

EE155/255 Green Electronics

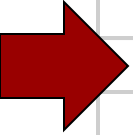
Photovoltaics
10/09/17

Prof. William Dally
Computer Systems Laboratory
Stanford University

Course Logistics

- HW2 due Today (In box outside Sue's office by 9AM tomorrow)
- HW3 out – Motor Matlab– Due Monday 10/16
- Lab2 signed off this week
- Lab3 out – PV MPPT

No	Date	Topic	HW out	HW in	Lab out	Lab ck	Lab	HW
1	9/25/17	Intro (basic converters)	1		1		Intro to ST32F3	Periodic Steady State
2	9/27/17	Embedded Prog/Power Elect.						
3	10/2/17	Power Electronics - 1 (switches)	2	1	2	1	AC Energy Meter	Power Devices
4	10/4/17	Power Electronics - 2 (circuits)						
5	10/9/17	Photovoltaics	3	2	3	2	PV MPPT	Motor control Matlab
6	10/11/17	Feedback Control						
7	10/16/17	Electric Motors	4	3	4	3	Motor control - Lab/	Feedback
8	10/18/17	Isolated Converters						
9	10/23/17	Solar Day	5/PP	4	5	4	PS	Isolated Converters
10	10/25/17	Magnetics						
11	10/30/17	Soft Switching	6	5/PP	6	5	Magnetics	Magnetics and Inverters
12	11/1/17	Project Discussions						
13	11/6/17	Inverters, Grid, PF, and Batteries		6	P	6	Project	
14	11/8/17	Thermal & EMI						
15	11/13/17	Quiz Review				C1		
16	11/15/17	Grounding, and Debugging						
Q	11/15/17	Quiz - in the evening						
	11/20/17	Thanksgiving Break				C2		
	11/22/17	Thanksgiving Break						
17	11/27/17	Wrapup						
18	11/29/17	Guest Lecture				C3		
19	12/4/17	Guest Lecture						
20	12/6/17	No Class						
	TBD	Project presentations			P			
	12/15/17	Project webpage due						



Course to Date

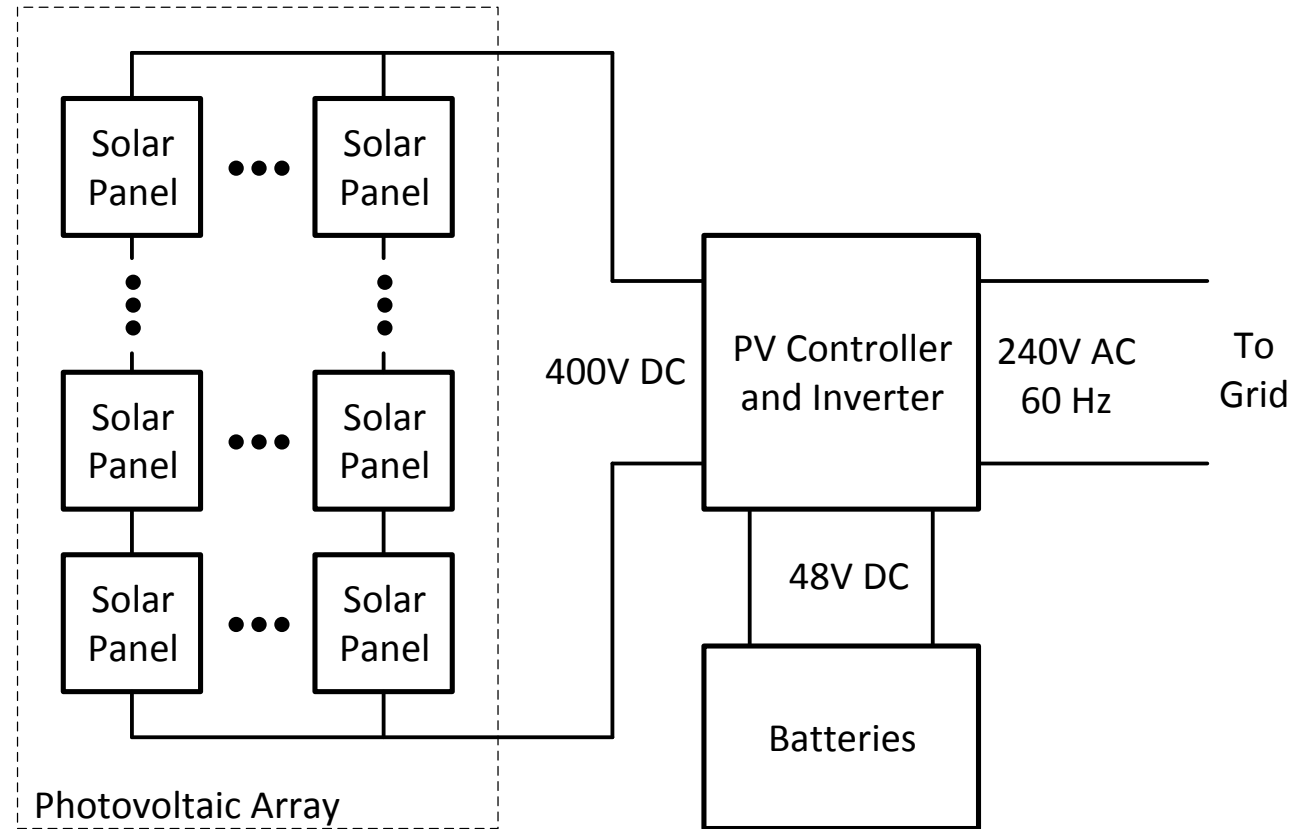
- We need sustainable energy systems
- At the core they are voltage converters
- Periodic steady-state analysis, buck and boost
- Intelligent control (embedded uC) + power path
- Real devices have switching and conduction loss
- Half-bridges, dead-time, and snubbers

Photovoltaics

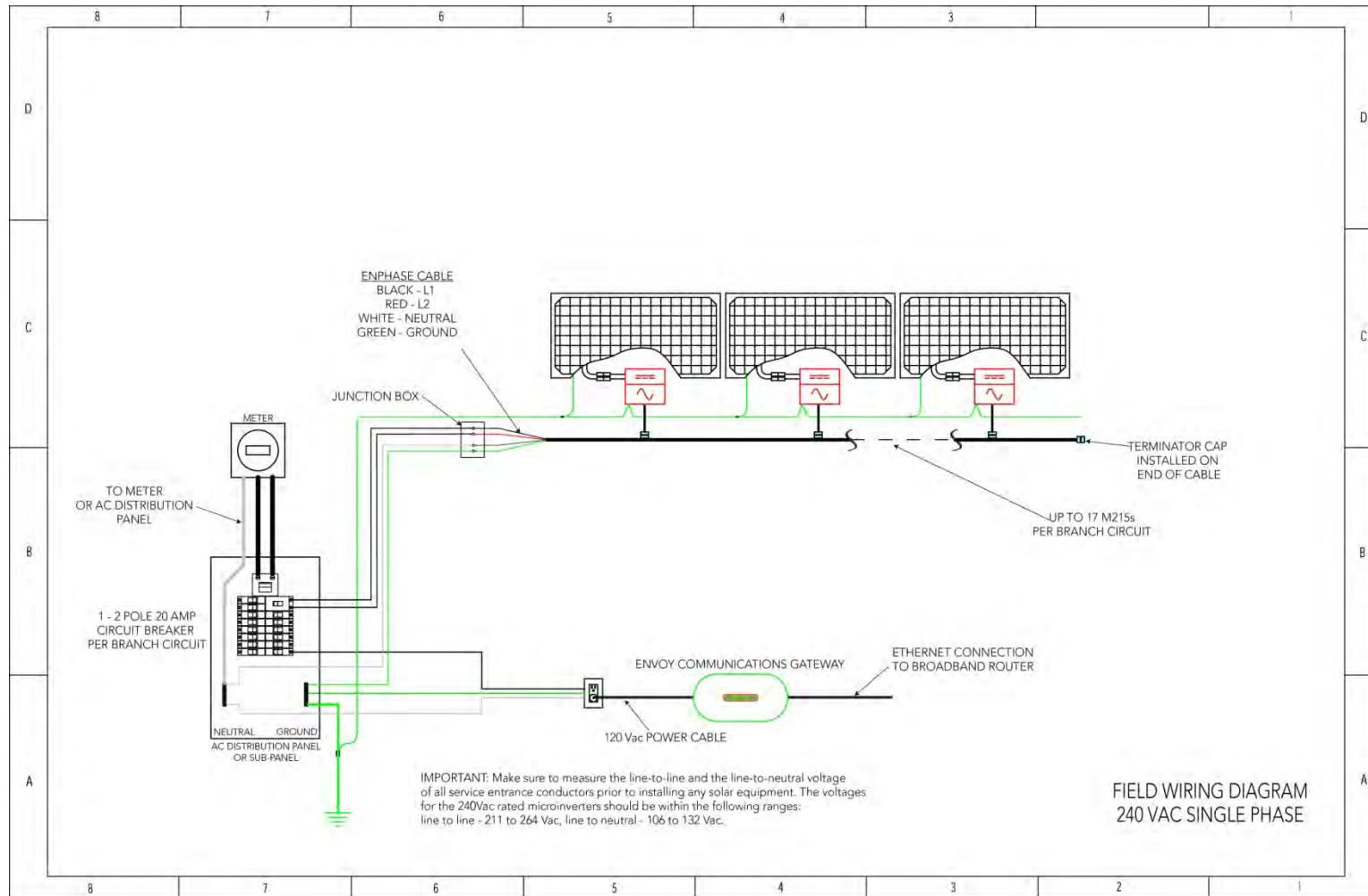




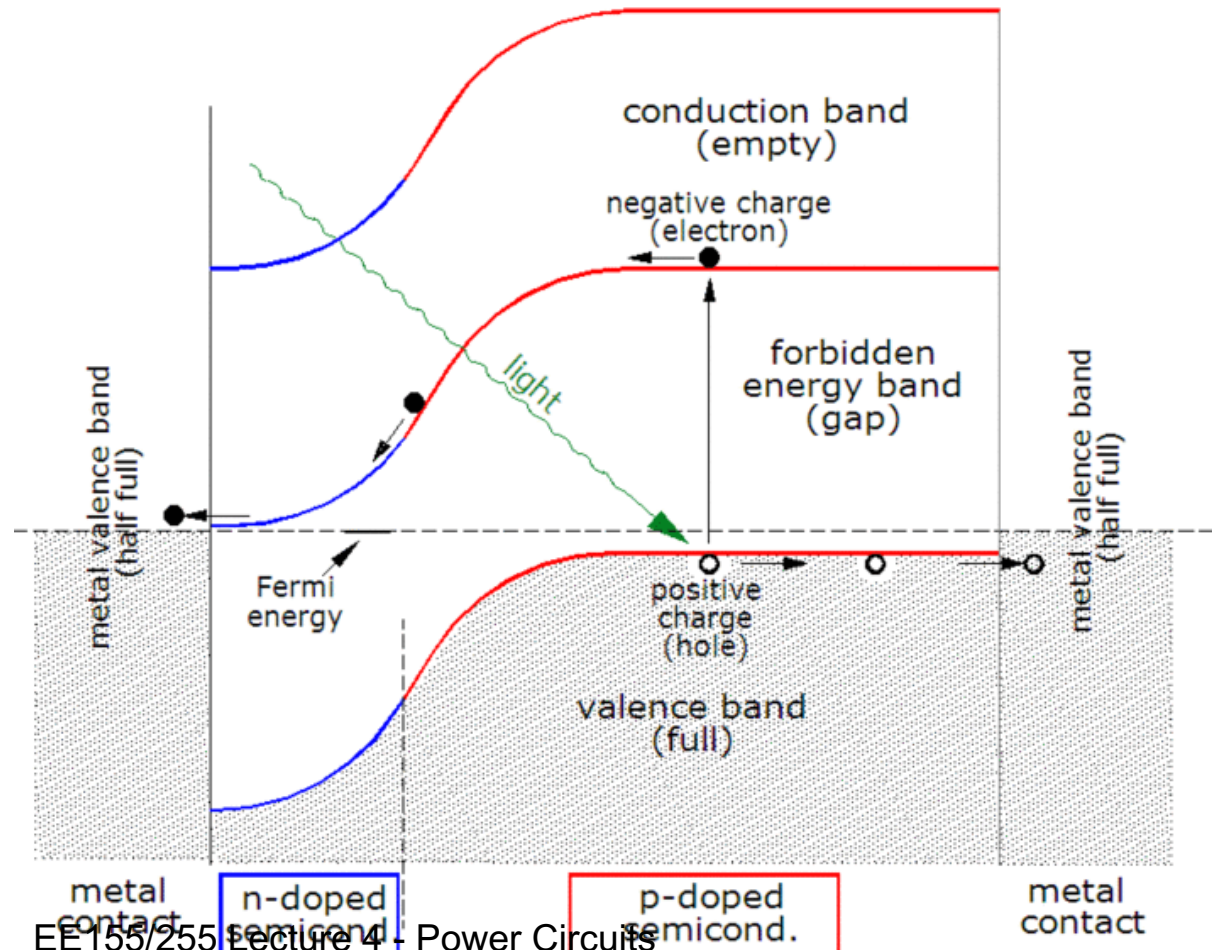
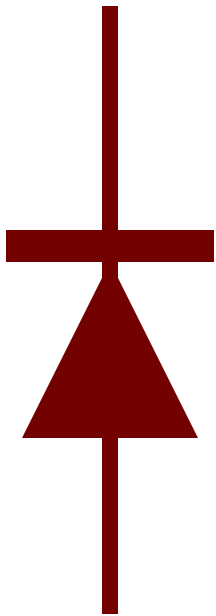
Photovoltaic System



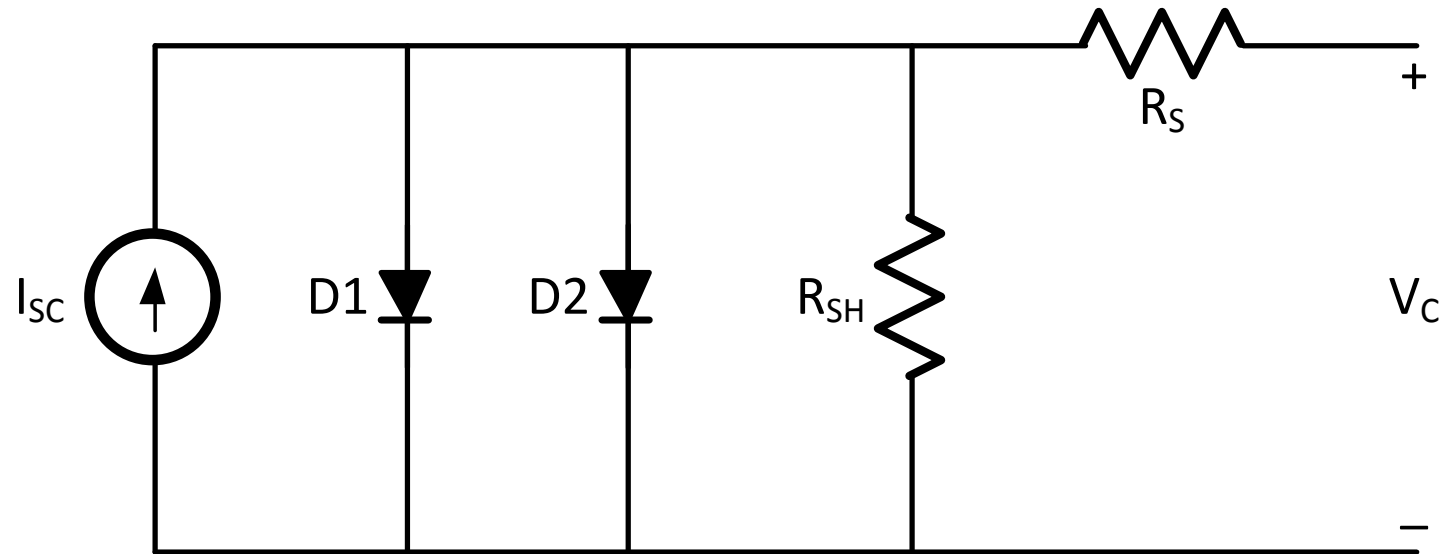




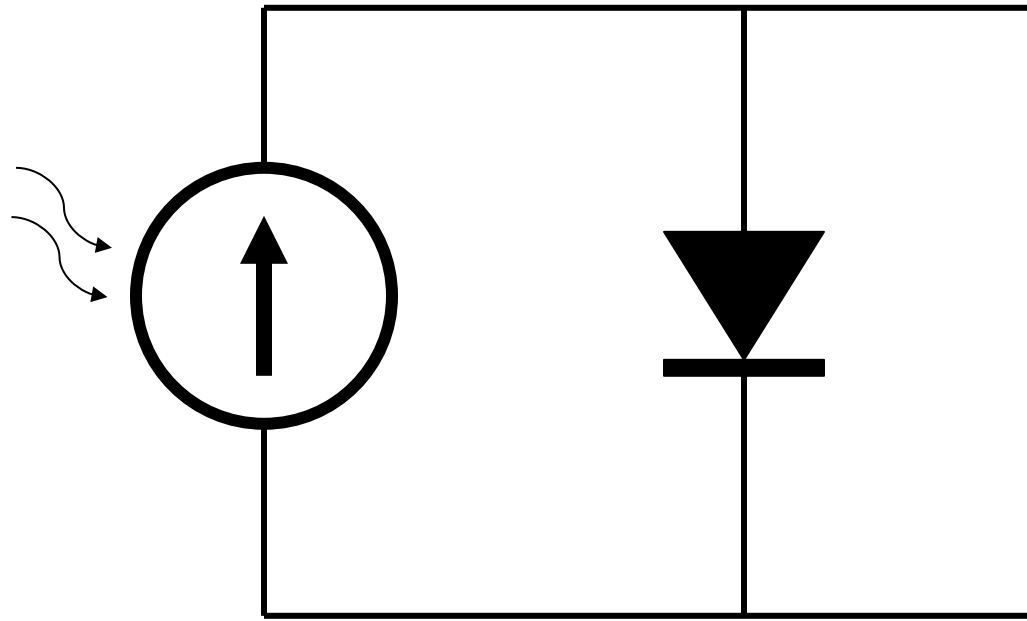
Electrons absorb energy from photons



Equivalent Circuit

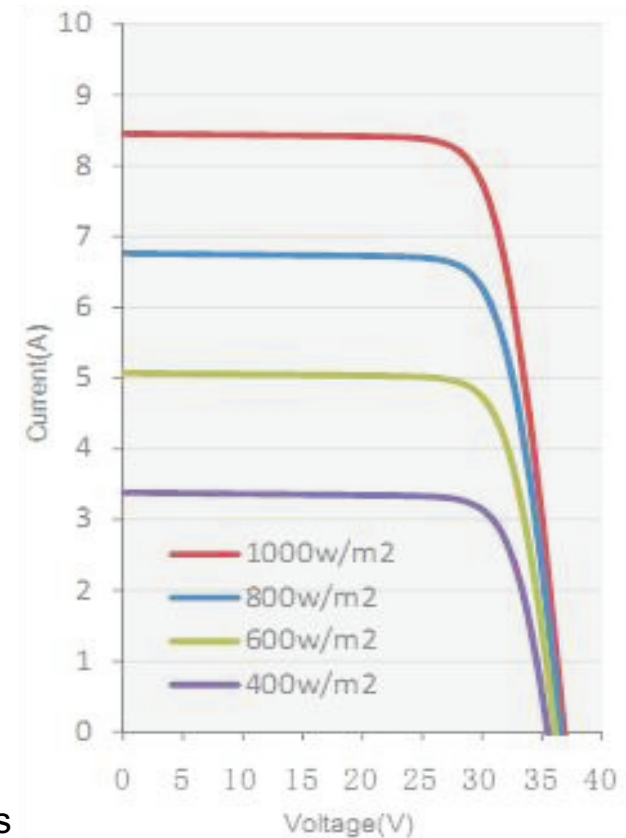


Simple Equivalent Circuit

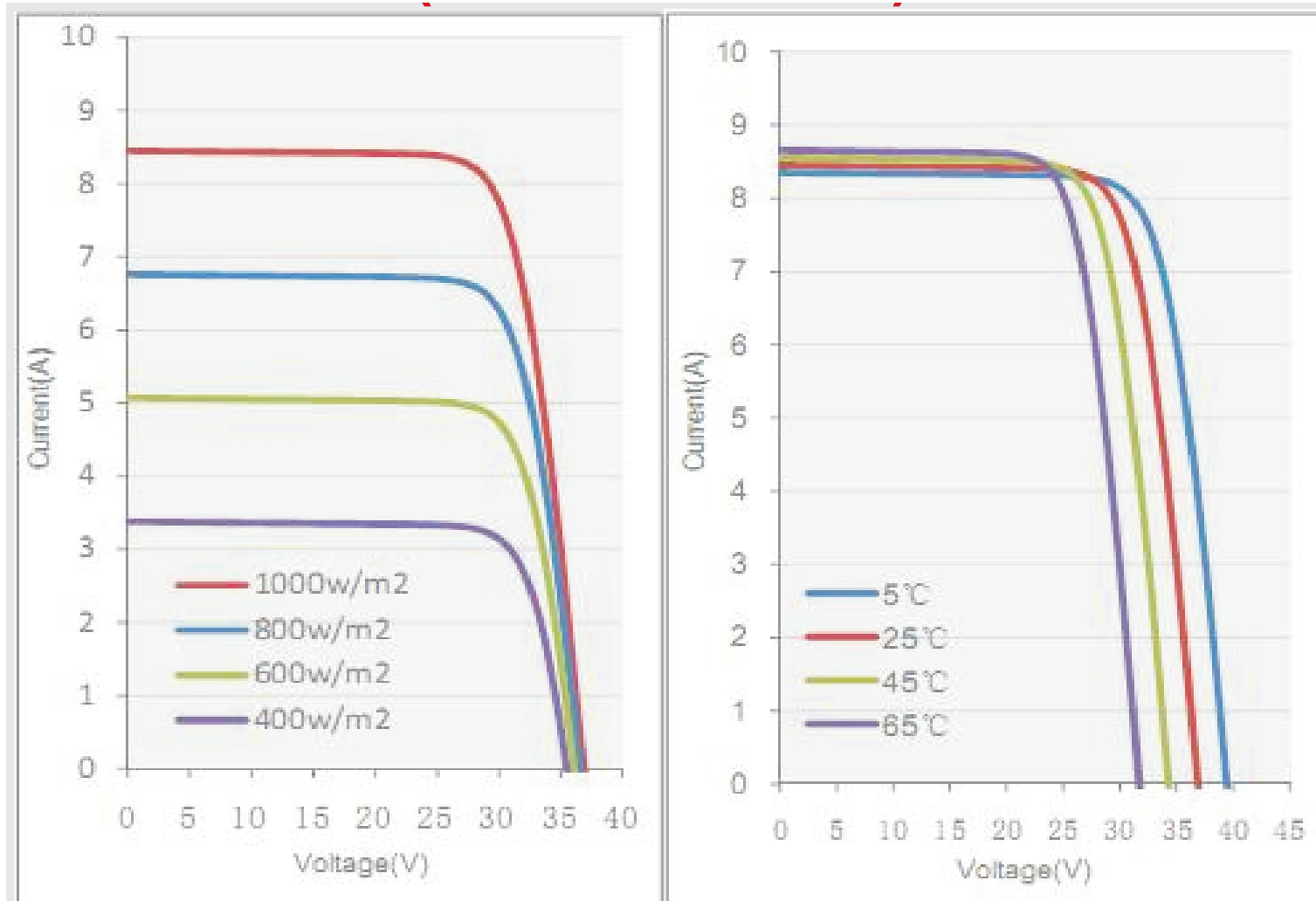


Current proportional to irradiance (I_{SC})

$$V_{OC} = V_{Diode}(I_{SC})$$



IV-Curve



Typical Module CS6P

60 cells in series

~0.5V per cell

3 strings of 20 with bypass diode on each string

CS6P-230/235/240/245/250M
All-black

Electrical Data

STC	CS6P-230M	CS6P-235M	CS6P-240M	CS6P-245M	CS6P-250M
Nominal Maximum Power (Pmax)	230W	235W	240W	245W	250W
Optimum Operating Voltage (Vmp)	29.9V	30.1V	30.2V	30.3V	30.4V
Optimum Operating Current (Imp)	7.70A	7.82A	7.95A	8.09A	8.22A
Open Circuit Voltage (Voc)	37.1V	37.2V	37.3V	37.4V	37.5V
Short Circuit Current (Isc)	8.22A	8.34A	8.48A	8.61A	8.74A
Module Efficiency	14.30%	14.61%	14.92%	15.23%	15.54%
Operating Temperature	-40°C ~ +85°C				
Maximum System Voltage	1000V (IEC)/600V (UL)				
Maximum Series Fuse Rating	15A				
Application Classification	Class A				
Power Tolerance	0 ~ +5W				

Under Standard Test Conditions (STC) of irradiance of 1000W/m², spectrum AM 1.5 and cell temperature of 25°C

NOCT	CS6P-230M	CS6P-235M	CS6P-240M	CS6P-245M	CS6P-250M
Nominal Maximum Power (Pmax)	166W	170W	173W	177W	180W
Optimum Operating Voltage (Vmp)	27.3V	27.5V	27.5V	27.6V	27.7V
Optimum Operating Current (Imp)	6.09A	6.18A	6.29A	6.40A	6.51A
Open Circuit Voltage (Voc)	34.0V	34.1V	34.2V	34.3V	34.4V
Short Circuit Current (Isc)	6.65A	6.75A	6.85A	6.97A	7.08A

Under Normal Operating Cell Temperature, Irradiance of 800 W/m², spectrum AM 1.5, ambient temperature 20°C, wind speed 1 m/s

Mechanical Data

Cell Type	Mono-crystalline 156 x 156mm, 2 or 3 Busbars
Cell Arrangement	60 (6 x 10)
Dimensions	1638 x 982 x 40mm (64.5 x 38.7 x 1.57in)
Weight	20kg (44.1 lbs)
Front Cover	3.2mm Tempered glass
Frame Material	Anodized aluminium alloy
J-BOX	IP65, 3 diodes
Cable	4mm ² (IEC)/12AWG(UL), 1100mm
Connectors	MC4 or MC4 Comparable
Standard Packaging (Modules per Pallet)	24pcs
Module Pieces per container (40 ft. Container)	672pcs (40'HQ)

I-V Curves (CS6P-250M)

Performance at Low Irradiance
Industry leading performance at low irradiation environment, +95.5% module efficiency from an irradiance of 1000w/m² to 200w/m² (AM 1.5, 25 °C)

Engineering Drawings

*Specifications included in this datasheet are subject to change without prior notice.

About Canadian Solar

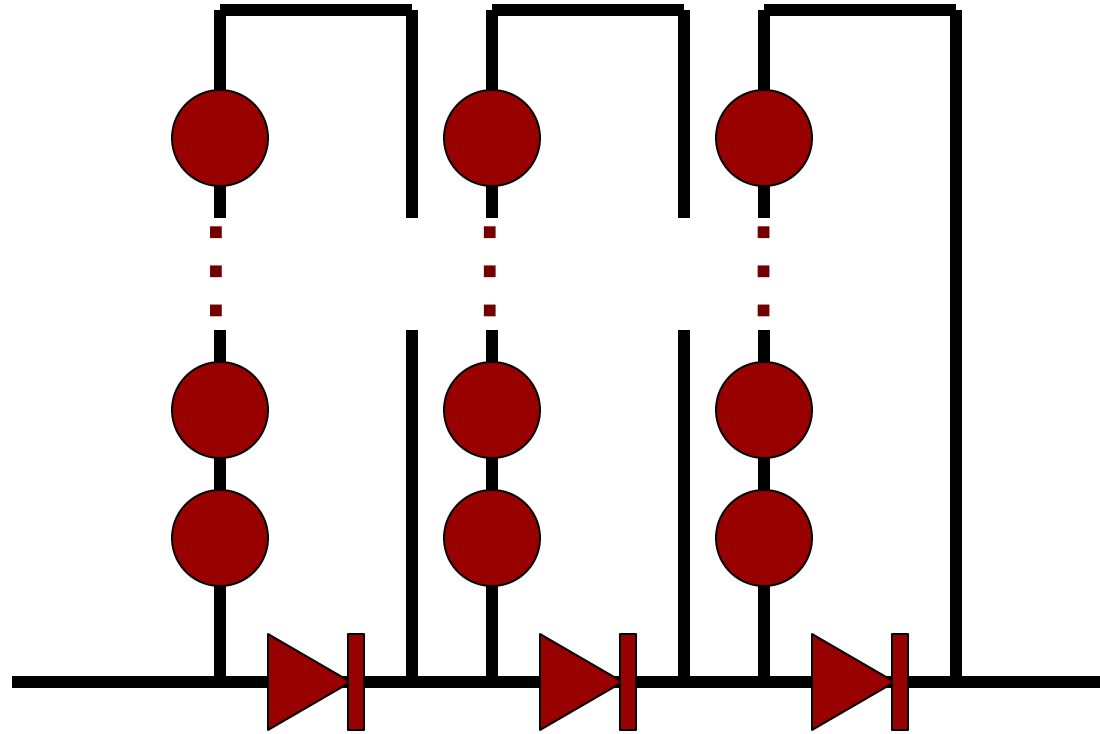
Canadian Solar Inc. is one of the world's largest solar companies. As a leading vertically-integrated manufacturer of ingots, wafers, cells, solar modules and solar systems, Canadian Solar delivers solar power products of uncompromising quality to worldwide customers. Canadian Solar's world class team of professionals works closely with our customers to provide them with solutions for all their solar needs.

Canadian Solar was founded in Canada in 2001 and was successfully listed on NASDAQ Exchange (symbol: CSIQ) in November 2006. Canadian Solar has already expanded its module manufacturing capacity to 2.05GW and cell manufacturing capacity to 1.3GW in 2011.

Headquarters | 545 Speedvale Avenue West
Guelph | Ontario N1K 1E6 | Canada
Tel: +1 519 837 1881
Fax: +1 519 837 2550
inquire.ca@canadiansolar.com
www.canadiansolar.com

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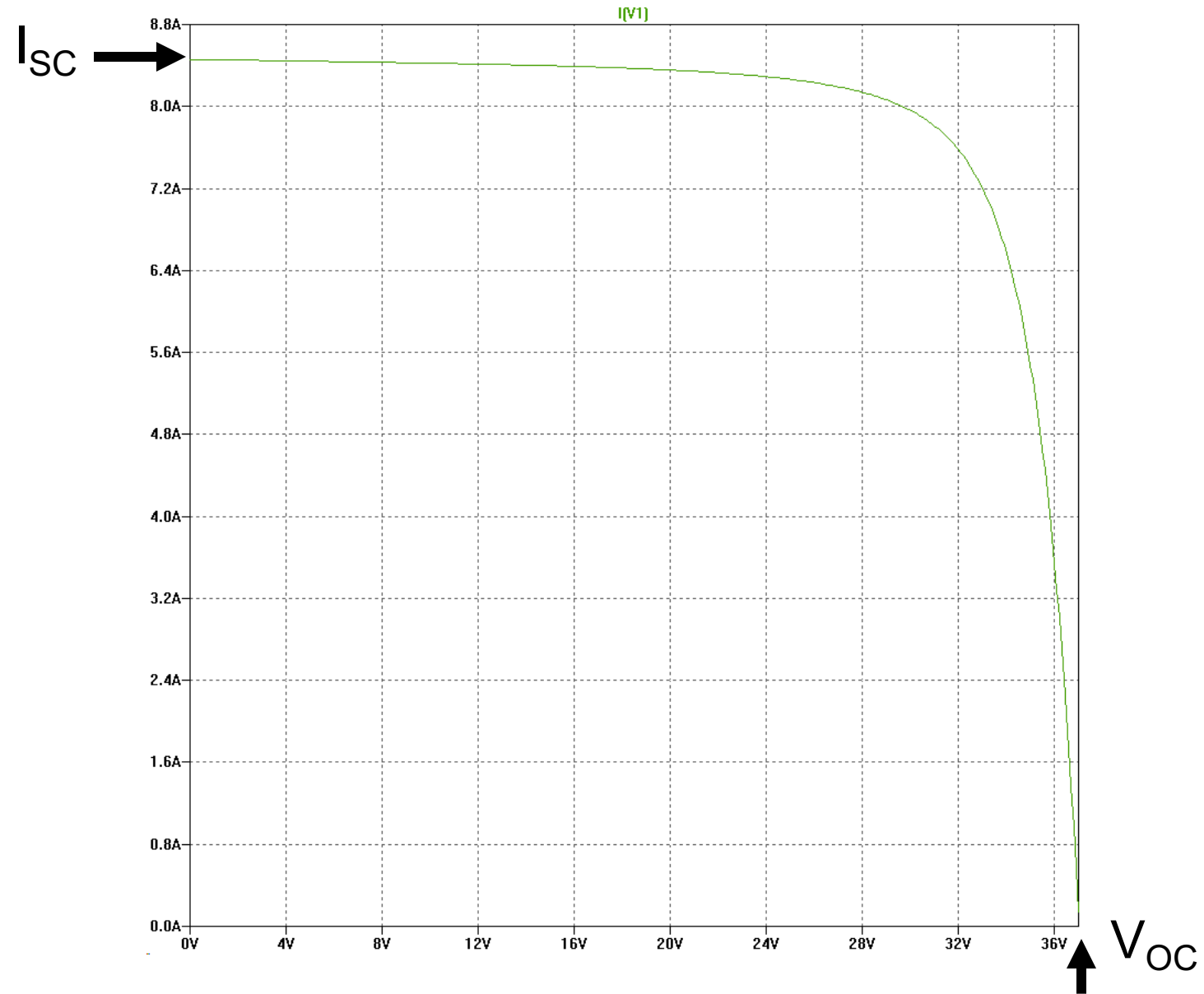
Typical PV Module



Typical 250W module:

- 3 strings of 20 cells
- “Bypass” diodes between strings
- Diodes turn on when voltage across string becomes negative
 - When $I_{\text{module}} > I_{\text{string}}$

IV Curve from SPICE Model



Peak-Power Tracking

- Find point on IV curve where power is maximized.

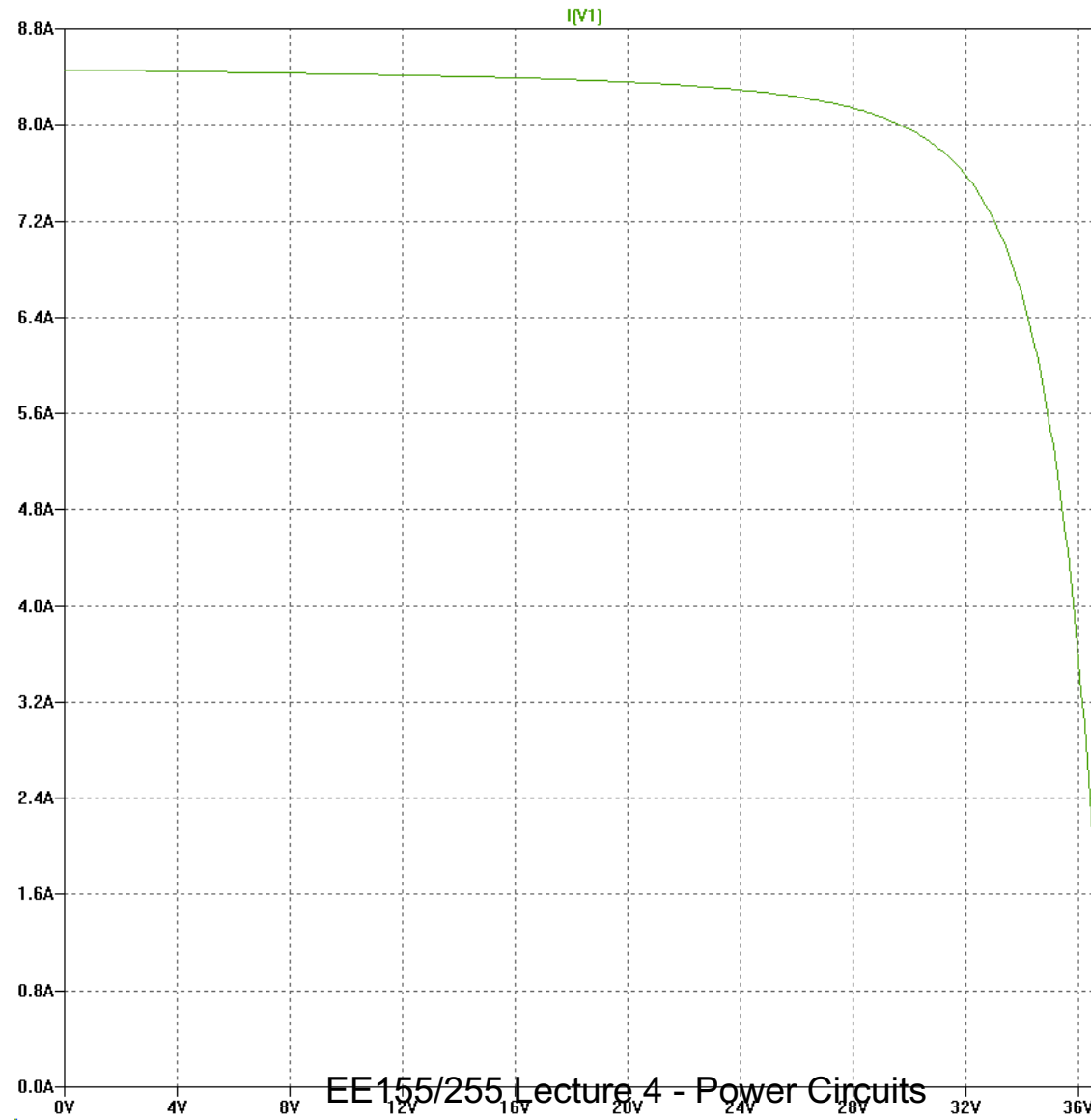
Start at any point $(v(0), i(0))$

“Dither” v , $v(i+1) = v(i) + \Delta v$

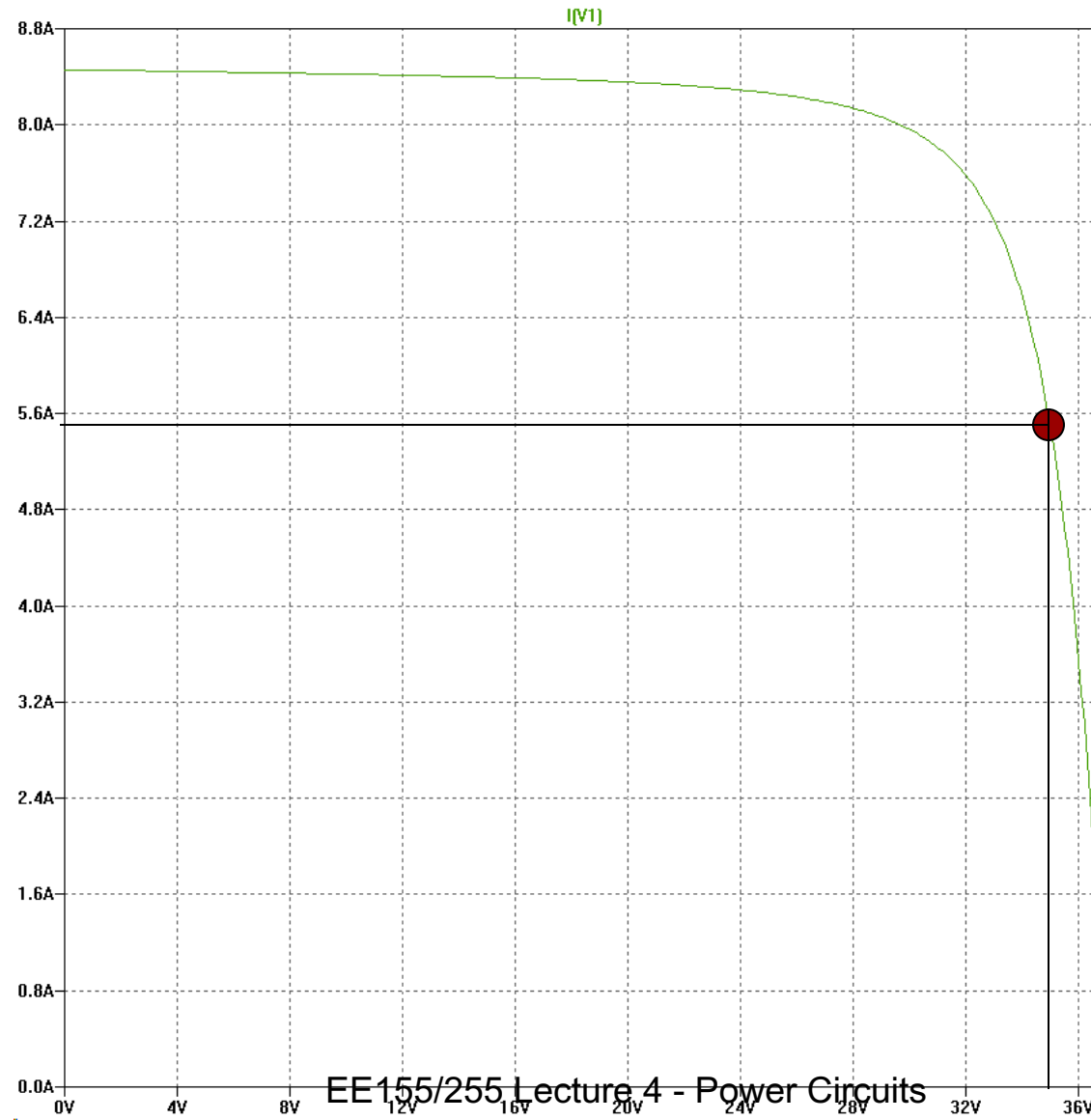
Check result: if $(p(i+1) < p(i))$ $v(i+1) = v(i)$

Try both directions: $\Delta v = -\Delta v$

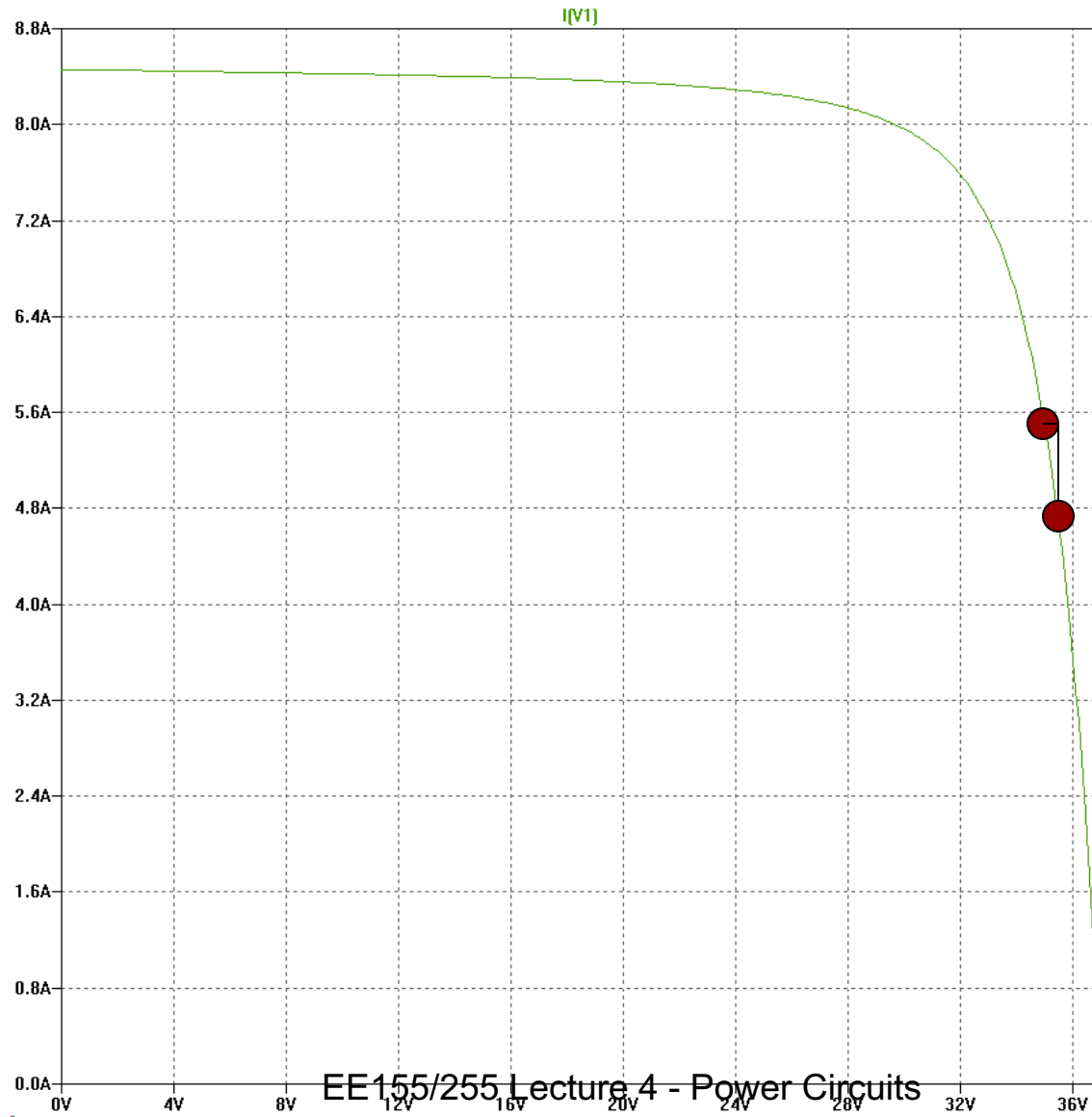
MPP Tracking – The Movie



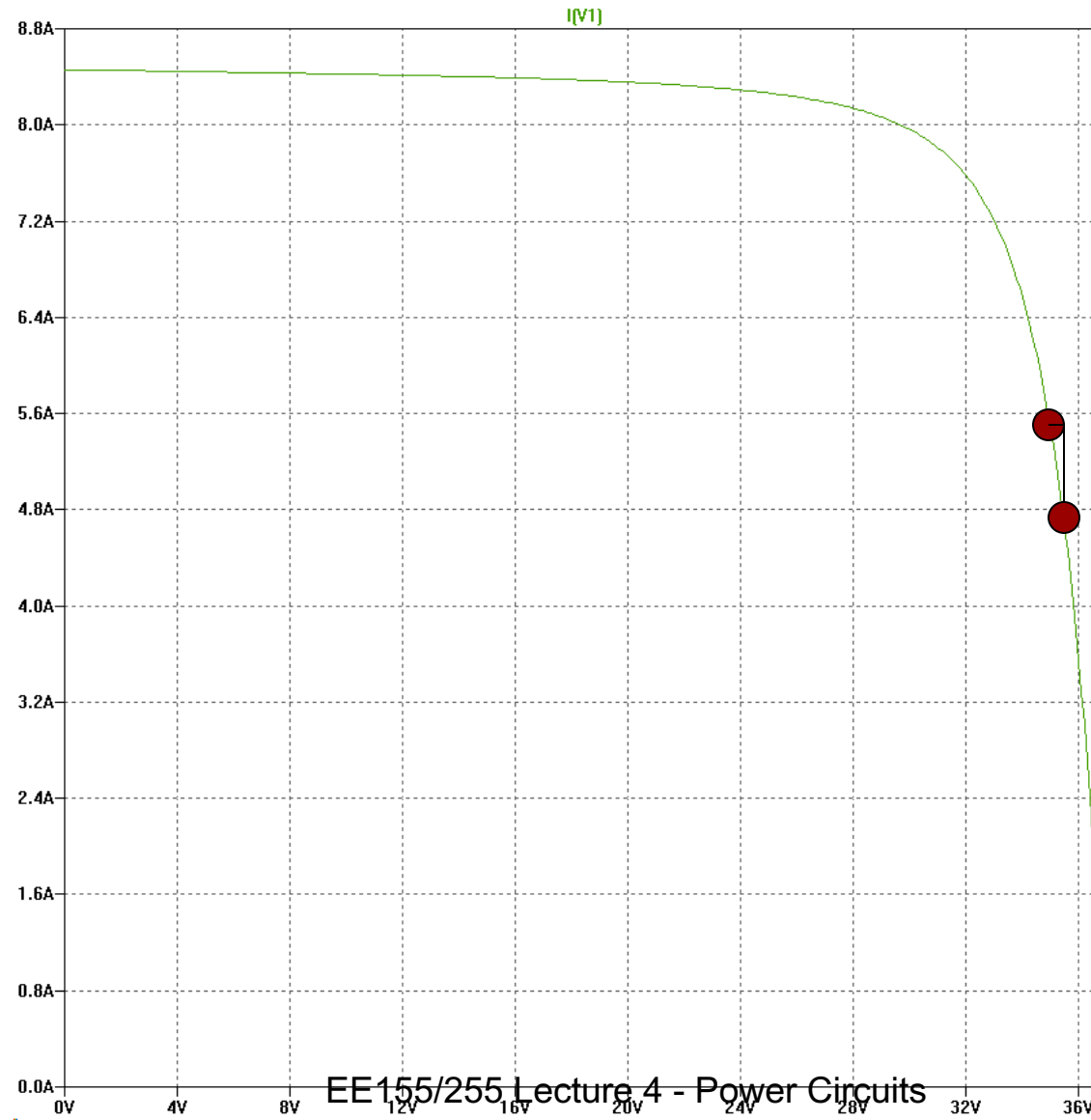
Start at (35 V, 5.5A) $P=192.5$



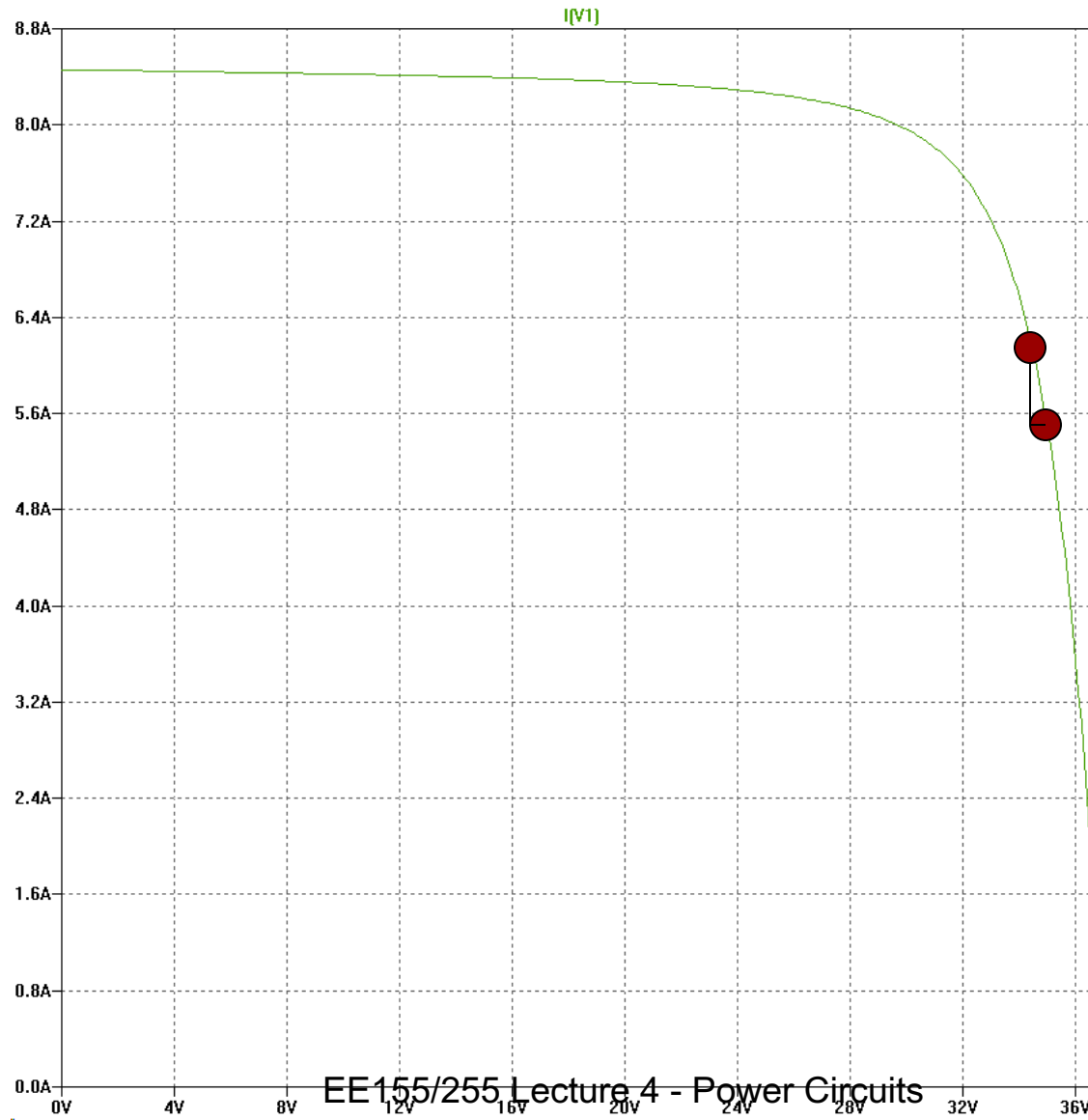
Dither by $DV = 0.5V$ to $V = 35.5V$
(35.5V, 4.7A) $P=166.9 < 192.5$



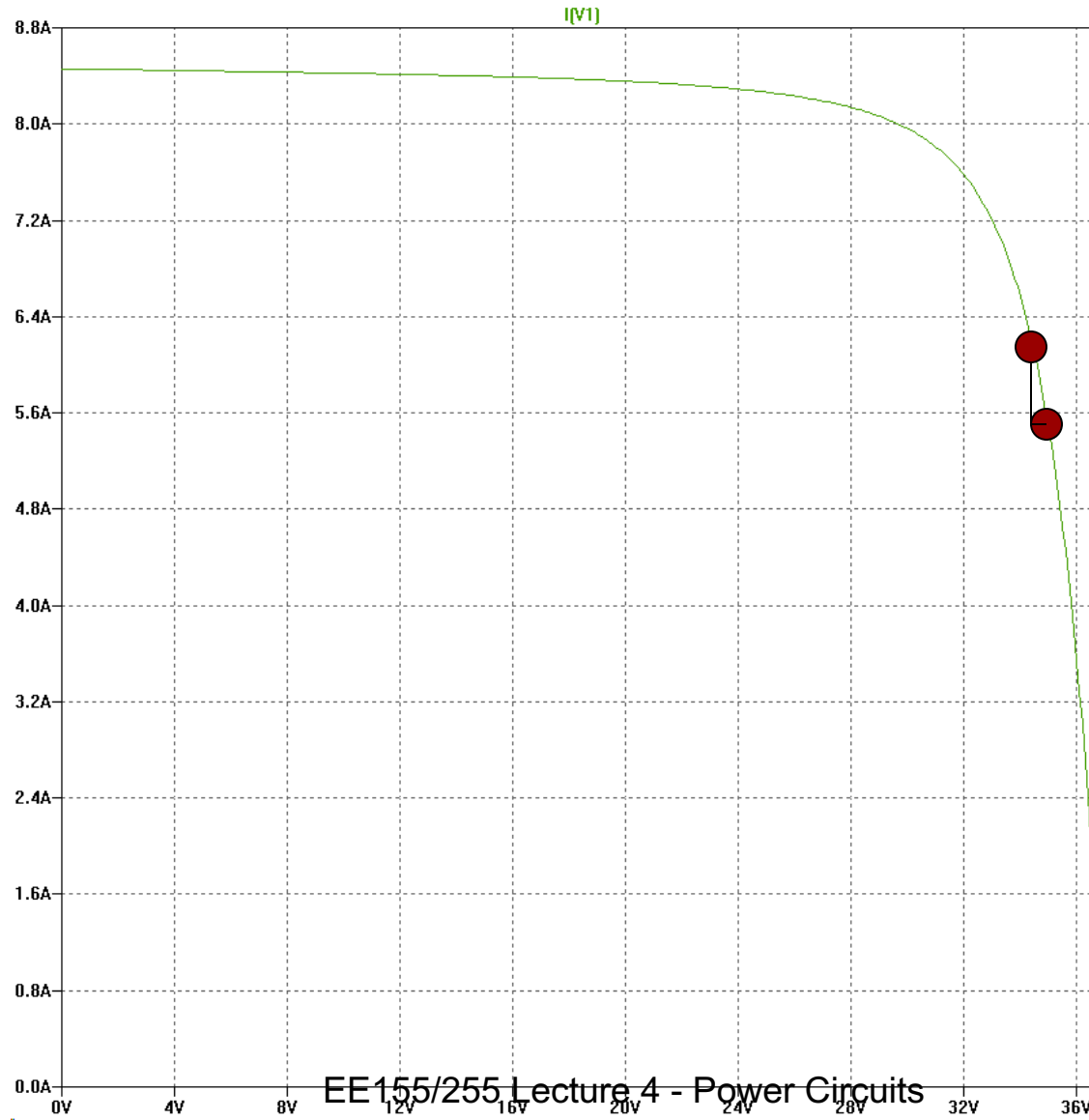
(35.5V, 4.7A) $P=166.9 < 192.5$
Bad Move – Go Back to (35, 5.5)



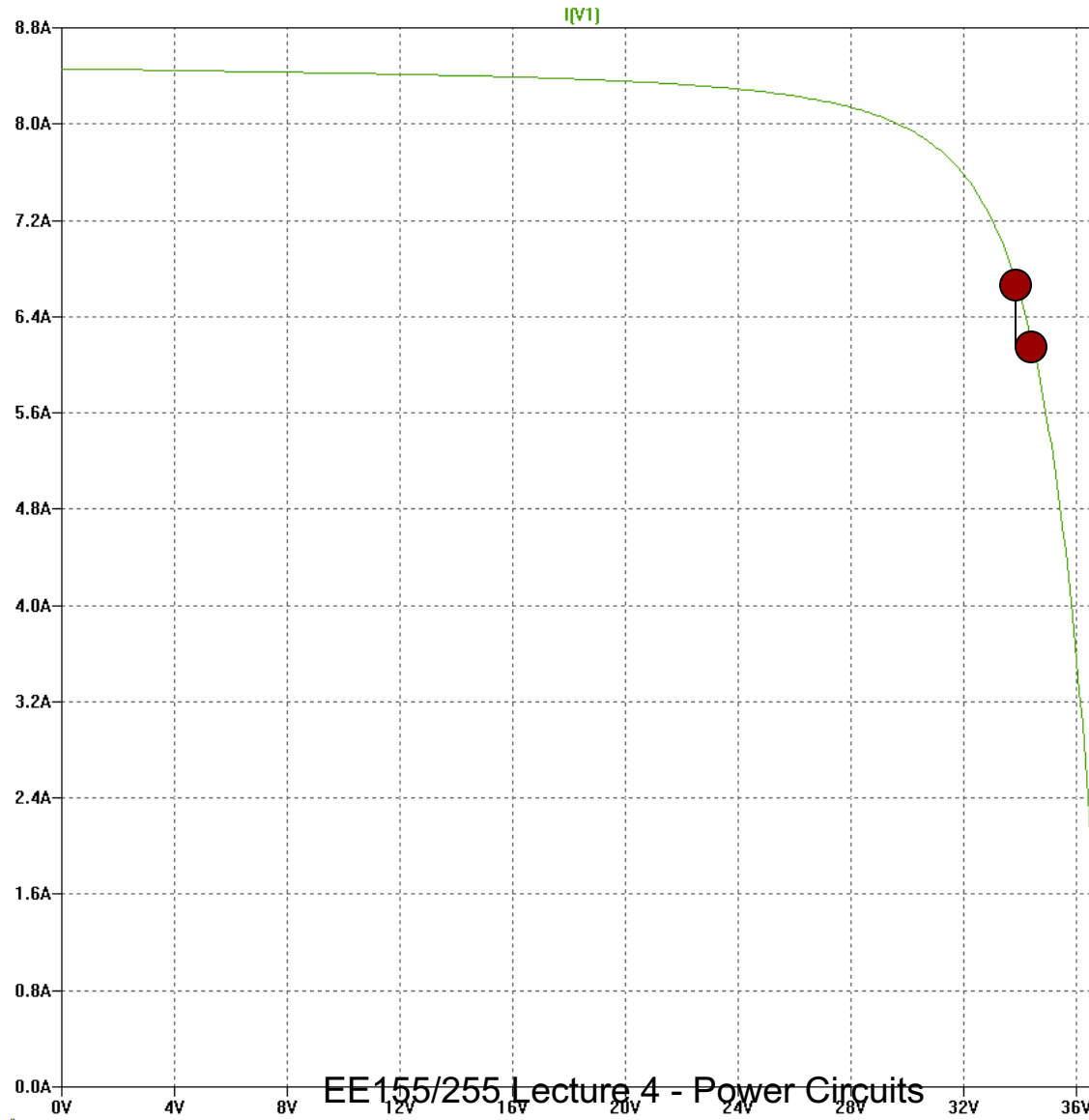
Dither by -0.5V to 34.5V
 $(34.5, 6.2) P=213.9 > 192.5$



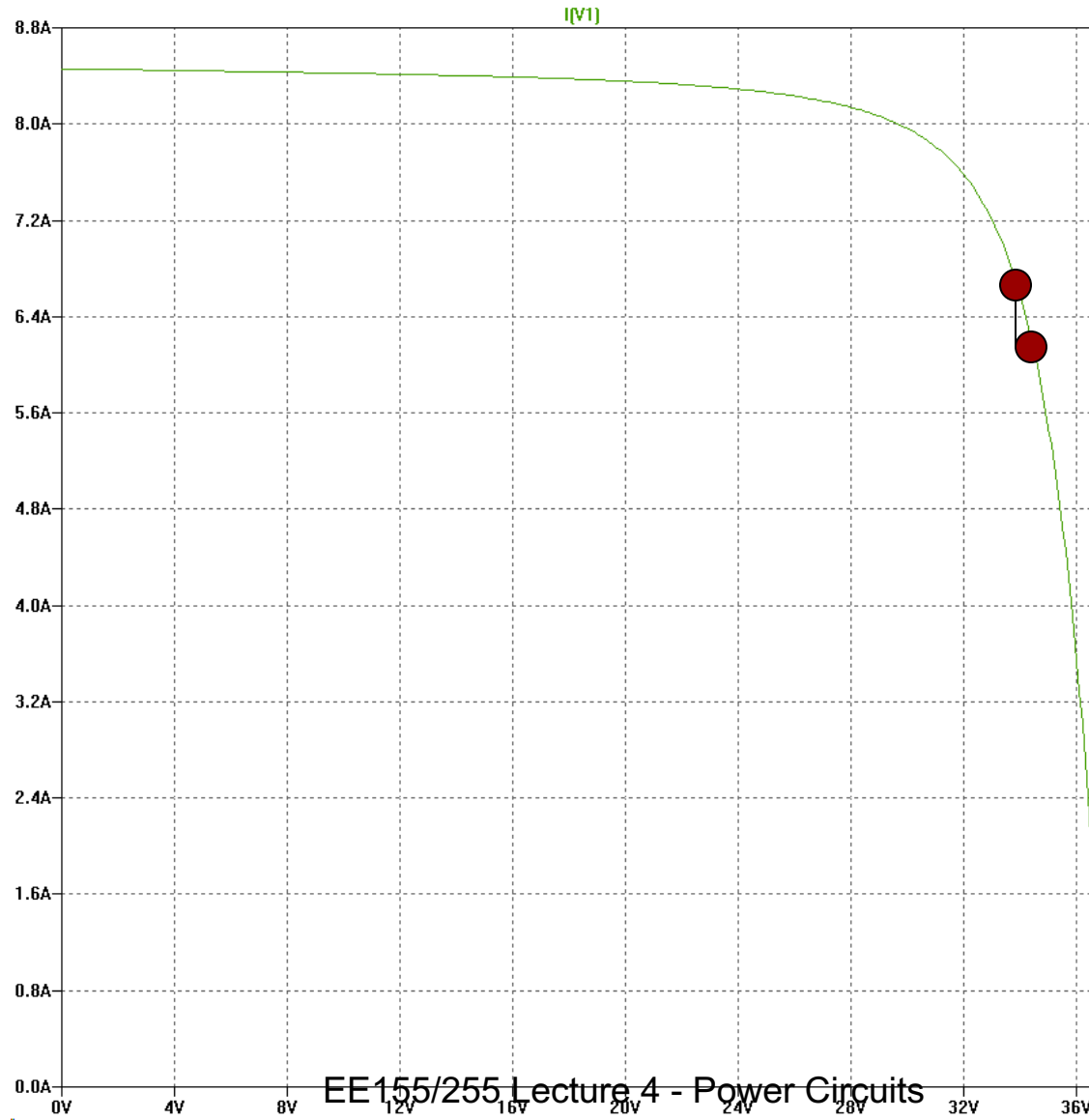
(34.5, 6.2) $P=213.9 > 192.5$
Keep move and keep going



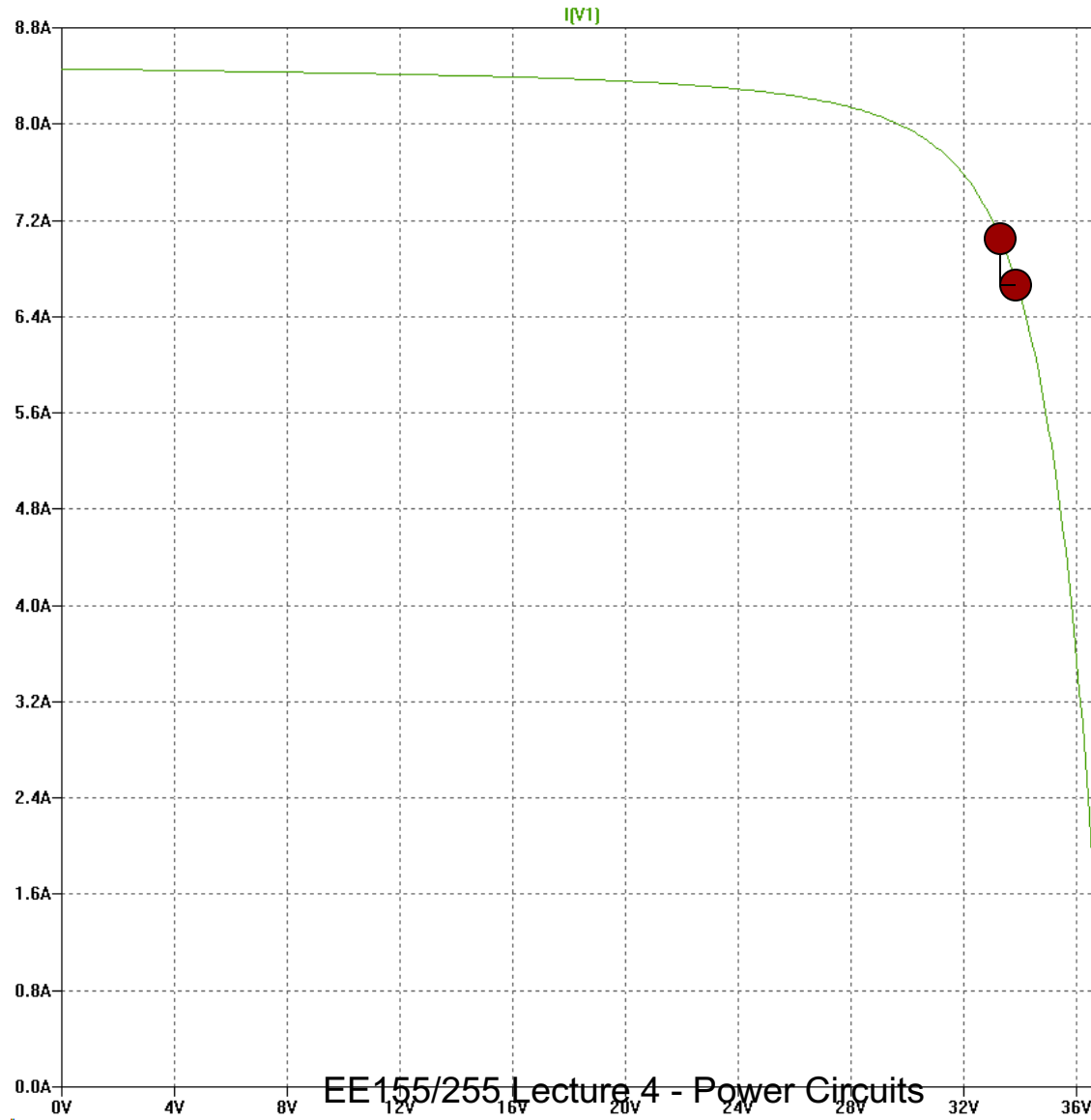
Move to 34.0
(34.0, 6.7) $P=227.8 > 213.9$



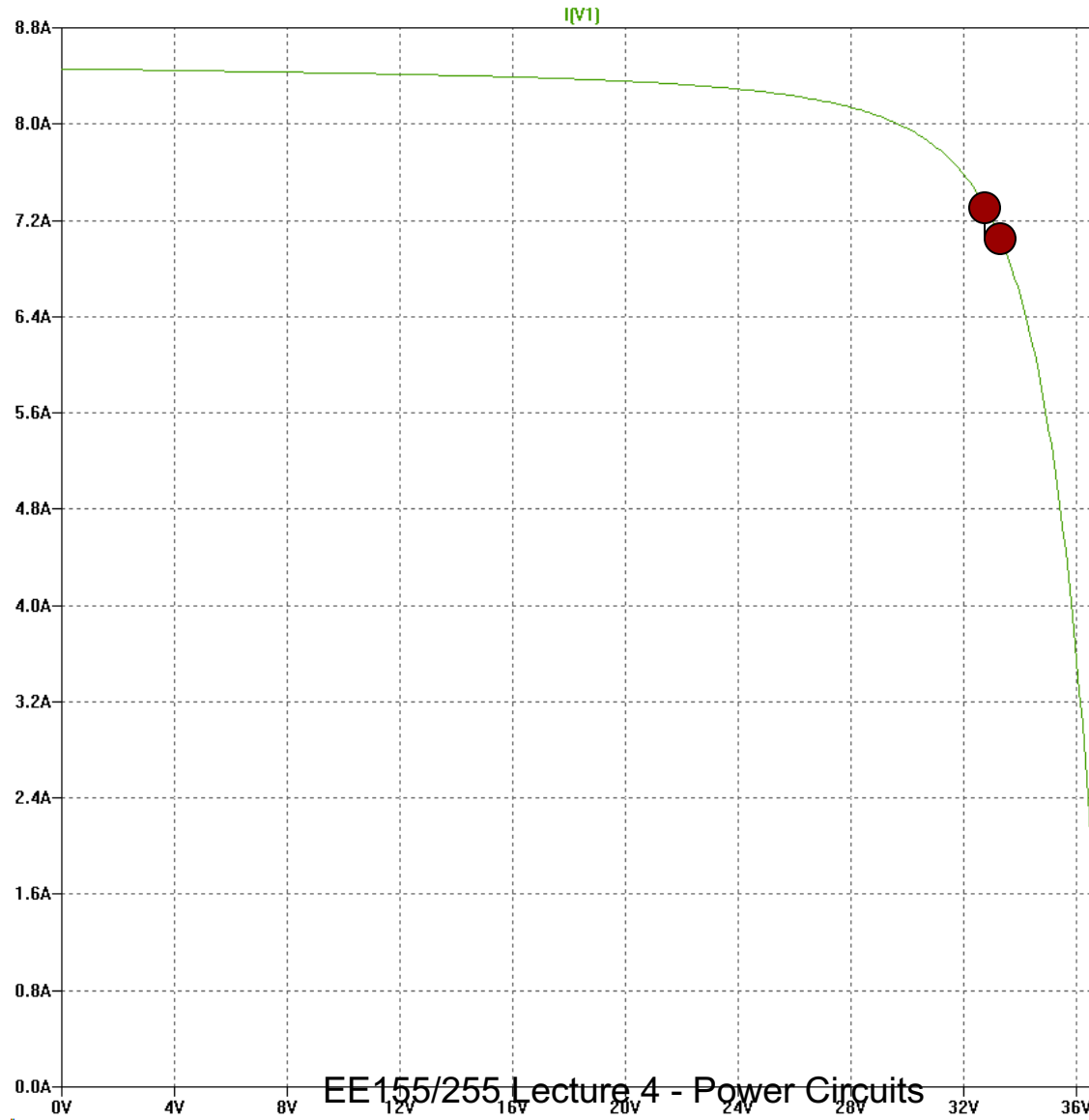
(34.0, 6.7) $P=227.8 > 213.9$
Keep move and keep going



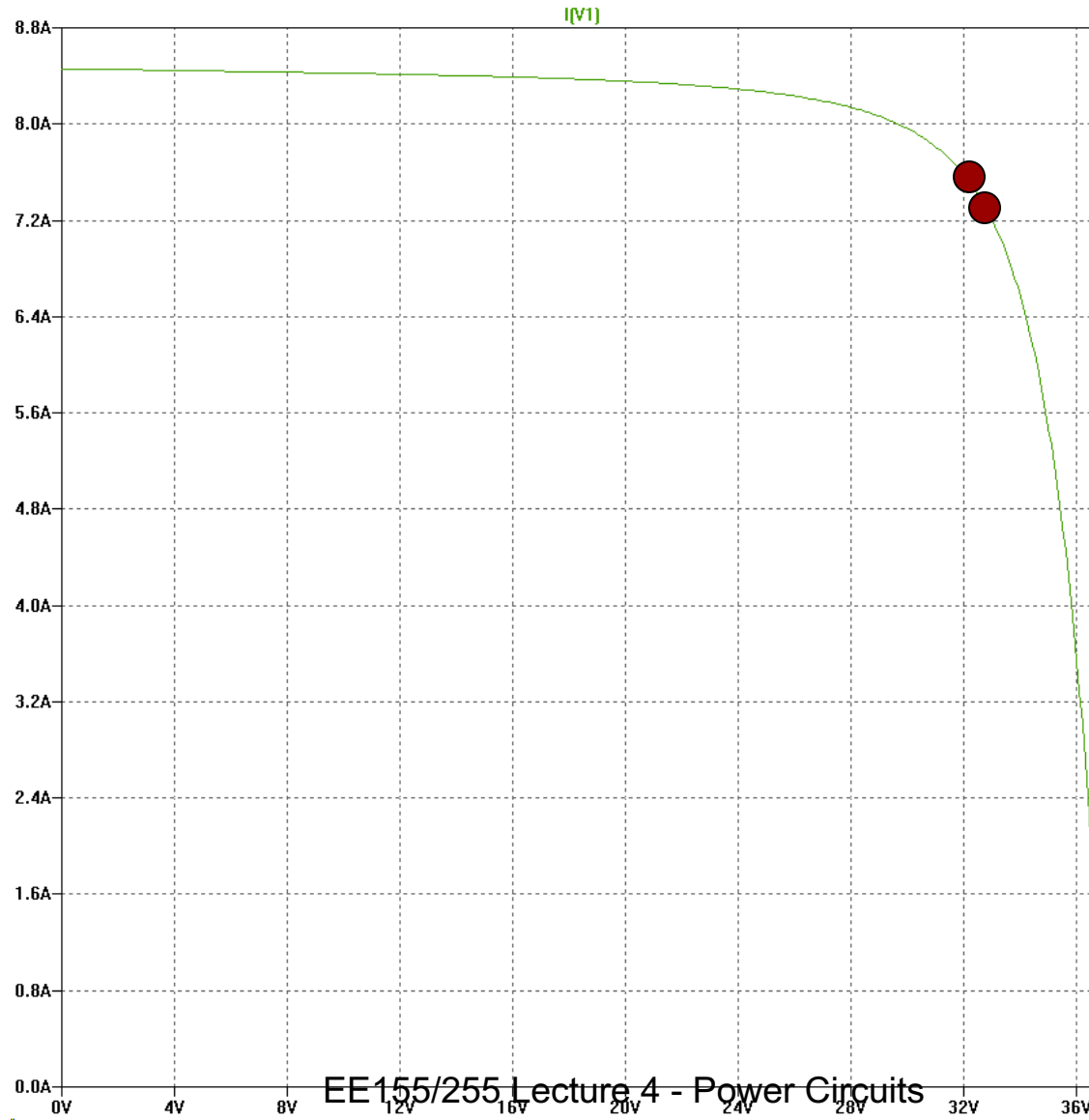
(33.5, 7.0) $P=234.5 > 227.8$
Keep move and keep going



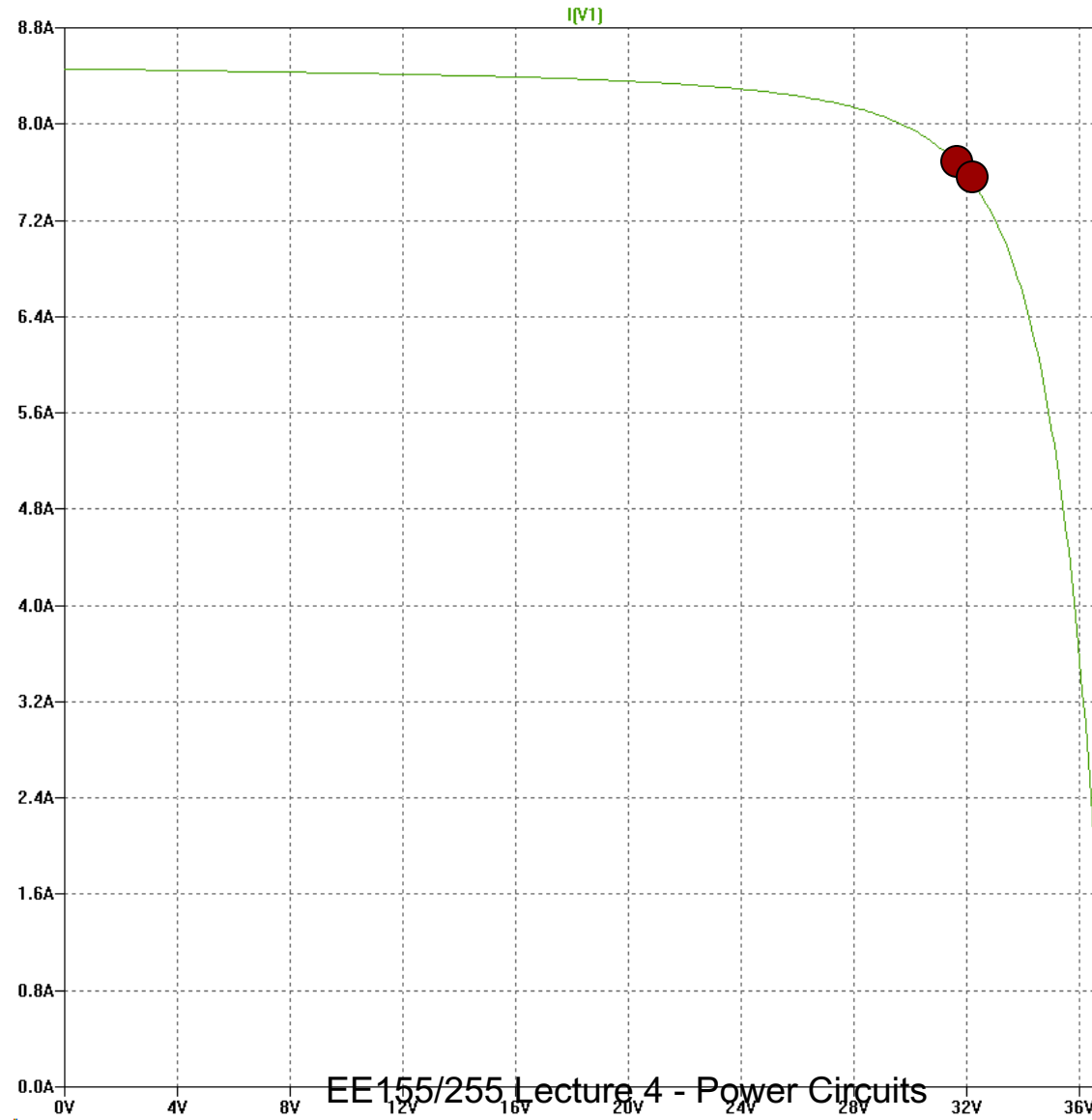
(33.0, 7.3) $P=240.9 > 234.5$
Keep move and keep going



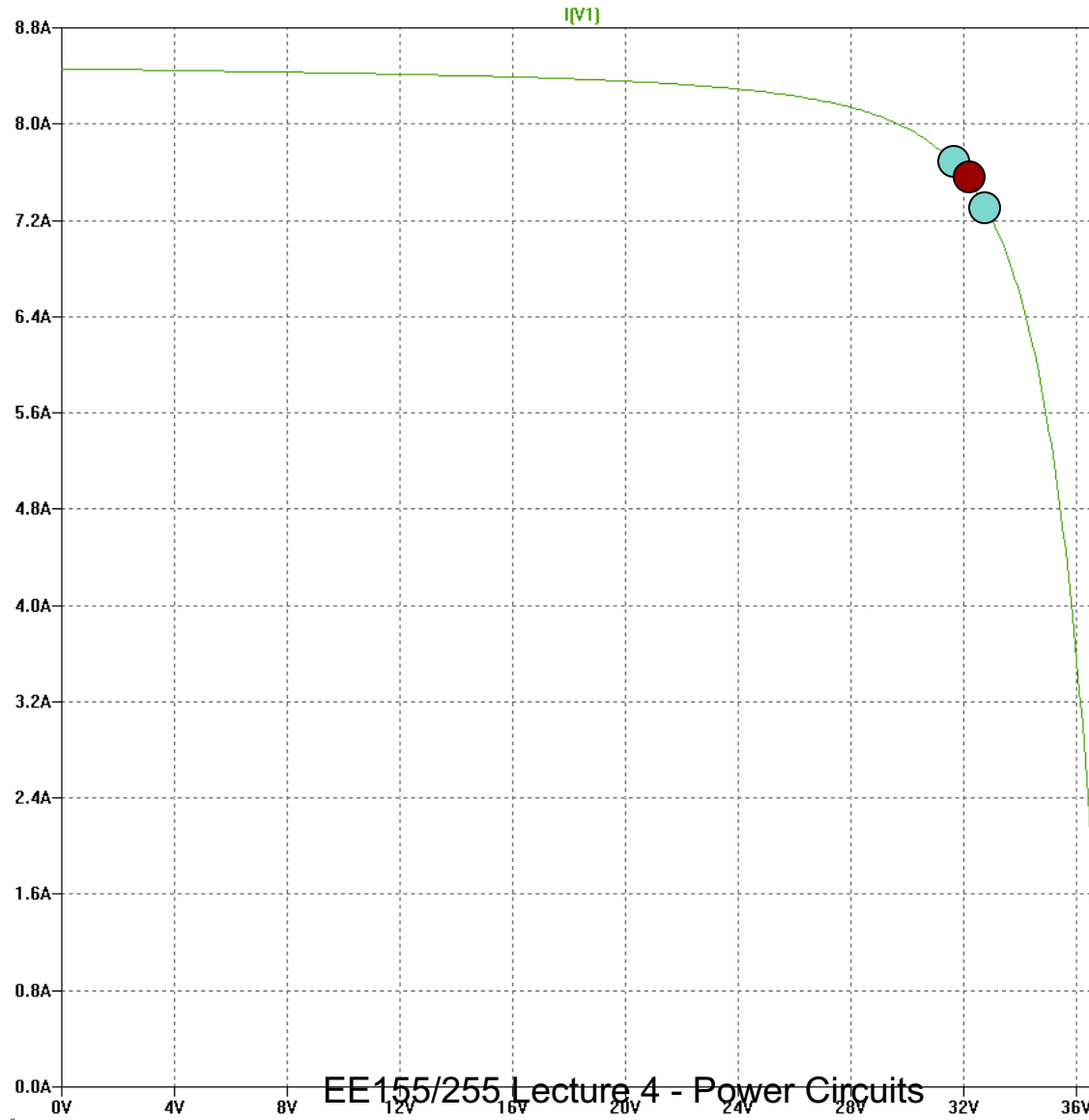
(32.5, 7.5) $P=243.75 > 240.9$
Keep move and keep going



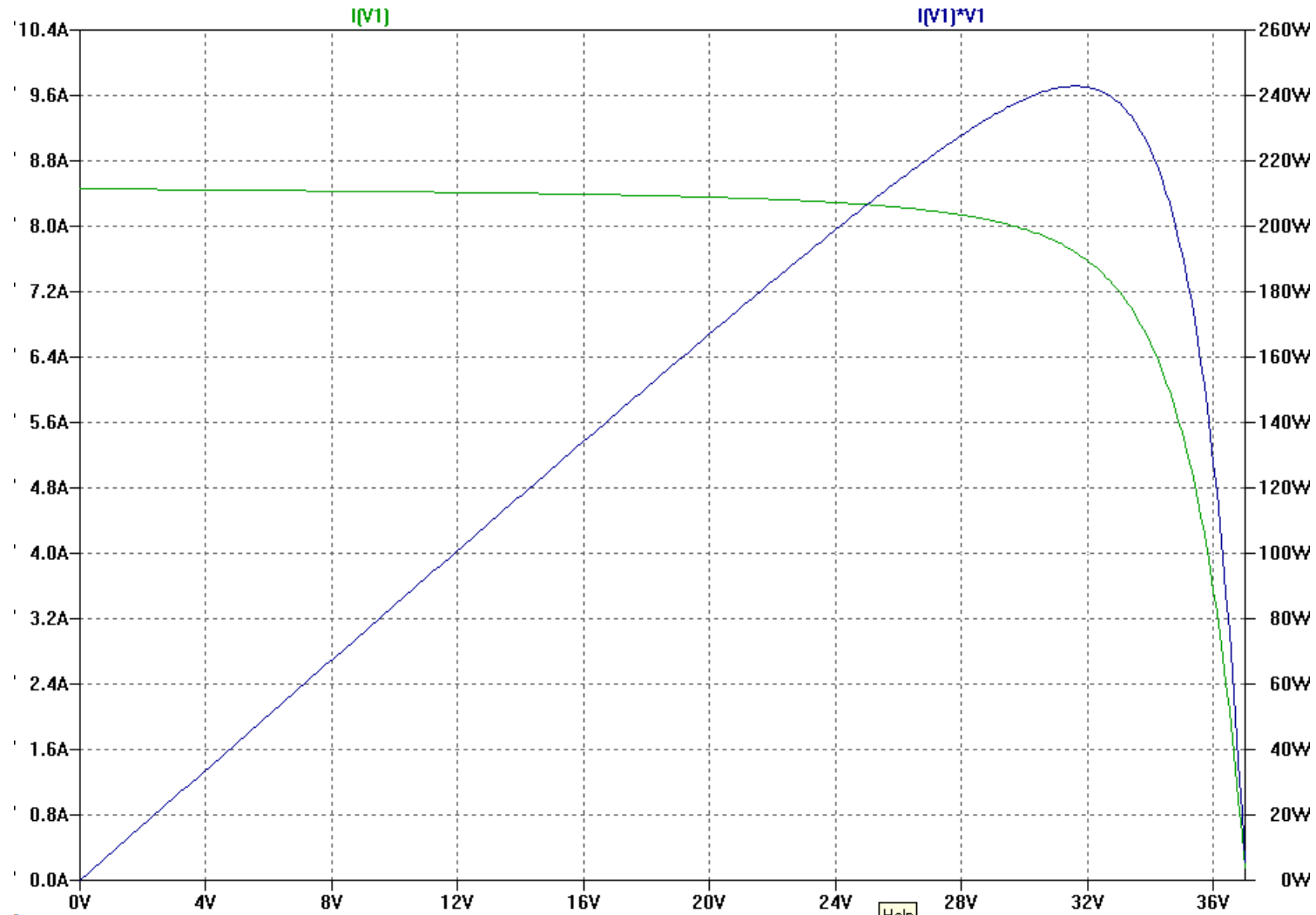
(32.0, 7.6) $P=243.2 < 243.75$
Abandon Move and Go Back!



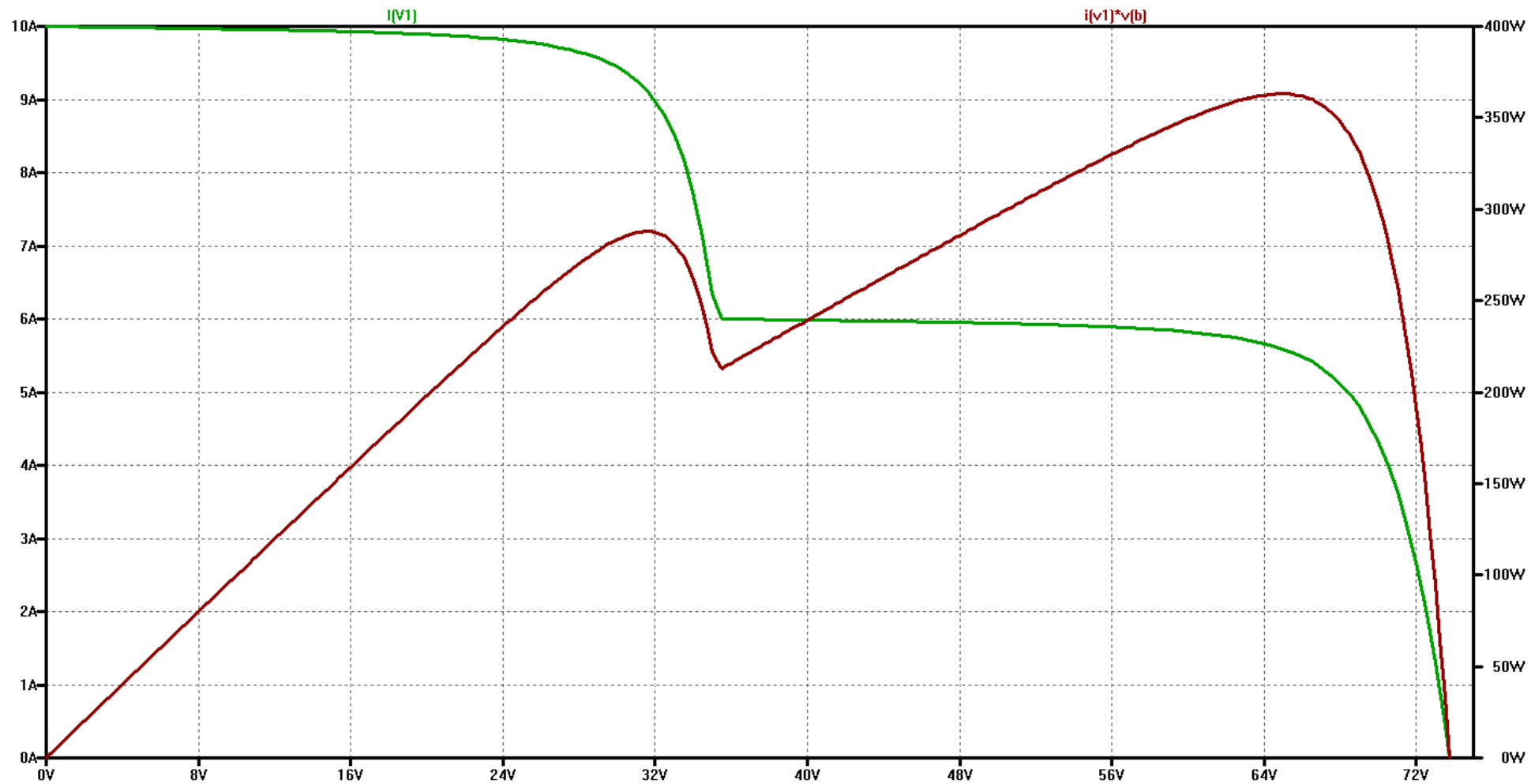
Operate at (32.5, 7.5) P=243.8
With occasional forays to 32.0 and 33.0



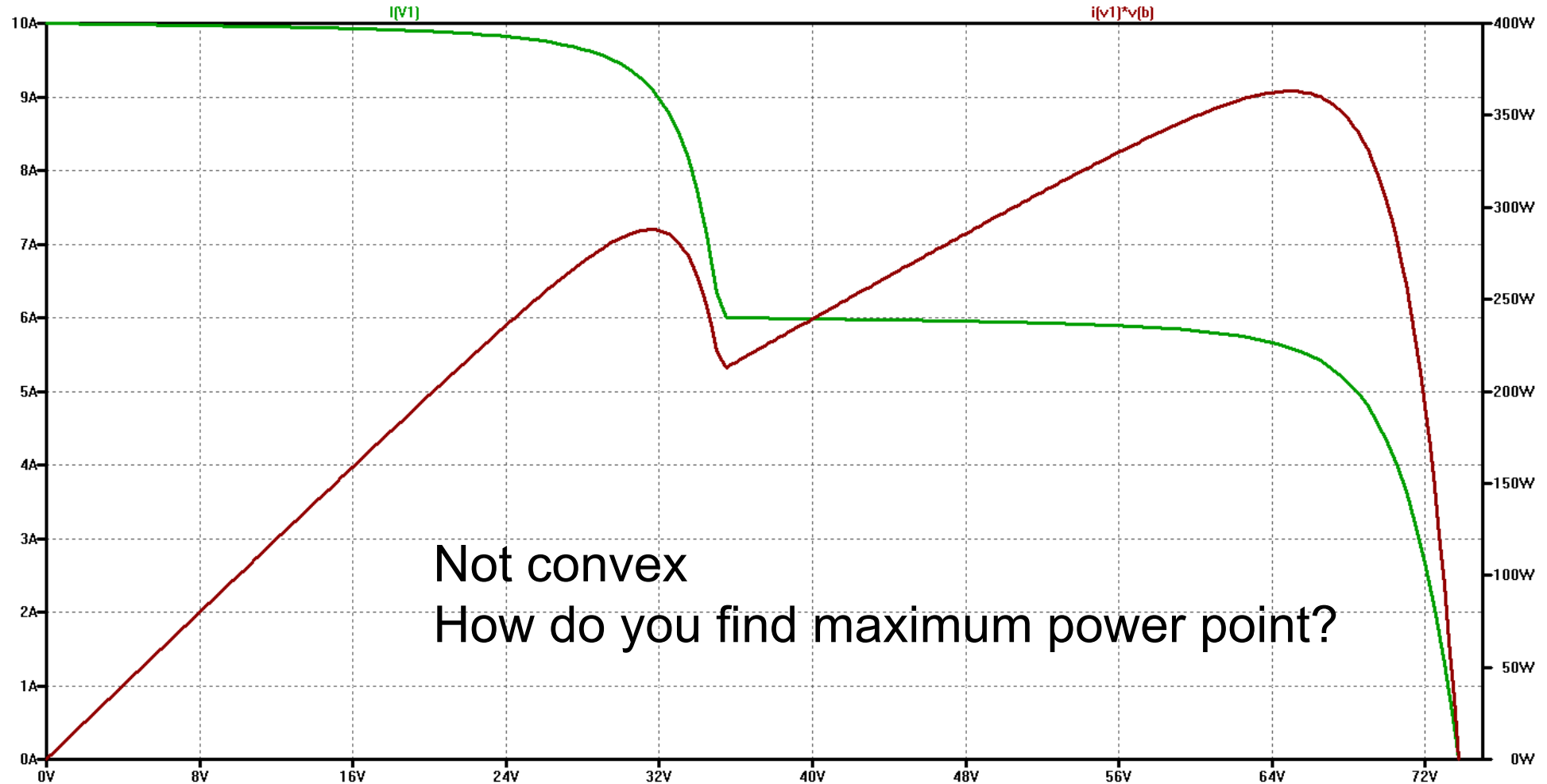
“Hillclimbing” On the Power Curve



Compound Power Curve



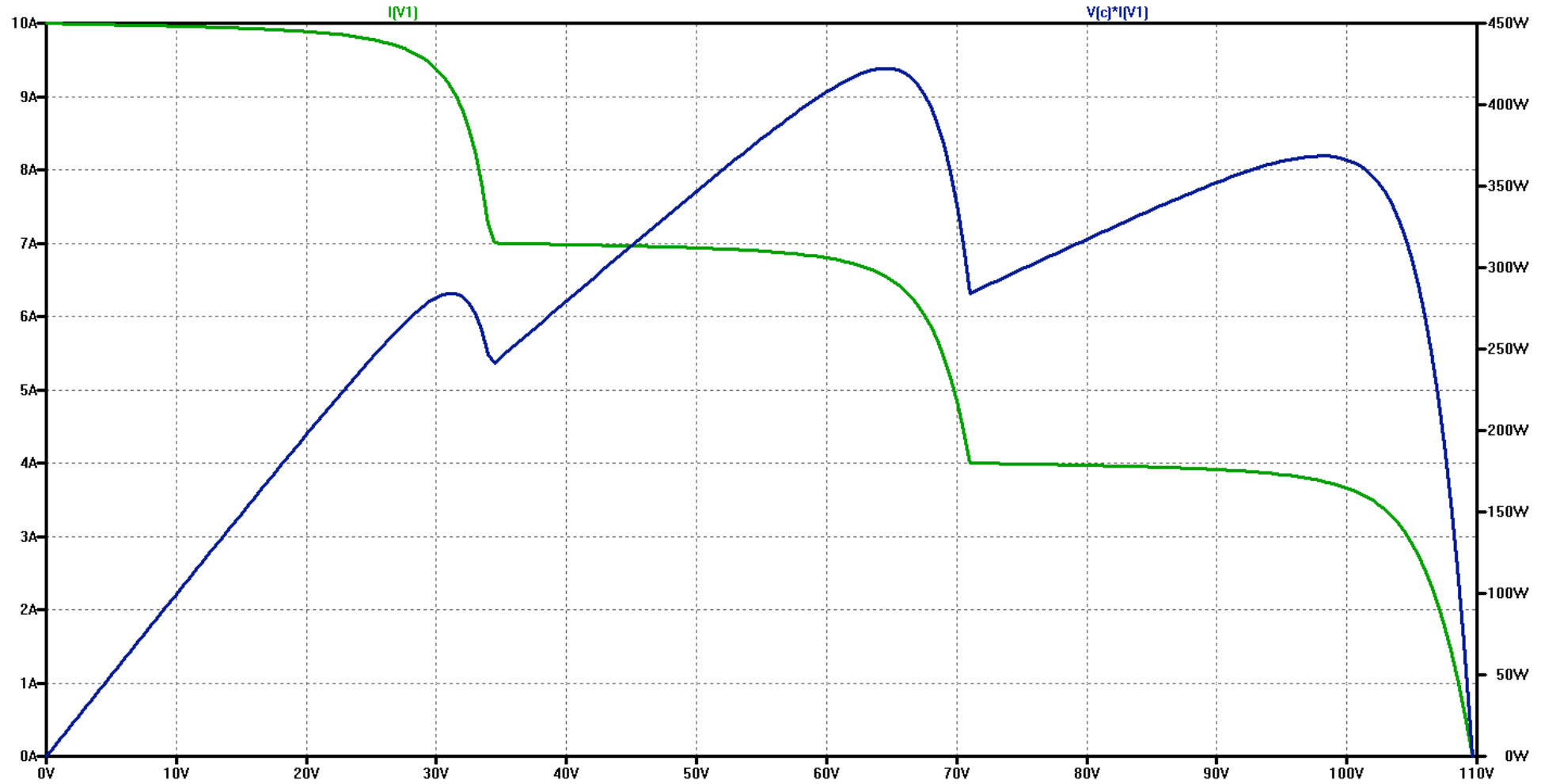
Compound Power Curve (2 Panels)



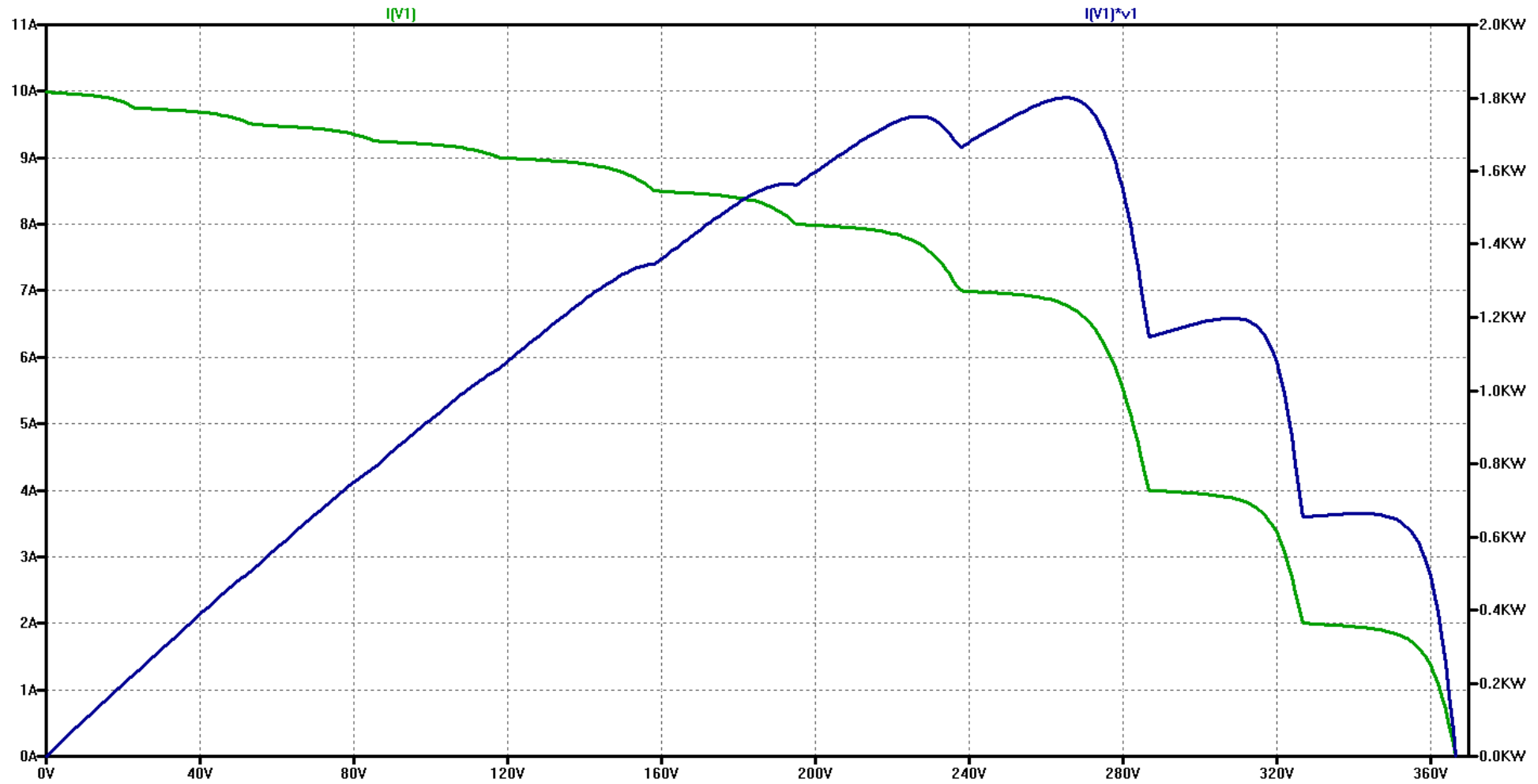
Not convex

How do you find maximum power point?

Three Panels



Typical String of 10 PV Panels



Search Strategies for Non-Convex MPPT

- Exhaustion
 - Try every operating point
- Random
 - Randomly pick new points – keep if better
- Hierarchical
 - Try every point – with coarse spacing
 - Try every point near best point with finer spacing
 - Repeat
- Acquire and Track
 - One of the above to acquire MPPT (e.g., hierarchical)
 - Then gradient search to track
 - Periodically revisit (devote some fraction of string time to this)
- Optimal method depends on
 - Shape of curve
 - How fast the curve changes
 - How the curve changes

Good Optimization Depends on Understanding The Problem

- Collect lots of data
 - Time series of IV curves from typical strings
- Understand the data
- What causes “dips”
 - Bad panels
 - Static offset in current
 - Fixed shading – trees, buildings, etc...
 - Periodic offset – same time each day
 - Variable shading – clouds, etc...
 - Unpredictable shading – but shifts across panels in one direction
- Develop algorithms
- Test on data

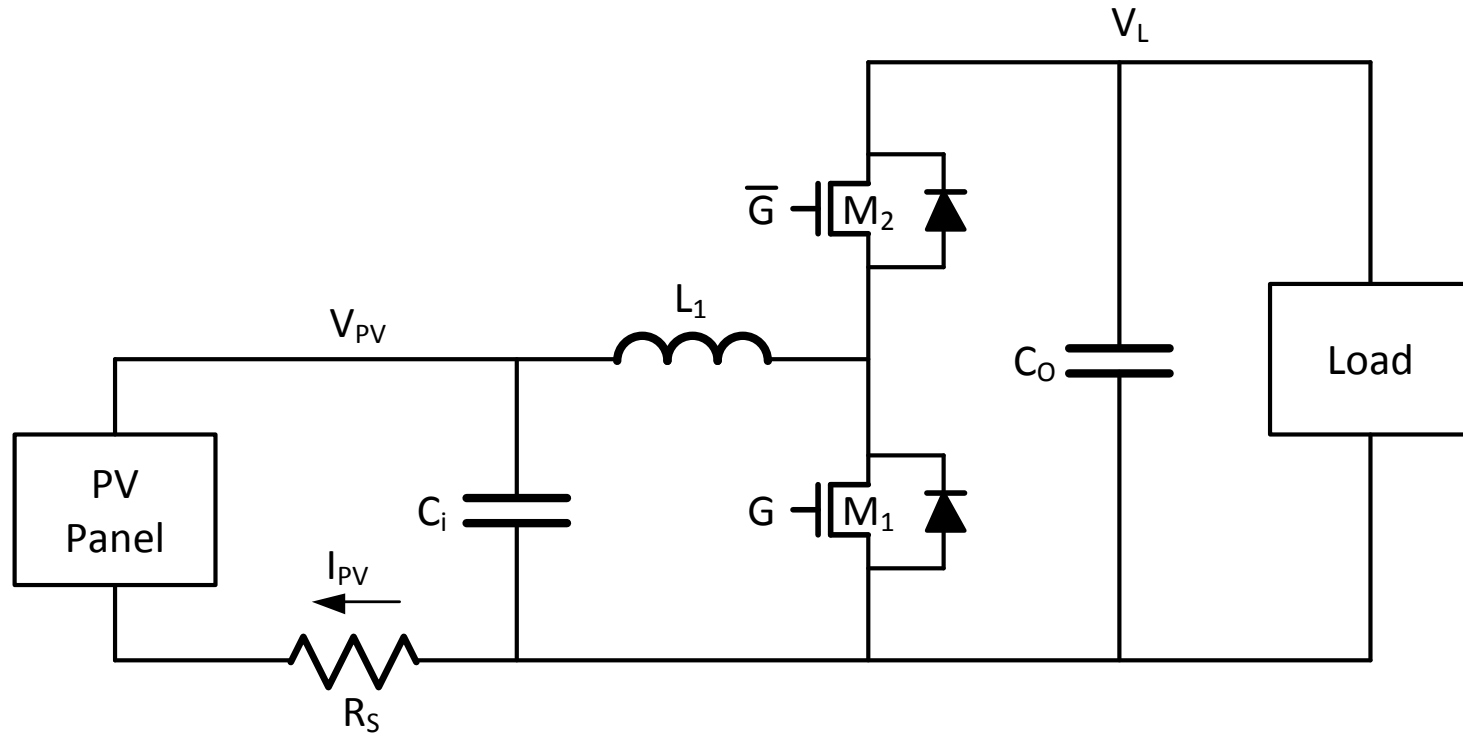
An Example of Optimization

- Trade-off parameters against one another to maximize a figure of merit.
- In this case, parameters are panel voltage and current.
- Figure of merit is power.
- Optimization is done real-time because temperature and irradiance change.
 - Sometimes optimization is done at design time, or calibration time.

PV Systems

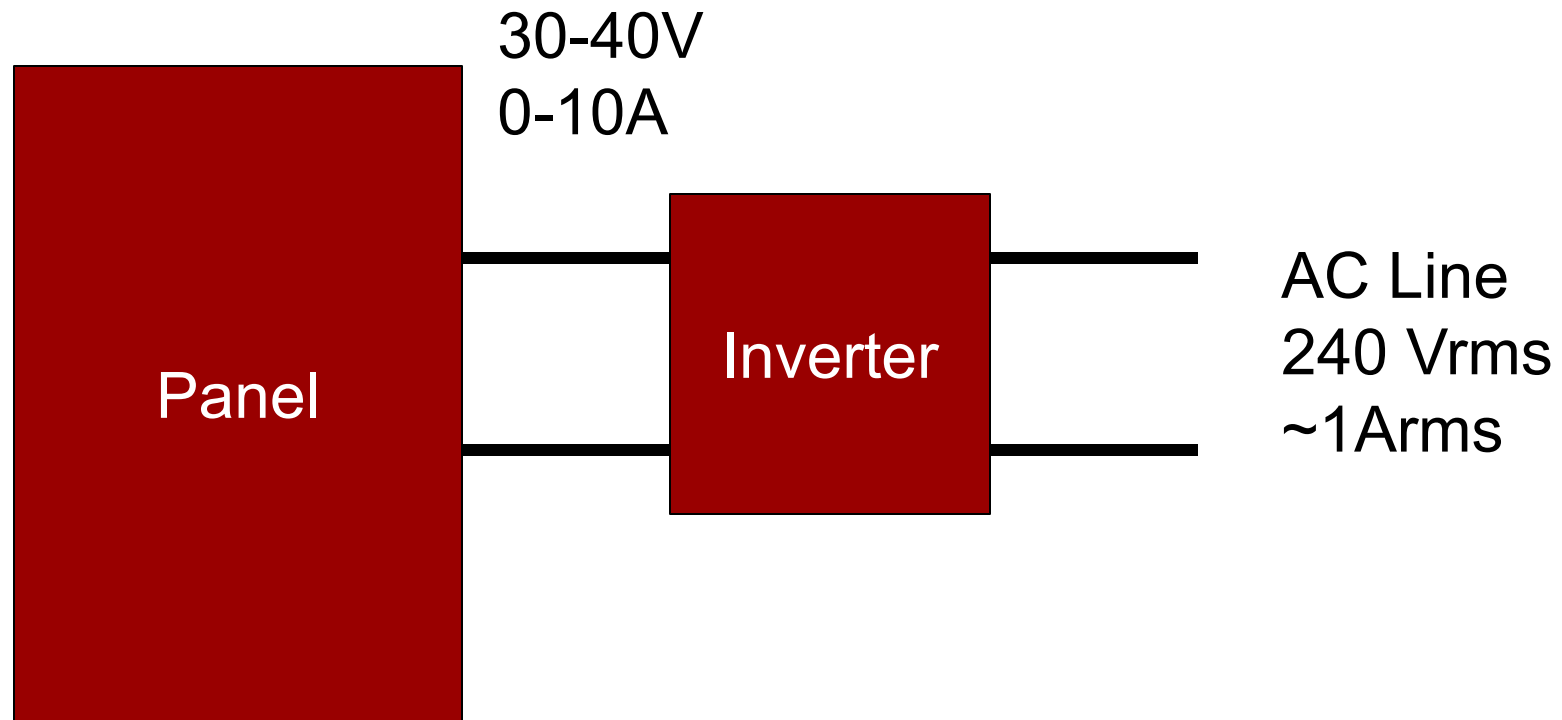
MPPT Power Path

(Boost Converter with Energy Meter)

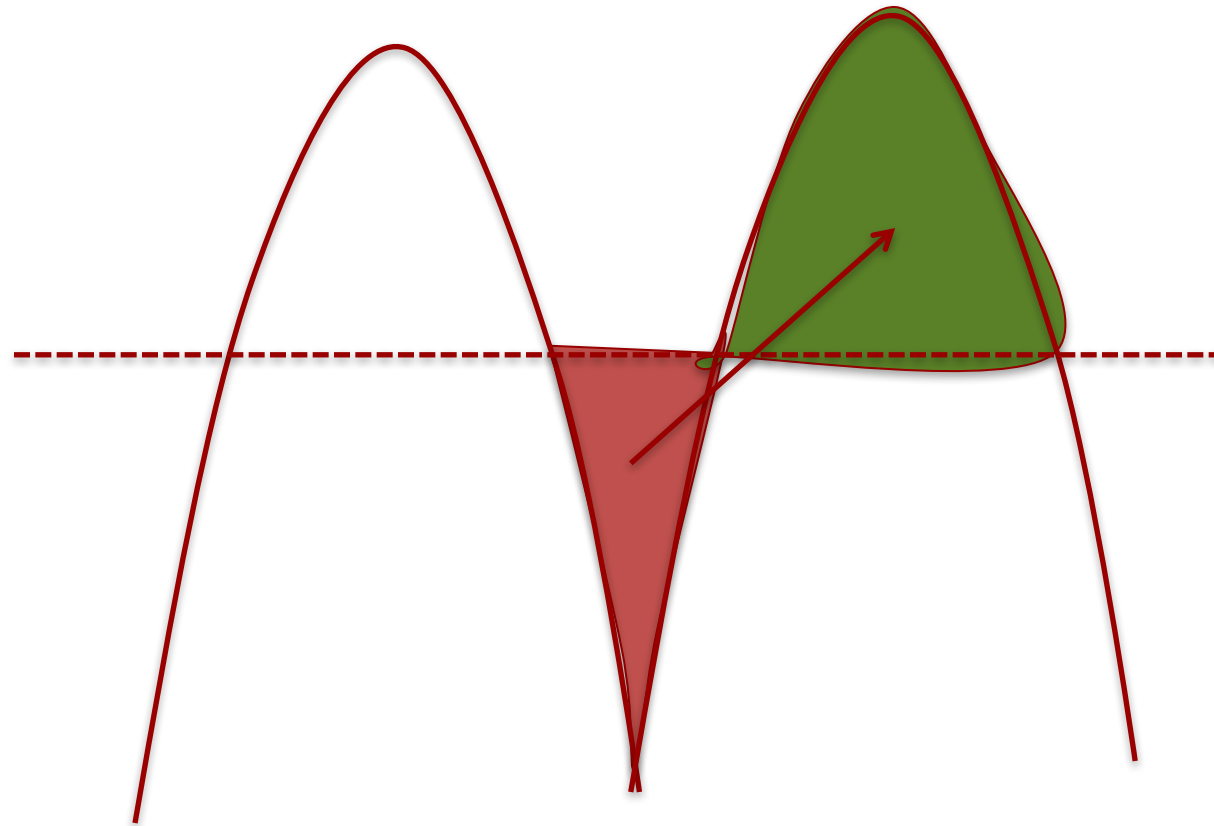


MPPT is a boost converter that regulates its INPUT voltage

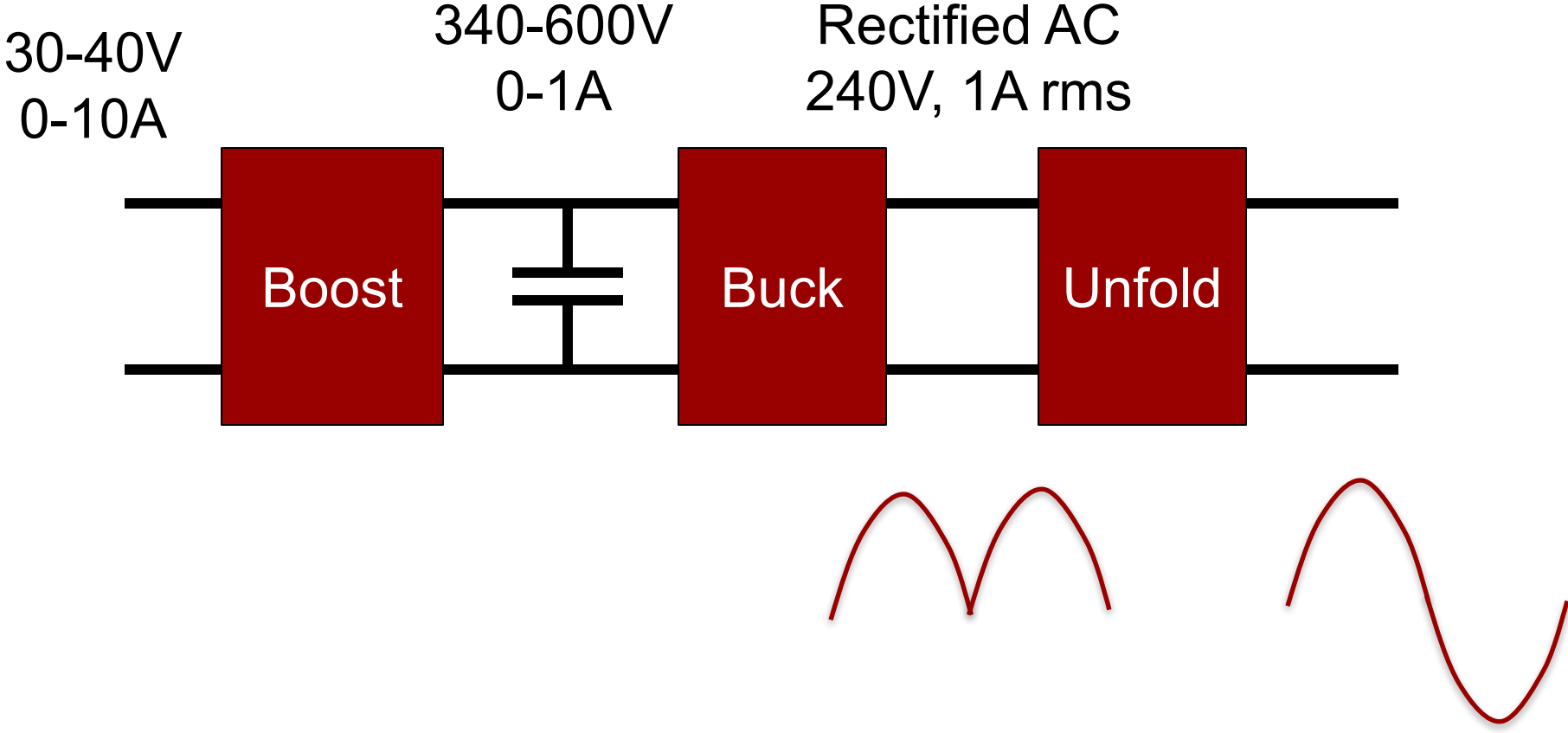
Microinverter



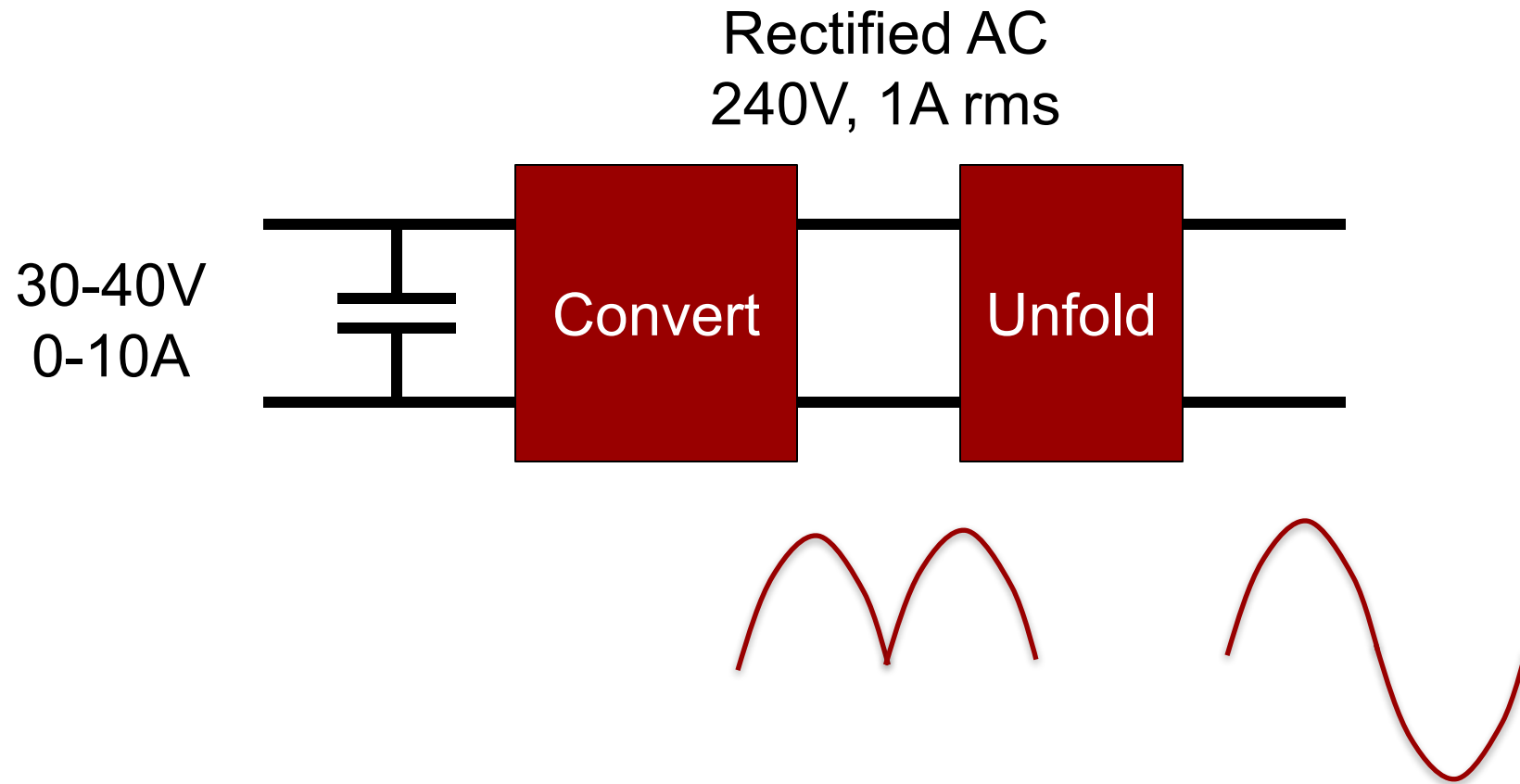
Store Energy During AC Null



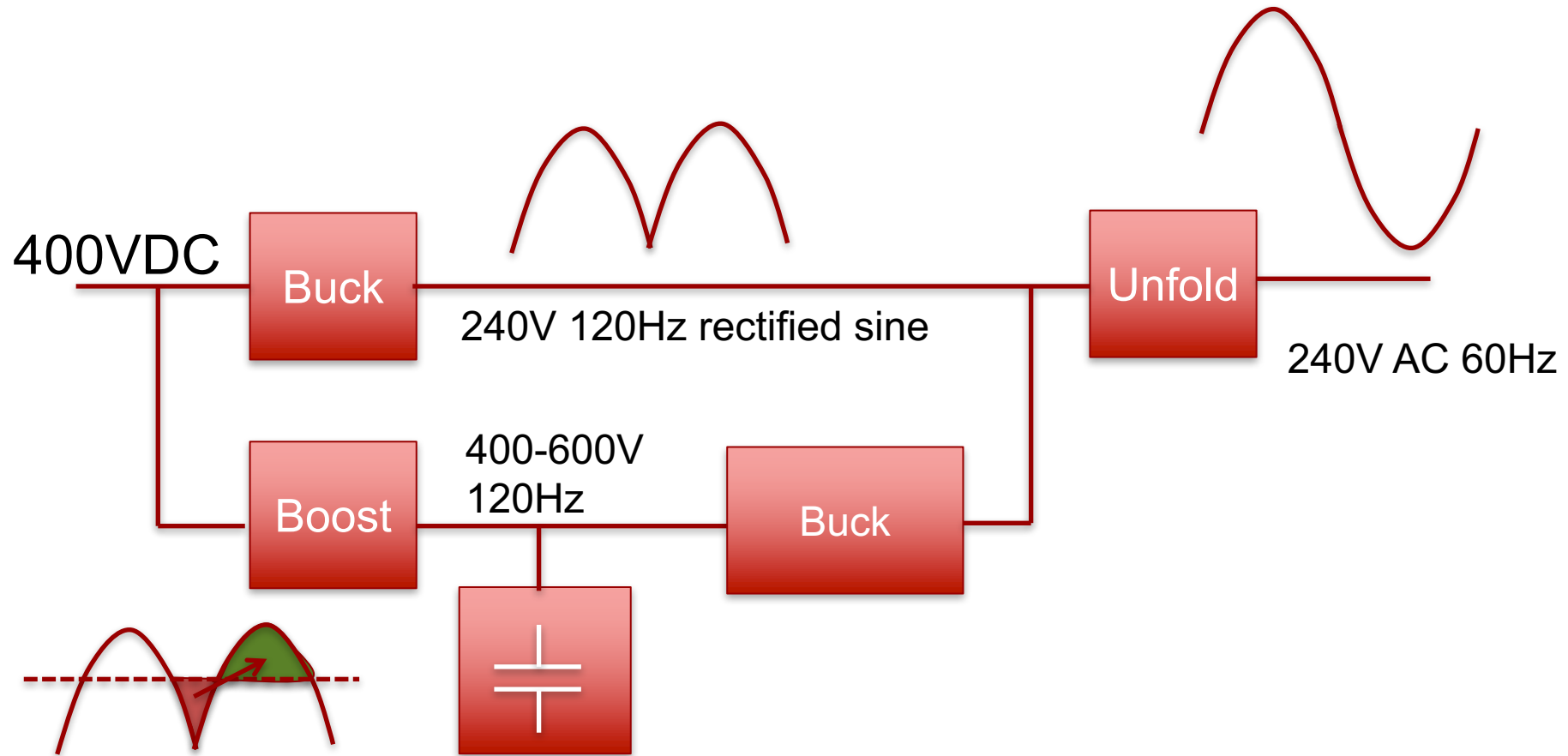
Approach 1 – DC Link



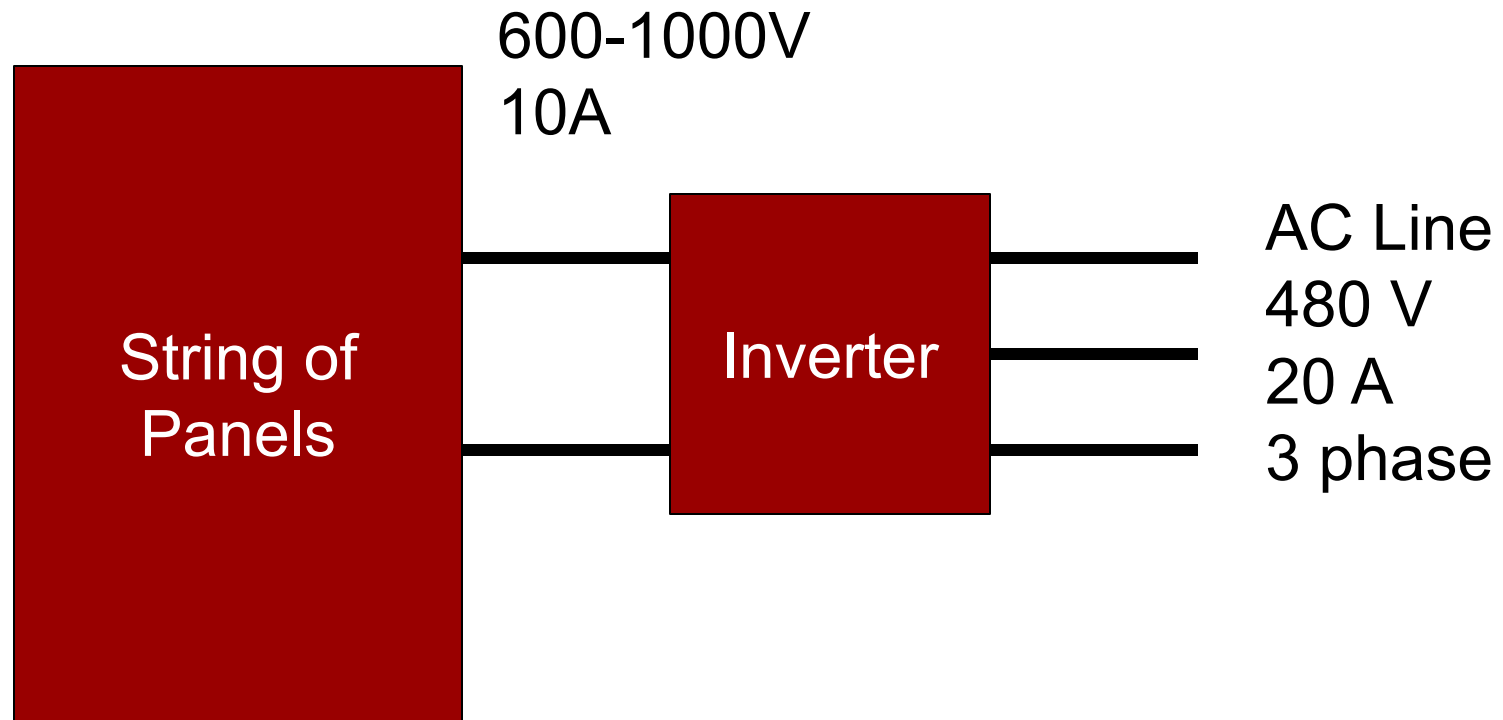
Approach 2 – Single Stage



Two-Path

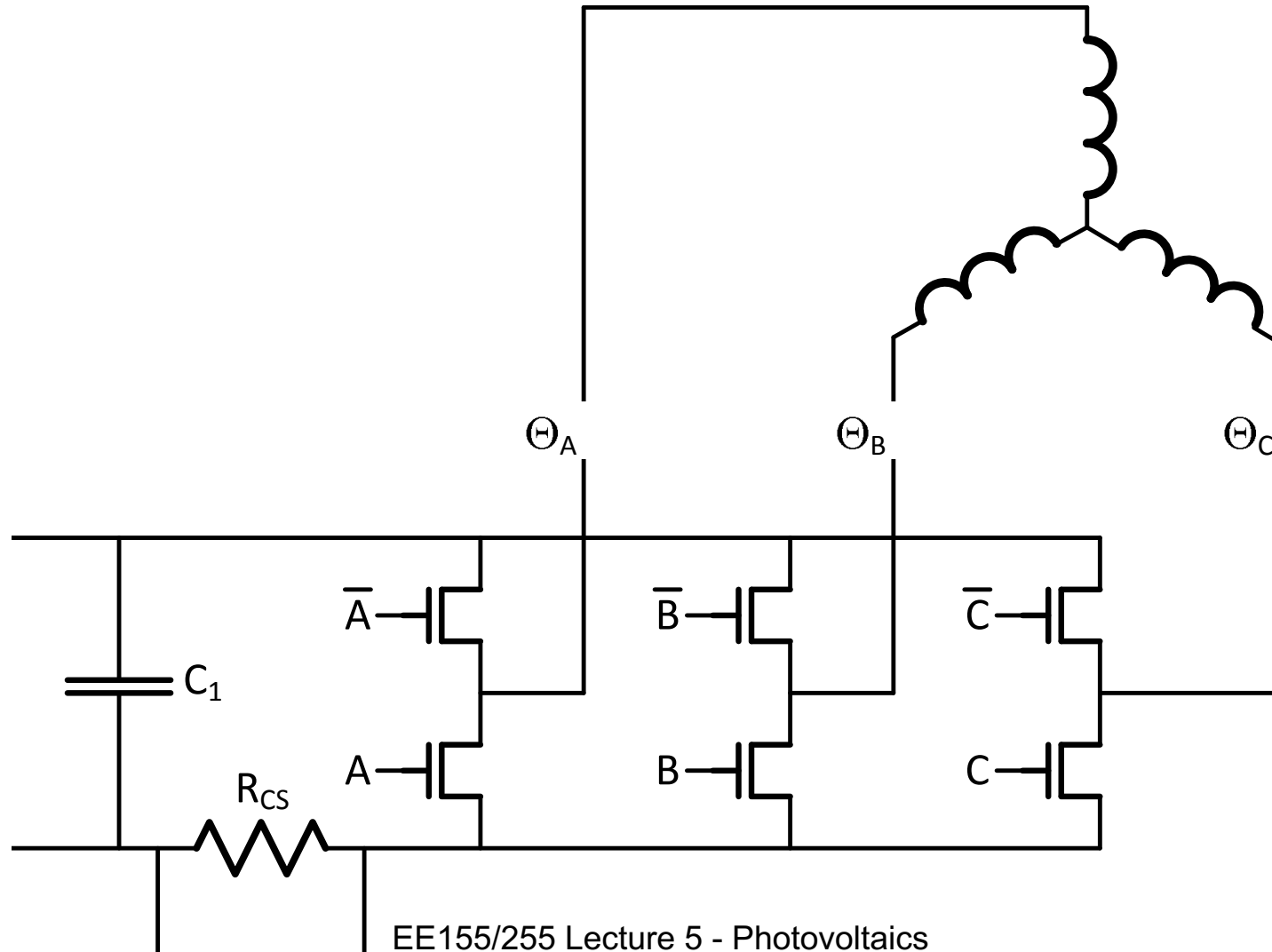


3-Phase



No need for energy storage

3- Φ Inverter Power Path



Transformerless

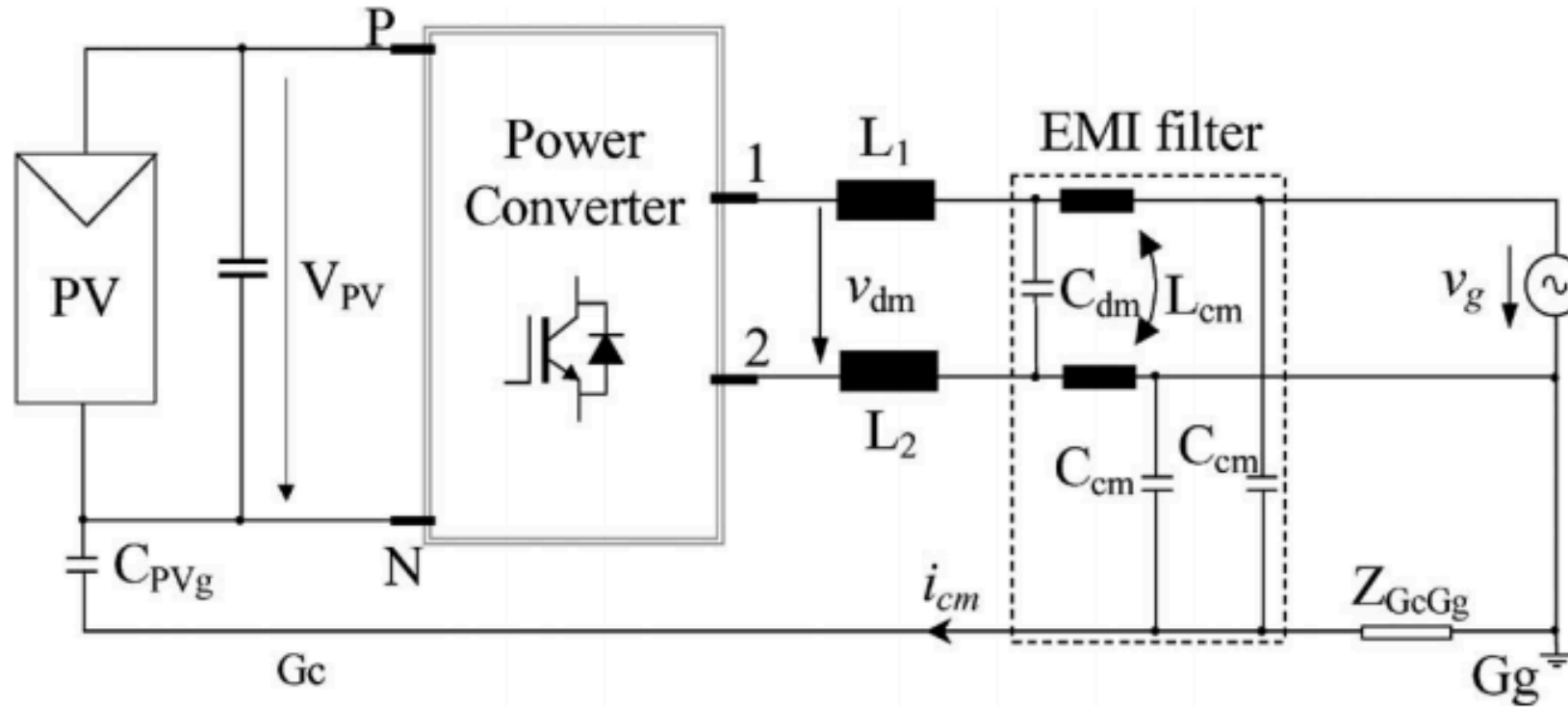


Fig. 1. Common-mode currents in a transformerless conversion stage.

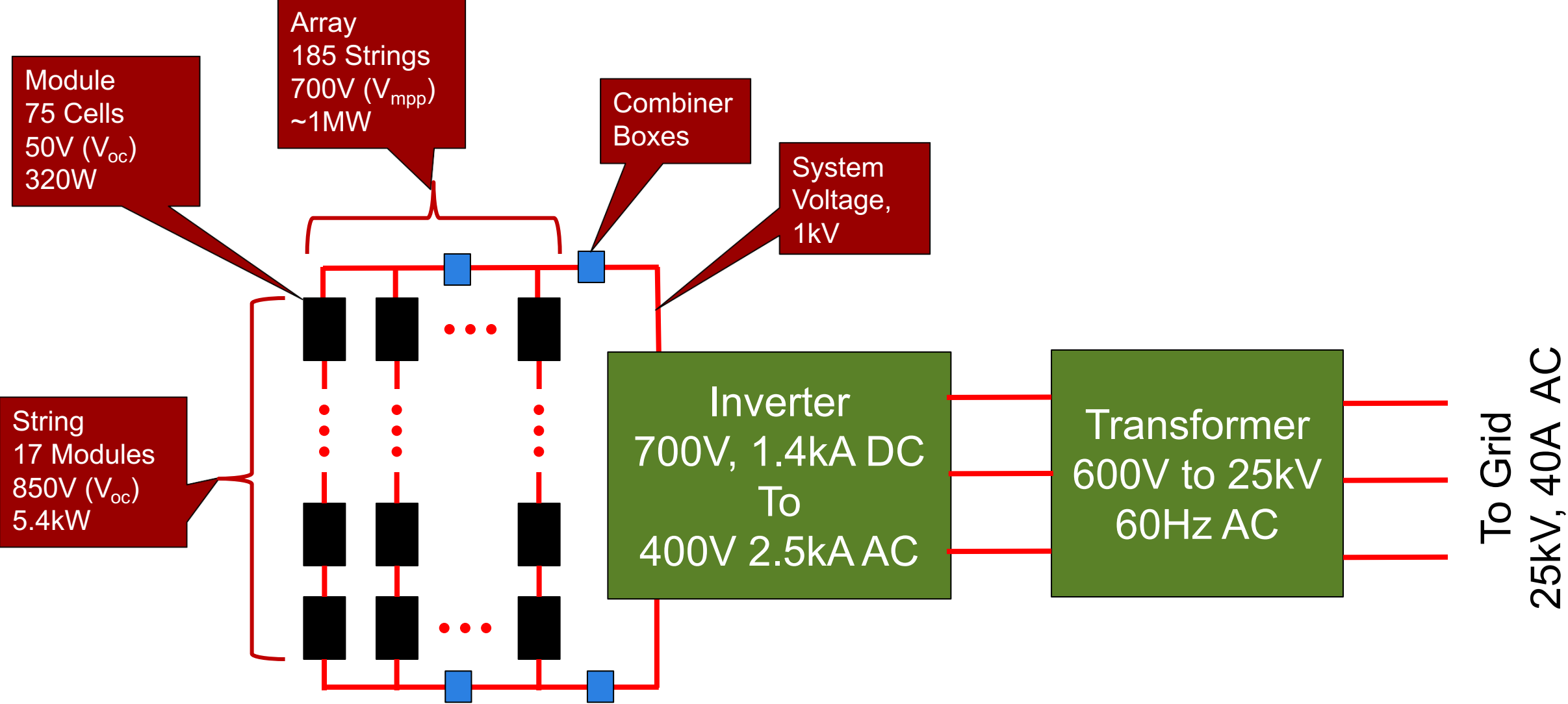
Typical Utility-Scale PV System



Typical Utility-Scale PV System

- 8,000 Modules – 400 strings of 20 modules each
 - 325W/module – 2.6MW DC total
- Central 2MW inverter
- Central 2MW step-up transformer to 34.5kv
- Single axis tracking
- This 2MW “block” is repeated for larger systems

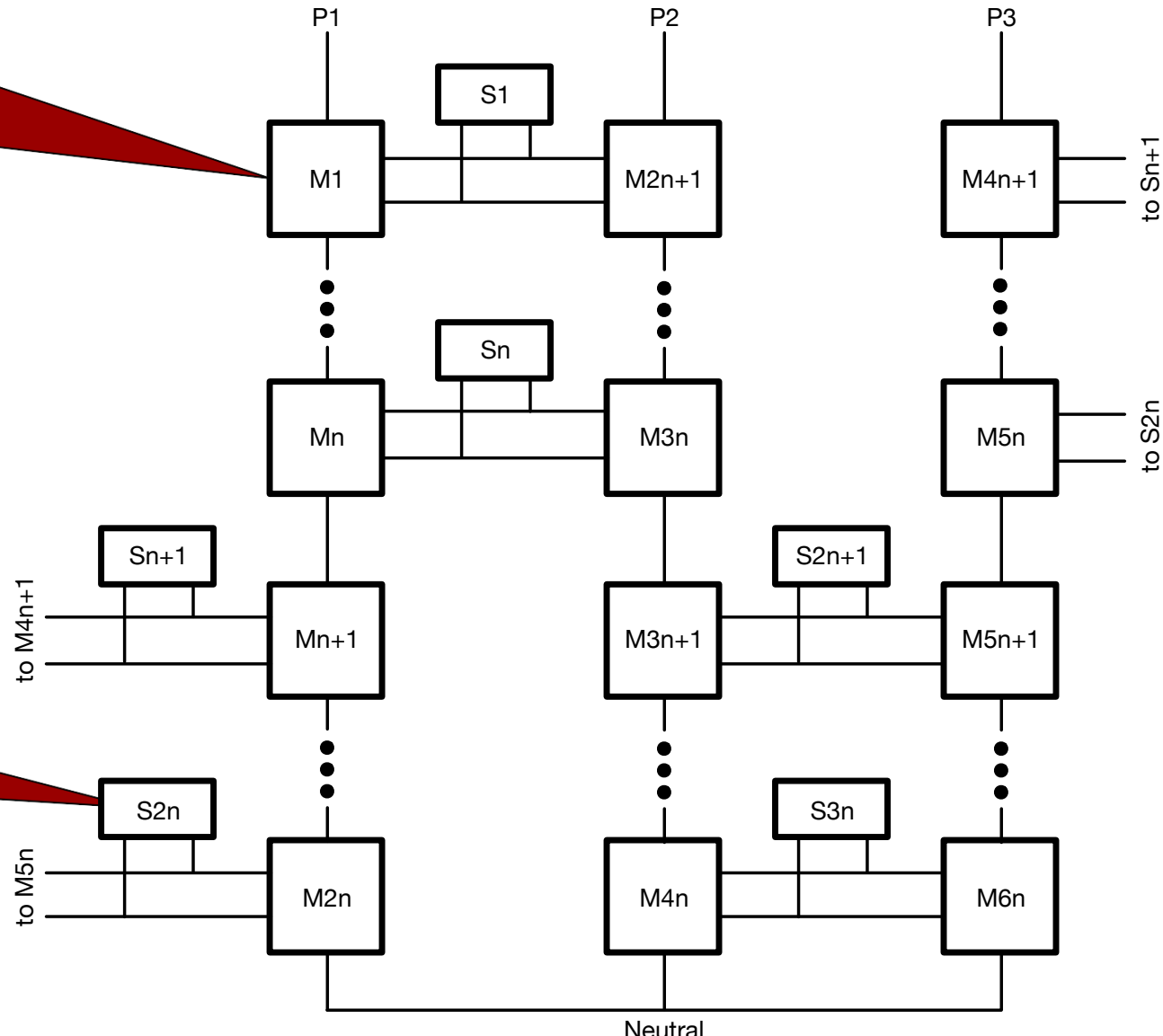
Utility-Scale PV System



Modular Multi-Level System

3 ϕ AC to Grid 25kV, 40A

Modular Inverter
700V DC to
700V AC
Single Phase
10kW each

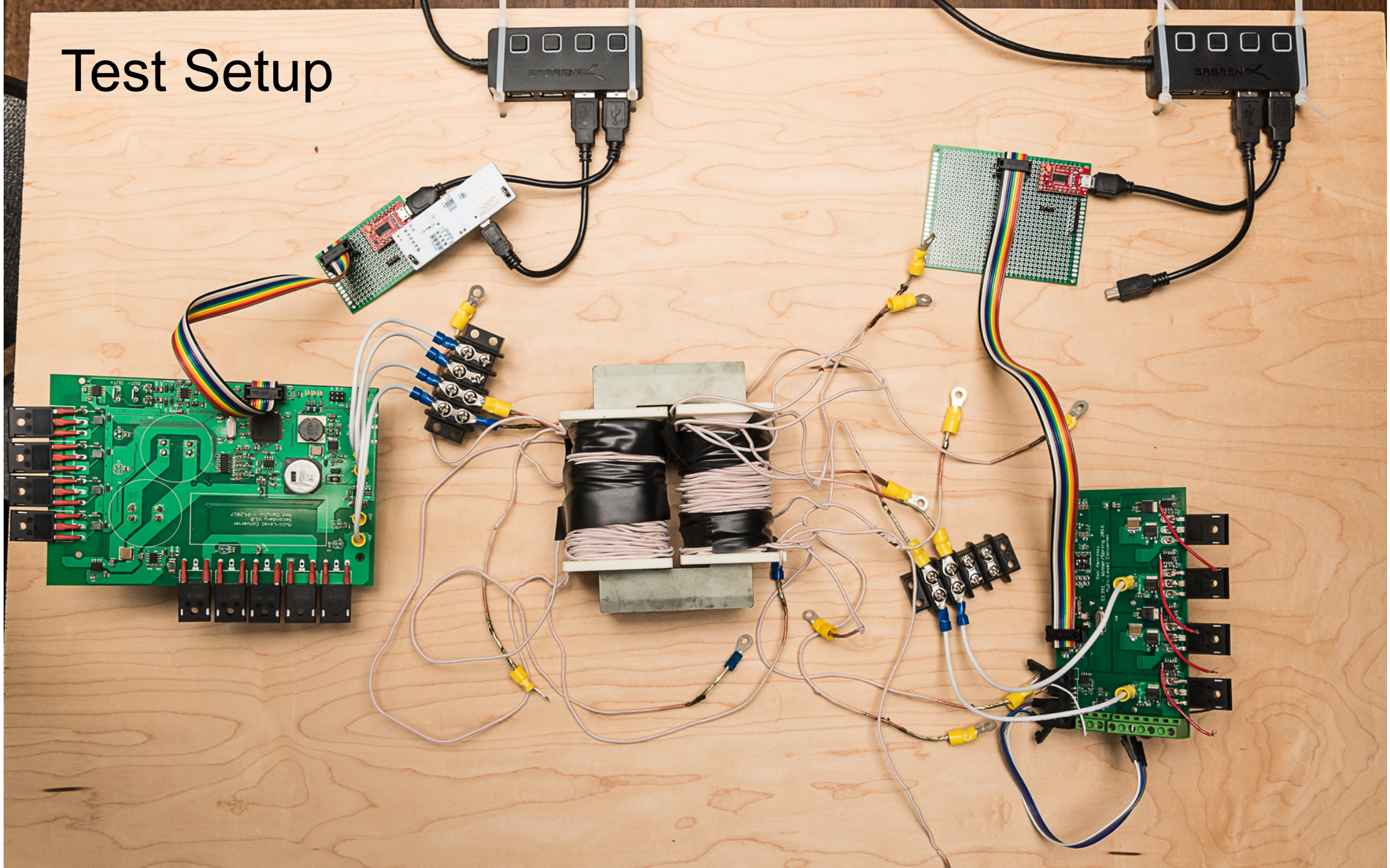


Distributed or
centralized
packaging

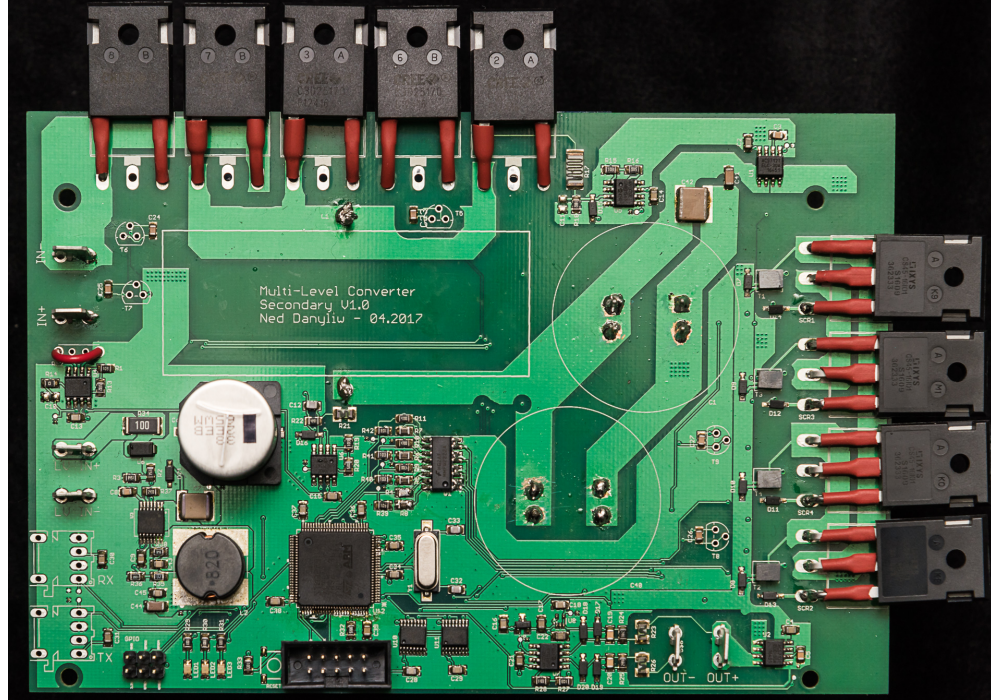
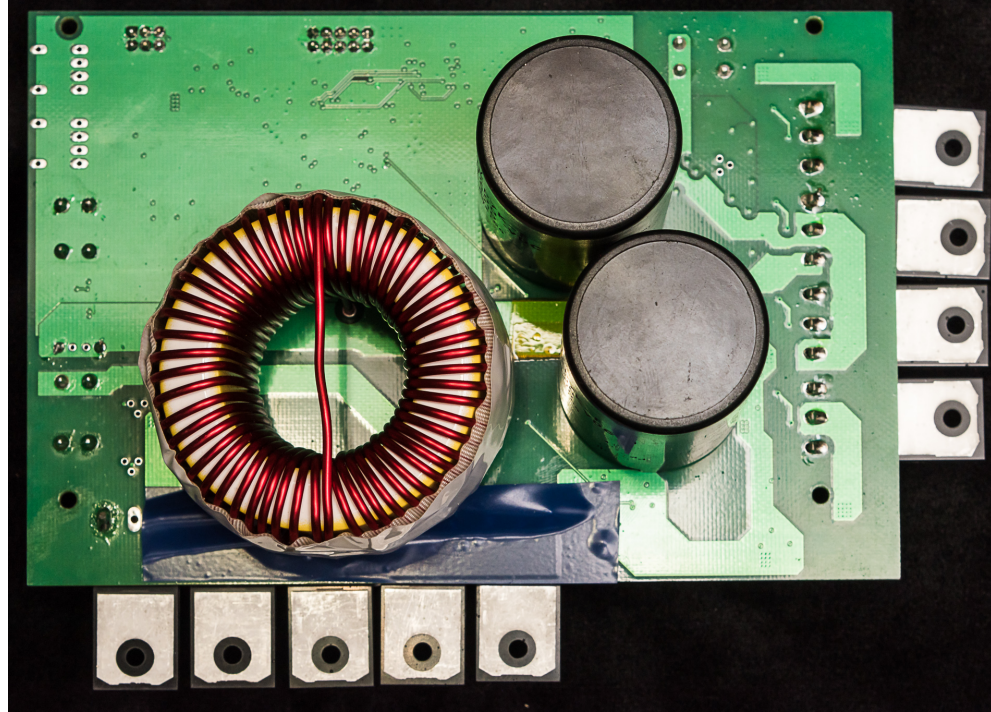
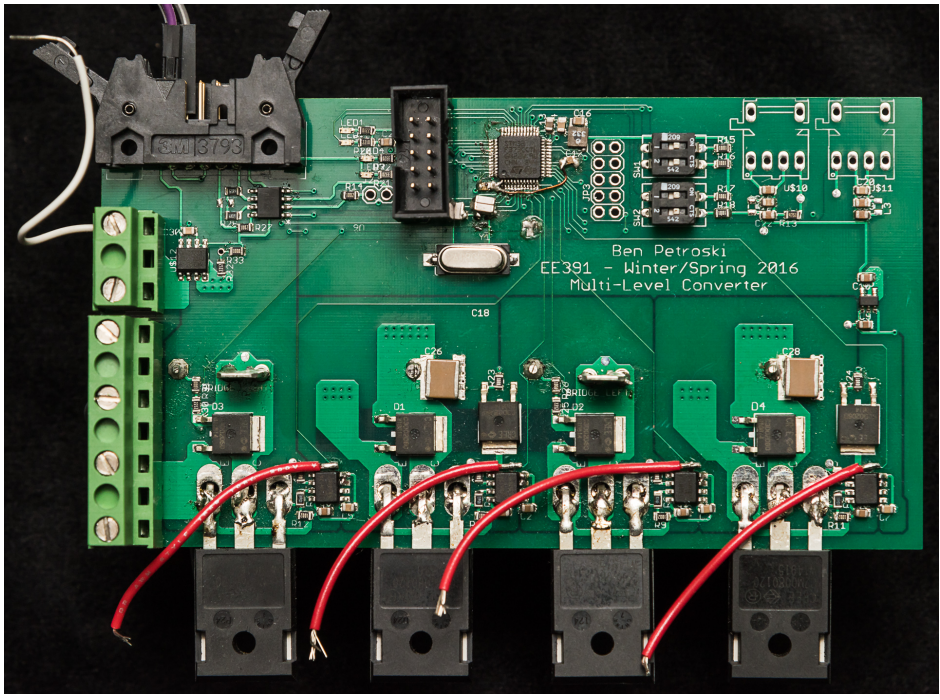
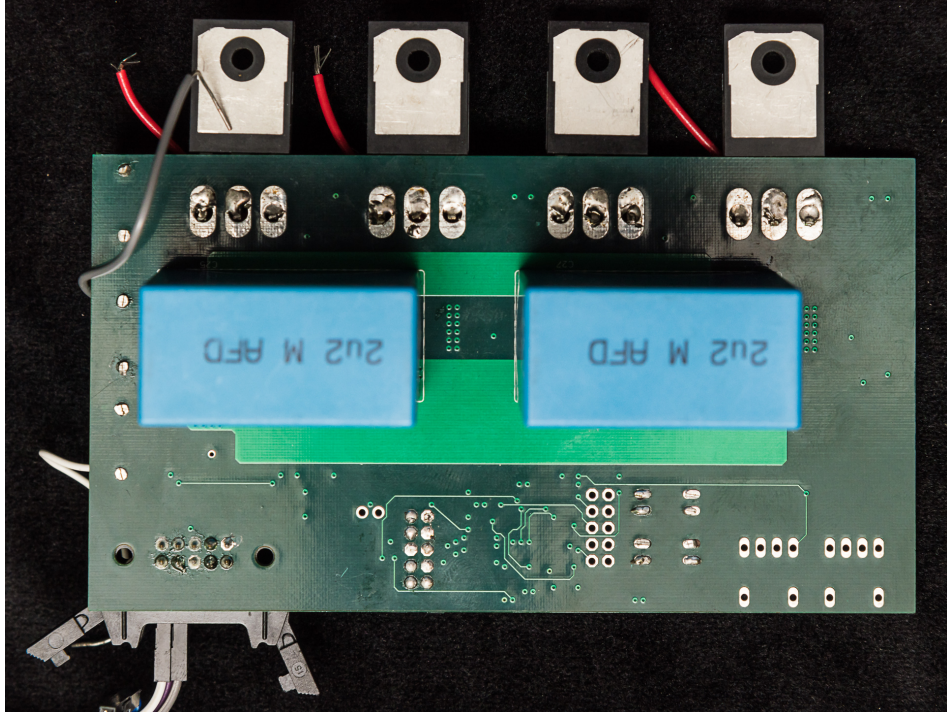
Stack of 36
inverters

4 Strings
17 Modules ea.
850V (V_{oc})
5.4kW

Test Setup



Primary and Secondary PCBs



PV Economics

PV Economics 1 (old 2016 costs)

- Utility scale costs
 - PV Module \$0.60/W
 - Inverter \$0.10/W
 - Mounting \$0.15/W
 - Balance \$0.65/W
 - TOTAL \$1.50/W
- Residential costs
 - PV Module \$0.60
 - Microinverter \$0.50
 - Mounting \$0.20
 - Balance \$1.70
 - TOTAL \$3.00
- Return
 - Hours/year 2,200
 - Wholesale \$0.05/kWh
 - TOTAL \$0.11/Wyear
 - 7.3% ROI
- Return
 - Hours/year 2,200
 - Retail \$0.15-\$0.35/kWh
 - TOTAL \$0.33-0.77/Wyear
 - 11% - 26% ROI

PV Economics 1 (new 2017 costs)

- Utility scale costs

- PV Module \$0.30/W
- Inverter \$0.10/W
- Mounting \$0.15/W
- Balance \$0.45/W
- TOTAL \$1.00/W

- Return

- Hours/year 2,200
- Wholesale \$0.05/kWh
- TOTAL \$0.11/Wyear
- 11% ROI

- Residential costs

- PV Module \$0.35
- Microinverter \$0.40
- Mounting \$0.20
- Balance \$1.70
- TOTAL \$2.65

- Return

- Hours/year 1,800
- Retail \$0.15-\$0.35/kWh
- TOTAL \$0.27-0.63/Wyear
- 10% - 24% ROI

All the latest reaction to the Section 201 solar trade case

By John Parnell | Sep 22, 2017 4:28 PM BST | 0

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Stocks:



The ITC unanimously finds injury to domestic US manufacturers from global imports. Source: Trina.

Updated: All the latest reaction to the Section 201 solar trade case as the [ITC unanimously finds injury to domestic US manufacturers from global imports](#).

Suniva company statement:

"Suniva is gratified that the ITC has found that a surge of imports into the US has decimated the American CSPV cell and module manufacturing industry. We brought this action because the US solar manufacturing industry finds itself at the precipice of extinction at the hands of foreign market overcapacity. The ITC has agreed, and now it will be in President Trump's hands to decide whether America will continue to have the capability to manufacture this energy source. President Trump can remedy this injury with relief that ensures U.S. energy dominance that includes a healthy US solar ecosystem and prevents China and its proxies from owning the sun."

Abigail Ross Hopper, president and CEO of the Solar Energy Industries Association (SEIA):

"The ITC's decision is disappointing for nearly 9,000 US solar companies and the 260,000 Americans they employ. Foreign-owned companies that brought business failures on themselves are attempting to exploit American trade laws to gain a bailout for their bad investments. Analysts say Suniva's remedy proposal will double the price of solar, destroy two-thirds of demand, erode billions of dollars in investment and unnecessarily force 88,000 Americans to lose their jobs in 2018. While we continue to believe that this is the wrong decision, based on Suniva and

Suniva & SolarWorld Modify Requested Remedies In Section 201 Solar Trade Case

October 3rd, 2017 by [Joshua S Hill](#)



Suniva and SolarWorld Americas last week submitted updated requests to the US International Trade Commission that suggest lowering their originally-requested tax remedies on imported solar equipment, but SolarWorld further petitioned the ITC to impose a limit on solar module imports into the United States.

I'll save you the run-down of the Section 201 trade case that Suniva and SolarWorld Americas brought to the US International Trade Commission (ITC), but [you can read all about it here](#), including the ITC's decision to rule in favor of the 'aggrieved' parties.

Reports last week revealed that both Suniva and SolarWorld Americas had posted filings with the ITC modifying their original requests, which were:

- a \$0.40/watt tariff for crystalline silicon photovoltaic (CSPV) cells
- a floor price of \$0.78/watt on CSPV modules

The modified requests differ between who is making the petition. Suniva has requested the following:

- a \$0.25/watt tariff for CSPV cells (down from \$0.40/watt)
- a \$0.32/watt for CSPV modules (this is new)
- a floor price of \$0.74/watt on CSPV modules (down from \$0.78/watt)

However, SolarWorld has differed its petition somewhat. Whereas it agrees with Suniva on the tariffs for CSPV cells and modules, SolarWorld Americas is looking for an import quota of at least 0.22 GW (gigawatts) for CSPV cells and 5.7 GW for CSPV modules.

Suniva explains that its tariff requests "are needed to address the serious injury confronting the domestic injury. Returning imports to normal volumes not distorted by foreign market overcapacity through the imposition of tariffs that are sufficiently high to deter evasion or avoidance is critical if the total market supply — and US producers' prices — are to stabilize."

Meanwhile, SolarWorld Americas explains that its suggested "four-year relief program" is intended to "address the serious injury inflicted on US solar cell and module manufacturers, and to ensure that the US solar industry as a whole, including downstream consumers, remains viable and a global leader in solar energy."

Unsurprisingly, the Solar Energy Industries Association (SEIA) — which has been leading the fight against Suniva and SolarWorld's original filing — filed its own pre-hearing briefing with the ITC, despite the fact that neither Suniva and SolarWorld had by filed their own pre-hearing briefings in the timely manner necessary. The SEIA nevertheless makes a long and legitimate case to the ITC that — to borrow from one of the filing's opening headings — "The Problems of the Domestic Industry Would Not Be Remedied by Global Trade Restrictions."

Specifically:

"As a result, tariffs that impose a cost on the importer would logically push CSPV cell and module prices higher, but the adverse demand effects and limitation on domestic industry capacity will make it impossible for the industry to become profitable. Binding quotas would also fail to help the industry. Imposing a limit on import supply in a market where the domestic industry's capacity is unable to fulfill the vast majority of demand will, by necessity, cause demand to shift to alternative products."

In the end, I am concerned that this will all come down, not to the merits of the case and the facts being presented (by either side), but rather the fact that the current US President, Donald Trump, [wants to impose tariffs](#) on something, *anything*.

Proposing

\$0.74/W price floor on modules \$0.32/W tariff on imported modules

U.S. Solar Industry Could Be Decimated If Suniva/SolarWorld Win Trade Case

Tariffs on solar imports could be bad for the solar industry, but quotas would be absolutely devastating.

Travis Holum (TMFFlushDraw)
Oct 5, 2017 at 10:25AM

Tuesday was the day bankrupt Suniva and SolarWorld made [their case to the International Trade Commission](#) arguing what they think protections against solar imports should look like. Tariffs, price floors, and import quotas were all discussed, and could all be bad for the solar industry as a whole in a variety of ways.

Coming out against protections were the diverse group of [Sunrun \(NASDAQ:RUN\)](#), [SunPower \(NASDAQ:SPWR\)](#), [NextEra Energy \(NYSE:NEE\)](#), [NRG Energy \(NYSE:NRG\)](#), and many more companies. It was rare solidarity against protections because if tariffs or quotas are imposed, the only real winner will probably be [First Solar \(NASDAQ:FSLR\)](#), which isn't involved in the case.

The ITC won't make a recommendation to President Trump as to what should be done to make U.S. solar manufacturing more competitive until November 13, but we at least know what's on the table. And depending on what commissioners choose to recommend and what President Trump chooses to do, it could be bad for almost everyone.


<https://www.fool.com/investing/2017/10/05/us-solar-industry-could-be-decimated-if-sunivasola.aspx>

<https://cleantechnica.com/2017/10/03/suniva-solarworld-modify-requested-remedies-section-201-solar-trade-case/>

<https://www.pv-tech.org/news/all-the-latest-reaction-to-the-section-201-solar-trade-case>

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Important information 

AUTHOR



PV Economics 2

- Module is only 40% of cost (20% for residential)
- Real issue is balance-of-system
 - For Utility Scale
 - Wiring – 1kA to central inverter – 4x 500MCM wires \$56/foot.
 - Large iron-core transformer
 - Installation labor
 - For Residential
 - Installation labor

Smart PV Systems

V_{OC} Limiting

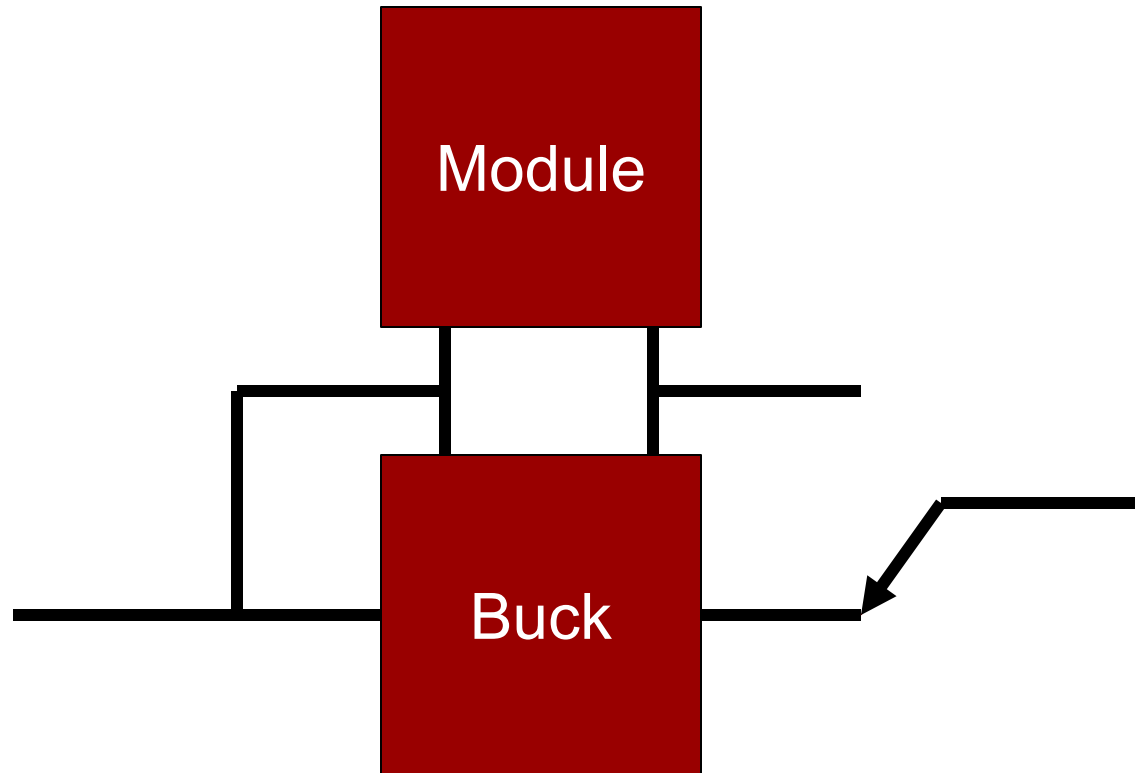
- Typical module (Trina TSM-310-PD14)
 - $V_{mp} = 36V$, $V_{oc} = 46V$ (worst-case cold temperature)
- Inverter input limited to 1kV
 - Limits strings to 21 modules
 - At V_{mp} could have 27 modules – 29% increase
 - Reduces string cost by ~30%.

Module (and Cell) Mismatch

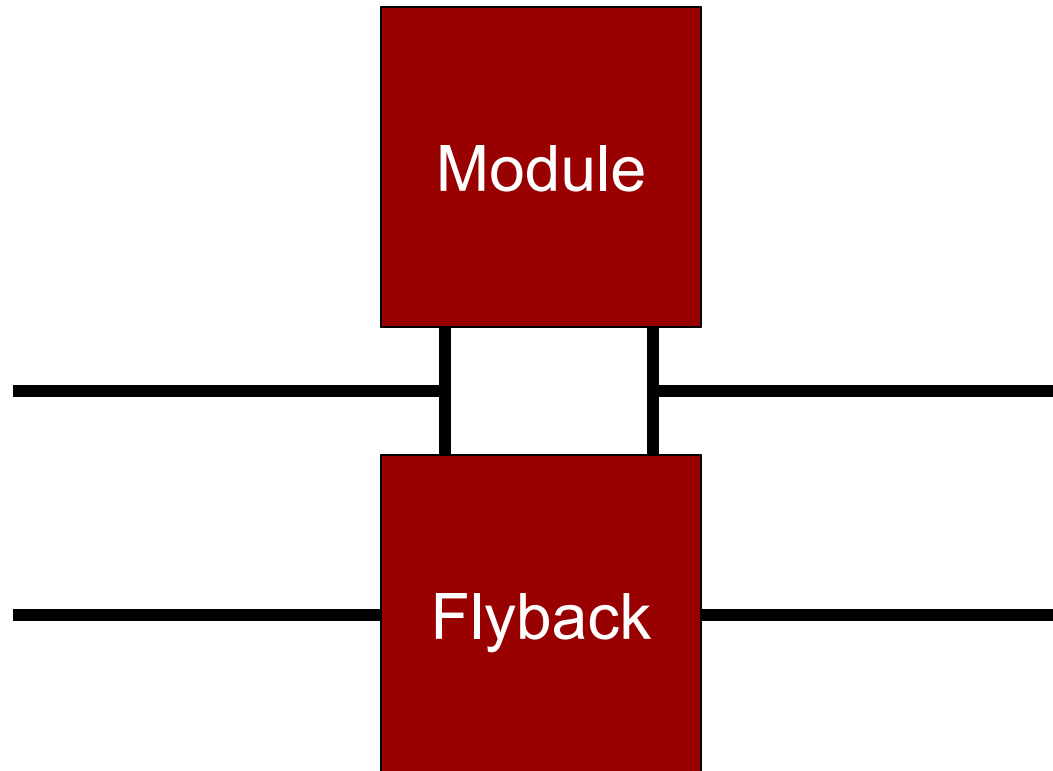
- String current limited to current from weakest cell
- Module current mismatch $\sigma = 5\%$
- Worse for residential installations (partial shading)

- Two questions:
 - What is the typical mismatch profile of a 10-module string?
 - What power reduction does a X % current mismatch result in?

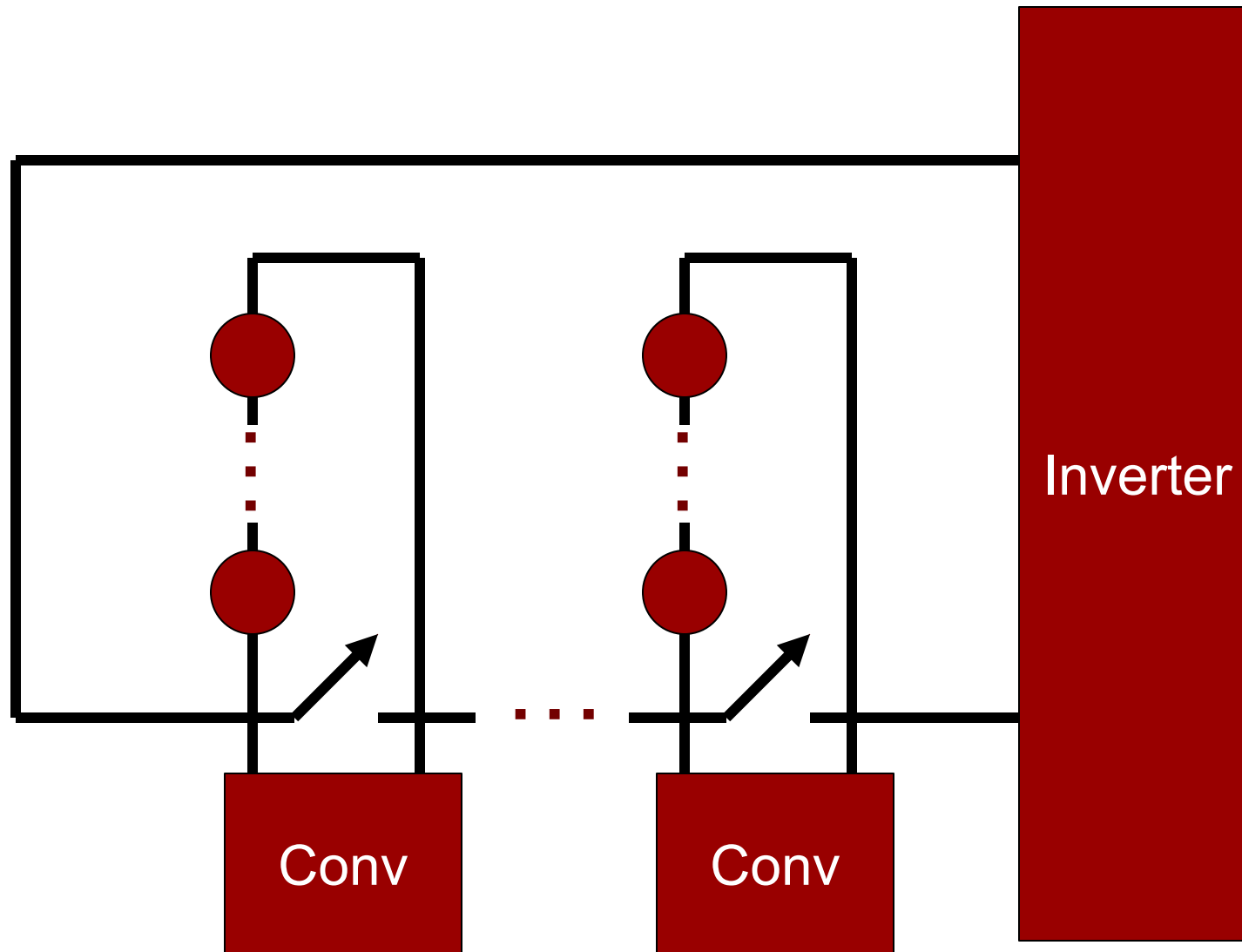
Individual MPPT with per-module buck



Individual MPPT with incremental harvesting



Smart PV Systems



Smart PV Systems

- Smart inverter provides central control over panels
- Turns off some substrings
 - Voc clipping
 - Smart bypass
 - Converter (if present) incrementally harvests mismatch
 - Without adding connections

Faults and Failures

- Cell open/short
- Diode open/short
- Arc fault

PV Monitoring

- https://enlighten.enphaseenergy.com/systems/153078/graphs?range=last7Days&view=power_production
- https://enlighten.enphaseenergy.com/systems/153078/arrays?range=last7Days&view=power_production

Summary of PV

- PV cells/strings are voltage-dependent current sources (Diode in parallel with current source)
- PV controllers regulate their **input** voltage/current to maximize power
 - *Maximum power-point tracking*
- Can apply almost any converter topology
 - Boost used for illustration
 - Regulate input rather than output
- Gradient search for convex optimization
- More sophisticated search needed for multi cell/panel string
- Single phase systems must store energy during AC cycle
- PV economics dominated by “balance of system”
- Opportunities for “intelligent” PV systems

No	Date	Topic	HW out	HW in	Lab out	Lab ck	Lab	HW
1	9/25/17	Intro (basic converters)	1		1		Intro to ST32F3	Periodic Steady State
2	9/27/17	Embedded Prog/Power Elect.						
3	10/2/17	Power Electronics - 1 (switches)	2	1	2	1	AC Energy Meter	Power Devices
4	10/4/17	Power Electronics - 2 (circuits)						
5	10/9/17	Photovoltaics	3	2	3	2	PV MPPT	Motor control Matlab
6	10/11/17	Feedback Control						
7	10/16/17	Electric Motors	4	3	4	3	Motor control - Lab/	Feedback
8	10/18/17	Isolated Converters						
9	10/23/17	Solar Day	5/PP	4	5	4	PS	Isolated Converters
10	10/25/17	Magnetics						
11	10/30/17	Soft Switching	6	5/PP	6	5	Magnetics	Magnetics and Inverters
12	11/1/17	Project Discussions						
13	11/6/17	Inverters, Grid, PF, and Batteries		6	P	6	Project	
14	11/8/17	Thermal & EMI						
15	11/13/17	Quiz Review				C1		
16	11/15/17	Grounding, and Debugging						
Q	11/15/17	Quiz - in the evening						
	11/20/17	Thanksgiving Break				C2		
	11/22/17	Thanksgiving Break						
17	11/27/17	Wrapup						
18	11/29/17	Guest Lecture				C3		
19	12/4/17	Guest Lecture						
20	12/6/17	No Class						
	TBD	Project presentations			P			
	12/15/17	Project webpage due						

