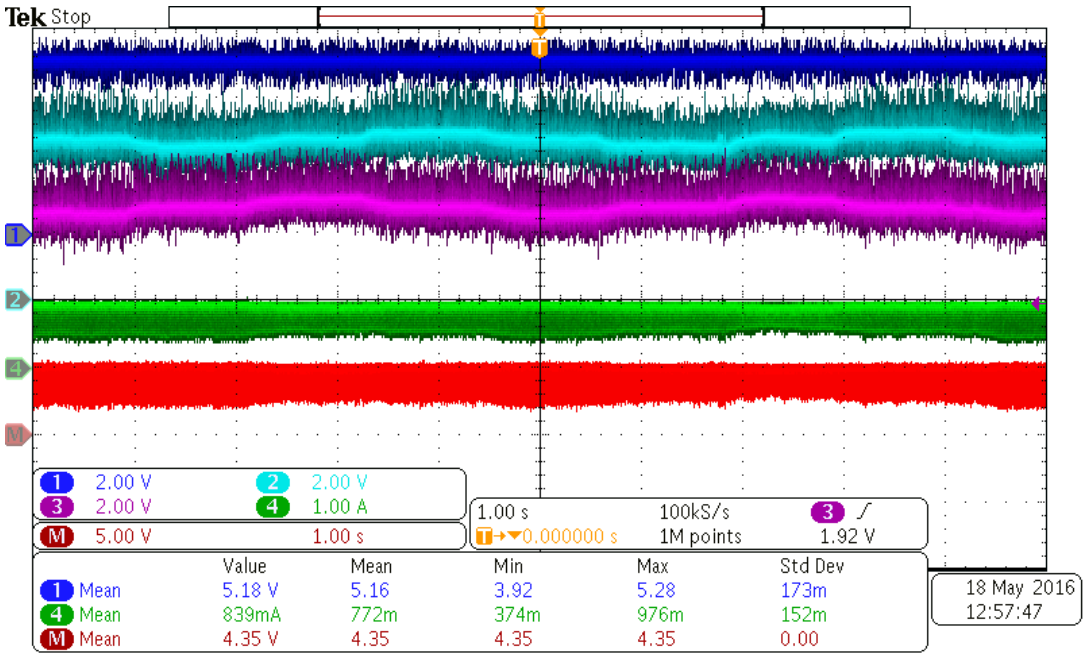
Element	Value
C_{in}	220 µF
$C_{in,fe}$	15 µF
$C_{out,fe}$	200 µF
$C_{in,dpp}$	47 µF
$C_{out,dpp}$	62 µF
L	2.7 µH
f_s	100 kHz

- 1 front-end converter, 4 DPP converters
- 4 PV cells, Zener diode, battery load



Experimental Results





- Average Values
  - V_{DC}: 5.18 V
  - I_{out}: 0.84A
  - P_{out}: 4.35 W

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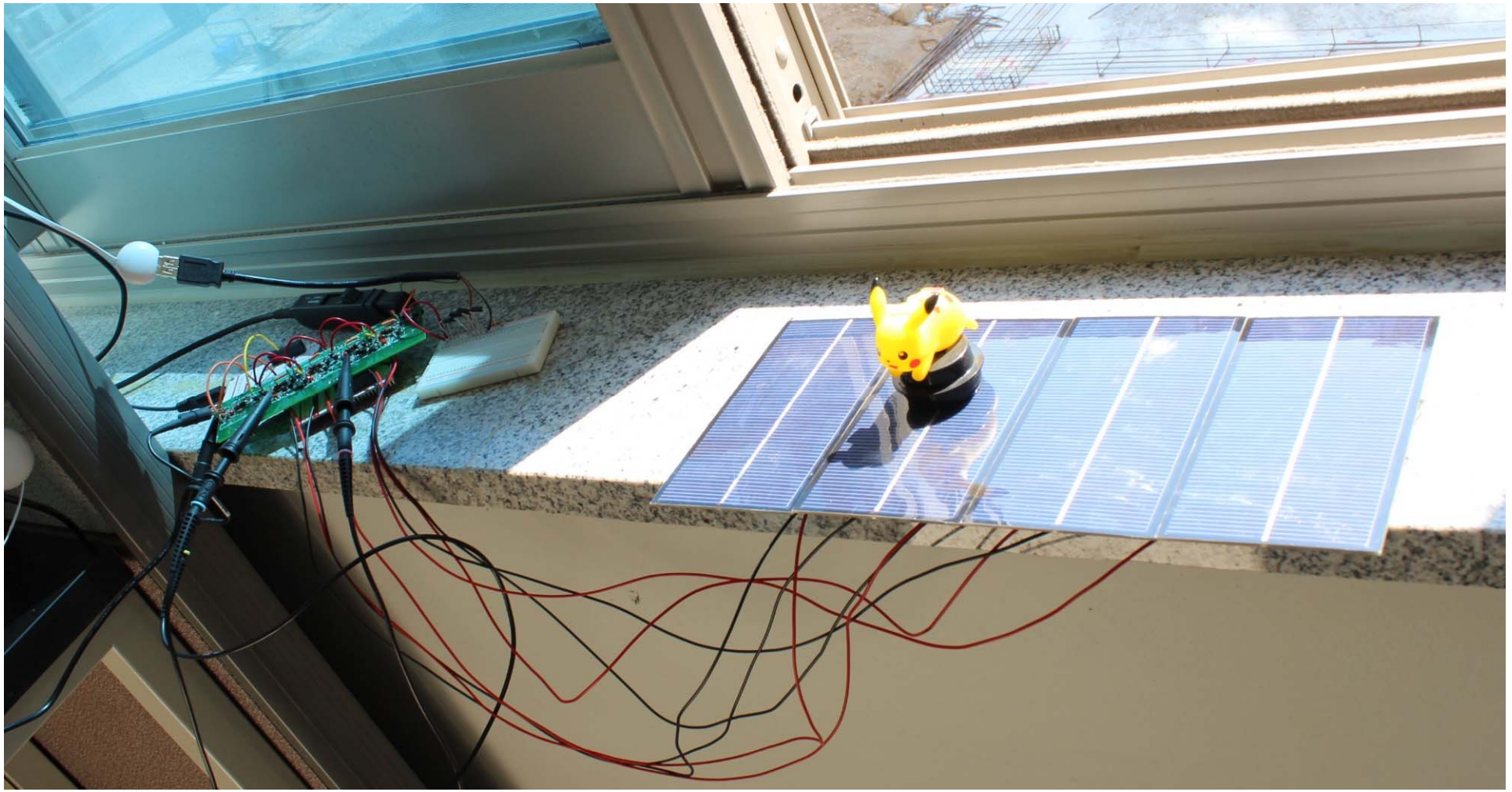
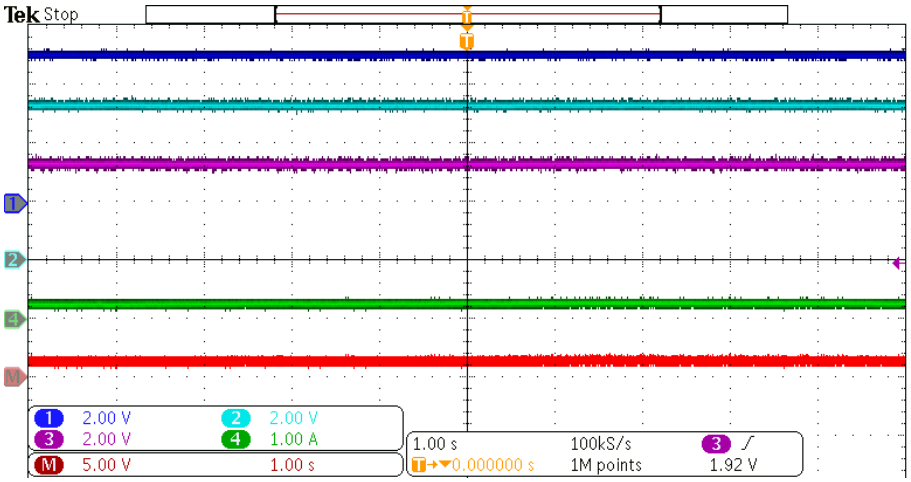
Experiment with Partial Shading



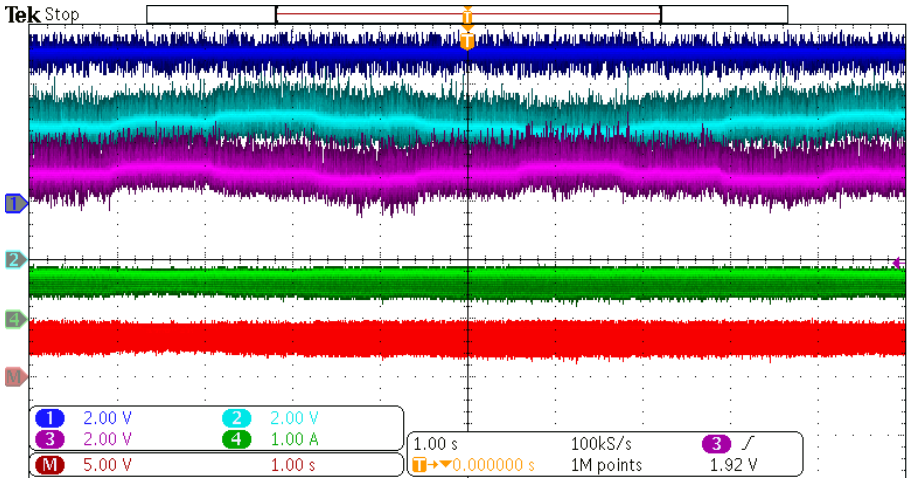
Partial Shading Experimental Results

Without DPP (Parallel)



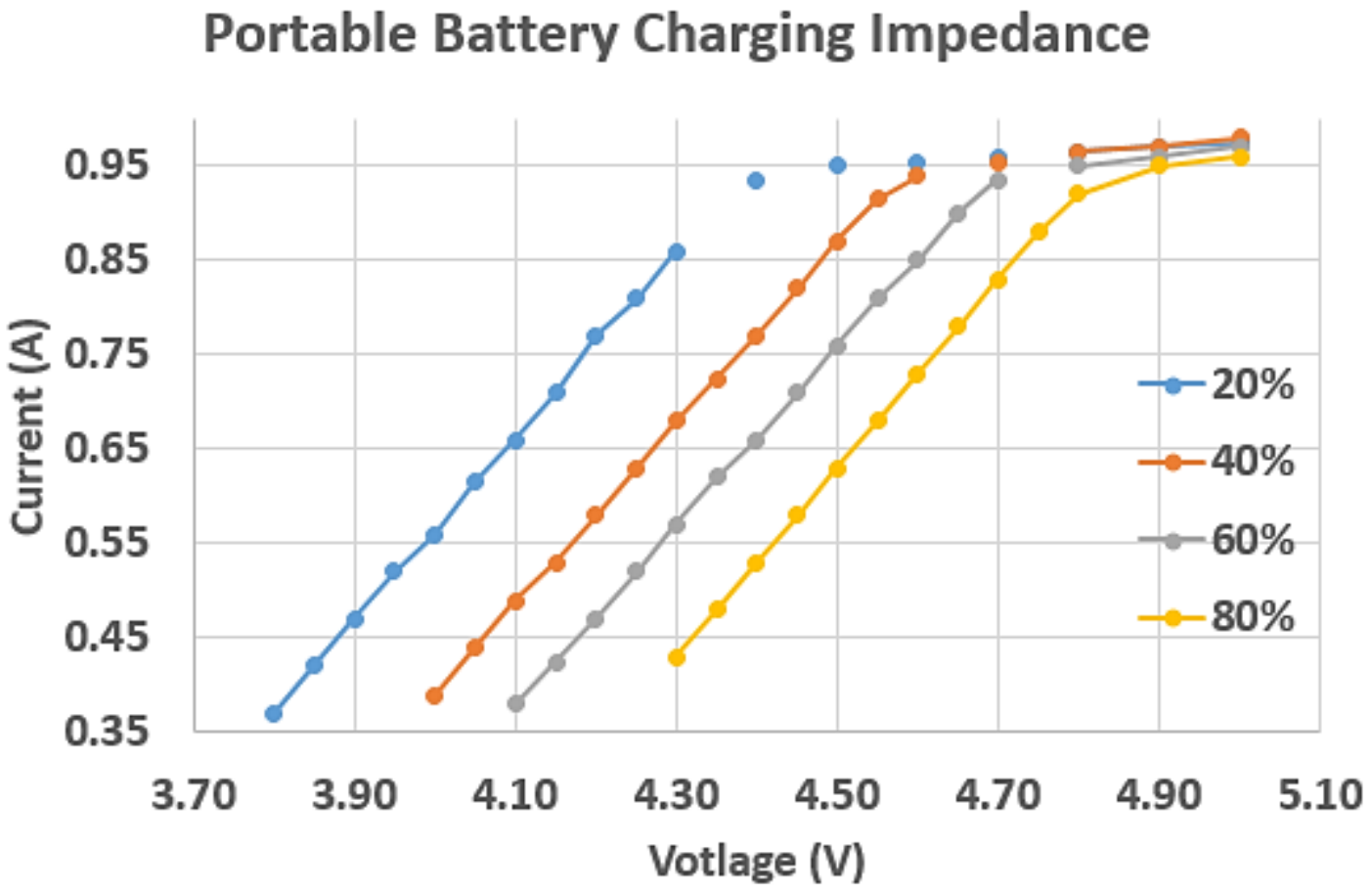
- Average Values
  - V_{DC}: 5.07 V
  - I_{out}: 0.27 A
  - P_{out}: 1.35 W

With DPP



- Average Values
  - V_{DC}: 5.19 V
  - I_{out}: 0.72 A
  - P_{out}: 3.73 W
    (2.7 times more power)

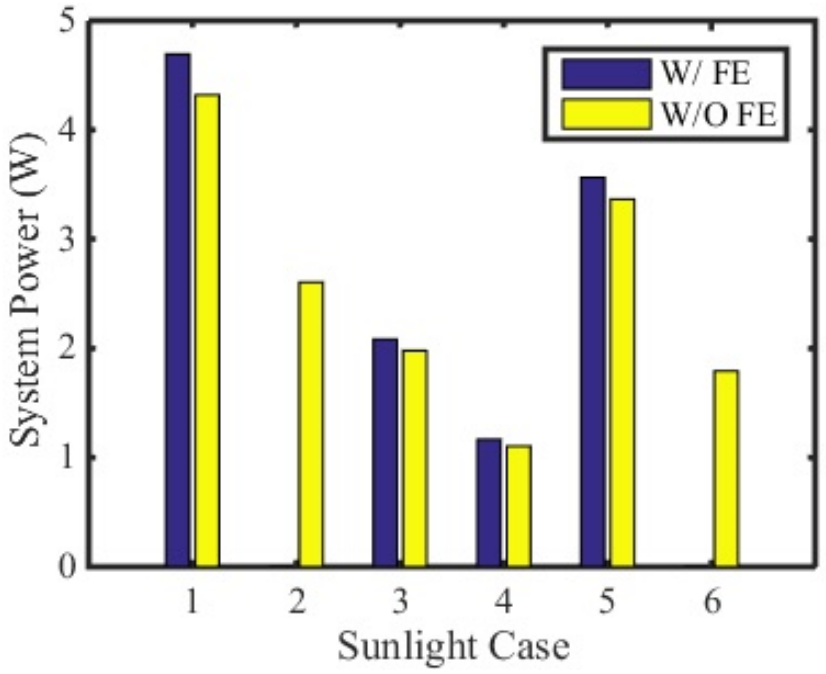
Portable Battery Charging Impedance



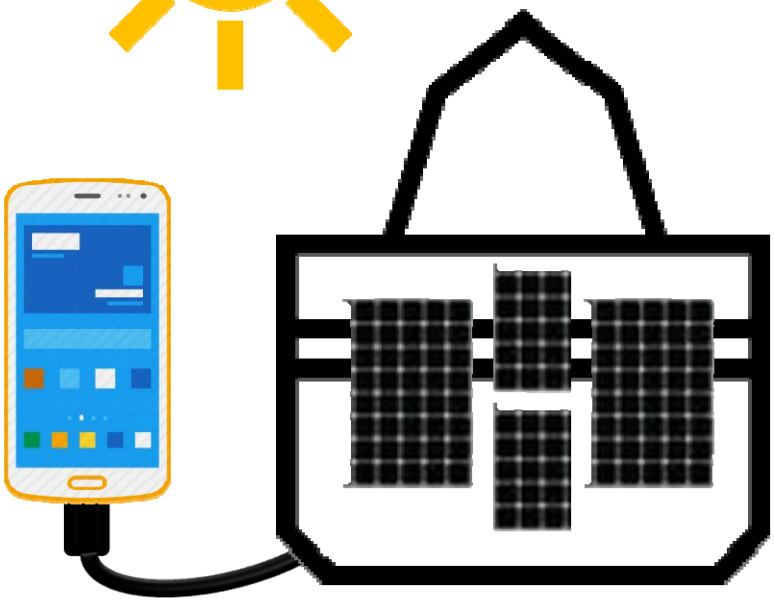
- For effective charging:
  DC Bus voltage should range from 3.7 V to 5.1 V

Comparing System Power Performance

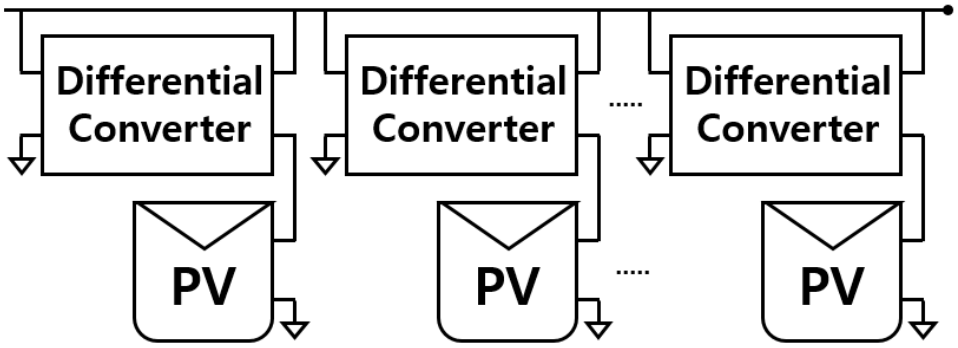
Test Case	Conditions
1	High Irradiance (Sunny) Small Variation
2	High Irradiance (Sunny) Gradient Variation
3	Medium Irradiance (Cloudy) Small Variation
4	Medium Irradiance (Cloudy) Gradient Variation
5	High Irradiance (Sunny) Partial Shading
6	Medium Irradiance (Cloudy) Partial Shading



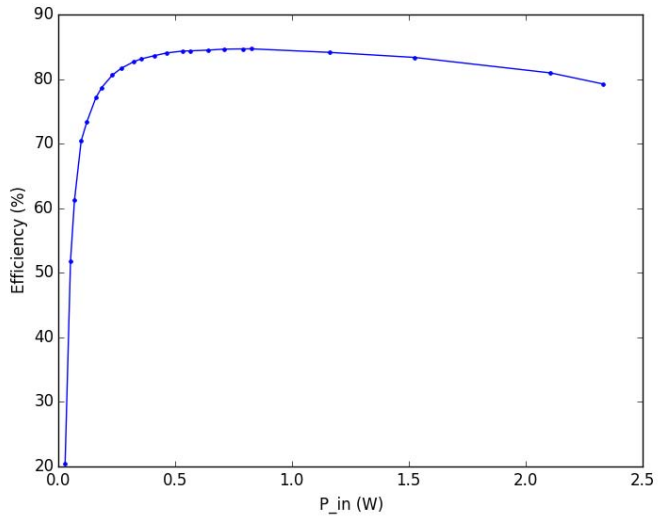
Version 2 Prototype



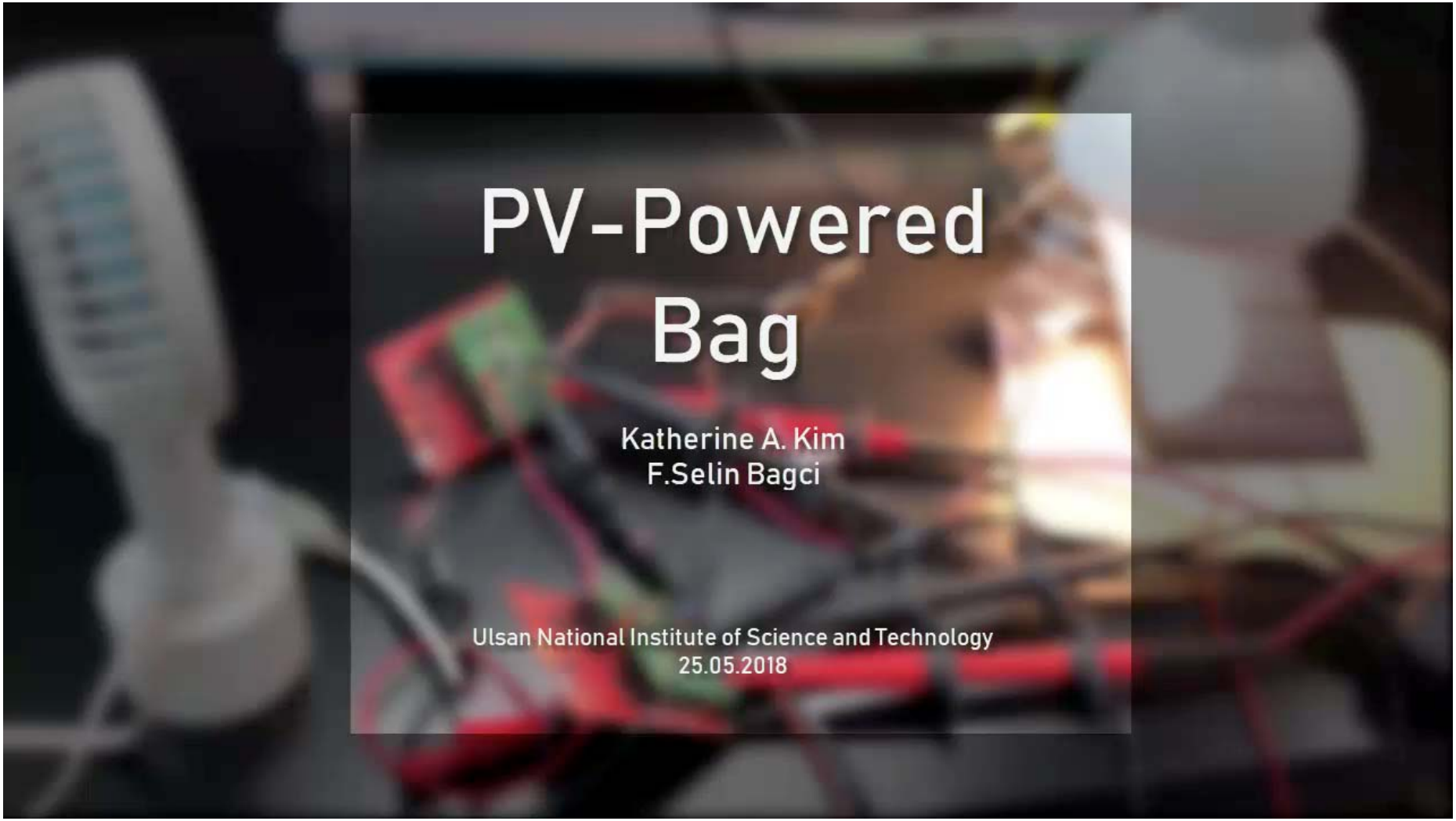
- Direct parallel configuration with out a front-end converter
- Different-sized cells to emphasize mismatch capability
- Converter efficiency improved



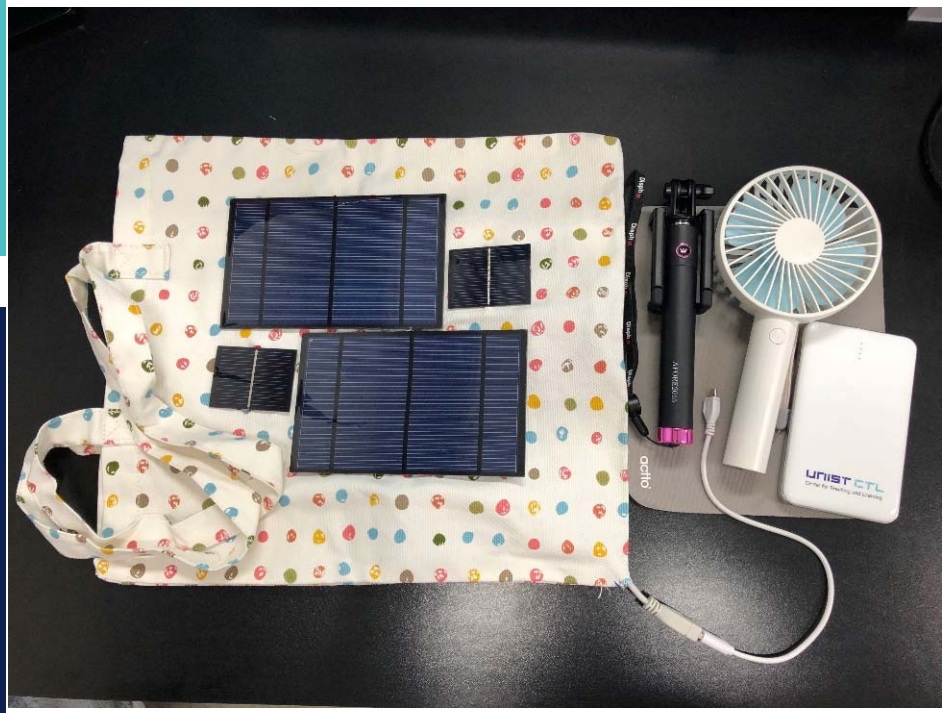
Converter Efficiency



Demonstration Video



Come See Our Demo!



Conclusions

- DPP converters increase PV output power
- DPP series configurations have previously been explored for grid-connected PV systems
  - Appropriate for higher-voltage applications
  - Challenging to scale up
- DPP parallel configurations show promise for uneven PV conditions
  - Appropriate for lower-voltage applications
  - Effective for heavy mismatch in PV cells
  - Promising for wearable applications
- Future work: Miniaturization, integration

Thank you! Questions?