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A Simple and Accurate Model for Predicting Mismatch Effects in Photovoltaic Arrays

Outline

- Motivations and objectives
- PV array modeling
- MPP maximization criteria
- Conclusions

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Motivations

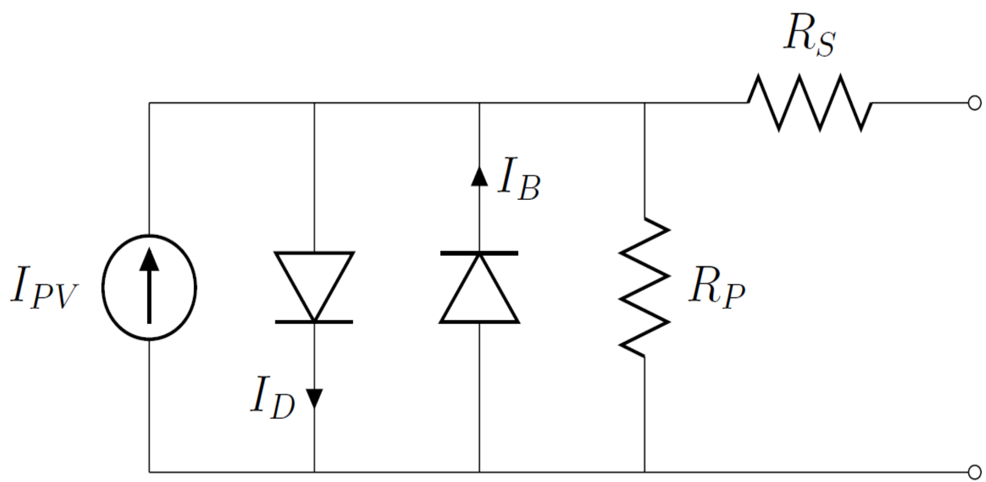
- Strong interest in optimizing power efficiency (even small improvements add up in time), under *tolerance* conditions
- PV cell/array models usually rely on numerical approximations
- Array modeling often assumes identical PV cells/modules
- Slow or failed convergence may be experienced when modeling complex PV arrays (e.g. 50 modules)
- Model accuracy may significantly affect the performance of Maximum Power Point (MPP) tracking algorithms

Objectives

- Development of a fast and accurate modeling and simulation framework
- Models should allow heterogeneous cells/modules (also useful to describe partial shading)
- Validation against circuit level simulators
- Investigation of MPP optimal module allocation strategies

Modeling assumptions

- Single diode cell model (also used to describe PV modules), extended with bypass diode (usually present practical PV modules)

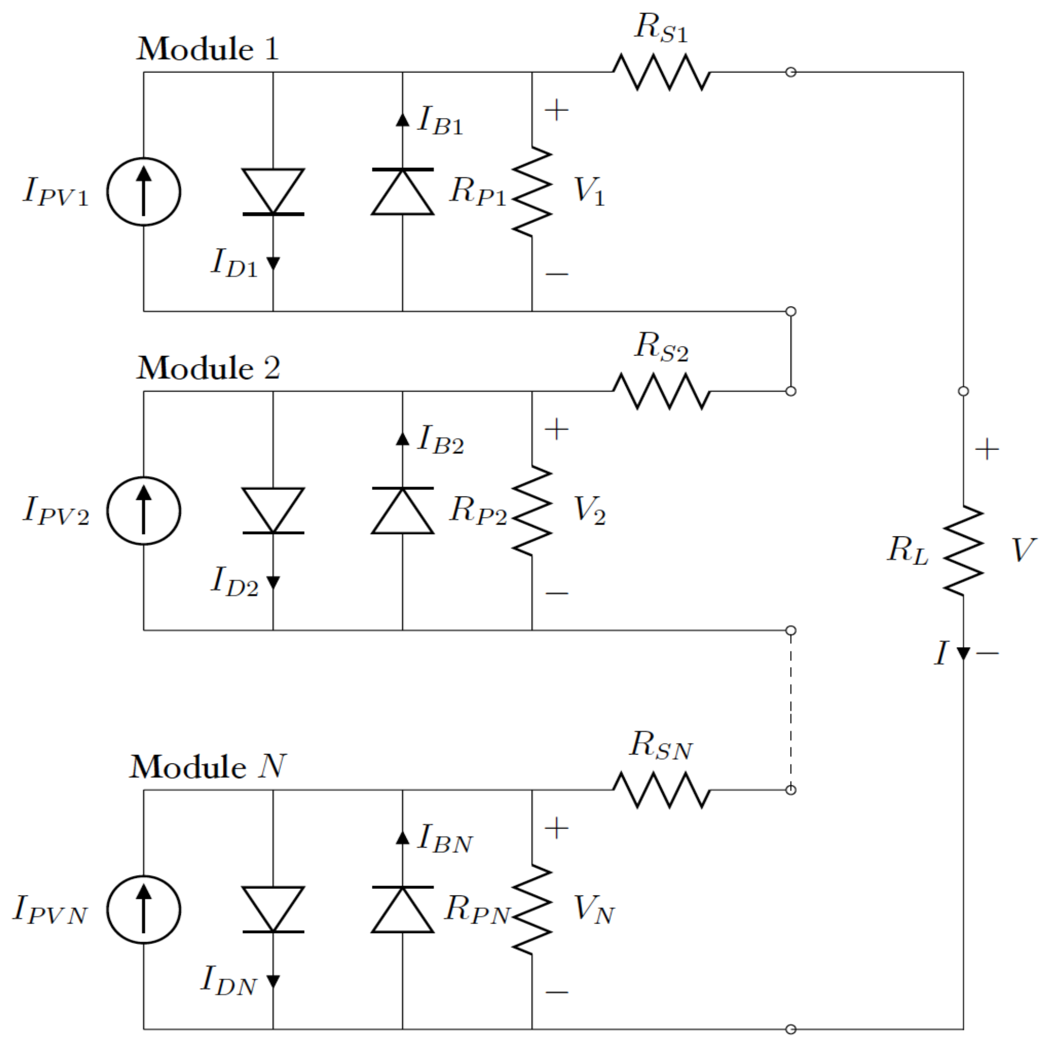


- Diode approximated threshold based *I-V* model (T=300 K):

$$I \cong \begin{cases} 0, & V < 0.7n \\ I_0\left(e^{\frac{V}{nV_T}} - 1\right), & V \geq 0.7n \end{cases}$$

Modeling assumptions (2)

- PV string as a series of modules
- String made of several modules with possibly different parameter values



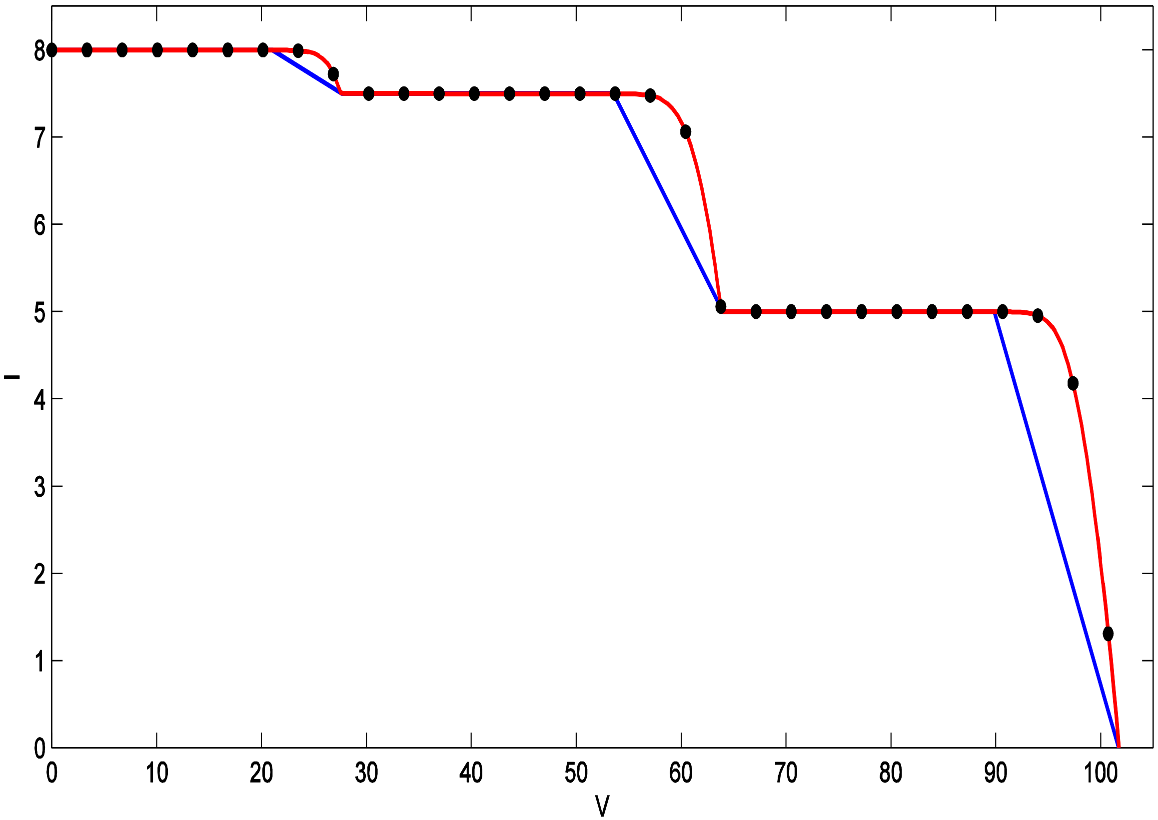
- $I_{PV1} \geq I_{PV2} \geq \ldots \geq I_{PVN}$
- Parallel resistors approximated with open circuits

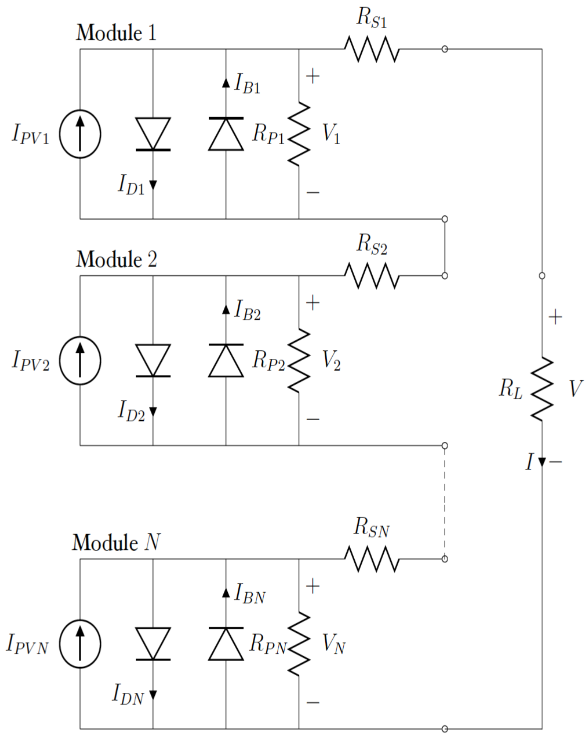
Modeling

- The threshold model allows derivation of an approximate string I-V characteristic curve
- I-V characteristic curve: made of a series of constant current regions (*plateaus*), linked by steep transients
- Each *plateau* level is the PV current I_{PV} of an individual module
- Each *plateau* is limited by breakpoints, corresponding to state commutations of the modules' diodes
- Iterative analysis, starting at V=0 (short circuit, output current is the maximum I_{PV} current among the individual models)

Example: 3 cells PV array

- V=0 (R_L=0), I=I_{PV1}

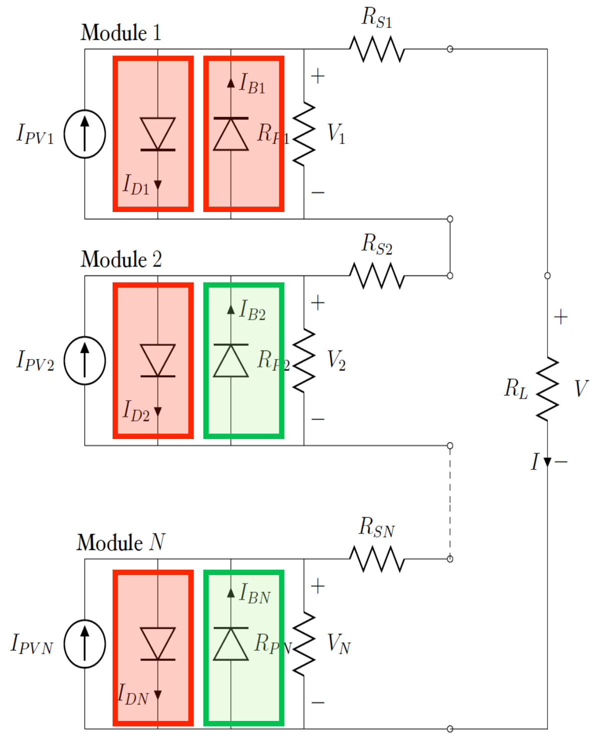




I-V characteristic of a 3-module PV string. The red curve has been obtained using circuit level simulation, the blue lines describe the initial approximation, and the points the following numerical fitting results.

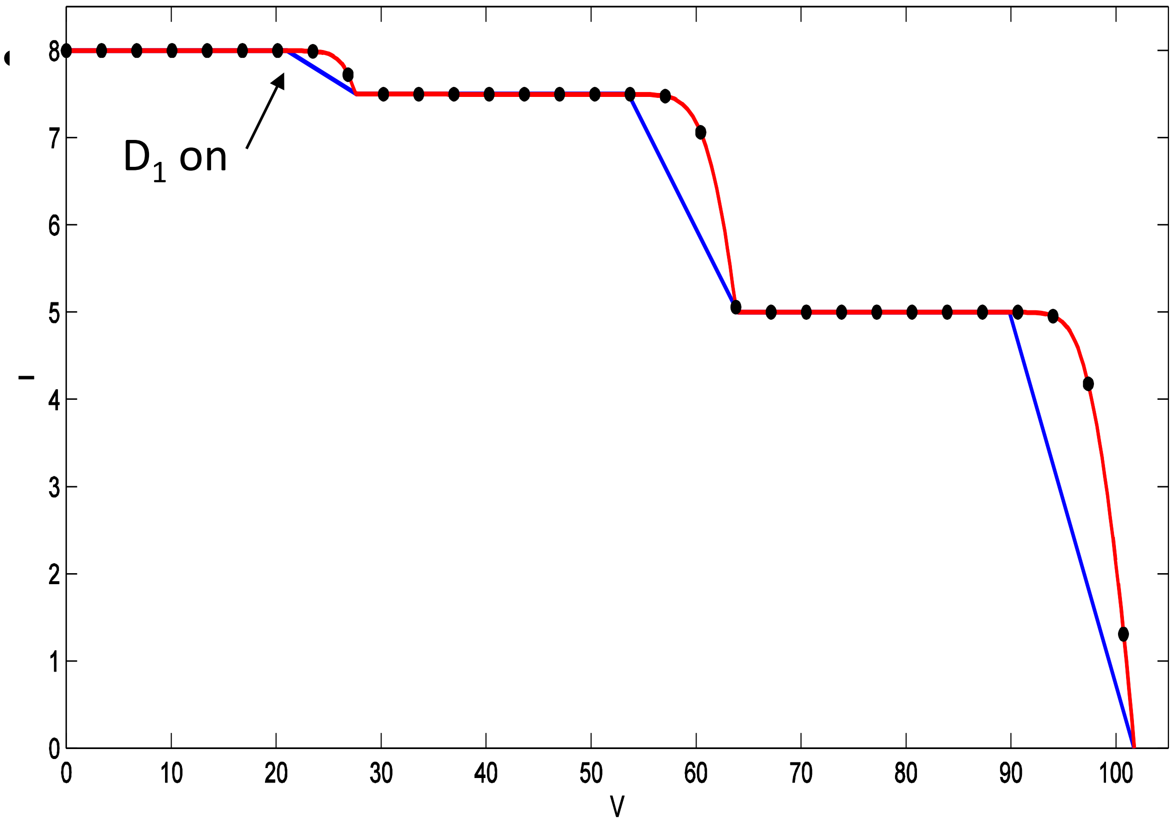
Example: 3 cells PV array

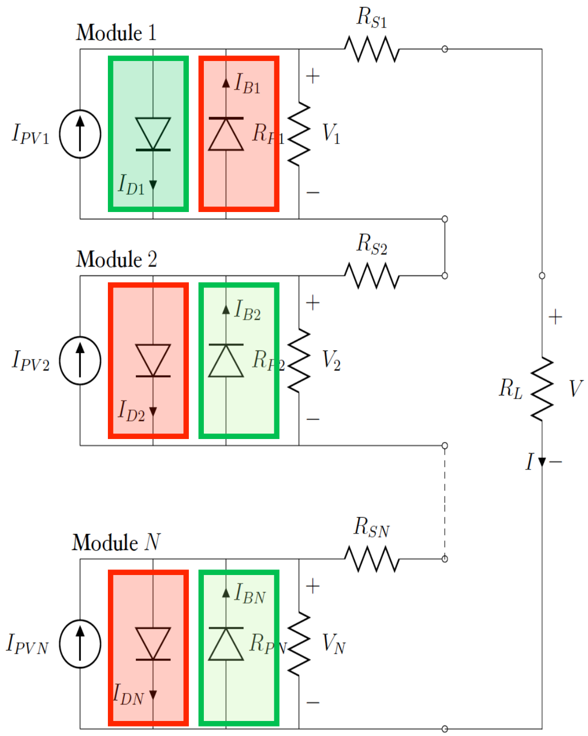
- V=0 (R_L=0), I=I_{PV1} (note: $I_{PV1} \geq I_{PV2} \geq I_{PV3}$)
- All forward diodes D_1, D_2 and D_3 are off
- Bypass diode B_1 is off
- Bypass diode B_2 shunts excess current I_{PV1} -I_{PV2}
- Bypass diode B_3 shunts excess current I_{PV1} -I_{PV3}



- When R_L increases, V increases as V=$R_L I_{PV1}$, until we have V=0.7n_D and forward diode D_1 switches on.

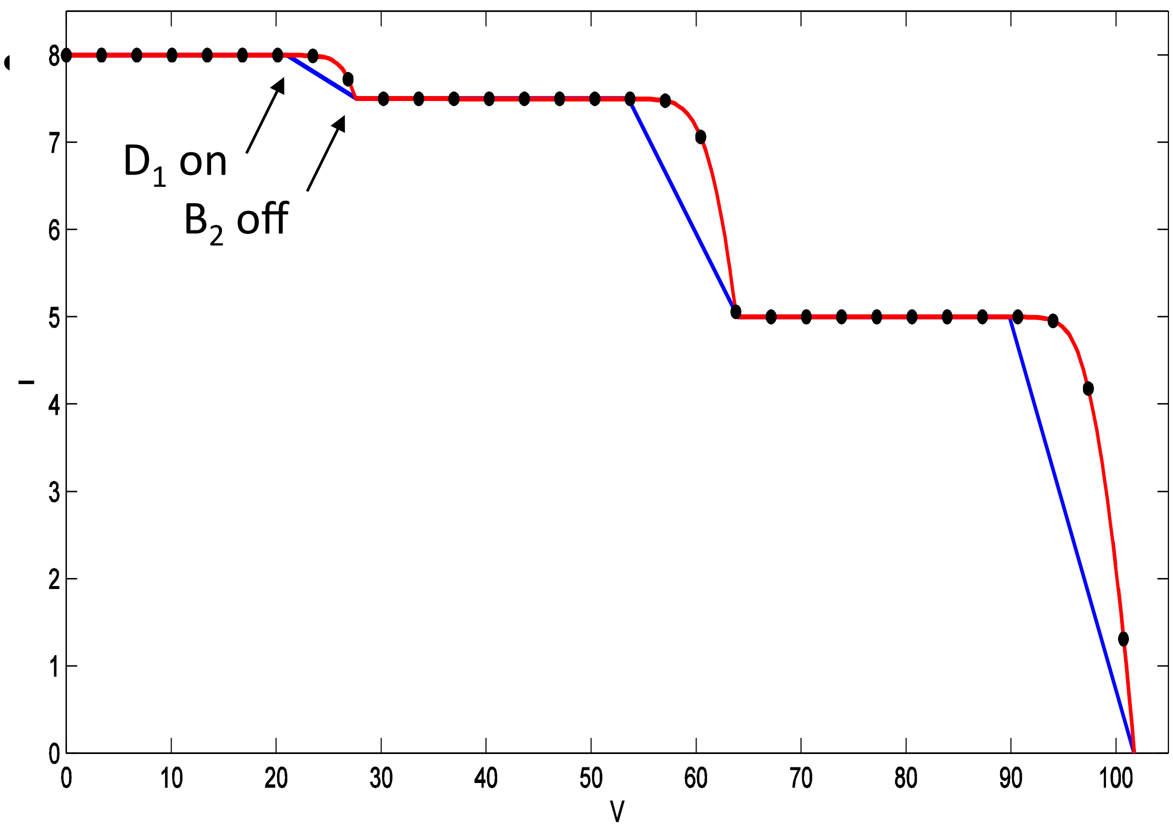
Example: 3 cells PV array

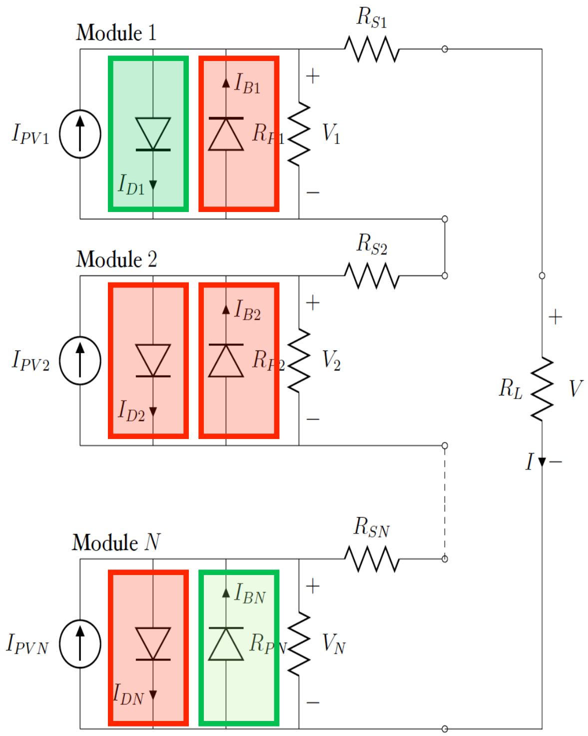




- For growing values of R_L (and V), I_{D1} increases and $I=I_{PV1}-I_{D1}$ is gradually reduced

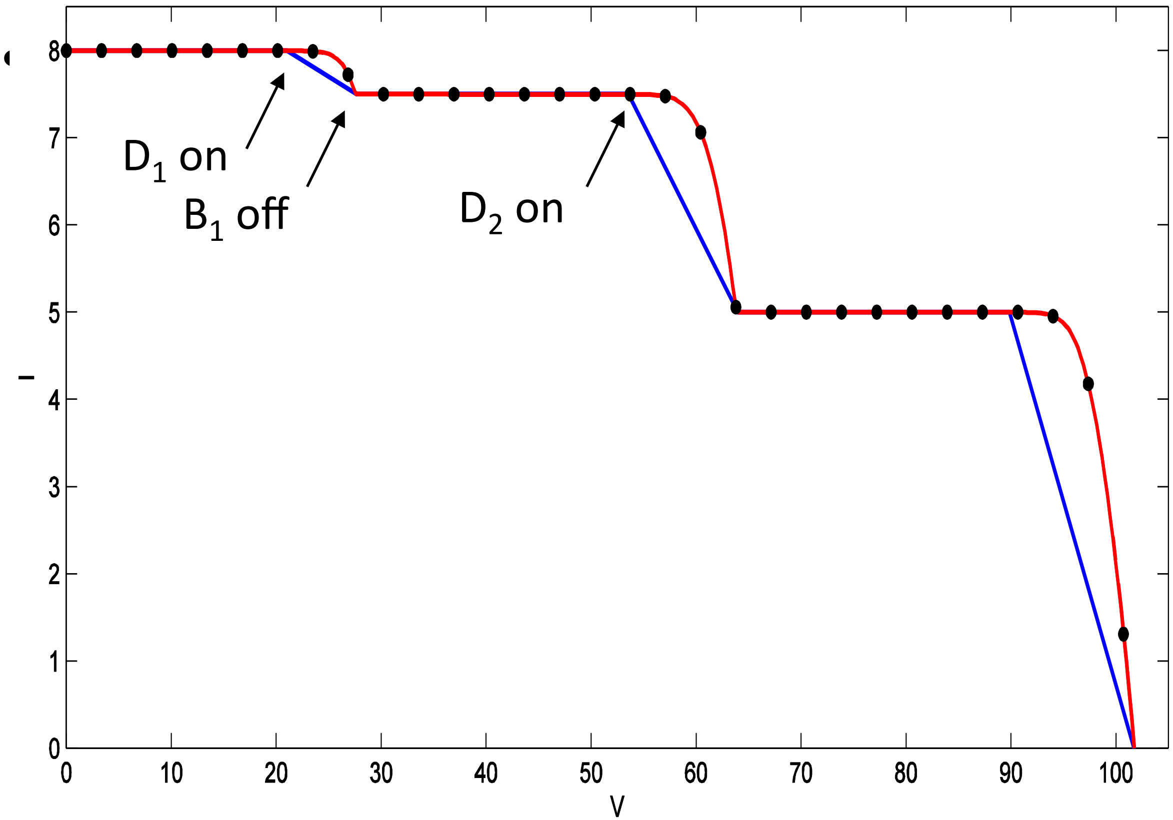
Example: 3 cells PV array

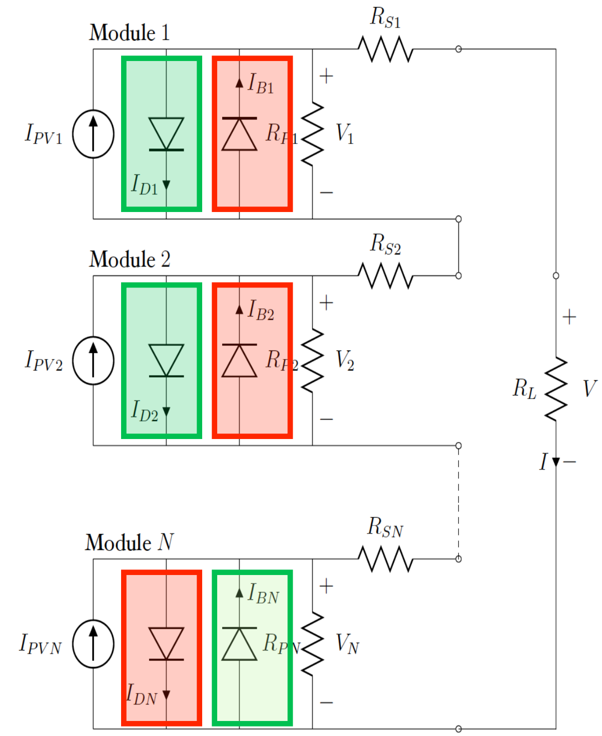




- When I_{D1}=I_{PV1}-I_{PV2}, bypass diode B_2 switches off
- Output current I settles to I_{PV2} (2^{nd} *plateau*)

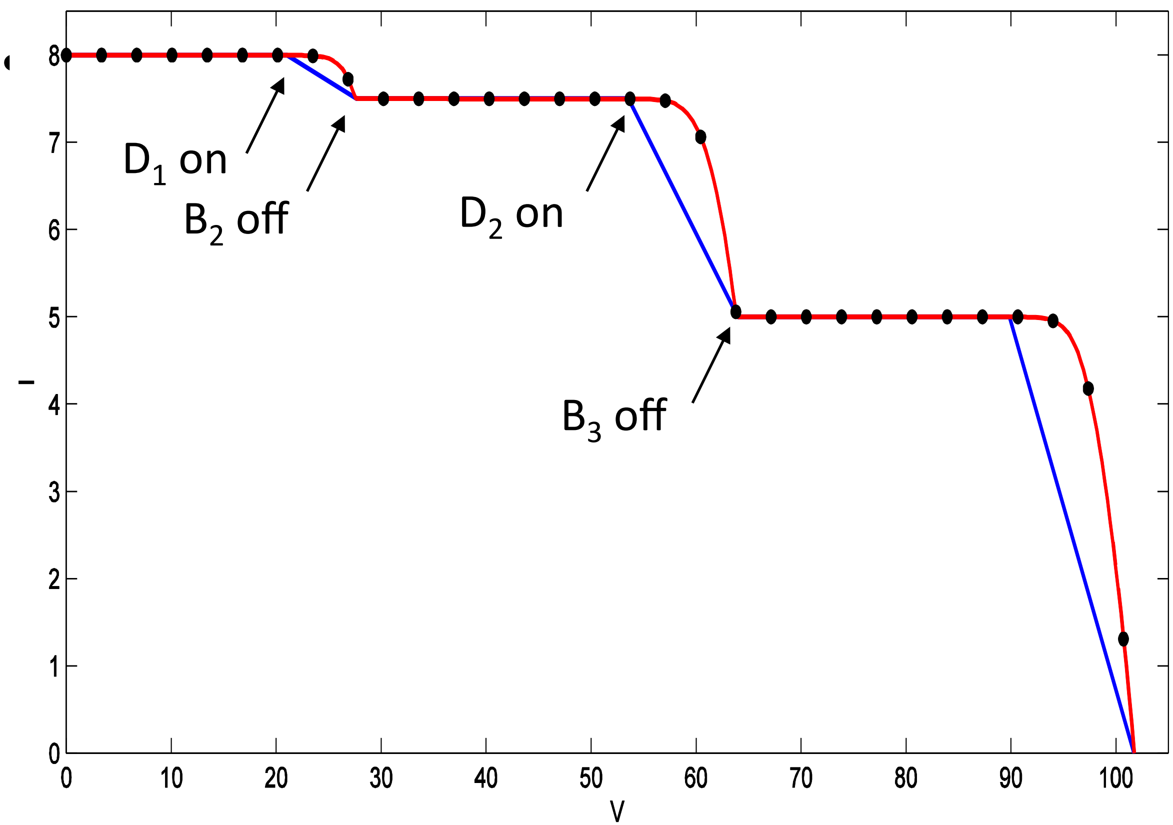
Example: 3 cells PV array

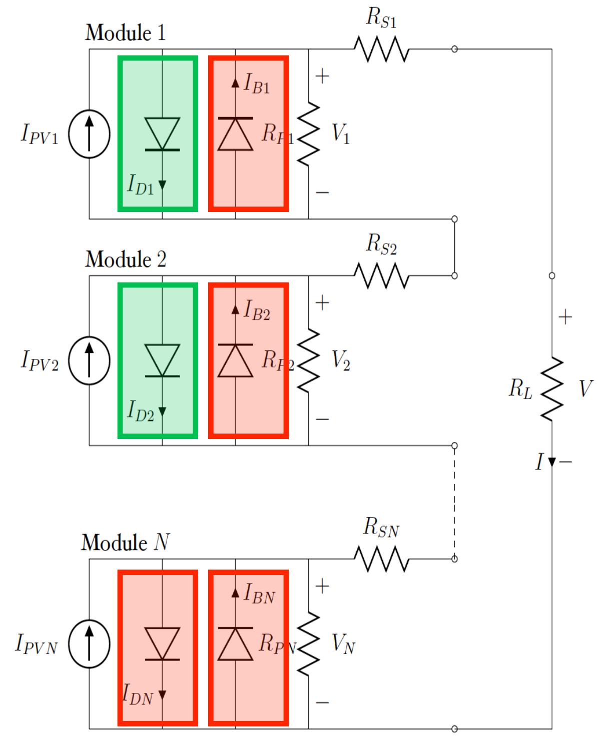




- By further increasing R_L (and V), 2nd *plateau* ends when D_2 switches on
- D_2 progressively shunts part of the PV current I_{PV2}

Example: 3 cells PV array



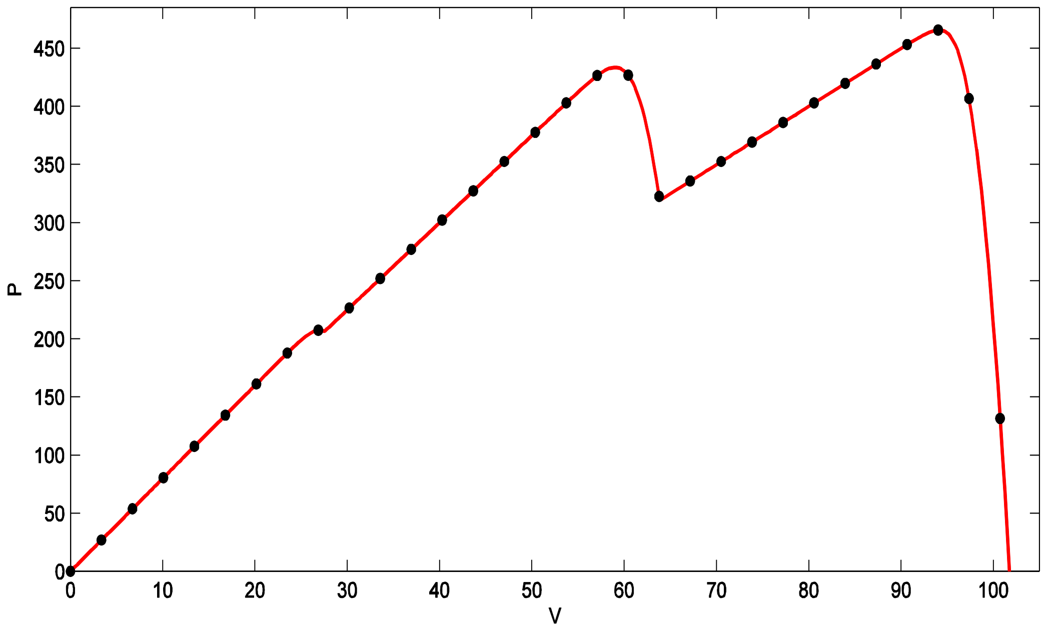


- When $I_{D2}=I_{PV2}-I_{PV3}$, bypass diode B_3 switches off
- Output current I settles to I_{PV3} (3rd *plateau*)

Example: 3 cells PV array

- The analysis can be iterated until the open circuit condition is reached
- The diode threshold based *I-V* model and the Kirchhoff laws may be used to derive each breakpoint voltage (see paper for detailed analysis and formulas)
- Numerical fitting is fast and results are in very good agreement with circuit level simulation results
- If the parallel resistor open circuit hypothesis is removed, breakpoint voltages are shifted to the left, and a linear *I-V* behavior replaces the *plateaus*

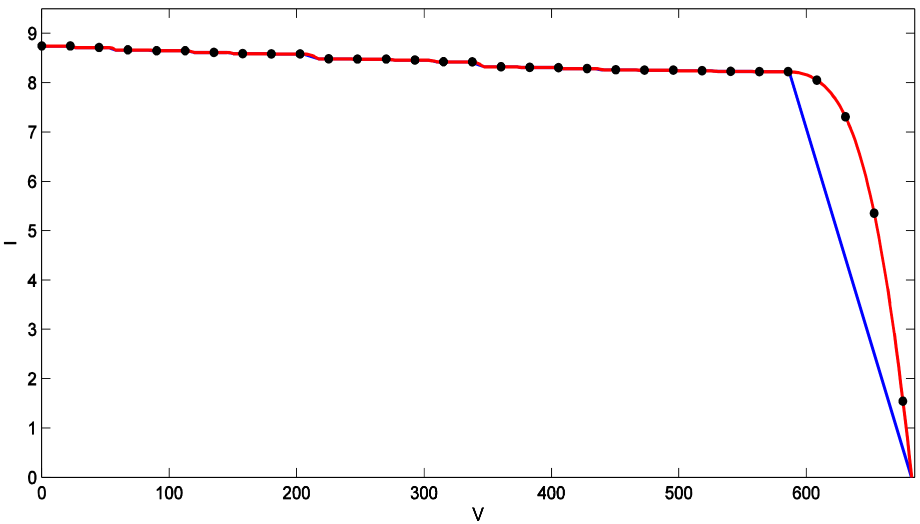
Example: 3 cells PV array



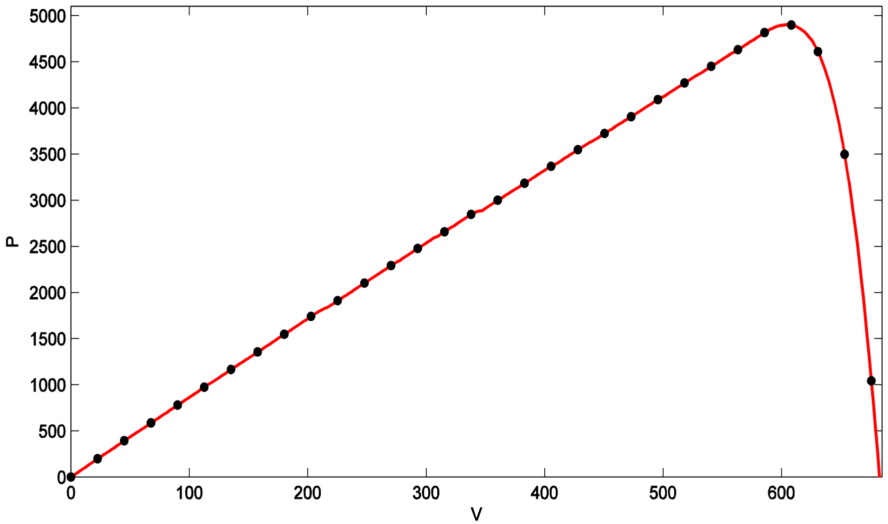
P-V characteristic of a 3-element PV array. The red curve has been obtained using circuit level simulation (using QUCS), while the points have been obtained via the proposed approach.

- Good accuracy also on *P-V* characteristic
- Helps identifying local maxima, that may lead MPP tracking algorithms to suboptimal performance

Example: 20 cells PV array



I-V characteristic of a 20-element PV array. The red curve has been obtained using circuit level simulation, the blue lines describe the initial approximation, and the points the following numerical fitting results.

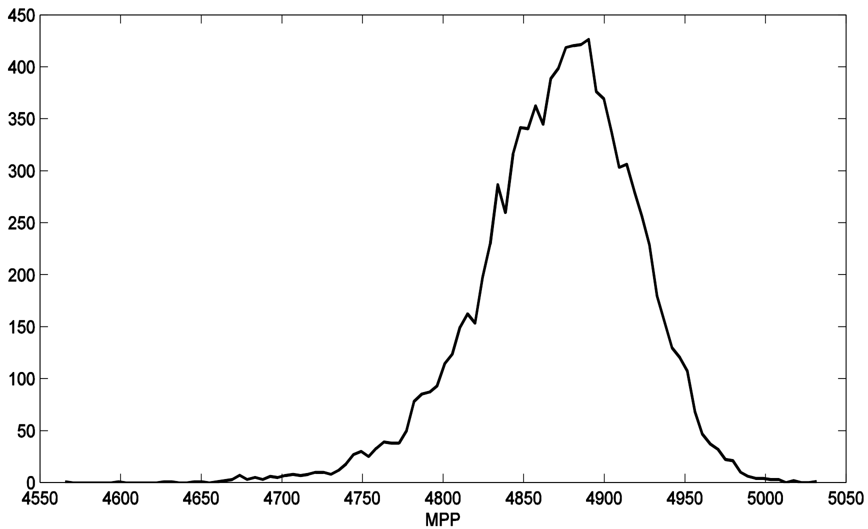


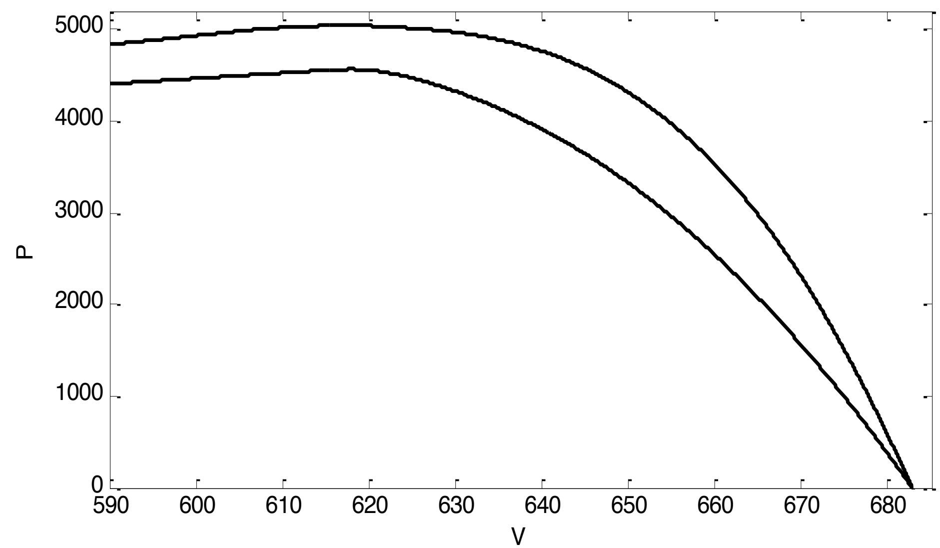
P-V characteristic of a 20-element PV array. The red curve has been obtained using circuit level simulation, while the points have been obtained using the proposed approach.

- Good accuracy and fast convergence are preserved when analyzing large arrays

Module allocation

- The reduced processing time allows simulation of several module configurations, and to assess the effect of process tolerances on the achievable MPP





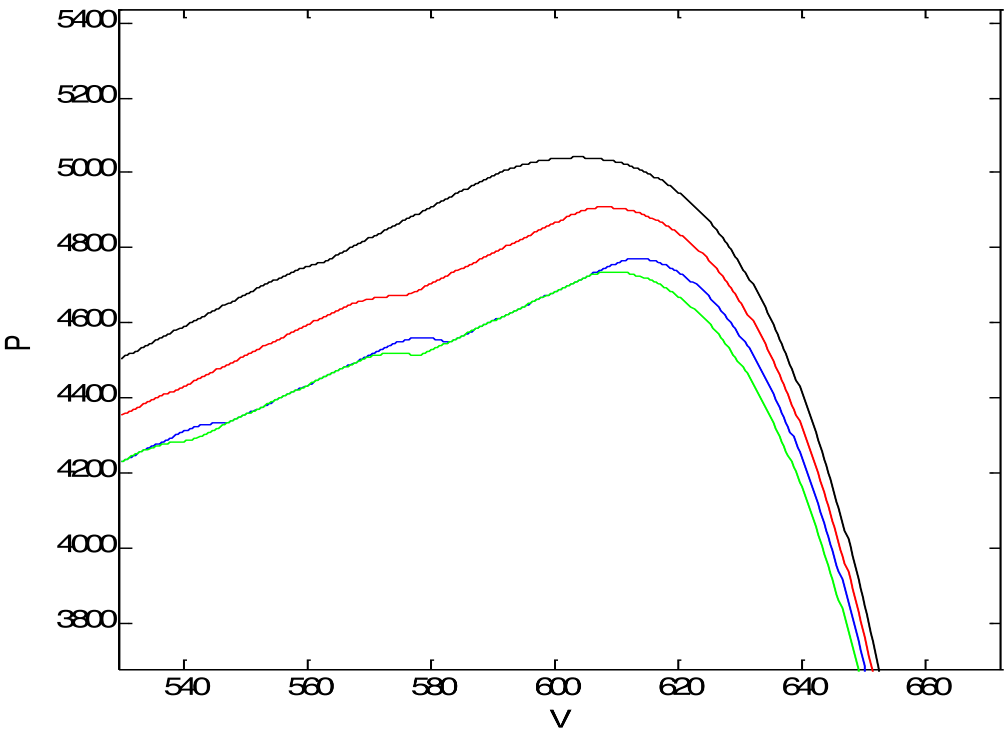
MPP distribution, evaluated over for a set of 10000 PV arrays, each of them comprising 20 modules. The I_{PV} current of each module is taken from a Gaussian distribution, with a tolerance of 1% about a central value of 8.5A.

Lowest and highest observed power, plotted as a function of *V*, observed in a set of 10000 PV arrays, each of 20 modules. The I_{PV} current of each module is taken from a Gaussian distribution, with a tolerance of 1% about a central value of 8.5A.

Module allocation

- Allocation problem: if a set of $M=kN$ available modules is used to obtain k series arrays ("strings") of N modules each, optimally allocate modules with respect to overall achievable MPP

Module allocation



P-*V* characteristics corresponding to the worst case selection (green and blue for each of the worst case arrays), random selection (red), and average of the *P*-*V* curves obtained by applying the proposed selection criterion (black).

- Hypothesis: in each string, the MPP is dominated by the lowest I_{PV} current (rightmost *plateau*)
- Possibly optimal solution: sort modules by I_{PV}, grouping "worst" modules together

Conclusions

- The proposed model consents an accurate and fast converging description of large PV arrays
- Heterogeneous modules and shading phenomena can easily be kept into account
- Electrical behavior of the equivalent network has been clarified
- Optimal module allocation strategies can be investigated and tested using the proposed approach