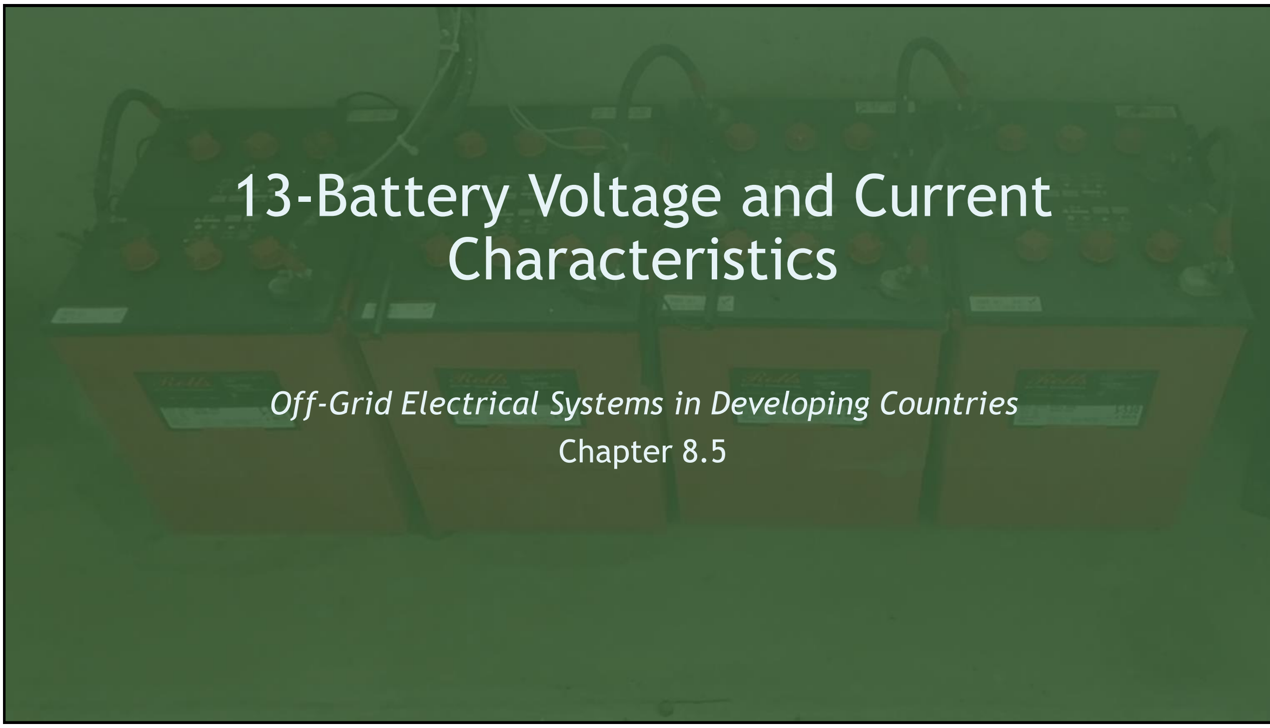

13-Battery Voltage and Current Characteristics

Off-Grid Electrical Systems in Developing Countries

Chapter 8.5

1

Learning Outcomes

At the end of this lecture, you will be able to:

- ✓define the nominal voltage of a battery
- ✓describe the I-V curve of a battery and explain why it is non-linear
- ✓develop and apply a circuit model for a battery

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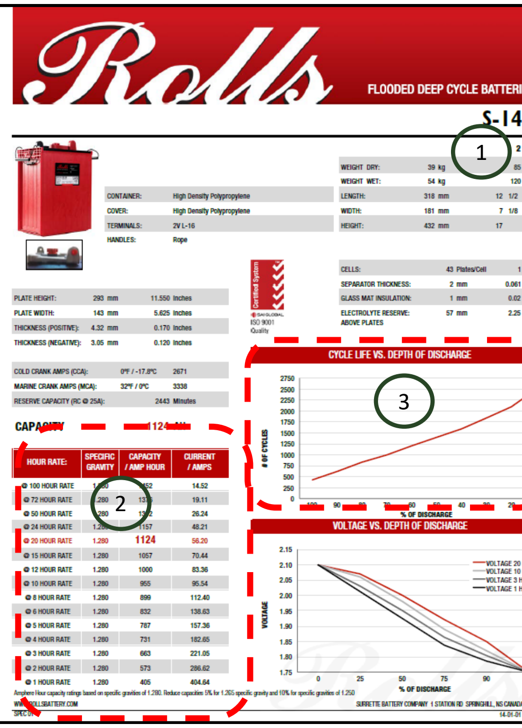
Battery Specification Sheets

- Provide technical information on battery characteristics and performance
- Not always easy to interpret
- Most important characteristics
  1. Nominal Voltage
  2. Capacity
  3. Cycle life

We will discuss these in a later lecture



Nominal Voltage

- Nominal voltage: approximately equal to the average battery voltage during a charge and discharge cycle
  - Not: open-circuit voltage when fully charged or discharged
- Lead-acid batteries typically have nominal voltages of 2V, 6V, 12V or 24V
- Nominal voltage of a lithium-ion cell typically between 3.2V and 3.8V (depending on the chemistry used)
- Open-circuit voltage for a fully-charged lead-acid cell is approximately 2.10 V

Nominal Voltage

A lead-acid battery with 24V nominal voltage (12 cells in series) will have a fully-charged open-circuit voltage of approximately 12 x 2.11 = 25.32V

Open-circuit	Approximate state-of-charge (%)										
cell voltage	0	10	20	30	40	50	60	70	80	90	100
Flooded (V/cell) (V/cell)	1.90	1.92	1.94	1.96	1.99	2.01	2.03	2.05	2.07	2.09	2.11
AGM (V/cell)	1.94	1.96	1.98	2.00	2.02	2.04	2.06	2.08	2.10	2.12	2.14

Open-Circuit Voltage

- Open-circuit voltage refers to the voltage between the positive and negative terminals of a cell, battery, or battery bank
- Remember that batteries exhibit non-linear, temperature-dependent behavior, and have long time constants (before steady-state is reached)

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Open-Circuit Voltage

- Open-circuit voltage can only reliably be used to estimate state-of-charge if the battery has been open-circuited, not hot or cold, and given enough time to "rest"
  - Resting allows the chemicals within the battery to mix/re-distribute, avoiding localized concentrations which affect voltage
  - Resting time required can be several minutes to several hours

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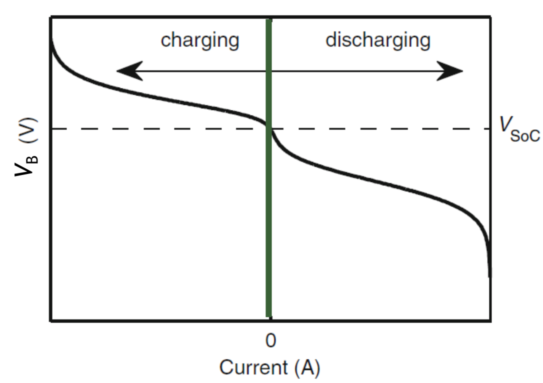
I-V Characteristic

- I-V characteristic shows how the *terminal* voltage (V_B) of the battery (cell) varies with charge/discharge current
- Note:
  - plot assumes the state-of-charge is constant at each point along the curve
  - non-linear dependence of terminal voltage with current
  - Asymmetry



V_{SoC}: open-circuit voltage (State-of-Charge)

Don't confuse the x-axis with time

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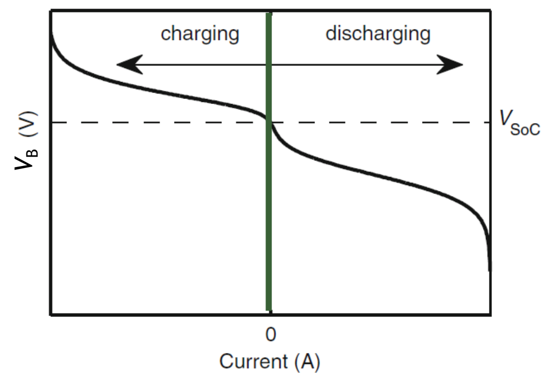
I-V Characteristic

- Important:
  - Charging: terminal voltage is increased from open-circuit
  - Discharging: terminal voltage is decreased from open-circuit voltage



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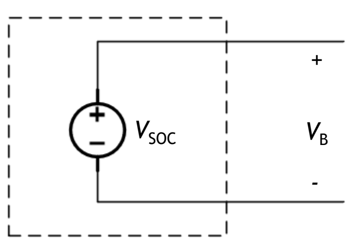
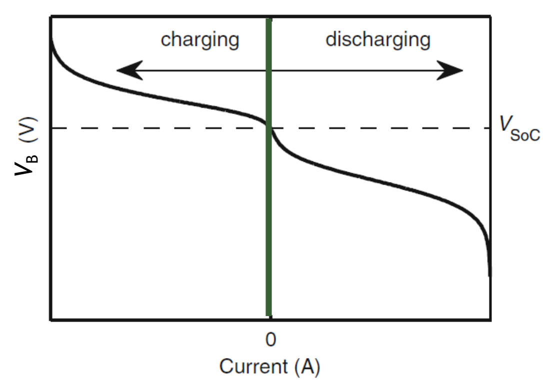
How can we explain the I-V curve?

What about this model?





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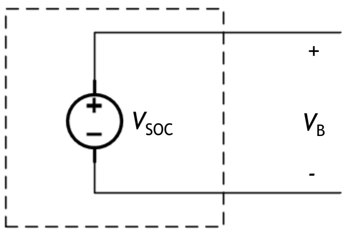

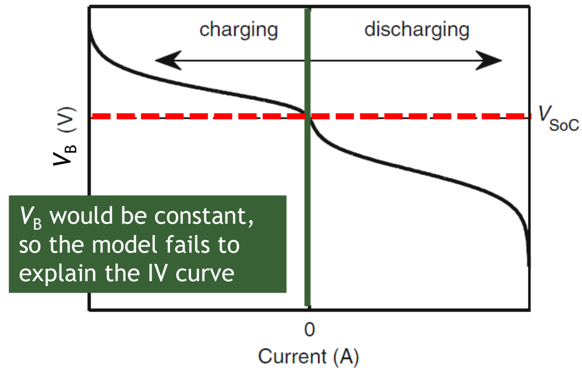

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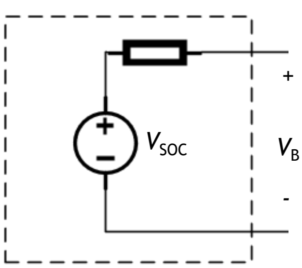
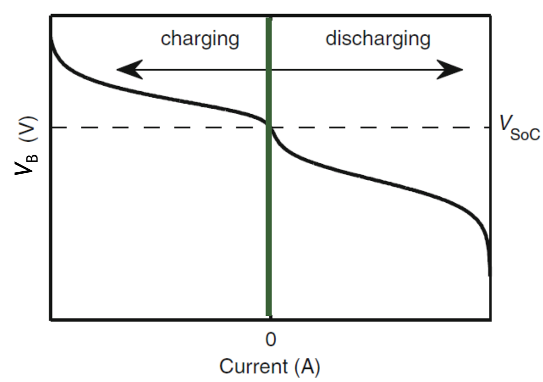
How can we explain the I-V curve?

What about this model?
Sketch the I-V curve.





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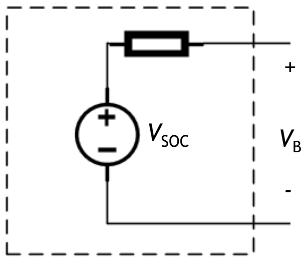
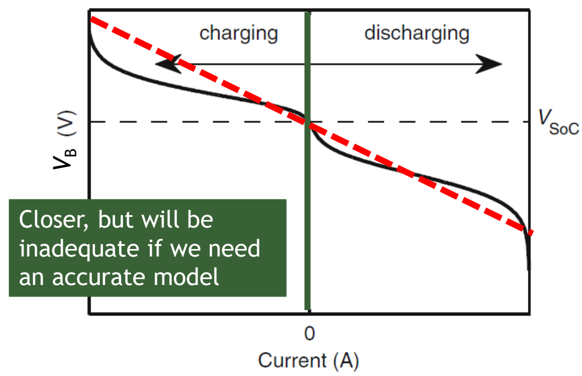
How can we explain the I-V curve?

What about this model?
Sketch the I-V curve.





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Polarization

- Non-linearity of I-V curve can be attributed to three mechanisms (*polarizations*)
- *Ohmic*: voltage drop caused by the battery current passing through the electrode resistance and electrolyte resistance (difficulty of ions moving through electrolyte)
- *Activation*: related to the kinetics of the reactions, for there to be current the equilibrium balance of chemical and electrostatic potential must be upset (decreased voltage when discharging, increased when charging)
- *Concentration*: at higher current, localized depletion or accumulation of ions can occur, which, per the Nernst equation will affect the cell voltage

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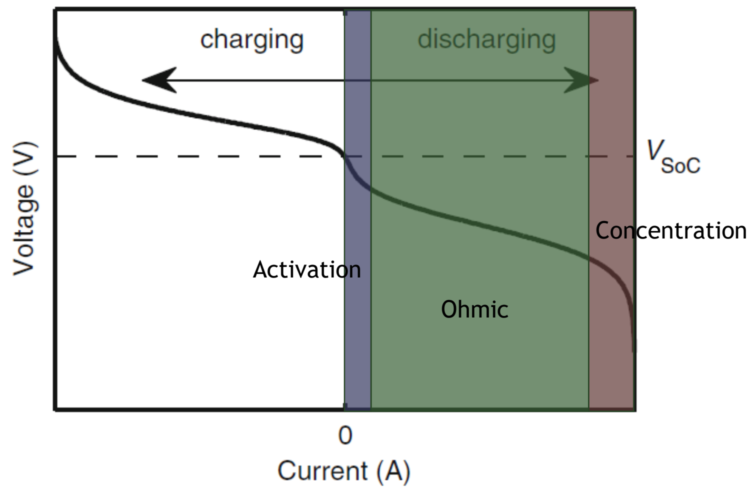
Polarizations



Only discharging shown, but analogous effects are present when charging

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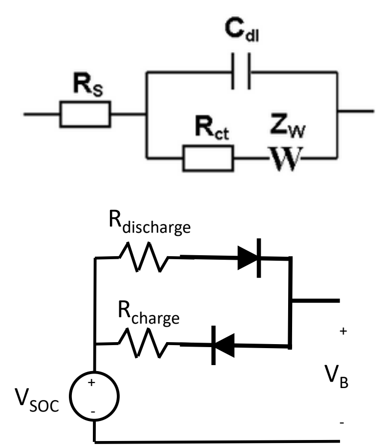
Cell Circuit Model

- Several circuit models of battery cells have been proposed and used
- Selection depends on what characteristics are of interest (e.g. steady-state, dynamics, etc.)



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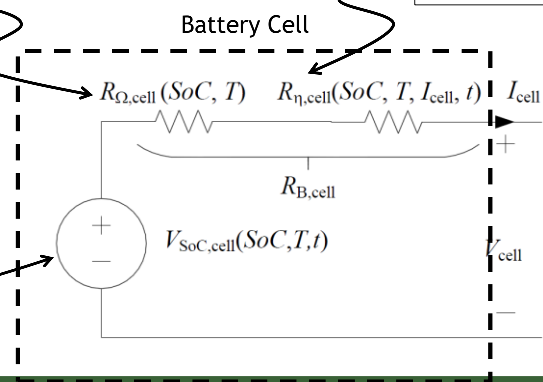
Circuit Model of a Battery Cell

Activation and concentration polarization dependent on: state-of-charge, temperature, current magnitude and polarity, time (since charged/discharged)

Ohmic polarization, dependent on: state-of-charge, temperature



State-of-charge voltage, dependent on: state-of-charge, temperature, time (since discharged/charged)

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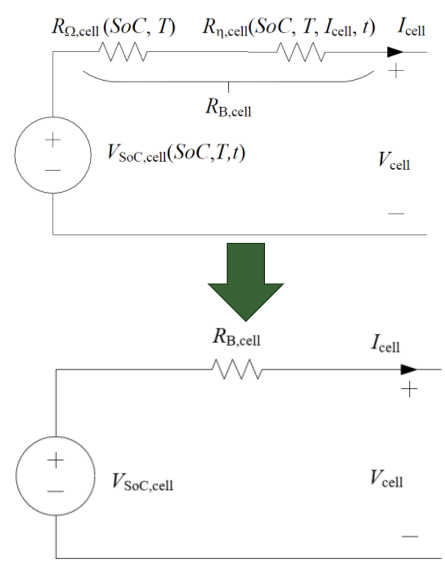
Cell Circuit Model

- Combine the resistances into a single quantity $R_{B,cell}$ which we will call the "battery resistance"
- Keep in mind:
  - $R_{B,cell}$ models the Ohmic, activation and concentration polarizations
  - $R_{B,cell}$ depends on many factors, and so there is no single $R_{B,cell}$ for a battery, rather we assume that $R_{B,cell}$ refers to the resistance at the present state of the battery
  - $R_{B,cell}$ is not the "internal resistance" sometimes reported on spec sheets, the reported value is usually the Ohmic resistance only



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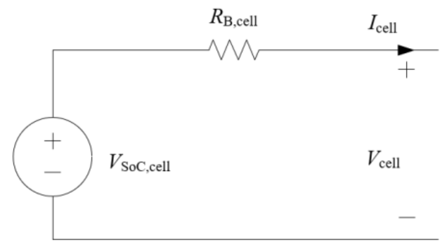
Cell Circuit Model

- Analysis via KVL:

  $V_{cell} = V_{SoC,cell} - I_{cell}R_{B,cell}$

- Voltage drop associated with $R_{B,cell}$ causes the terminal voltage to greater than $V_{SoC,cell}$ when charging, and lower than $V_{SoC,cell}$ when discharging



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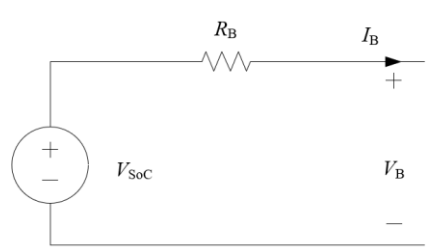
Battery Circuit Model

Extension of model to a battery with two or more series connected cells is straightforward

$$R_B = N_{cells} \times R_{B,cell}$$
$$I_B = I_{cell}$$
$$V_{SoC} = N_{cells} \times V_{SoC,cell}$$
$$V_B = V_{SoC} - I_B R_B$$



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Exercise

The equilibrium open-circuit cell voltage of a 24 V lead-acid battery is 24.96 V. An external circuit is connected to the battery that draws 21 A. Assume the battery resistance R_B under the these conditions is 0.060 Ω. Compute the terminal voltage.

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Exercise

The equilibrium open-circuit cell voltage of a 24 V lead-acid battery is 24.96 V. An external circuit is connected to the battery that draws 21 A. Assume the battery resistance R_B under the these conditions is 0.060 Ω. Compute the terminal voltage.

$$V_B = V_{SoC} - I_B R_B$$

$$V_B = 24.96 - 21.0 \times 0.060 = 23.70\,\text{V}$$

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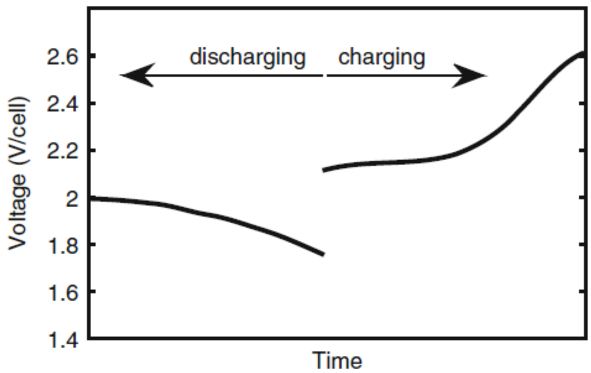
Cell Voltage During Discharging/Charging

Curves are influenced by the dual effects of increasing V_{SoC} and changes
In the polarizations as function of state-of-charge



Current magnitude is kept constant throughout

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Contact Information

Henry Louie, PhD

Associate Professor

Fr. Wood Endowed Research Chair

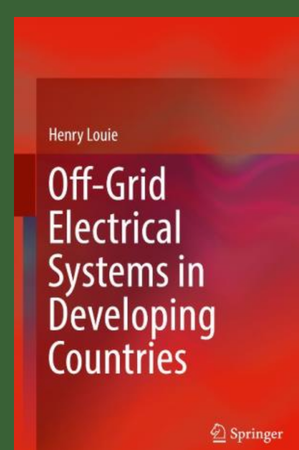
Seattle University

@henrylouie

hlouie@ieee.org

www.drhenrylouie.com

Office: +1-206-398-4619



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