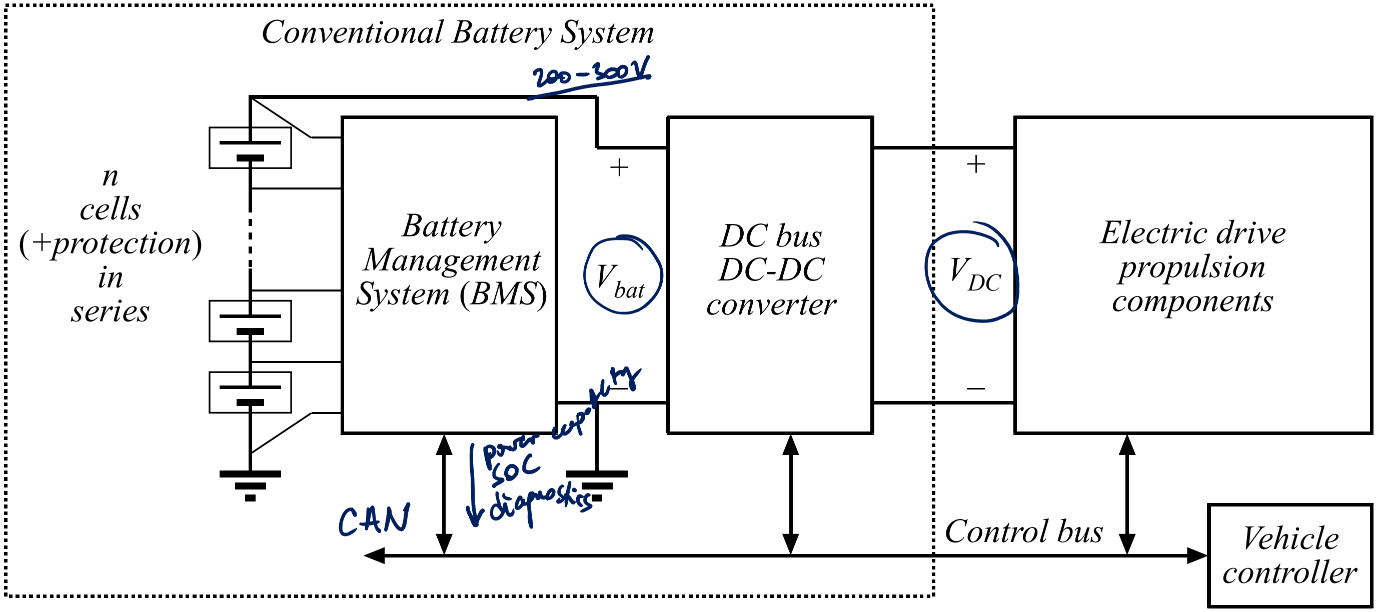
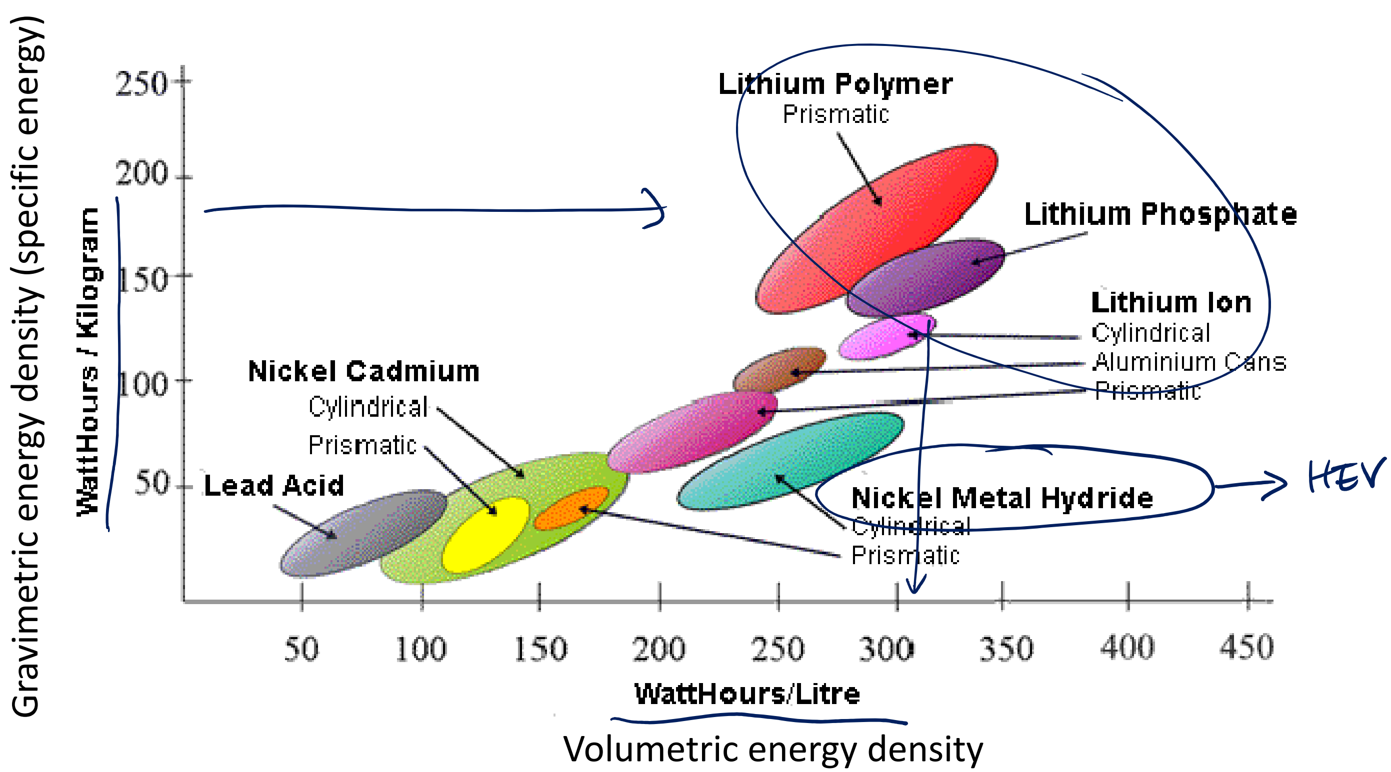
Battery System in Electrified Drivetrain



- Many battery cells (or sets of parallel cells) connected in series; V_{batt} in EV's, HEV's and PHEV's is commonly in the 200-300 V range
- BMS provides protection, battery health monitoring, charge balancing among series cells; BMS communicates SOC, power capability and diagnostic information to a vehicle system controller
- In some EV/HEV/PHEV realizations, a dc-dc converter regulates dc bus voltage V_{DC}

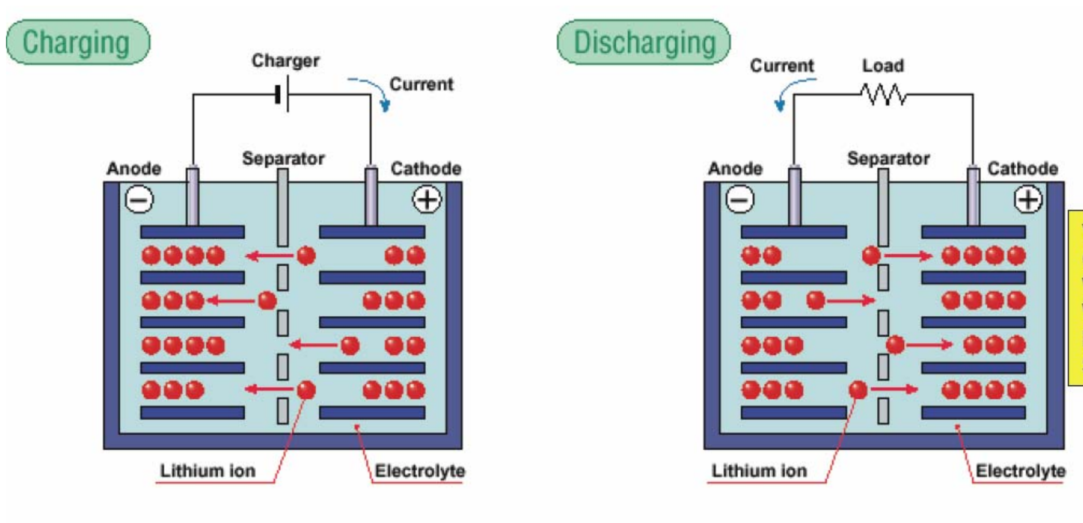
Specific Energy and Energy Density



For comparison, energy density and specific energy of gasoline are orders of magnitude higher: 9700 Wh/L, 13000 Wh/kg

Lithium-Ion Chemistry

"Intercalation" = insertion of Li ions into electrode crystalline lattice



Voltage ~3.2-3.8 V
Cycle life ~1000-3000
Wh/kg >150
Wh/l >400
Discharge -30 to 60°C
Shelf life <10%/year

Many anodes are possible	Many electrolytes are possible	Many cathodes are possible
Carbon/Graphite	$LiPF_6$ based	Cobalt oxide mobile electronics.
Titanate ($Li_4Ti_5O_{12}$)	$LiBF_4$ based	Manganese oxide
Titanium oxide based	Various solid electrolytes	Mixed oxides with Nickel
Thin Oxide based	Polymer electrolytes	Iron phosphate
Tungsten oxide		Vanadium oxide based

Source: Robert M. Spotnitz, Battery Design LLC, "Advanced EV and HEV Batteries," 2005 IEEE Vehicle Power and
10 Propulsion Conference, September 7-9, 2005, IIT, Chicago, IL

NREL National Renewable Energy Laboratory

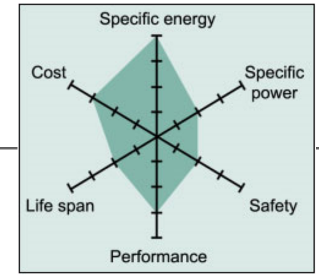
A. Pesaran (NREL), "Battery Choices for Different Plug-in HEV Configurations," Plug-in HEV Forum, July 12, 2006

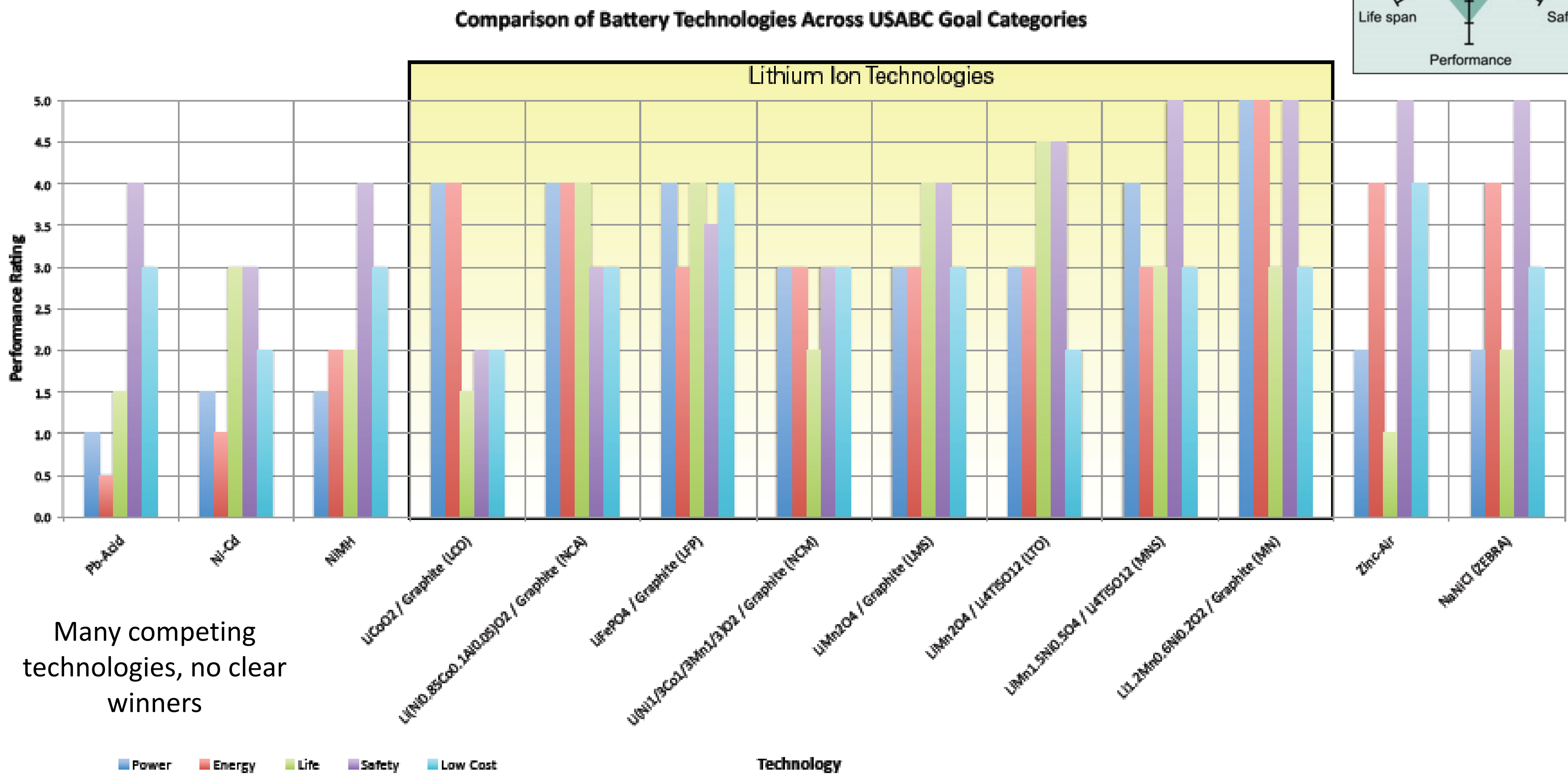
Li-Ion Chemistry Cells

Lithium Ion Cathode Chemistry Comparison (Used With Carbon Anodes)

Cathode Material	Typical Voltage (V)	Energy Density		Thermal Stability
		Gravimeric (Wh/Kg)	Volumetric (Wh/L)	
Cobalt Oxide	3.7	195	560	Poor
Nickel Cobalt Aluminum Oxide (NCA)	3.6	220	600	Fair
NMC Nickel Cobalt Manganese Oxide (NCM)	3.6	205	580	Fair
Manganese Oxide (Spinel)	3.9	150	420	Good
Iron Phosphate (LFP)	3.2	90-130	333	Very Good

Comparison of Battery Technologies

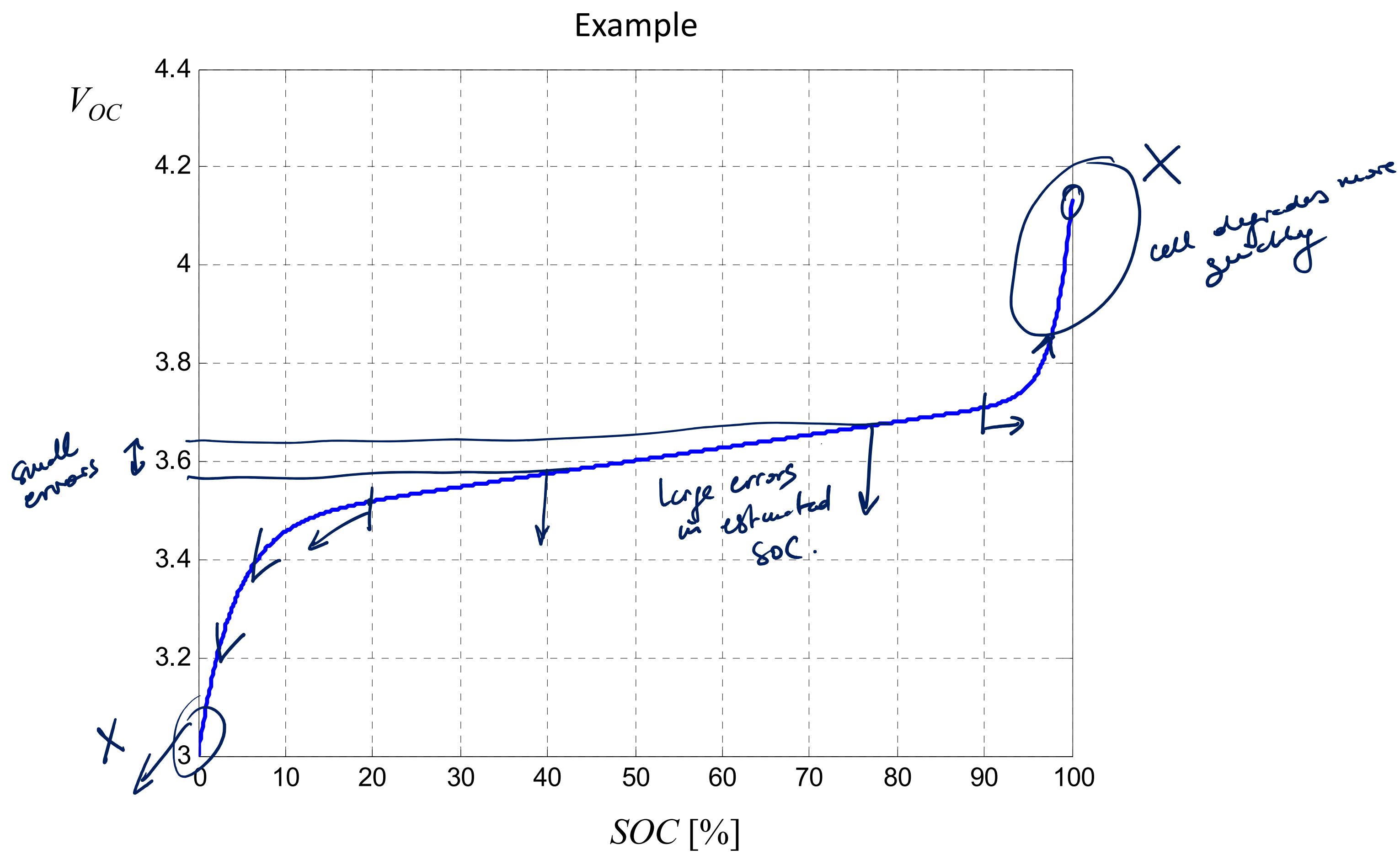




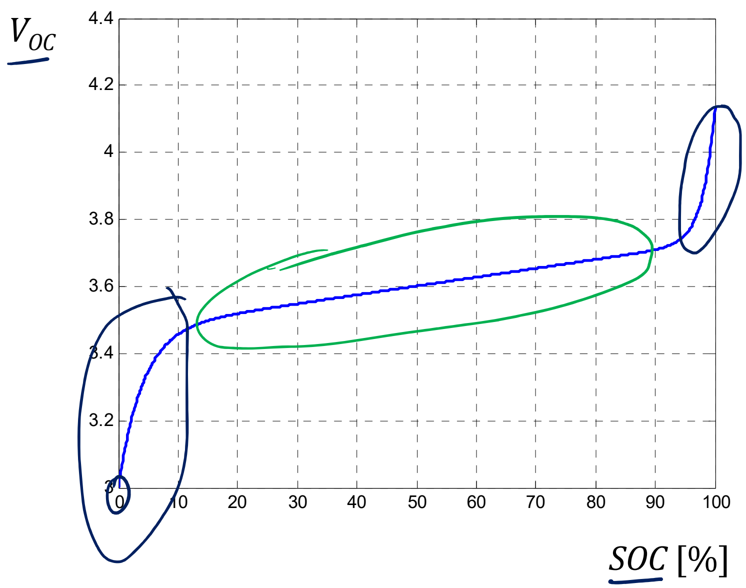
Many competing technologies, no clear winners

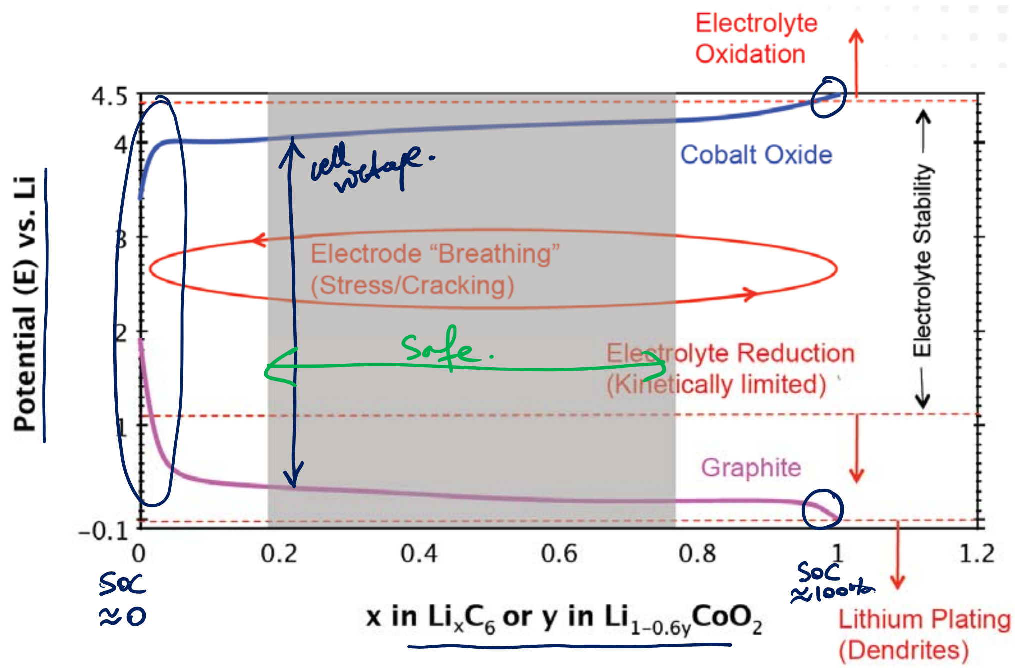
Source: Axsen et al (2008), Nelson et al (2007), Kromer et al (2007), Kalhammer et al (2007), & RMI Analysis

Li-Ion: Open-Circuit Voltage as a Function of SOC



Limits of Operation





Guest lectures by Prof. Greg Plett (UCCS) and Dr. Kandler Smith (NREL) will address physics-based models and degradation mechanisms in more detail.

Li-Ion Technology Summary

- Advantages
  - High power density
  - Relatively high energy density, 150-250 Wh/kg, 250-700 Wh/l
  - Cells can be optimized for energy density or power density
  - Higher voltage, approx. 3.2 V to 3.8 V
  - Low self-discharge rate, retain charge for months
  - Relatively long cycle life (1,000-3,000 deep cycles)

- Disadvantages
  - More complex to manufacture, more expensive (0.5-1 $/Wh)
  - Safety concerns: require circuitry to protect against overcharging or over-discharging

Cell Equivalent-Circuit Models

- Objective:
  - Dynamic circuit model capable of predicting cell voltage in response to charge/discharge current, SOC, temperature

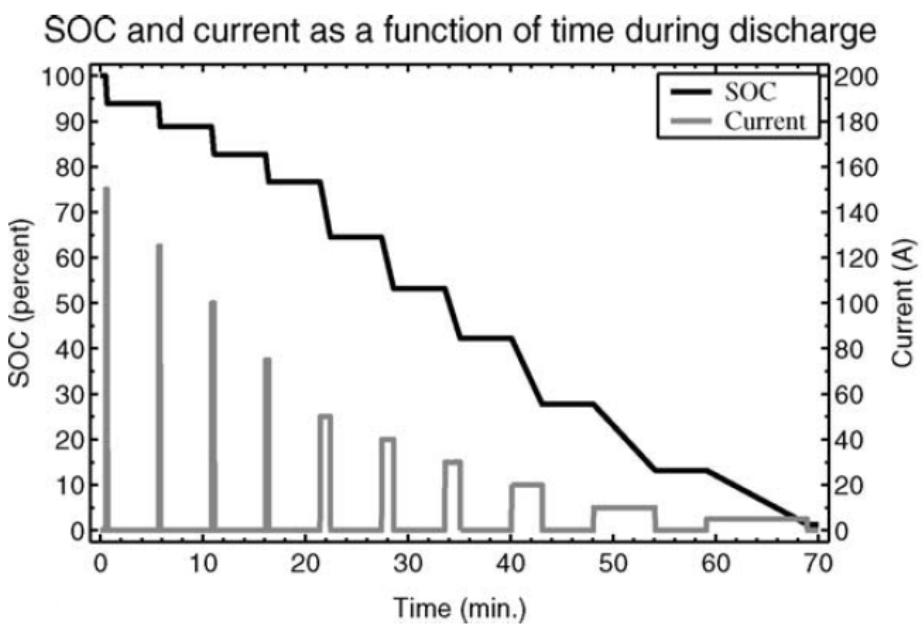
- Cell equivalent circuit model developed here is based on:
  - G. Plett, "Extended Kalman Filtering for Battery Management Systems of LiPB-Based HEV Battery Packs—Part 2: Modeling and Identification," *Journal of Power Sources*, Vol. 134, No. 2, pp. 262–276, August 2004. [Plett 2004-2*]
  - Model parameters are found using least-square estimation or Kalman filter techniques based on experimental test data

- Further techniques discussed in companion paper (Part 3)
  - Run-time estimation of state of charge (SOC)

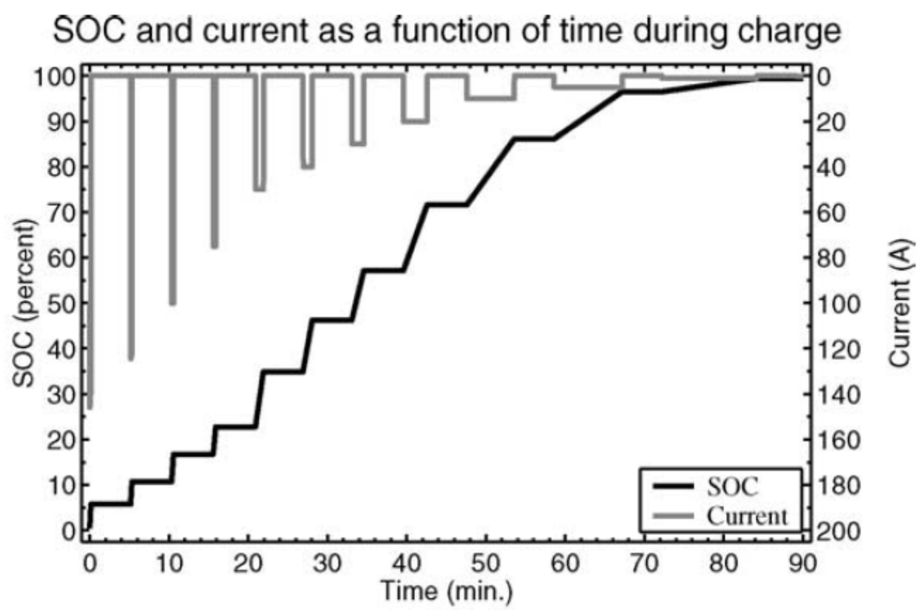
*The paper by Prof. Plett is posted on D2L among Supplementary materials

Models Tested Using Pulsed-Current Tests

Discharge

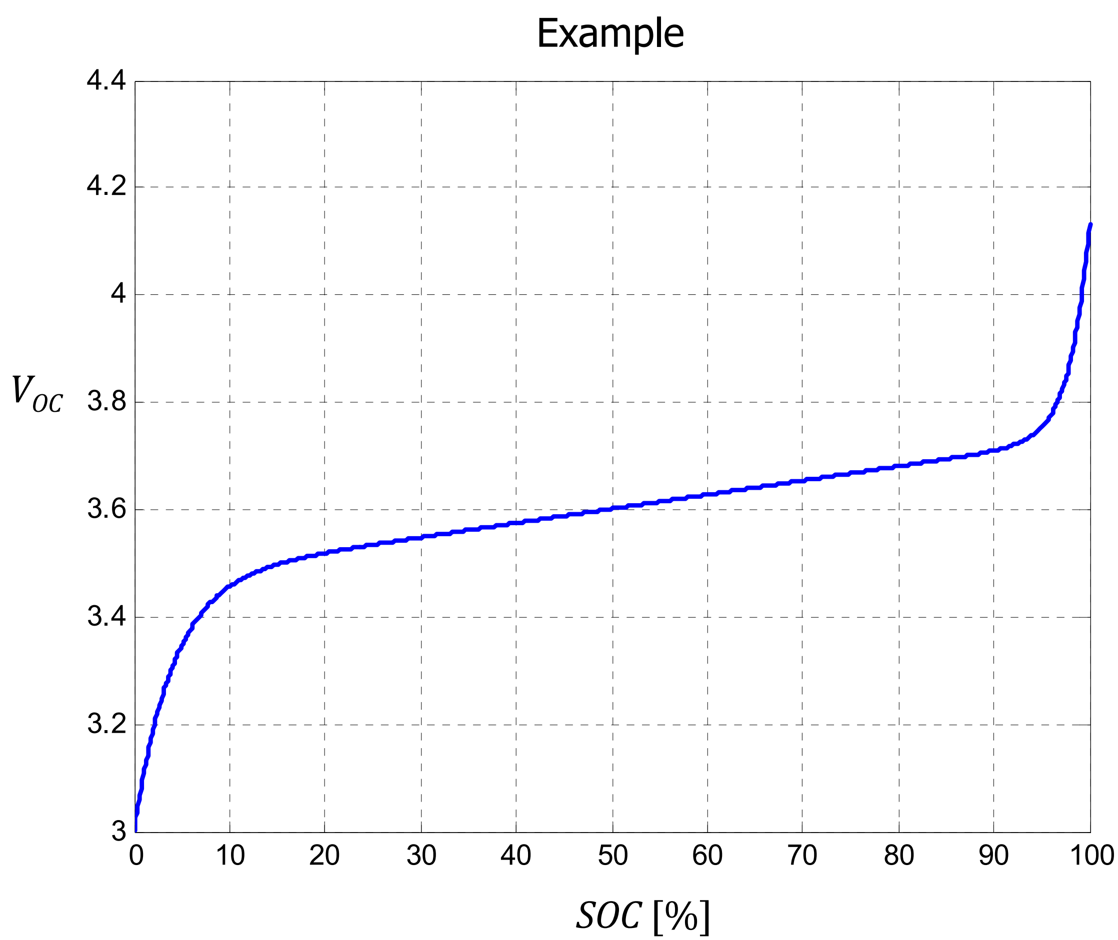


Charge

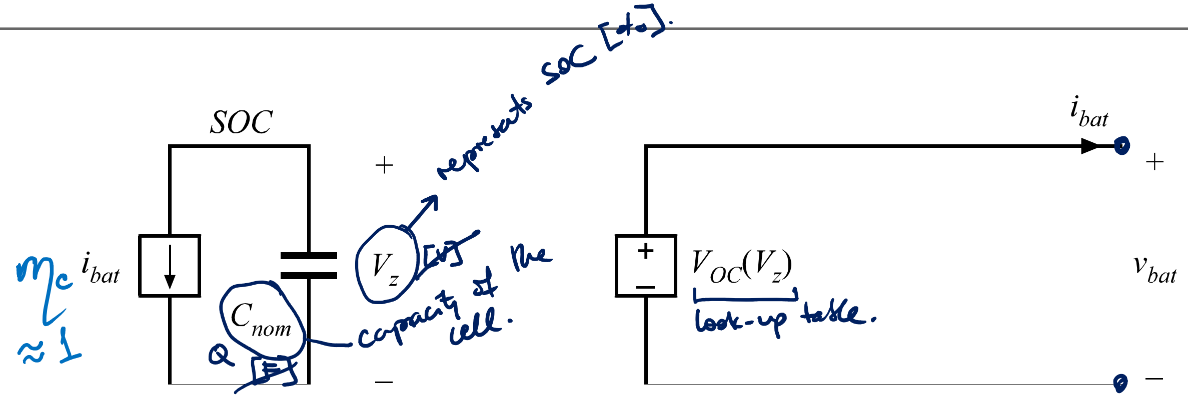


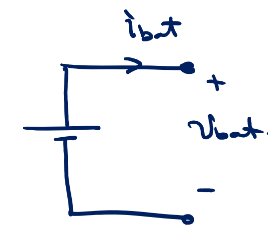
[Plett 2004-2]

Li-Ion: Open-Circuit Voltage as a Function of SOC



Model A: State of Charge and Open-Circuit Voltage





electrical : $C_{nom}\frac{dV_z}{dt} = -i_{bat}$ $\qquad \frac{dV_z}{dt} = -\frac{i_{bat}}{C_{nom}}$.

cell : $\frac{dQ}{dt} = -i_{bat}$, $\quad SOC = \frac{Q}{C_{nom}}$.

$\underbrace{\frac{d(SOC)}{dt}}_{[\frac{1}{s}]} = -\frac{i_{bat}}{\boxed{C_{nom}}}$ $\quad [\frac{Q}{s}]$ $\quad$ Coulombs.

$\frac{d}{dt}(SOC)\cdot C_{nom} = -i_{bat}$

Ah $\rightarrow$ A · 3600 s $\rightarrow C_{nom}$.

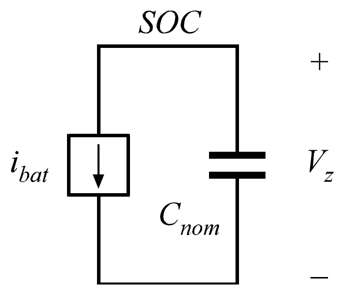
$$\frac{d(SOC)}{dt} = -\frac{i_{bat}}{C_{nom}}$$

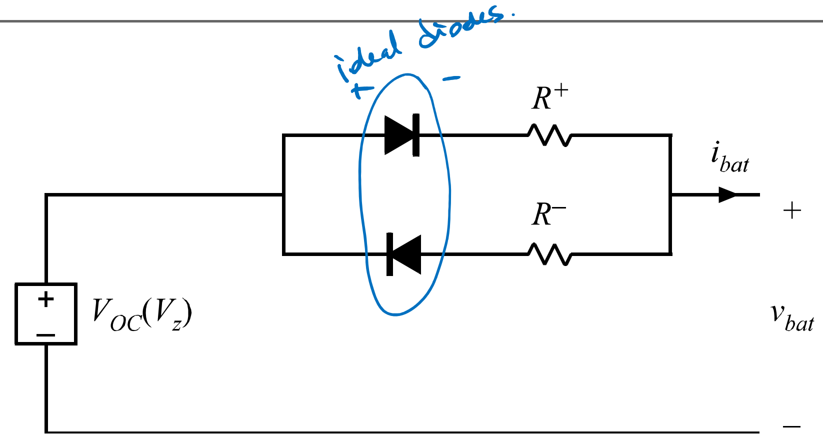
C_{nom}: Nominal Charge Capacity [Coulombs]

$\boxed{\eta_c\text{: Coulomb Efficiency}}$

For Li-Ion: $\eta_c = \begin{cases} 1, & i_{bat} > 0 \\ 0.997, & i_{bat} < 0 \end{cases}$ $\quad$ discharging. charging.

Model B: Incorporate Series Resistance



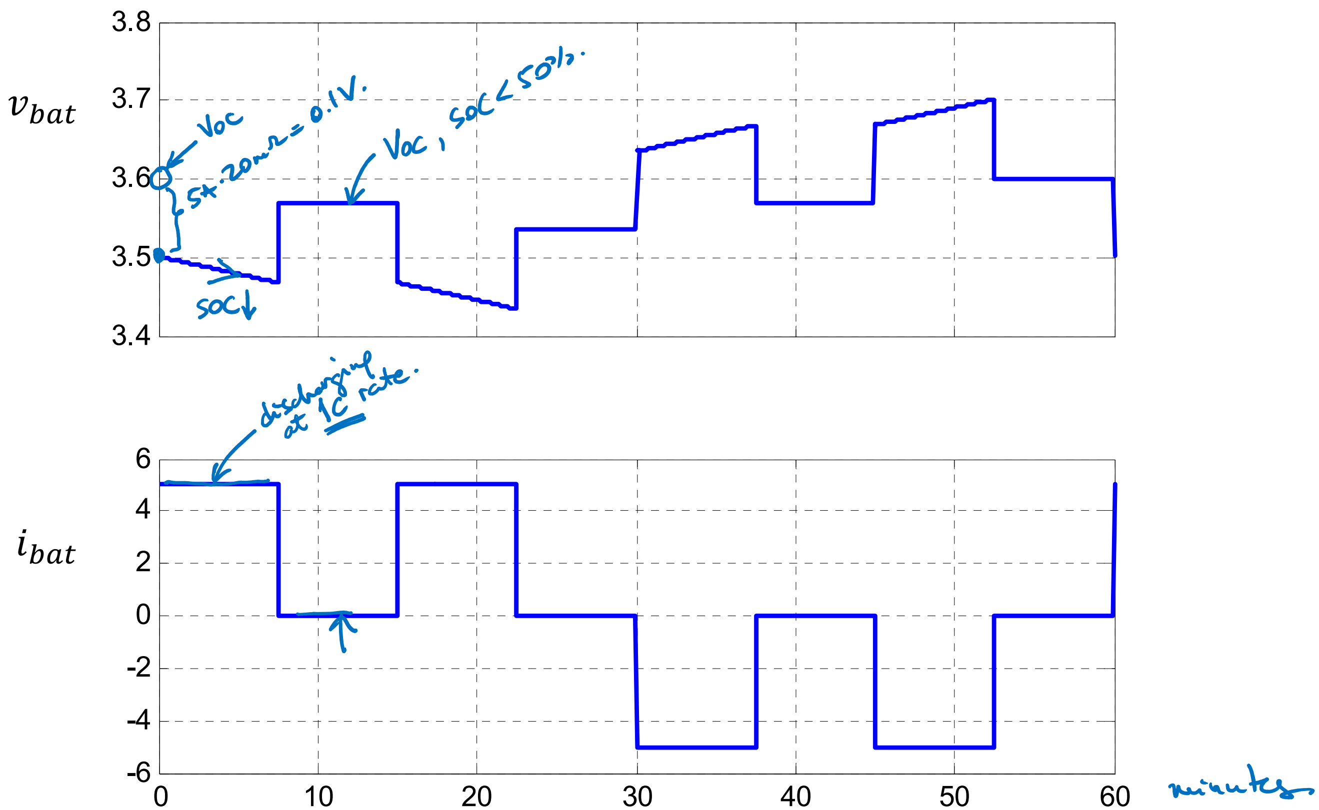


$$v_{bat} = V_{oc} - R\, i_{bat}.$$

$$R = \begin{cases} R^+ & i_{bat} > 0 \\ R^- & i_{bat} < 0 \end{cases}$$

$R^+ \approx R^- \approx$ single value.

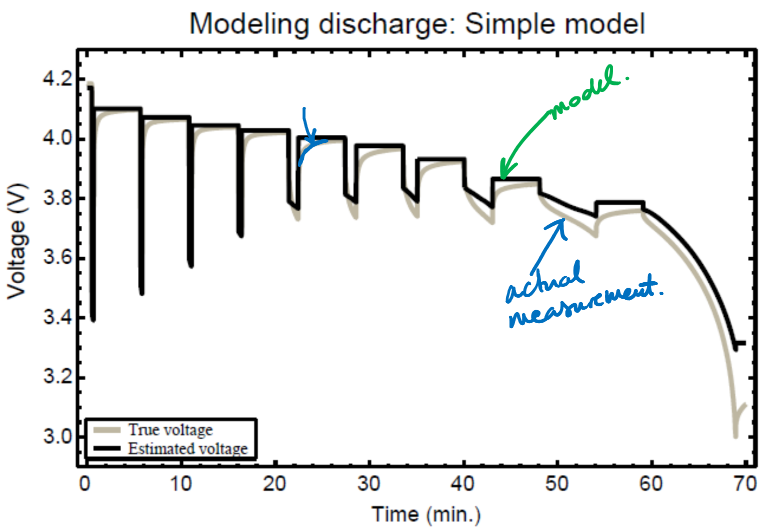
Model B Pulse Current Response



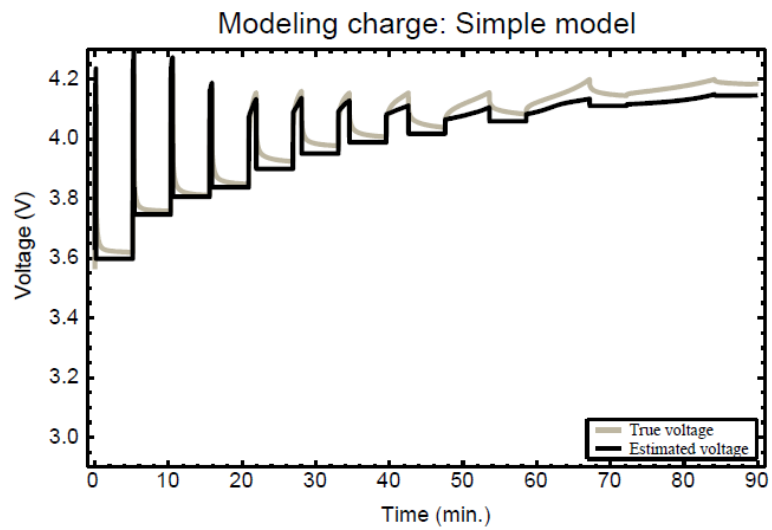
Example: $R^+ = R^- = 20\ m\Omega$, SOC(0) = 50%, $\boxed{C_{nom} = 5\ Ah}$

Model B Performance

Discharge



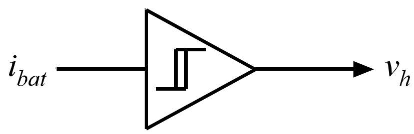
Charge



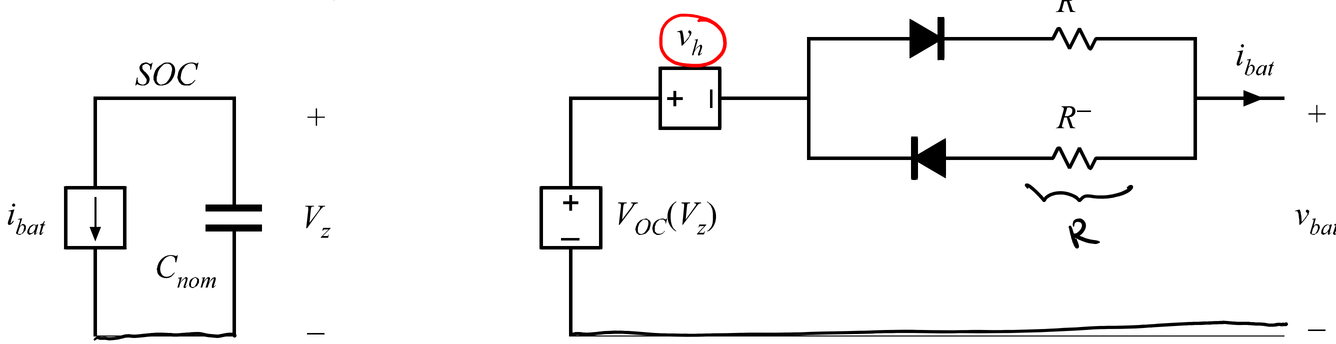
RMS voltage error with respect to experimental data: 36.2 mV

[Plett 2004-2]

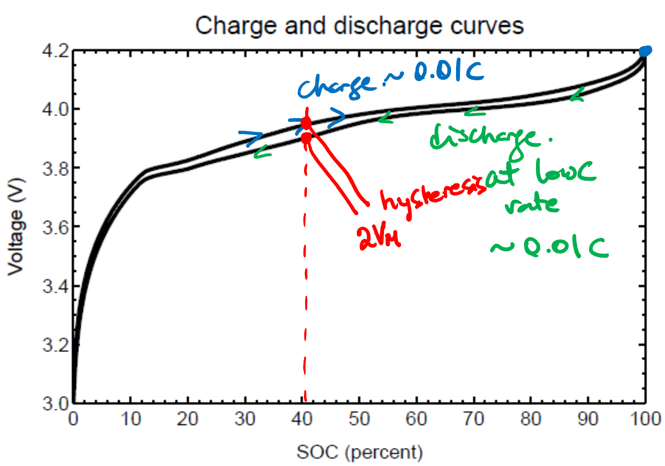
Model C: Incorporate Voltage Hysteresis (0-State)

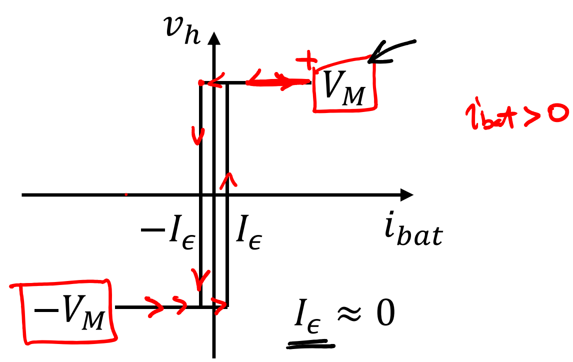


zero-state hysteresis model

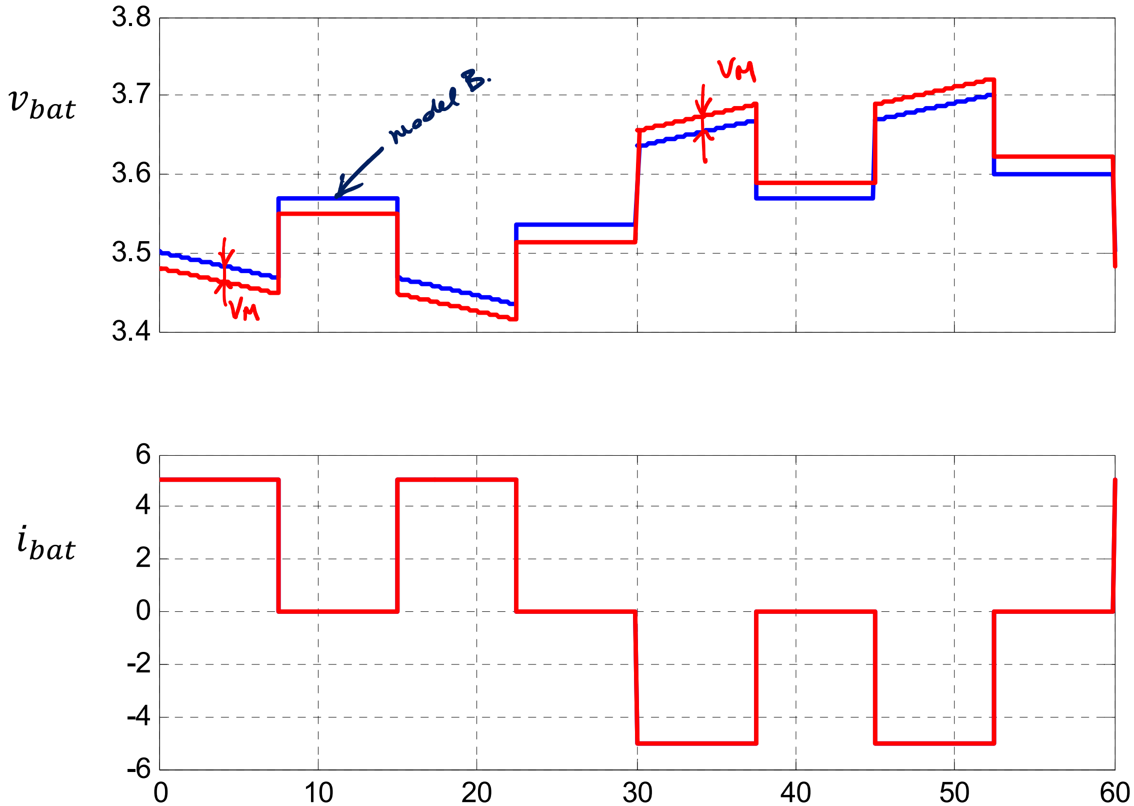


$v_{bat} = V_{oc}(soc) - v_h - R\, i_{bat}.$





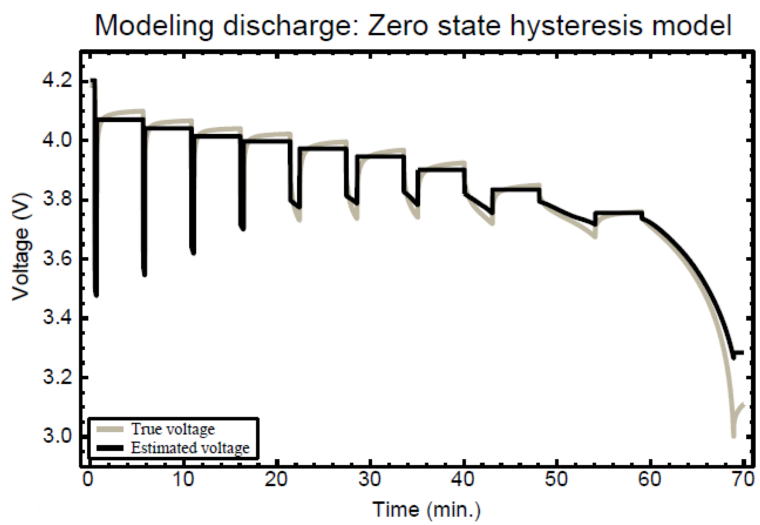
Model C Pulse Current Response



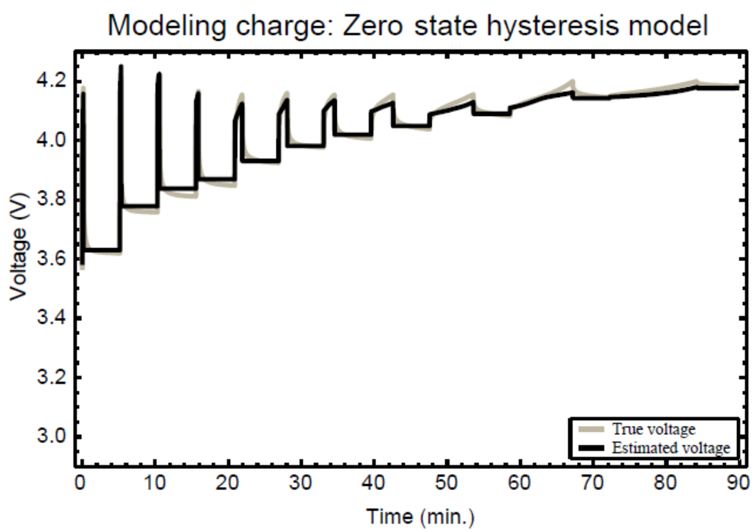
Example: $R^+ = R^- = 20$ mΩ, SOC(0) = 50%, $C_{nom} = 5$ Ah, $V_M = 20$ mV

Model C Performance

Discharge



Charge

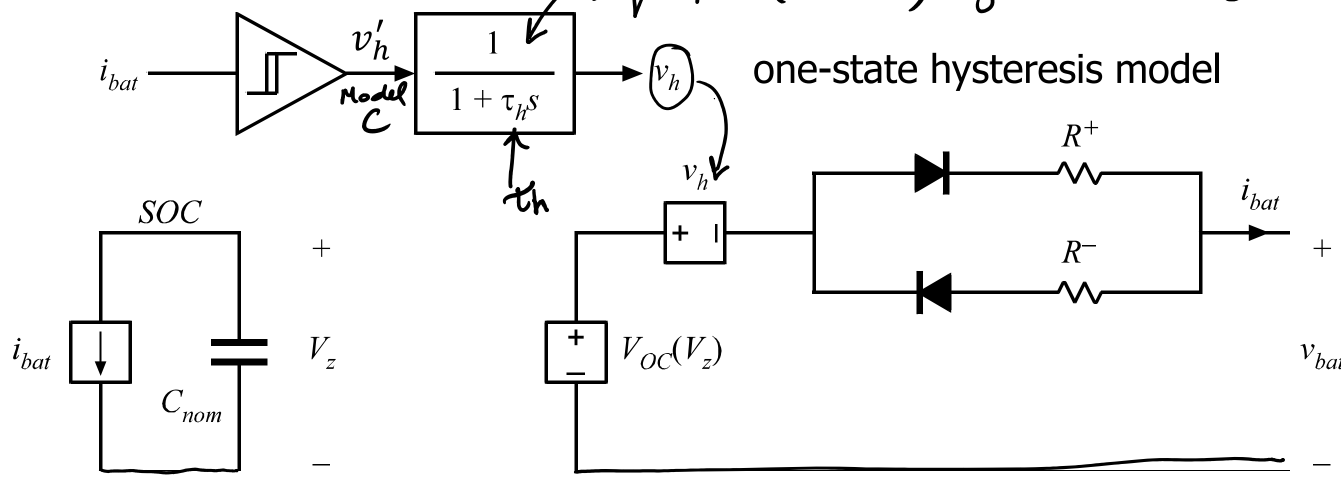


RMS voltage error with respect to experimental data: 21.5 mV

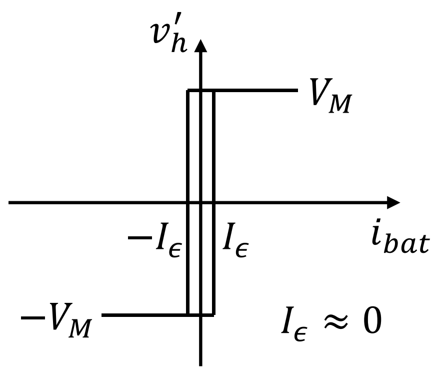
[Plett 2004-2]

Model C1: Incorporate Voltage Hysteresis (1-State)

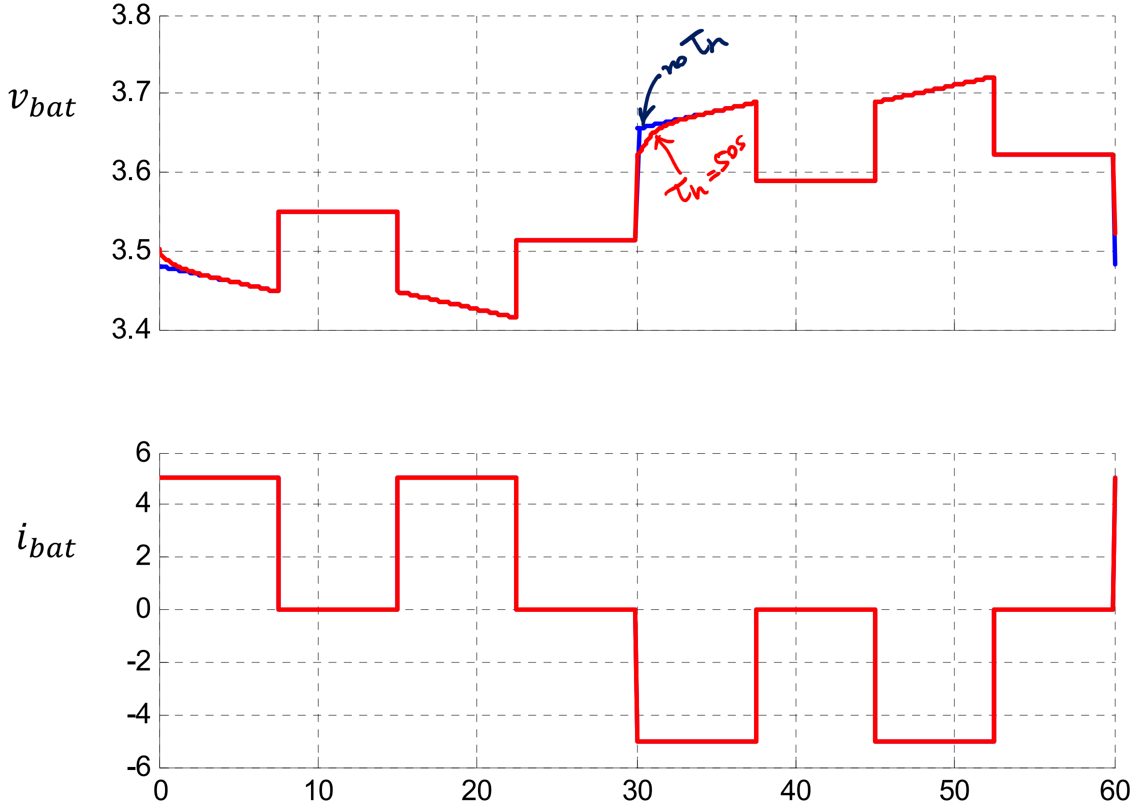
single-pole (1-state) dynamics in the hysteresis.



one-state hysteresis model



Model C1 Pulse Current Response



Example: $R^+ = R^- = 20\ m\Omega$, $SOC(0) = 50\%$, $C_{nom} = 5$ Ah, $V_M = 20$ mV, $\tau_h = 50$ s

Model C2

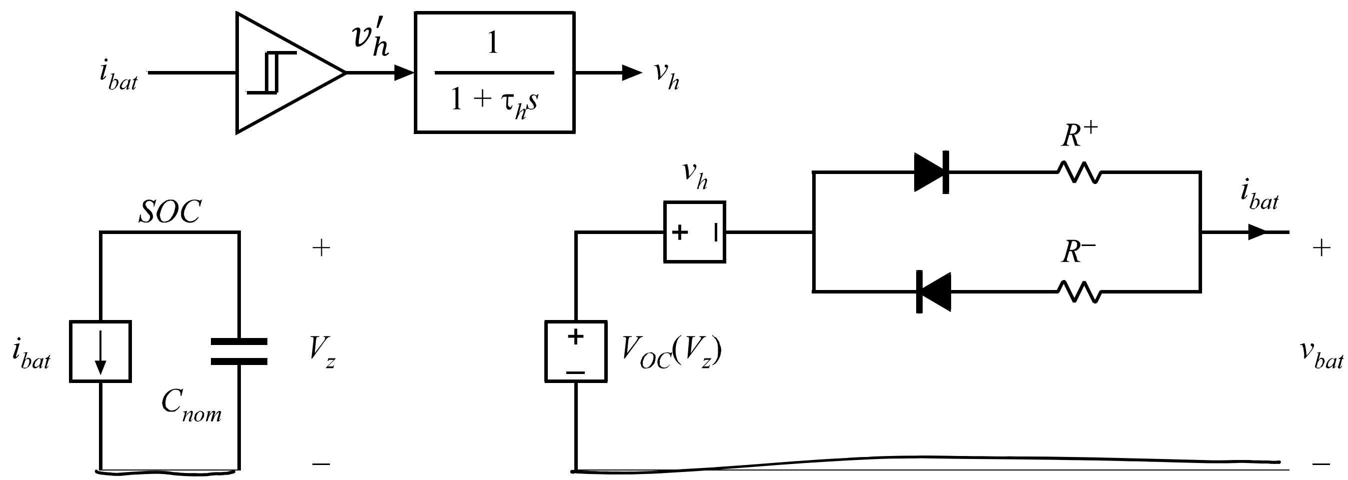
$$v_h = \underbrace{\frac{1}{1+\tau_h s}}_{\text{one-state.}} \cdot v_H'$$

$$v_h + \tau_h \frac{dv_h}{dt} = v_H'$$

model C1 : $\boxed{\dfrac{dv_h}{dt} = \dfrac{1}{\tau_h}\left(v_H' - v_h\right)}$ one-state

model C2 : $\dfrac{dv_h}{dt} = \underbrace{\gamma \left| \dfrac{i_{bat}}{C_{nom}} \right|}_{\text{dependence of } \tau_h \text{ on } i_{bat}.} \left(v_H' - v_h\right)$ non-linear.

Model C2: Incorporate Non-Linear Dynamics

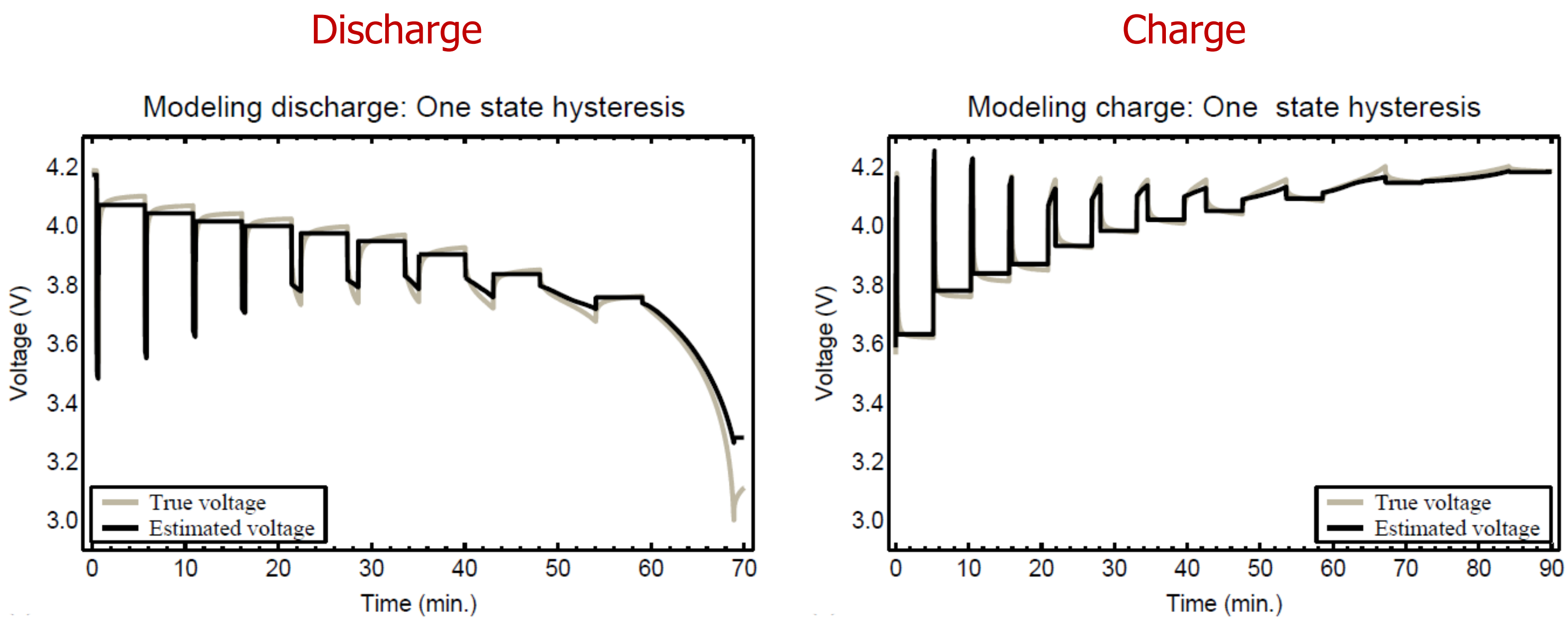


$$v_h = \frac{1}{1+\tau_h s} v_h'$$

$$\tau_h = \frac{1}{\gamma}\left|\frac{C_{nom}}{i_{bat}}\right|$$

one-state hysteresis model with non-linear dynamics

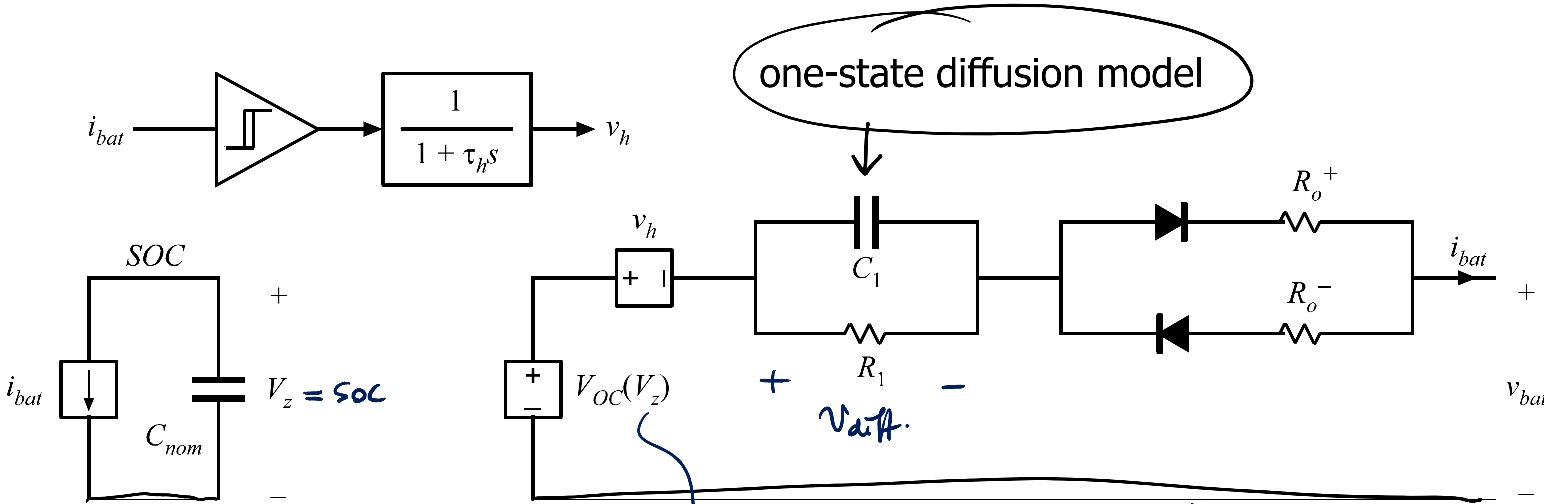
Model C2 Performance



RMS voltage error with respect to experimental data: 21.5 mV

[Plett 2004-2]

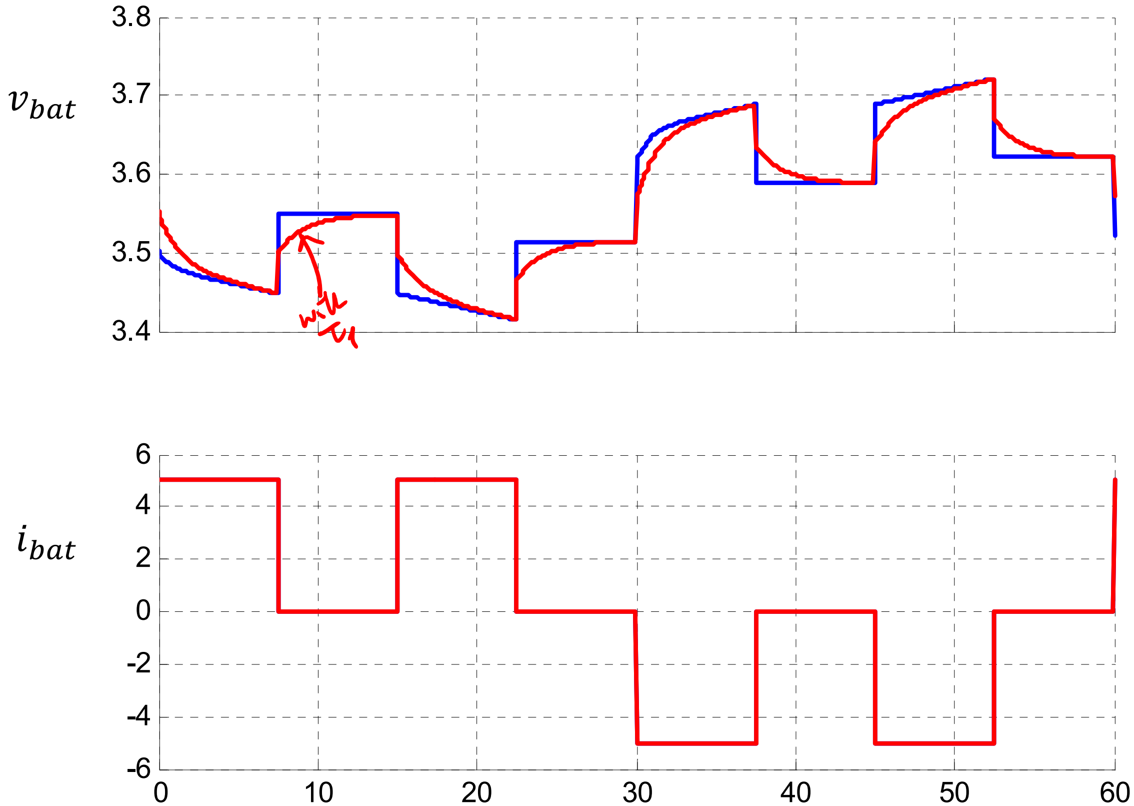
Model D: Incorporate Diffusion



$$v_{bat} = V_{oc}(soc) - v_h - v_{diff} - \begin{cases} R_o^+ \, i_{bat} \\ R_o^- \, i_{bat}. \end{cases}$$

$$R_o^- \approx R_o^+$$

Model D Pulse Current Response

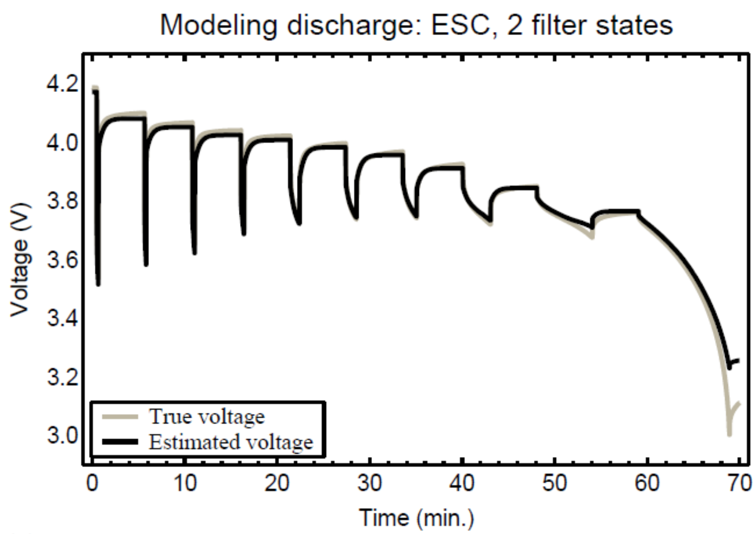


Example: $R_o^+ = R_o^- = 10$ mΩ, SOC(0) = 50%, $C_{nom} = 5$ Ah, $V_M = 20$ mV, $\tau_h = 50$ s,
$R_1 = 10$ mΩ, $\tau_1 = 100$ s $\tau_1 = R_1 C_1$

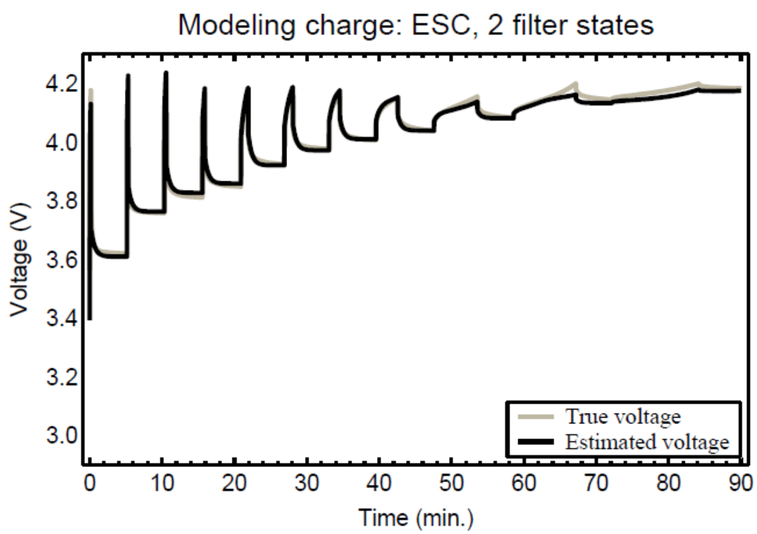
Model D (ESC) Performance

ESC – Enhanced Self Correcting

Discharge



Charge



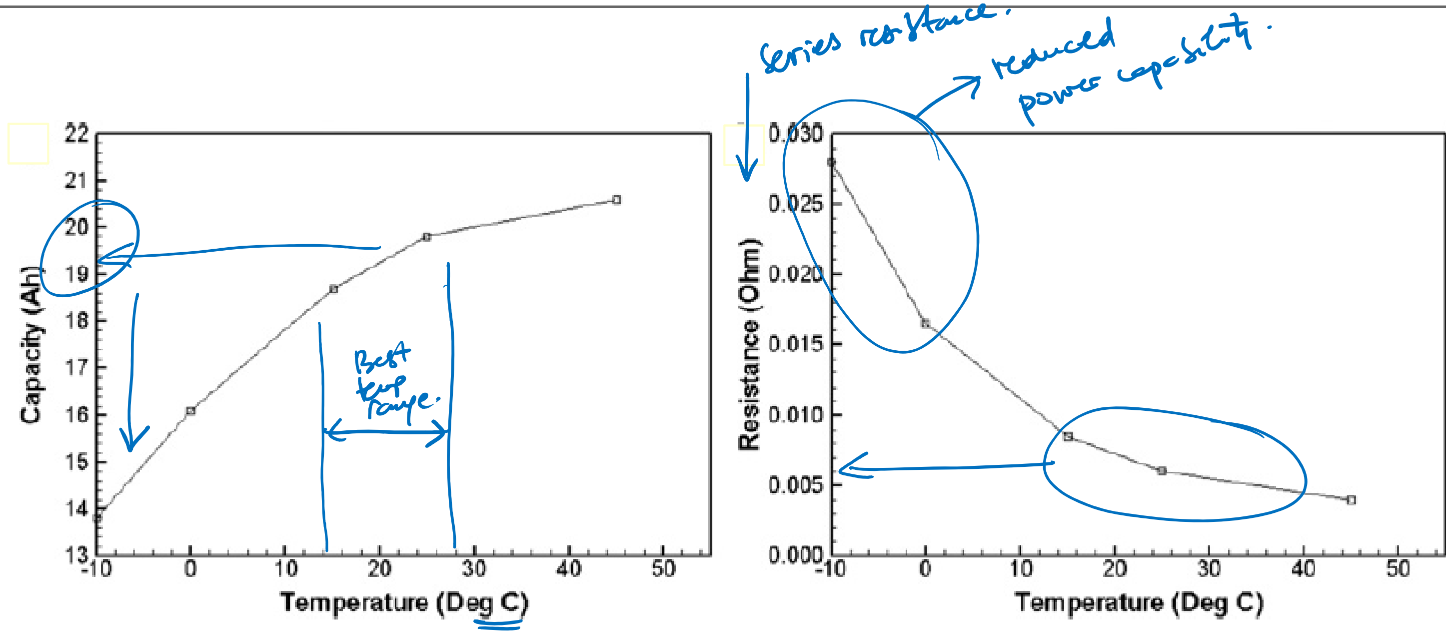
RMS voltage error with respect to experimental data

2nd order filter: 13.8 mV

4th order filter: 6.7 mV

[Plett 2004-2]

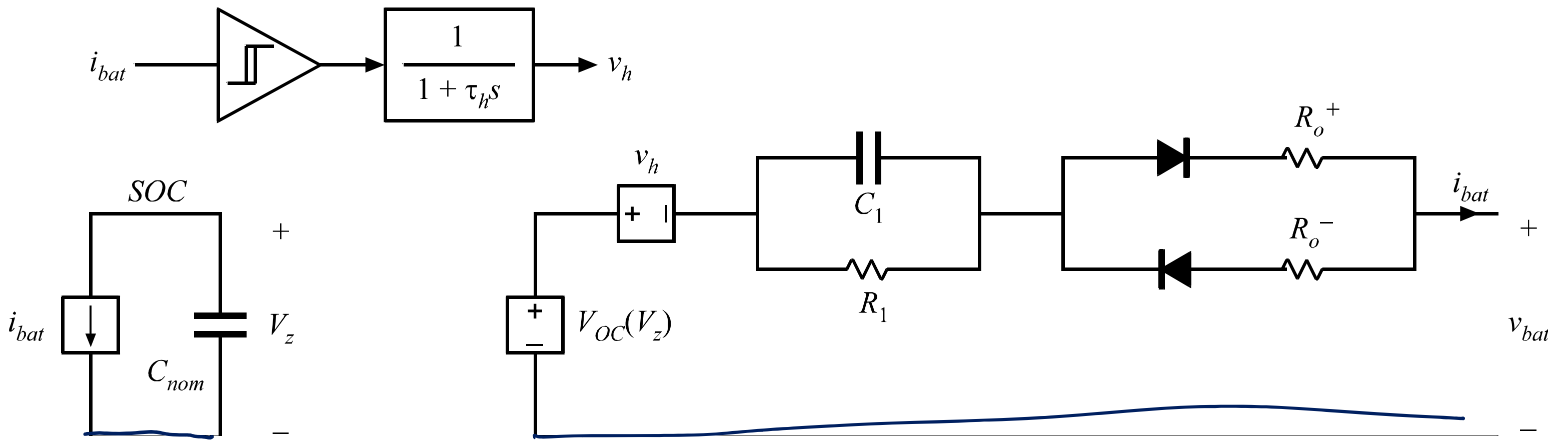
Impact of Temperature on Cell Characteristics



C_{nom} = 20 Ah cell tested at 0.5C charge/discharge rate

Reference: S. Chackoa, Y.M. Chunga, “Thermal Modeling of Li-ion Polymer Battery for Electric Vehicle Drive Cycles,” Journal of Power Sources, vol. 213, no. 1, pp. 296–303, September 2012.

Temperature effects: V_{OC}

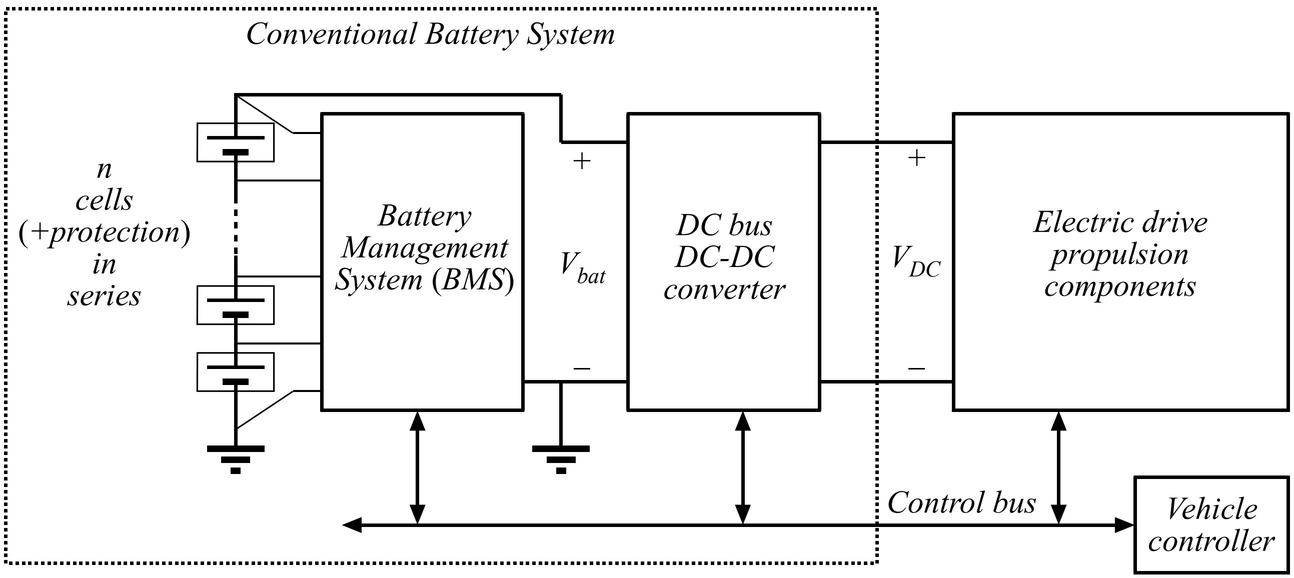


$$V_{OC}(V_z, T) = V_{OC}(V_z, 25^oC) + \underbrace{\Delta T\, A_{temp}(V_z)}$$

Impact of Temperature on Aging and Cycle Life

- Aging leads to:
  - Reduced capacity
  - Increased series resistance, reduced power rating
- End of life definition: drop to 80% of the original energy or power rating
- Aging mechanisms:
  - Crystal formation around the electrodes, reduces the effective surface area
  - Passivation: growth of a resistive layer that impedes the chemical reactions
  - Corrosion consumes some of the active chemicals
- All aging processes are accelerated with increased temperature

Battery Pack and Battery Management System



- Battery pack: Stack battery cells in parallel and series
- Battery Management System (BMS): Monitor battery state (voltage, SOC, SOH), perform cell balancing, communicate with vehicle controller

Packaging: Cylindrical Cells

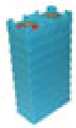
LiFePO4 Single Cells

14430, 14505, 17335, 18500,
18650, 26650, 32600, 32900,
38120, 40160, 42120

Nominal Voltage	Average 3.2 - 3.3 V
Nominal Capacity	1500mAh (at 0.2C rate, 3.8V cut-off) 1.5 Ah. Energy density: 120.96 wh/kg
Max.Charging current	1.50 A Max. 1C
Max.Discharging current	4.50 A max. 3C
Dimensions (DxH) (max with tab)	18.3 mm (Max 18.6) x 65.0 mm (Max 65.5)
Weight	1.40 oz (39.68 grams)
Operation Temperature	• Charging: 0°C (32F) - 45 °C (113F) • Discharging: - 20 °C(-4F) - 60 °C(140F)
Cycle Performance	• **>2000** (80% of initial capacity at 0.2C rate, IEC standard) ◦ 2 times more than NiMH and 10 time more than SLA

Packaging: Prismatic Cells

LiFePO4 Prismatic Batteries



20Ah, 40Ah, 60Ah, 100Ah, 200Ah

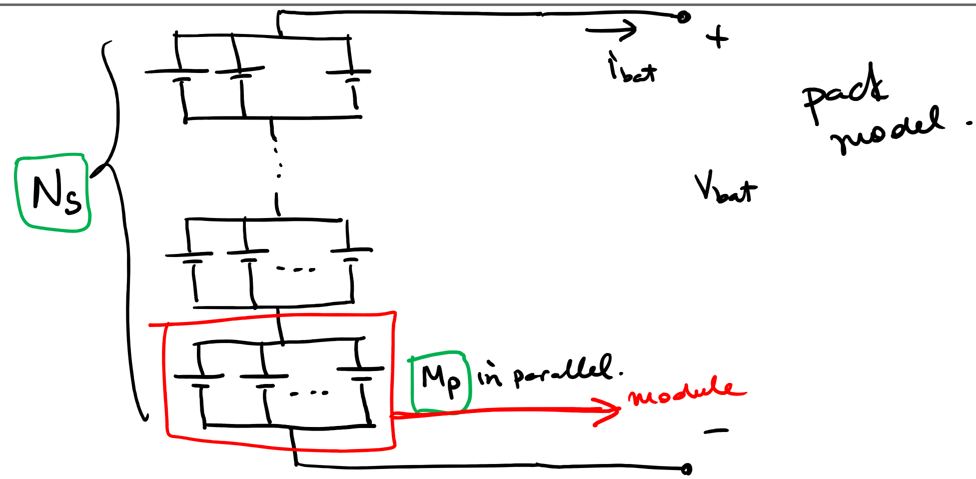
Chemistry	LiFePO4 in prismatic case
Nominal Voltage	Average 3.2 V (working) 3.65V-3.8V (peak) 2.5 V (cut-off low)
Capacity	40Ah (128 wh)
Energy Density	85.33Wh/kg
Charging current	• 1C rate (40A) Recommended • 3C rate (120A) Maximum charging rate
Discharging current	• Constant discharge current: 80A (2C rate) • Impulse discharge current (<10sec): 400A (10C rate)
Dimensions (LxWxH)	126mm(5.0") x 46mm(1.8") x 180mm(7.1")
Weight	1.5 kg (3.3 lbs)
Operation Temperature	• Charging: > 0'C (32F) • Discharging: -20'C (-4F) - 65'C(149F) • Self-discharging <3% monthly • Temperature Durability of case =< 135'C(275F)
Cycle Performance	• 2000 (80DOD%@0.2C rate, IEC Standard)

Battery Packs

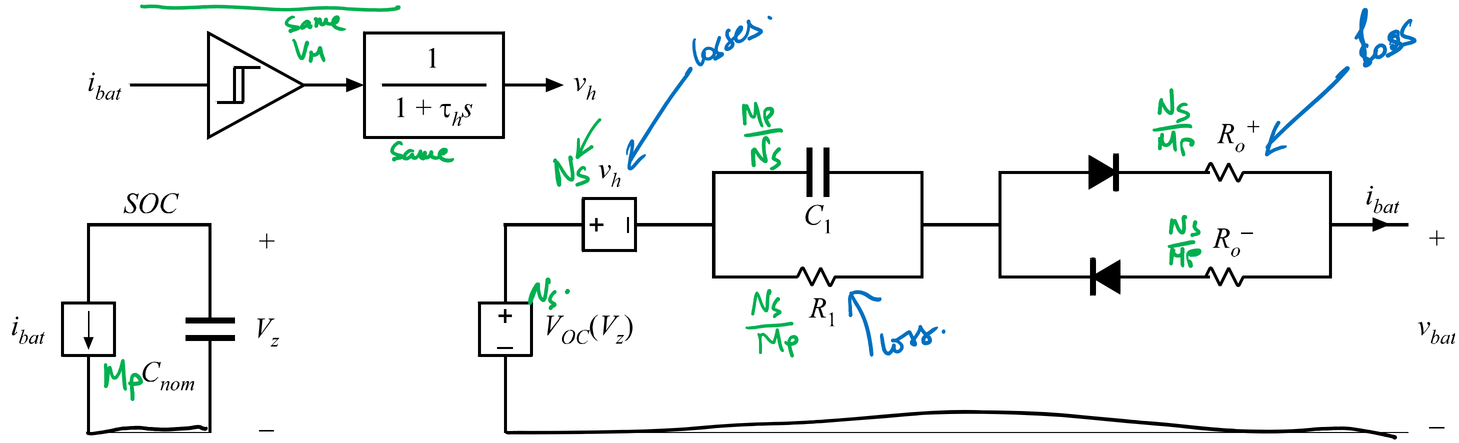
Nissan Leaf (EV)
24 kWh
192 cells
EV range: 73 miles (100 km)

Ford C-Max Energi (PHEV)
7.6 kWh
84 cells
EV range: 19 miles (30 km)

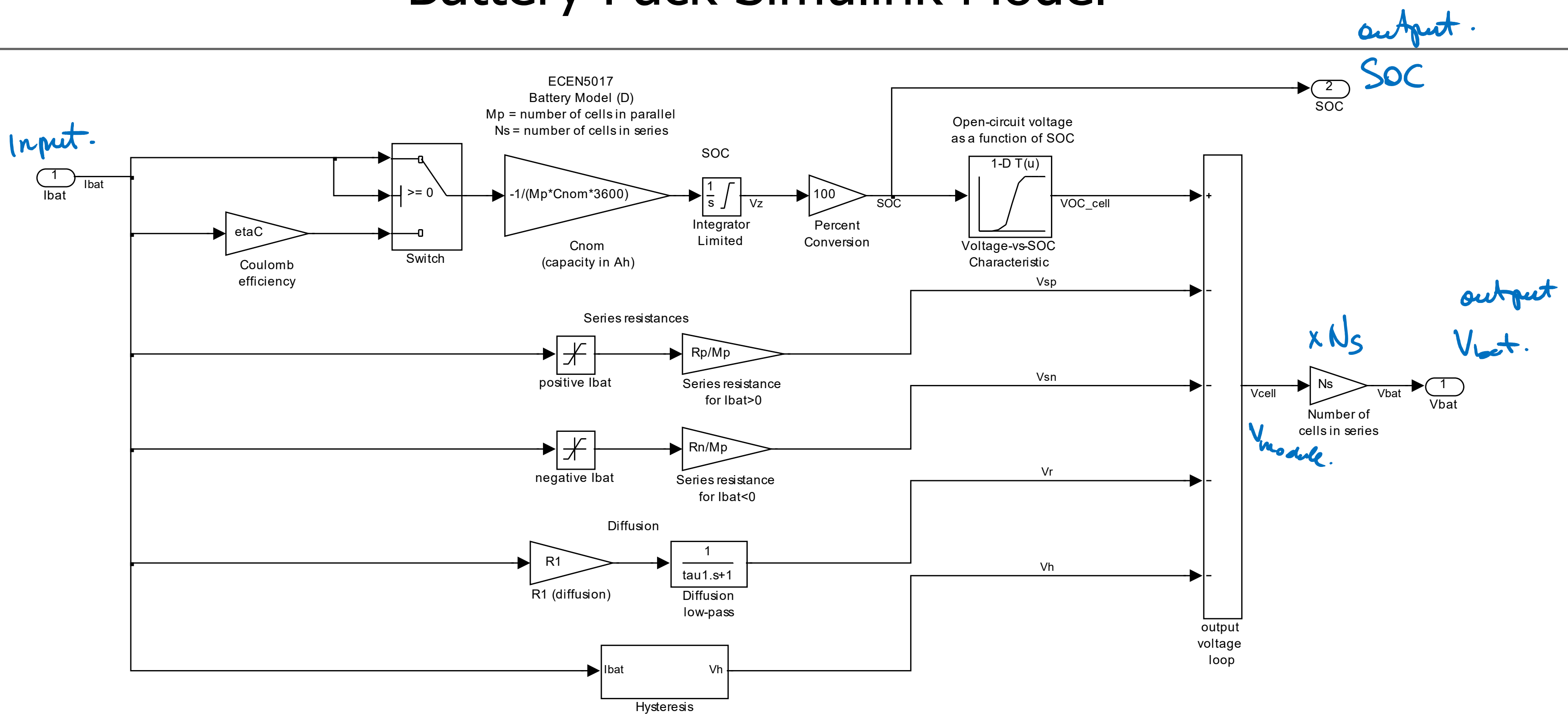
Battery Pack Electrical Circuit Model (assuming identical cells)



Assume: identical cells



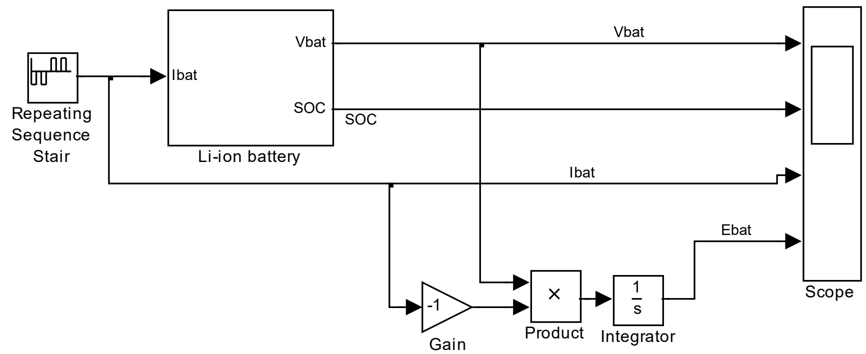
Battery Pack Simulink Model

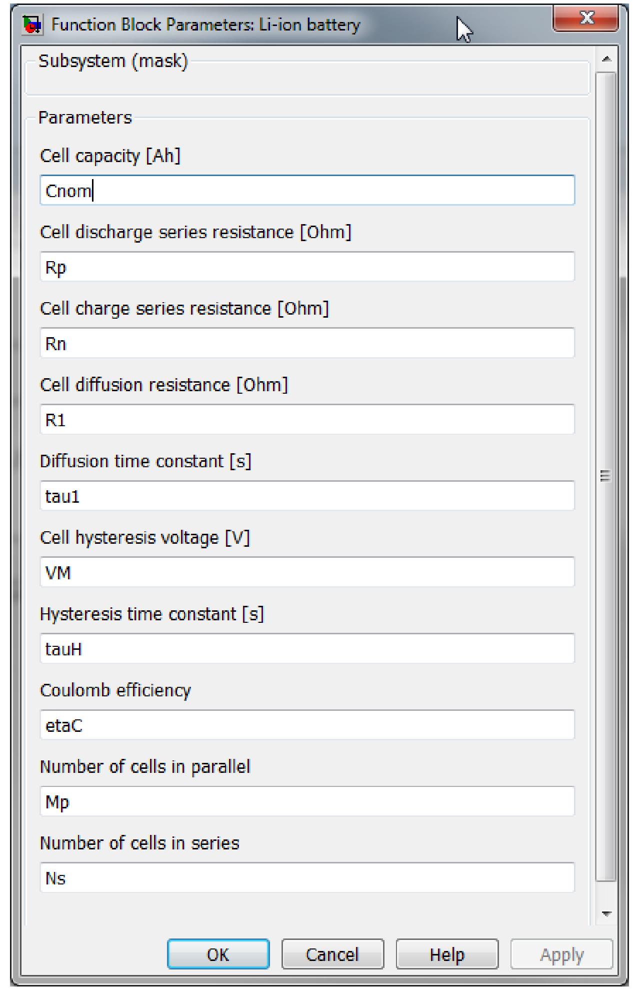


$$v_{\cancel{cell}\,\text{Module}} = V_{OCcell} - \frac{R_0}{M_p} i_{bat} - \frac{R_1}{M_p}\frac{1}{1+\tau_1 s} i_{bat} - v_h \qquad \text{where } R_0 = \begin{cases} R_0^+, & i_{bat} > 0 \\ R_0^-, & i_{bat} < 0 \end{cases}$$

$$v_{bat} = \boxed{N_s} v_{\cancel{cell}\,\text{module}}.$$

Battery Pack Simulink Model (Cont.)

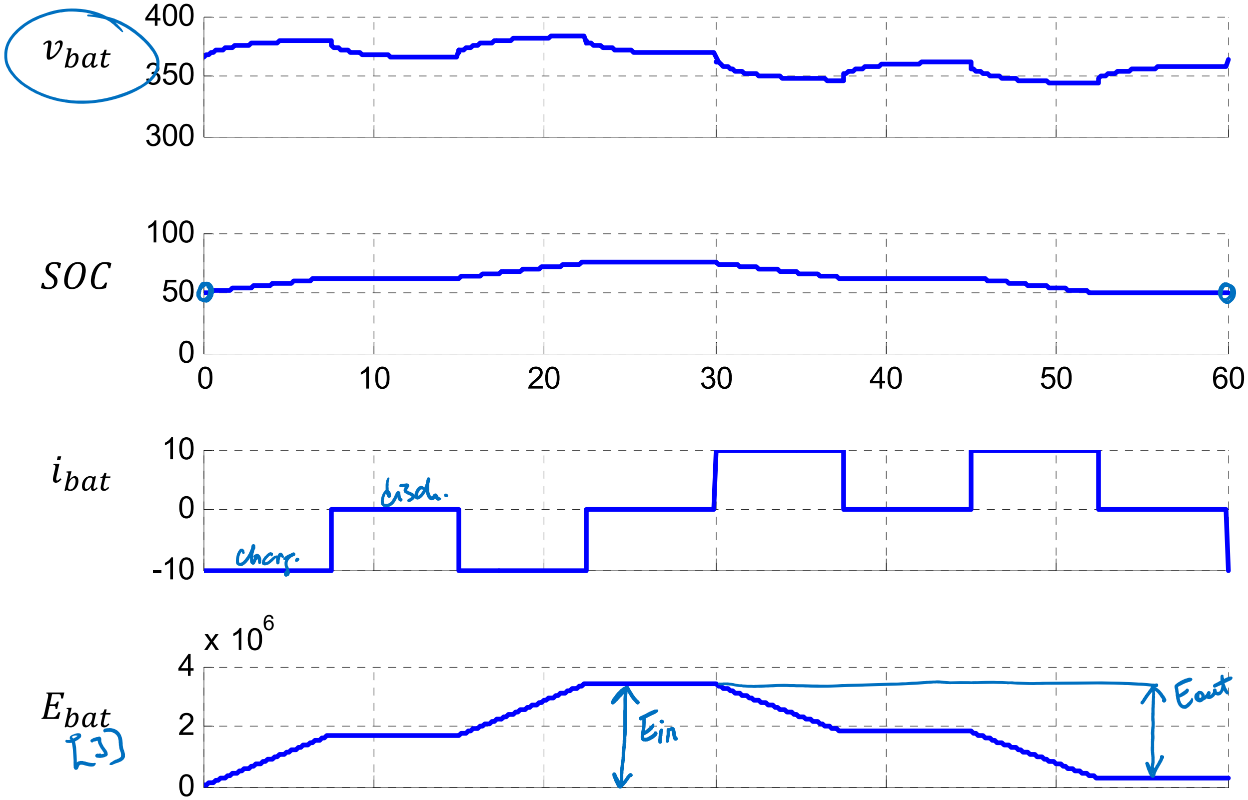




Example: $M_p = 2$, $N_s = 100$

$R_o^+ = R_o^- = 10$ mΩ, SOC(0) = 50%, $C_{nom} = 5$ Ah, $V_M = 20$ mV, $\tau_h = 50$ s, $R_1 = 10$ mΩ, $\tau_1 = 100$ s

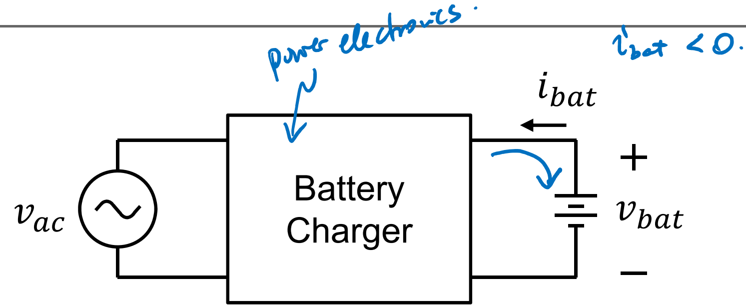
Example Battery Waveforms



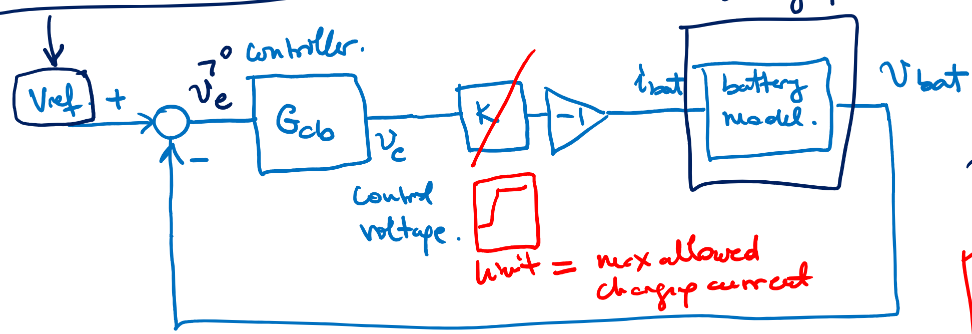
internal losses in the pack.

$$\boxed{\eta_{bat} = \frac{E_{out}}{E_{in}}}$$

Battery Charging Control



$\boxed{V_{oc} \text{ at SOC} = \text{target value.}}$ because $i_{bat} \to 0$ at the end of charging.



$v_{bat}(0) < V_{ref}$.

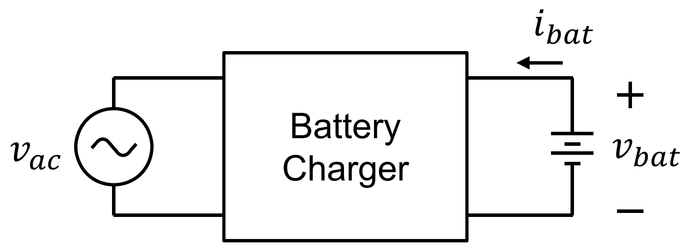
SOC(0) < target value.

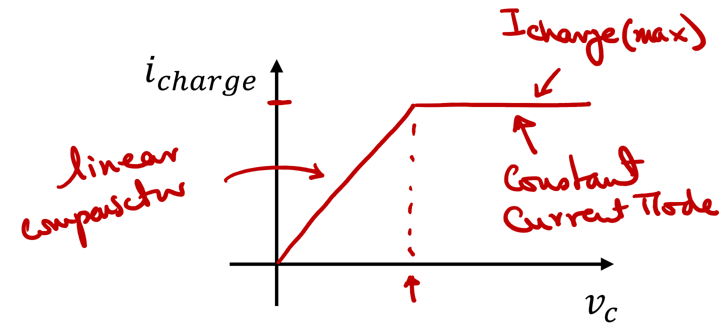
During charging i_{bat} must not exceed a max. rate.

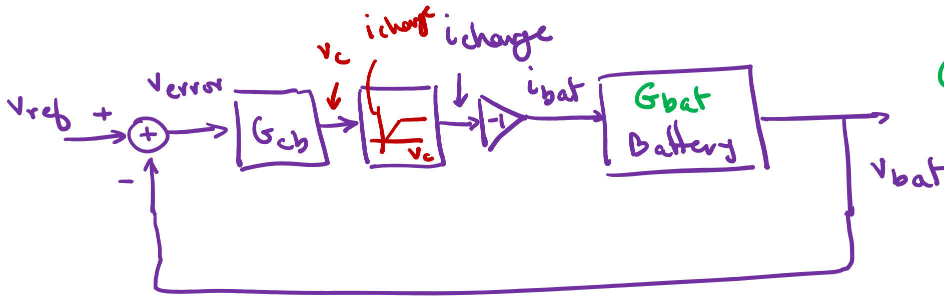
cells have max charge rate

power rating of the charger power electronics.

Constant-Current Constant-Voltage (CCCV) Charging







$$G_{bat}(s) = \frac{\hat{v}_{bat}(s)}{\hat{i}_{bat}(s)}$$

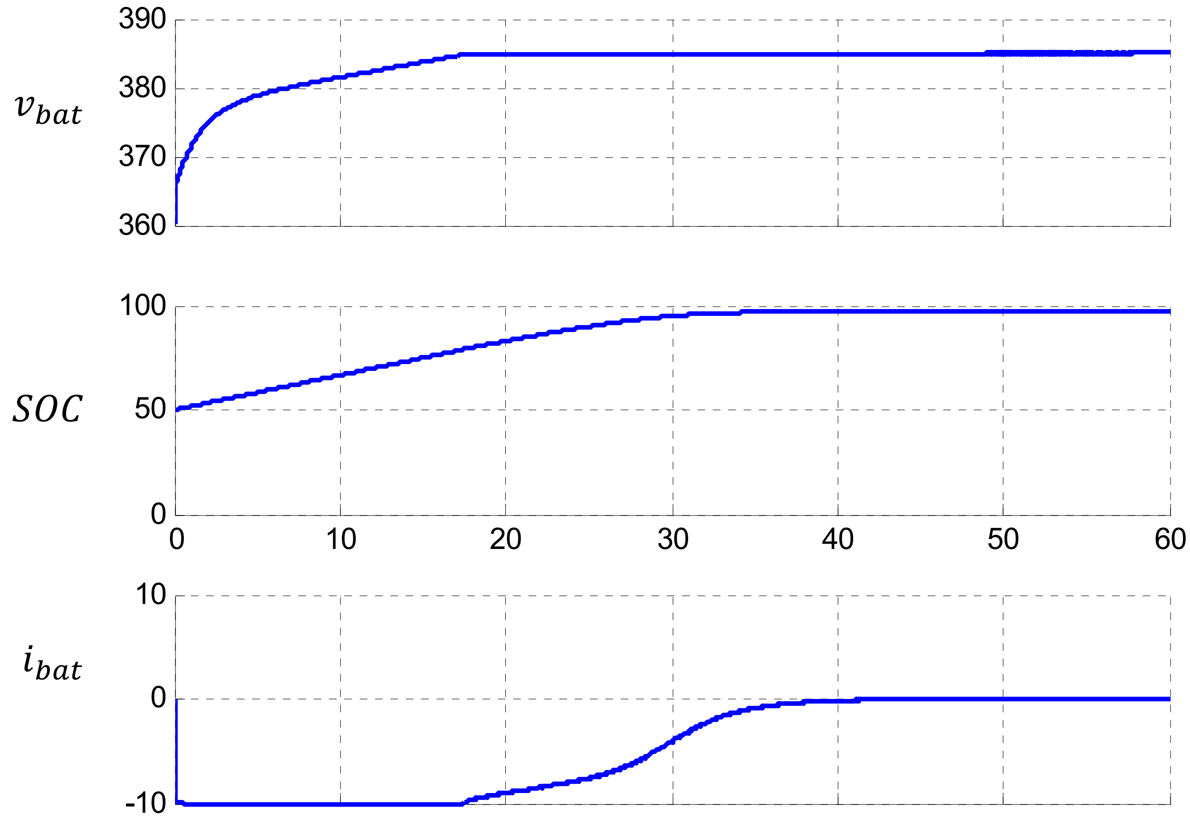
If SOC is low & compensator gain is high then at

Start: Constant-Current Charge Mode

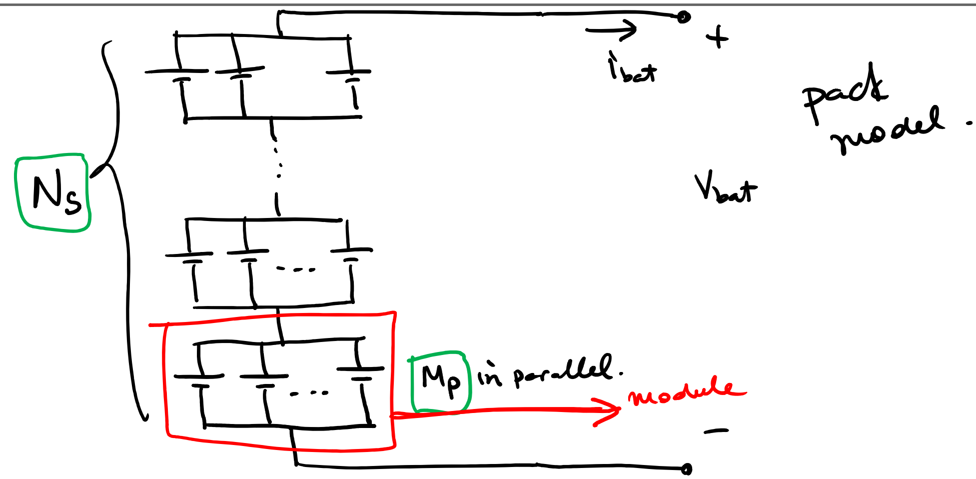
End: Constant-Voltage

This charging strategy is called CCCV

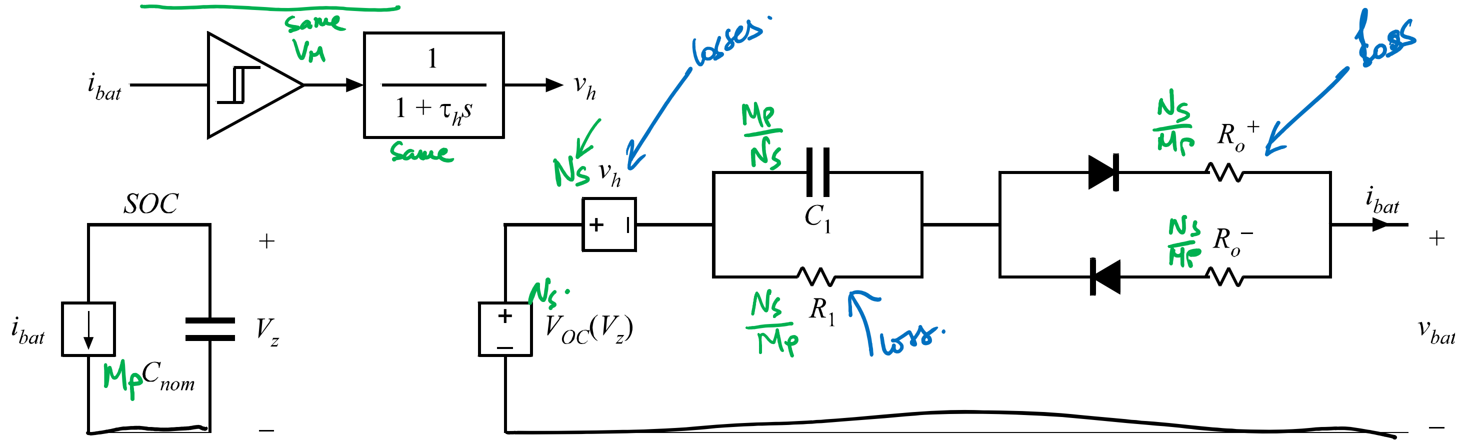
CCCV Charging Example



Battery Pack Electrical Circuit Model (assuming identical cells)



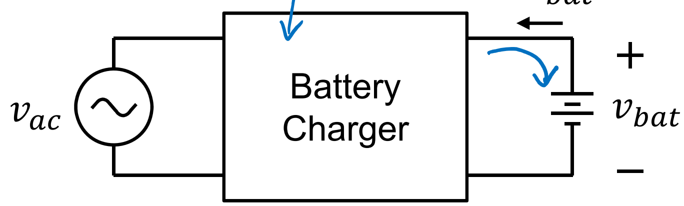
Assume: identical cells



Battery Charging Control

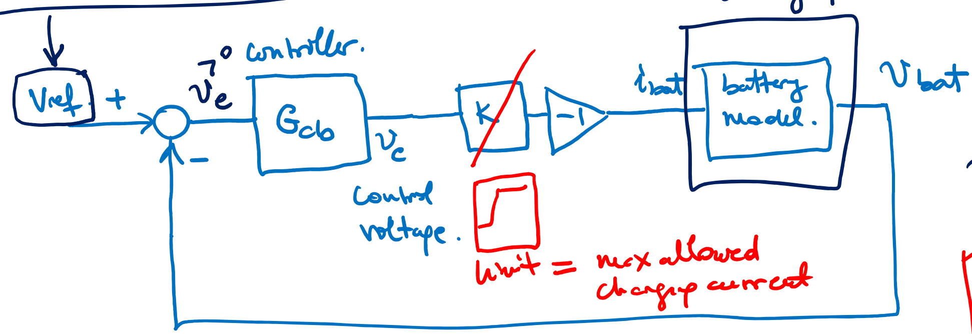
power electronics.

$i_{bat} < 0$.



$\boxed{V_{oc} \text{ at } soc = \text{target value.}}$ because $i_{bat} \to 0$ at the end of charging.

battery pack



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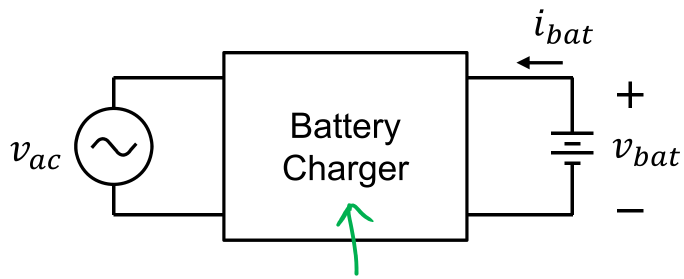
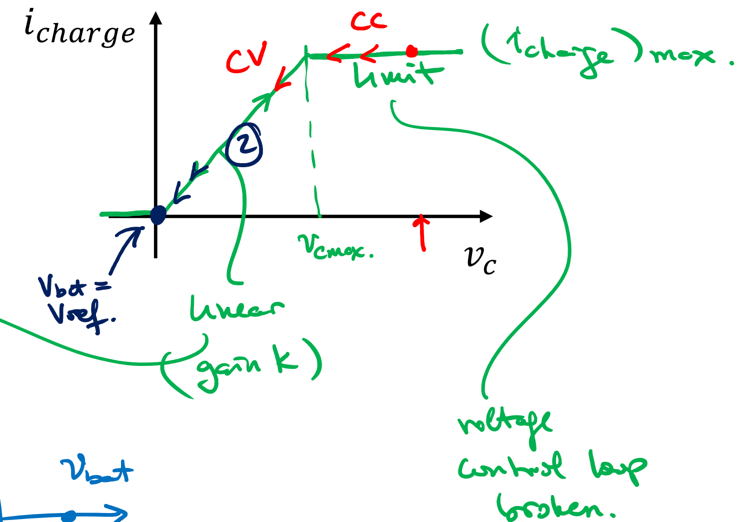
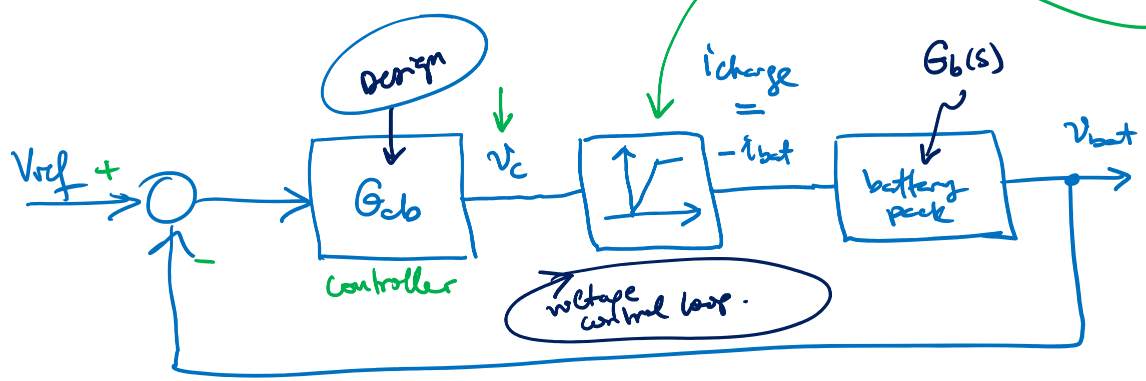


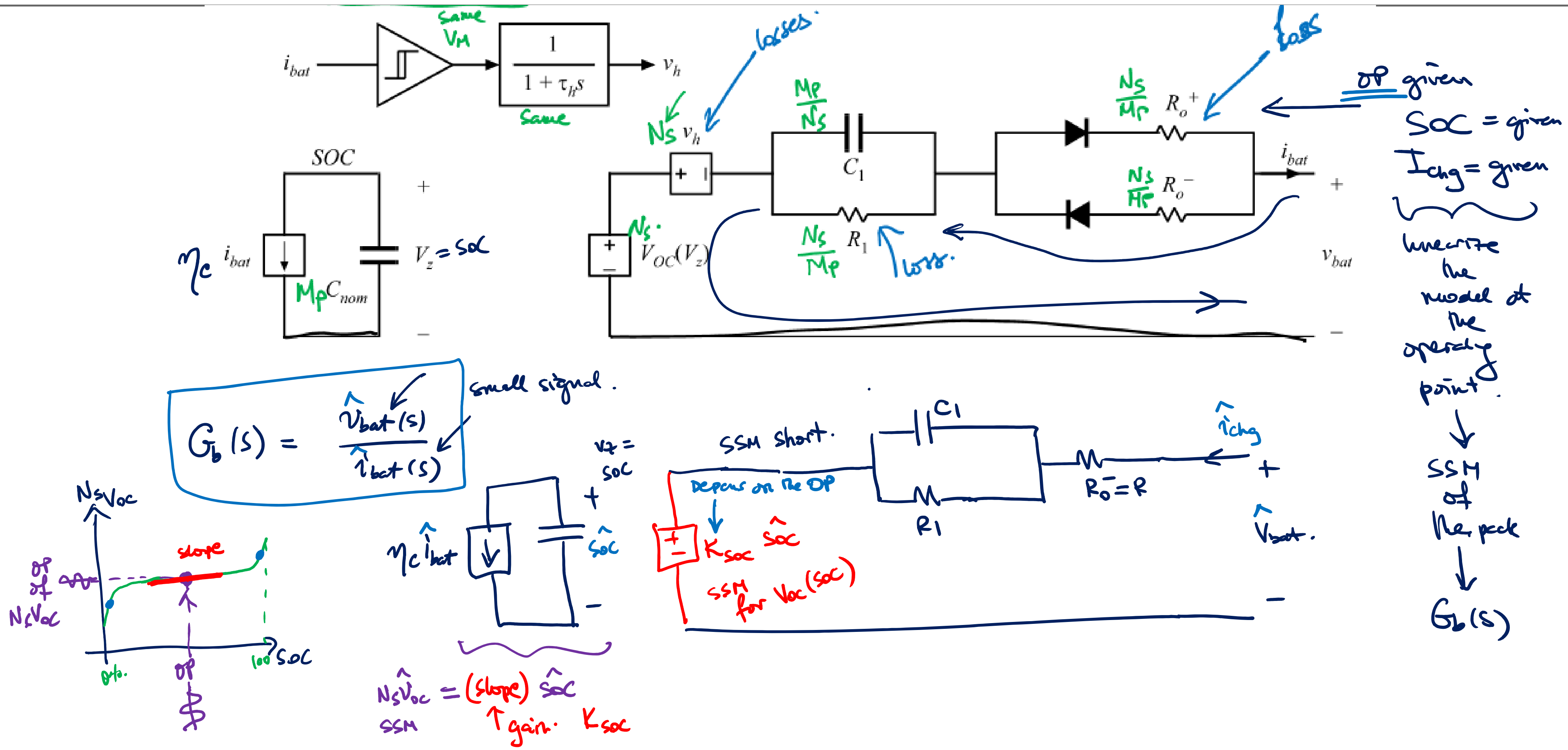




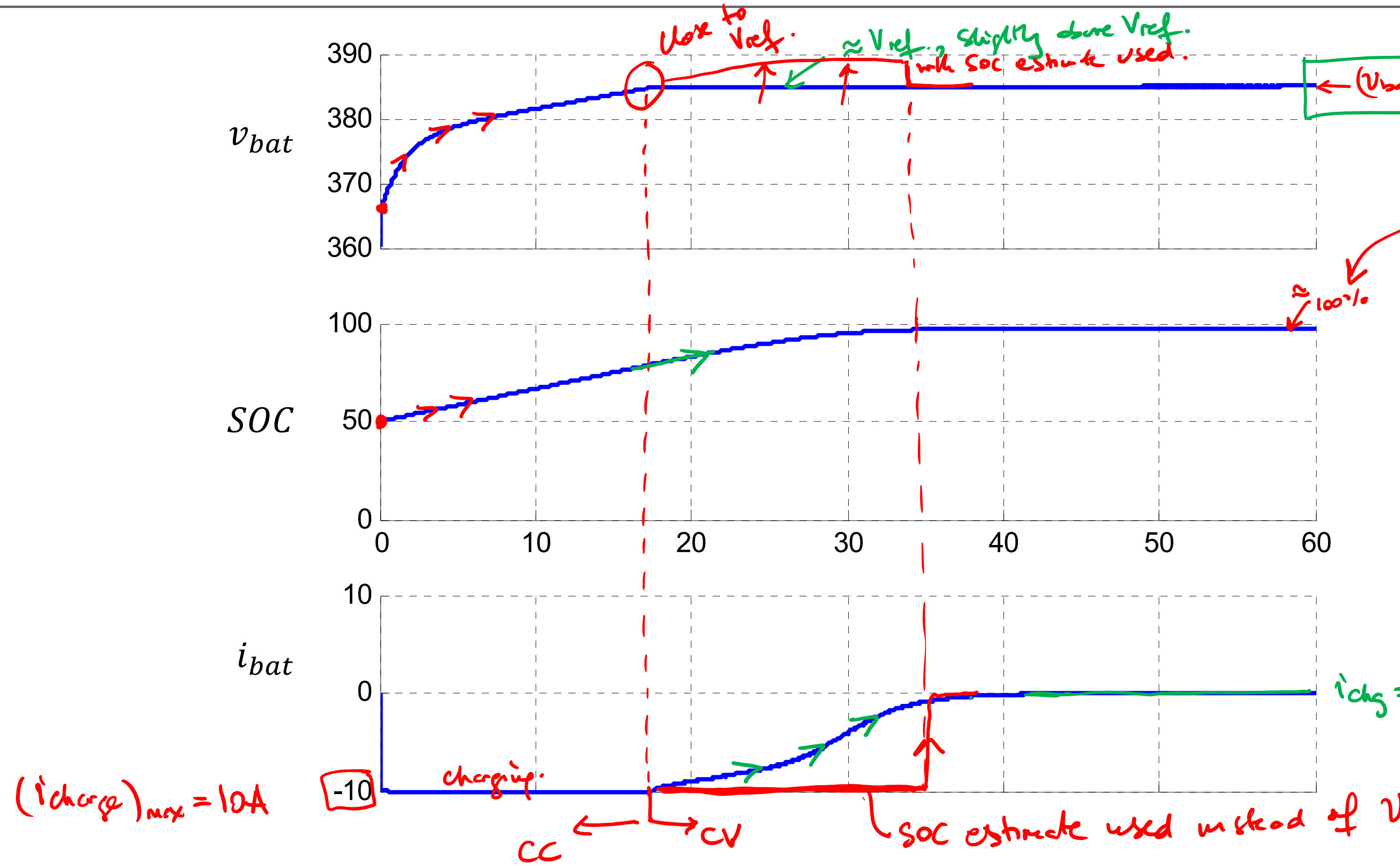
well below.
① $V_{bat} < V_{ref}$
$i_{charge} = (i_{charge})_{max}$. } CC

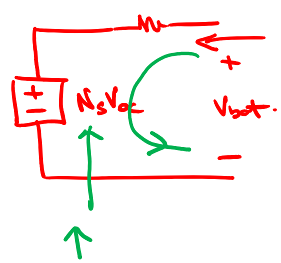
close to
② $v_{bat} < V_{ref}$.
$i_{charge} < (i_{charge})_{max}$.
voltage loop active. } CV.

Small-signal battery pack model

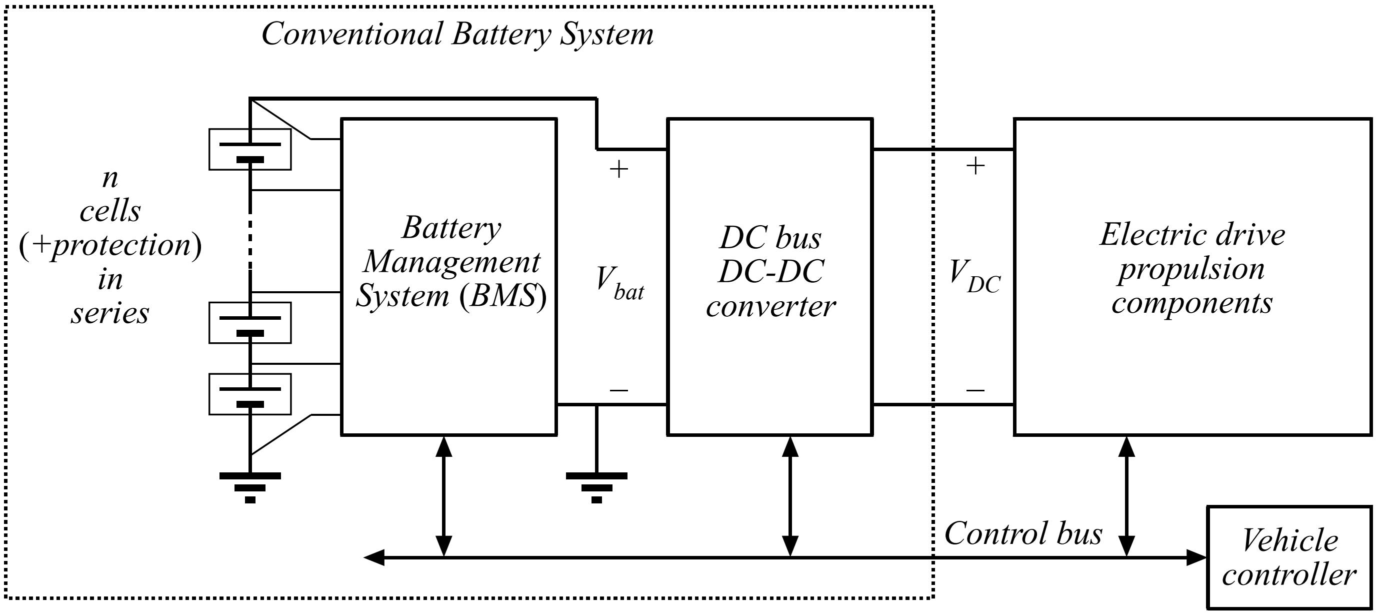


CCCV Charging Example





Battery Management System (BMS)



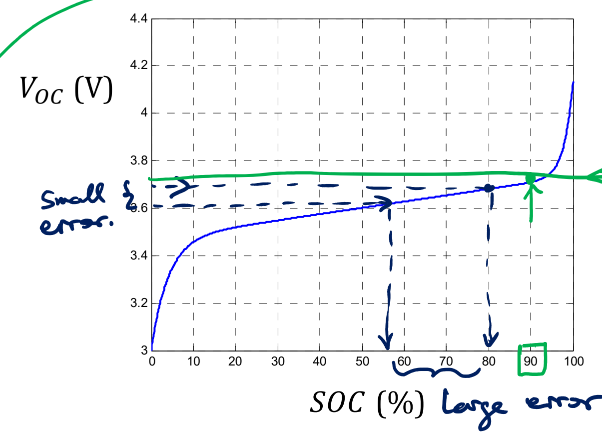
- Functionality of BMS:
  - Estimates and reports to vehicle controller: SOC and power capability
  - Performs charge balancing
  - Diagnostics, state of health (SOH)

SOC Estimation Techniques

- Voltage measurement: very crude, not used on EV packs.

1. small voltage error => large SOC error.
2. $V_{bat} = V_{oc} - V_n - (R \| \frac{1}{sC}) i_{bat} \ldots$

Large errors if $i_{bat} \neq 0$.



For this purpose Voc is used as soc estimate.

Voc at target full soc (e.g. 90%).

- Coulomb counting requires.

$$SOC(t) = SOC(0) - \frac{1}{C_{nom}} \int_0^t i_{bat}(\tau)\, d\tau$$

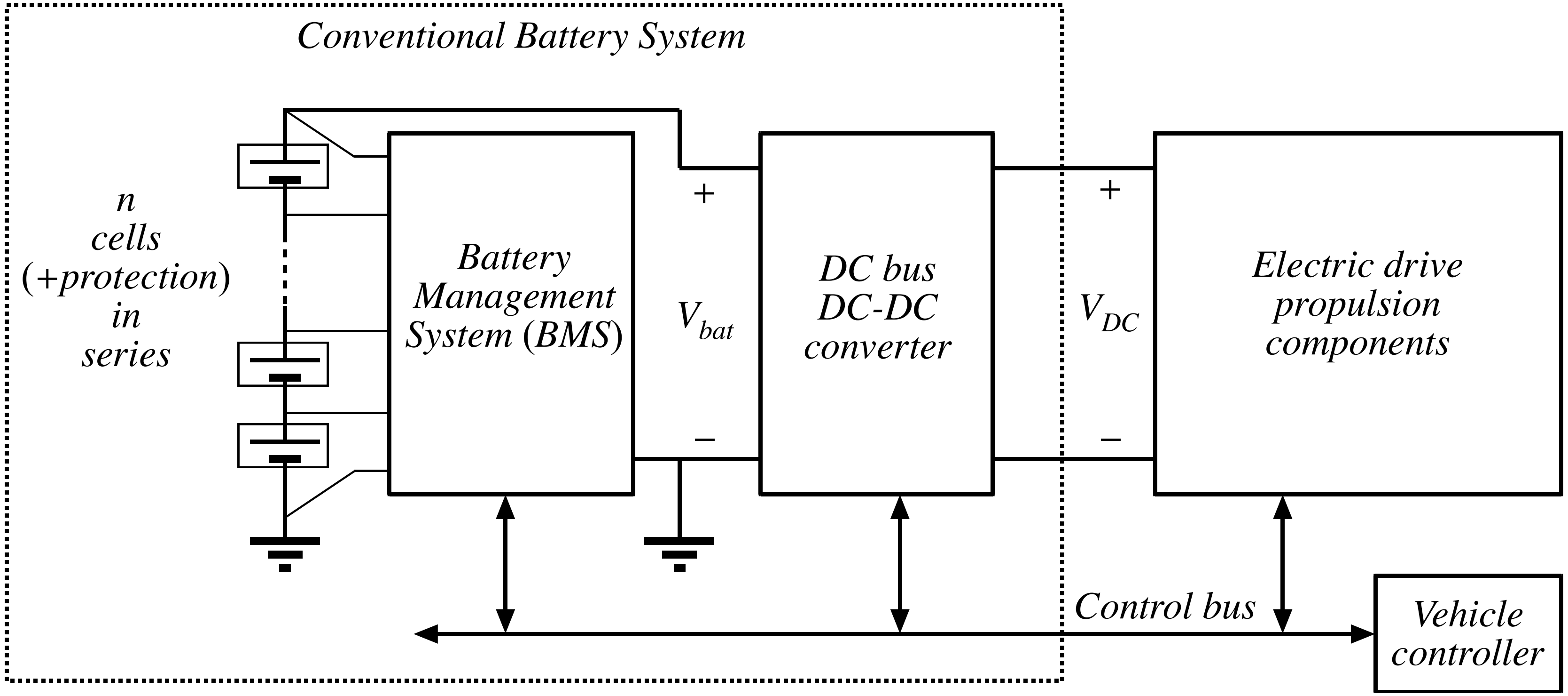
works ok for short period of time.

errors in current sensing accumulate.
small dc error ⟶ increasing soc(t) error.

combine.

- More advanced estimators, e.g. Kalman filter

Battery Management System (BMS)



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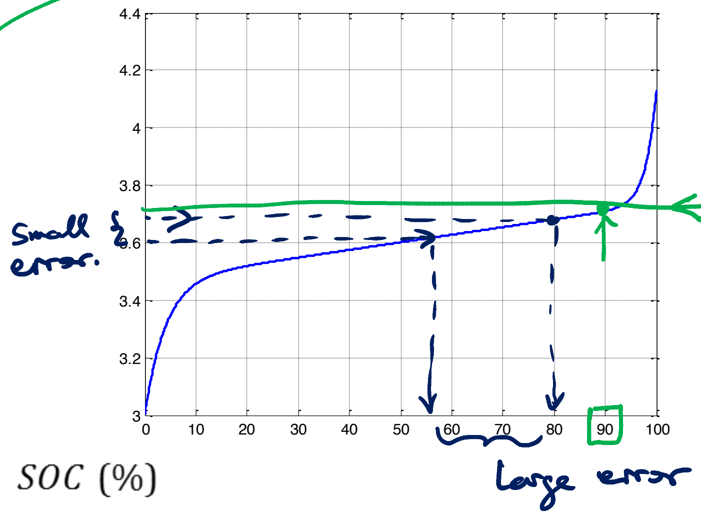


Voc at target full SOC (e.g. 90%).

Estimation of Power Capability

Typically based on safety driven v_{bat} limits: $v_{bat(max)}$ and $v_{bat(min)}$

$$v_{bat} = N_s V_{OCcell} - \frac{N_s R_0}{M_p} i_{bat} - \frac{N_s R_1}{M_p} \frac{1}{1+\tau_1 s} i_{bat} - N_s v_h$$

$\geq v_{bat(min)}$

$\leq v_{bat(max)}$

fixed

$\underbrace{i_{bat,min} \quad i_{bat,max}.}$

$$P_{bat} = v_{bat} i_{bat}$$

Requires $V_{oc}, R_0, R_1, \ldots$

$P_{bat,max}$. > 0

< 0.

Need for $\boxed{\text{Cell Balancing}}$

- Mismatches in cell characteristics
  - Capacity
  - Leakage (self-discharge) current
  - Other parameters: series resistance, …

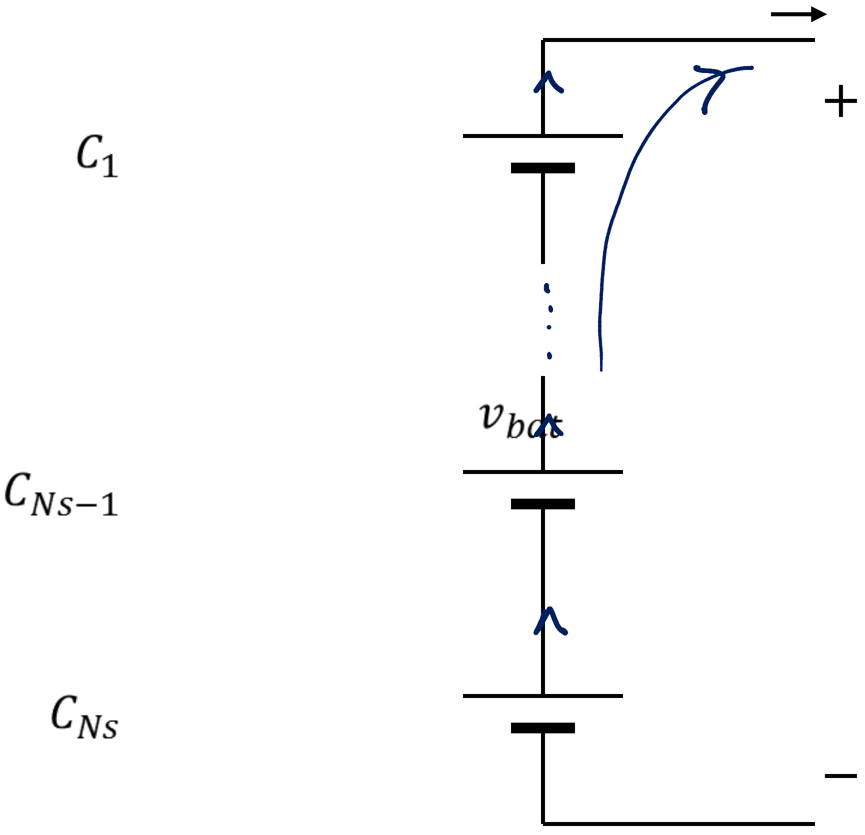
- Mismatches in cell SOC's during operation

Reference: Davide Andrea, Battery Management Systems for Large Lithium-Ion Battery Packs, Artech House 2011

Animations at: http://liionbms.com/balance/index.html

Cell Versus System Capacity

$C_1 \neq C_2 \cdot i_{bat}$



$C_i = C_{nom} \pm \Delta C$

Discharge, assuming equal starting $\boxed{SOC=100\%}$

$SoC_i = \dfrac{Q_i}{C_i}$ $\qquad SoC_i = \dfrac{Q}{C_i}$, $\quad Q_1 = Q_2 = \ldots$

because we assume i_{bat} = same for all.

Charge that can be taken out of a cell:

$$Q = C_i(1 - SOC_{min,i})$$

100%.

$\underset{total}{Q_i} = \underset{\text{not the same.}}{C_i}$

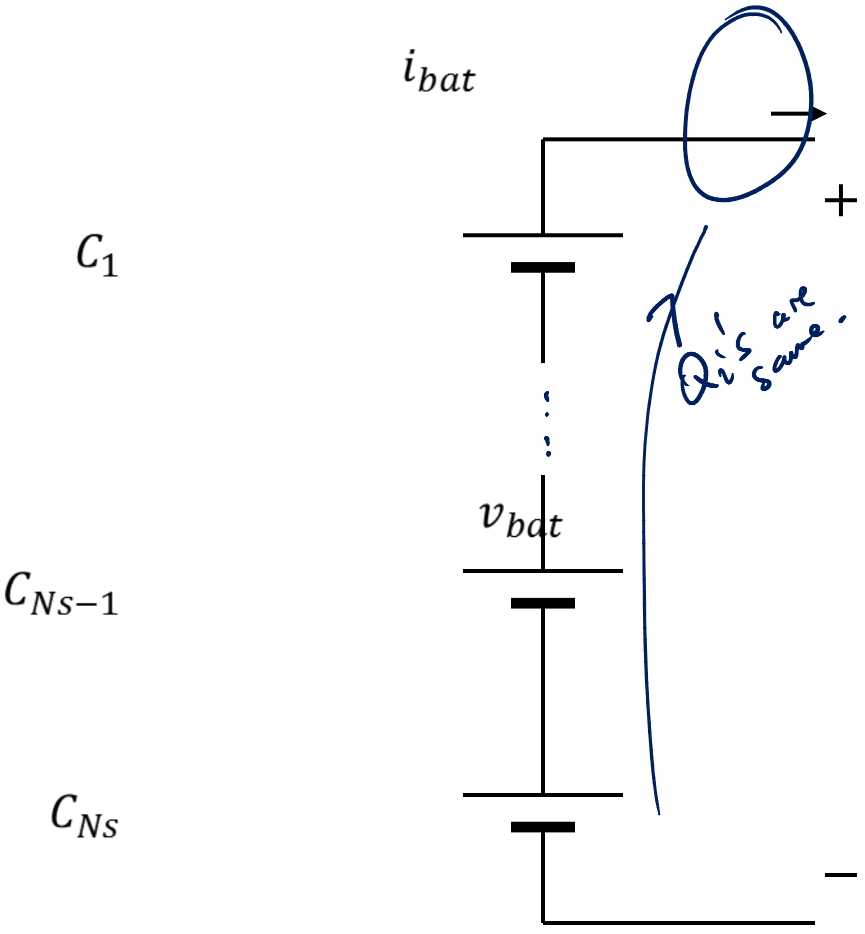
Charge that can be taken out of the pack:

$$Q_{pack} = C_{min}(1 - 0)$$

$$C_{min} = \min(C_i)$$

$$C_{system} = C_{min} = C_{nom} - \Delta C.$$

System Capacity With Unbalanced SOC's



Discharge, assuming unequal starting SOC's

$SOC_i \neq SOC_j$

Charge that can be taken out of a cell:

$$Q = C_i(SOC_{0,i} - SOC_{min,i})$$

initial final

Charge that can be taken out of the pack:

E_{bat}

SO where

Balancing

$\Downarrow$

$C_{system} = C_{min}$.

$\cancel{< C_{min}}$

v_{bat}

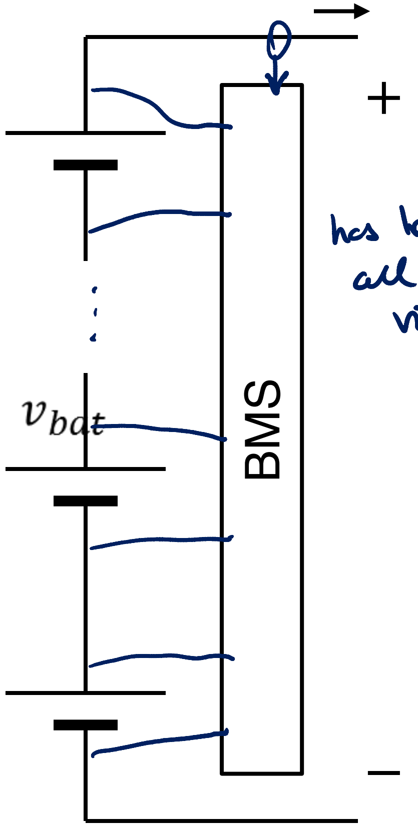
Mismatched-Cell Pack Charging and Discharging

i_{bat}

V_1

v_{bat}

V_{Ns-1}



has to sense all cell voltages.

Example: $M_p = 2$, $N_s = 100$

$R_0^+ = R_0^- = 10$ mΩ, SOC(0) = 50%, $C_{nom} = 5$ Ah, V_H = 20 mV, $\tau_H = 50$ s, $R_1 = 10$ mΩ, $\tau_1 = 100$ s

$$V_{bat} = \sum_i V_{cell,i}$$

$$V_{cell,i} \neq V_{cell,j}$$

Charge up to: $V_{bat} = V_{bat(max)}$

$V_i > V_{imax}$.

$\boxed{V_i = V_{imax}.}$

Discharge down to: $V_{bat} = V_{bat(min)}$

$V_i < V_{imin}$.

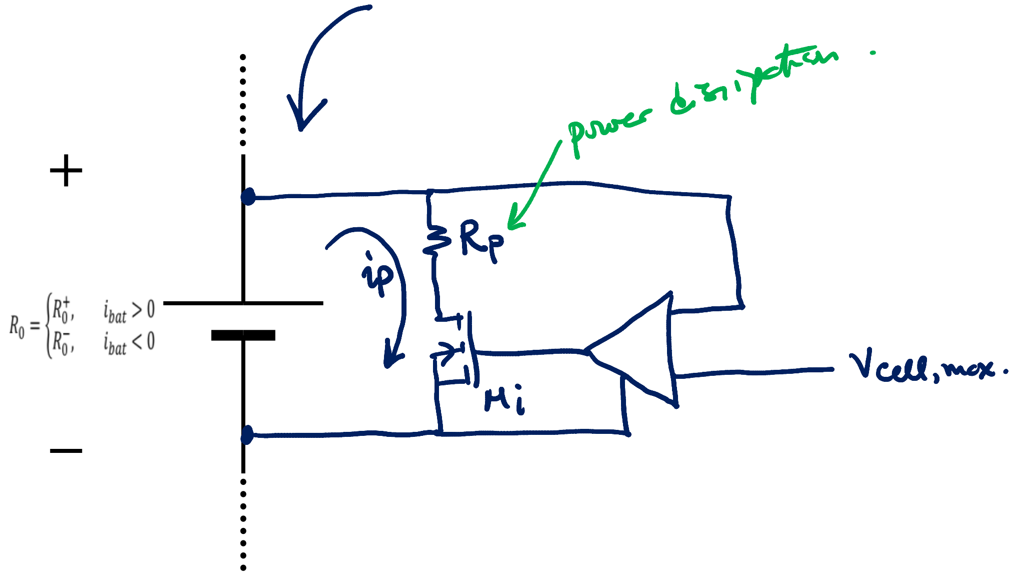
→ Individual cell voltages may exceed safe limits

System must sense individual cell voltages or (better) employ individual cell SOC estimators

Passive "Top" Balancing

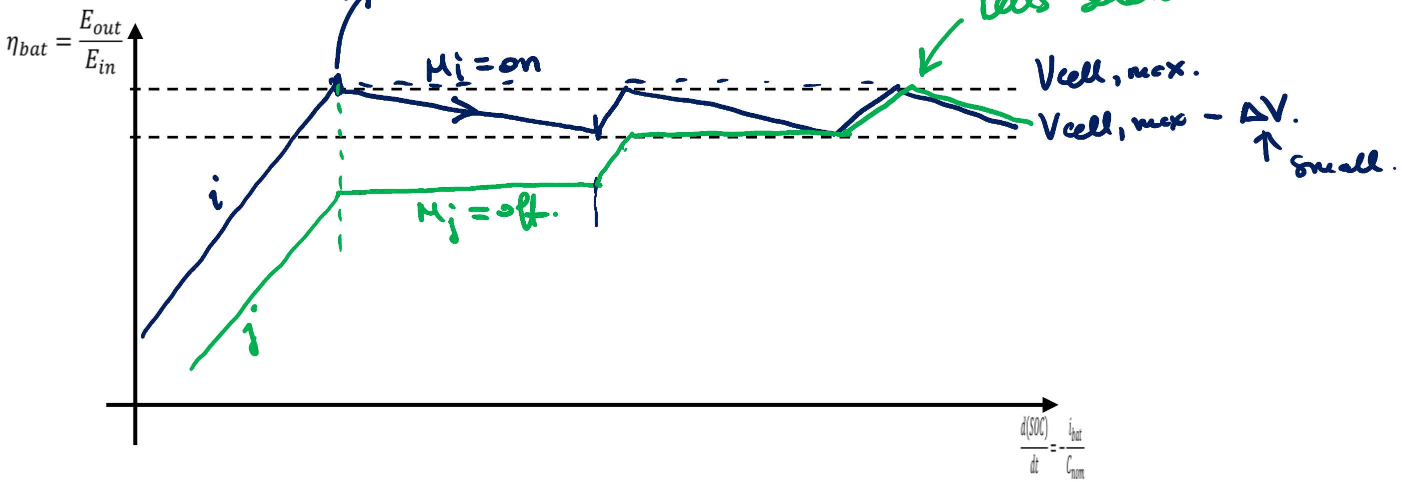
larger i_p => faster balancing.

$\sim$ 1–10 mA.



stop charging, turn on M_i, so that i_p is discharging $V_{cell,i}$

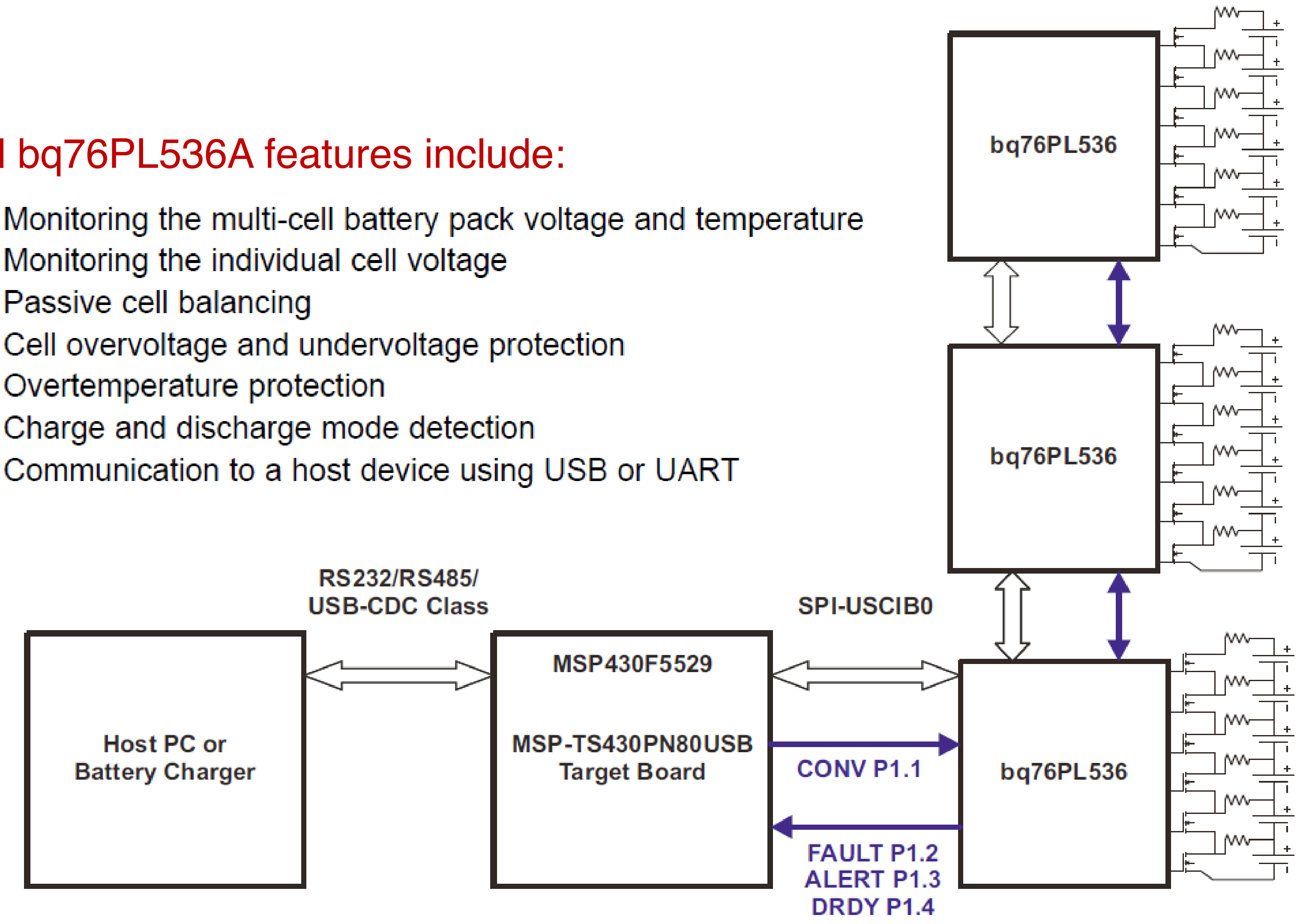
cells balanced at "top".



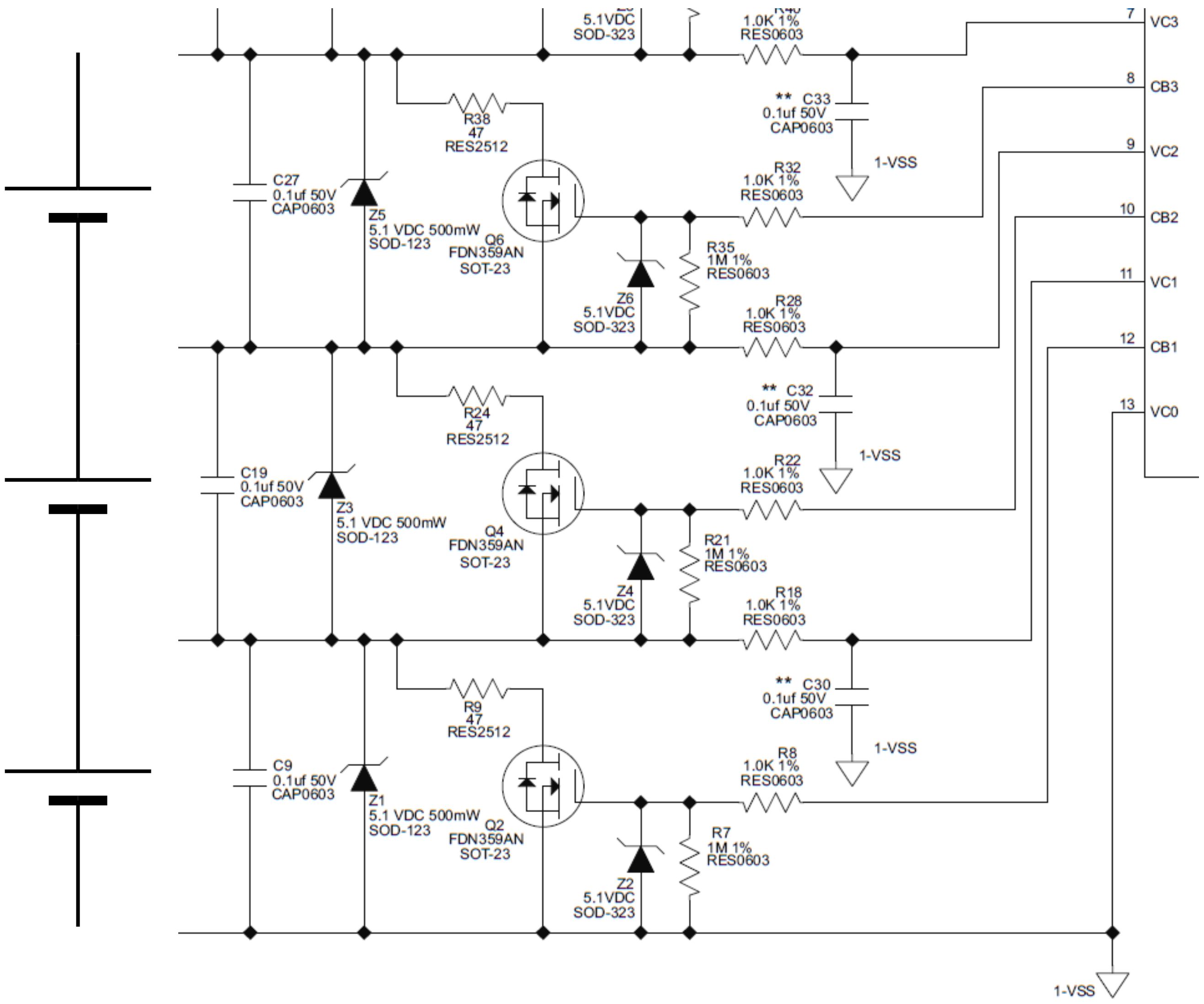
Passive Cell Balancing IC Example

TI bq76PL536A features include:

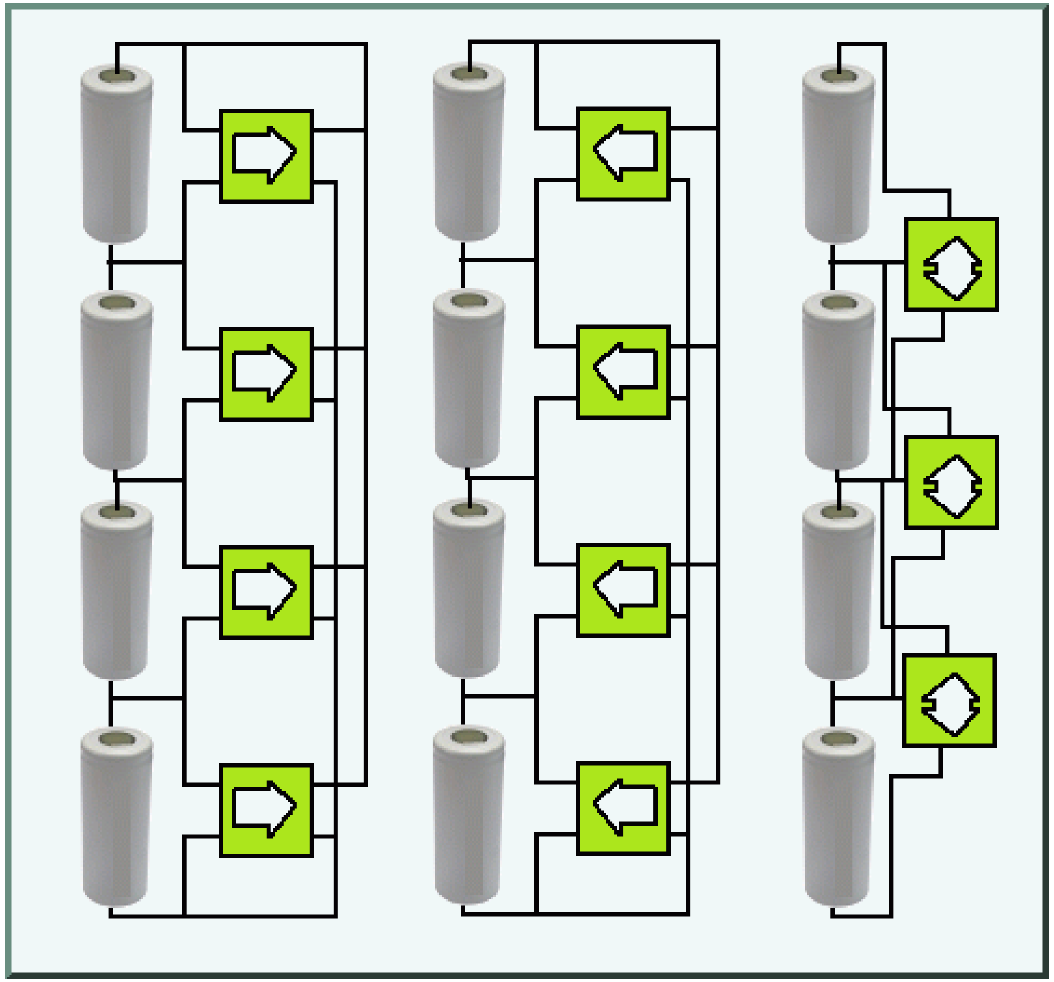
- Monitoring the multi-cell battery pack voltage and temperature
- Monitoring the individual cell voltage
- Passive cell balancing
- Cell overvoltage and undervoltage protection
- Overtemperature protection
- Charge and discharge mode detection
- Communication to a host device using USB or UART



Cell Balancing Using TI bq76PL536A IC

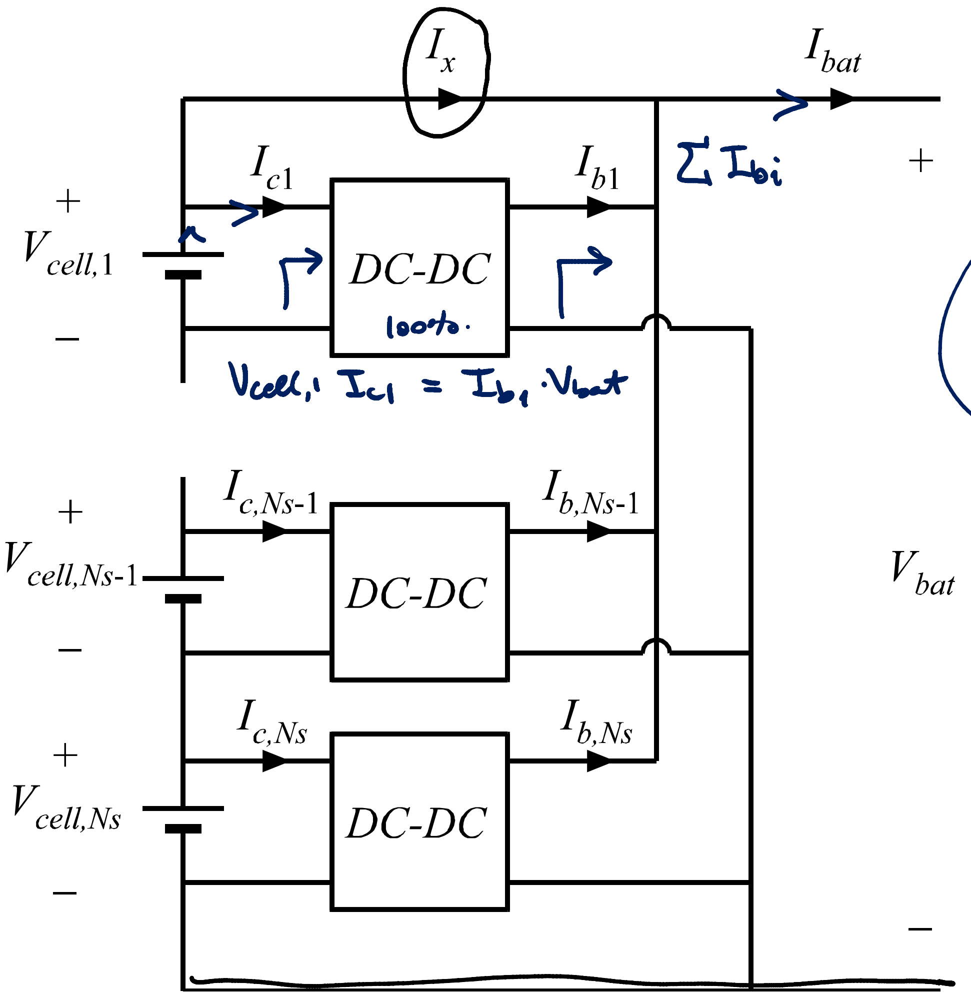


Active Cell Balancing Architectures



Nondissipative balancing topologies: (L to R) Cell-to-battery; battery-to-cell; cell-to-cell.

Cell-to-Battery Pack Active Cell Balancing Architecture



$C_i = C_{nom} \pm \Delta C$

Objective: $\frac{Q_i}{C_i}$ = const for all cells.

$$\frac{Q_1}{C_1} = \frac{Q_2}{C_2} = \dots$$

$$Q_1 \neq Q_2 \neq \dots$$

$$I_{cell,i} = I_x - I_{c,i}$$

$\frac{I_{cell,i}}{C_i}$ = same for all cells.

$$C_i = C_{nom} \Rightarrow \boxed{I_{c,i} = 0}$$

$$M = \frac{V_{bat}}{V_{cell}}$$

$V_{cell,i}$ = same = V_{cell}.

passive: $C_{system} = C_{nom} - \Delta C$

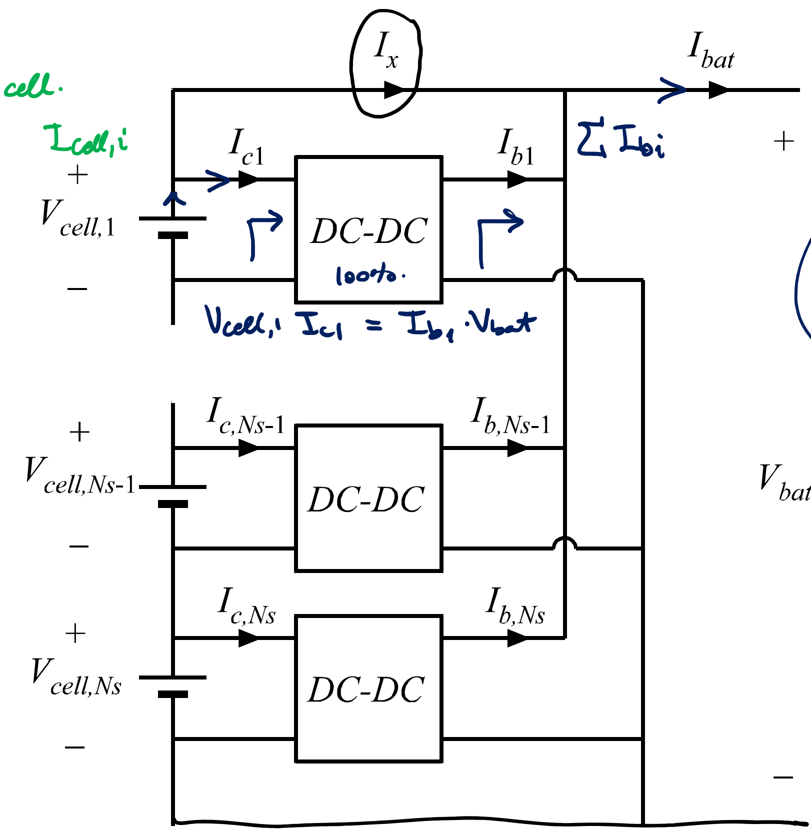
active: $C_{system} = C_{nom}$

Cell-to-Battery Pack Active Cell Balancing Architecture

Know:

? ① C_i for each cell.

② SOC_i for each cell.



$V_{cell,1} \cdot I_{c1} = I_{b1} \cdot V_{bat}$

$C_i = C_{nom} \pm \Delta C$

Objective: $\frac{Q_i}{C_i}$ = const for all cells.

$\frac{Q_1}{C_1} = \frac{Q_2}{C_2} = \ldots$

$Q_1 \neq Q_2 \neq \ldots$

$I_{cell,i} = I_x + I_{c,i}$

$\frac{I_{cell,i}}{C_i}$ = same for all cells.

$C_i = C_{min} \Rightarrow \boxed{I_{c,i} = 0}$

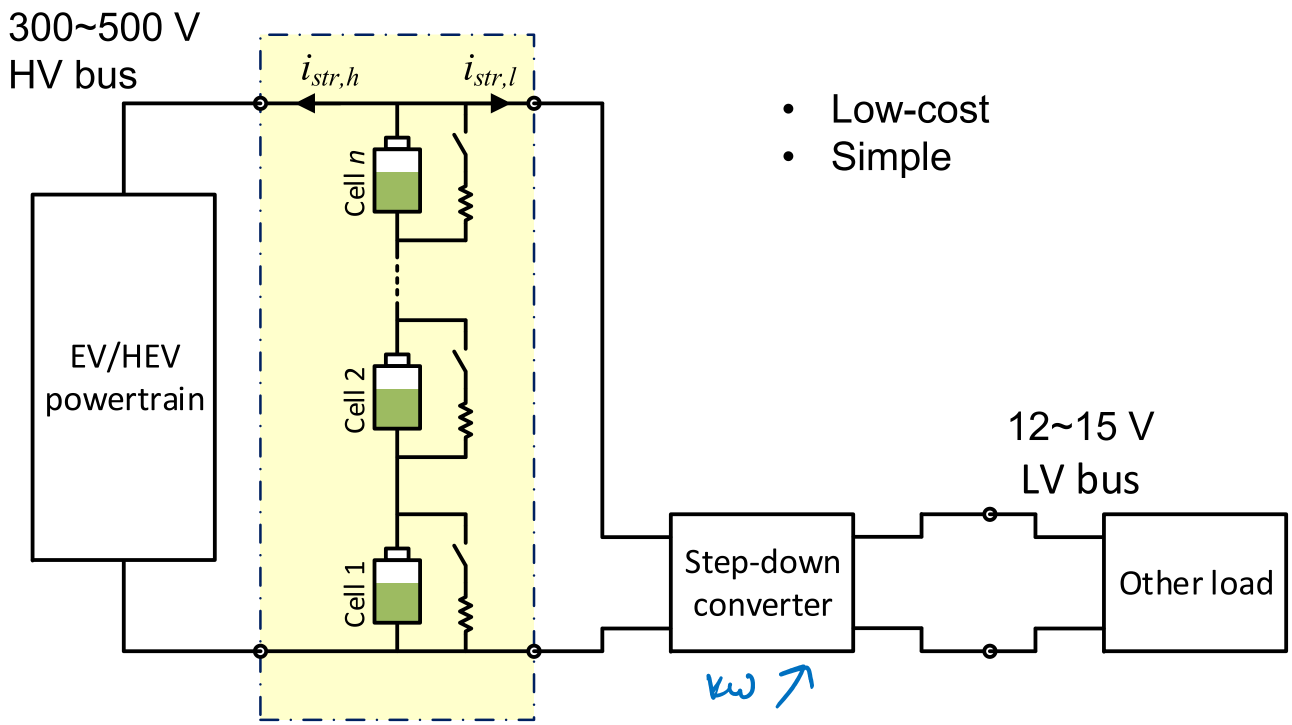
$M = \frac{V_{bat}}{V_{cell}}$

$V_{cell,i}$ = same = V_{cell}.

passive : $C_{system} = C_{nom} - \Delta C$

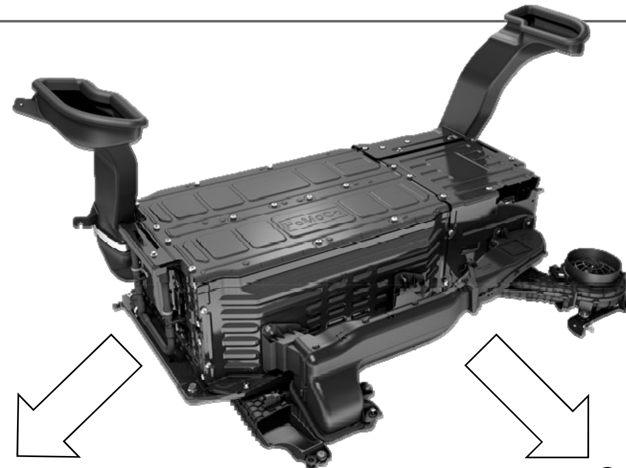
active : $C_{system} = C_{nom}$

Conventional BMS and High-Voltage-to-Low-Voltage DC-DC Converter



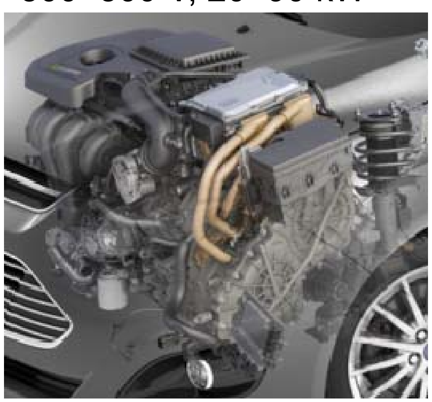
- Low-cost
- Simple

Conventional BMS and High-Voltage-to-Low-Voltage DC-DC Converter



Example: battery pack in the Ford C-Max Energi PHEV, 19 miles EV range

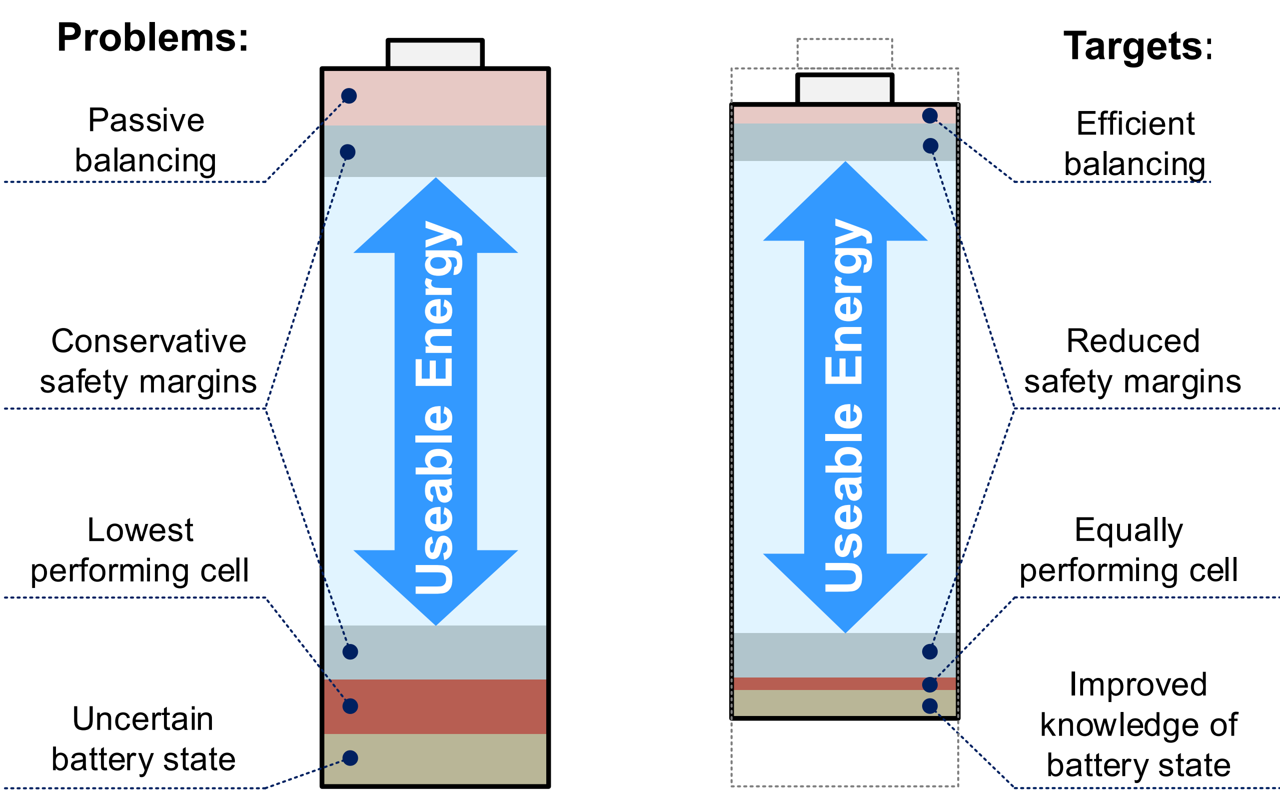
1. Drivetrain
300~500 V, 20~90 kW



2. Low voltage load
12~15 V, 1~8 kW

Robust Cell-Level Modeling and Control of Large Battery Packs

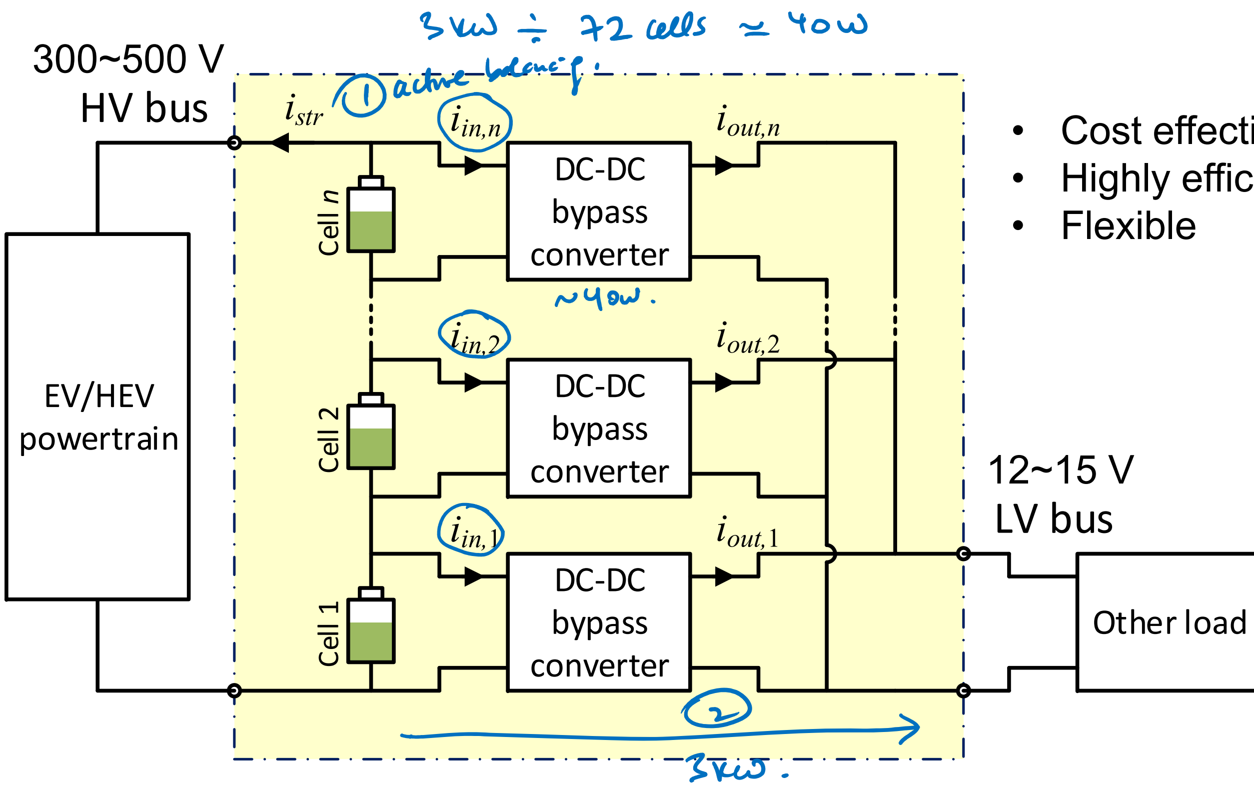
Research Project Summary



Collaborative research project sponsored by DOE ARPA-E

Modular System Architecture

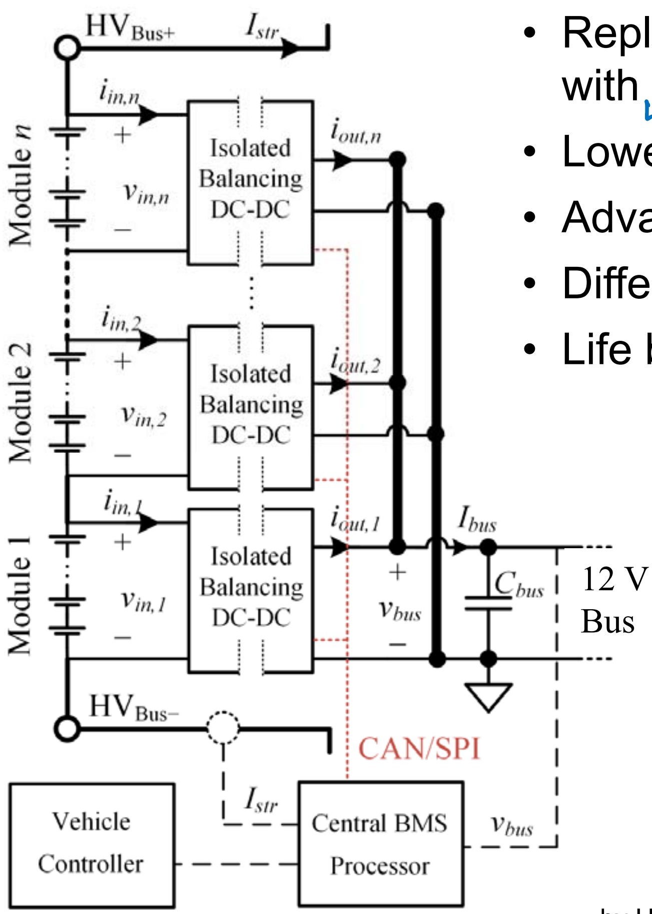
Active balancing system with series-input, parallel-output DC-DC converters[1-2]



- Cost effective
- Highly efficient
- Flexible

[1] D. Costinett, K. Hathaway, M. Rehman, M. Evzelman, R. Zane, Y. Levron, and D. Maksimović, "Active balancing system for electric vehicles with incorporated low voltage bus," 2014 29th Annual IEEE, APEC, pp. 3230-3236, 2014.
[2] M. Rehman, M. Evzelman, K. Hathaway, R. Zane, G. Plett, K. Smith, and D. Maksimović, "Modular approach for continuous cell-level balancing to improve performance of large battery packs," 2014 IEEE, ECCE, pp. 4327-4334, 2014.

System prototype: integrated modular BMS+DC/DC



- Replaced existing battery management system and DC/DC with integrated modular BMS+DC/DC
- Lower total hardware cost
- Advanced cell-level physics-based modeling and control
- Differentially balance battery cells with 12 V load
- Life balancing: weaker cells balanced to reduced SOC_{max}

Prototype system is based on Ford C-Max system

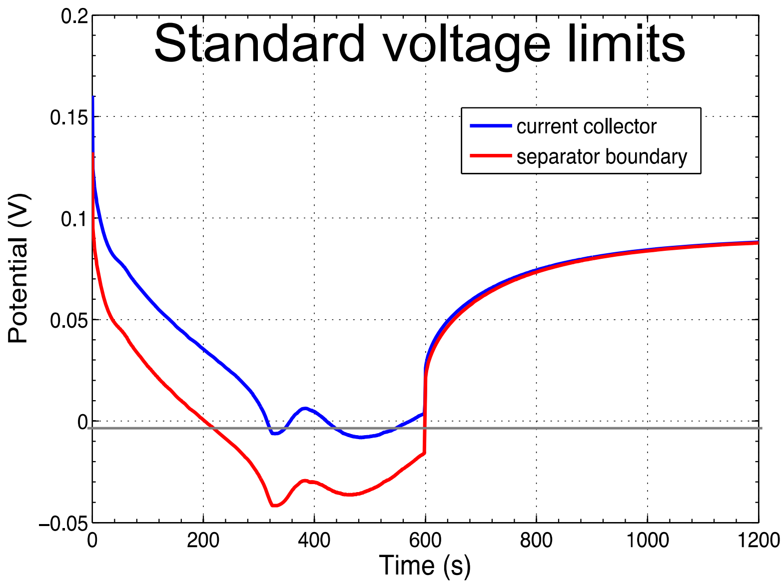
Undergoing side-by-side comparison cycling tests at NREL, team led by Dr. Kandler Smith

System modeling, control algorithms, hardware and firmware
by USU and CU-Boulder students; advisors: Regan Zane and Dragan Maksimovic

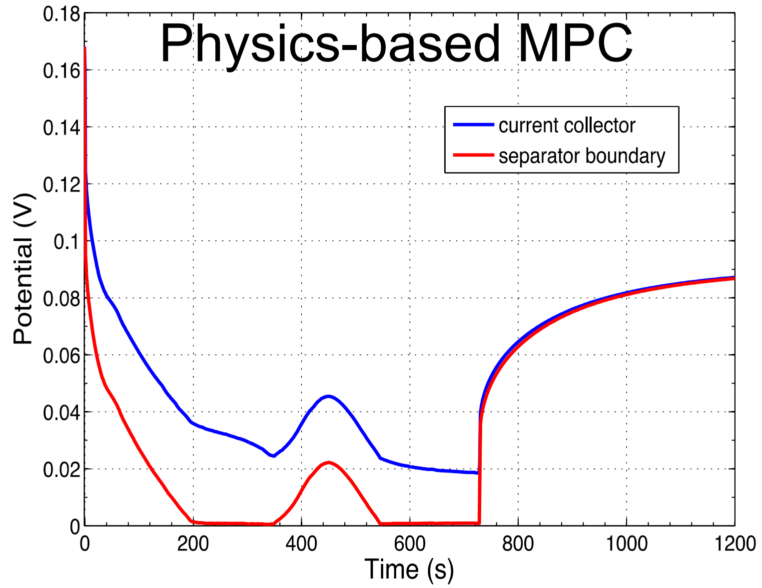
Cell-level physics-based model predictive control (MPC)

Safely enables performance to physical limits without cell degradation

Side-reaction over-potential, 4C charging, 0ºC



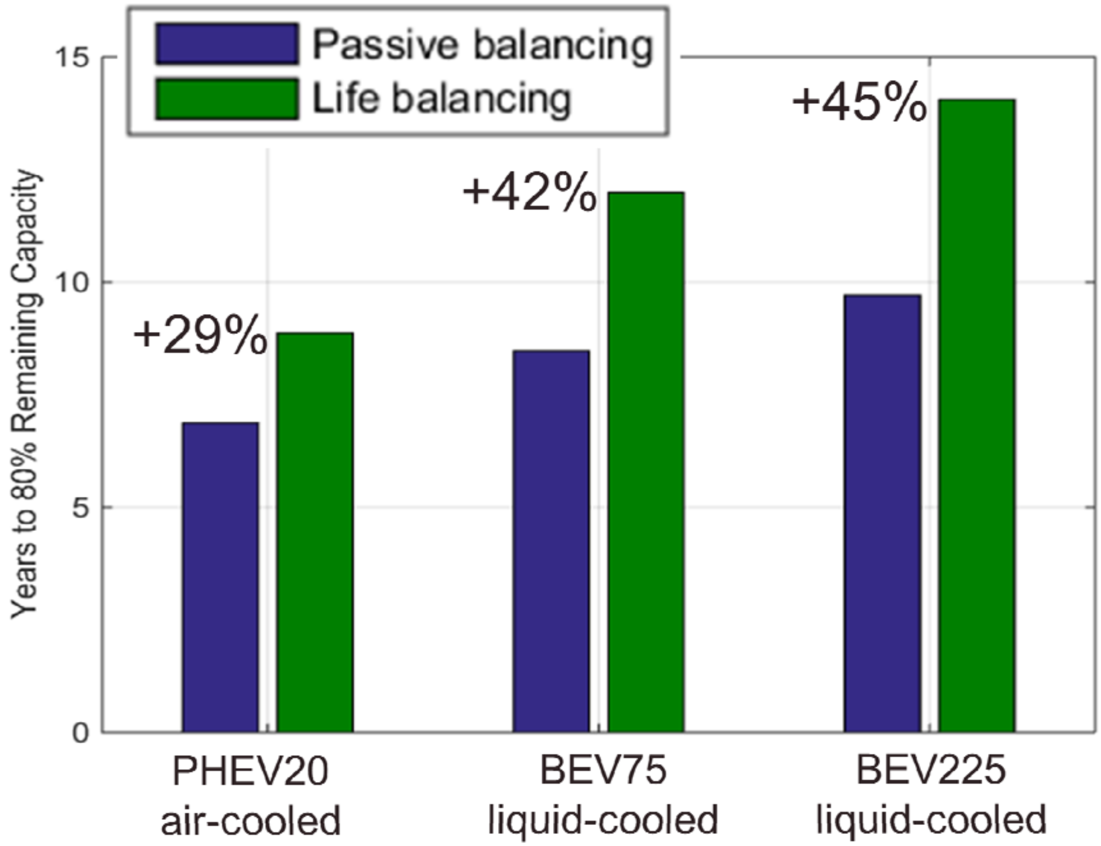
10% capacity loss in 256 cycles!



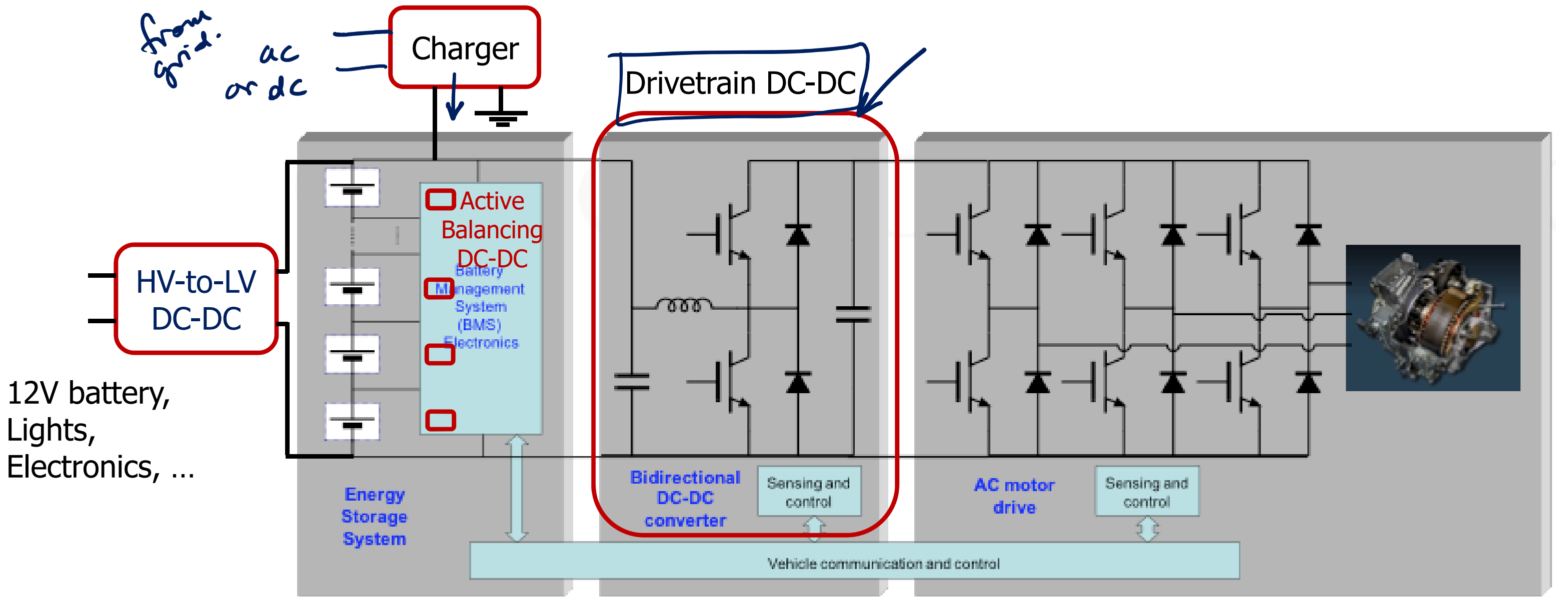
No capacity loss

Cell-level physics-based modeling and control by UCCS students, advisors: Greg Plett and Scott Trimboli

Projected Improvements in Battery Life



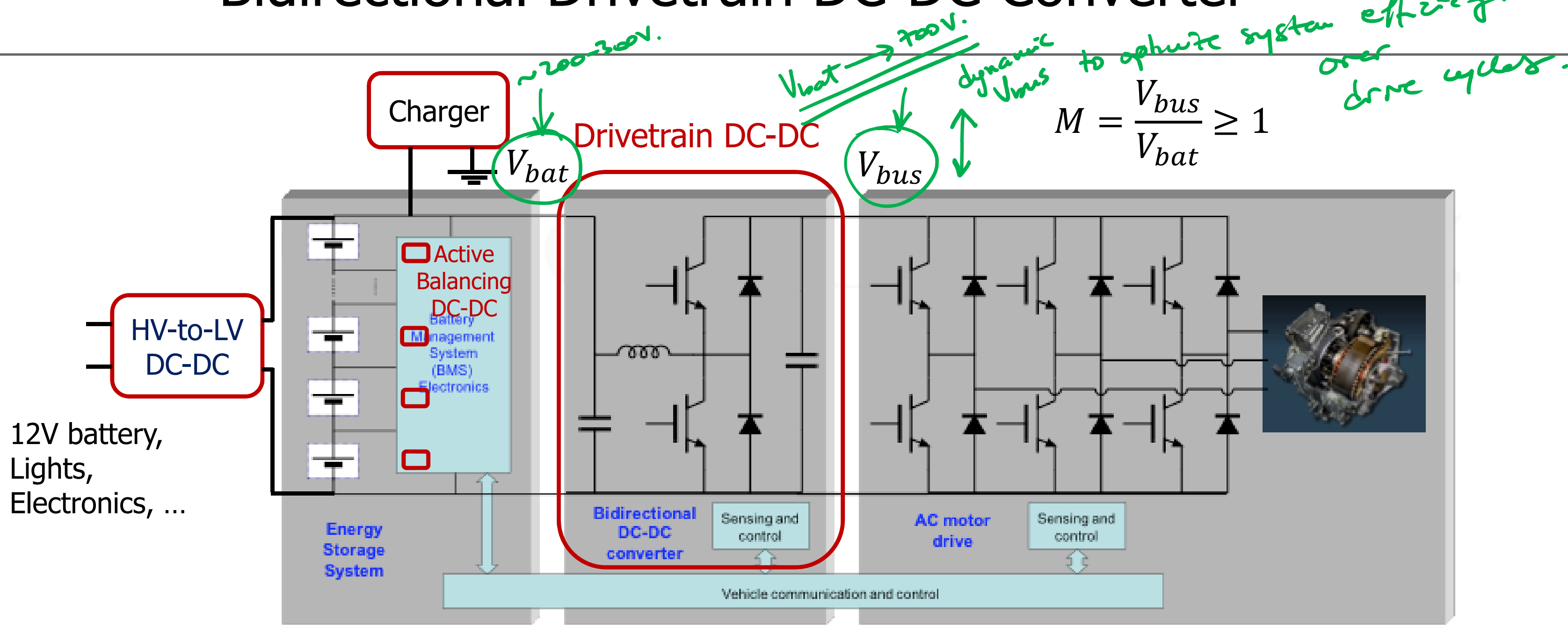
Introduction to DC-DC Conversion in Electric Drivetrains



Applications:

- Drivetrain DC-DC converter: power rating of the battery system (10's of kW)
- Auxiliary high-voltage DC to low-voltage DC (12V): several kW
- Battery system active balancing: <10W per converter
- Charger: 1 kW-100 kW

Bidirectional Drivetrain DC-DC Converter



$$M = \frac{V_{bus}}{V_{bat}} \geq 1$$

Purpose:

- V_{bus} (DC supply for the electric drive) is decoupled from V_{bat} (DC battery voltage), and can be set independently to optimize motor drive performance and system efficiency

Key performance metrics:

- Efficiency, size and cost

dynamic response.

Bidirectional Drivetrain DC-DC Converter

- Introduction to efficient switched-mode power conversion
- Steady-state analysis: inductor volt-seconds balance, capacitor charge balance
- Power semiconductor components: IGBTs, MOSFETs, diodes
  WBG
- Modeling of losses ✓
- Thermal management ✓
- Control
- Simulations (Simulink)-

Reference: R.W.Erickson, D.Maksimovic, *Fundamentals of Power Electronics*, 2nd edition, Springer 2001. Available on-line from campus network.

Chapters 2, 3, 4, sections from Chapters 7, 8, 9, sections from Chapter 13

ECEN 5017

Power Electronics for Electric Drive Vehicles

Lecture 20

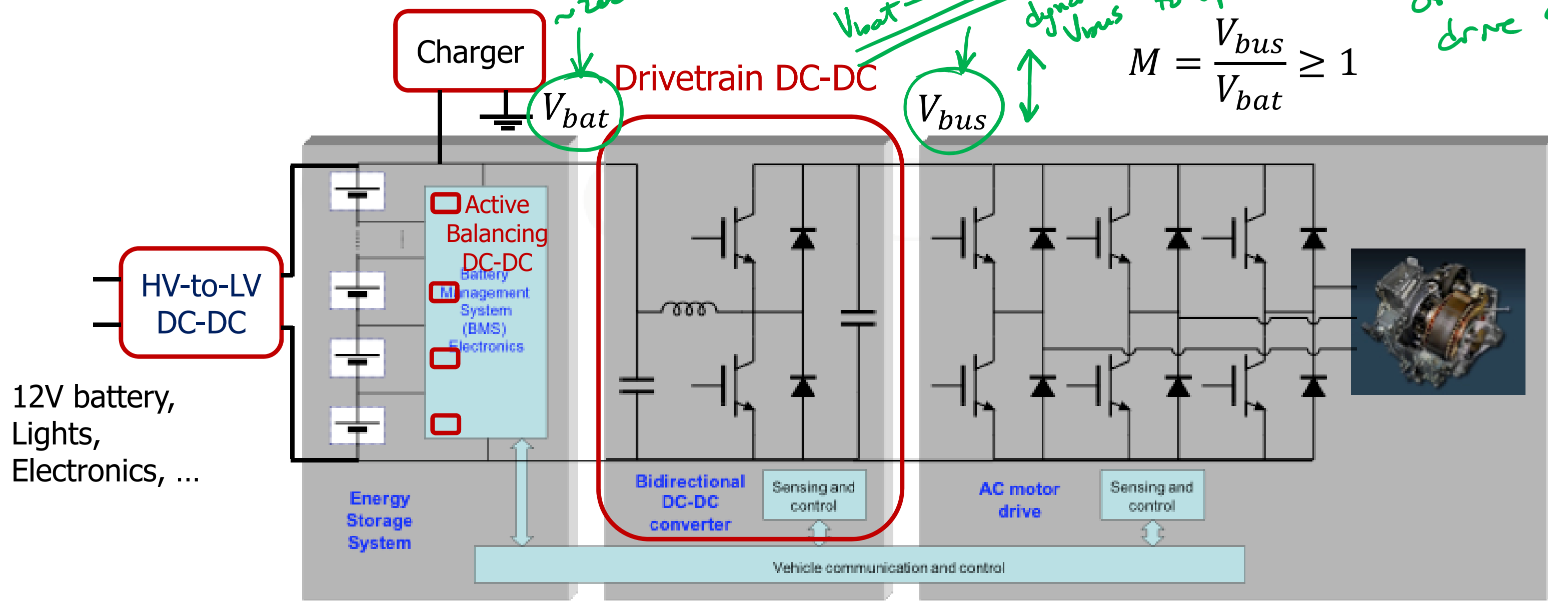
Powertrain Boost DC-DC Converter:

Steady-State Analysis

Announcements

- Homework 7 is out
  - Due by 10 pm (Mountain Time) on Thursday October 13
  - Guest lecture (pre-recorded): "Overview of Li-Ion Battery Physics and Life Prediction Models" by Dr. Kandler Smith, National Renewable Energy Lab (NREL), has been posted on D2L. A part of HW7 is to review the lecture and lecture slides, and answer short questions in Problem 1 of HW7.
- Midterm exam will be out Friday October 14
  - Will cover materials up to and including Lecture 23, assignments up to and including HW7

Bidirectional Drivetrain DC-DC Converter



~200-300V.

$V_{bat} \rightarrow$ 700V.

dynamic V_{bus} to optimize system efficiency over drive cycles.

$$M = \frac{V_{bus}}{V_{bat}} \geq 1$$

Purpose:

- V_{bus} (DC supply for the electric drive) is decoupled from V_{bat} (DC battery voltage), and can be set independently to optimize motor drive performance and system efficiency

Key performance metrics:

- Efficiency, size and cost

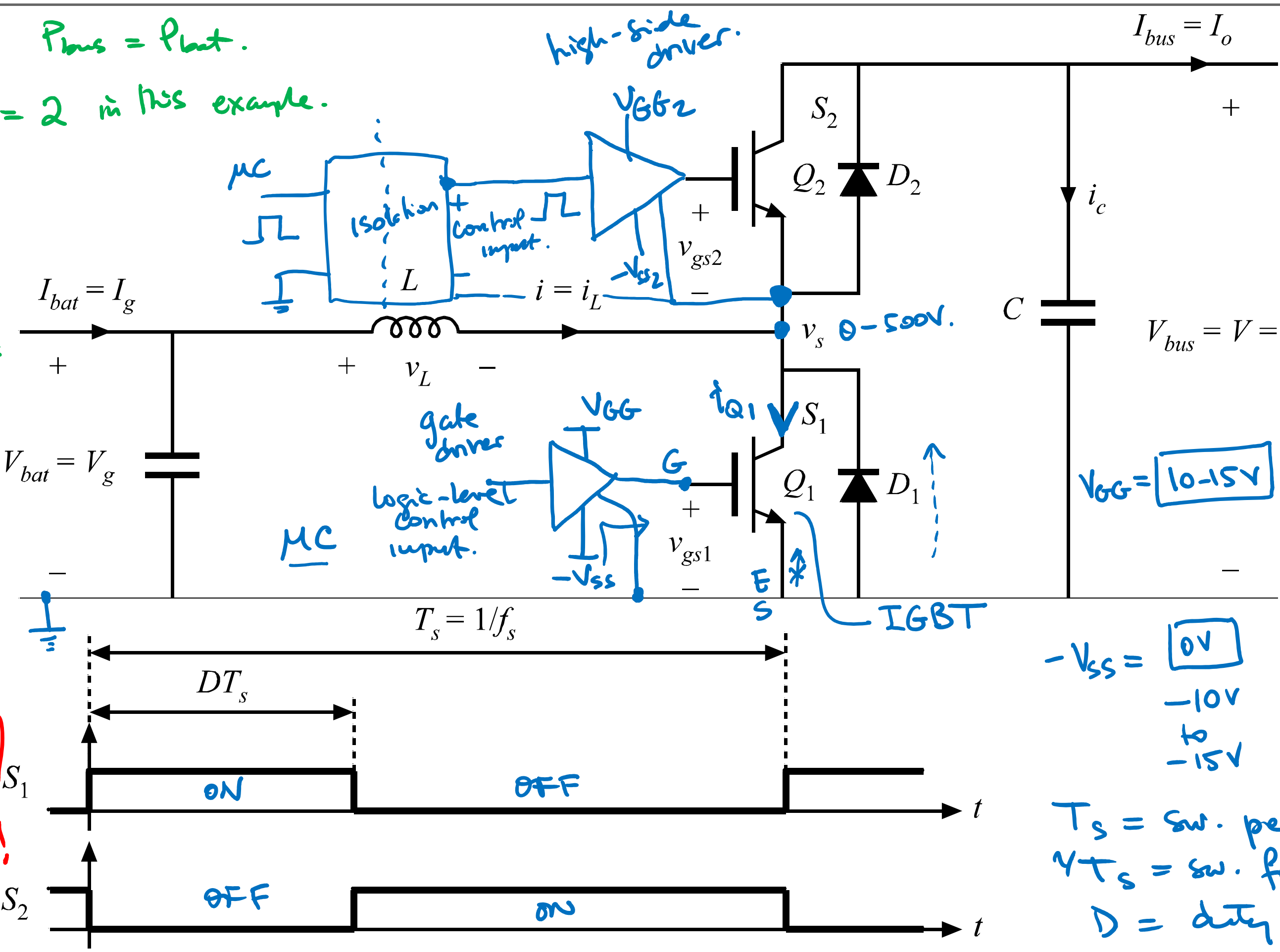
dynamic response.

Boost (or Buck) DC-DC Converter

$\eta = 100\%$. $P_{bus} = P_{bat}$.

$M = \frac{V_{bus}}{V_{bat}} = 2$ in this example.

P_{bat} 50kW { 250V. 200A



+500V, 100A

$P_{bus} = 50kW$.

$\eta = \cancel{98\%}$

$P_{bus} = 50kW$.

$\eta = \frac{P_{bus}}{P_{bat}}$

$P_{bat} = 51$ kW

$P_{loss} = 51-50 = \boxed{1kW}$

thermal management!

$V_{GG} = \boxed{10\text{-}15V}$

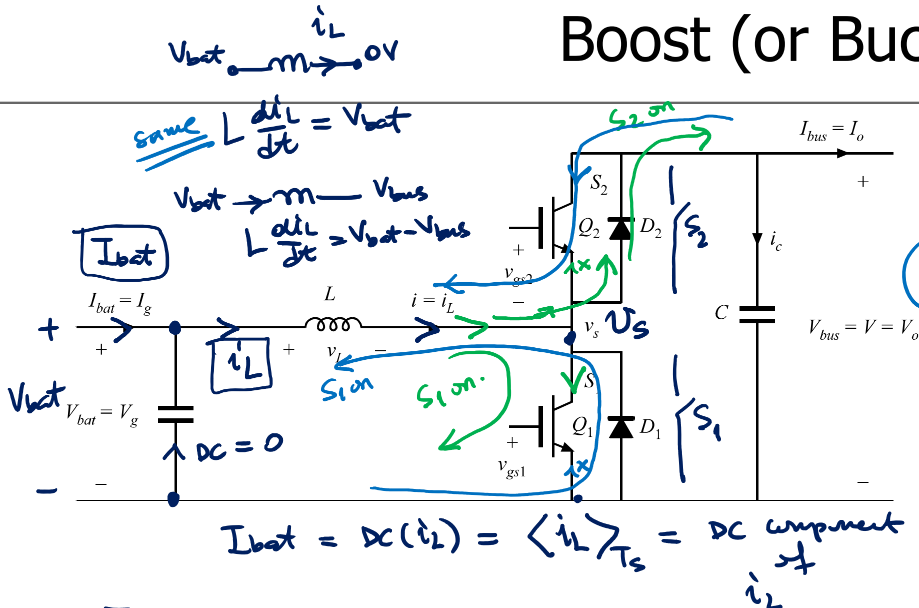
$V_{gs1} \gg V_{th} \sim$ volts.
Q_1 on
$i_{Q1} > 0$

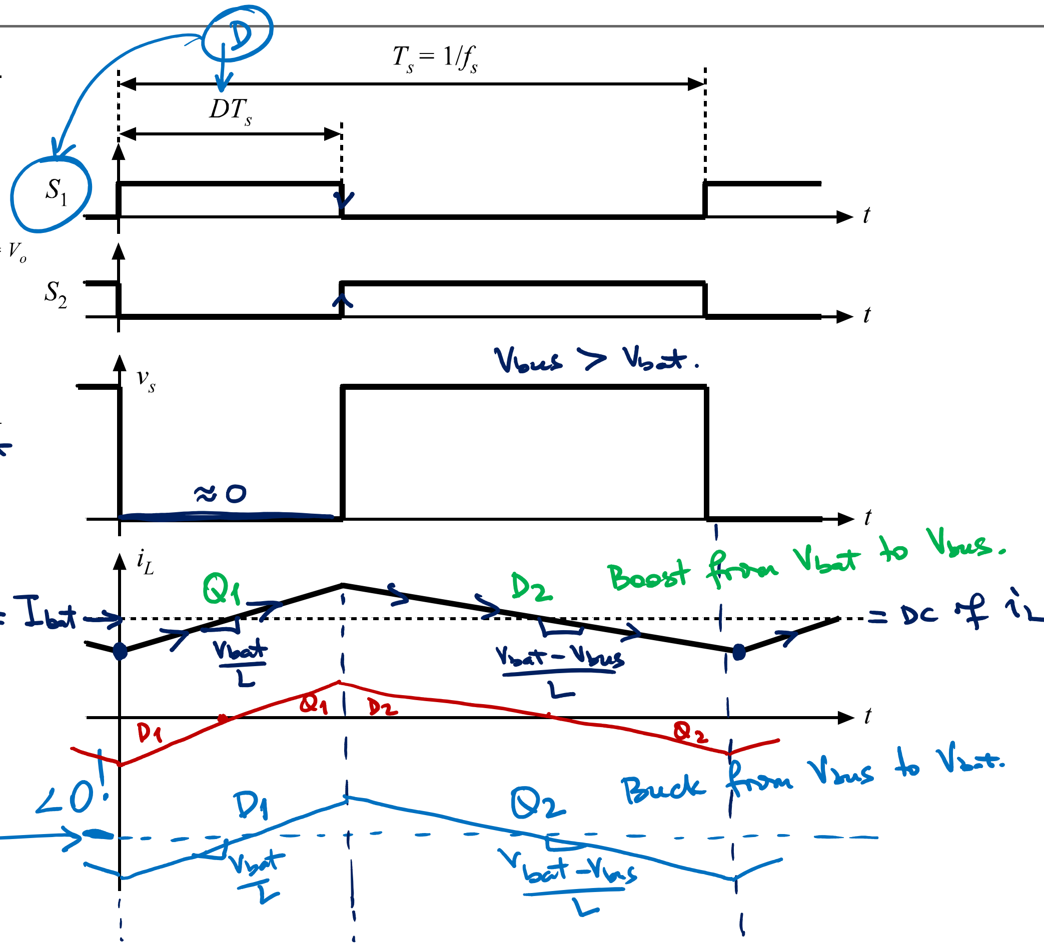
$-V_{ss} = \boxed{0V}$
-10V to -15V

$V_{gs1} < V_{th}$
Q_1 off.
$i_{Q1} = 0$

T_s = sw. period
$1/T_s$ = sw. frequency.
D = duty cycle.

Boost (or Buck) DC-DC Converter





$I_{bat} > 0$

Q_1, D_2: $P_{bat} > 0$
from battery to bus.

V_{bat} —m→ 0, i_L

same $L \frac{di_L}{dt} = V_{bat}$.

$P_{bat} < 0$
from bus to battery.

Steady-state analysis of switched-mode power converters

Small-ripple approximation

- Capacitor voltages: $v(t) \approx V$
- Inductor currents*: $i(t) \approx I$

Inductor volt-seconds balance

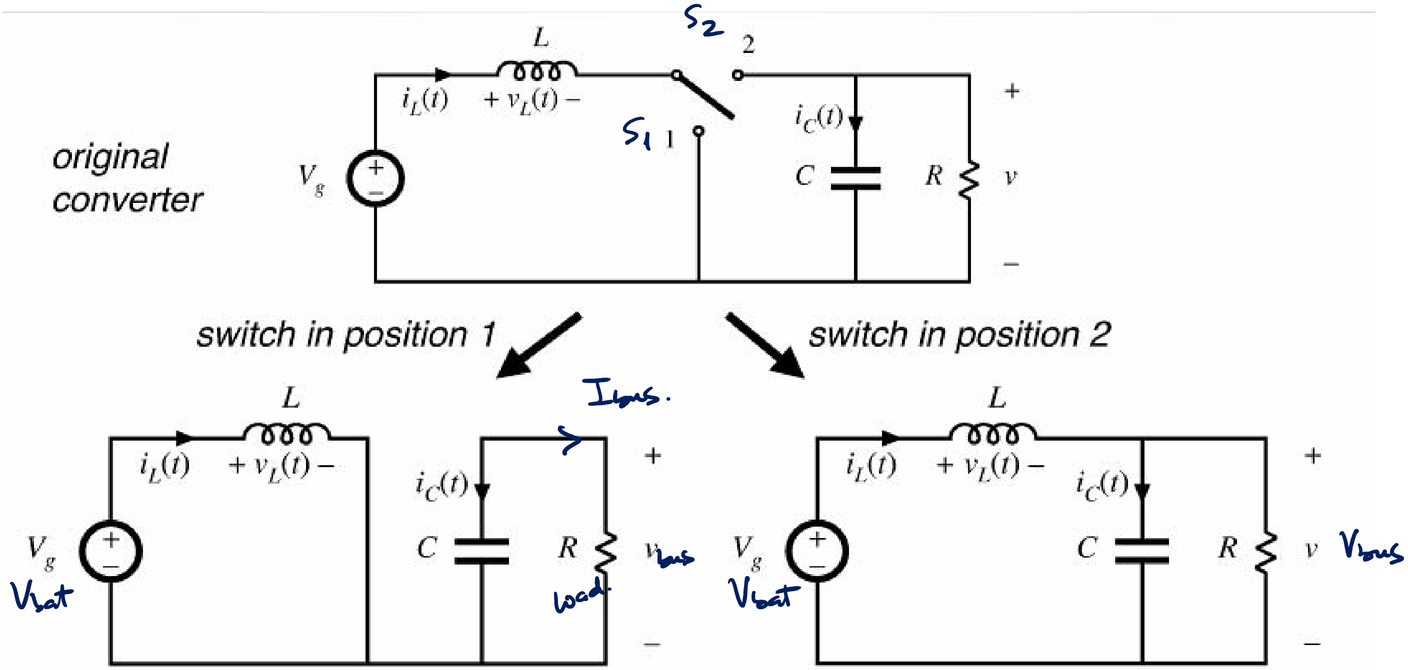
- Average (DC) inductor voltage = 0 $\int_0^{T_s} v_L(t)dt = 0$

Capacitor charge balance

- Average (DC) capacitor current = 0 $\int_0^{T_s} i_C(t)dt = 0$

Calculation of current and voltage ripples

Boost converter switched circuits



$$L \frac{di_L}{dt} = v_L = V_{bat}.$$

$$i_c = -\frac{V_{bus}}{R}$$

$$v_L = V_{bat} - V.$$

$$i_c = I_L - \frac{V_{bus}}{R}$$

Analysis: v_L and i_c

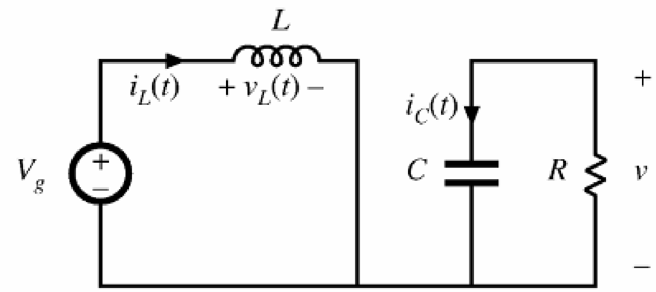
Inductor voltage and capacitor current

$$v_L = V_g$$
$$i_C = -v/R$$

Small ripple approximation:

$$v_L = V_g$$
$$i_C = -V/R$$

Position 1: DT_s



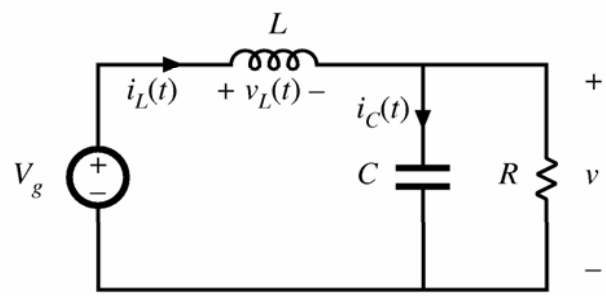
Inductor voltage and capacitor current

$$v_L = V_g - v$$
$$i_C = i_L - v/R$$

Small ripple approximation:

$$v_L = V_g - V$$
$$i_C = I - V/R$$

Position 2: $(1-D)T_s = D'T_s$

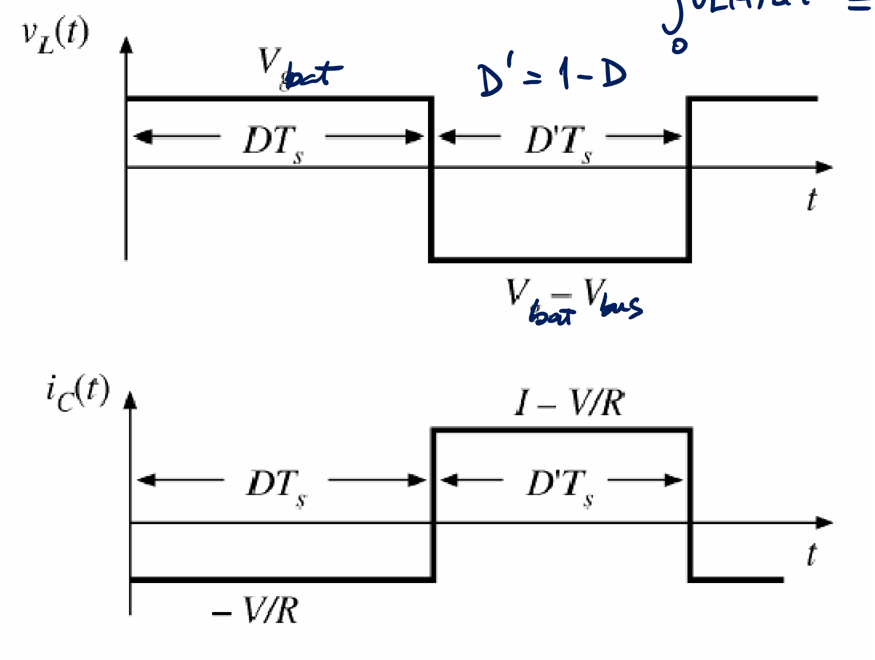


Inductor voltage and capacitor current

$$\int_0^{T_s} v_L(t)\,dt = D\cancel{T_s}(V_{bat}) + D'\cancel{T_s}(V_{bat} - V_{bus}) = 0$$

$$= V_{bat} - D'V_{bus} = 0 \qquad \frac{V_{bus}}{V_{bat}} = \frac{1}{D'} = \frac{1}{1-D} = M(D)$$

conv. ratio of the boost DC-DC converter.



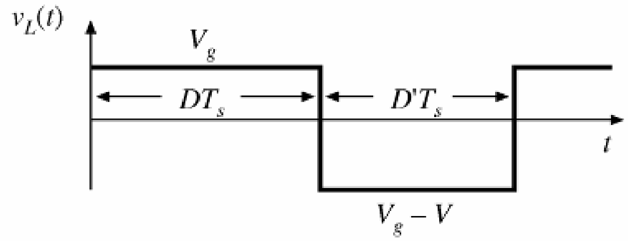
Express v_L in terms of input voltage and capacitor voltages

Express i_C in terms of load current and inductor currents

Inductor volt-seconds balance

Net volt-seconds applied to inductor over one switching period:

$$\int_0^{T_s} v_L(t)\, dt = (V_g)\, DT_s + (V_g - V)\, D'T_s$$



Equate to zero and collect terms:

$$V_g\,(D + D') - V\, D' = 0$$

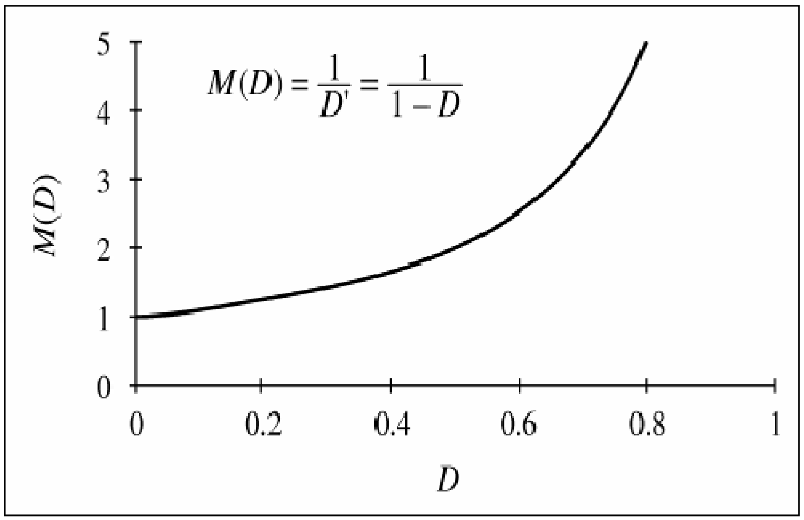
Solve for V:

$$V = \frac{V_g}{D'}$$

The voltage conversion ratio is therefore

$$M(D) = \frac{V}{V_g} = \frac{1}{D'} = \boxed{\frac{1}{1-D}}$$

Boost ideal DC conversion ratio *M*(*D*)



Capacitor charge balance

Capacitor charge balance:

$$\int_0^{T_s} i_C(t)\, dt = (-\frac{V}{R})\, DT_s + (I - \frac{V}{R})\, D'T_s$$

Collect terms and equate to zero:

$$-\frac{V}{R}(D + D') + I\, D' = 0$$

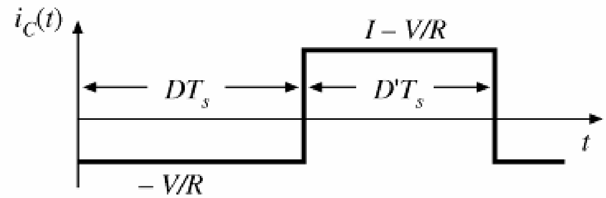
Solve for I:

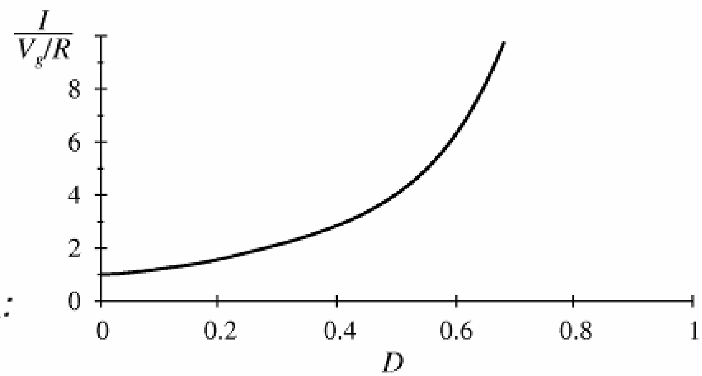
$$\boxed{I = \frac{V}{D'\, R}}$$ = average inductor current.

Eliminate V to express in terms of V_g:

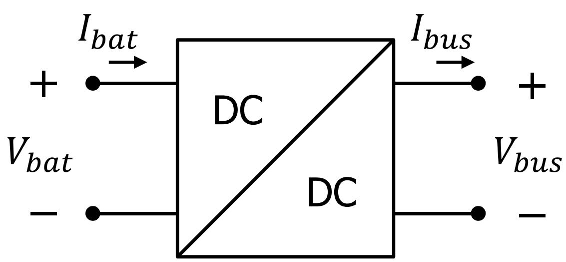
$$\boxed{I = \frac{V_g}{D'^2\, R}}$$

$V_g = V_{bat}$.





DC (Average) Model of DC/DC Converter

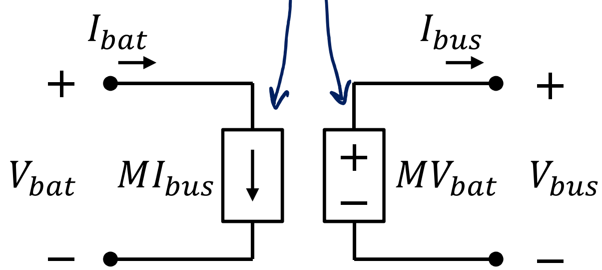


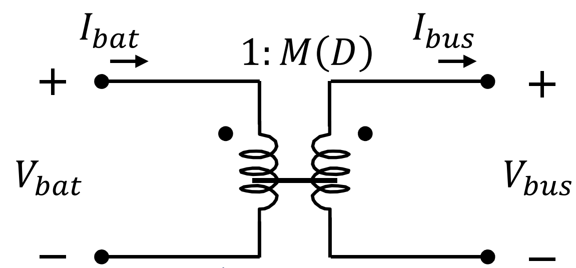
$$\boxed{V_{bus} = \frac{1}{1-D} V_{bat} = M(D) V_{bat}}$$

$V_{bus} \geq V_{bat}.$

If converter is lossless: $\boxed{P_{OUT} = P_{IN}}$

$$\boxed{I_{bat} = \frac{1}{1-D} I_{bus} = M(D) I_{bus}}$$





ideal transformer.

ECEN 5017

Power Electronics for Electric Drive Vehicles

Lecture 21

Powertrain DC-DC Converter:

Steady-State Analysis, Losses

Announcements

- Midterm exam will be out Friday October 14
  - Take-home exam, similar in length to HW assignments
  - Covers materials up to and including Lecture 23, assignments up to and including HW7. Will include simulations.
  - Open all course materials
  - Absolutely no collaboration allowed

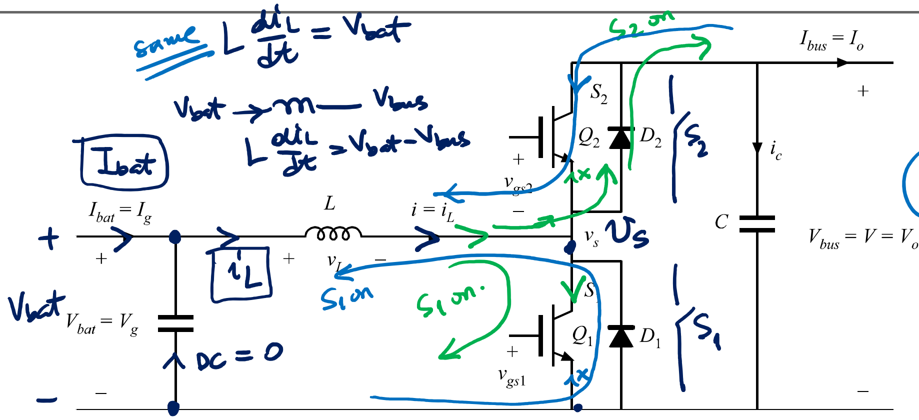
Boost (or Buck) DC-DC Converter

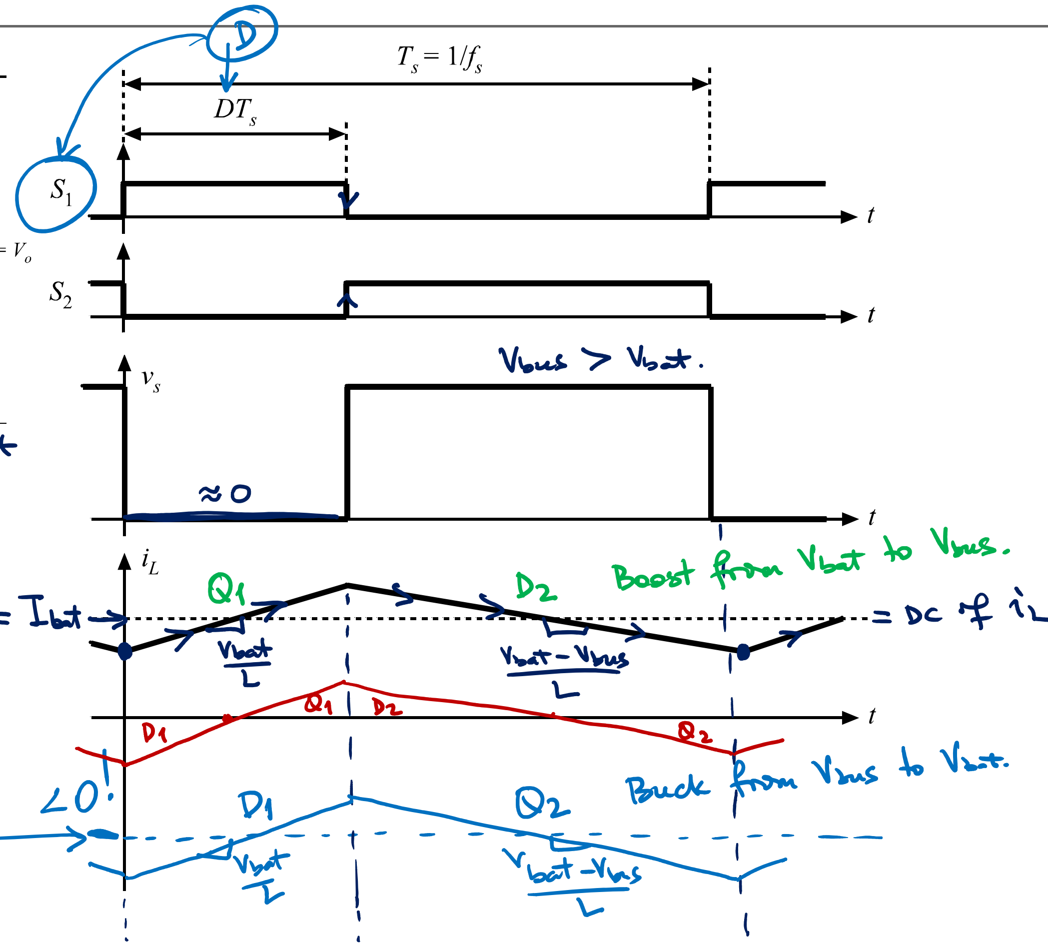
$V_{bat} \xrightarrow{i_L} 0V$

same $L\frac{di_L}{dt} = V_{bat}$

$V_{bat} \rightarrow V_{bus}$

$L\frac{di_L}{dt} = V_{bat} - V_{bus}$





$I_{bat} = DC(i_L) = \langle i_L \rangle_{T_s}$ = DC component of i_L

$I_{bat} > 0$

Q_1, D_2 : $P_{bat} > 0$ from battery to bus.

$V_{bat} \xrightarrow{i_L} 0$

same $L\frac{di_L}{dt} = V_{bat}$.

$P_{bat} < 0$ from bus to battery.

Steady-state analysis of switched-mode power converters

Small-ripple approximation

- Capacitor voltages: $v(t) \approx V$
- Inductor currents*: $i(t) \approx I$

Inductor volt-seconds balance

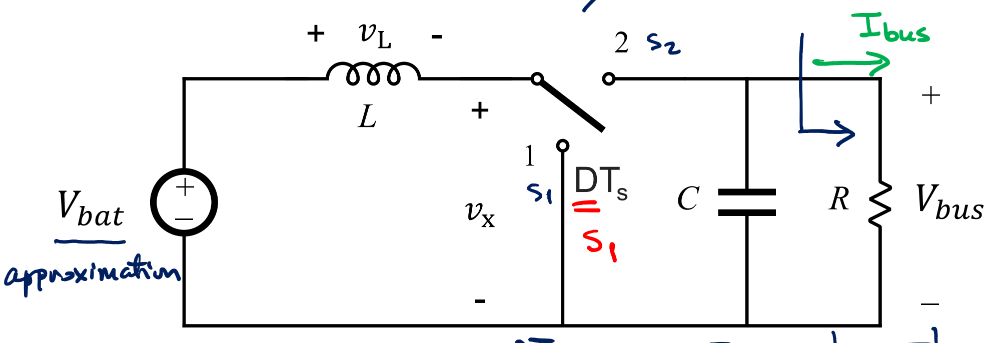
- Average (DC) inductor voltage = 0 $\int_0^{T_s} v_L(t)\,dt = 0$

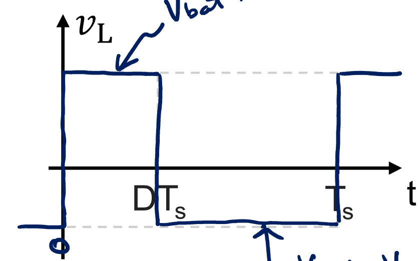
Capacitor charge balance

- Average (DC) capacitor current = 0 $\int_0^{T_s} i_C(t)\,dt = 0$

Calculation of current and voltage ripples

Analysis of Boost Converter – Volt-Sec Balance





$$\underbrace{\langle v_L \rangle_{T_s}}_{} = \frac{1}{T_s}\int_0^{T_s} v_L(t)\,dt = \frac{1}{T_s}\int_0^{DT_s} V_{bat}\,dt + \frac{1}{T_s}\int_{DT_s}^{T_s} (V_{bat}-V_{bus})\,dt = D V_{bat} + (1-D)(V_{bat}-V_{bus}) \boxed{= 0}$$

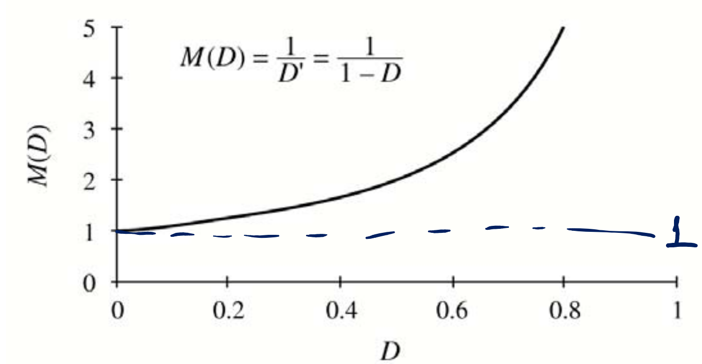
volt-sec. balance

average of inductor voltage over T_s period

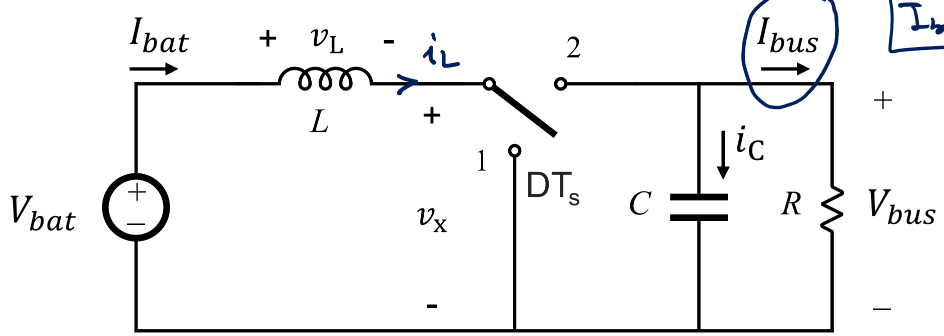
$$M(D) = \frac{V_{bus}}{V_{bat}} = \frac{1}{1-D} = \frac{1}{D'}$$

$$D' = 1 - D$$

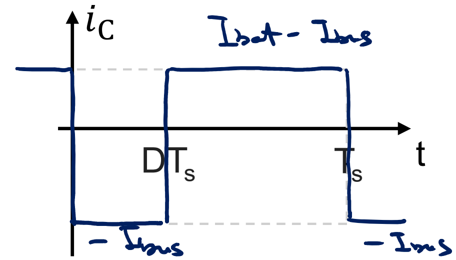
$$M(D) = \frac{V_{bus}}{V_{bat}} = \text{same.}$$



Analysis of Boost Converter – Charge Balance



$I_{bus} > 0.$



$$i_C(t) = \begin{cases} -\underbrace{I_{bus}}_{\text{const.}}, & DT_s \\ i_L - I_{bus} \approx \langle i_L \rangle - I_{bus} = \underbrace{I_{bat} - I_{bus}}_{\text{const.}} \end{cases}$$

$\approx$: small-ripple approx.

Charge balance.

$$\langle i_C \rangle_{T_s} = 0, \quad \langle i_C \rangle_{T_s} = \frac{1}{T_s}\int_0^{T_s} i_C(t)\,dt = \underbrace{D(-I_{bus}) + (1-D)(I_{bat} - I_{bus})}\boxed{= 0}$$

$$-I_{bus} + (1-D) I_{bat} = 0$$

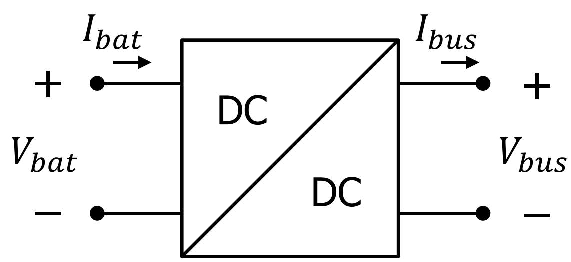
$$I_{bat} = \frac{1}{1-D} I_{bus} = \frac{1}{D'} I_{bus}$$

$$V_{bus} = \frac{1}{1-D} \cdot V_{bat}.$$

$$I_{bat} V_{bat} = I_{bus} V_{bus}.$$

$\underbrace{\ =\ }$ $\eta = 100\%$ efficiency.

DC (Average) Model of DC/DC Converter

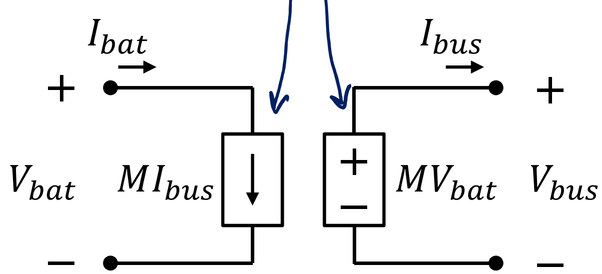


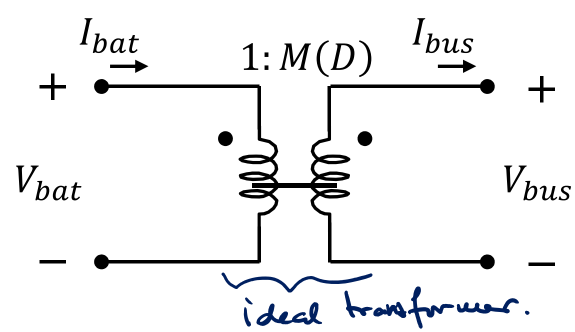
$$\boxed{V_{bus} = \frac{1}{1-D} V_{bat} = M(D) V_{bat}}$$

$V_{bus} > V_{bat}$.

If converter is lossless: $\boxed{P_{OUT} = P_{IN}}$

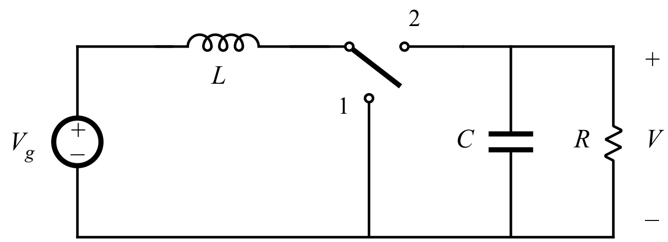
$$\boxed{I_{bat} = \frac{1}{1-D} I_{bus} = M(D) I_{bus}}$$





Voltage and Current Ripple

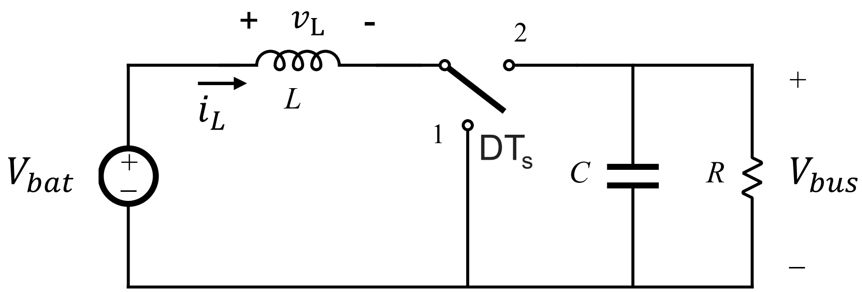
- So far we have ignored ripple in inductor current and capacitor voltage
  - We select inductor and capacitor values based on ripple specifications

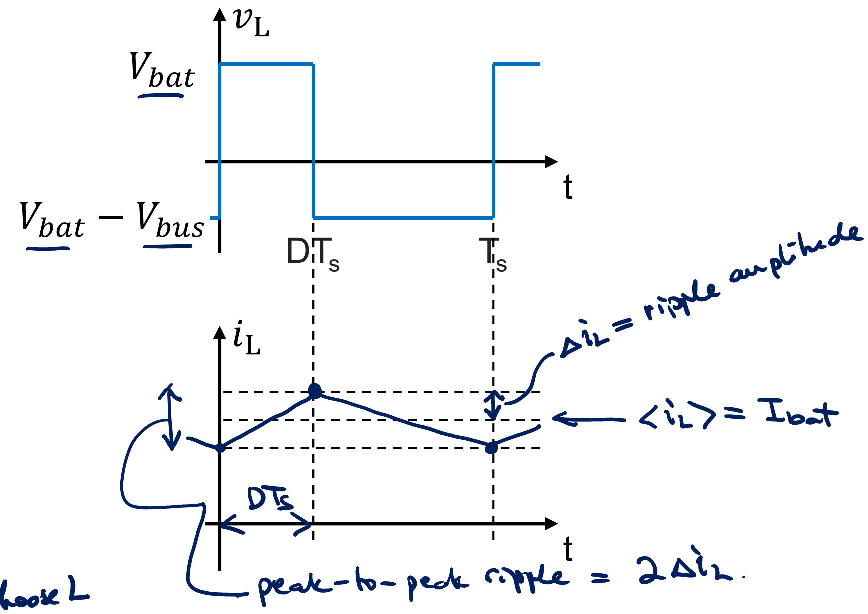


Analysis approach:
- Small ripple approximation
- Use dc inductor currents found using volt-second balance and capacitors voltages found using charge balance

- Approximate calculation of inductor current ripple
  - Neglect ripple in capacitor voltage (i.e., assume C ≈ ∞)
  - Assume all voltage ripple drops across inductor
  - Calculate inductor current ripple
- Approximate calculation of capacitor voltage ripple
  - Neglect ripple in inductor current (i.e., assume L ≈ ∞)
  - Assume all current ripple goes into capacitor
  - Calculate capacitor voltage ripple

Inductor Current Ripple in Boost Converter





$$\longrightarrow v_L = L\frac{di_L}{dt}$$

$\frac{di_L}{dt} = \frac{V_{bat}}{L}$, $\frac{V_{bat}}{L} \cdot DT_s = 2\Delta i_L$

use to choose L

$$\boxed{\Delta i_L = \frac{V_{bat} D T_s}{2L}} = \frac{V_{bat} D}{2L f_s} , \quad \boxed{L = \frac{V_{bat} D}{2\Delta i_L f_s}}$$

$f_s \uparrow$ $\Delta i_L \downarrow$

- Neglect ripple in capacitor voltage
- Assume all voltage ripple drops across inductor

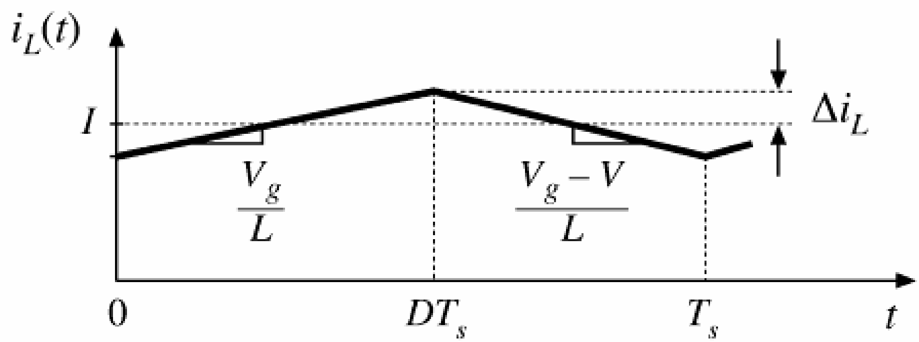
Inductor current ripple

Inductor current slope during subinterval 1:

$$\frac{di_L(t)}{dt} = \frac{v_L(t)}{L} = \frac{V_g}{L}$$

Inductor current slope during subinterval 2:

$$\frac{di_L(t)}{dt} = \frac{v_L(t)}{L} = \frac{V_g - V}{L}$$



Change in inductor current during subinterval 1 is *(slope) (length of subinterval):*

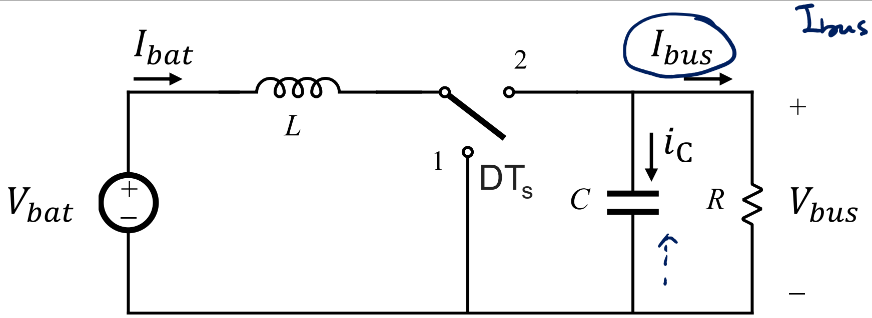
$$2\Delta i_L = \frac{V_g}{L} DT_s$$

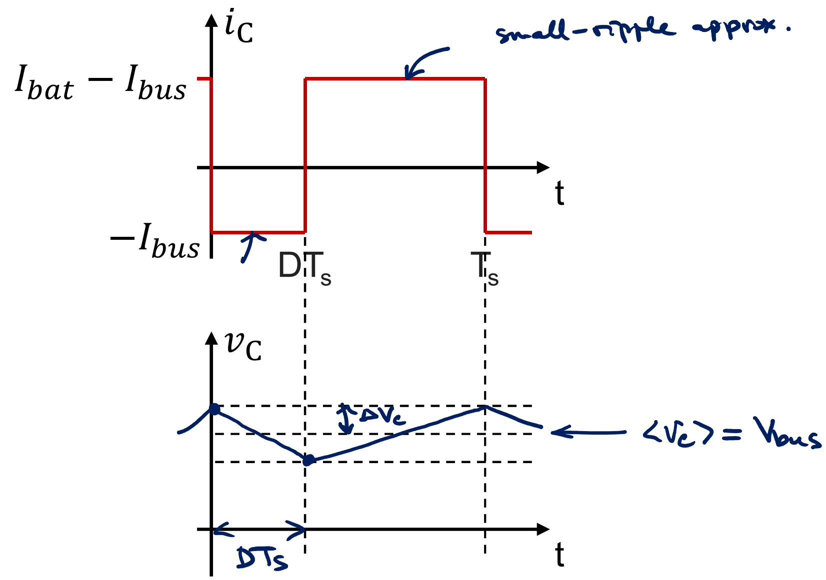
Solve for peak ripple:

$$\Delta i_L = \frac{V_g}{2L} DT_s$$

- Choose L such that desired ripple magnitude is obtained

Capacitor Voltage Ripple in Boost Converter





$$i_C = C\frac{dv_C}{dt}$$

$$2\Delta v_c = \frac{I_{bus}}{C} \cdot DT_s$$

$$\Delta v_C = \frac{I_{bus} DT_s}{2C} \quad , \qquad \boxed{C = \frac{I_{bus} D}{2\Delta v_c f_s}}$$

- Neglect ripple in inductor current
- Assume all current ripple goes into capacitor

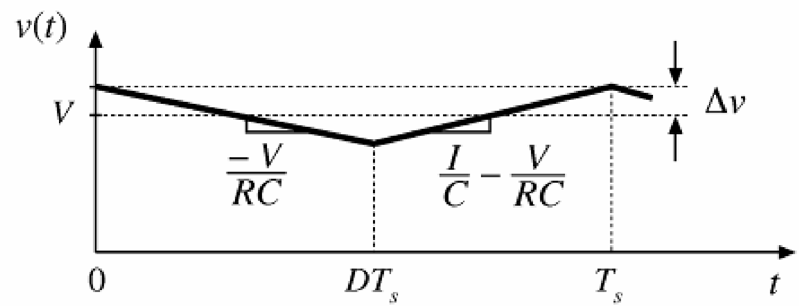
Capacitor Voltage Ripple

Capacitor voltage slope during subinterval 1:

$$\frac{dv_C(t)}{dt} = \frac{i_C(t)}{C} = \frac{-V}{RC}$$

Capacitor voltage slope during subinterval 2:

$$\frac{dv_C(t)}{dt} = \frac{i_C(t)}{C} = \frac{I}{C} - \frac{V}{RC}$$



Change in capacitor voltage during subinterval 1 is *(slope) (length of subinterval):*

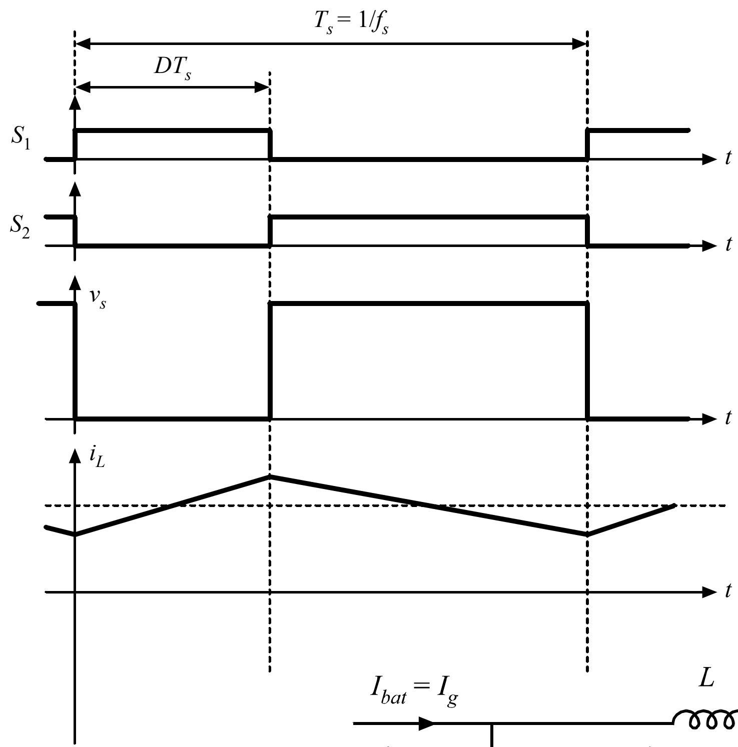
$$-2\Delta v = \frac{-V}{RC} DT_s$$

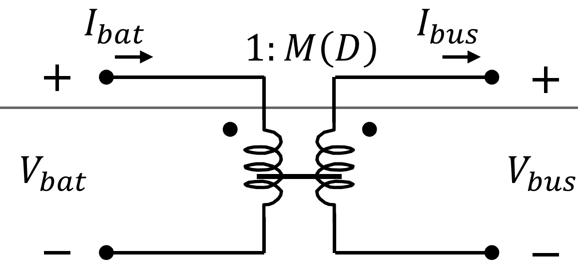
Solve for peak ripple:

$$\Delta v = \frac{V}{2RC} DT_s$$

- Choose *C* such that desired voltage ripple magnitude is obtained
- In practice, capacitor *equivalent series resistance* (esr) leads to increased voltage ripple

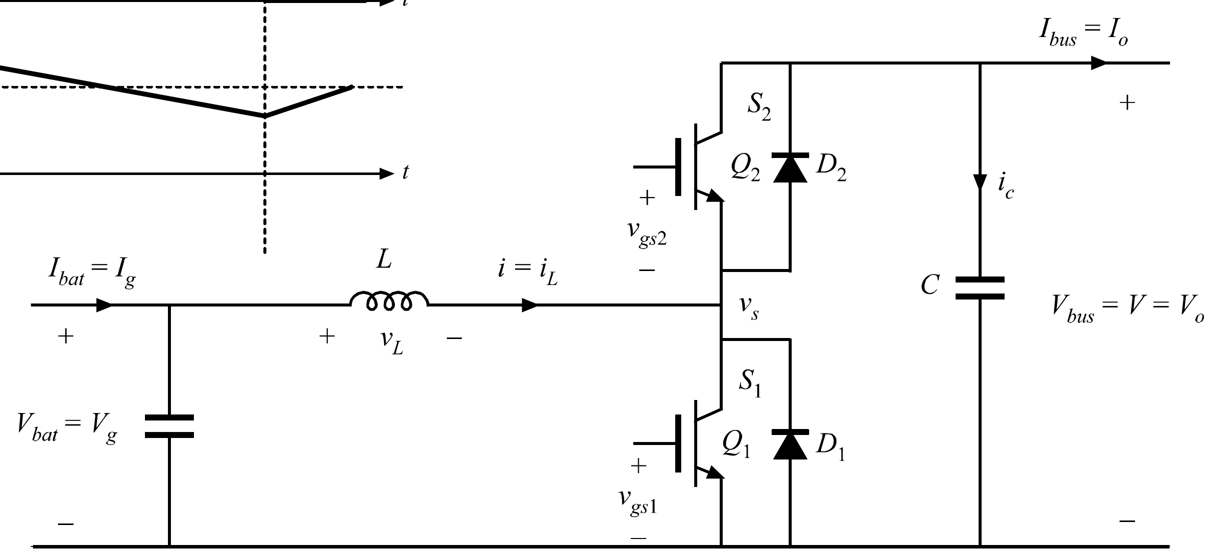
Boost Converter Summary





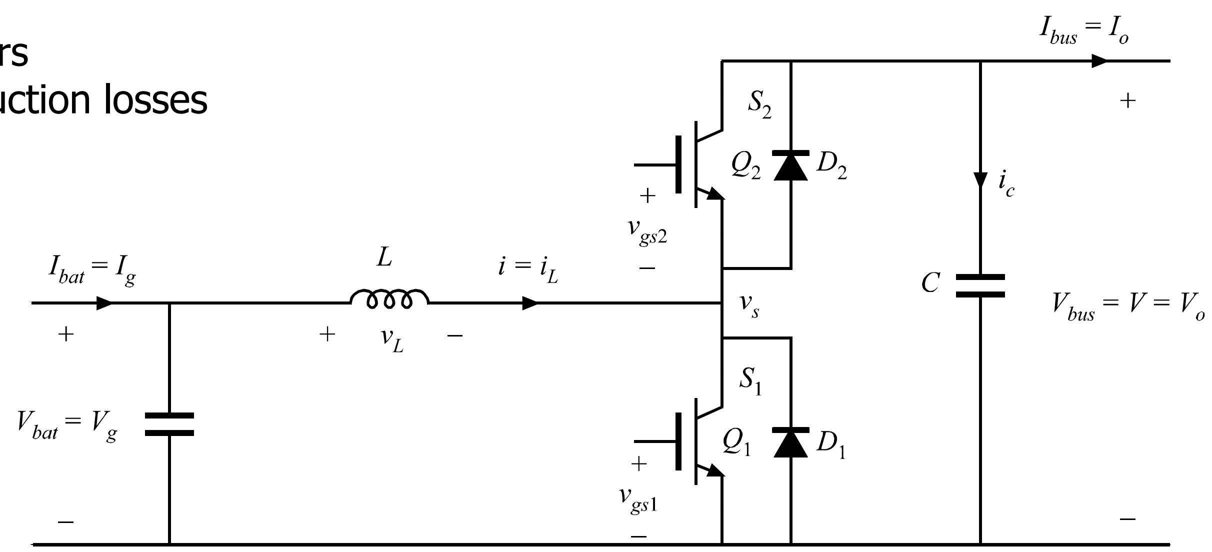
$$V_{bus} = \frac{1}{1-D} V_{bat} = M(D) V_{bat}$$

$$I_{bat} = \frac{1}{1-D} I_{bus} = M(D) I_{bus}$$

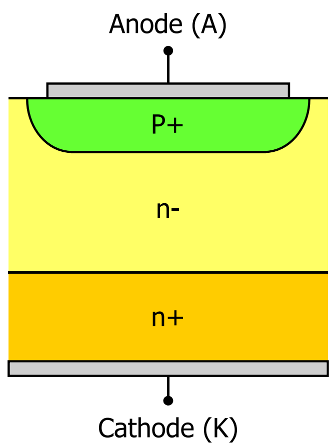


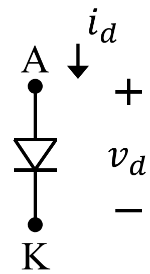
Losses

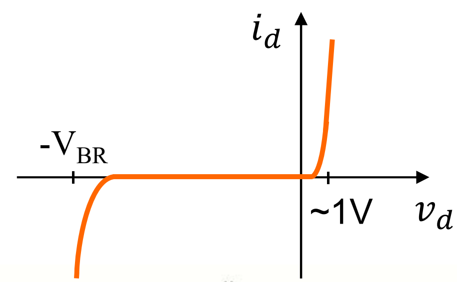
- Power semiconductor devices: diodes, IGBTs
  - Conduction losses
  - Switching losses
- Inductors
  - Conduction losses
  - Core losses
- Capacitors
  - Conduction losses

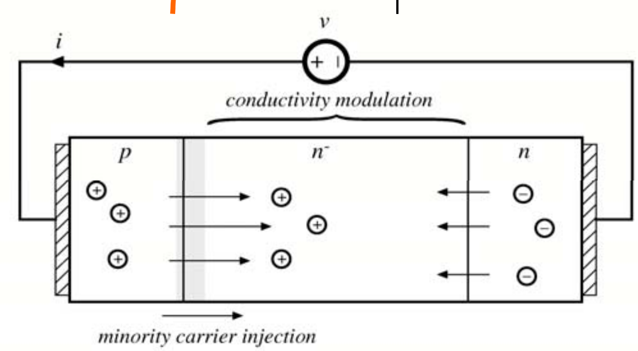


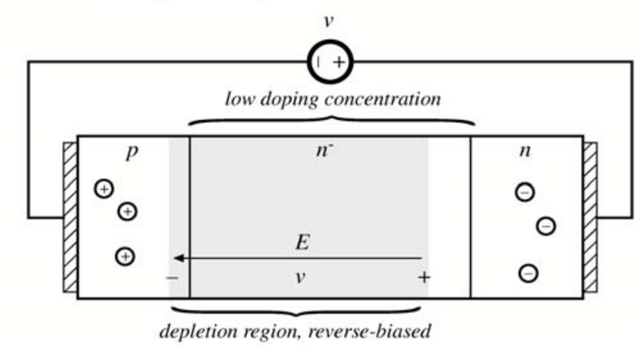
Power Bipolar PN-junction Diodes









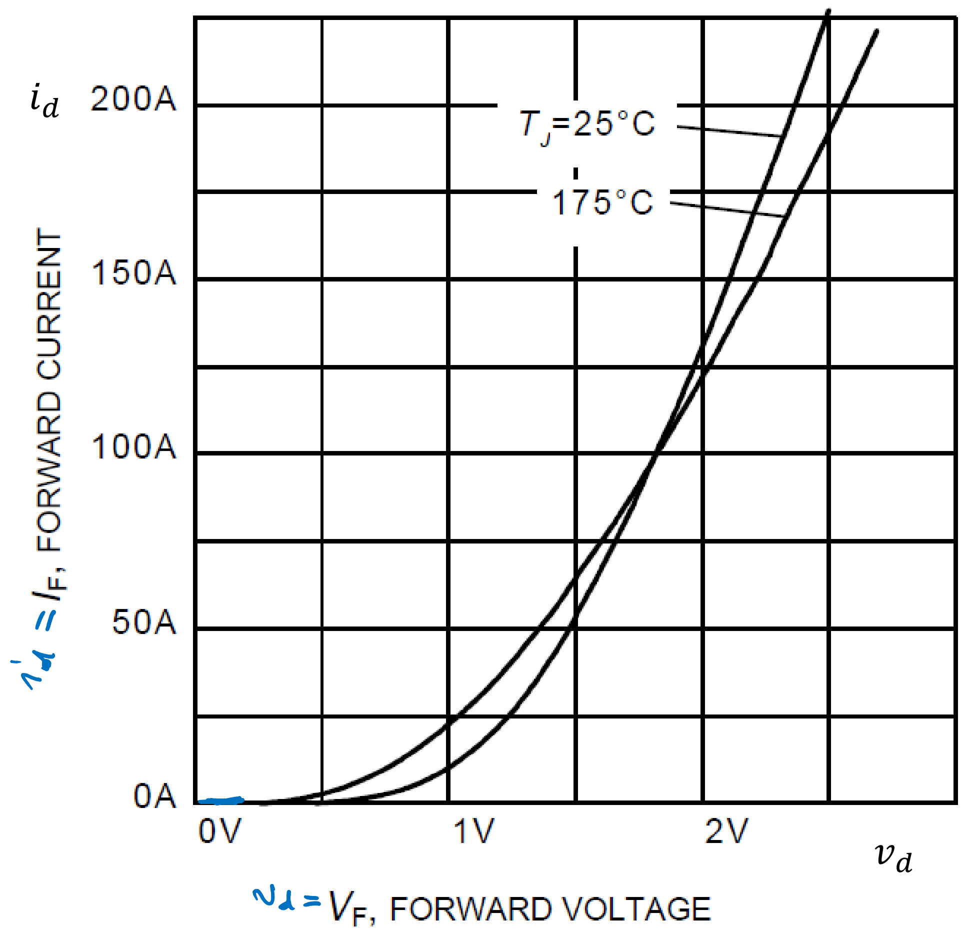


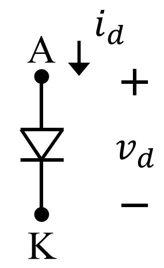
- Structural differences from small signal bipolar diodes
  - Vertical structure to maximize area for current flow
  - Very lightly doped n- drift region to block large reverse voltages
- *i-v* characteristic holds for equilibrium conditions

Diode Characteristic (Forward Biased)

forward bias.

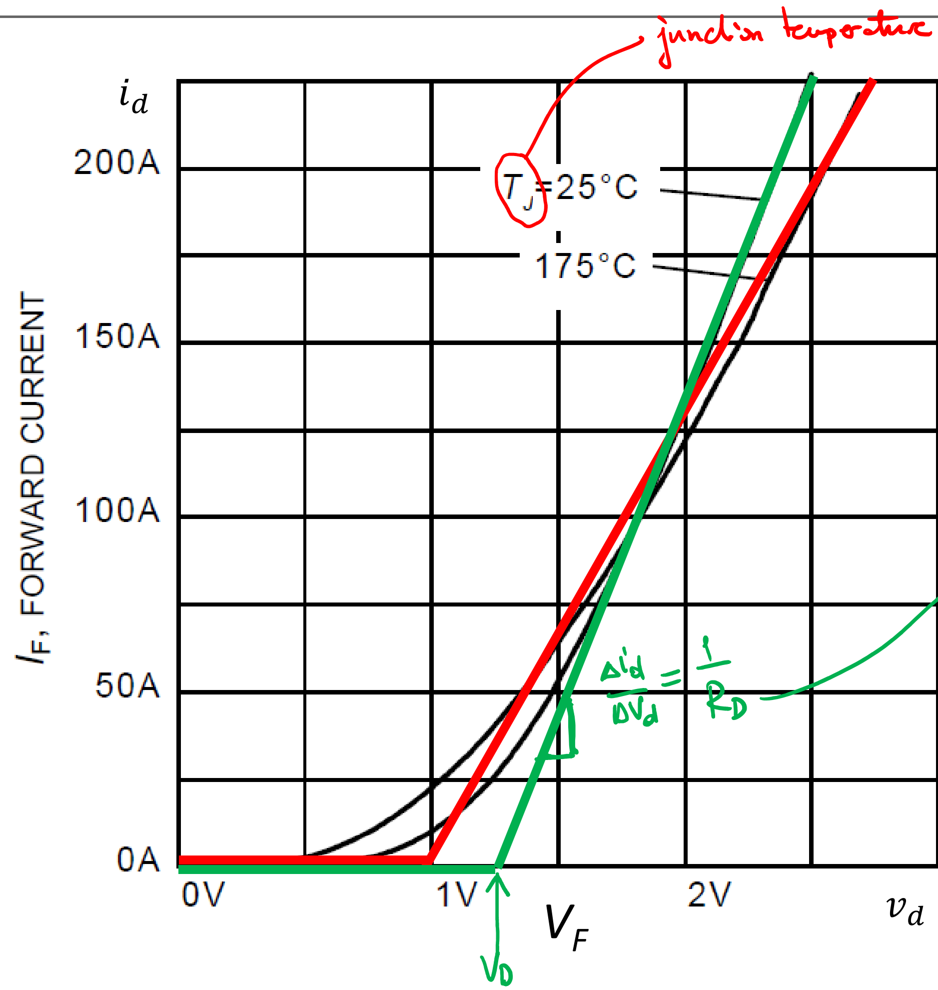
$i_d > 0$
$v_d > 0$

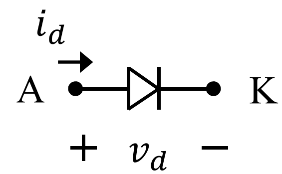




Example: Diode in Infineon IKW75N60T 600V, 75A IGBT module

Simple Diode Model



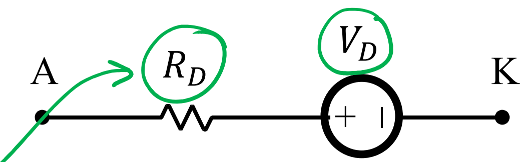


At higher Temp.

$R_D \uparrow$

$V_D \downarrow$

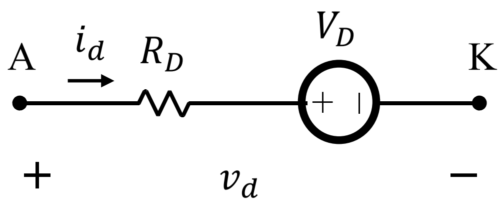
Forward biased (ON)



Reverse biased (OFF)

$i_d = 0$

Diode Conduction Loss



Instantaneous Loss: $p_{d,loss}(t) = v_d i_d$

heat

Average Loss: $P_{d,loss} = \frac{1}{T_s}\int_0^{T_s} v_d i_d dt = \frac{1}{T_s}\int_0^{T_s} (V_D + R_D i_d) i_d \, dt$

$$= \frac{1}{T_s}\int_0^{T_s} \underbrace{V_D}_{\text{const.}} i_d \, dt + \frac{1}{T_s}\int_0^{T_s} R_D i_d^2 \, dt =$$

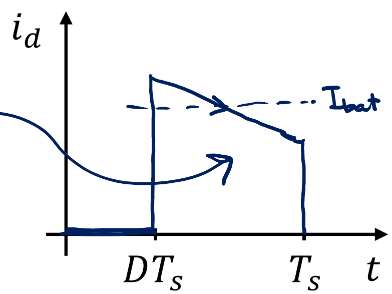
$$= \boxed{V_D \langle i_d \rangle_{T_s} + R_D I_{D,rms}^2}$$

Diode Conduction Loss Example

$\frac{1}{T_s}\int_0^{T_s} i_d(t)\,dt = D' I_{bat}$

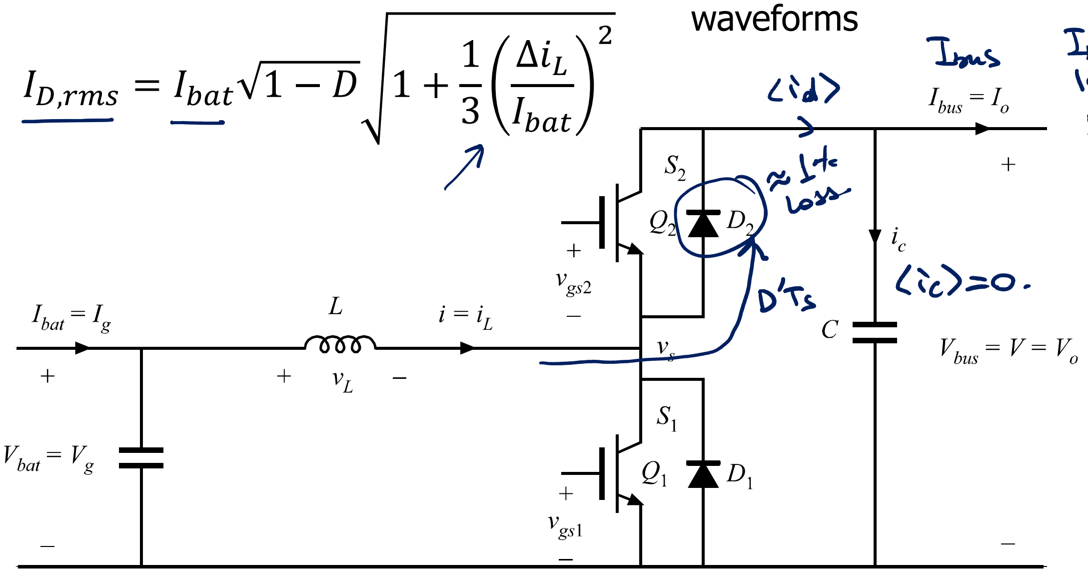
$$\langle i_d \rangle = I_D = (1-D) I_{bat}$$

$I_{D,rms}^2 = \frac{1}{T_s}\int_0^{T_s} i_d^2(t)\,dt$



$$I_{D,rms} = I_{bat}\sqrt{1-D}\sqrt{1+\frac{1}{3}\left(\frac{\Delta i_L}{I_{bat}}\right)^2}$$

Textbook Appendix A: RMS values of commonly observed converter waveforms



DC-DC Converter:

$V_{bat} = 250$ V, $V_{bus} = 500$ V, $I_{bus} = 100$ A,

$D \approx 0.5$, $I_L = I_{bat} \approx 200$ A, $\Delta i_L = 20$ A (example)

Diode:

$V_D = 1$ V, $R_D = 18$ mΩ

$\langle i_d \rangle = I_D = 100$ A

$I_{D,rms} = 142$ A

$P_D = V_D I_D + R_D I_{D,rms}^2$

$= 100$ W + 363 W = 463 W (0.9%)

ECEN 5017

Power Electronics for Electric Drive Vehicles

Lecture 22

Powertrain DC-DC Converter:

Loss Modeling and Efficiency Analysis

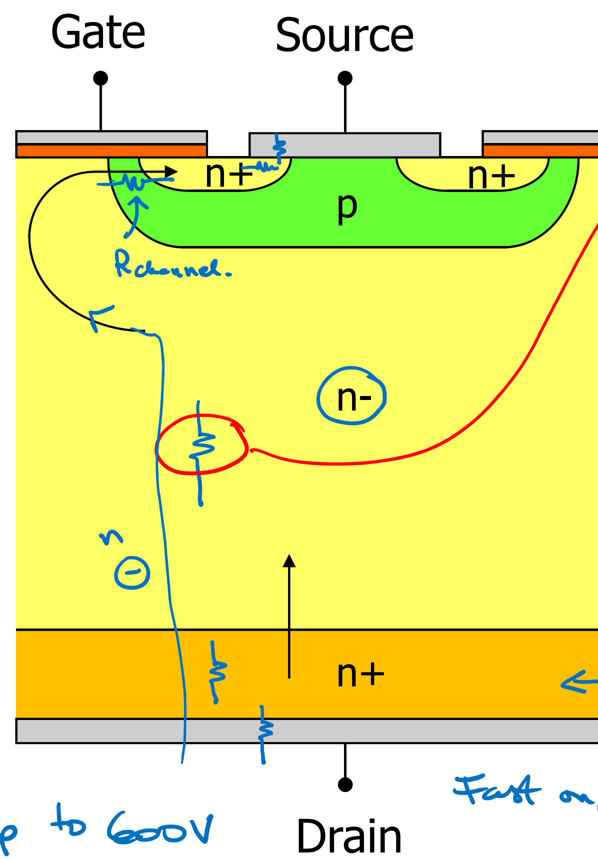
Announcements

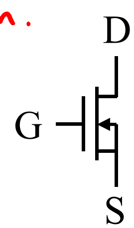
- Midterm exam will be out Friday October 14
  - Take-home exam, similar in length to HW assignments
  - Covers materials up to and including Lecture 23, assignments up to and including HW7. Will include simulations.
  - Open all course materials
  - Absolutely no collaboration allowed

Power MOSFET Structure

- Vertical structure to maximize area for current flow
- Source side composed of thousands of cells connected in parallel to maximize channel width
- There is a parasitic npn transistor between source and drain
  - To minimize possibility of this transistor turning on, p-well (body region) is shorted to source
  - Hence there is a parasitic diode between source and drain: body diode

Large V_{BD} => long n^- => large R_{on}.
(large voltage rating)





$R_{channel}$.

n
⊖

up to 600V

$V_{GS} >> V_{th}$.

S
$R_{on} = \sum R's$
D

$V_{GS} << V_{th}$
$R_{channel} \to \infty$
OFF

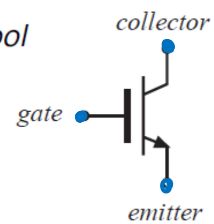
Fast on/off times

Insulated Gate Bipolar Transistor (IGBT)

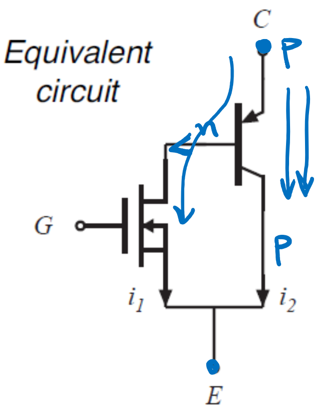
600V +

- Structure very similar to Power MOSFET
  - Substrate is p+ instead of n+
- In on-state p+ substrate injects holes into the drift region

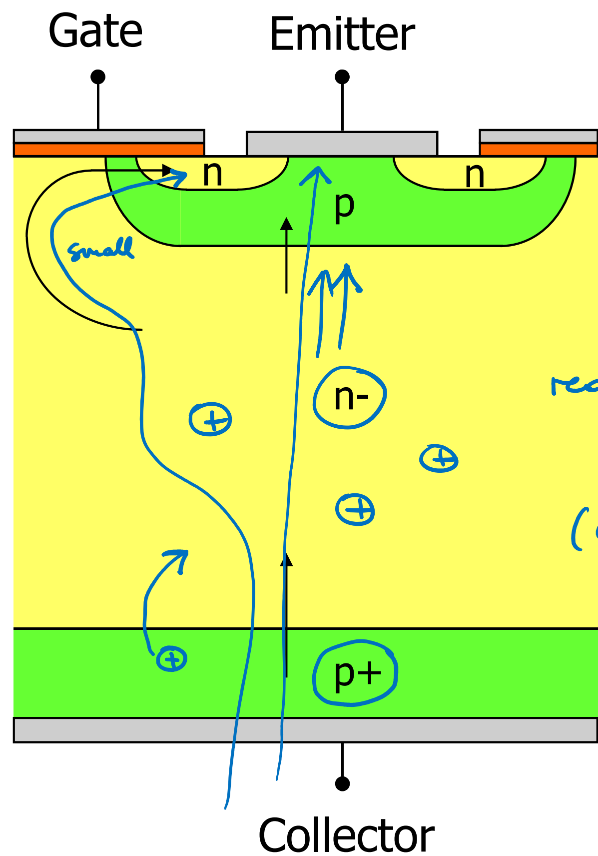
Symbol



Equivalent circuit



- Compared to MOSFET: slower switching times, lower on-resistance, useful at higher voltages (above 600 V)



$V_{GE} >> V_{th}$.
ON.
small forward voltage drop.

$V_{GE} << V_{th}$.
OFF

reduce on-resistance of the
n^- region.
(conductivity modulation)

slows turn OFF and turn ON

IGBT Characteristics

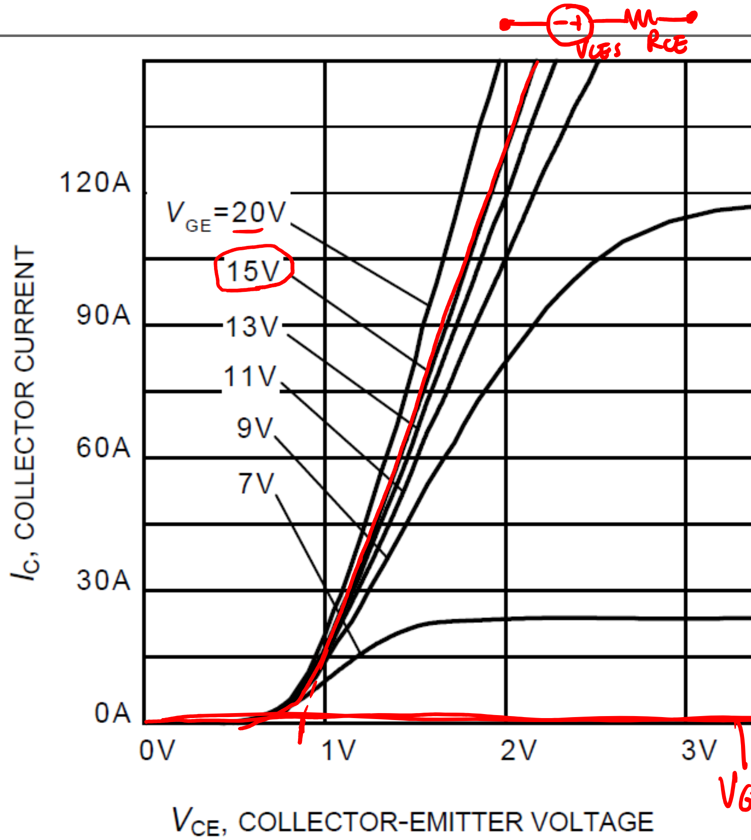


Figure 5. Typical output characteristic
(T_j = 25°C)

$V_{GE} < V_{th}$

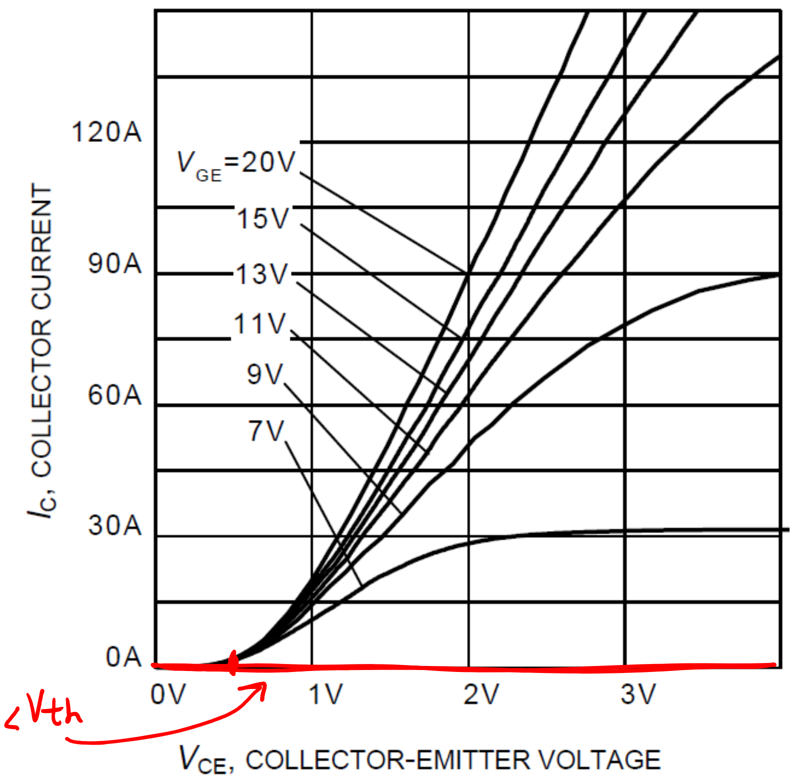


Figure 6. Typical output characteristic
(T_j = 175°C)

$R_{CE}\uparrow$
$V_{CES}\downarrow$

Example: Infineon IKW75N60T 600V, 75A IGBT

Simple IGBT Model

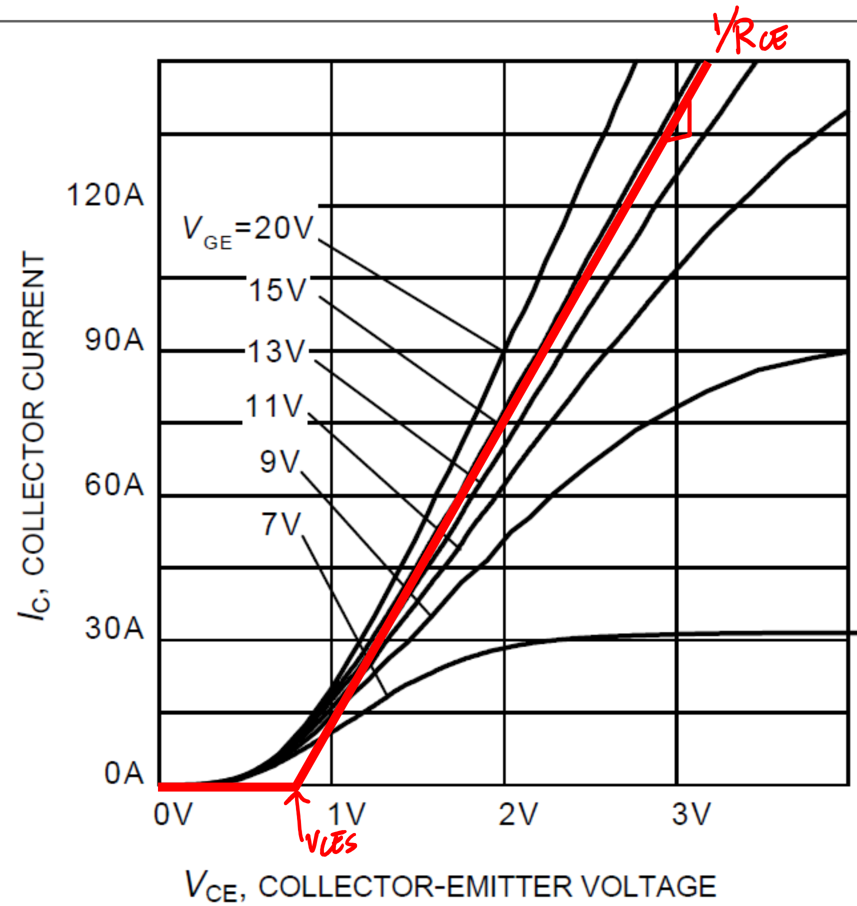
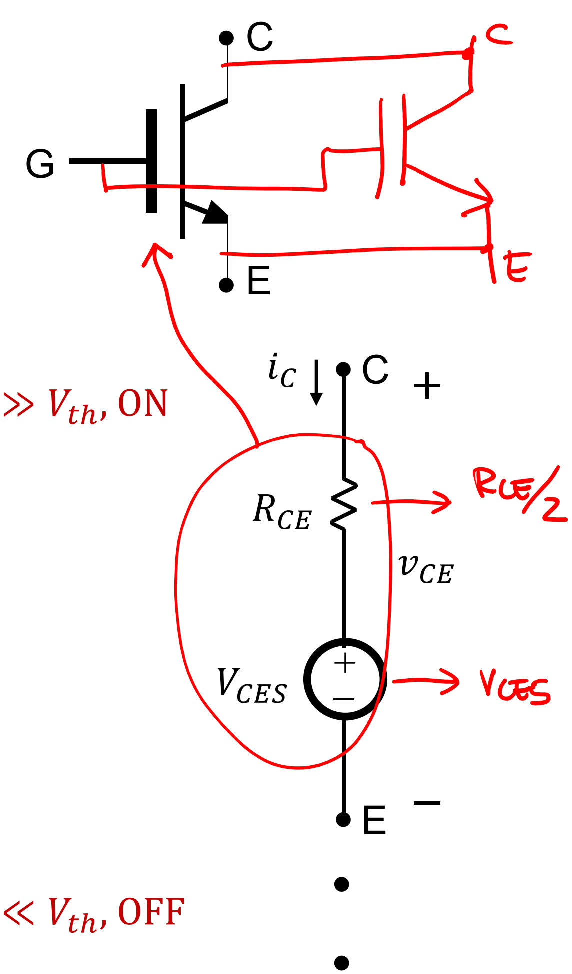


Figure 6. Typical output characteristic
(T_j = 175°C)

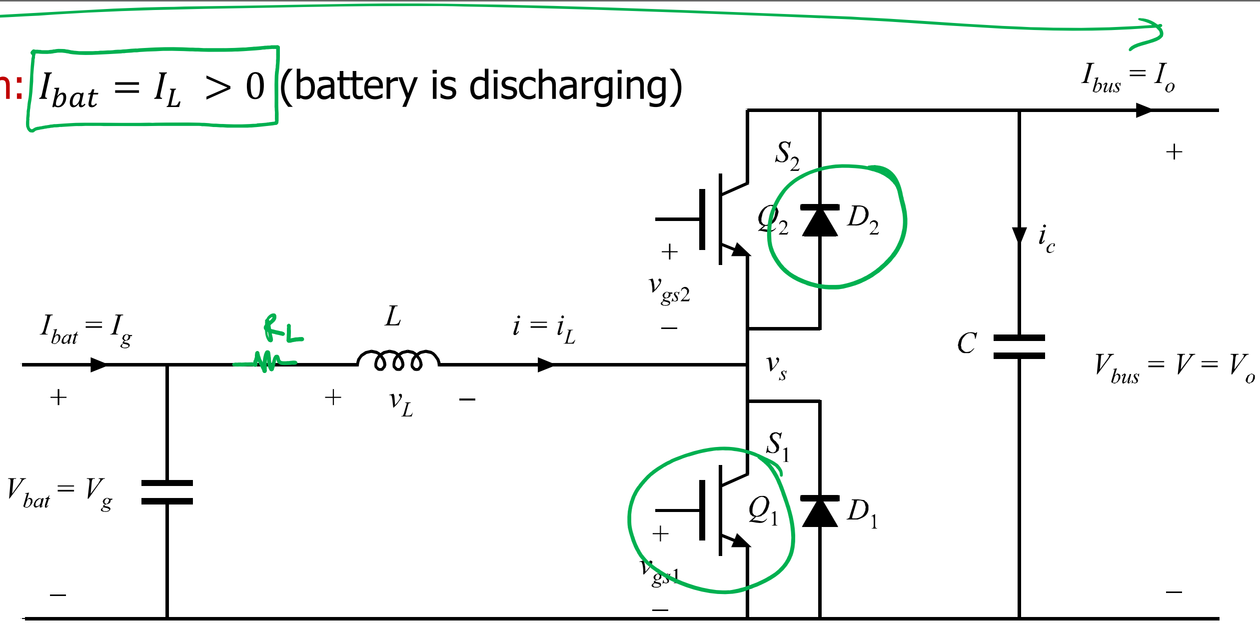


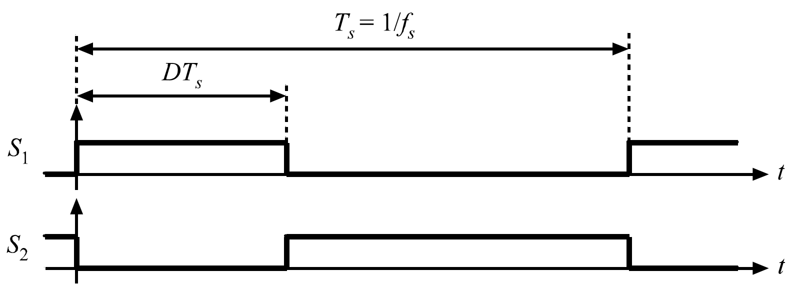
$v_{GE} \gg V_{th}$, ON

$v_{GE} \ll V_{th}$, OFF

Boost Converter with Conduction Losses

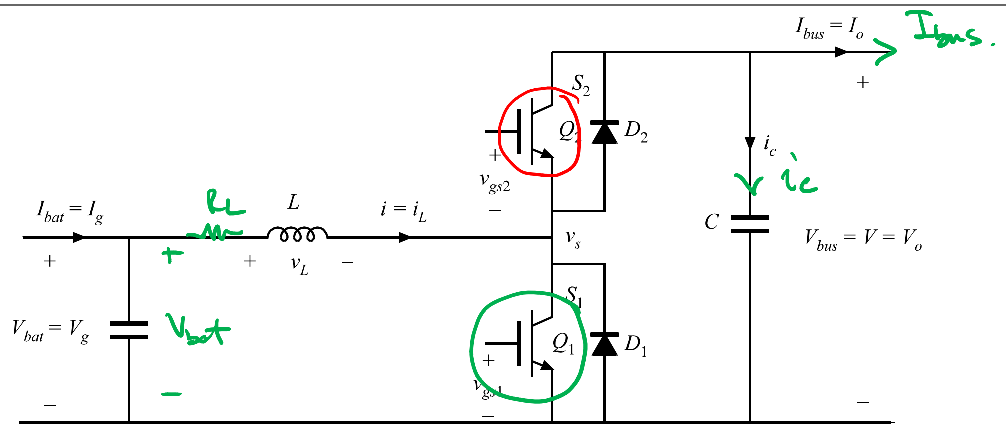
Assumption: $\boxed{I_{bat} = I_L > 0}$ (battery is discharging)





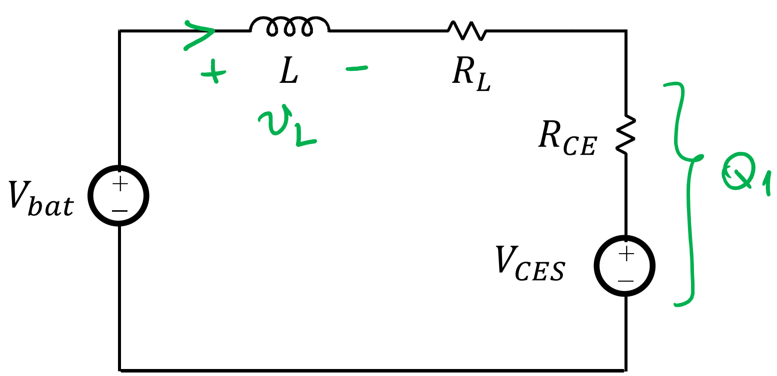
Boost Converter with S_1 on, S_2 off ($I_L > 0$)

IGBT Q_1 conducting



small ripple approx.

$i_L \approx I_L = I_{bat}$

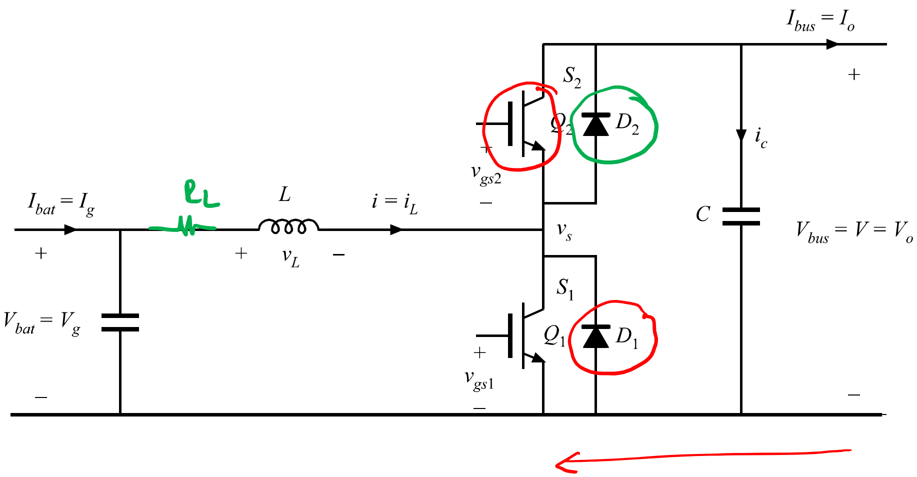


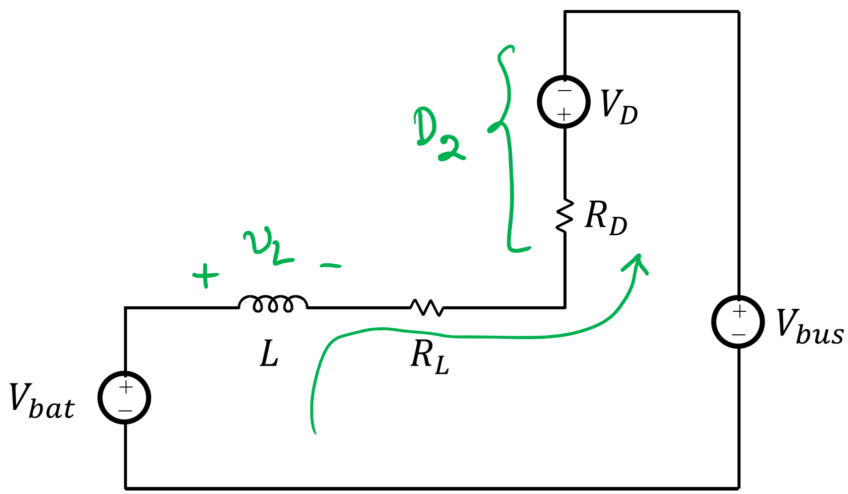
$$v_L = V_{bat} - (R_L + R_{CE})I_{bat} - V_{CES}$$

$$i_C = -I_{bus}$$

Boost Converter with S_1 off, S_2 on ($I_L > 0$)

Diode D_2 conducting





$$v_L = V_{bat} - (R_L + R_D)I_{bat} - V_D - V_{bus}$$

$$i_C = I_{bat} - I_{bus}$$

Volt-Seconds Balance and Charge Balance

For time DT_s:

$$v_L = V_{bat} - (R_L + R_{CE})I_{bat} - V_{CES}$$

For time $(1 - D)T_s$:

$$v_L = V_{bat} - (R_L + R_D)I_{bat} - V_D - V_{bus}$$

$\langle v_L \rangle = 0$

$$\langle v_L \rangle = D\left(V_{bat} - (R_L + R_{CE})I_{bat} - V_{CES}\right) + (1-D)\left(V_{bat} - (R_L + R_D)I_{bat} - V_D - V_{bus}\right) = 0$$

$$\boxed{V_{bat} - (R_L + DR_{CE} + D'R_D)\cdot I_{bat} - (DV_{CES} + D'V_D) = D' V_{bus}.}$$

For time DT_s:

$$i_C = -I_{bus}$$

For time $(1 - D)T_s$:

$$i_C = I_{bat} - I_{bus}$$

$\langle i_C \rangle = 0$

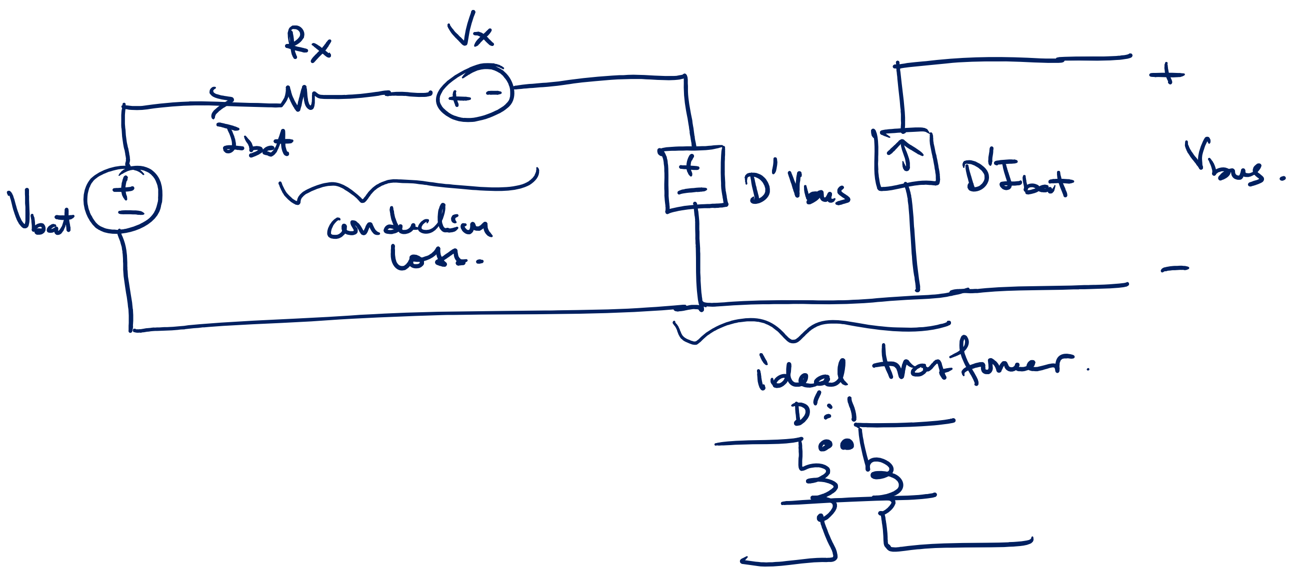
$$\langle i_C \rangle = D(-I_{bus}) + (1-D)(I_{bat} - I_{bus}) = 0$$

$$\boxed{(1-D)I_{bat} = I_{bus}}$$

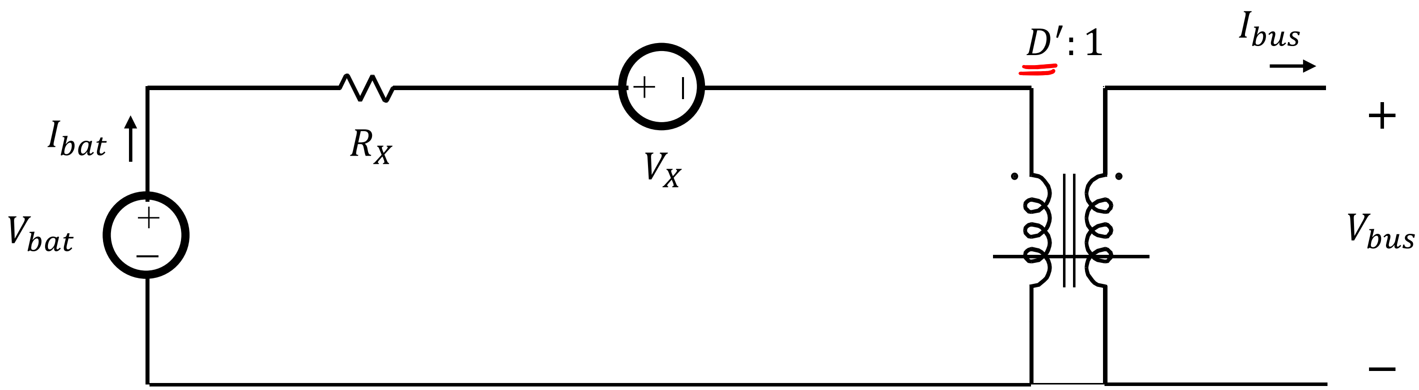
Average Circuit Model of Boost Converter with Conduction Loses ($I_L > 0$)

$$\langle v_L \rangle = V_{bat} - \underbrace{(R_L + DR_{CE} + D'R_D)}_{R_x} I_{bat} - \underbrace{(DV_{CES} + D'V_D)}_{V_x} - D'V_{bus} = 0$$

$$\langle i_L \rangle = D'I_{bat} - I_{bus} = 0$$



Average Model of Boost with Conduction Losses ($I_{BAT} > 0$)



$$R_X = R_L + DR_{CE} + D'R_D$$

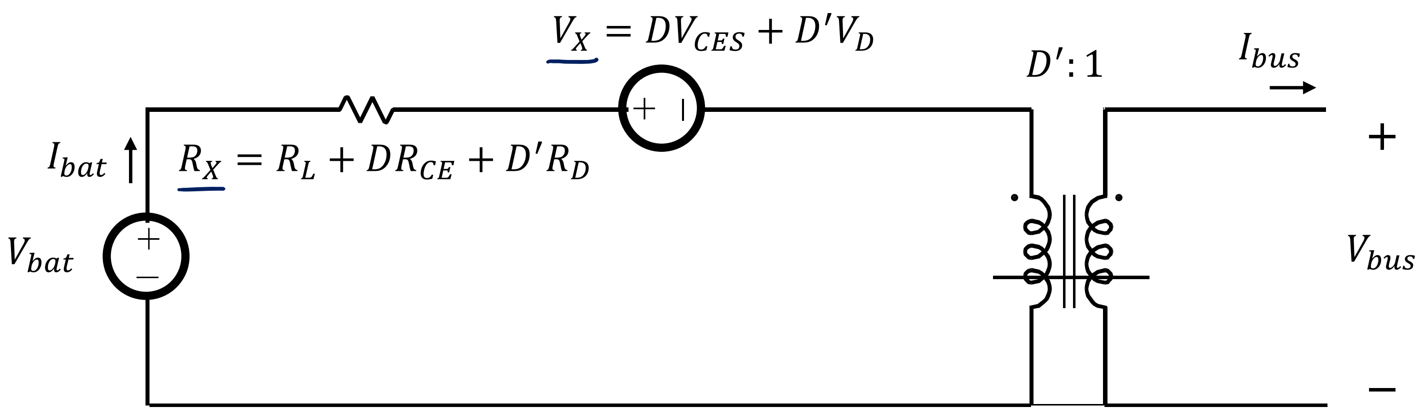
$$V_X = DV_{CES} + D'V_D$$

What if $I_{bat} < 0$?

$R_x = D' R_{CE} + D R_D$

$V_x = D' V_{CES} + D V_D$.

Analysis of Conduction Losses and Efficiency , $I_{bat} > 0$.



$I_{bat} > 0$: $\eta = \underbrace{\dfrac{V_{bus}I_{bus}}{V_{bat}I_{bat}}} = \dfrac{P_{bus}}{P_{bat}} = \dfrac{P_{bus}}{P_{bus} + P_{loss}}. = \dfrac{P_{bat} - P_{loss}.}{P_{bat}}$

Solve the circuit.

$I_{bat} > 0$.

ideal conversion ratio.

$M = \boxed{\dfrac{1}{D'}}\eta$

when only conduction losses are considered.

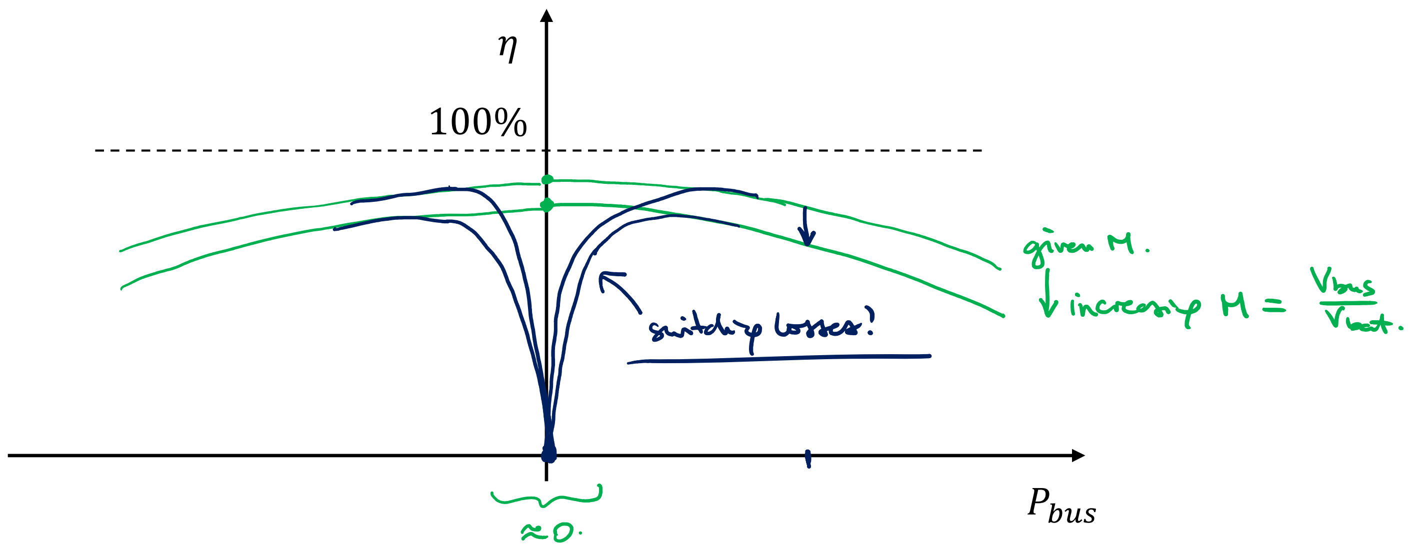
$$\boxed{\eta = 1 - \frac{R_X I_{bat} + V_X}{V_{bat}}}$$

$$\boxed{M \equiv \frac{V_{bus}}{V_{bat}} = \frac{1}{D'}\left(1 - \frac{R_X I_{bat} + V_X}{V_{bat}}\right)}$$

Efficiency and Duty Cycle

$$\eta = 1 - \frac{(R_L + DR_{CE} + D'R_D)I_{bat} + DV_{CES} + D'V_D}{V_{bat}}$$

given M, given D.



ECEN 5017

Power Electronics for Electric Drive Vehicles

Lecture 23

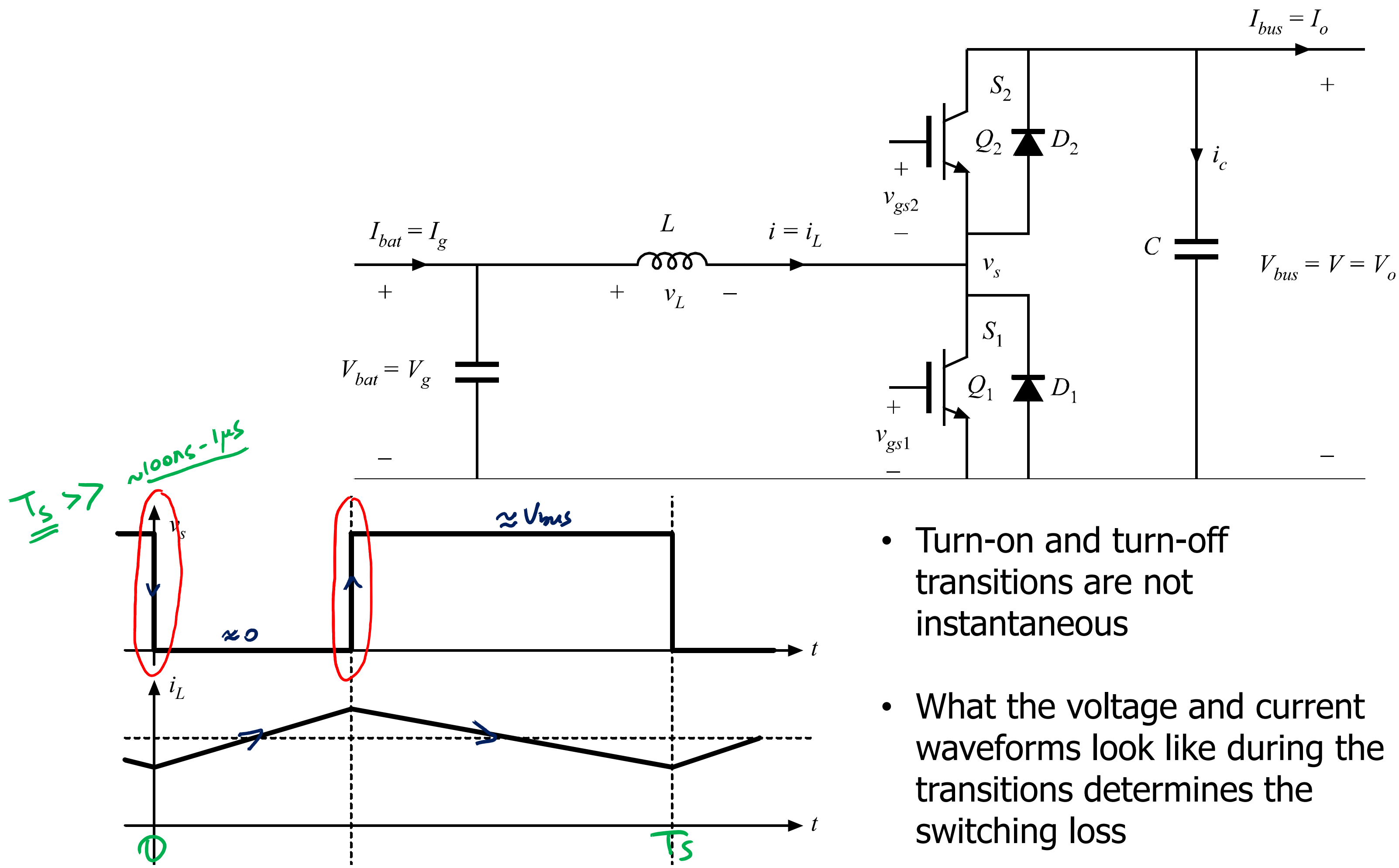
Powertrain DC-DC Converter:

Switching Losses

Announcements

- Midterm exam starts 9am (Mountain time) on Friday, Oct 14, due by 10pm (Mountain time) on Thursday, Oct 20
- Open-book, open-notes exam.
- Show all work, partial credit will be given.
- During the exam, you may ask for clarifications of the exam problem statements, but the instructor will not answer any questions related to the exam problem solutions.
- **Absolutely no collaboration is allowed.** You may not consult with anyone about the exam problems or use anyone else's work related to solutions of the exam problems in any form. You are not allowed to give or receive any assistance on this exam.

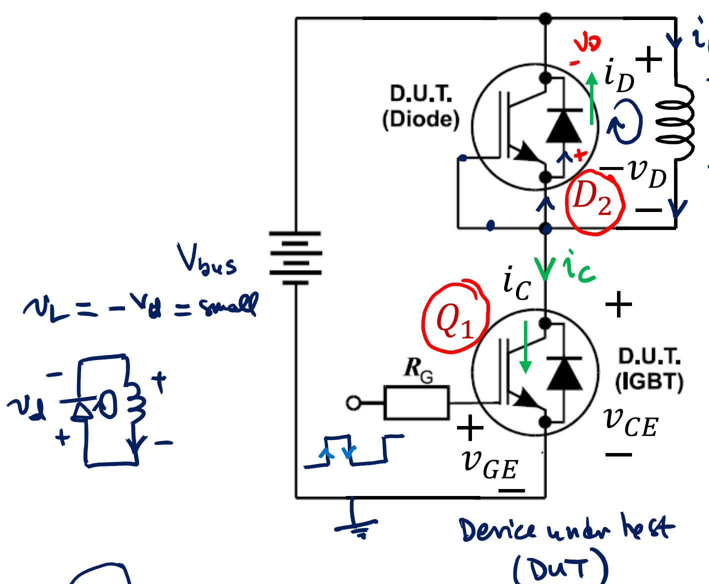
Switching Losses

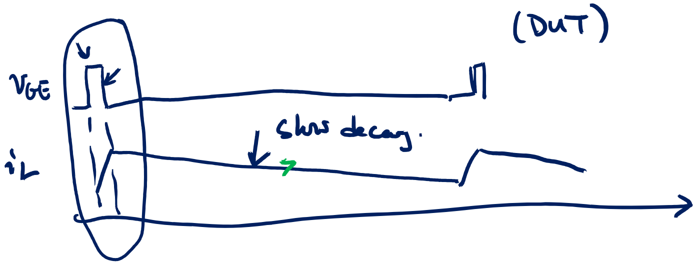


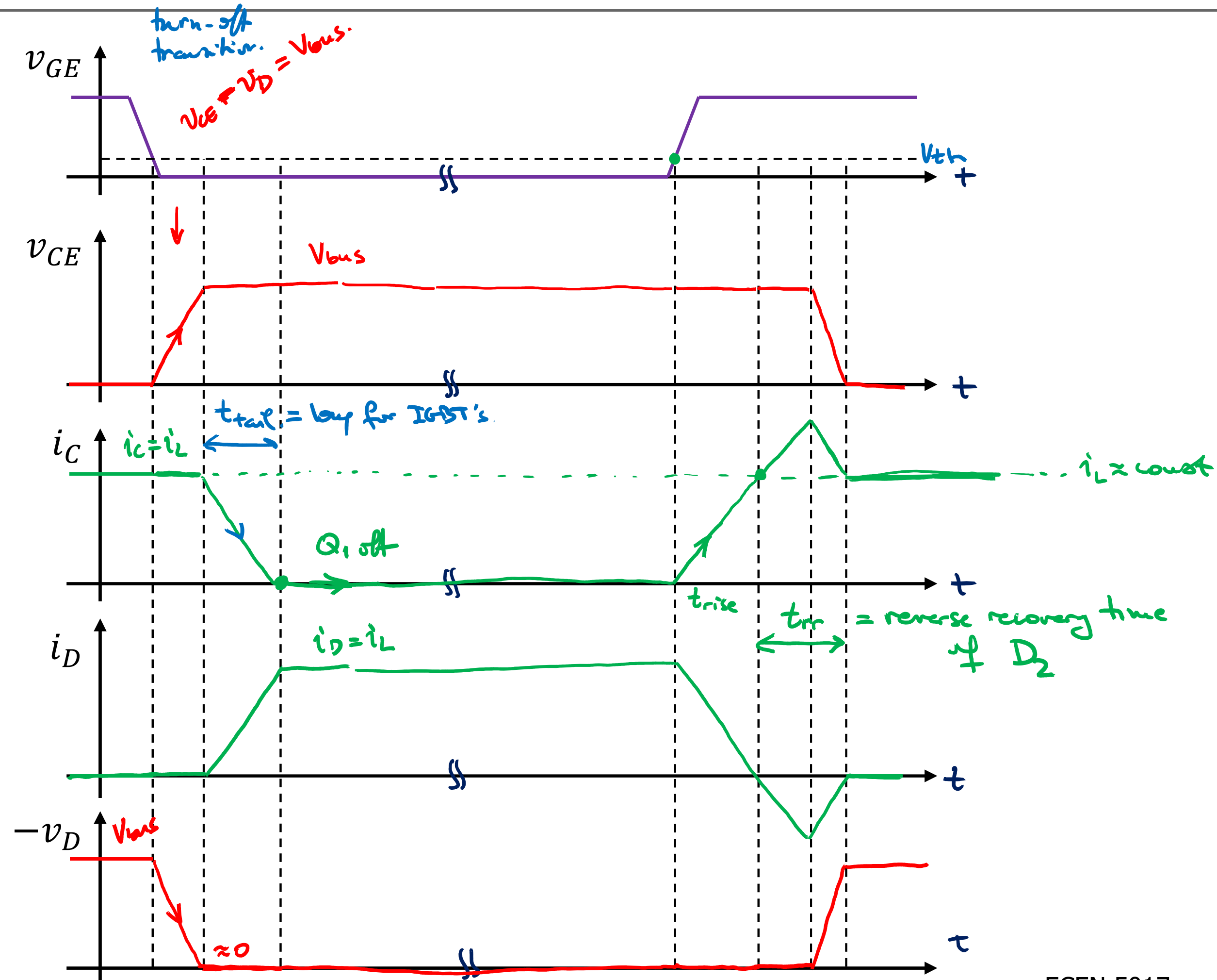
- Turn-on and turn-off transitions are not instantaneous
- What the voltage and current waveforms look like during the transitions determines the switching loss

Switching Waveforms in Test Circuit

Test Circuit
(inductive switching)

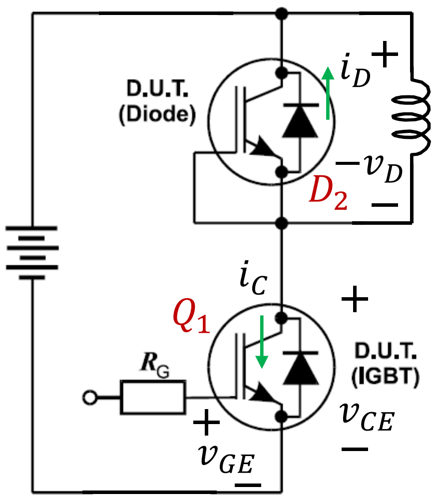


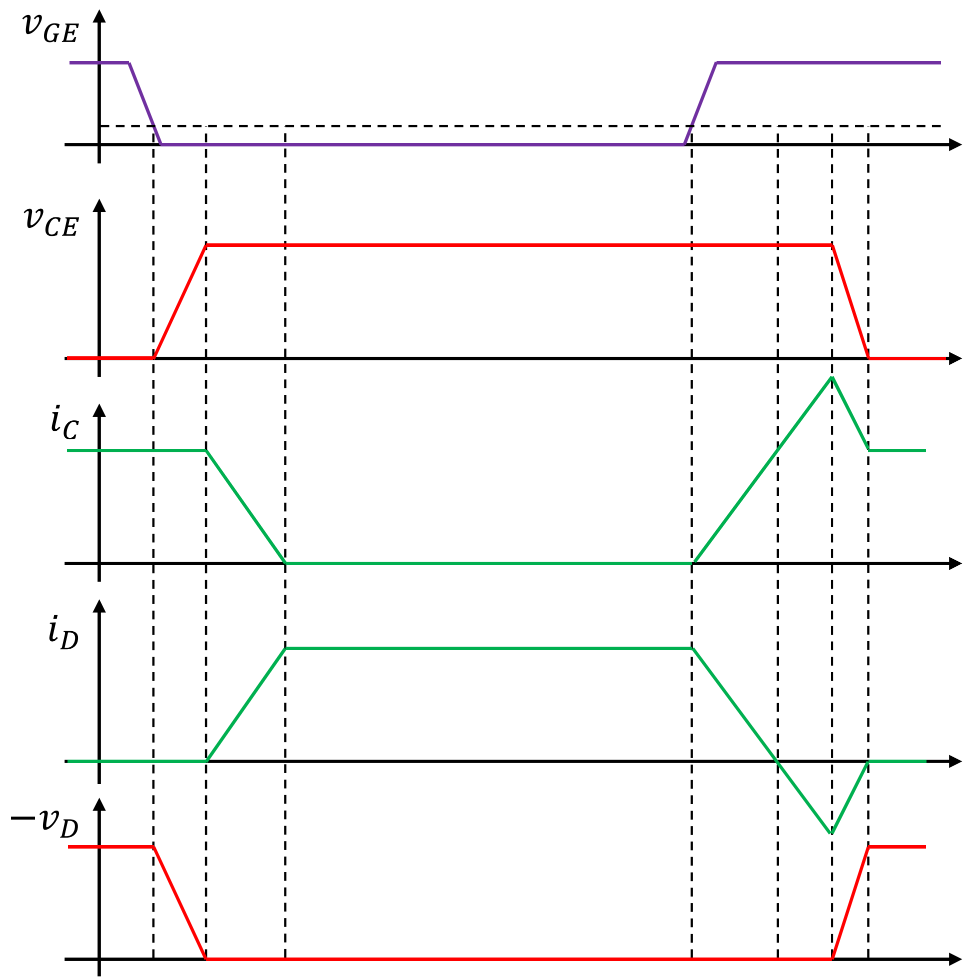




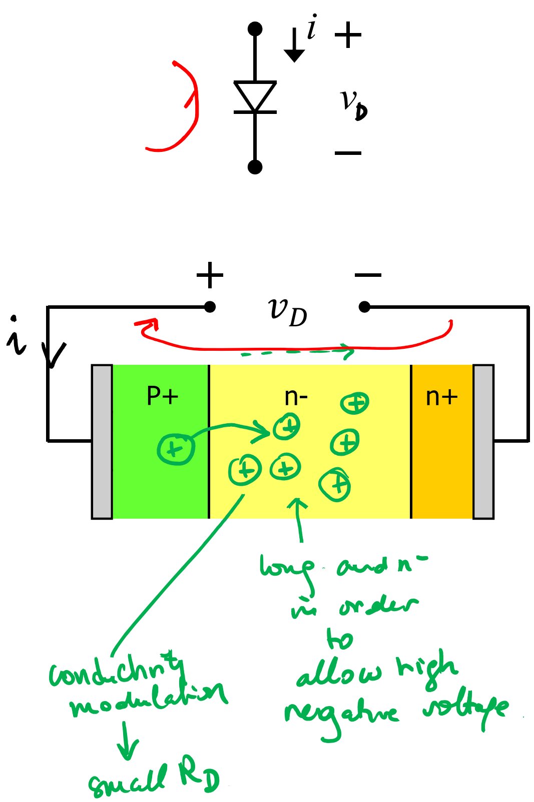
Switching Waveforms in Test Circuit

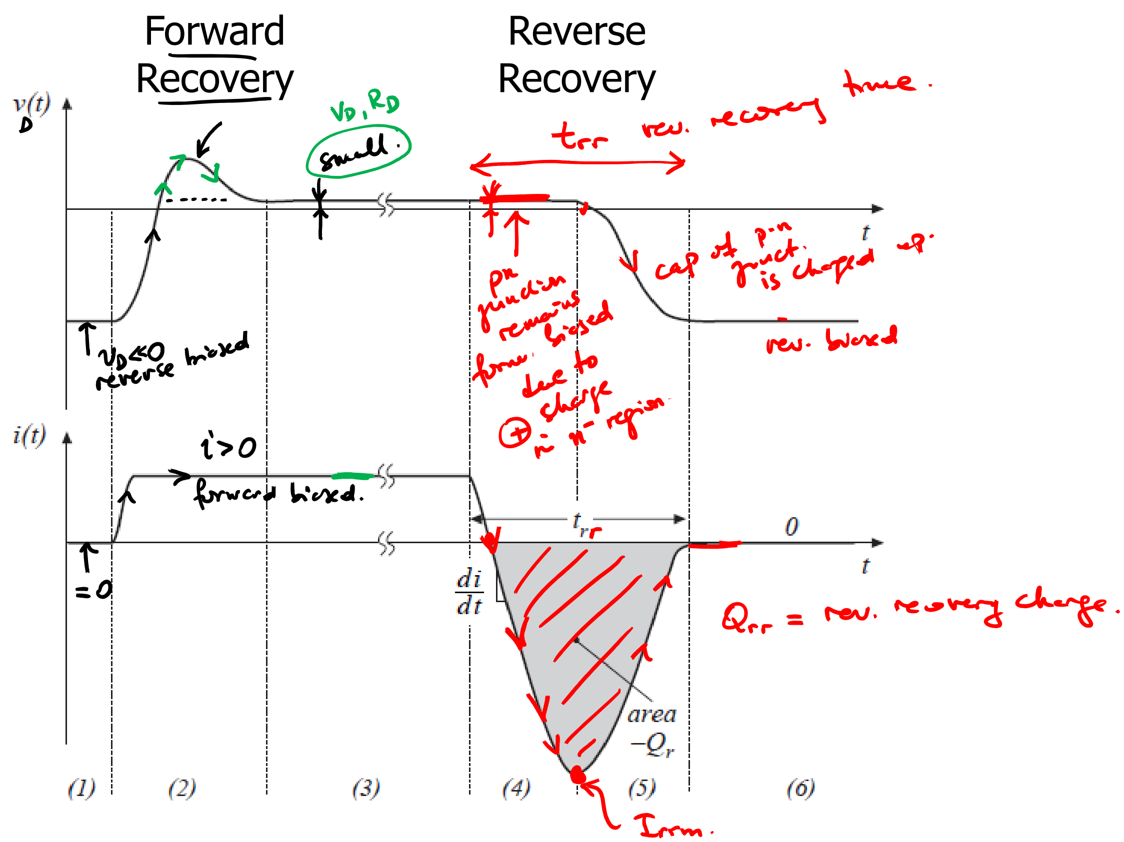
Test Circuit
(inductive switching)





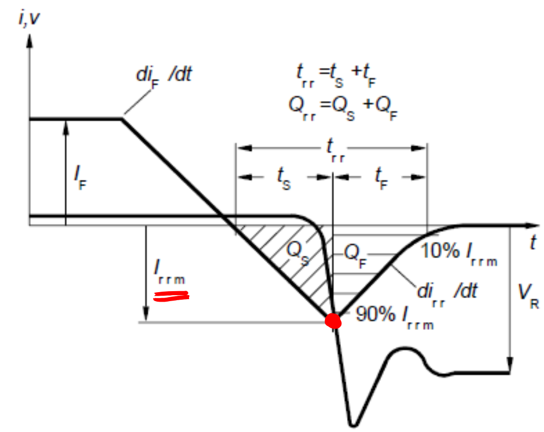
Diode Switching Characteristics





Example Diode Data

Diode in Infineon IKW75N60T
600V, 75A IGBT module



Anti-Parallel Diode Characteristic

Diode reverse recovery time	t_{rr}	T_j=25°C,	-	121	-	ns
Diode reverse recovery charge	Q_{rr}	V_R=400V, I_F=75A,	-	2.4	-	µC
Diode peak reverse recovery current	I_{rrm}	di_F/dt=1460A/µs	-	38.5	-	A
Diode peak rate of fall of reverse recovery current during t_b	di_{rr}/dt		-	921	-	A/µs

coulomb.

sw. loss → design.

Anti-Parallel Diode Characteristic

Diode reverse recovery time	t_{rr}	T_j=175°C	-	182	-	ns
Diode reverse recovery charge	Q_{rr}	V_R=400V, I_F=75A,	-	5.8	-	µC
Diode peak reverse recovery current	I_{rrm}	di_F/dt=1460A/µs	-	56.2	-	A
Diode peak rate of fall of reverse recovery current during t_b	di_{rr}/dt		-	1013	-	A/µs

Diode Reverse Recovery Characteristics

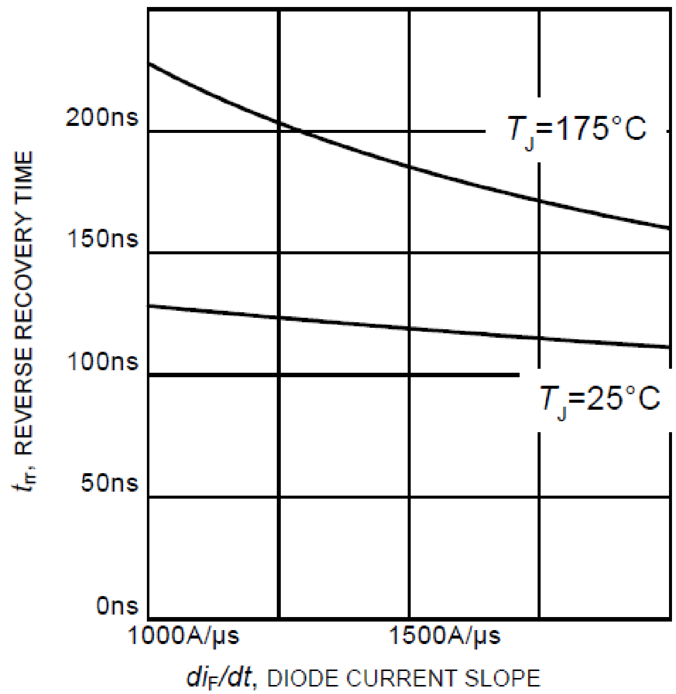


Figure 23. Typical reverse recovery time as a function of diode current slope
(V_R=400V, I_F=75A,
Dynamic test circuit in Figure E)

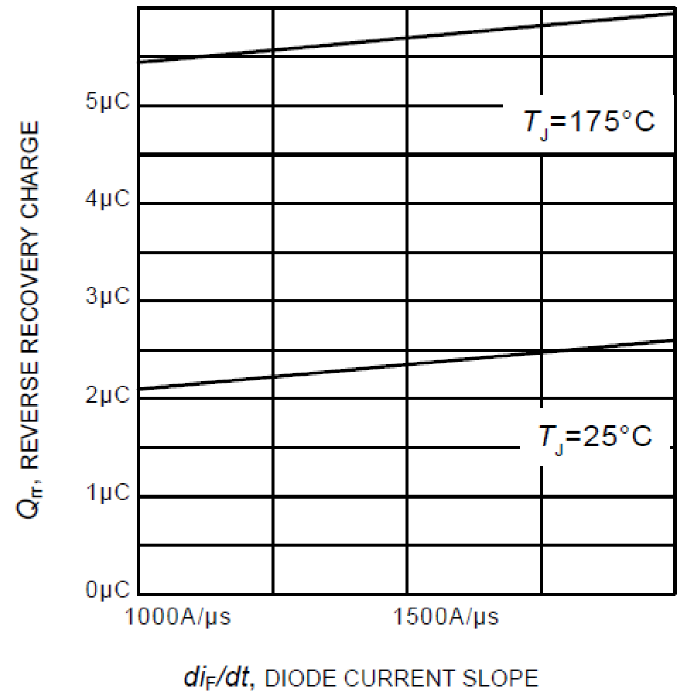


Figure 24. Typical reverse recovery charge as a function of diode current slope
(V_R = 400V, I_F = 75A,
Dynamic test circuit in Figure E)

Diode in Infineon IKW75N60T 600V, 75A IGBT module

ECEN 5017

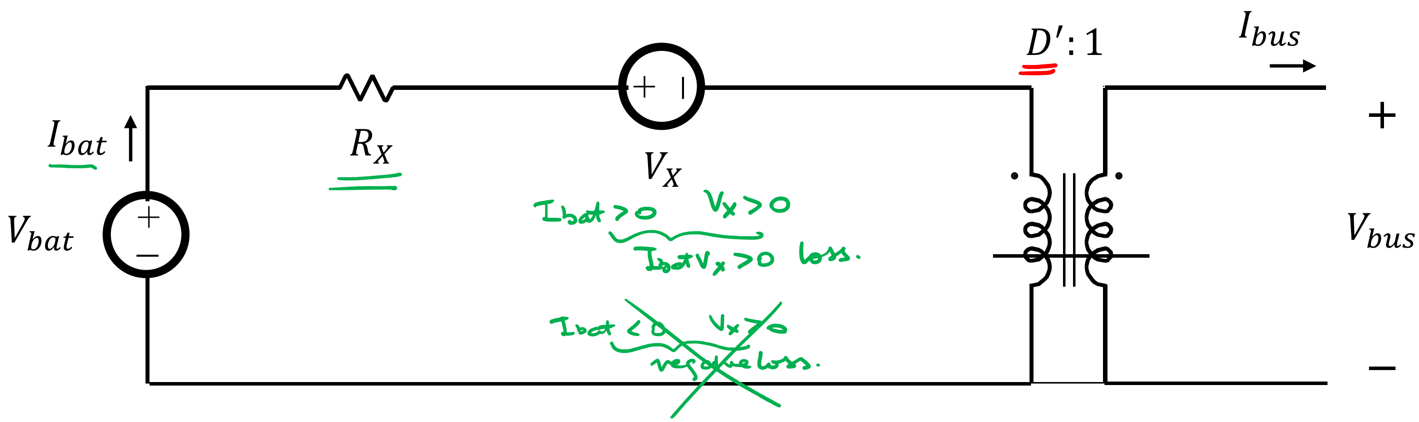
Power Electronics for Electric Drive Vehicles

Lecture 24

Powertrain DC-DC Converter:

Modeling of Switching Losses

Average Model of Boost with Conduction Losses ($I_{BAT} > 0$)



$$R_X = R_L + DR_{CE} + D'R_D$$

$$V_X = DV_{CES} + D'V_D$$

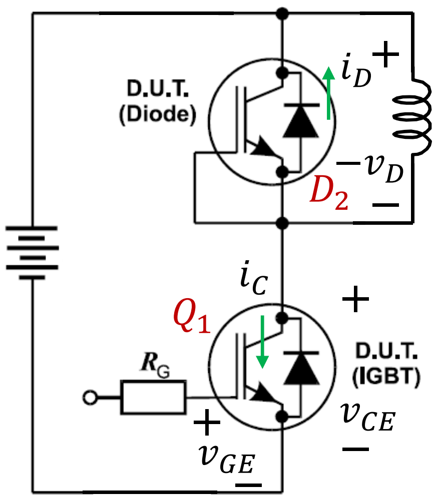
What if $I_{bat} < 0$?

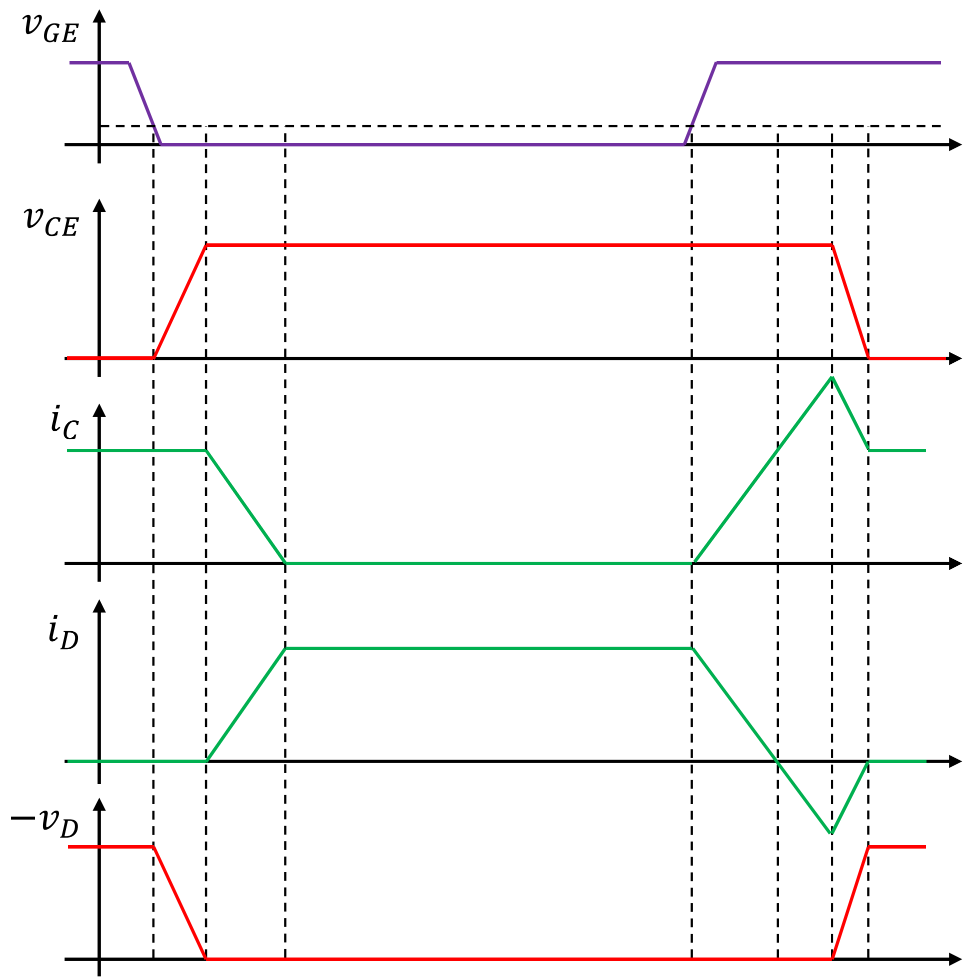
$$R_x = D'R_{CE} + DR_D$$

$$V_x = -(D'V_{CES} + DV_D)$$

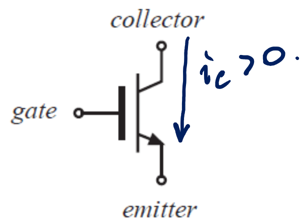
Switching Waveforms in Test Circuit

Test Circuit
(inductive switching)

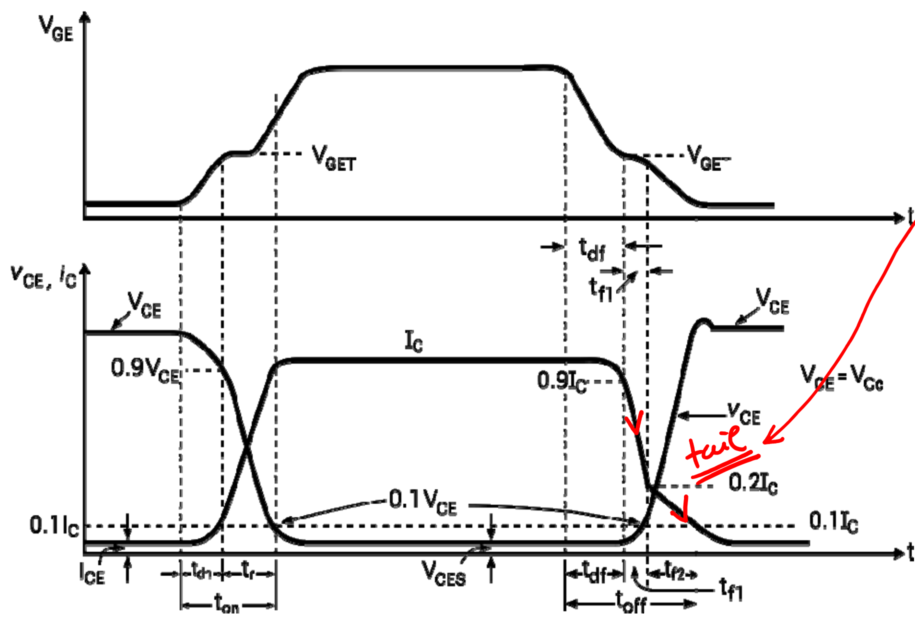


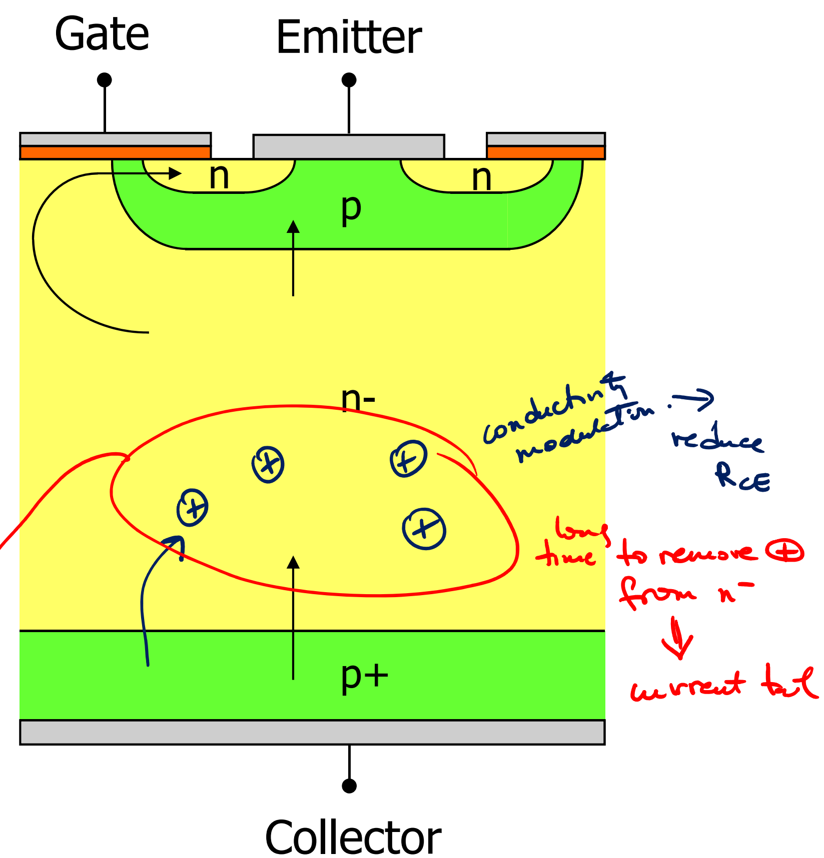


IGBT Switching Characteristics



- In on-state, n- drift region has excess charge, which results in a current tail during turn-off





Example IGBT Data

Infineon IKW75N60T 600V, 75A IGBT module

IGBT Characteristic

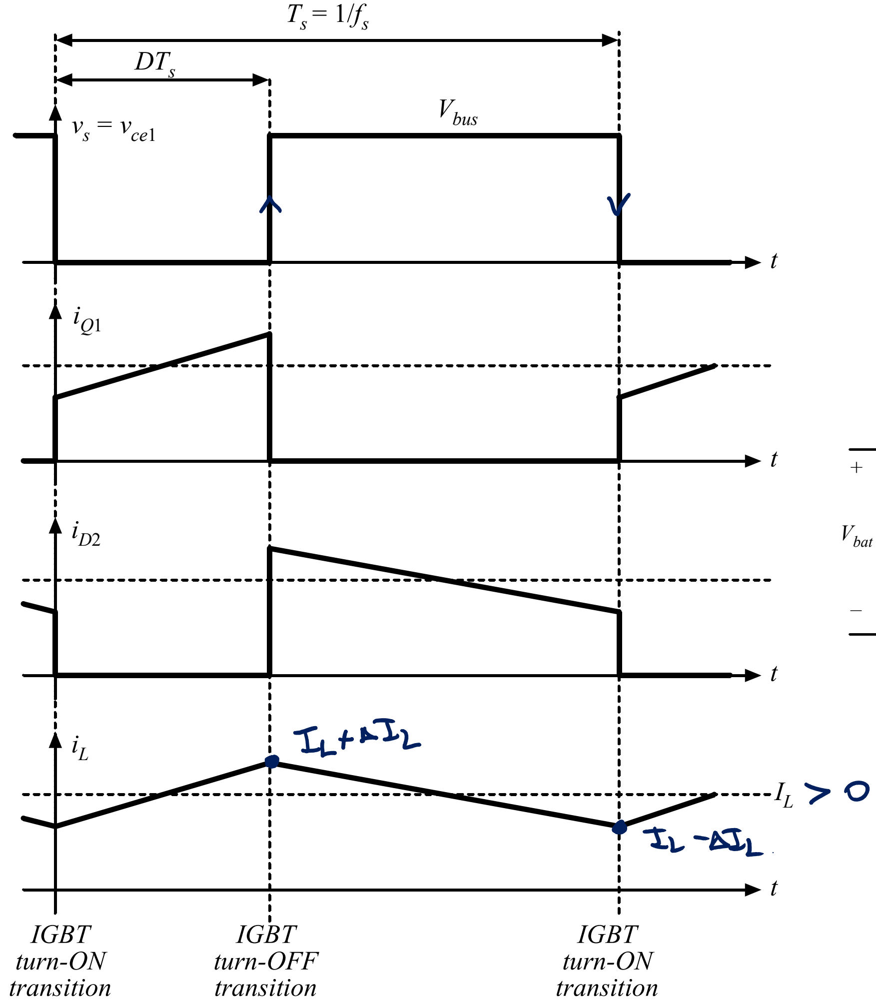
Turn-on delay time	$t_{d(on)}$	T_j=25°C, V_{CC}=400V, I_C=75A, V_{GE}=0/15V, R_G=5Ω, L_σ[1)]=100nH, C_σ[1)]=39pF Energy losses include “tail” and diode reverse recovery.	-	33	-	ns
Rise time	t_r		-	36	-	
Turn-off delay time	$t_{d(off)}$		-	330	-	
Fall time	t_f		-	35	-	
Turn-on energy	E_{on}		-	2.0	-	mJ
Turn-off energy	E_{off}		-	2.5	-	
Total switching energy	E_{ts}		-	4.5	-	

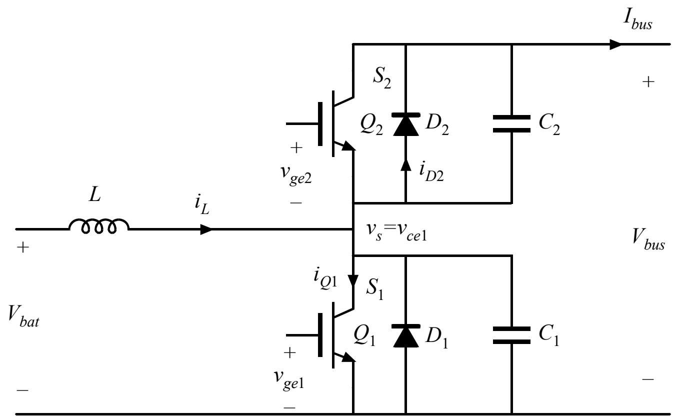
IGBT Characteristic

Turn-on delay time	$t_{d(on)}$	T_j=175°C, V_{CC}=400V, I_C=75A, V_{GE}=0/15V, R_G= 5Ω, L_σ[1)]=100nH, C_σ[1)]=39pF Energy losses include “tail” and diode reverse recovery.	-	32	-	ns
Rise time	t_r		-	37	-	
Turn-off delay time	$t_{d(off)}$		-	363	-	
Fall time	t_f		-	38	-	
Turn-on energy	E_{on}		-	2.9	-	mJ
Turn-off energy	E_{off}		-	2.9	-	
Total switching energy	E_{ts}		-	5.8	-	

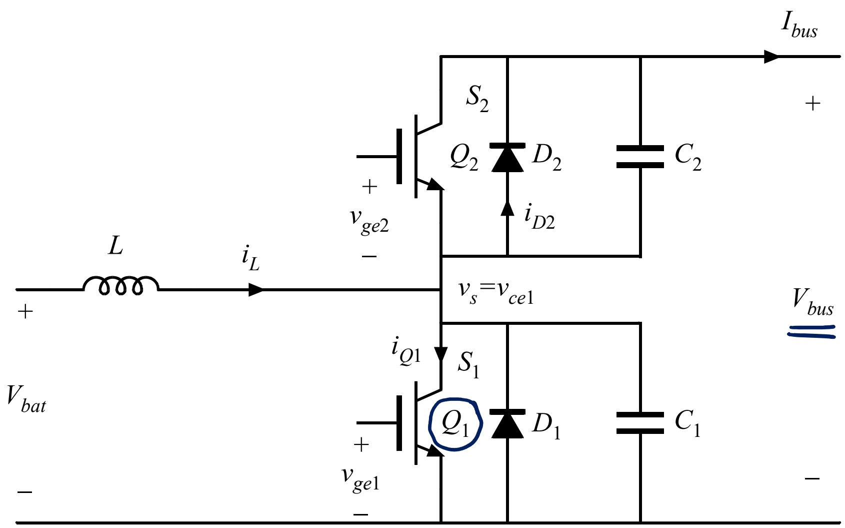
Switching Waveforms for Boost Converter

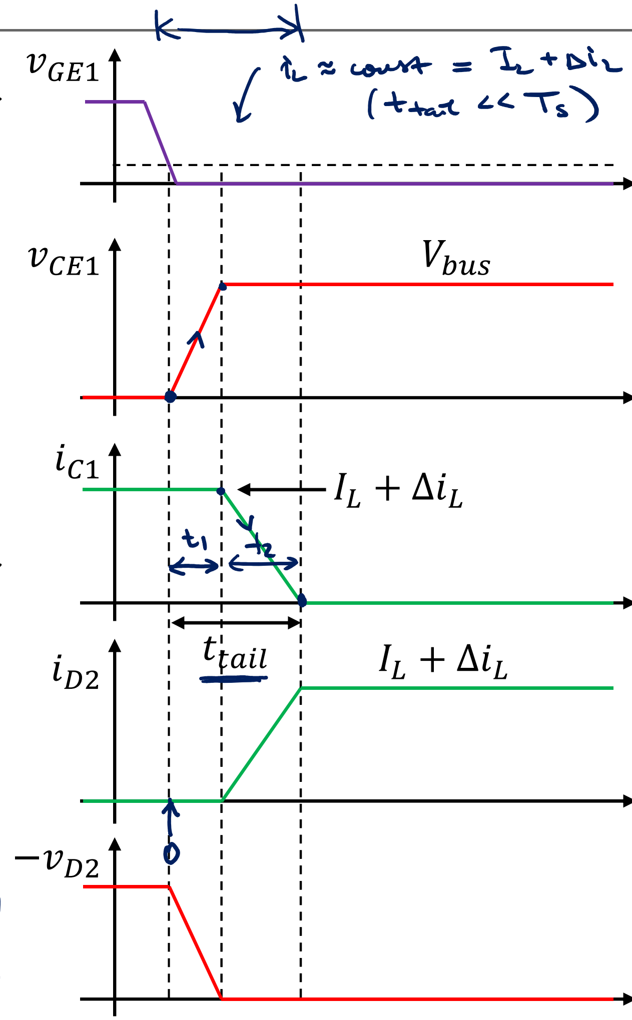
$I_{bat} > 0$





Turn-Off Losses





$i_L \approx$ const $= I_L + \Delta i_L$ $(t_{tail} \ll T_s)$

$P_{Q_1}(t) = v_{CE_1} \cdot i_{C_1}$

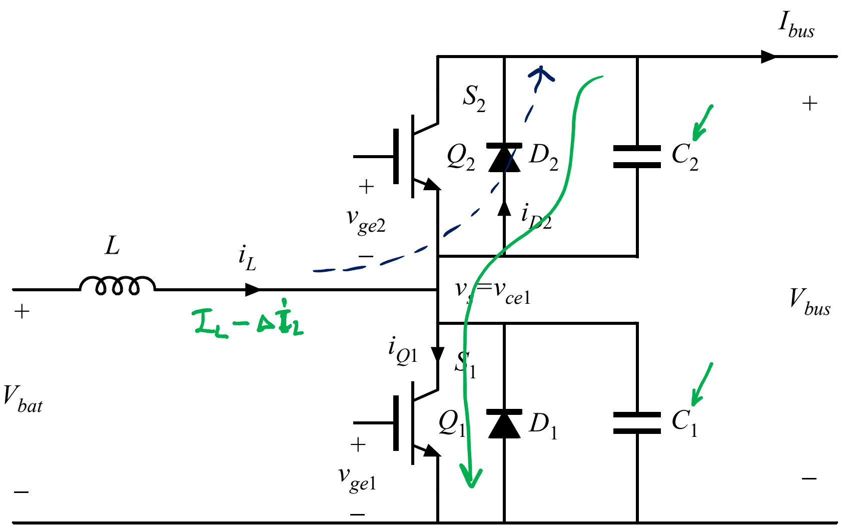
$$E_{off} = \int_0^{t_{tail}} P_{Q_1}(t)\,dt \approx \frac{1}{2} V_{bus}(I_L + \Delta i_L)t_1 + \frac{1}{2} V_{bus}(I_L + \Delta i_L)t_2$$

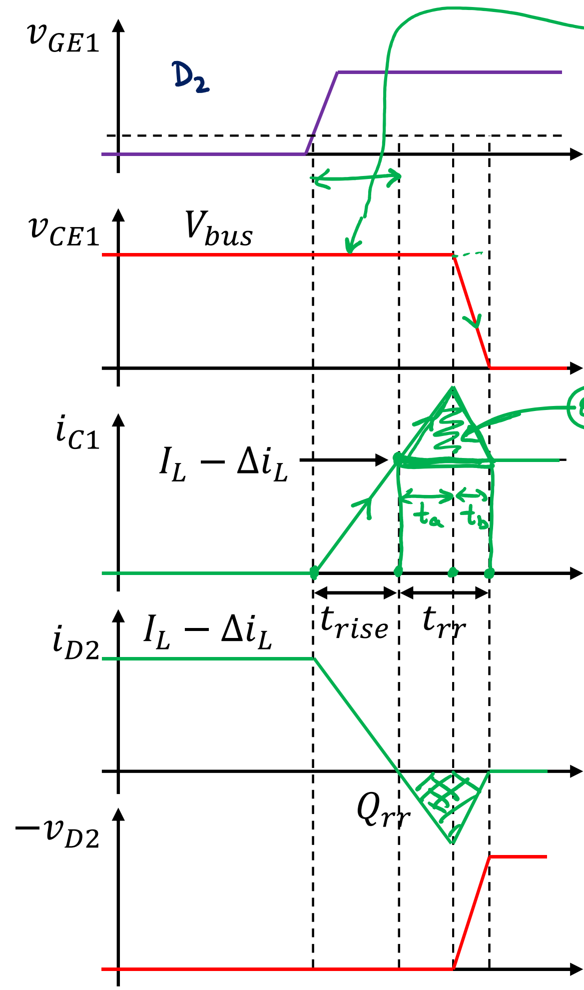
$$\boxed{E_{off} \approx \frac{1}{2}(I_L + \Delta i_L)V_{bus}t_{tail}}$$

$P_{off} = \frac{E_{off}}{T_s}$

$$\boxed{P_{off} = E_{off} \cdot f_s}$$

Turn-On Loss without Device Capacitance





$\frac{1}{2}(I_L - \Delta i_L) V_{bus} t_{rise}$.

simplify:
$t_{rr} \approx t_a$
$t_b \approx 0$.
worst case.

$(I_L - \Delta i_L) t_{rr} V_{bus}$
$+ V_{bus} \cdot Q_{rr}$.

$$E_{on,rise} = \frac{1}{2}(I_L - \Delta i_L) V_{bus} t_{rise}$$

$$E_{on,rr} \approx (I_L - \Delta i_L) V_{bus} t_{rr} + Q_{rr} V_{bus}$$

$$\boxed{E_{on} = E_{on,rise} + E_{on,rr}}$$

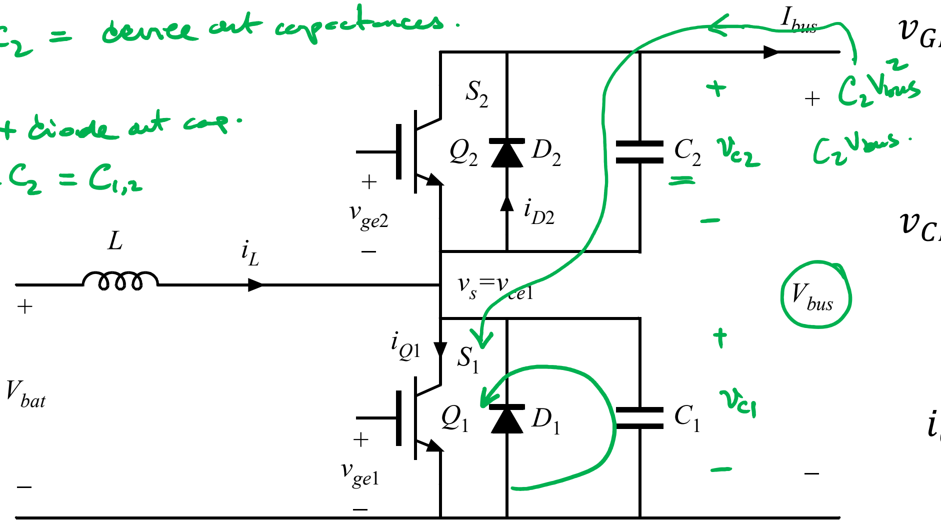
$P_{on} = E_{on} \cdot f_s$

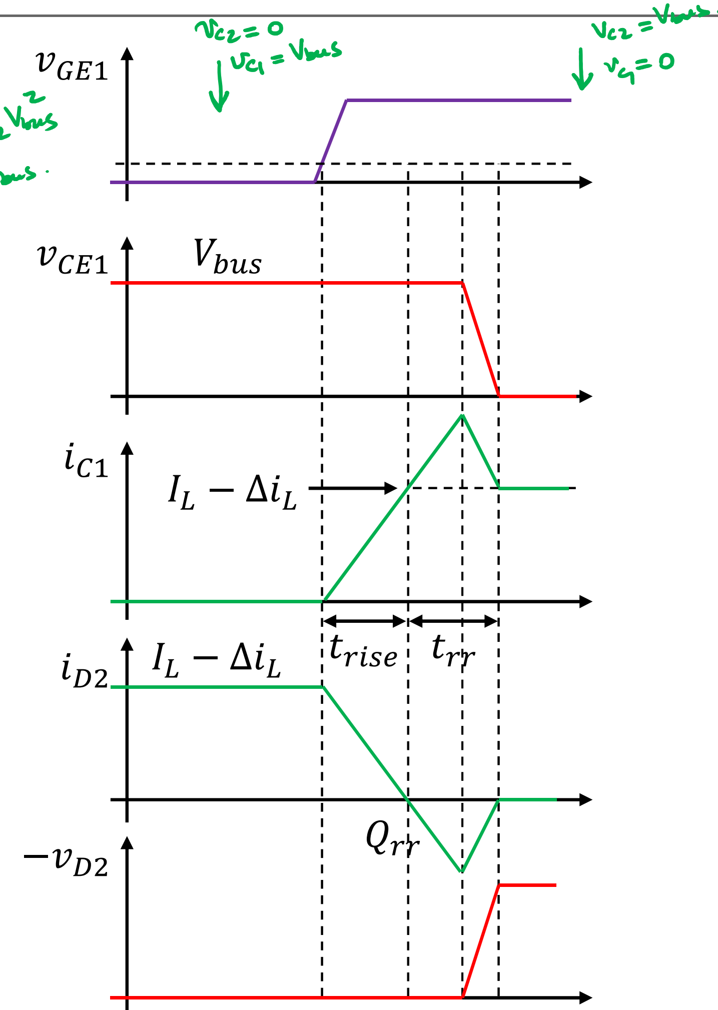
Turn-On Loss due to Device Capacitance

C_1, C_2 = device out capacitances.

IGBT + diode out cap.

$C_1 = C_2 = C_{1,2}$





Assume C1 and C2 are linear capacitances

C_1 starts at $\frac{1}{2} C_1 V_{bus}^2$, ends at 0

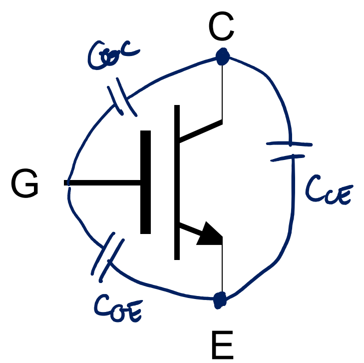
→ loss = $\frac{1}{2} C_1 V_{bus}^2$

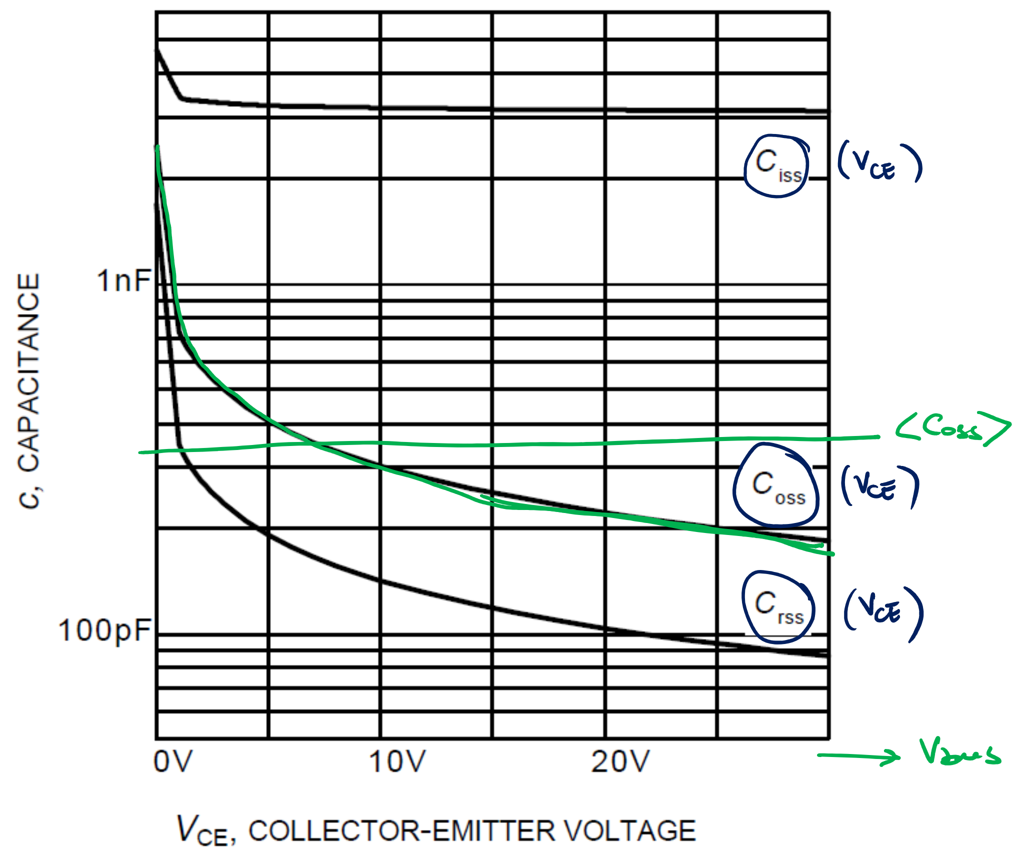
C_2 starts at 0, end at $\frac{1}{2} C_2 V_{bus}^2$

loss = $\frac{1}{2} C_2 V_{bus}^2$

$\boxed{C_{1,2} V_{bus}^2}$ energy. → $C_{1,2} V_{bus}^2 f_s$ power loss.

IGBT Device Capacitances are Highly Nonlinear





Infineon IKW75N60T 600V, 75A IGBT module

$C_{iss} = \underline{C_{GE}} + \underline{C_{GC}}$, with C_{CE} shorted

$C_{oss} = \underline{C_{CE}} + \underline{C_{GC}}$, $C_{CE} >> C_{GC}$

$C_{rss} = \underline{C_{GC}}$

Turn-On Loss due to Nonlinear Device Capacitances

Energy stored in C_1 before turn on:

$\frac{1}{2} C_1 V_{bus}^2$

$$E_{C1}(V_{bus}) = \int_0^{V_{bus}} v_{CE1} \underbrace{C_1(v_{CE}) dv_{CE}}_{dq} = \frac{1}{2} C_{1,eq} V_{bus}^2$$

?

Cancel

Energy stored in C_2 after turn on (assuming Q_1/D_1 and Q_2/D_2 are the same devices):

$$E_{C2}(V_{bus}) = E_{C1}(V_{bus})$$

Energy taken from V_{bus} during turn on:

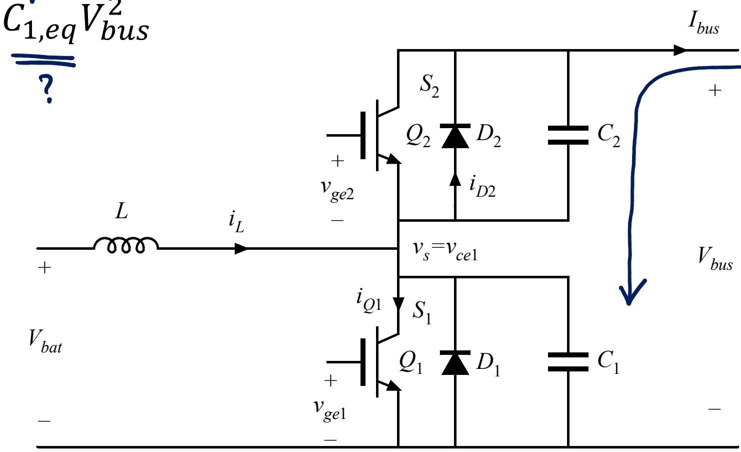
$$E_{bus}(V_{bus}) = V_{bus} \int_0^{V_{bus}} \underbrace{C_2(v_{CE2}) dv_{CE2}}_{dq} = \langle C_2 \rangle V_{bus}^2$$

average of C_2 over 0 to V_{bus} voltage range.

$\langle C_1 \rangle = \langle C_2 \rangle = \langle C_{1,2} \rangle$.

Energy loss during turn on (due to device capacitance):

$$E_{cap}(V_{bus}) = \cancel{E_{C1}(V_{bus})} + E_{bus}(V_{bus}) - \cancel{E_{C2}(V_{bus})} = \langle C_{1,2} \rangle V_{bus}^2$$



+

Q?

V_{bus} = const.

−

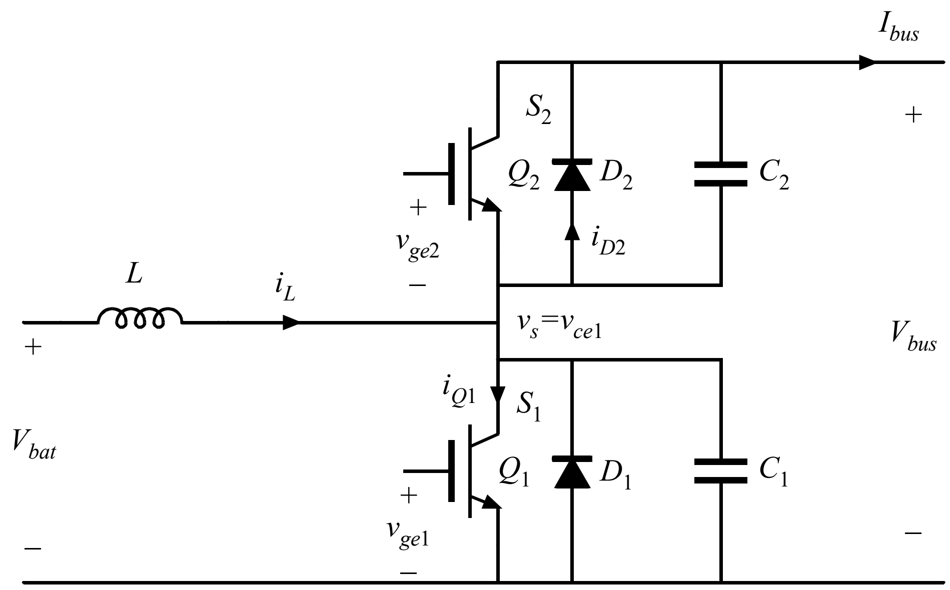
Example Switching Loss Calculation

Converter operating point:

- $V_{bus} = 500$ V
- $V_{bat} = 200$ V
- $I_{bat} = I_L = 100$ A
- $\Delta i_L = 20$ A

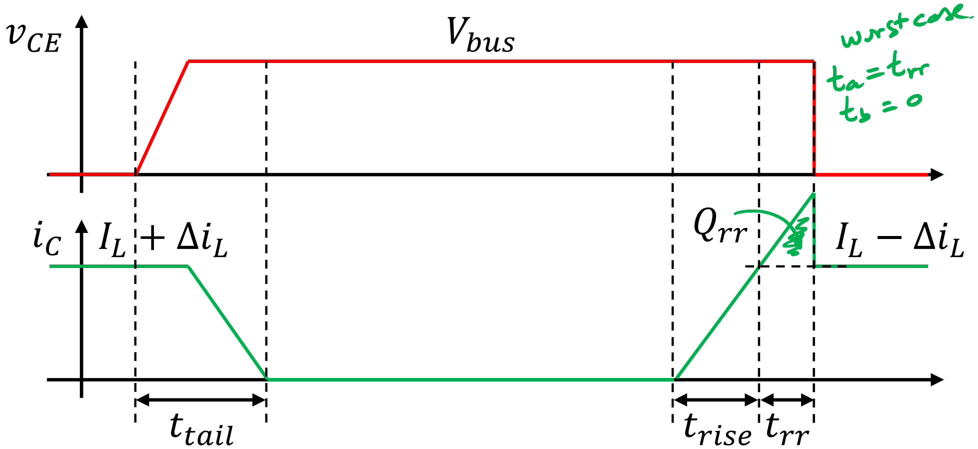
Device Parameters:

- IGBT
  $t_{tail} = 400$ ns
  $t_{rise} = 60$ ns
- Diode
  $Q_{rr} = 5\ \mu$C
  $t_{rr} = 150$ ns
- IGBT + Diode
  $\langle C_{1,2} \rangle = 300$ pF



Example Switching Loss Calculation (Cont.)

20kW from battery.



- IGBT
  - $t_{tail} = 400$ ns
  - $t_{rise} = 60$ ns
- Diode
  - $Q_{rr} = 5\ \mu$C
  - $t_{rr} = 150$ ns
- IGBT + Diode
  - $\langle C_{1,2} \rangle = 300$ pF

$$E_{on,rise} = \frac{1}{2}(I_L - \Delta i_L)V_{bus}t_{rise} = 1.2 \text{ mJ}$$

$$E_{on,rr} = \big((I_L - \Delta i_L)t_{rr} + Q_{rr}\big)V_{bus} = 6 \text{ mJ} + 2.5 \text{ mJ} = 8.5 \text{ mJ}$$

$$E_{on,cap} = \langle C_{1,2} \rangle V_{bus}^2 = 0.075 \text{ mJ}$$

$$\boxed{E_{off} = \frac{1}{2}(I_L + \Delta i_L)V_{bus}t_{tail} = 12 \text{ mJ}}$$

$$\boxed{E_{on} = E_{on,rise} + E_{on,rr} + E_{on,cap} = 9.8 \text{ mJ}}$$

$$P_{sw} = \big(E_{on} + E_{off}\big)f_s = \begin{cases} 218 \text{ W at } f_s = 10 \text{ kHz} \\ 1090 \text{ W at } f_s = 50 \text{ kHz} \end{cases}$$

Switching Loss from Datasheet

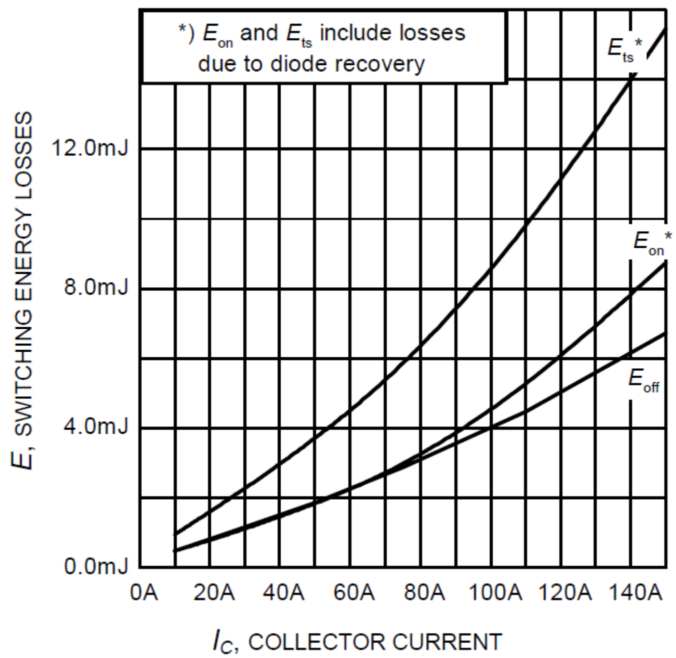


Figure 13. Typical switching energy losses as a function of collector current
(inductive load, $T_J = 175°C$, $V_{CE} = 400V$, $V_{GE} = 0/15V$, $R_G = 5\Omega$,

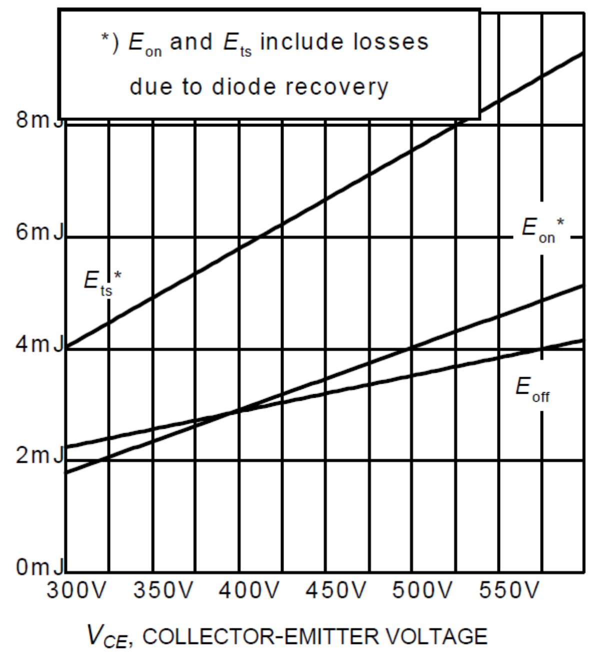
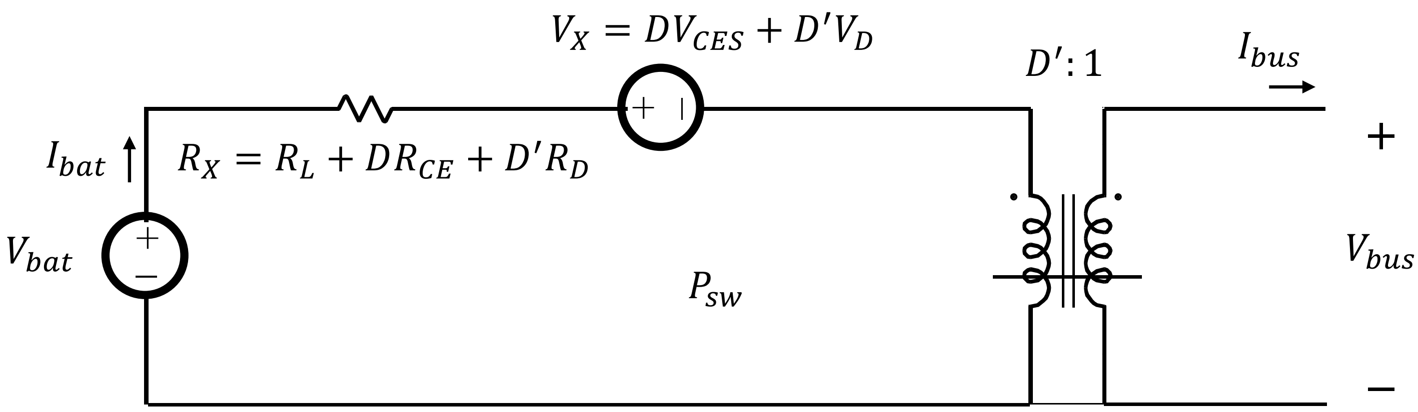


Figure 16. Typical switching energy losses as a function of collector emitter voltage
(inductive load, $T_J = 175°C$, $V_{GE} = 0/15V$, $I_C = 75A$, $R_G = 5\Omega$,

Infineon IKW75N60T 600V, 75A IGBT module

Average Model with Conduction & Switching Losses

Assumption: $I_L = I_{bat} > 0$ (battery discharging), and $I_L > \Delta i_L$



$$P_{sw} = \left[\frac{1}{2}(I_L + \Delta i_L)t_{tail} + \frac{1}{2}(I_L - \Delta i_L)t_{rise} + (I_L - \Delta i_L)t_{rr} + Q_{rr} + \langle C_{1,2}\rangle V_{bus}\right] V_{bus} f_s$$

$$I_{sw} = \left[\frac{1}{2}(I_L + \Delta i_L)t_{tail} + \frac{1}{2}(I_L - \Delta i_L)t_{rise} + (I_L - \Delta i_L)t_{rr} + Q_{rr} + \langle C_{1,2}\rangle V_{bus}\right] f_s$$

ECEN 5017

Power Electronics for Electric Drive Vehicles

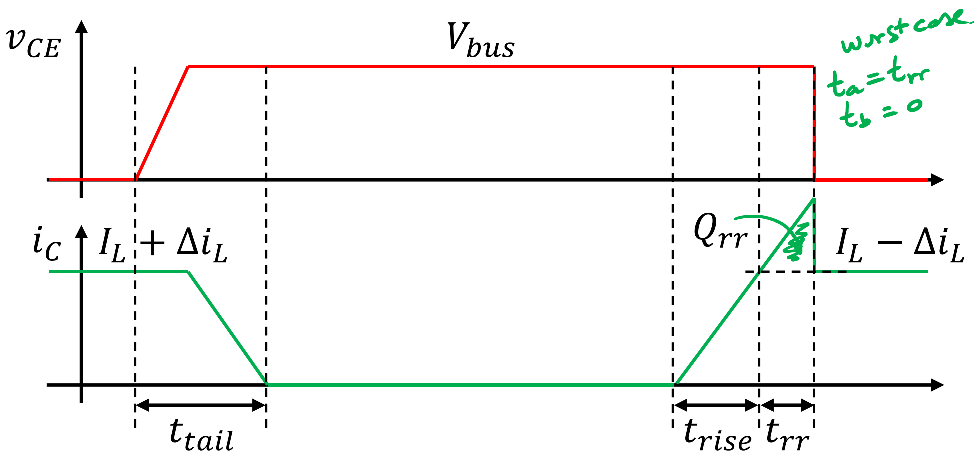
Lecture 25

Powertrain DC-DC Converter:

Modeling of Conduction and Switching Losses

Example Switching Loss Calculations

20kW from battery.



- IGBT
  $t_{tail} = 400$ ns
  $t_{rise} = 60$ ns
- Diode
  $Q_{rr} = 5\ \mu$C
  $t_{rr} = 150$ ns
- IGBT + Diode
  $\langle C_{1,2} \rangle = 300$ pF

$$E_{on,rise} = \frac{1}{2}(I_L - \Delta i_L)V_{bus}t_{rise} = 1.2 \text{ mJ}$$

$$E_{on,rr} = \big((I_L - \Delta i_L)t_{rr} + Q_{rr}\big)V_{bus} = 6 \text{ mJ} + 2.5 \text{ mJ} = \underline{8.5 \text{ mJ}}$$

$$E_{on,cap} = \langle C_{1,2} \rangle V_{bus}^2 = 0.075 \text{ mJ} \leftarrow$$

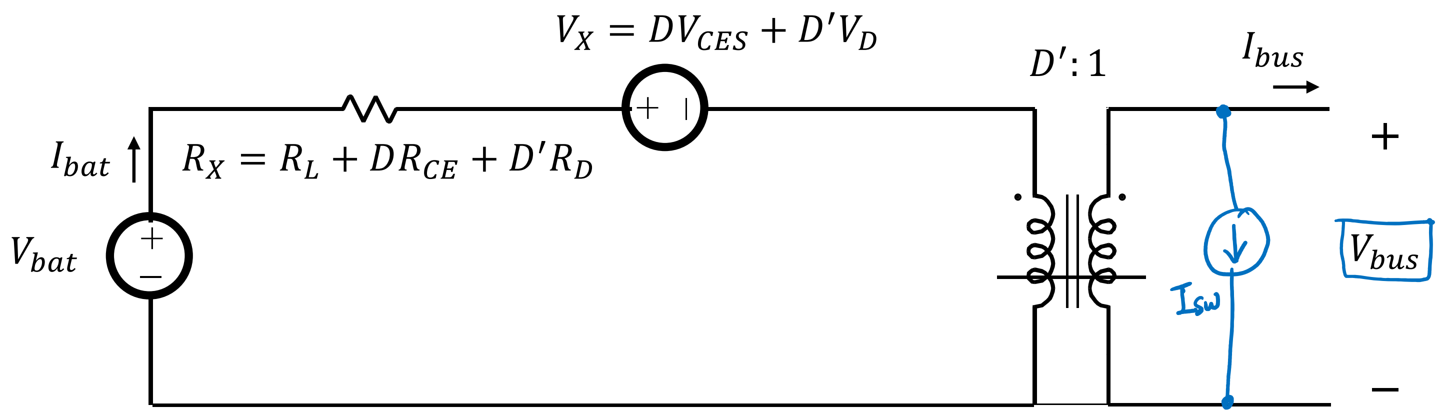
$$\boxed{E_{off} = \frac{1}{2}(I_L + \Delta i_L)V_{bus}t_{tail} = 12 \text{ mJ}}$$

$$\boxed{E_{on} = E_{on,rise} + E_{on,rr} + E_{on,cap} = 9.8 \text{ mJ}}$$

$$P_{sw} = \big(E_{on} + E_{off}\big)f_s = \begin{cases} 218 \text{ W at } f_s = 10 \text{ kHz} \\ \underline{1090} \text{ W at } f_s = \underline{50 \text{ kHz}} \end{cases}$$

Average Model with Conduction & Switching Losses

Assumption: $I_L = I_{bat} > 0$ (battery discharging), and $I_L > \Delta i_L$

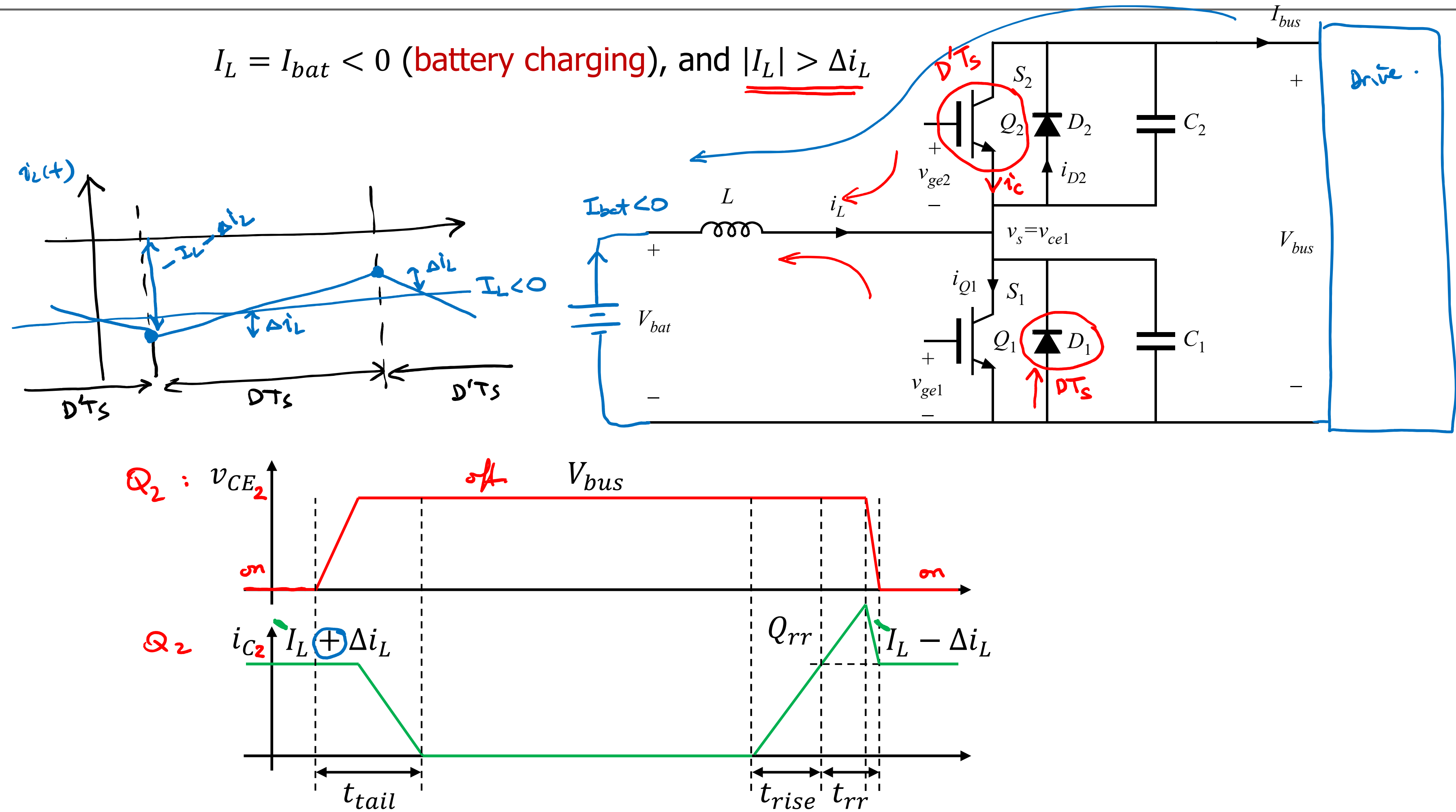


$$P_{sw} = \Bigg[\overbrace{\frac{1}{2}(I_L + \Delta i_L)t_{tail} + \frac{1}{2}(I_L - \Delta i_L)t_{rise} + (I_L - \Delta i_L)t_{rr} + Q_{rr} + \langle C_{1,2}\rangle V_{bus}}^{I_{sw}}\Bigg] V_{bus} f_s$$

$$I_{sw} = \left[\frac{1}{2}(I_L + \Delta i_L)t_{tail} + \frac{1}{2}(I_L - \Delta i_L)t_{rise} + (I_L - \Delta i_L)t_{rr} + Q_{rr} + \langle C_{1,2}\rangle V_{bus}\right] f_s$$

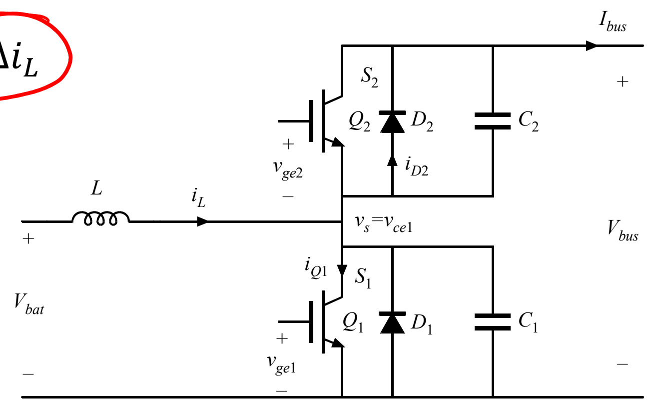
Switching Losses when Battery is Charging

$I_L = I_{bat} < 0$ (battery charging), and $|I_L| > \Delta i_L$

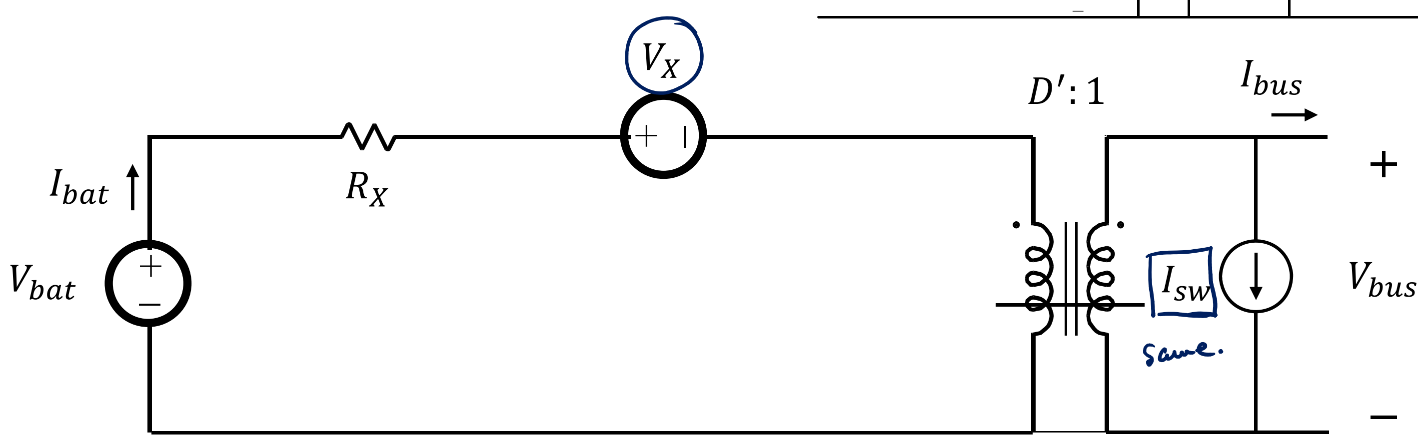


Average Model with Losses when Charging

$I_L = I_{bat} < 0$ (battery charging), and $|I_L| > \Delta i_L$



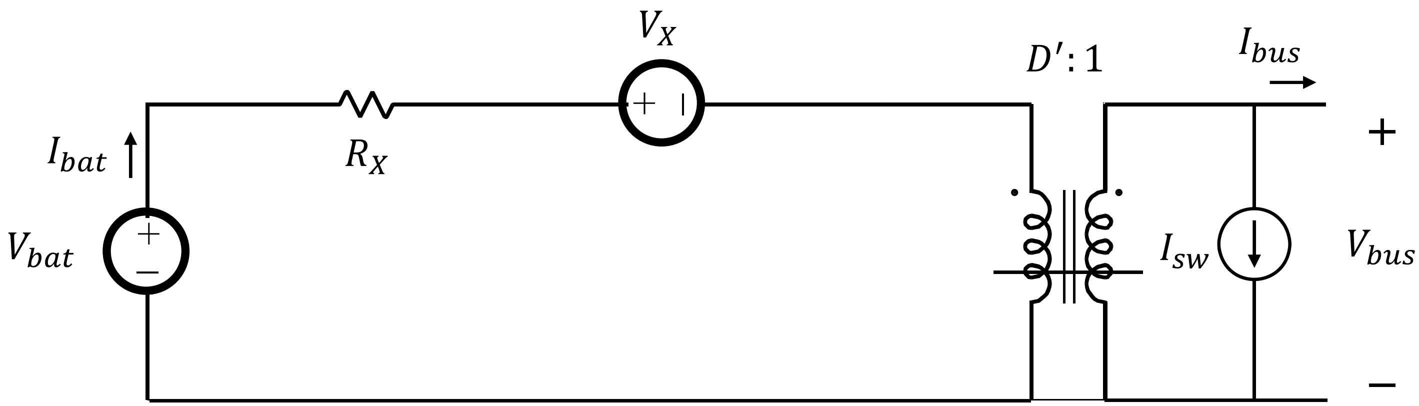
$$V_X = \begin{cases} D V_{CES} + D' V_D & I_L = I_{bat} > 0 \\ -(D' V_{CES} + D V_D) & I_L = I_{bat} < 0. \end{cases}$$



$$I_{sw} = \left[\frac{1}{2}(|I_L| + \Delta i_L)t_{tail} + \frac{1}{2}(|I_L| - \Delta i_L)t_{rise} + (|I_L| - \Delta i_L)t_{rr} + Q_{rr} + \langle C_{1,2}\rangle V_{bus}\right] f_s$$

× $|I_L| < \Delta i_L$

Efficiency Calculation from Average Circuit Model



$$\eta = \frac{P_{out}}{P_{in}}$$

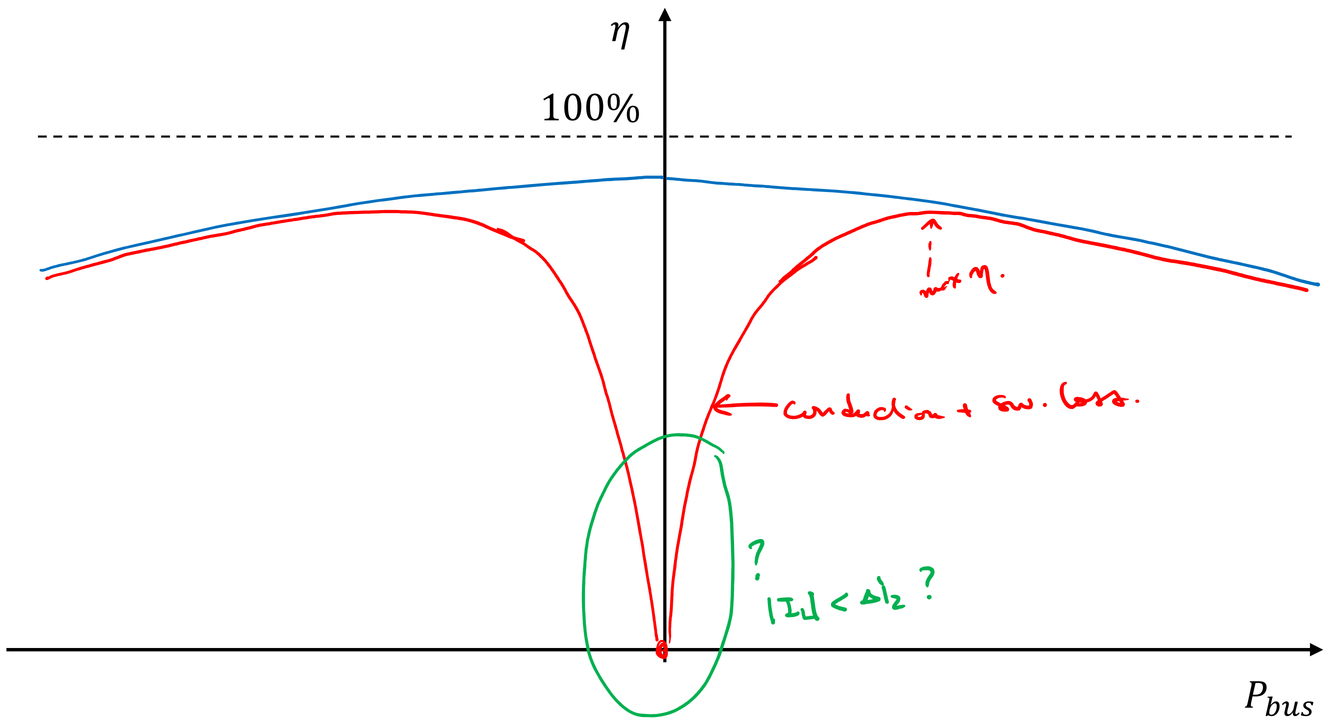
Battery Discharging

$$\eta = \frac{P_{bus}}{P_{bat}} = \frac{P_{bat} - P_{loss}}{P_{bat}} = \frac{P_{bus}}{P_{bus} + P_{loss}}$$

Battery Charging

$$\eta = \frac{P_{bat}}{P_{bus}} = \frac{P_{bus} - P_{loss}}{P_{bus}} = \frac{P_{bat}}{P_{bat} + P_{loss}}$$

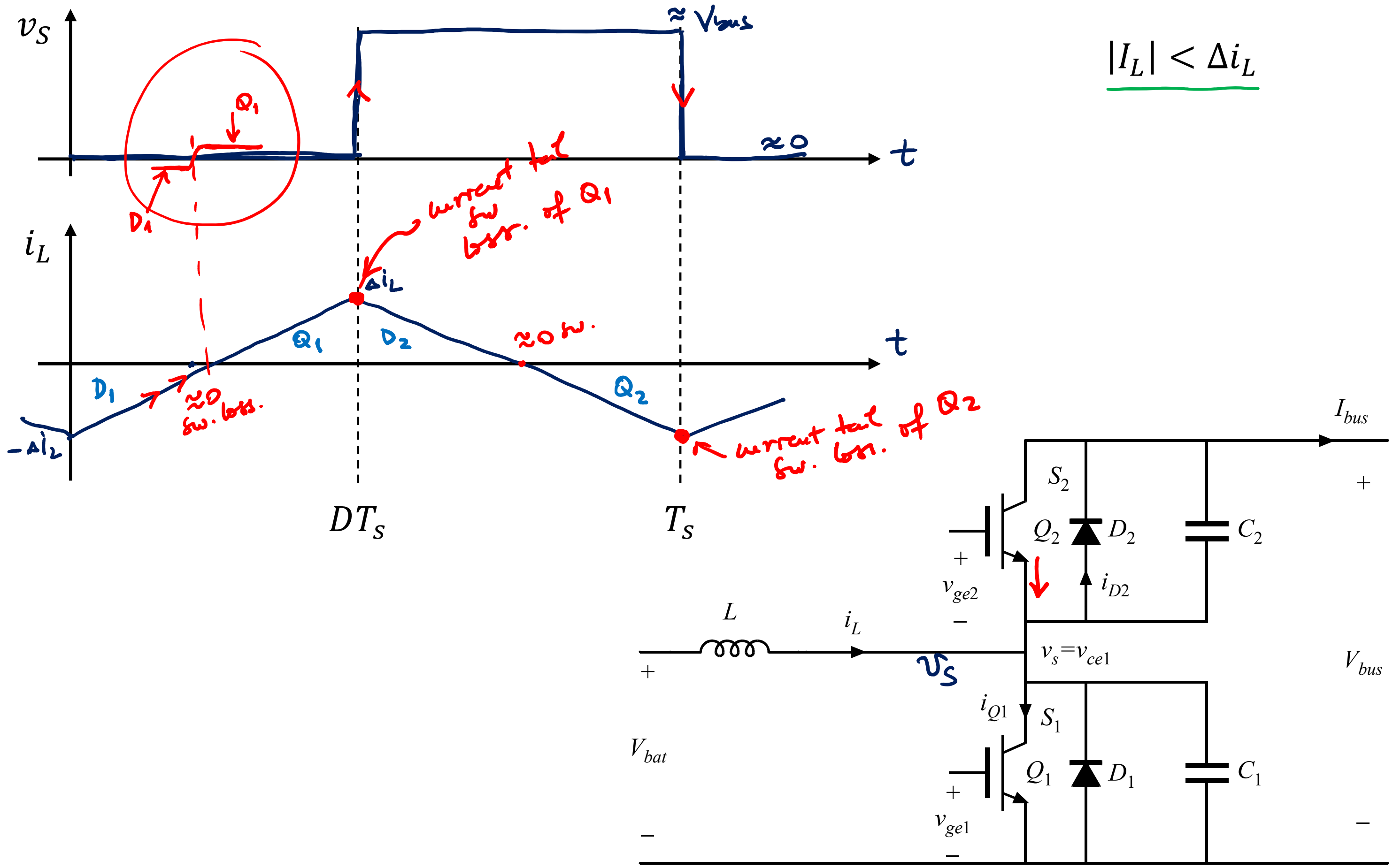
Efficiency



Losses at Low Power

$I_L = 0$

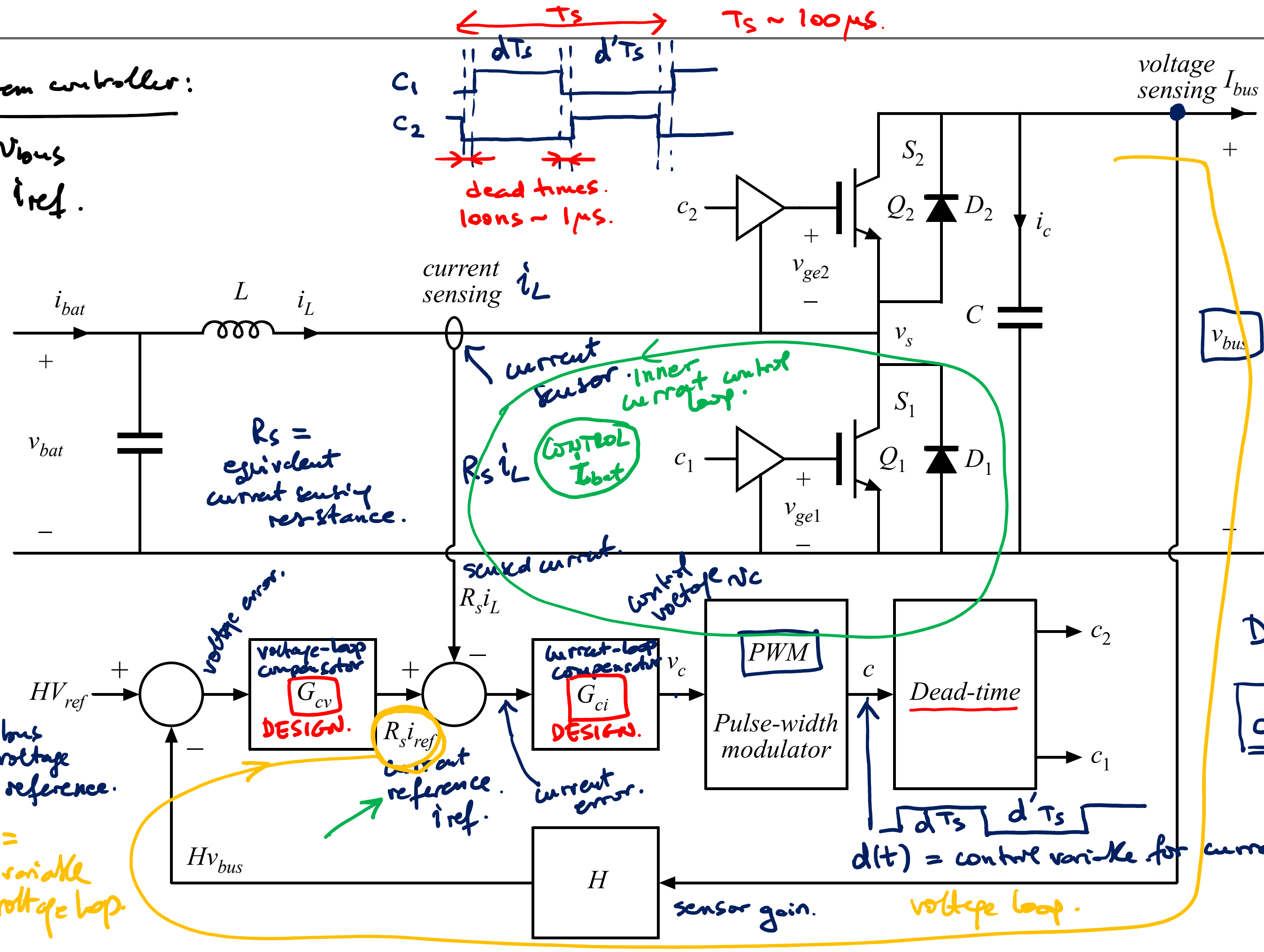
$|I_L| < \Delta i_L$



Feedback Control of Drivetrain DC-DC Converter

From vehicle system controller:

1. Vref for Vbus
2. limits for iref.



bus voltage reference.

iref = control variable for the voltage loop.

open-loop responses: from d or vc to iL, Vbus

D = steady-state duty cycle.

$\boxed{d(t)}$ = dynamic.