Efficient micro-Power Conditioning for Solar Cells with Time Domain Array Reconfiguration

Dissertation Defense
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Harnessing the Sun

on the large scale...

Total Energy Demand of the World: **12** TeraWatts
Average Solar Energy Received on Earth: **84** TeraWatts
Changes output when hot or shaded, or loaded!

Deal with: Insolation Change / Load variation / Shading...

Energy In = Energy Out!

Needs enough voltage,
*When sensing @ 1µW
*When processing @ 50µW
*When transmitting @ 1mW!
Chasing Maximum Power

Maximum Power Point! (MPP)

OPV Characteristics v/s Insolation
Left to Right: 0.1, 1, 10, and 100 W/sq.m.

Normalized Power (%)
-Dissipated - Generated -
0 100
-50 0 50
-100 -50 0 50

Voltage (V)

Maximum Power Point v/s Insolation

MPP Voltage (V)
-0.5 -0.45 -0.4 -0.35 -0.3 -0.25 -0.2 -0.15 -0.1 -0.05 0

Insolation (W/sq.m.)

Maximum Power v/s Insolation

Power output at MPP (mW)

0 1 2 3 4 5

Insolation (W/sq.m.)
Chasing Maximum Power

hill climbing...

fractional $V_{oc}/I_{sc}$

fuzzy logic control

array reconfiguration

perturb & observe...

incremental conductance

ripple correlation control

load $I/V$ maximization

ripple correlation,

and array reconfiguration...

fixed solution to partial shading

dynamic solution = reconfigurable array!

Figs Ref: T. Esram et al., (Review Paper) Sept 2006,
Nguyen et al., Transactions on Industrial Electronics 2008
Recap

• Solar Energy – Abundant in large scale, key ‘application-enabler’ at small scale

• PV Cell management - maximum power point, power balancing between cells

• Array Reconfiguration is complex to implement, precluded from portable applications
Can we have a simple and efficient system?

• Can we have array reconfiguration in a simple system?

• Can we use simple, automatic control loops?

• Can we do this in less than 100µW and under 1gram?
array reconfiguration...

...in the ‘time domain’?

re-routing spatially...

re-routing temporally...
The System

[Diagram of the system with labeled components such as MPPn Tracking, MPP2 Tracking, MPP1 Tracking, Off-Chip Inductor, Boost Converter, Battery, and Clocking and Control.]
Hmmm testing...

- Does TDAR Work?
- Are the switching losses prohibitive?
- Can the control loop be a small system?

- Discrete TDAR system
  - off the shelf ICs that mirror chip control loop
- TDAR Chip
- 10mA and 40mA solar cells – 3-strings
- SMU’s and Oscilloscopes!
Does T.D.A.R. Work?

- **red** - drops below 2-cell level...
- **green** - optimal
- **blue** - duty cycle limited

**Inferences:**
- TDAR is only as good as:
  - The control loop
  - The power switches
**Power consumption of Chip**

Inferences:

3 TDAR cells at 55μA total

Boost converter near 80% for 3-cell-string voltage range

Single-cell voltages see lower efficiency

=> TDAR can be more efficient!
Comparing control loops

Inferences:
On-chip control loop unstable at low duty-cycles

Other Notes:
Chip sensitive to light (!)
PV dynamic models can improve accuracy
SMU’s can be faulty
Oscilloscopes can auto-calibrate
Conclusions...

• T.D.A.R. improves power availability under shading for any-sized array

• T.D.A.R. is a strong contender for low-power PV-string management

• Higher efficiencies with a PV string than a single cell for ultra-portable applications

• Scalable and Modular, but only as good as its control loop and power switches!

... the story continues!...