
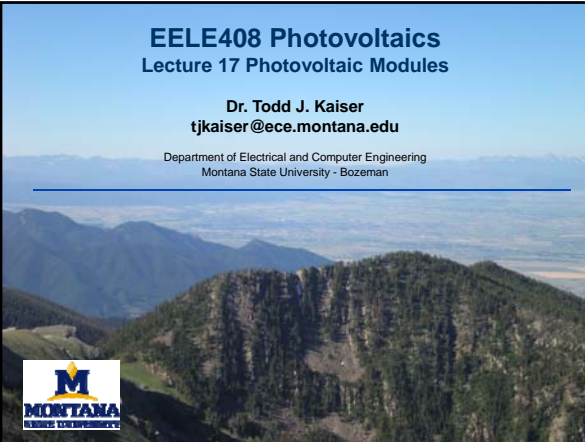


EELE408 Photovoltaics


Lecture 17 Photovoltaic Modules

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Linking Cells


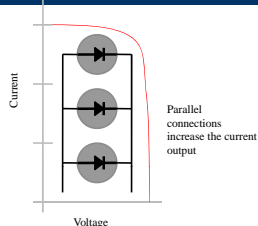
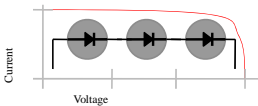
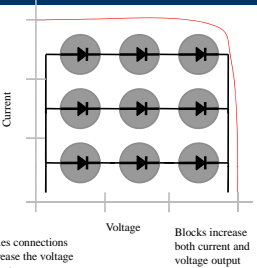



- Solar cells are not usually used individually because they do not output sufficient voltage and power to meet typical electrical demands
- The amount of voltage and current they output can be increased by combining cells together with wires to produce larger area solar modules
- Cells can be connected in a number of ways
 - Strings – where cells are connected in **series**
 - Blocks 2 or more strings connected together in **parallel**
 - Joining 2 or more blocks together




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Solar Cell Panels









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Module Structure




- Typically 36 cells wired in series
- Encapsulated in a single long-lasting stable unit
- Purpose to protect solar cells and interconnecting wires
- Prevent mechanical and water damage





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Encapsulation




- Solar cells are thin & brittle and need to be exposed to outdoor conditions for 25-30 years
- A physical casing (encapsulation) protects the PV cells and provide structural strength
- Accomplishes
 - Electrically isolate cells and make contacts
 - Protect from water and oxygen ingress
 - Withstand heavy winds, hail & installation
 - Maintain protection for decades
 - Allow modules to attach to each other




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Module Materials



- Tempered Glass(low Iron):
 - Used for the transparent top surface.
 - AR coatings are cost prohibited and can not with stand environment
 - Needs to be highly transparent, scratch-resistant & rain, wind, hail, human... proof.
- Tedlar
 - Typical back layer because it is strong material
 - Gives structural support
 - Removes excess heat that reduces efficiency
- Ethylene Vinyl Acetate (EVA)
 - Transparent encapsulant that is UV resistant
 - Fills all the spaces between the front, rear edges and between layers
- Frame
 - Typically aluminum, strong and light weight



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Module Structure

Labels: Glass, EVA, Solar Cells, EVA, Tedlar

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Packing Density

- Ratio of area of module that is covered with solar cells to total area of module face
- Multi-crystalline are usually square and have a higher packing density

Edges of circular cells removed to increase packing density

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Module Design

A typical module has 36 cells in series

Sufficient to charge a 12 volt battery

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Module Open Circuit Voltage

- Typically 0.6 Volts per cell at 25°C and AM1.5
- Gives about 21 volts per module
- Allows for reductions due to temperature effects and other non-ideal conditions
- Allows for voltage drops across other PV system components
- Requires 15 V to charge a 12 V battery

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Module Current

- Depends primarily on size of solar cell and efficiency
- At AM1.5 commercial cells produce 30-36 mA/cm²
- Typical cells produce 3-4 A per cell
- Not temperature dependent
- But depends heavily on tilt angle

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Identical Cells

$$I_{total} = MI_L - MI_0 \left[e^{\left(\frac{qV_{total}}{nkTN} \right)} - 1 \right]$$

$I_T = M \times I_c$

$V_T = N \times V_c$

N : number of cells in series
M : number of cells in parallel
I_{total} : total current from the circuit
V_{total} : total voltage from the circuit
I₀ : saturation current from a single cell
I_L : short-circuit current from a single cell
n : ideality factor for a single cell

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Mismatch Effects

- Interconnecting of cells or modules not having identical properties
- **Module Output determined by the cell with the lowest output**
- Cells usually matched to each other
- Shaded cell acts like poor cell
 - Significantly reduces output power
 - Localized power dissipation and localized heating
 - Can cause irreversible damage to module

Non-ideal cell

Possible junction breakdown at high reverse voltages

Slope caused by shunt resistance

Cell Dissipates Power

Ideal Cell

Cell Generates Power

Non-ideal Cell

Extra slope caused by series resistance

Cell Dissipates Power

Open Circuit Voltage Mismatch connected in series

V_1

V_2

V_{oc}

V_{oc}

$V_T = V_1 + V_2$

Short Circuit Current Mismatch connected in series

$I_1 = I_2$

V_1

V_2

$V_T = V_1 + V_2$

Series connected solar cells with identical short circuit currents

Series connected solar cells with mismatched circuit currents

Solar cell with 50% shading

Current flow across "good" cell junction is $I_{sc1} - I_{sc2}$

The current from the "poor" cell (2) is lower than the current from the "good" cell (1)

+ -0.6 - -0.6 +

The forward bias of the "good" cell reverse biases the "poor" cell

The two solar cells are short-circuited such that the net voltage across them is zero

Hot-Spot Heating

- Mismatched cells within a module can result in some cells generating power and others dissipating power.
- Worst case: whole output of 'good' cells can dissipate in the 'bad' cell
- The enormous power dissipated in a small area results in local heating (hot-spot) which in turn results in destructive effects: glass cracking, solder melting or degradation of solar cell

10 cells in series
9 unshaded cells 1 shaded cell

If the terminals of the module are connected (module Isc), the power from the unshaded cells is dissipated across the shaded cell.

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Crack module due to heat dissipated from shaded cell

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By-Pass Diode

- The destructive effects of hot-spot heating can be circumvented through the use of a by-pass diode
- A diode is connected in parallel with the solar cell but with opposite polarity
- The maximum reverse bias across the 'poor' cell is reduced to about the single diode drop

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Series connected solar cells with by-pass diode (matched) at short circuit

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Series connected solar cells with by-pass diode (mismatched) at short circuit

The 'poor' cell is reverse biased, but only about -0.5 V

Some current from the 'good' cell forward biases the 'good' cell

The bypass diode of the 'poor' cell forward biased from the 'good' cell and conducts current

The bypass diode of the 'good' cell is reverse biased and has no effect

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Series connected solar cells with by-pass diode (matched) at open circuit

The solar cell diodes are forward biased by I_{sc} and are at V_{oc}

The by-pass diodes are reverse biased and have no effect

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Series connected solar cells with by-pass diode (mismatched) at open circuit

The solar cell diodes are forward biased by I_{sc} and are at their respective V_{oc}

The by-pass diodes are reverse biased and have no effect

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Effect of By-Pass Diode

- The by-pass diode effects the solar cell only in reverse bias
- If the reverse bias is greater than the knee voltage of the solar cell, the diode turns on and conducts current

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By-Pass diode in 10 Cell Module

The combined I_{sc} is the same as an individual cell

With 10 identical cells the total V_{oc} is equal to 10 times an individual V_{oc} .

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By-Pass diode in 10 Cell Module

Reflecting the I-V curve of the unshaded cells through the I-axis gives the operating point at I_{sc}

The I_{sc} of the combined module falls to near that of the shaded cell

If one cell is shaded its I_{sc} falls, if half the cell is shaded its I_{sc} is reduced in half

Large amount of power dissipated in shaded solar cell

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By-Pass diode in 10 Cell Module

Adding a by-pass diode in parallel with the shaded cell limits reverse voltage to about 0.7 volts

The by-pass diode dramatically reduces the effect of the shaded cell on the module

Power dissipated in by-pass diode

Power dissipated in shaded cell reduced

At the new operating point, I_{sc} , the shaded cell has a much lower voltage and power dissipation

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By-pass diodes used across groups

- Cost prohibitive to use one diode per cell
- By-pass diodes from unshaded cells are reversed bias and have no impact
- Current from string of cells limited by lowest current cell, if some cells are shaded extra current from good cells in the string forward bias the diode

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Mismatch for Modules connected in Parallel

- In small modules the cells are usually placed in series so parallel mismatch is not an issue
- Modules are placed in parallel in large arrays

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Cells in Parallel with Current Mismatch

Cells connected in parallel. The voltage across the cell combination is always the same and the current is sum of the individual cells

$I_T = I_1 + I_2$

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Cells in Parallel with Voltage Mismatch

At this point cell 2 stops producing power and starts to dissipate power

The Voc of the combination is lower than from cell 2 alone

The intersection point where $I_1 + I_2 = 0$ is the Voc of the parallel configuration

The curve in one cell is reflected through the voltage axis

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Calculating Voltage and Current

- Series** connections are made by connecting one cell's n-type contact to the p-type of the next cell
- Parallel** connections are made by joining each cells n-type contacts together and p-type contacts together
- Series** connections the voltages add
- Parallel** connections the current add
- Series** connections the current flow is equal to the current from the cell generating the smallest current (limited by poorest cell)
- Parallel** connections the voltage is the average of the cells or string in parallel

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Example: Cells Series Connected

- The voltage across terminals 12 is the sum of the voltages
- $V_{12} = V_A + V_B + V_C = 0.58 + 0.54 + 0.61 = 1.73(V)$
- The current through the cells is restricted by the smallest current produce by any of the cells
- $I_{12} = 0.25 (A)$

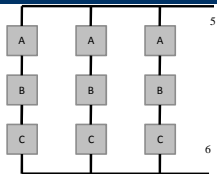
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Example: Cells Parallel Connected

- The voltage across terminals 34 is the average of the voltages
- $V_{34} = (V_A + V_B + V_C) / 3 = (0.58 + 0.54 + 0.61) / 3 = 0.58(V)$
- The current at the terminals 34 is the sum of the currents in each cell
- $I_{34} = (I_A + I_B + I_C) = (0.28 + 0.31 + 0.25) = 0.84(A)$

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Example: Block Connected



- The voltage across terminals 56 given by the series voltage already calculated:
- $V_{56} = V_A + V_B + V_C = 0.58 + 0.54 + 0.61 = 1.73(V)$
- The current at the terminals 56 is the sum of the currents in each string already calculated
- $I_{56} = 3(I_{\text{string}}) = 3(0.25) = 0.75(A)$



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Summary Linking Cells



- Linking modules or batteries is similar to connecting PV cells
 - Series Connections
 - Voltages are added in series connections
 - The current is restricted to the smallest current
 - Parallel connections
 - The currents are added in parallel connections
 - The voltages are averaged from each string
- Solar Cells and Modules are Matched to improve the power generated



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