Flexible PV-cell Modeling for Energy Harvesting in Wearable IoT Applications

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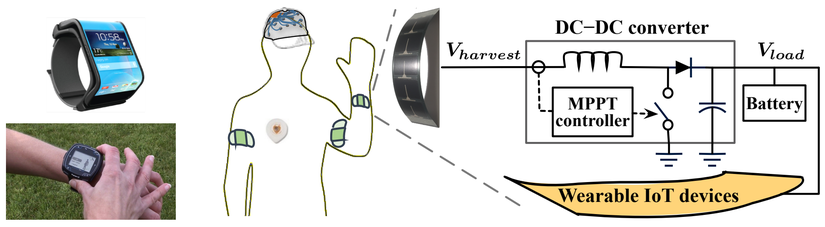
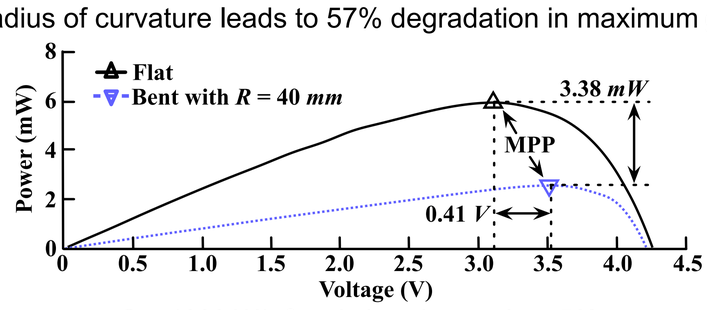
Motivation

- **A flexible PV-cell can power wearable IoT devices**
  - 10−100 *mW/cm²* @ outdoor 100 *μW/cm²* @ indoor



- **Bending a flexible PV-cell has a significant impact on the harvested power**
  - R = 40 mm radius of curvature leads to 57% degradation in maximum generated power



G = 1000 W/m² and elevation angle = *50°*

- **We proposed the first analytical model that quantifies this behaviour [1]**

Analytical Irradiation Model with Bending

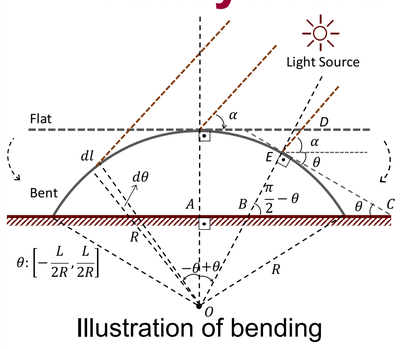


Illustration of bending

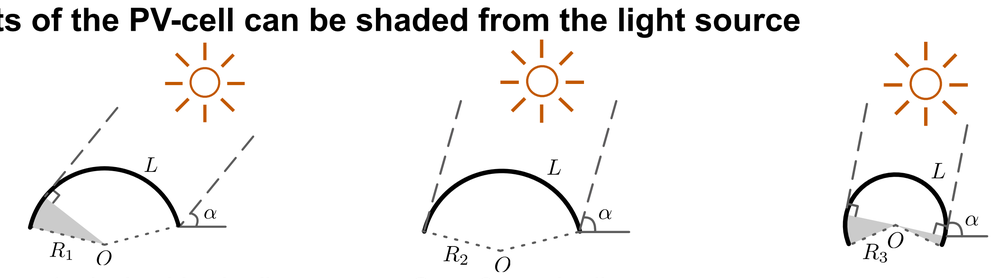
- **The irradiation at the PV-cell surface is expressed as:**

$$\lambda = \int_{\frac{-L}{2}}^{\frac{L}{2}} \int_0^W G \sin(\alpha+\beta)\, dw\, dl$$

- **The radiation received by the bent PV-cell is expressed as:**

$$\lambda_{bent} = \int_{\frac{-L}{2}}^{\frac{L}{2}} R \int_0^W G \sin(\alpha+\beta+\theta)\, dw d\theta$$

- **Parts of the PV-cell can be shaded from the light source**



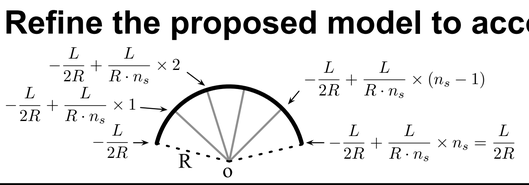
Case 1: single-side shading — Case 2: no shading — Case 3: both side shading

$$\lambda_{bent.1} = \int_{-(\alpha+\beta)}^{\frac{L}{2R_1}} R_1 \int_0^W G \cdot \sin(\alpha+\beta+\theta)\, dw d\theta = W \cdot G \cdot R_1 \left(1 - \cos\left(\alpha+\beta+\frac{L}{2R_1}\right)\right)$$

$$\lambda_{bent.2} = \int_{\frac{-L}{2R_2}}^{\frac{L}{2R_2}} R_2 \int_0^W G \cdot \sin(\alpha+\beta+\theta)\, dw d\theta = 2W \cdot G \cdot R_2 \sin(\alpha+\beta) \sin\left(\frac{L}{2R_2}\right)$$

$$\lambda_{bent.3} = \int_{-(\alpha+\beta)}^{\pi-(\alpha+\beta)} R_3 \int_0^W G \cdot \sin(\alpha+\beta+\theta)\, dw d\theta = 2W \cdot G \cdot R_3$$

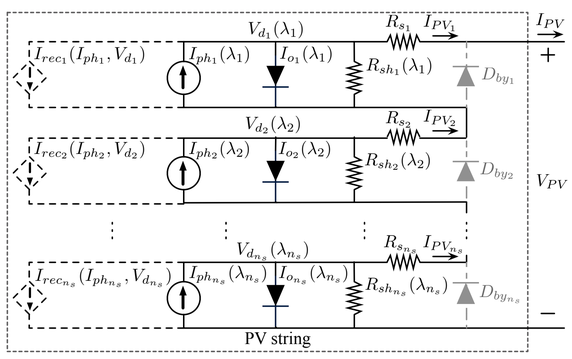
- **Partial shading has significant impact on the harvested energy**
  - Shaded cells act as power consumers in a PV-string
  - Bending a PV-string changes the amount of radiation at each PV-cell
- **Refine the proposed model to account partial shading**



$$\lambda_i = \int_{\frac{-L}{2R}+\frac{L\cdot(i-1)}{R\cdot n_s}}^{\frac{-L}{2R}+\frac{L\cdot i}{R\cdot n_s}} R \int_0^W G \cdot \sin(\alpha+\beta+\theta)\, dw d\theta, 1 \le i \le n_s$$

Current-Voltage Modeling of PV-cells

- **An equivalent circuit model for a PV-string**
  - Using a single diode equivalent circuit model considering recombination losses
  - A single diode equivalent circuit model is not enough to consider partial shading
    - The equivalent circuit consists of multiple single diode equivalent circuits connected in series



$$I_{PV_i} = I_{ph_i} \cdot \left(1 - \frac{d_I^2}{\mu\tau_{eff}(V_{bi}-V_{d_i})}\right) - I_{o_i} \cdot \left(e^{\frac{V_{d_i}}{A \cdot V_t}} - 1\right) - \frac{V_{d_i}}{R_{sh_i}}$$

$$I_{ph_i} = a_{IPH} \cdot \left(\frac{\lambda_i}{W \cdot (\frac{L}{n_s})}\right)^{b_{IPH}}$$

$$V_{d_i} = V_{PV_i} + I_{PV_i} \cdot R_{s_i}, \quad R_{s_i} = \frac{R_s}{n_s}$$

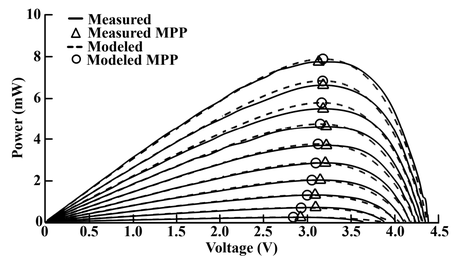
$$I_{o_i} = a_{IO} \cdot \left(\frac{\lambda_i}{W \cdot (\frac{L}{n_s})}\right)^2 + b_{IO} \cdot \left(\frac{\lambda_i}{W \cdot (\frac{L}{n_s})}\right) + c_{IO}$$

$$R_{sh_i} = a_{RPH} \cdot e^{b_{RSH} \cdot \left(\frac{\lambda_i}{W \cdot (\frac{L}{n_s})}\right)}$$

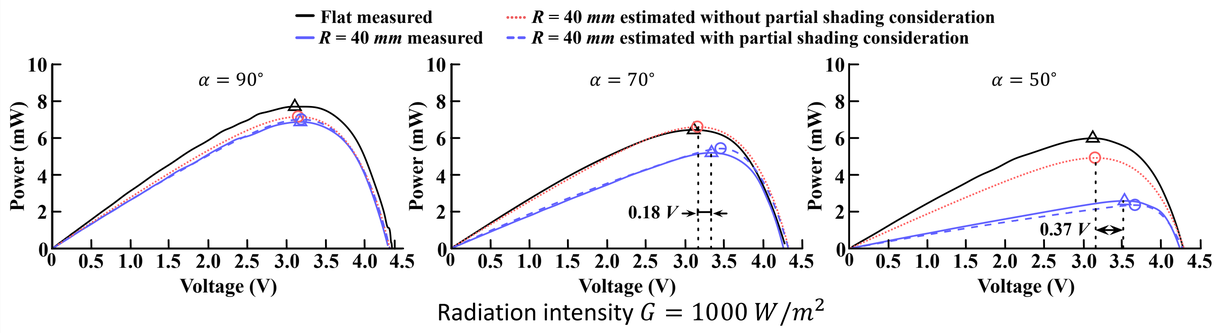
- Without bypass diodes: $I_{PV} = I_{PV_1} = I_{PV_2} = \cdots = I_{PV_{n_s}}$
- With bypass diodes: $I_{PV} = I_{PV_1} + I_{D_1} = I_{PV_2} + I_{D_2} = \cdots = I_{PV_{n_s}} + I_{D_{n_s}}$

Model Validation

- **PV-cell parameter extraction**
  - Use commercial PV-cell: FlexSolarCells SP3-12
  - Radiation intensity: 100~1000 W/m^2
  - Maintain the temperature of PV-cell constant
  - The relative percentage error of the $P_{MPP} < 5.3\%$

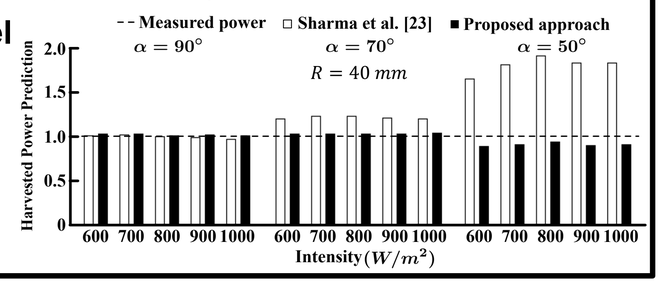


- **Flexible PV-cell model validation**
  - Relative percentage error of $P_{MPP} < 10.5\%$



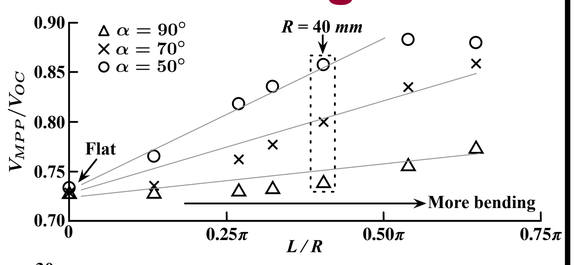
Radiation intensity $G = 1000\ W/m^2$

- **Comparison to *Sharma et al.* model**
  - Sharma et al. model shows high errors when elevation angle changes
    - No consideration of elevation angle
    - Rely on regression analysis to fit a nonlinear model

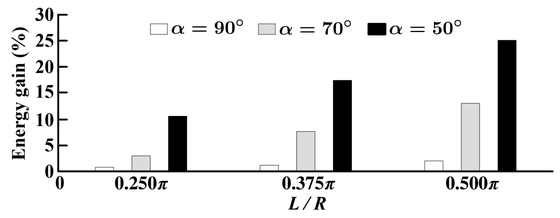


Improved Fractional Open-Circuit Voltage MPPT

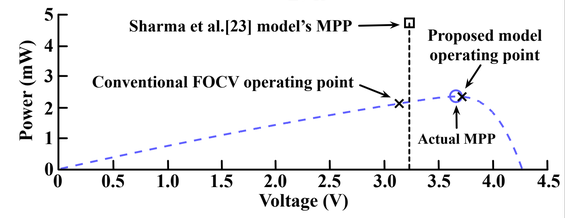
- **FOCV MPPT assumes V_{MPP}/V_{OC} does not vary significantly with radiation intensity**
  - V_{MPP}/V_{OC} increases linearly when a flexible PV is bent
  - The rate of increase is a function of elevation angle α



- **Consider V_{MPP}/V_{OC} changes to set the operating point**
  - Accounting for bending increases the harvested energy up to 25.0%



- **Importance of accurate model**
  - Improved FOCV MPPT gain according to the V_{MPP} model
    - Sharma el al. model: 4.6 %
    - Proposed model: 18.8%



$G = 1000\ W/m^2, R = 40\ mm$

Runtime Operation and Overhead Analysis

- **Implemented with a TI CC2650 processor**
- **Total computation overhead is less than 1% (0.9 *ms* out of 100 *ms*)**

Parameter	Operation	Overhead	Period
Radius of curvature R	Read a flex sensor	2.7 μs	100 ms
Inclination angle β	Compute using accelerometer	570.7 μs	100 ms
V_{OC}	Read V_{OC}	30.5 μs	100 ms
V_{MPP}	Compute and set V_{MPP}	277.8 μs	100 ms
Elevation angle α	Get time/location from BLE	2.4 ms	10 min
	Calculate α	1.0 ms	10 min

Conclusions

- **Energy harvesting is the one of most important problems in wearable IoT devices**
- **Bending has a dramatic impact on the harvested energy**
- **We presented a Flexible PV-cell modeling for energy harvesting**
  - We achieve 1.8% and 4.8% estimation error for V_{MPP} and P_{MPP}, respectively
  - Our analytical model leads up to 25.0% increase in harvested energy when used with MPPT algorithm
  - The details can be found in [1]

References

[1] Jaehyun Park, Hitesh Joshi, Hyung Gyu Lee, Sayfe Kiaei, and Umit Y. Ogras. "Flexible PV-cell Modeling for Energy Harvesting in Wearable IoT Applications," in ACM Tran. on Embedded Comp. Sys. (ESWEEK Special Issue), October 2017.

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