NPTEL ONLINE CERTIFICATION COURSES

CONTROL AND TUNING METHODS IN SMPCs

Dr. Santanu Kapat
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Module 01: Switched Mode Power Converters and Simulation

Lecture 01: DC Power Conversion Systems – Introduction

Concepts Covered

- Recent trends in power electronics
- Few emerging applications and challenges
- Understanding need for DC power conversion
- Primary objectives of voltage and current regulators
- Course overview and reference resources

High efficiency

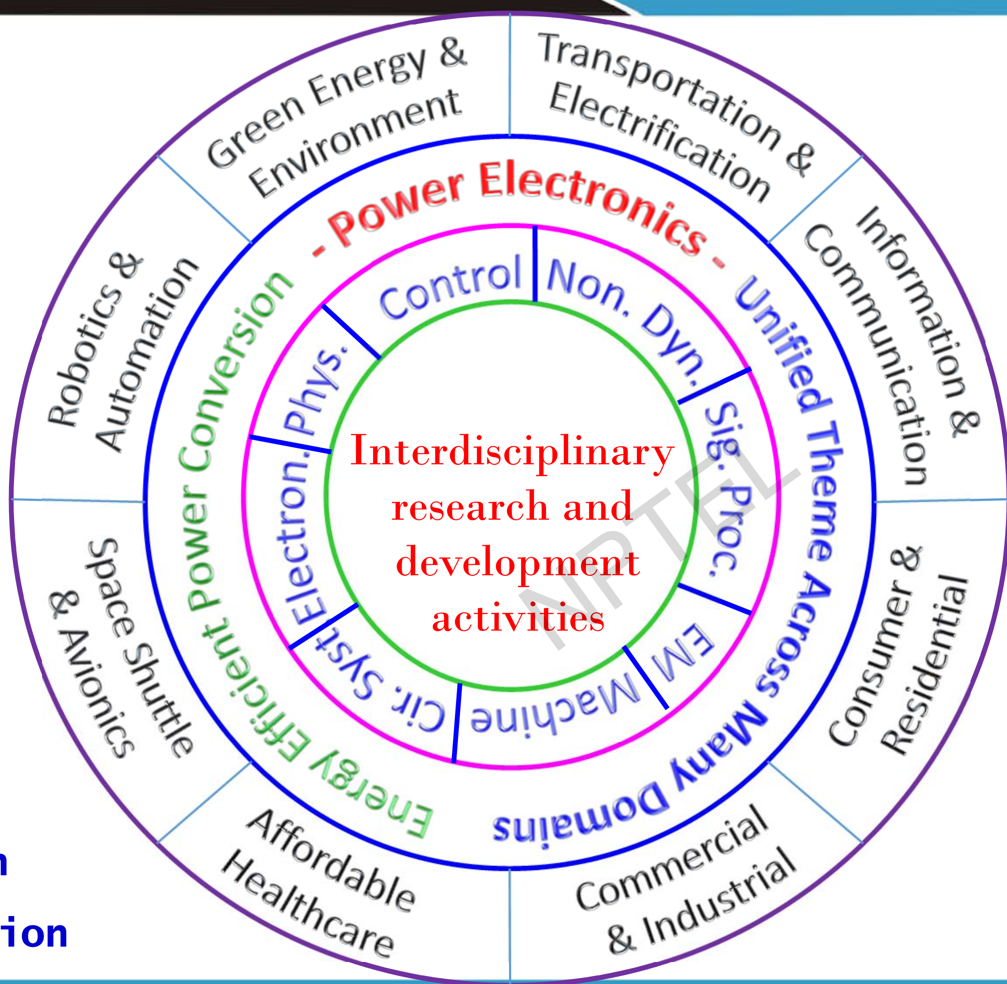
High frequency

Size & power

Compliance

EMI reduction

Harmonic reduction

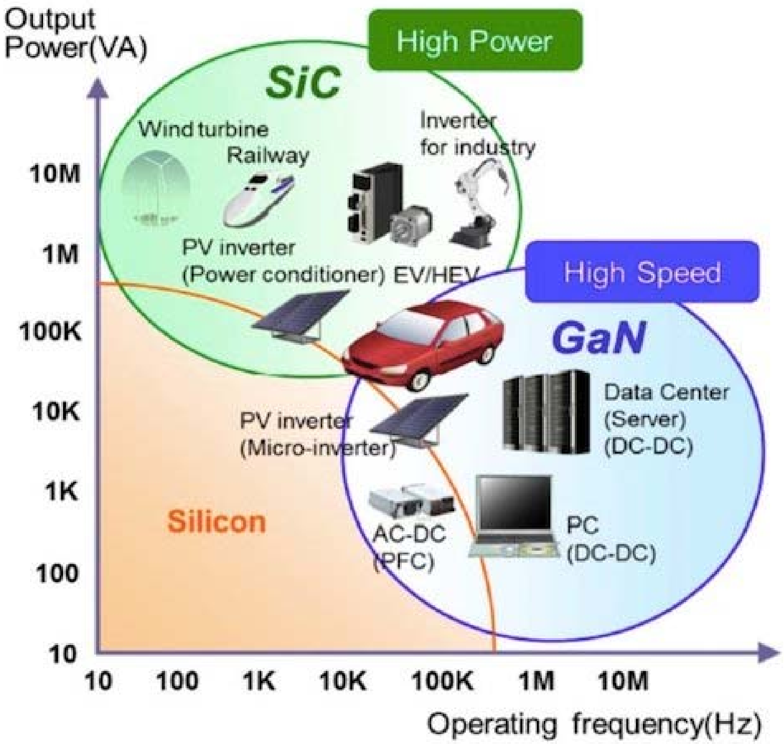


High performance

Small resource

Throughput

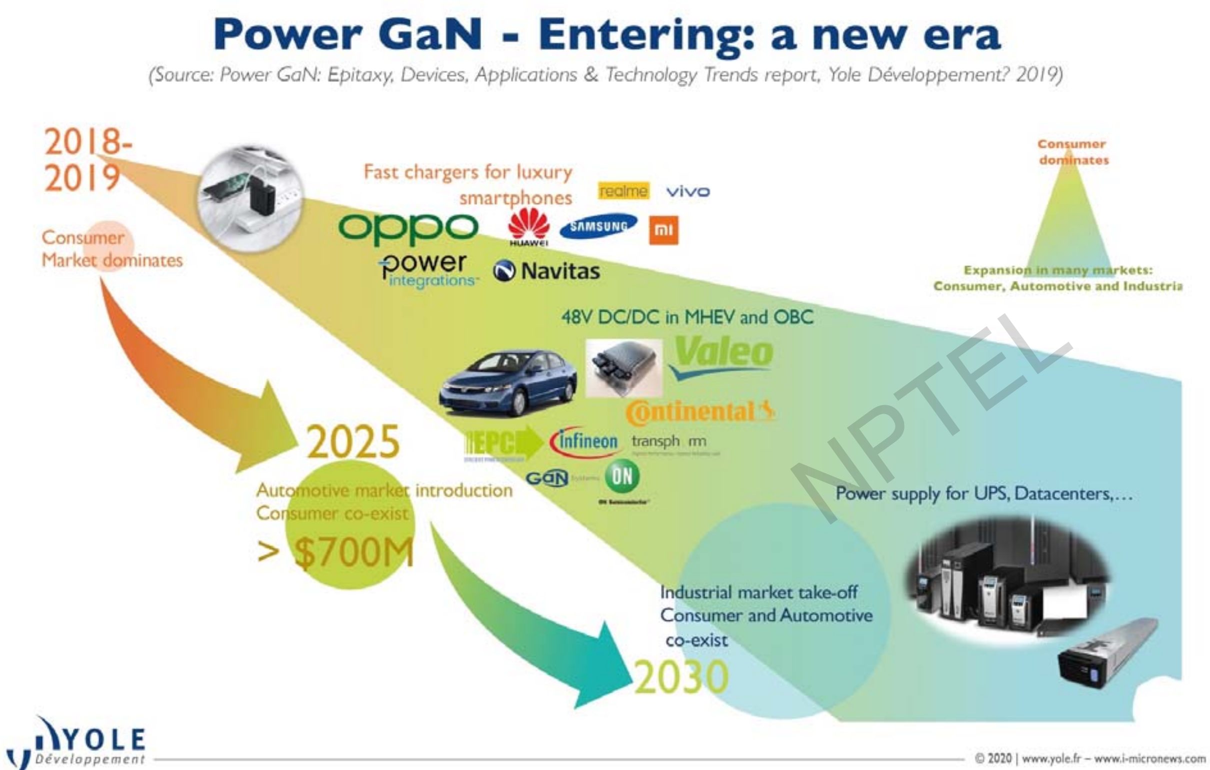
Wide Band Gap (WBG) Devices in Power Electronics



Source: The Graham Lab, Georgia Tech

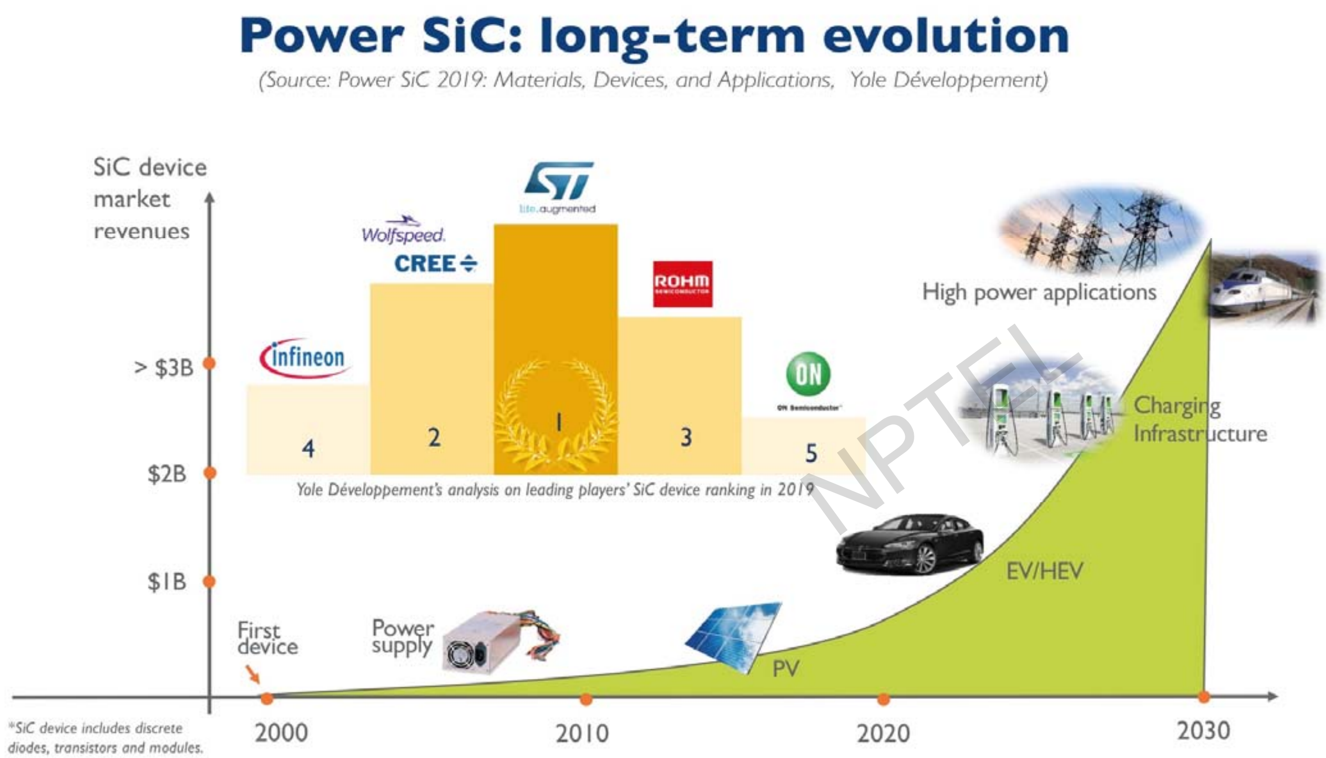
- ❑ Wide band gap
- ❑ High junction temperature
- ❑ Lower on resistance
- ❑ Lower gate charge requirement
- ❑ Negligible reverse recovery

GaN Based Power Electronics – Market Forecast



Source: Yole Development

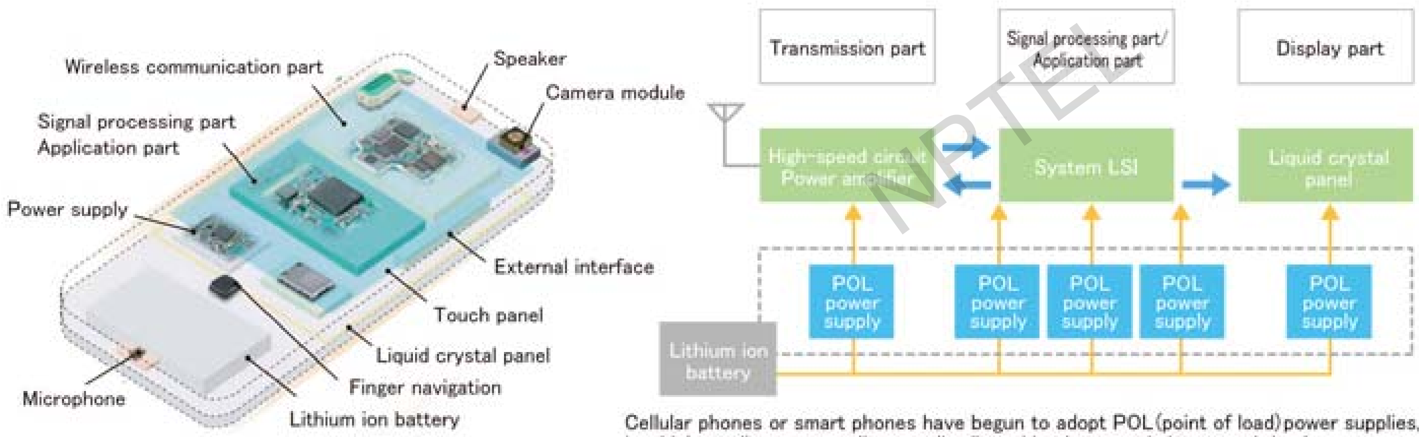
SiC Based Power Electronics and Applications



Source: Yole Development

DC Power Conversion in a Smartphone

Samsung smartphone Multiple step-down and step-up voltage regulators

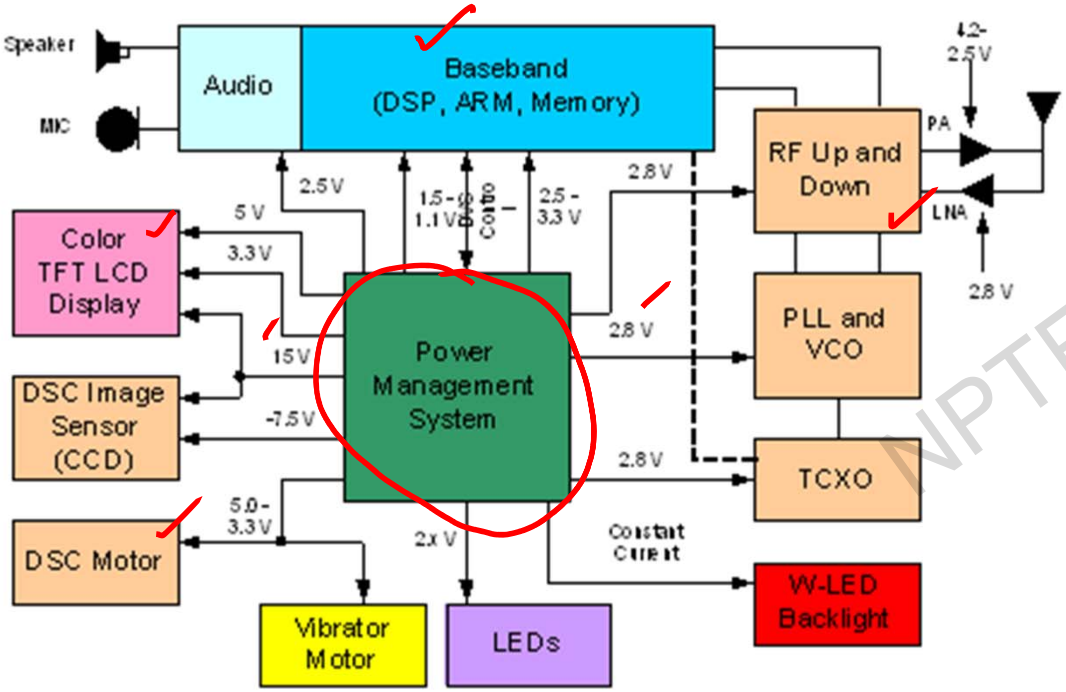


Cellular phones or smart phones have begun to adopt POL (point of load) power supplies, in which small power supplies are distributed in close proximity to each load, as the number of channels of power supplies increases.

Source: TDK product center

POL
(Point of load)

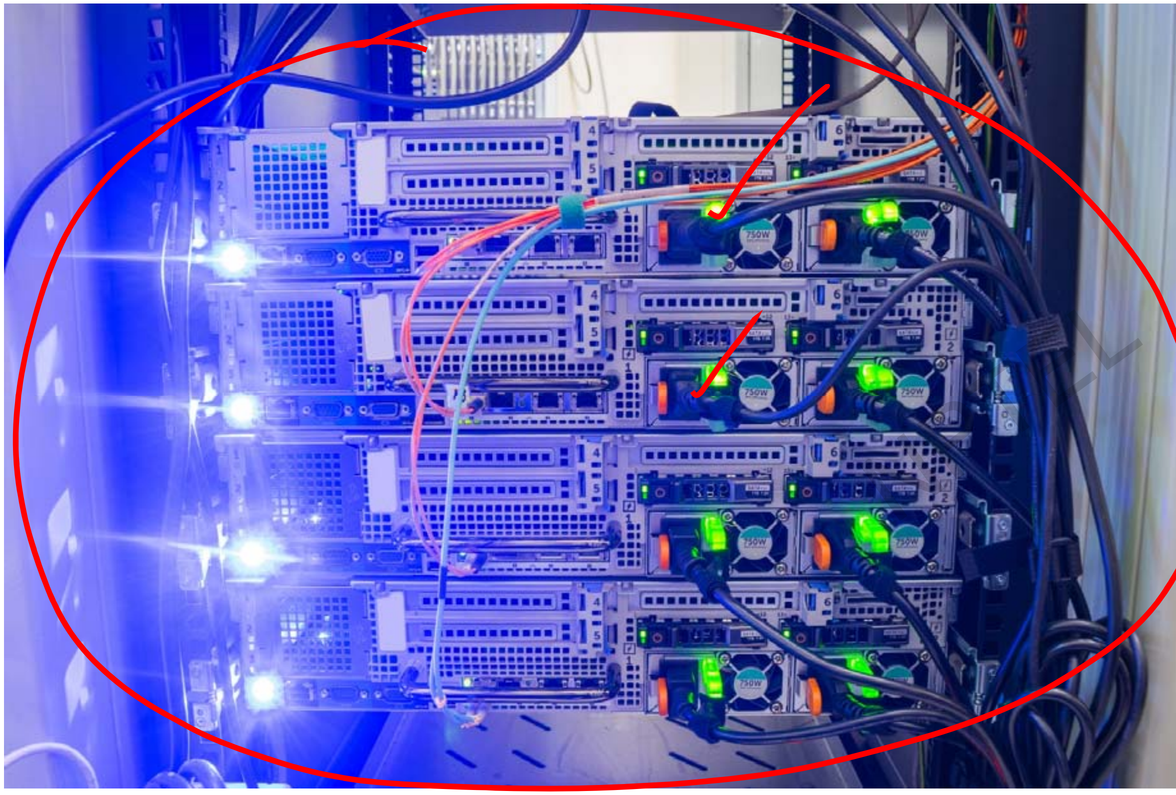
Power Supply Network in a Smartphone



Source: [EDN Network]

- Multiple outputs with multiple voltage/current requirements
- Only one source – Li-ion battery
- Require multiple DC voltage regulators

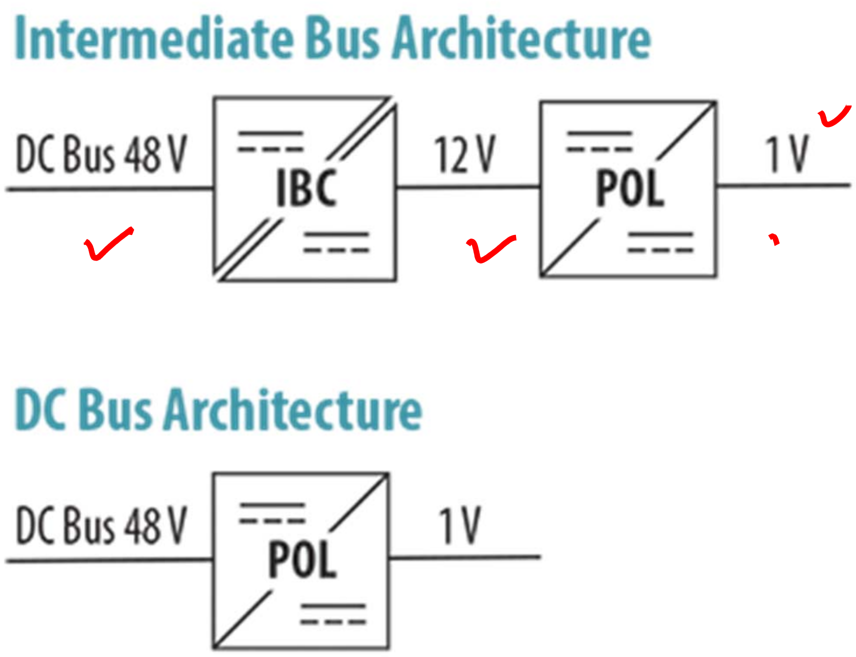
Power Supply Network in Data Center



Source: [DataCenter Knowledge]

- Low voltage high current
- Modular plug-and-play power supply with hot swapping
- Ultra-fast transient performance
- High efficiency

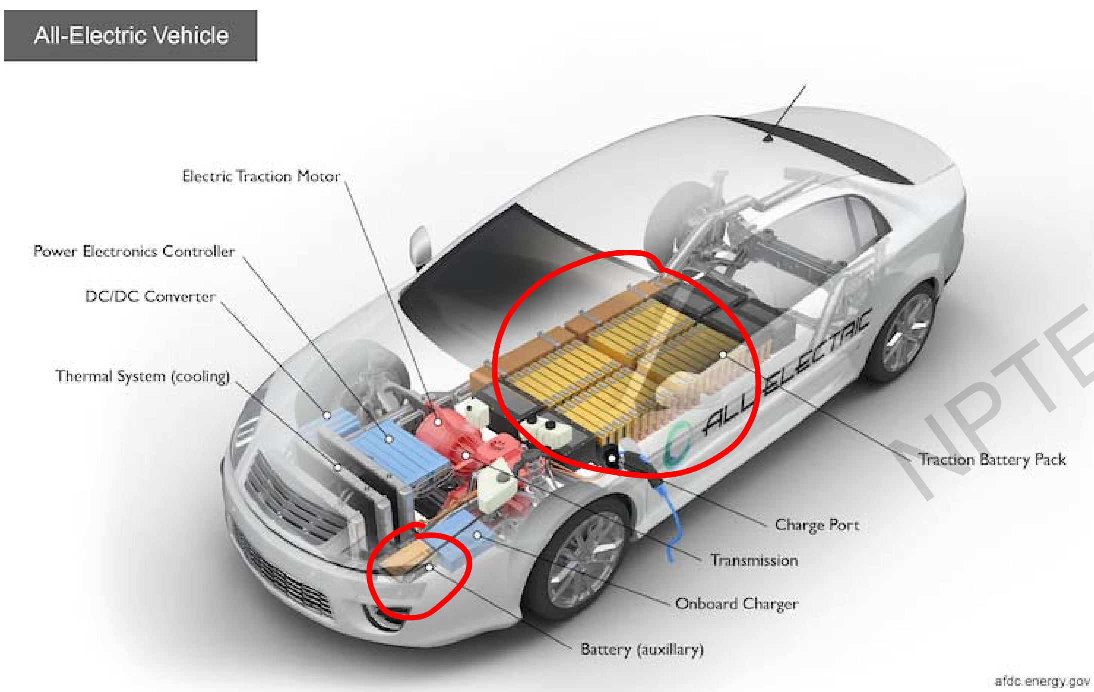
48V DC Power Conversion in Data Center



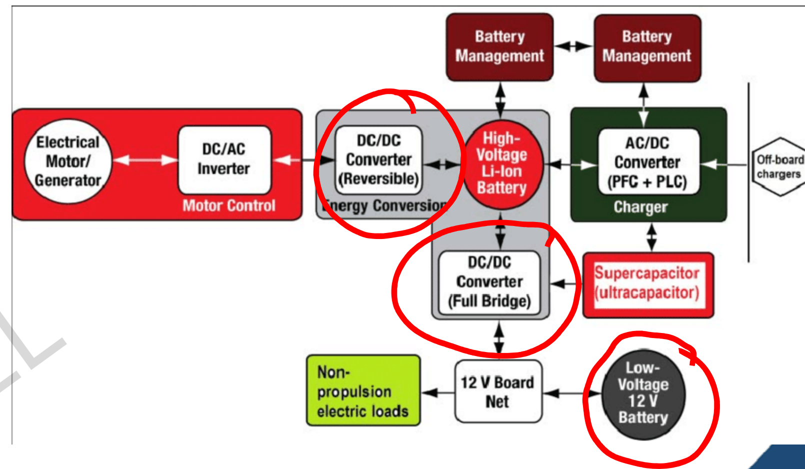
- ❑ POL (point of load) converter may need to drive 100s of A, even more
- ❑ Challenges – POL architectures and control methods to meet high efficiency and fast transient

Source: [Efficient Power Conversion (EPC)]()

Power Supply Network in Electric Vehicles

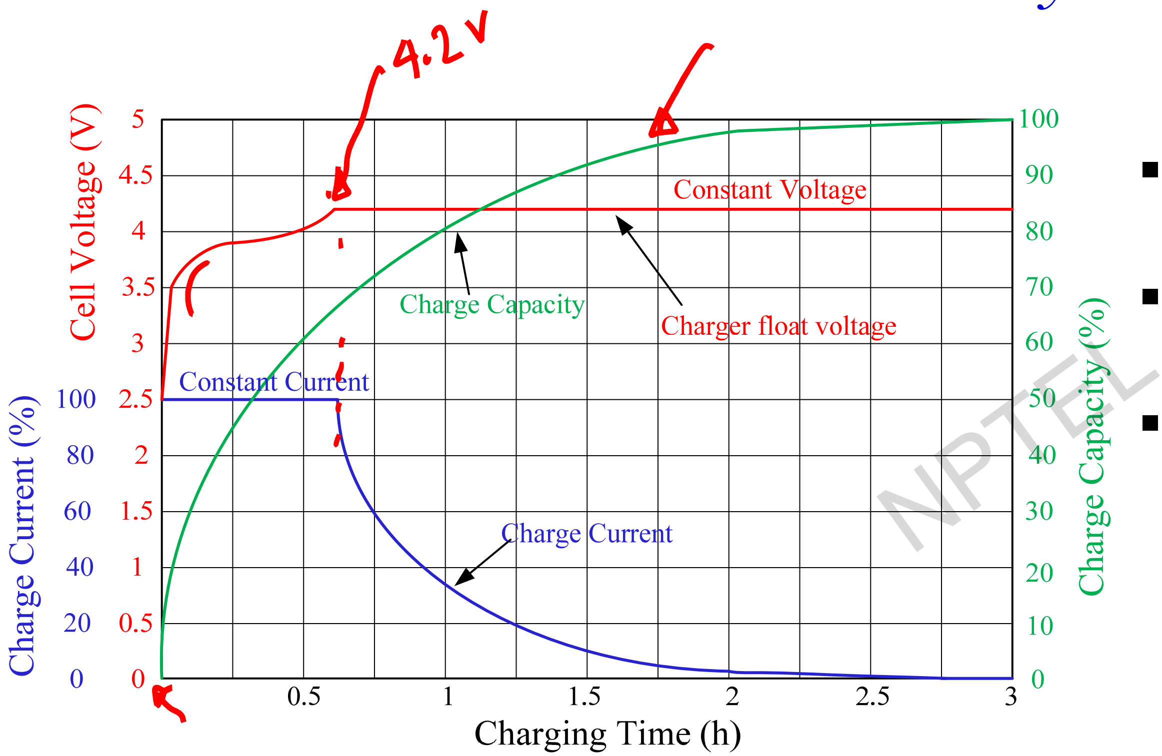


Source: [AFDC, Department of Energy](), USA



Source: [Texas Instruments]()

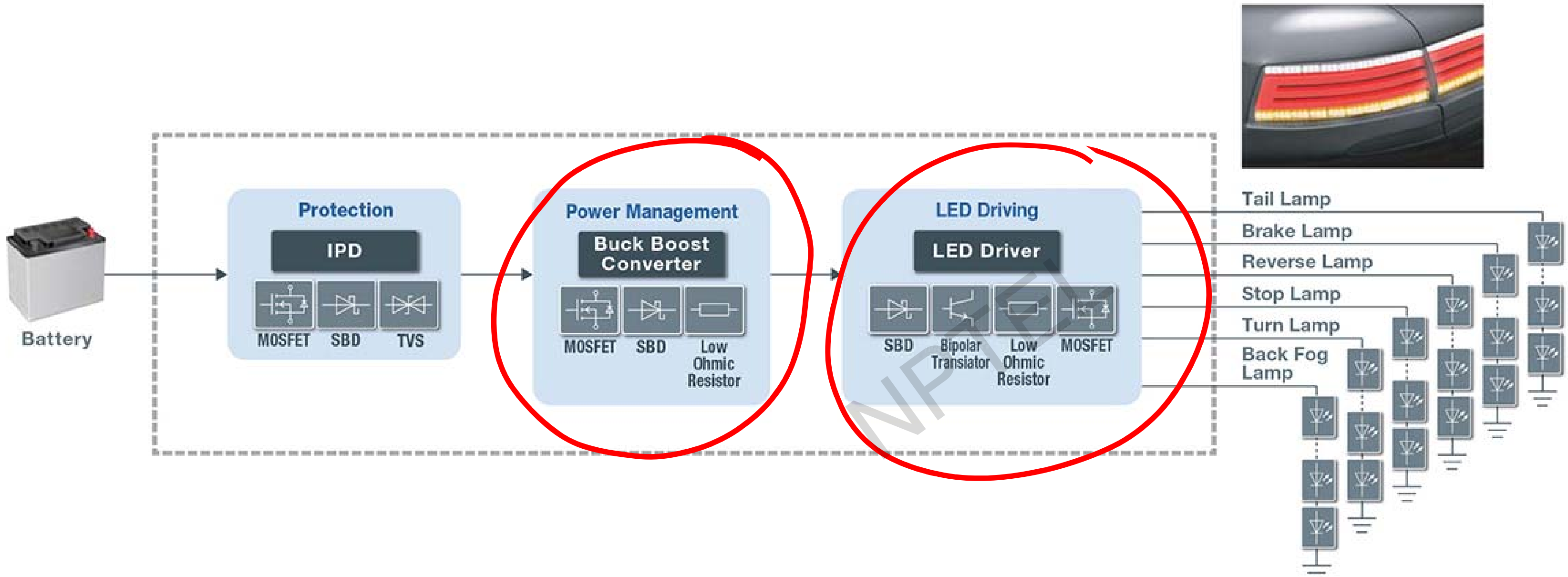
DC Power Conversion in Fast Battery Charging



(Volts/capacity vs. time when charging lithium-ion)

- Constant current charge/ discharge
- Constant voltage charging
- Need for seamless transition from CC to CV mode

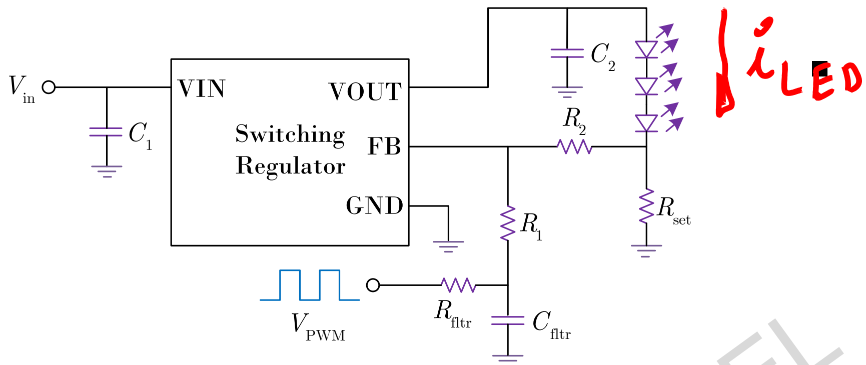
DC Power Conversion in Automotive LED Driving



Source: ROHM Semiconductor

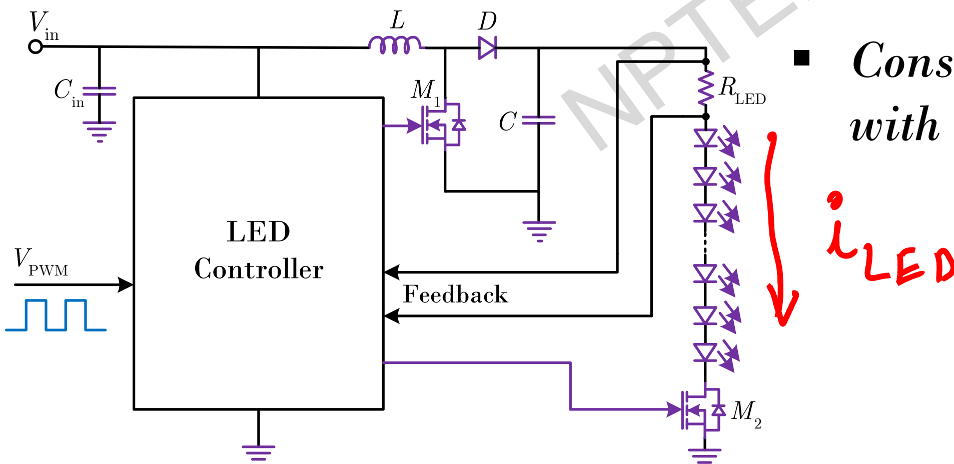
DC Power Conversion in LED Driving

- *Analog dimming*



- *Constant Current control with constant current command*

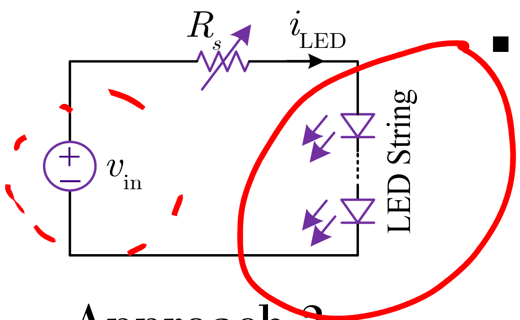
- *PWM dimming*



- *Constant Current control with step current command*

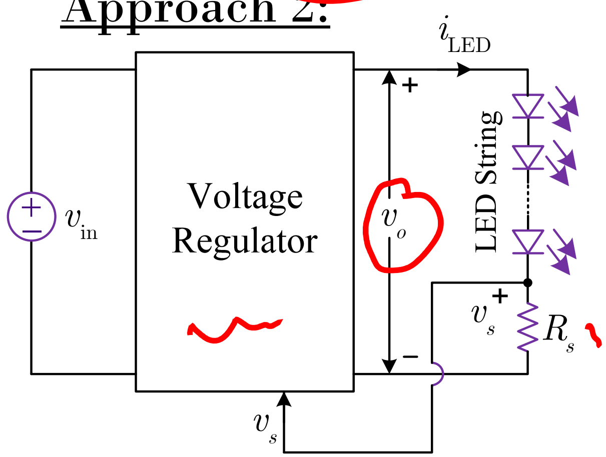
Constant Current Source in LED Driving

Approach 1:



- Control of i_{LED} by varying $\boldsymbol{R_s}$
  - Varying losses
  - Poor efficiency
  - Large heatsink

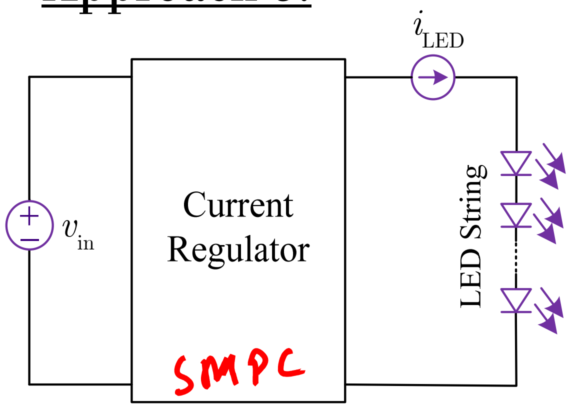
Approach 2:



- Control of i_{LED} by adjusting $\boldsymbol{v_o}$
  - Improved efficiency
  - Efficiency of VR crucial
  - Losses in series resistance

Constant Current Source in LED Driving

Approach 3:

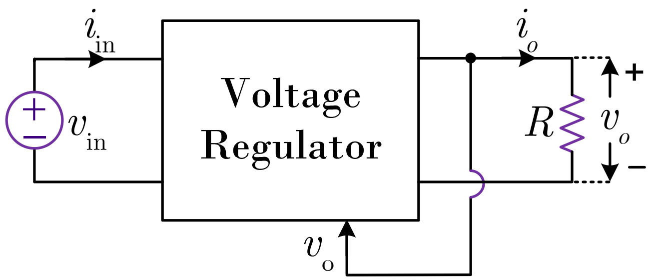


- Control of i_{LED} by varying using a current regulator

Approach 4:

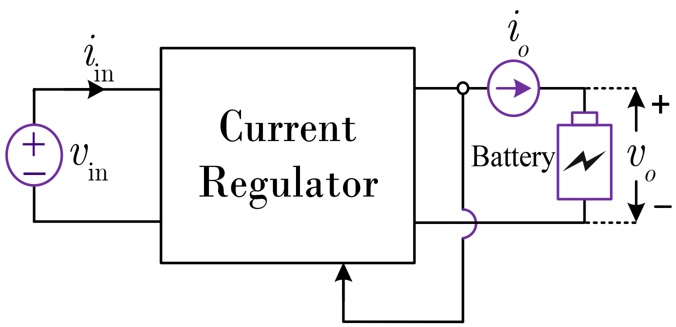
A combination of current source mode and voltage source mode configurations !!

DC Power Conversion – Objectives



Voltage feedback

$v_o \rightarrow$ tightly regulated

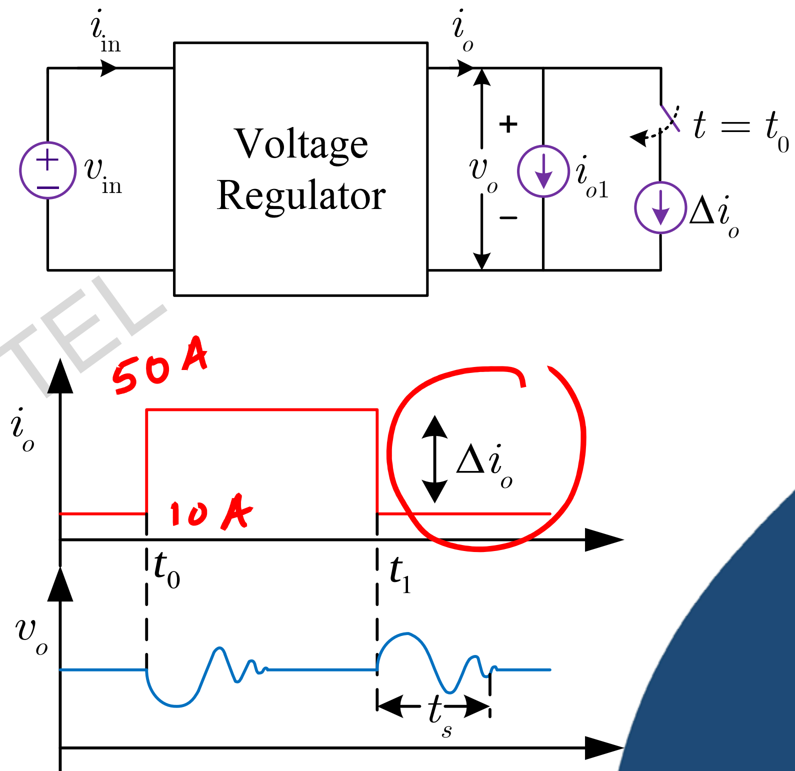


Current feedback

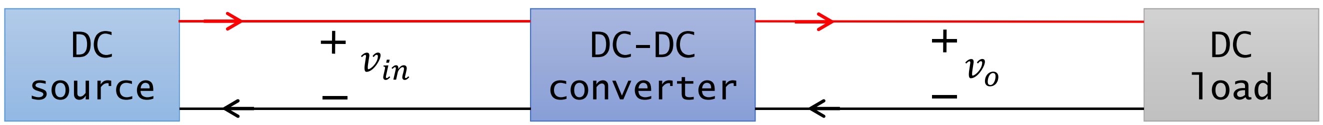
$i_o \rightarrow$ tightly regulated

Transient Scenario in a Voltage Regulator

- Typical load profile
  - Fast load slew rates
  - Frequent transients
- Challenges
  - Overshoot/ undershoot reduction
  - Fast transient recovery



DC Power Conversion System

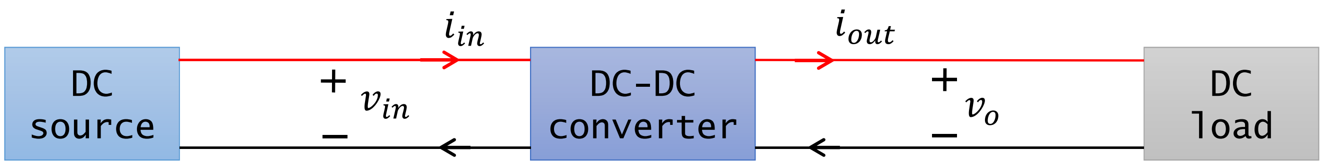


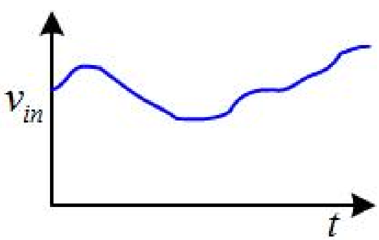
- Battery
- DC grid
- Ultra-cap
- Solar

- Step-down or step-up or both
- Without isolation or with isolation

- Mobile devices
- Cloud computing
- Automotive
- LED driving

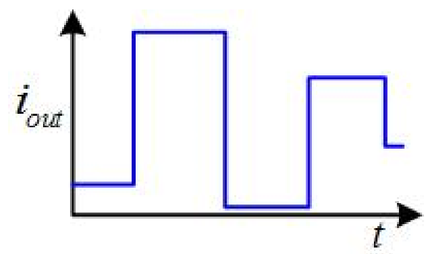
DC Power Conversion – Primary Objectives





Source voltage variations

- ❑ Tight voltage or current regulation
- ❑ High efficiency over a wide range
- ❑ Very fast transient performance
- ❑ High power density – smaller size
- ❑ Stable behavior – predictable ripple



Load current variations

Summary of Objectives

- Suitable choice of voltage and current regulators – important
- Understanding behavior and estimating losses – crucial
- Size reduction of DC power conversion – growing trend
- High efficiency and fast transient performance – mandatory
- Selection of suitable modulation and control techniques – essential
- Design and control of voltage and/or current regulators – critical

Overview of this course

- Brief introduction of switched mode power converters – primarily non-isolated
- Well-known fixed-frequency and variable-frequency modulation techniques
- Introduction to various feedback and feedforward control methods
- Overview of modeling and analysis techniques

Overview of this course

- Small-signal and frequency response analysis
- Small-signal based controller design and tuning methods
- Understanding large-signal based modeling and control
- Large-signal based tuning methods and critical performance limits

Reference

[1] S. Kapat and P. T. Krein, "A Tutorial and Review Discussion of Modulation, Control and Tuning of High-Performance DC-DC Converters based on Small-Signal and Large-Signal Approaches" *IEEE Open Journal of Power Electronics*, vol. 1, pp. 339 - 371, Aug. 2020.

[2] R. W. Erickson and D. Maksimovic, Fundamentals of Power Electronics, 3rd Ed., Springer, 2020.

[3] P. T. Krein, Elements of Power Electronics, Indian Edition, Oxford University Press, 2012

Prior NPTEL resources: For more detailed SMPC topologies, please refer to NPTEL course on "***Switched Mode Power Conversion***" – Link here

THANK YOU !

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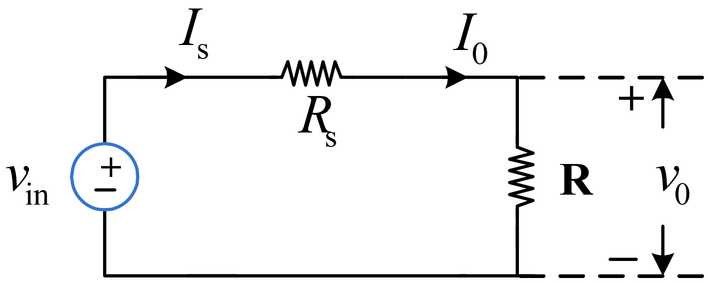
Module 01: Switched Mode Power Converters and Simulation

Lecture 02: Overview of voltage regulators

Concepts Covered

- Overview of linear voltage regulators
- Introduction to switched capacitor converters
- Understanding hybrid switched capacitor converters
- Basics switched mode power converters

Voltage Regulator – Simplest Form



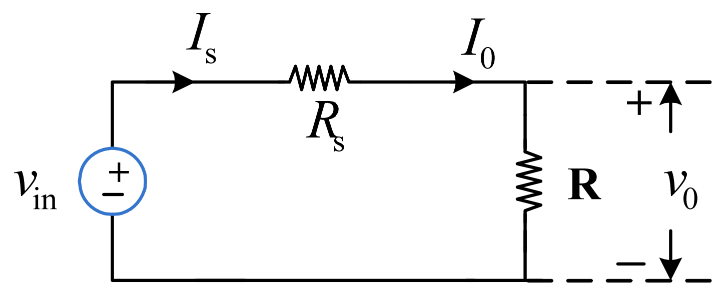
Voltage gain

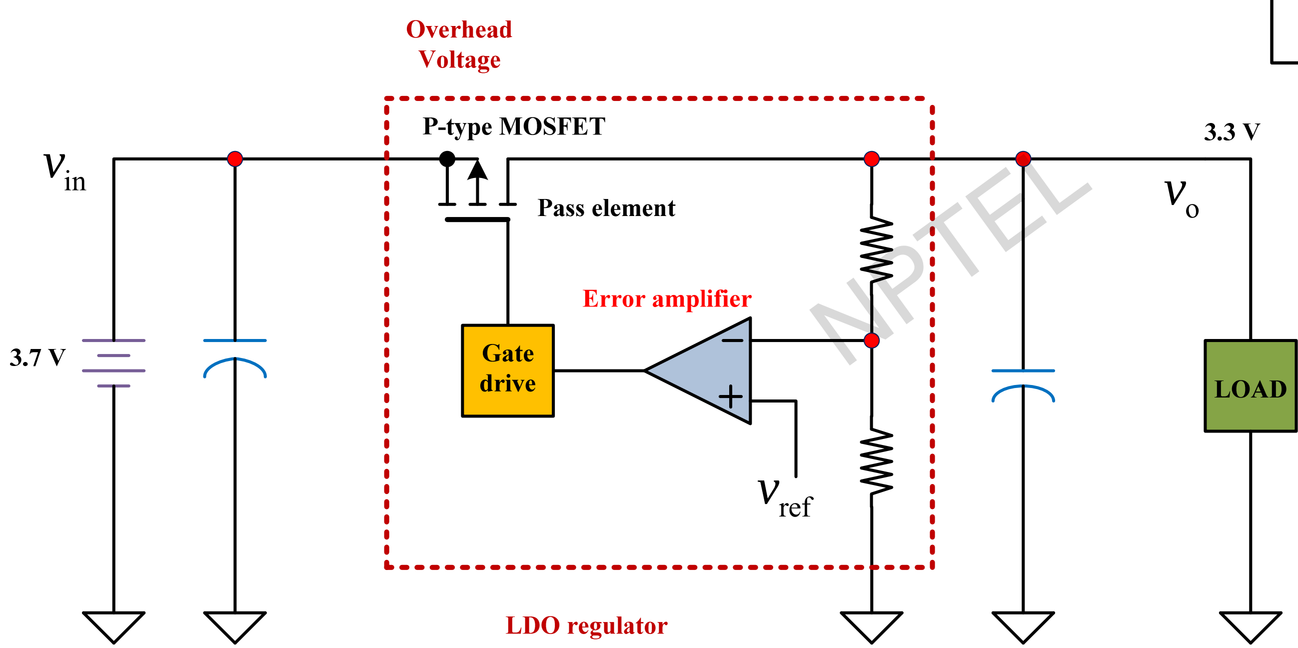
$$k_v = \frac{v_o}{v_{in}} = \frac{R}{R + R_s}$$

Theoretical efficiency

$$\eta = k_v$$

Voltage Regulator – LDO





Advantages and Limitations of Linear Voltage Regulators

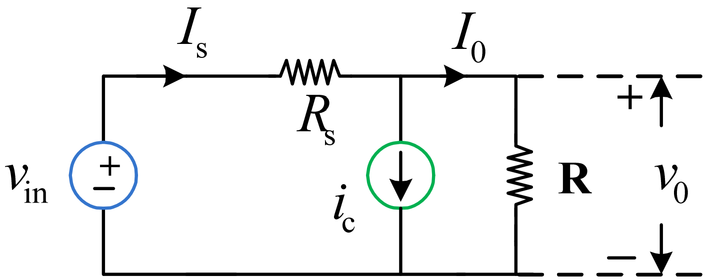
Advantages

- Simple to analyze and design
- Ultra-low power applications
- Negligible switching noise, low EMI
- Compact design using IC

Limitations

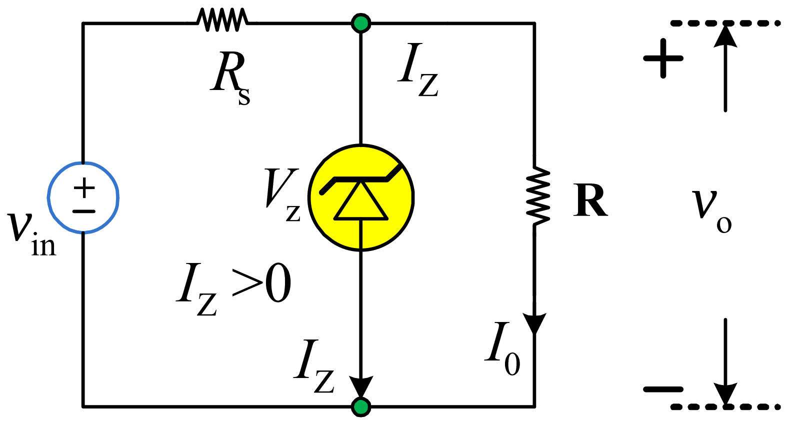
- Low efficiency at high dropout voltage
- Poor current handling capability
- Higher losses at higher power level
- Step-up operation not possible

Shunt Voltage Regulators – Simplest Form



$$k_v = \frac{v_o}{v_{in}} = \frac{R}{R+R_s} \times \left(1 - \frac{R_s i_c}{v_{in}}\right)$$

$$\eta = k_v \times \left(1 - \frac{R_s i_c}{v_{in}}\right) \Big/ \left(1 + \frac{R i_c}{v_{in}}\right)$$



Advantages and Limitations of Shunt Voltage Regulators

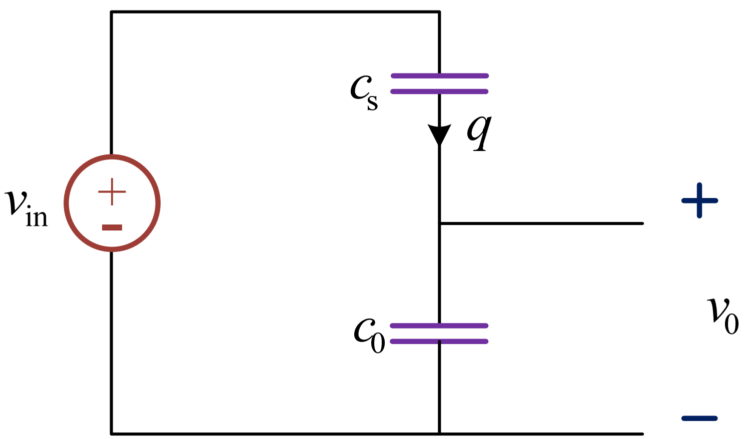
Advantages

- Additional current sink path for better output voltage regulation - current source/sink applications
- Common in voltage ref. circuits

Limitations

- Power losses in series & shunt paths
- Poor efficiency than series VR
- Non zero power loss for Pout=0
- Step-up operation not possible

Capacitor Voltage Regulators – Simplest Form



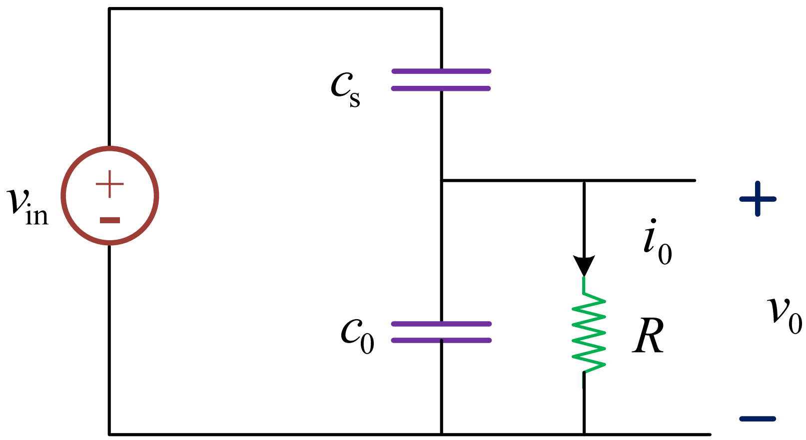
Under no load condition

$$q = C_o v_o = C_s \left(v_{in} - v_o \right)$$

$$v_o(\infty) = \frac{C_s}{C_s + C_o} \times v_{in}$$

What happens after connecting load?

Capacitor Voltage Regulators Contd …



After connecting load resistance

$$v_o(t) = v_o(0) \times \exp\left(\frac{-t}{\tau_{eq}}\right),$$

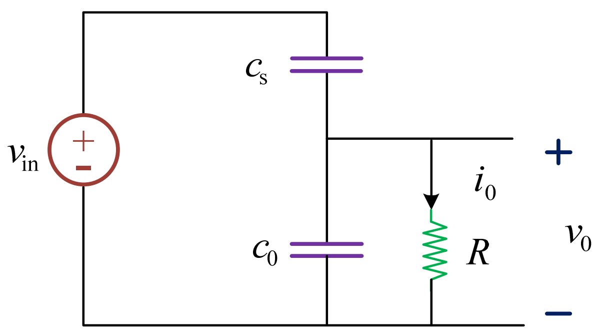
$$\tau_{eq} = R \times (C_s + C_o)$$

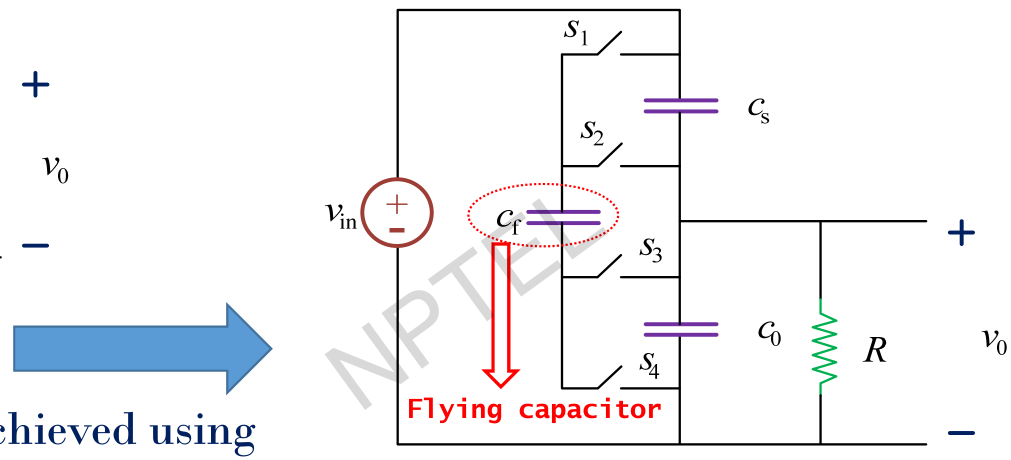
$$v_o(\infty) = 0$$

Output voltage collapses!!

What is the next step?

Capacitor Voltage Regulators using Flying Capacitor

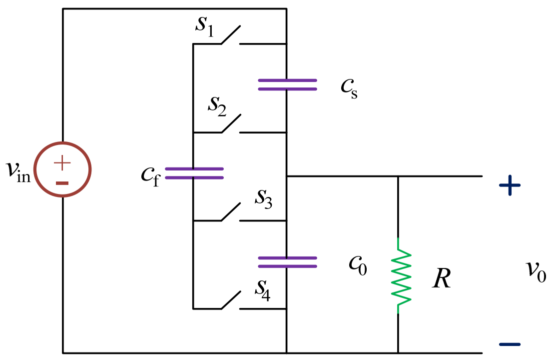


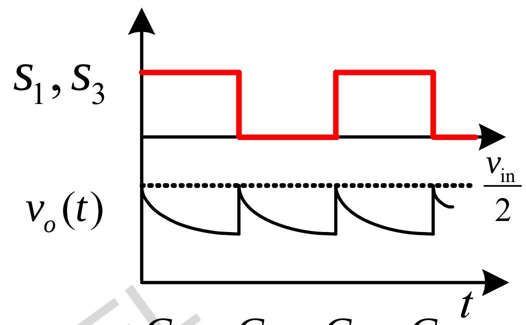


Charge balance can be achieved using a flying capacitor and by periodically switching among source and o/p Caps

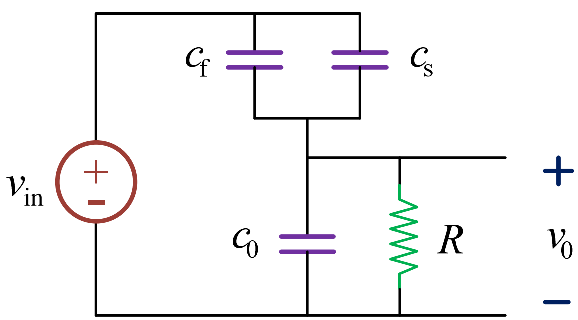
Step-down switched capacitor VR

Capacitor Voltage Regulators using Flying Capacitor

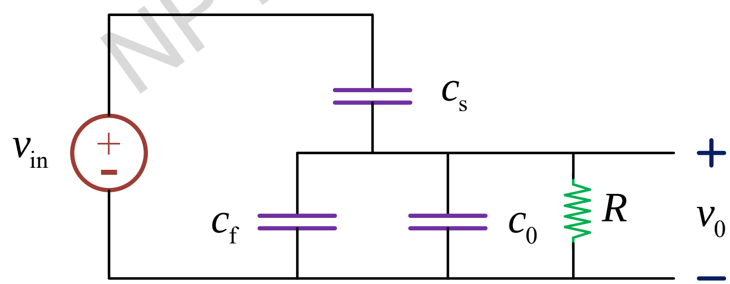




$$C_f = C_o = C_s = C$$

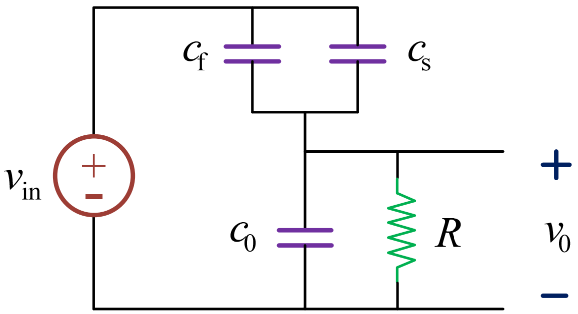


Charging phase of flying cap

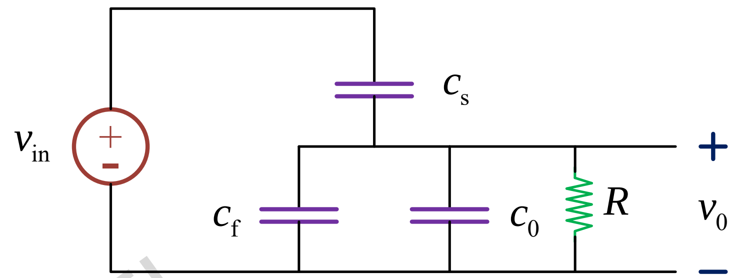


Discharging phase of flying cap

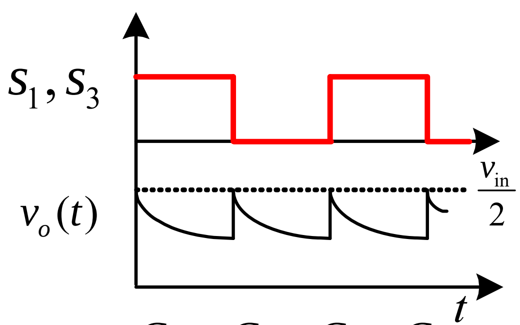
Capacitor Voltage Regulators using Flying Capacitor



Charging phase of flying cap



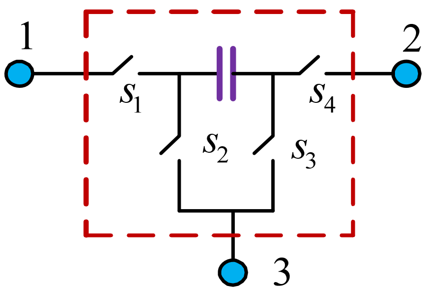
Discharging phase of flying cap



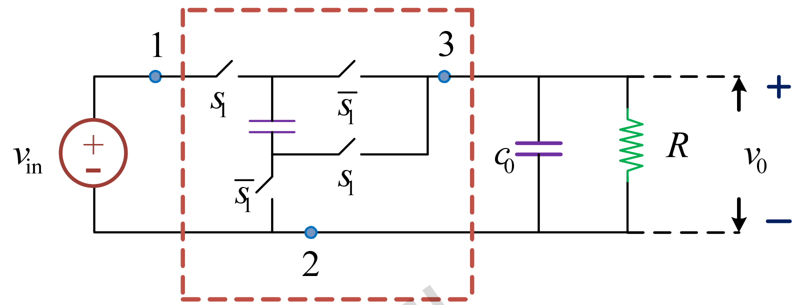
$C_f = C_o = C_s = C$

- ❑ Voltage ripple – load dependent
- ❑ Poor line & load regulation
- ❑ Inrush current during switching

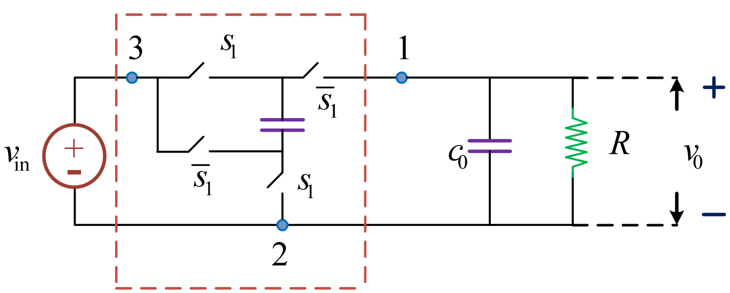
Basic Switch Capacitor Configurations



Basic switch cap cell



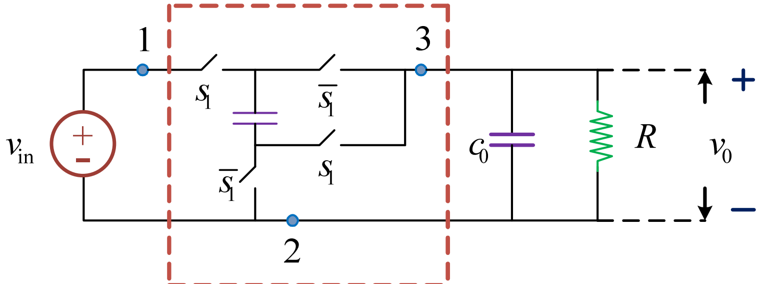
Step-down switch cap converter



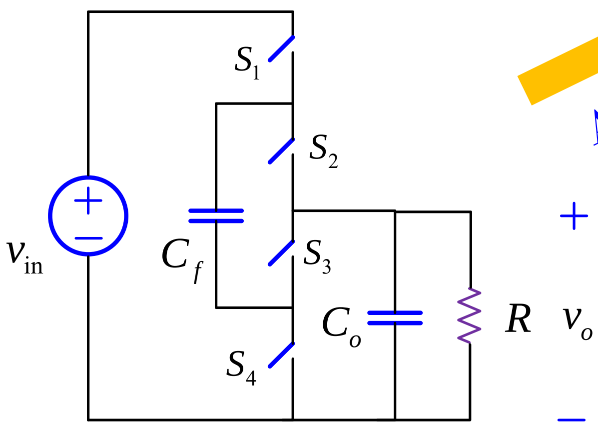
Step-up switch cap converter

- Step-up and step-down voltage regulation possible, however, voltage gain is factor of 2

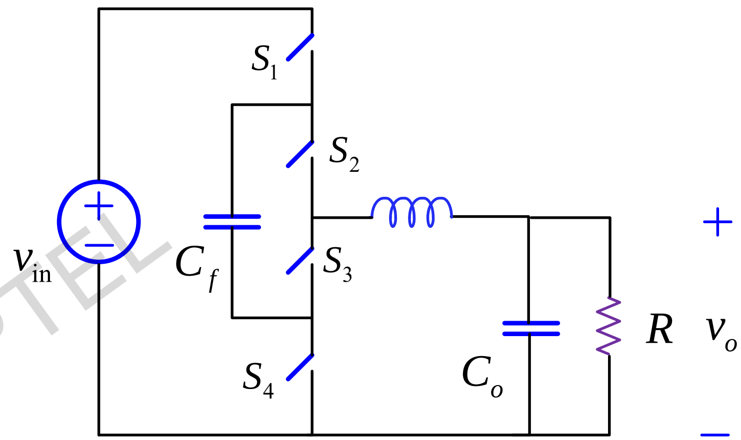
Hybrid Step-down Switch Capacitor Converter



Redrawing

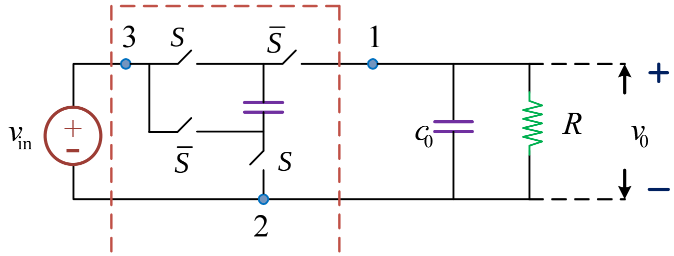


Adding a small inductor

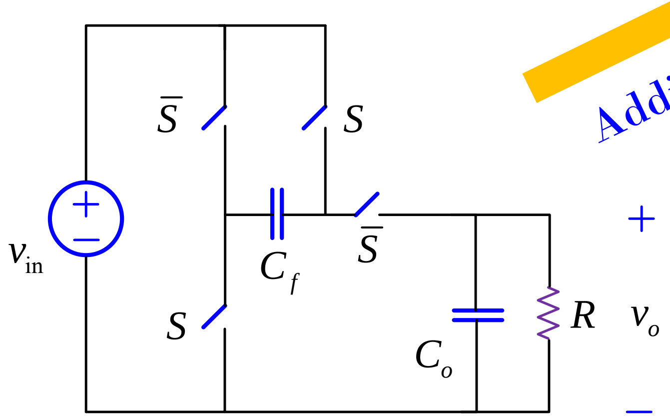


Hybrid switch cap step-down converter

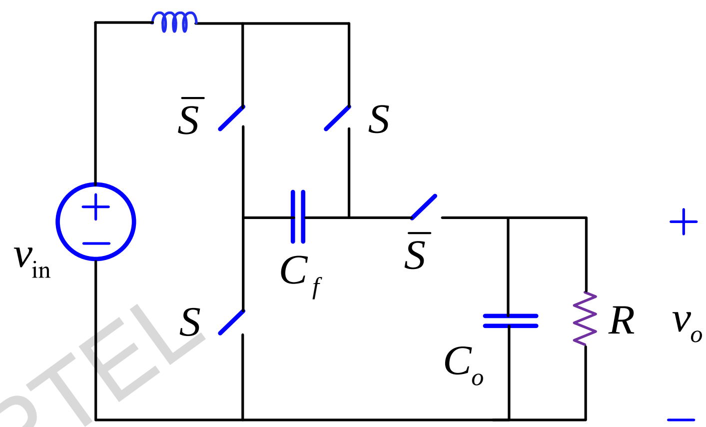
Hybrid Step-up Switch Capacitor Converter



Redrawing



Adding a small inductor

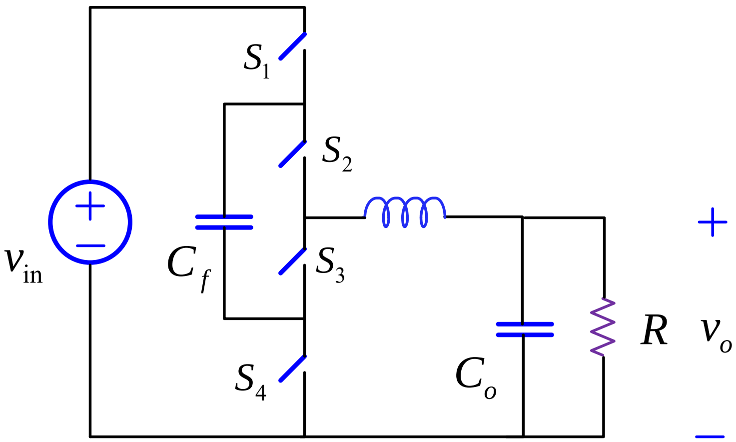


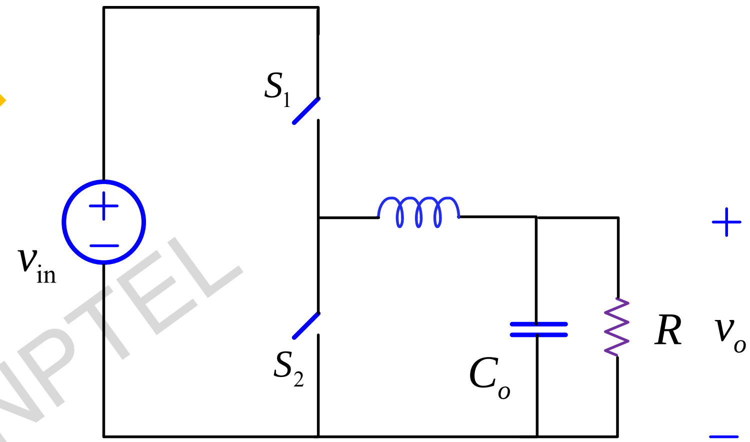
Hybrid switch cap step-up converter

Switched Capacitor Voltage Regulators – Summary

- Switch cap VR – more efficient & higher power than LDO, step-up possible
- Switch cap VR – poor line/load regulation, poor efficiency for varying D
- Hybrid switch cap VR – superior efficiency/regulation, step-up/down conv.
- Hybrid switch cap VR – many switches, voltage balance control of C_f
- Hybrid switch cap VR – research opportunities on control & optimization

Inductive Step-down Converter

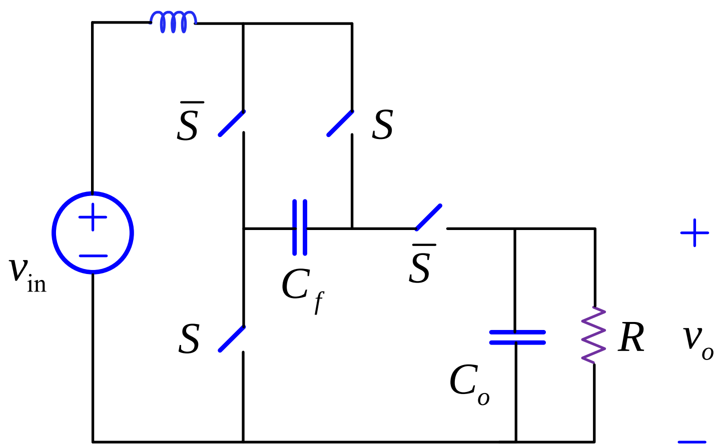


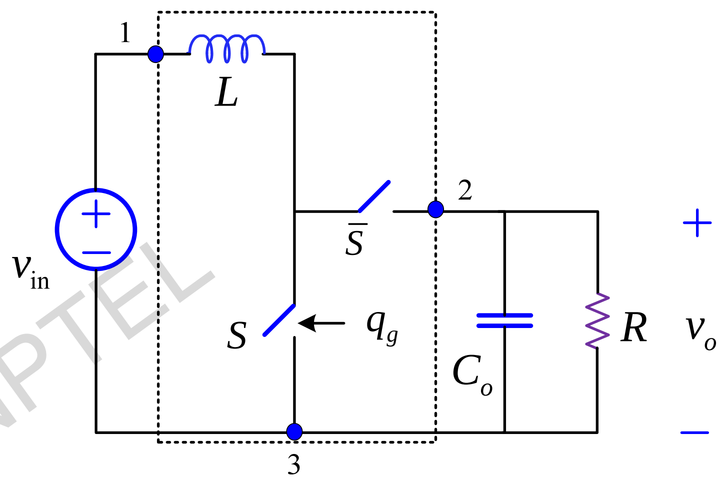


Hybrid switch cap step-down converter with capacitive energy transfer and small inductor

Inductive step-down converter (known as buck converter) with inductive energy transfer

Inductive Step-up Converter





Hybrid switch cap step – up converter with capacitive energy transfer and small inductor

Inductive step – up converter (known as boost converter) with inductive energy transfer

Summary of Concepts

- Linear voltage regulators – suitable for ultra-low power applications
- Linear regulators – not suitable for higher power or step-up purposes
- Pure switched capacitor (SC) converters – not suitable at high power
- Hybrid SC converters – challenging, but emerging architectures
- Inductive converters – dominate in commercial products

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THANK YOU !

NPTEL ONLINE CERTIFICATION COURSES

CONTROL AND TUNING METHODS IN SMPCs

Dr. Santanu Kapat
Electrical Engineering Department, IIT KHARAGPUR

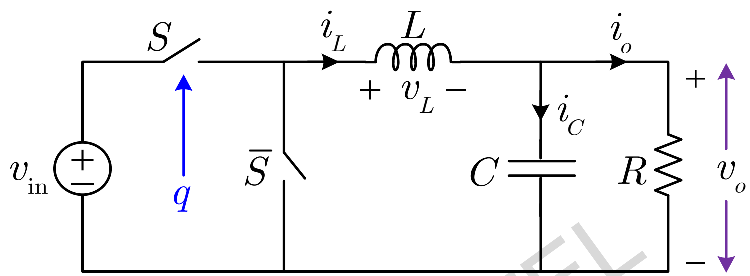
Module 01: Switched Mode Power Converters and Simulation

Lecture 03: Switched mode power converter (SMPC)

Concepts Covered

- Basic DC-DC converters
- Step-down converter
- Step-up converter
- Step-up/down converter
- Basics of isolated DC-DC converters

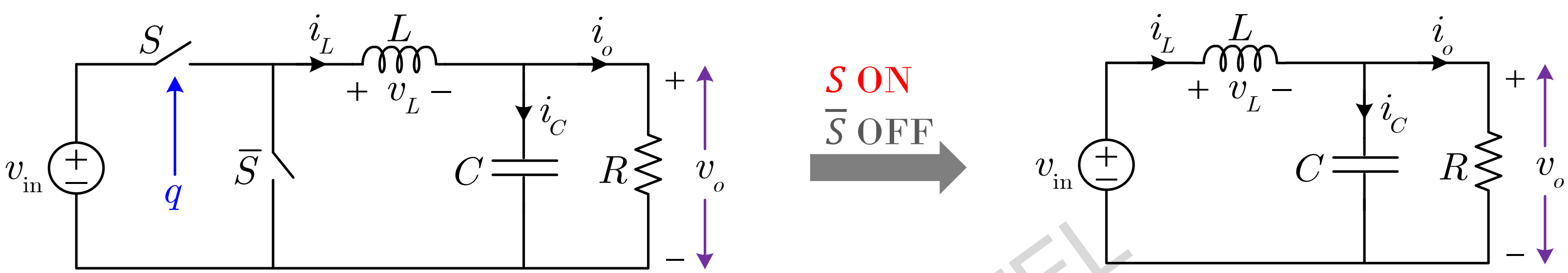
Step-down Converter (Buck Converter)



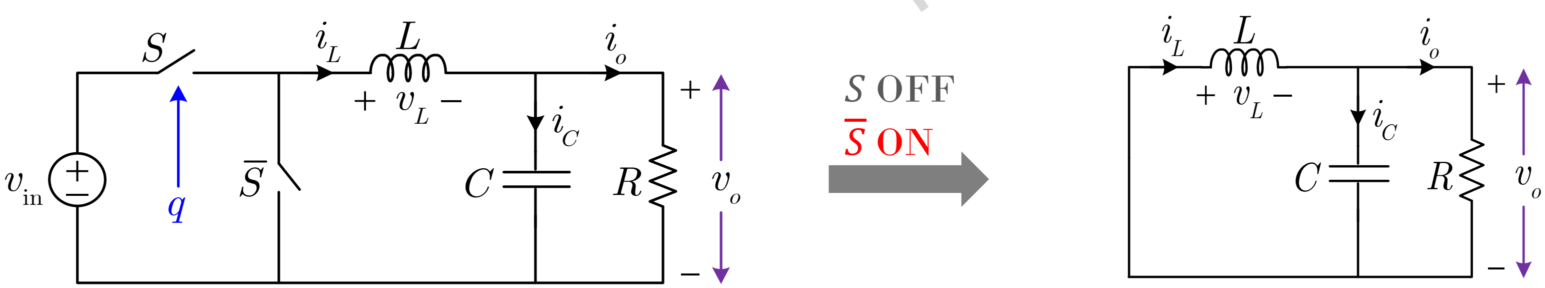
Buck Converter

- S and $\overline{S}$ $\rightarrow$ single-pole single throw switches
- S and $\overline{S}$ $\rightarrow$ in complementary fashion
- $\boldsymbol{q} \rightarrow$ command signal to turn ON or OFF of S

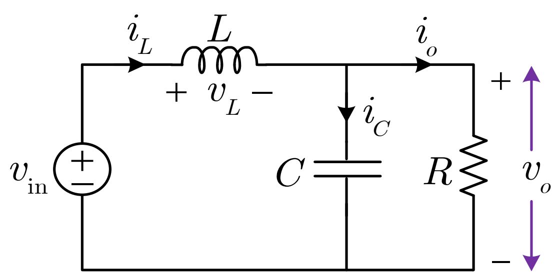
If S on and $\overline{\text{S}}$ off



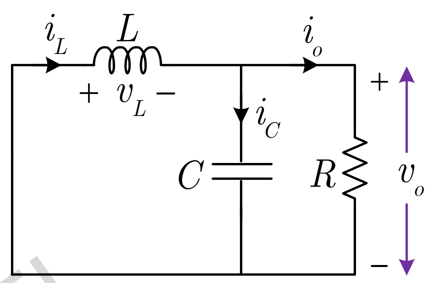
If S off and $\overline{\text{S}}$ on



Overall Operation



Mode 1: S - ON

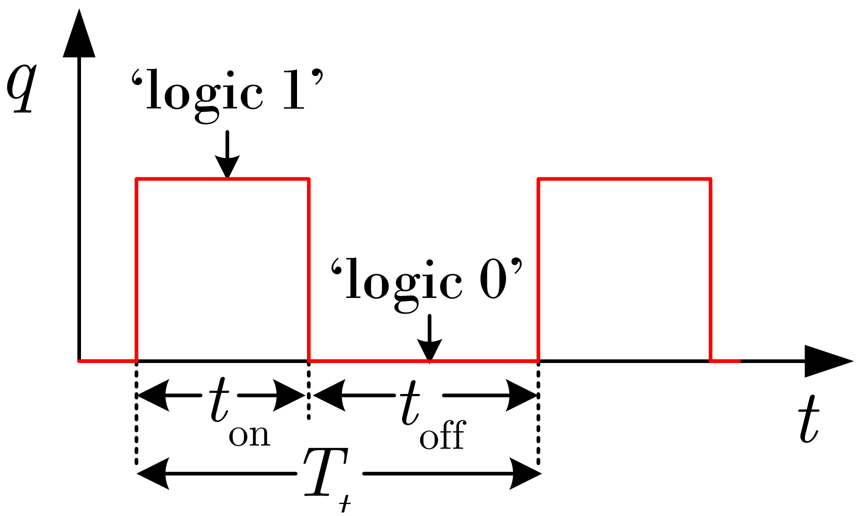


Mode 2: S - OFF

- None of the above configurations alone can achieve $0 < v_o < v_{in}$

❑ Question: How can we achieve $0 < v_o < v_{in}$ in finite time?

Switching between Two Configurations



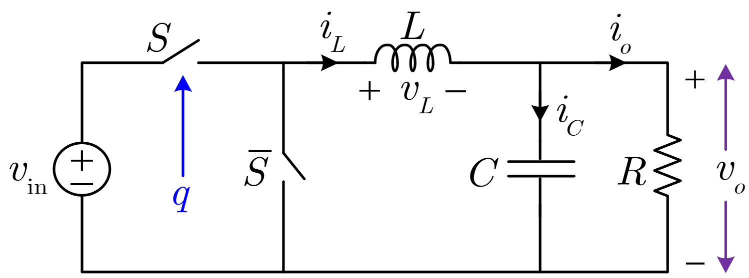
$t_{\text{on}} \rightarrow$ On-time of switch S

$t_{\text{off}} \rightarrow$ Off-time of switch S

$T_t \rightarrow$ total time in a periodic cycle

$$T_t = t_{\text{on}} + t_{\text{off}}$$

Volt-Second Balance in a Buck Converter



Buck Converter

$$v_L = \begin{cases} v_{in} - v_o & (q = 1) \\ -v_o & (q = 0) \end{cases}$$

$$\langle v_L \rangle_{T_t} = \frac{1}{T_t} \int_0^{T_t} v_L(t)dt$$

Steady-state notations:

$$\langle v_L \rangle_{T_t} \triangleq V_L \qquad t_{on} \triangleq T_{on}$$

$$\langle v_{in} \rangle_{T_t} \triangleq V_{IN} \qquad t_{off} \triangleq T_{off}$$

$$\langle v_o \rangle_{T_t} \triangleq V_O \qquad T_t \triangleq T_{sw}$$

$$\langle i_L \rangle_{T_t} \triangleq I_L \qquad f_{sw} = \frac{1}{T_{sw}}$$

$$\langle i_o \rangle_{T_t} \triangleq I_O$$

Volt-Second Balance and Charge Balance (contd…)

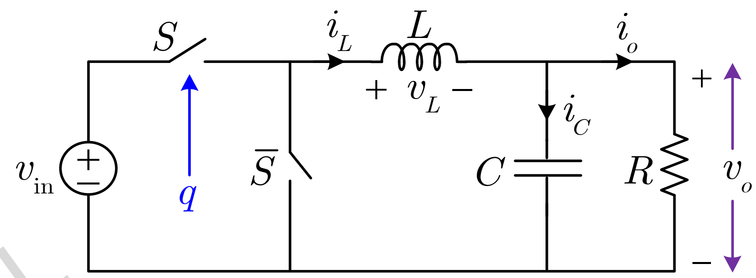
- **At steady-state:**

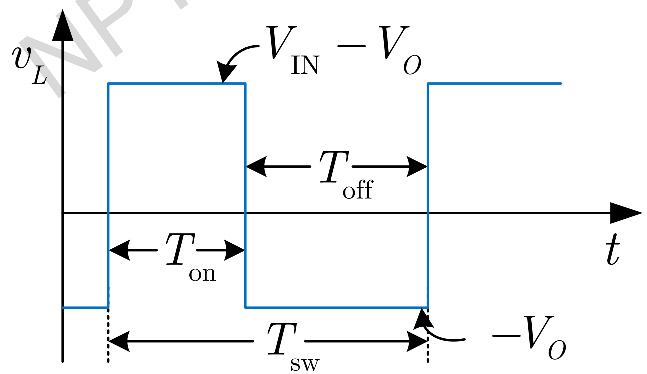
$$V_L = \frac{1}{T_{sw}}\left[\left(V_{IN} - V_O\right)T_{on} + \left(-V_O\right)T_{off}\right] = 0$$

$$\Rightarrow V_O = \left(\frac{T_{on}}{T_{on} + T_{off}}\right) \times V_{IN}$$

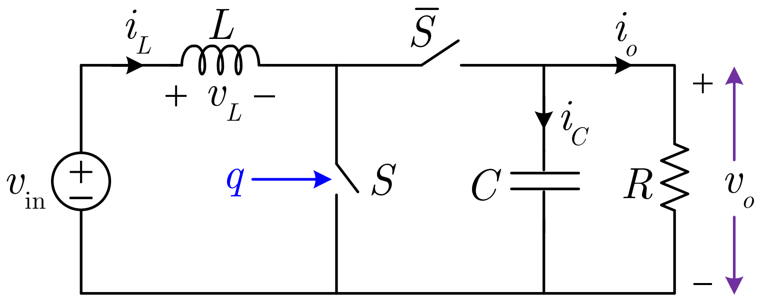
$$I_C = \left(I_L - I_O\right) = 0$$

$$\Rightarrow I_L = I_O$$





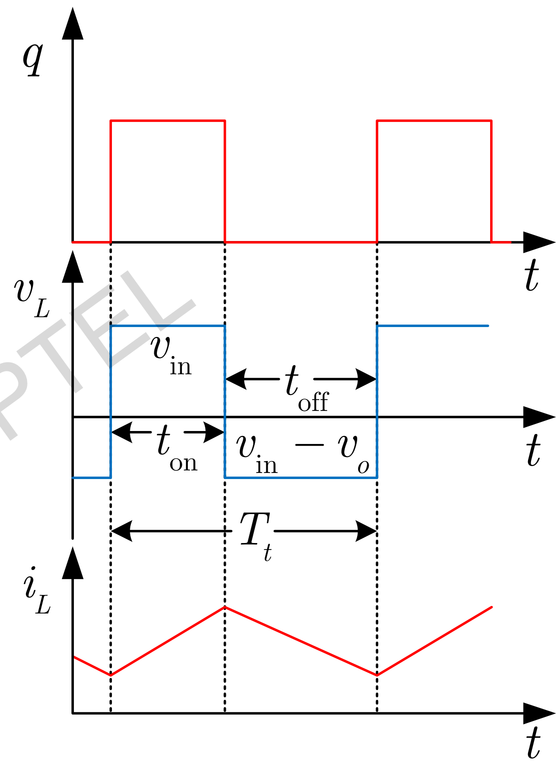
Step-up (Boost) Converter



Boost Converter

$$v_L = \begin{cases} v_{in} & (q=1) \\ v_{in} - v_o & (q=0) \end{cases}$$

$$i_c = \begin{cases} -i_o & (q=1) \\ i_L - i_o & (q=0) \end{cases}$$



Boost Converter (contd...)

Steady-state notations:

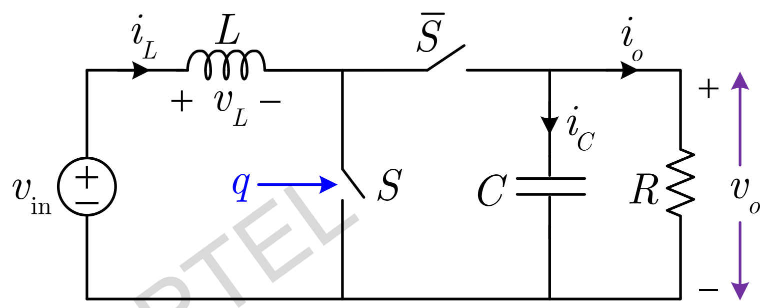
$$\langle v_L \rangle_{T_t} \triangleq V_L \qquad t_{on} \triangleq T_{\mathrm{on}}$$

$$\langle v_{\mathrm{in}} \rangle_{T_t} \triangleq V_{\mathrm{IN}} \qquad t_{\mathrm{off}} \triangleq T_{\mathrm{off}}$$

$$\langle v_o \rangle_{T_t} \triangleq V_O \qquad T_t \triangleq T_{\mathrm{sw}}$$

$$\langle i_L \rangle_{T_t} \triangleq I_L \qquad f_{\mathrm{sw}} = \frac{1}{T_{\mathrm{sw}}}$$

$$\langle i_o \rangle_{T_t} \triangleq I_O$$



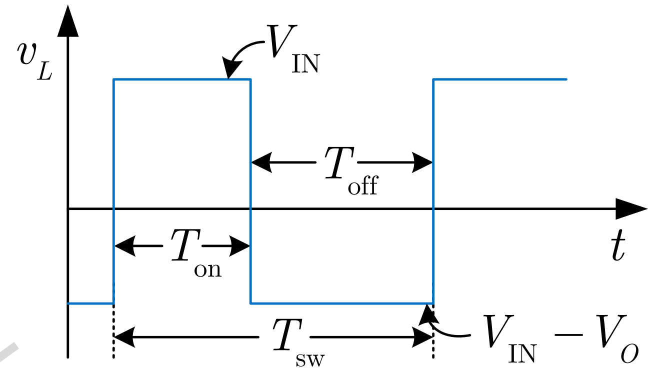
Boost Converter

Boost Converter (contd...)

- **At steady-state:**

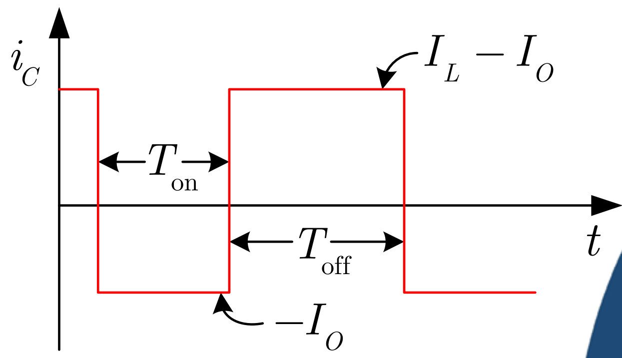
$$V_L = \frac{1}{T_{sw}}\left[\left(V_{IN}\right)T_{on} + \left(V_{IN} - V_O\right)T_{off}\right] = 0$$

$$\Rightarrow V_O = \left(\frac{T_{on} + T_{off}}{T_{off}}\right) \times V_{IN}$$



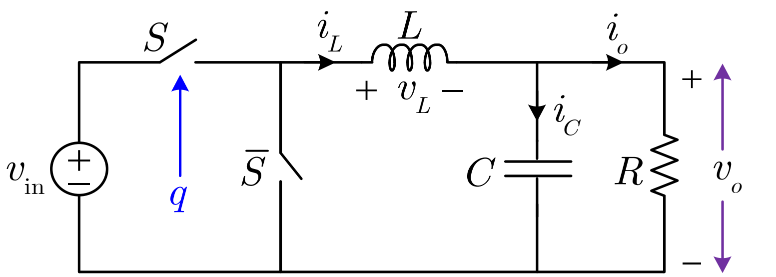
$$I_C = \frac{1}{T_{sw}}\left[\left(-I_O\right)T_{on} + \left(I_L - I_O\right)T_{off}\right] = 0$$

$$\Rightarrow I_L = \left(\frac{T_{on} + T_{off}}{T_{off}}\right) \times I_O$$



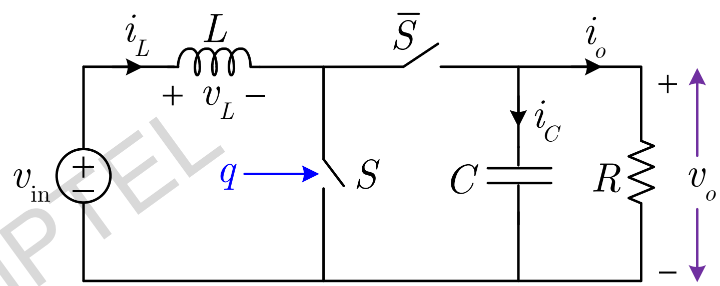
Voltage Gain and Voltage Regulation

- Steady-state voltage gain, $K_V = \dfrac{V_O}{V_{\text{IN}}}$



Buck Converter

$$K_V = \left(\frac{T_{\text{on}}}{T_{\text{on}} + T_{\text{off}}}\right)$$



Boost Converter

$$K_V = \left(\frac{T_{\text{on}} + T_{\text{off}}}{T_{\text{off}}}\right)$$

Voltage Regulation — Degree of Freedom

- Voltage regulation in both cases is achieved by

  a) Adjusting T_{on} by keeping T_{sw} constant

  - Control variable $\dfrac{T_{\text{on}}}{T_{\text{sw}}} = D$ (duty ratio)
  - Known as pulse width modulation (PWM)

Voltage Regulation — Degree of Freedom (contd…)

b) Adjusting $\boldsymbol{T}_{\mathbf{on}}$ by keeping $\boldsymbol{T}_{\mathbf{off}}$ constant

- Off-time constant i.e. $\boldsymbol{T}_{\mathbf{off}} \triangleq \boldsymbol{T}_{c}$
- Control variable $\rightarrow \boldsymbol{t}_{\mathbf{on}}$
- Time period, $\boldsymbol{T}_{\mathbf{sw}} = \boldsymbol{T}_{\mathbf{on}} + \boldsymbol{T}_{c}$, varies with voltage gain as

$$T_{\text{sw}} = \begin{cases} \dfrac{1}{1-K_V} \times T_{\text{off}} & \textbf{Buck} \\ K_V \times T_{\text{off}} & \textbf{Boost} \end{cases}$$

- Known as constant off-time modulation

Voltage Regulation — Degree of Freedom (contd…)

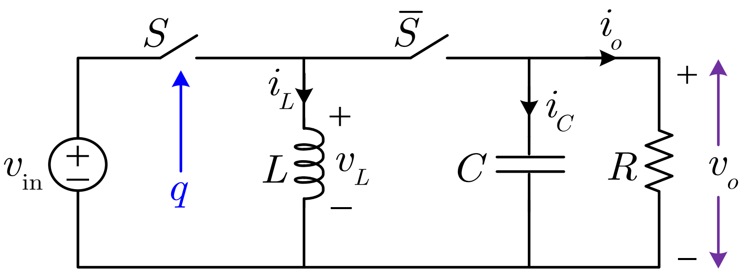
c) Adjusting T_{off} by keeping T_{on} constant

- On-time constant i.e. $T_{\text{on}} \triangleq T_c$
- Control variable $\rightarrow t_{\text{off}}$
- Time period $T_{\text{sw}} = T_{\text{off}} + T_c$, varies with voltage gain as

$$T_{\text{sw}} = \begin{cases} \dfrac{1}{K_V} \times T_{\text{on}} & \text{Buck} \\ \dfrac{K_V}{K_V - 1} \times T_{\text{on}} & \text{Boost} \end{cases}$$

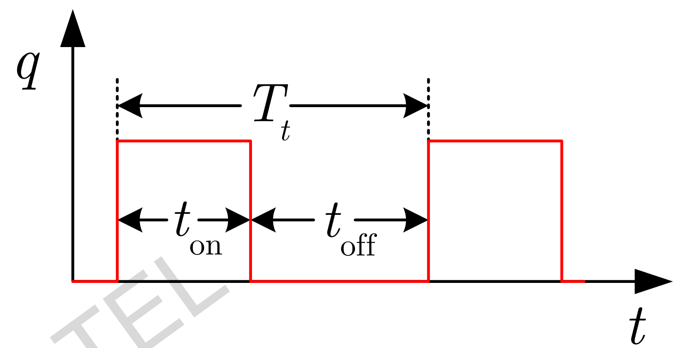
- Known as constant on-time modulation

Buck-boost Converter



Buck-Boost Converter

$$v_L = \begin{cases} v_{\text{in}} & (q = 1) \\ v_o & (q = 0) \end{cases}$$



Steady-state notations:

$$\langle v_L \rangle_{T_t} \triangleq V_L \qquad t_{on} \triangleq T_{\text{on}}$$

$$\langle v_{in} \rangle_{T_t} \triangleq V_{\text{IN}} \qquad t_{\text{off}} \triangleq T_{\text{off}}$$

$$\langle v_o \rangle_{T_t} \triangleq V_O \qquad T_t \triangleq T_{\text{sw}}$$

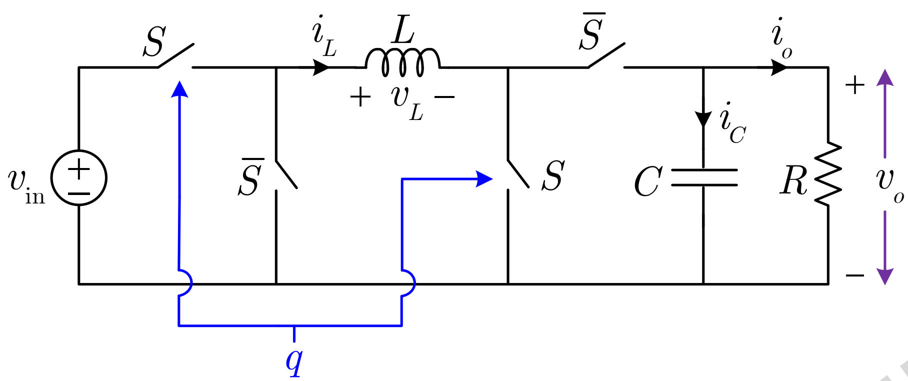
Buck-boost Converter (contd…)

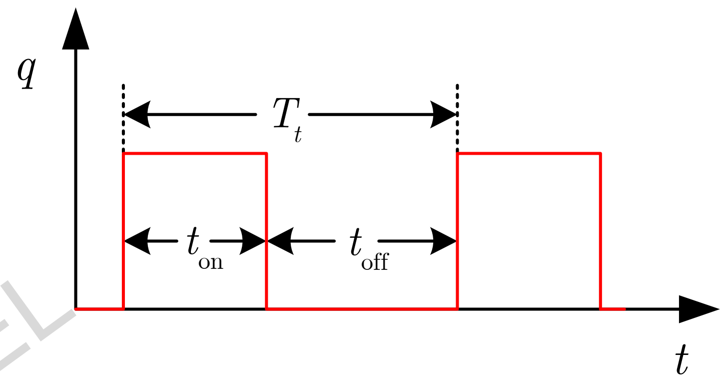
- At steady-state:

$$V_L = \frac{1}{T_{\text{sw}}}\left[V_{\text{IN}} T_{\text{on}} + V_O T_{\text{off}}\right] = 0 \quad \Rightarrow V_O = -\left(\frac{T_{\text{on}}}{T_{\text{off}}}\right) \times V_{\text{IN}}$$

- Output voltage is negative
- Magnitude of V_O can be higher, lower or equal to V_{IN}
- Other buck-boost converters available with positive output voltage
- Non-inverting buck-boost → a potential low power candidate

Non-inverting Buck-boost Converter



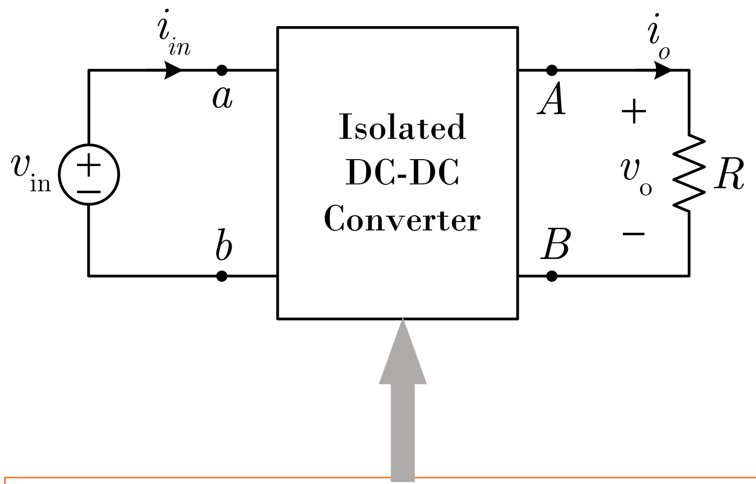


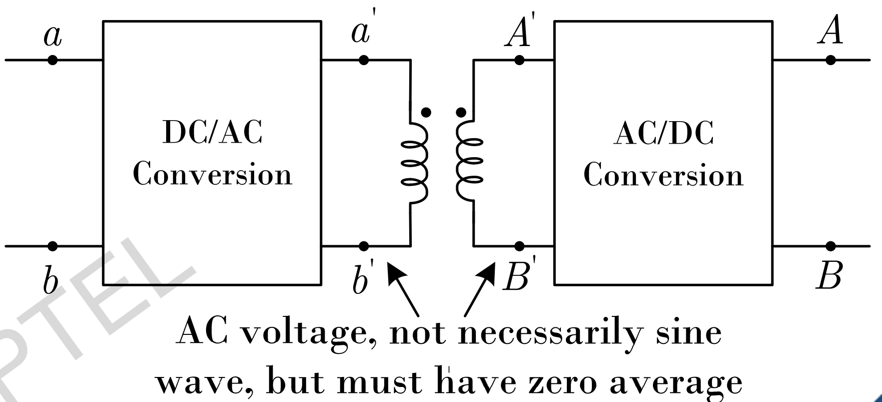
- Voltage across the inductor

$$v_L = \begin{cases} v_{in} & \text{for } q = 1 \\ -v_o & \text{for } q = 0 \end{cases}$$

Derive steady-state voltage gain

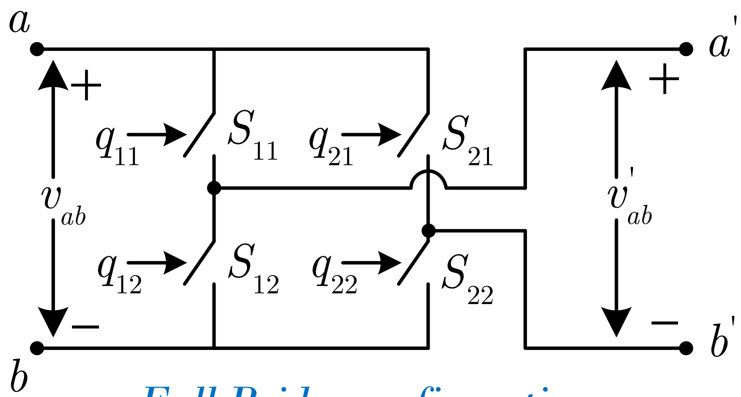
Introduction to Isolated SMPC





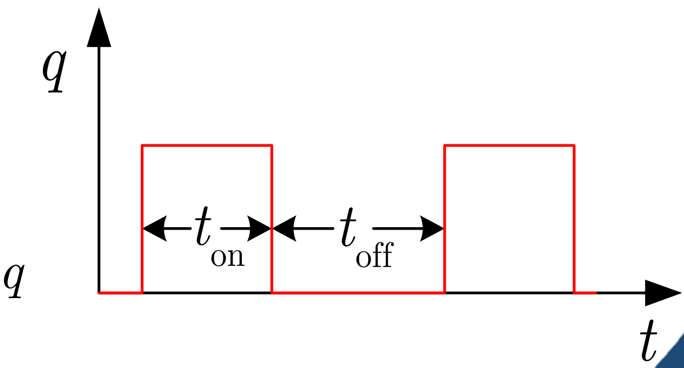
- Transformer used for galvanic isolation
- Transformer can not be directly used with a DC source

Possible DC/ AC Configurations



Full Bridge configuration

$$q_{12} = \overline{q}_{11}$$
$$q_{22} = \overline{q}_{21}$$
$$q_{11} = q_{22} \triangleq q$$



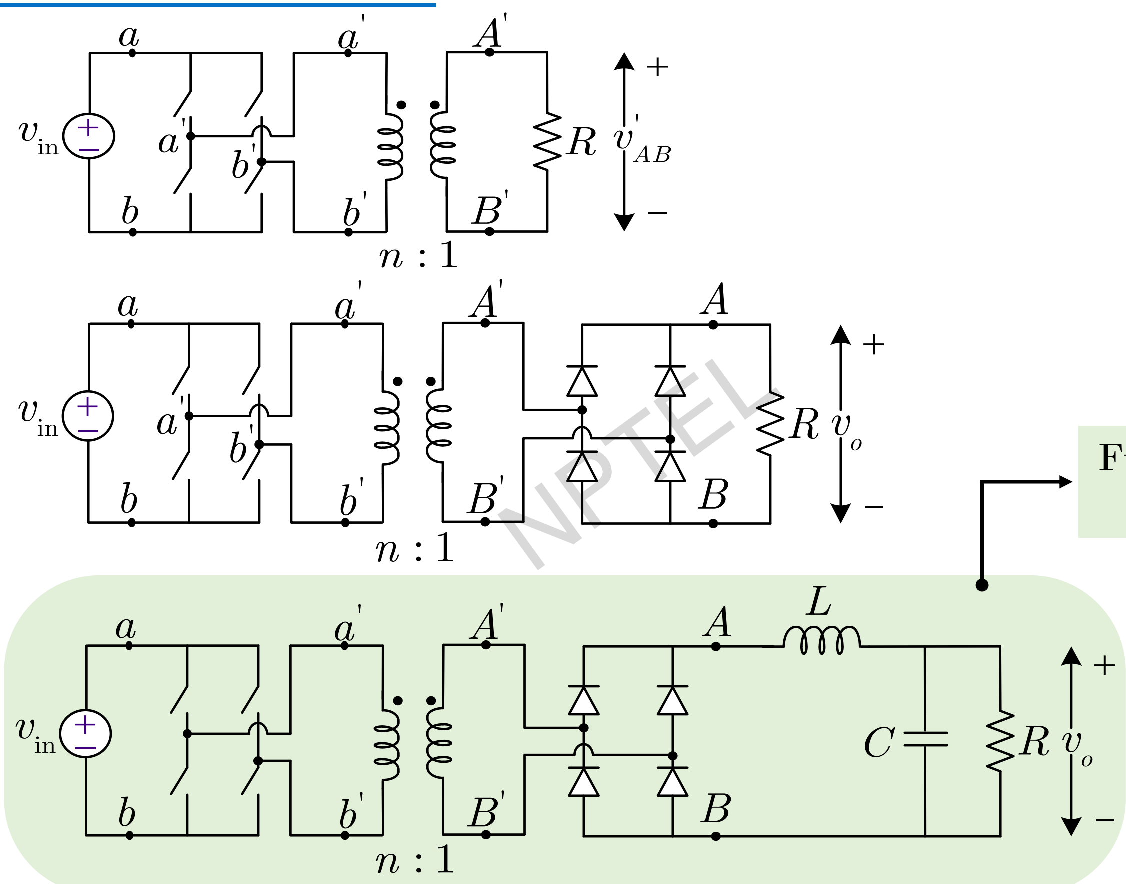
For q=1: $v'_{ab} = v_{ab}$

For q=0: $v'_{ab} = -v_{ab}$

Connect to the Transformer

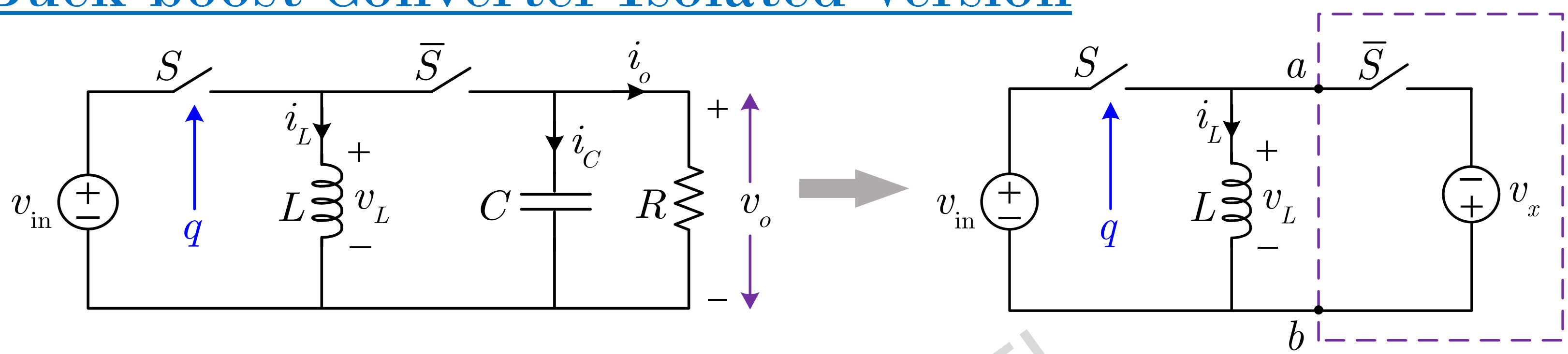
Consider a diode bridge rectifier in the secondary side of the transformer

Consider an output filter



Full Bridge DC-DC Converter

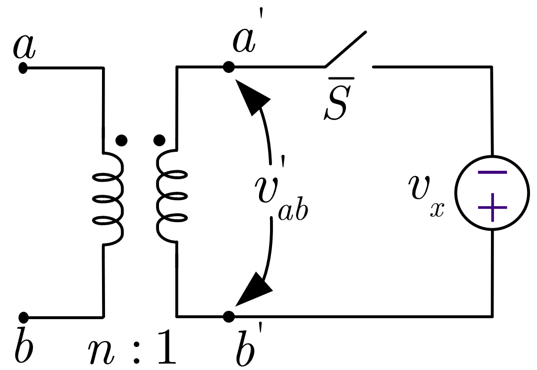
Buck-boost Converter Isolated Version



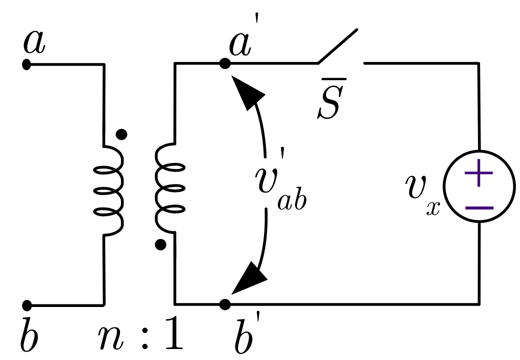
1. Start with a buck-boost converter
2. Replace capacitor and resistance at the output side with a floating voltage v_x

Can be replaced by a pulsating voltage

Buck-boost Converter Isolated Version (contd…)



Polarity of v_x can be changed by changing dot convention



When S ON ($\overline{S}$ OFF)

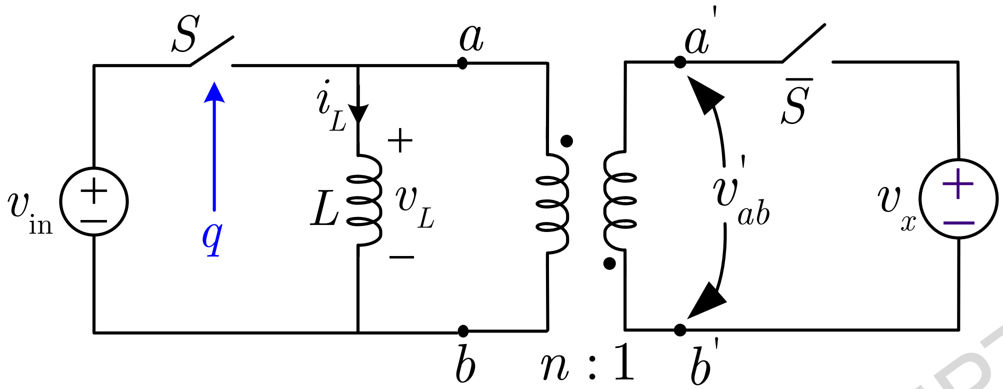
$$v_{\text{ab}} = v_{\text{in}} \Rightarrow v'_{\text{ab}} = \frac{v_{\text{ab}}}{n}$$

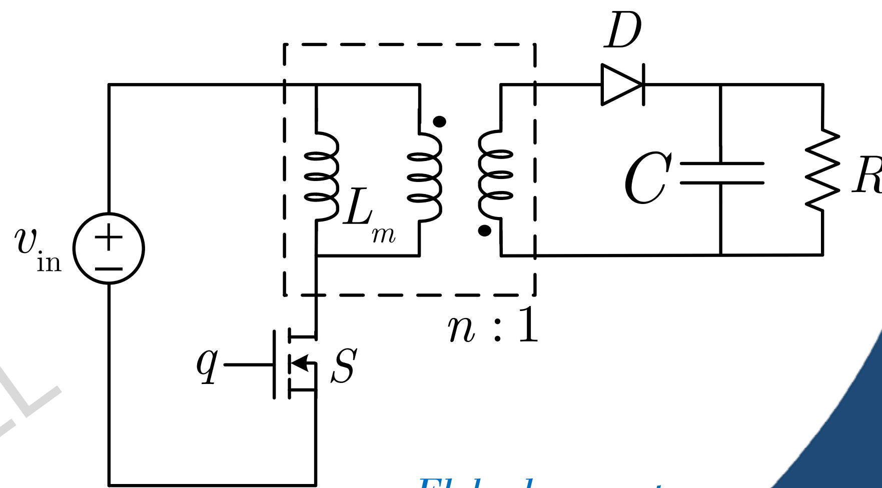
When S OFF ($\overline{S}$ ON)

$$v'_{\text{ab}} = -v_x \Rightarrow v_{\text{ab}} = -nv_x$$

$$v_L = \begin{cases} v_{\text{in}} & \text{for } q = 1 \\ -v_o & \text{for } q = 0 \end{cases}$$

Overall Circuit





Flyback converter

- High side switch to low side switch
- Complementary switch replaced with a diode
- v_x replaced by capacitor and resistance in parallel
- Inductor integrated as the magnetizing reactance

Summary

- Buck converter → step down purpose
- Boost converter → step-up purpose
- Buck-boost converter → both step-up and step-down, but –ve polarity
- Non-inverting buck-boost → both step-up and step-down
- Flyback converter → Isolated buck-boost converter with +ve output

THANK YOU !

NPTEL ONLINE CERTIFICATION COURSES

CONTROL AND TUNING METHODS IN SMPCs

Dr. Santanu Kapat
DEPARTMENT NAME, IIT KHARAGPUR

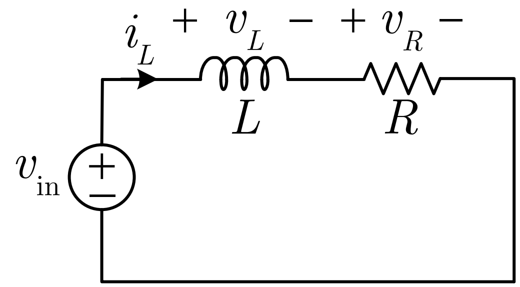
Module 01: Switched Mode Power Converters and Simulation

Lecture 04: Model Development for MATLAB Simulation

Concepts Covered

- Modeling of a series RL circuit and block diagram for simulation
- Modeling of series and parallel RLC circuits along with parasitic
- Modeling of parallel RLC circuits with parasitic components
- Modeling of conventional and synchronous buck converters
- Modeling of a boost converter and model generalization

Series RL Circuit



- **Voltages**

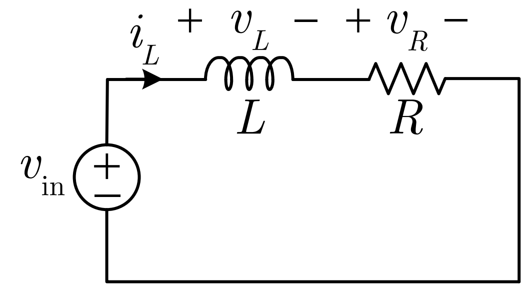
$$v_L = v_{\text{in}} - v_R \qquad v_R = i_L \times R$$

$$v_L = (v_{\text{in}} - v_R) = (v_{\text{in}} - i_L R)$$

- **Dynamics**

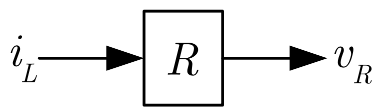
$$L\frac{di_L}{dt} = v_L = (v_{\text{in}} - i_L R)$$

Series RL Circuit – Implementation

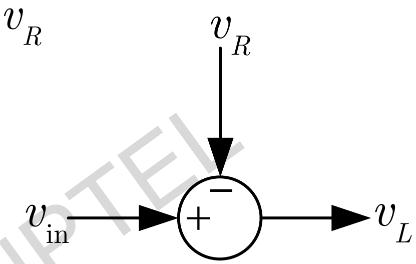


- **Voltages**

$$v_R = i_L \times R$$

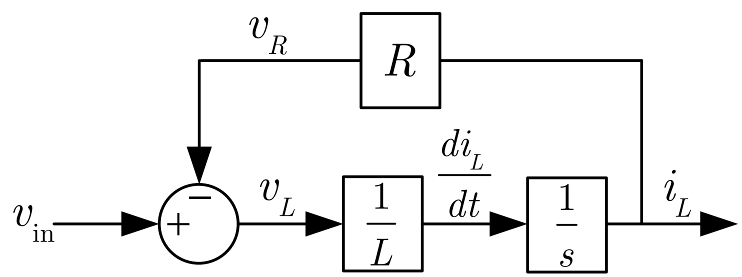


$$v_L = (v_{\text{in}} - v_R)$$



- **Dynamics**

$$\frac{di_L}{dt} = \frac{1}{L} \times (v_{\text{in}} - \underbrace{i_L R}_{v_R})$$



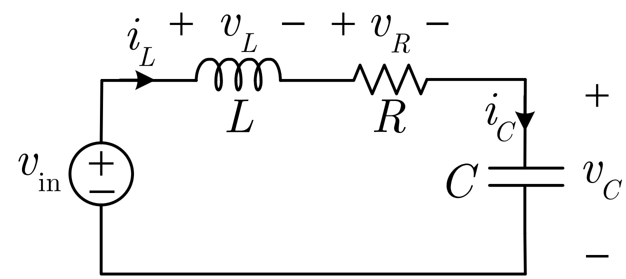
Series RLC Circuit

- **Dynamics**

$$\frac{di_L}{dt} = \frac{1}{L} \times (v_{\text{in}} - v_R - v_C)$$

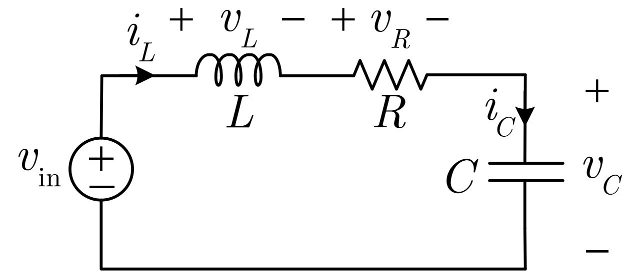
$$\frac{di_L}{dt} = \frac{1}{L} \times (v_{\text{in}} - i_L R - v_C)$$

$$\frac{dv_C}{dt} = \frac{1}{C} \times i_L$$

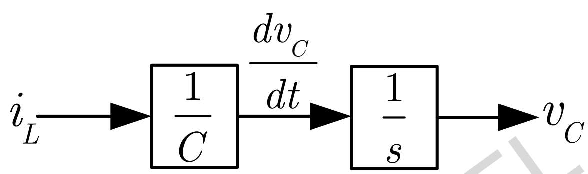


Series RLC Circuit – Implementation

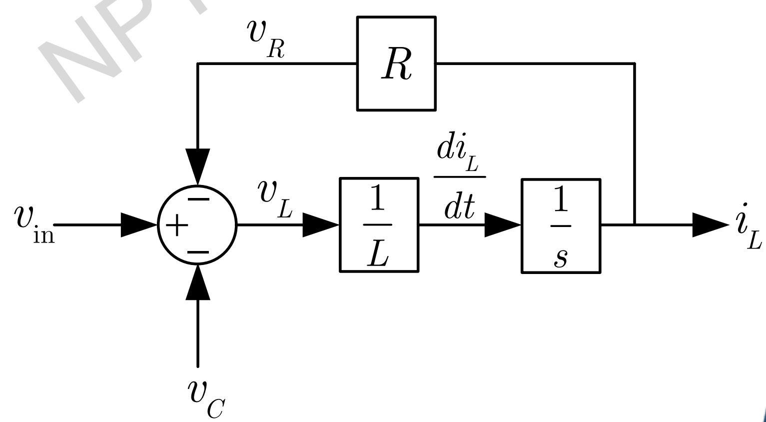
- **Dynamics**



$$\frac{dv_C}{dt} = \frac{1}{C} \times i_L$$

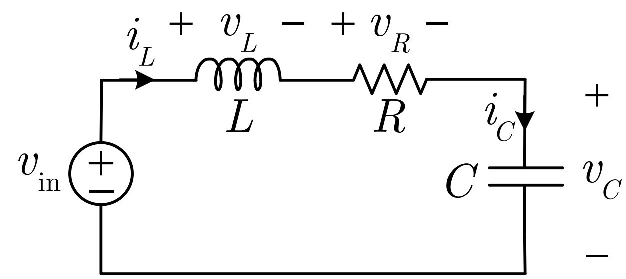


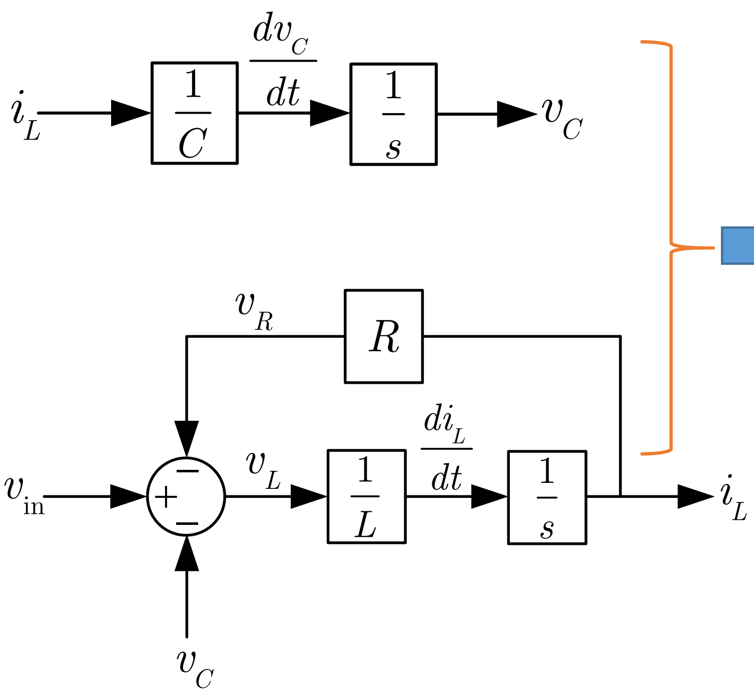
$$\frac{di_L}{dt} = \frac{1}{L} \times (v_{\text{in}} - i_L R - v_C)$$

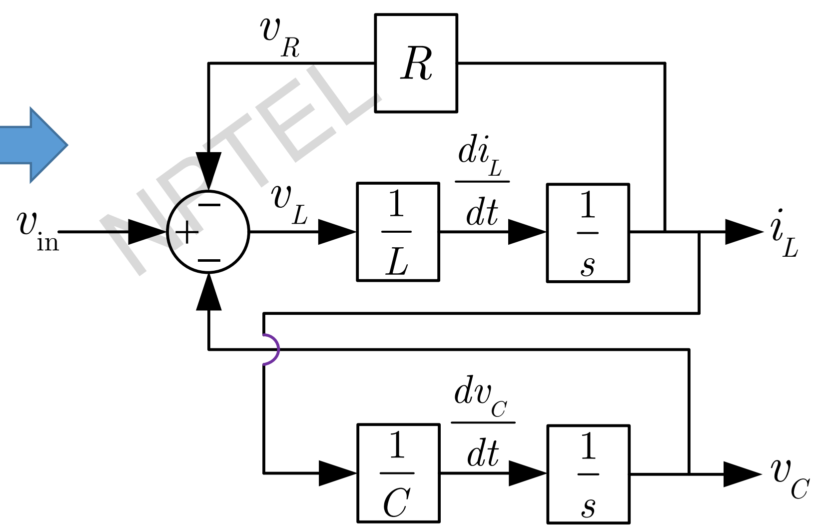


Series RLC Circuit – Implementation

- **Complete Dynamics**







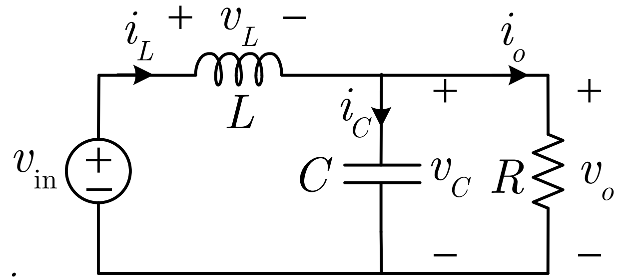
Parallel RLC Circuit – Implementation

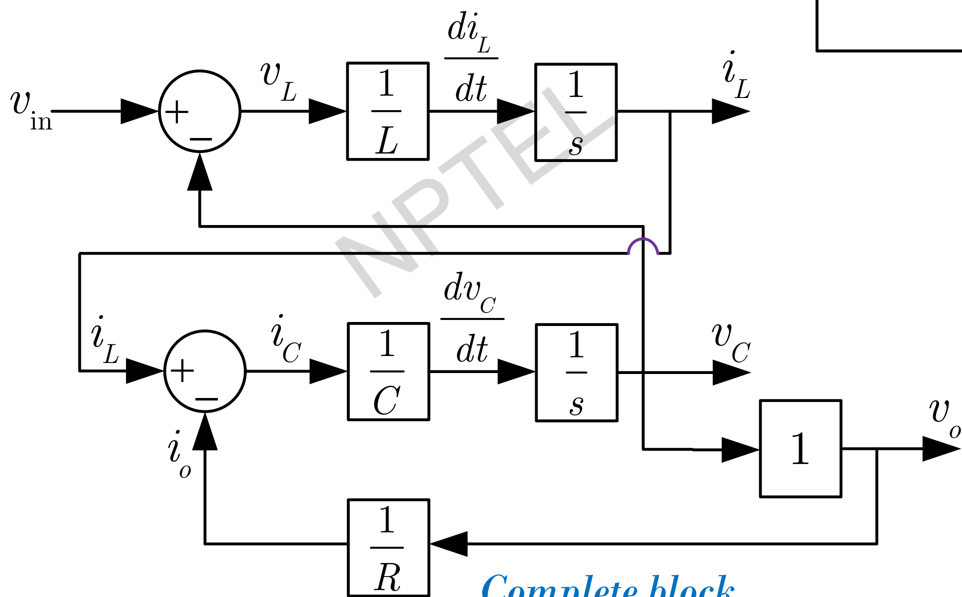
$$\frac{di_L}{dt} = \frac{1}{L} \times v_L = \frac{1}{L} \times (v_{\text{in}} - v_C)$$

$$\frac{dv_C}{dt} = \frac{1}{C} \times \underbrace{(i_L - i_o)}_{i_C}$$

$$v_o = v_C$$

$$i_o = \left(\frac{1}{R}\right) \times v_o$$

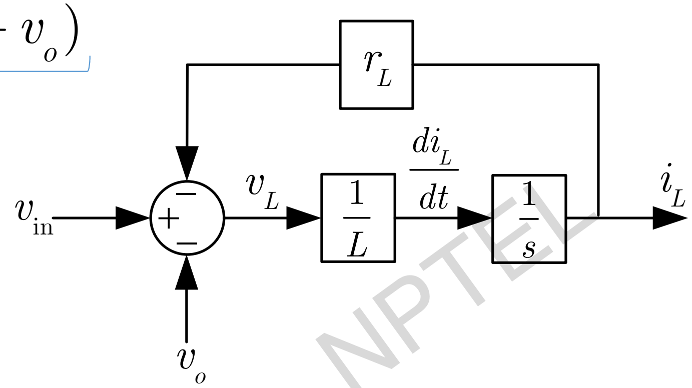


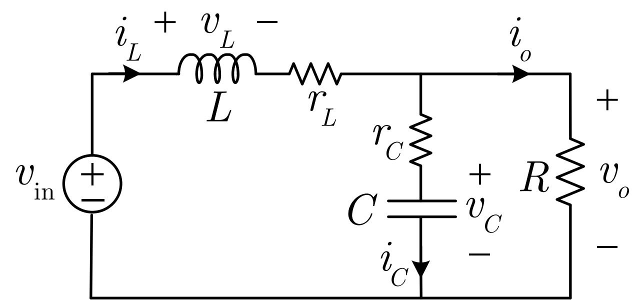


Complete block

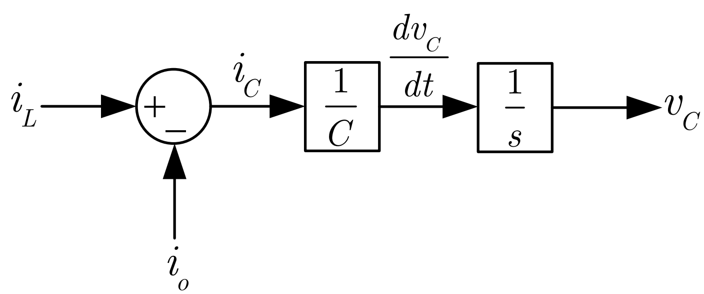
Parallel RLC Circuit with Parasitic Components

$$\frac{di_L}{dt} = \frac{1}{L} \times \underbrace{(v_{\text{in}} - i_L r_L - v_o)}_{v_L}$$





$$\frac{dv_C}{dt} = \frac{1}{C} \times (i_L - i_o)$$

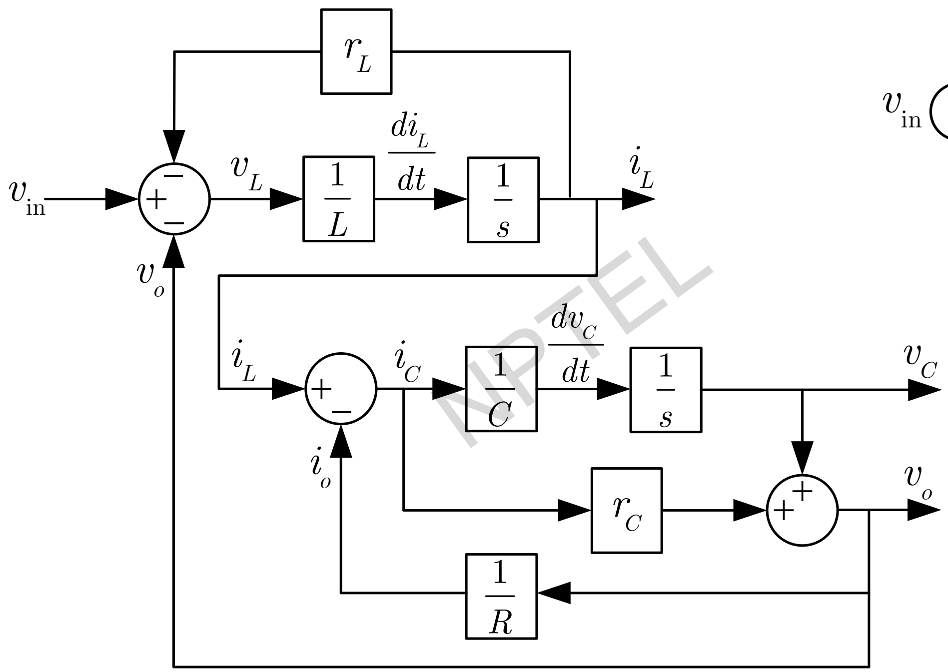


Parallel RLC Circuit with Parasitic Components

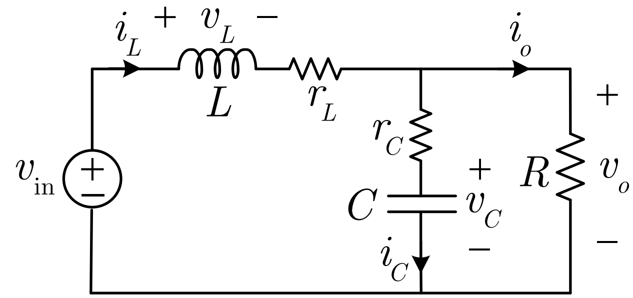
$$v_o = i_C r_C + v_C$$

$$i_C = i_L - i_o$$

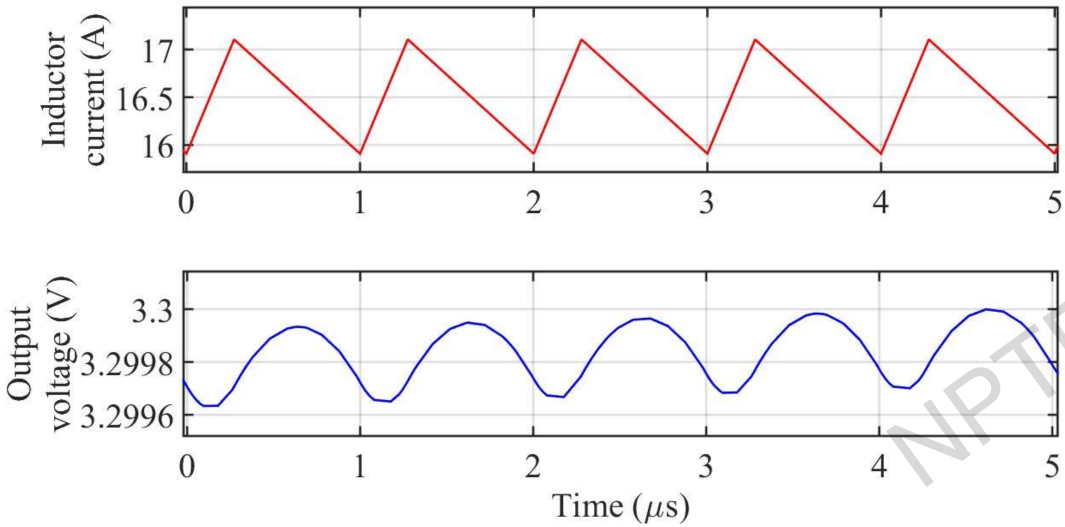
$$i_o = \left(\frac{1}{R}\right) \times v_o$$

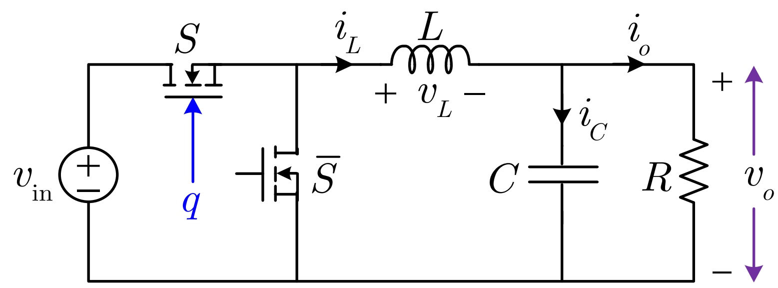


Complete block



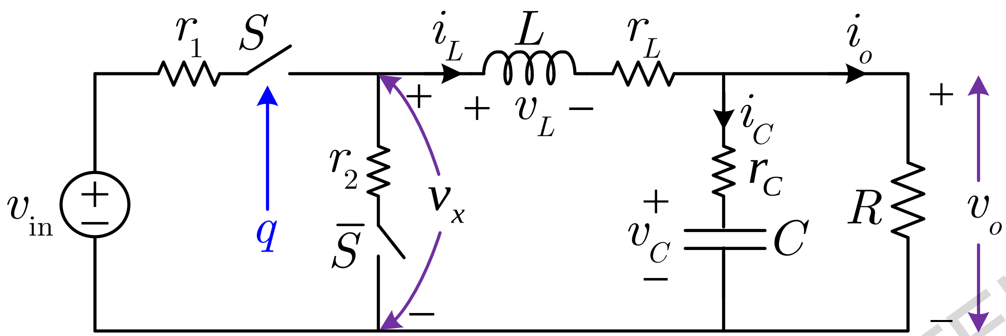
Synchronous Buck Converter

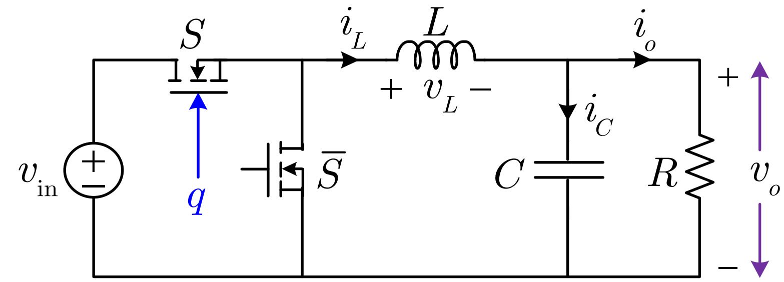




- ❑ Synchronous buck converter – always in continuous conduction mode (CCM)
- ❑ Inductor current can be negative under light load conditions

Synchronous Buck Converter





Replace real components with parasitic

$$\frac{di_L}{dt} = \frac{1}{L} \times \underbrace{(v_x - i_L r_L - v_o)}_{v_L}$$

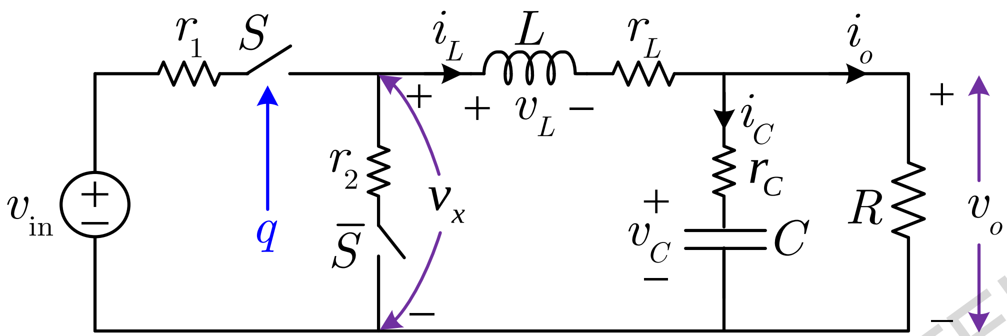
$$\frac{dv_C}{dt} = \frac{1}{C} \times i_C$$

$$i_C = i_L - i_o$$

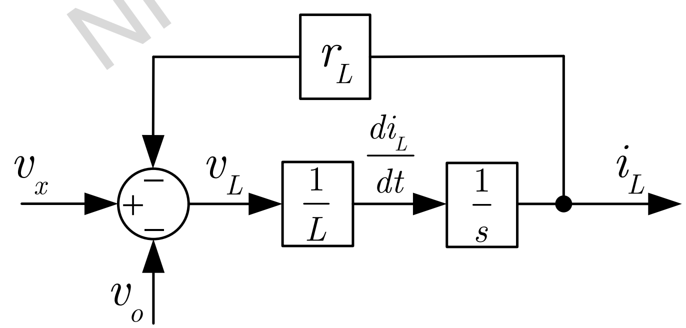
$$v_x = q(v_{\text{in}} - i_L r_1) + (1 - q)(-i_L r_2)$$

$$v_o = i_C r_C + v_C$$

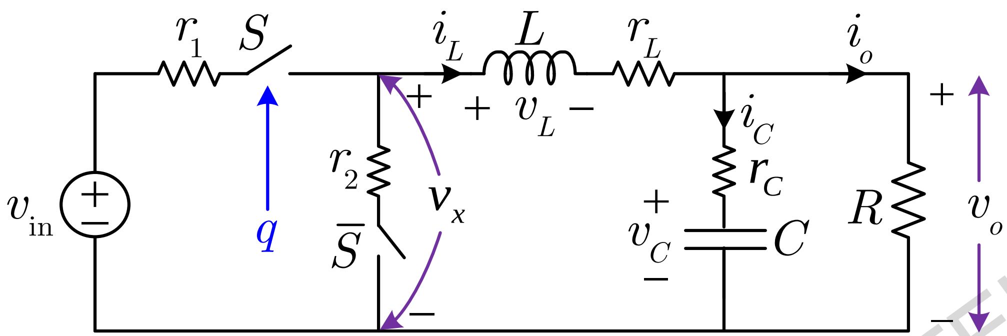
Synchronous Buck Converter – Implementation



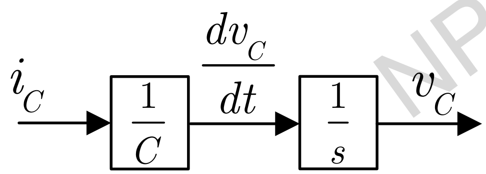
$$\frac{di_L}{dt} = \frac{1}{L} \times \underbrace{(v_x - i_L r_L - v_o)}_{v_L}$$

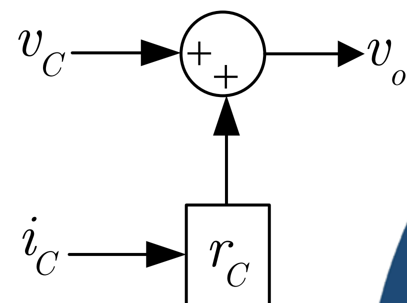


Synchronous Buck Converter – Implementation

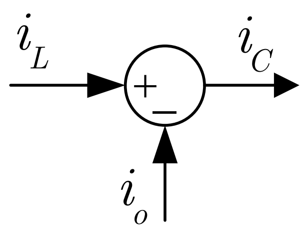


$$\frac{dv_C}{dt} = \frac{1}{C} \times i_C$$



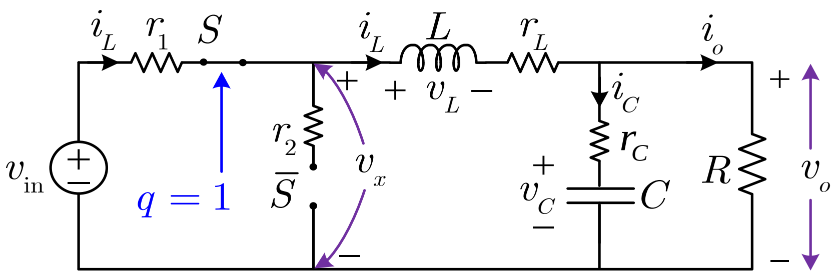


$$i_C = i_L - i_o$$

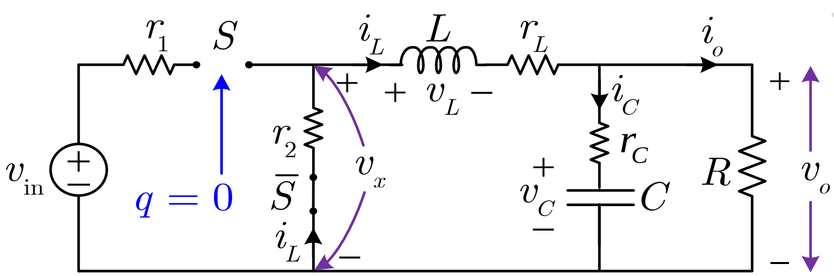


$$v_o = i_C r_C + v_C$$

Synchronous Buck Converter – Implementation

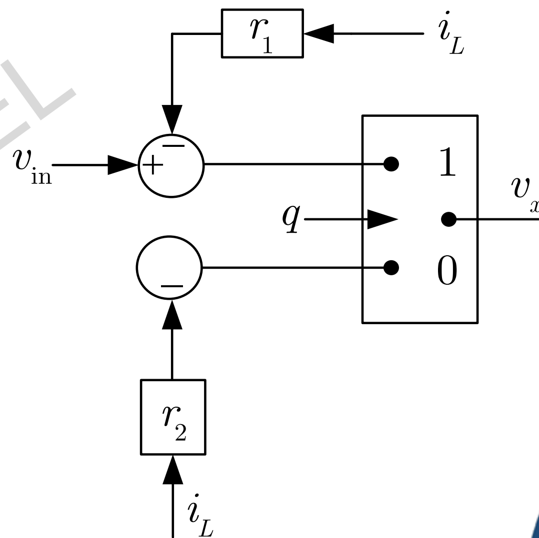


$$v_x = (v_{in} - i_L r_1)$$

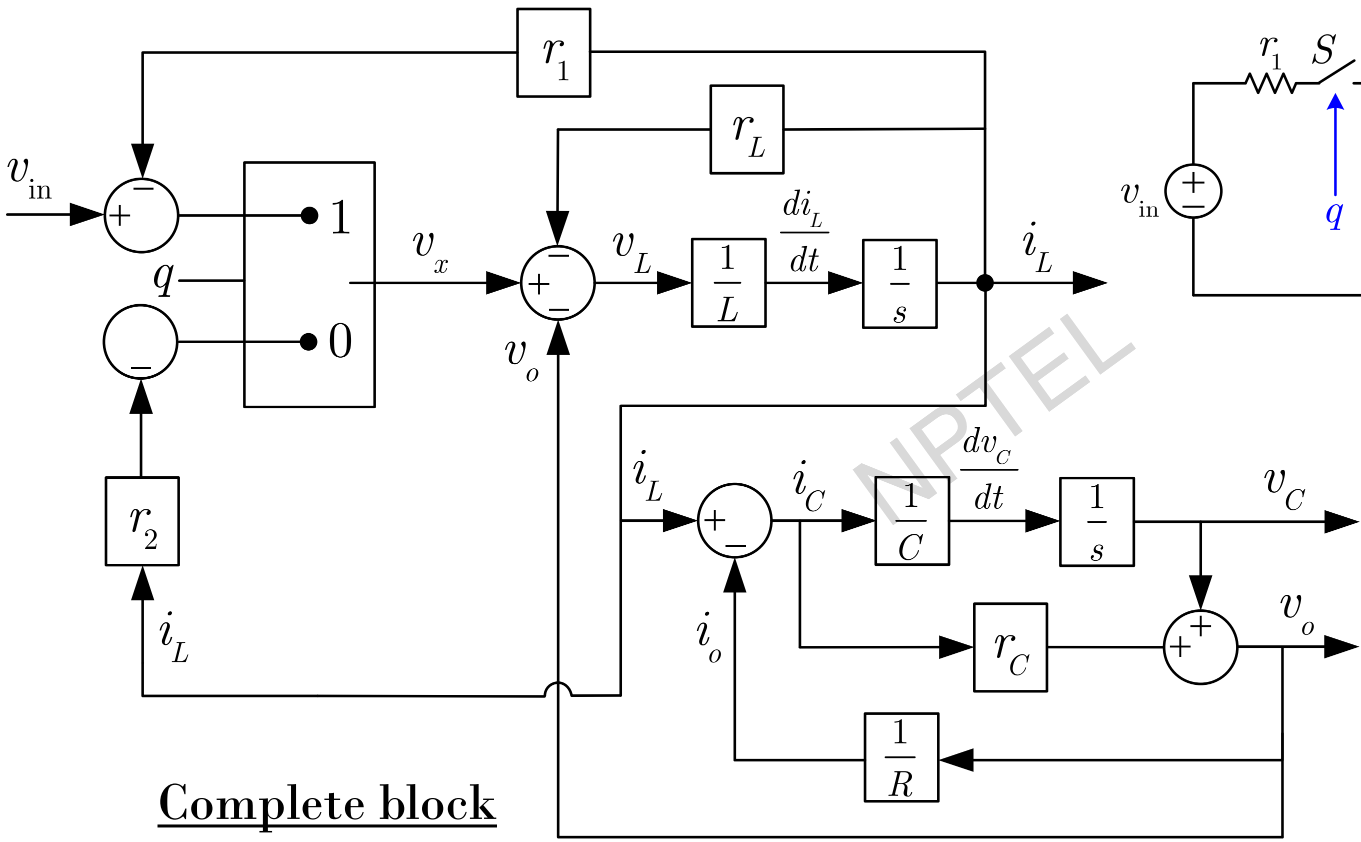


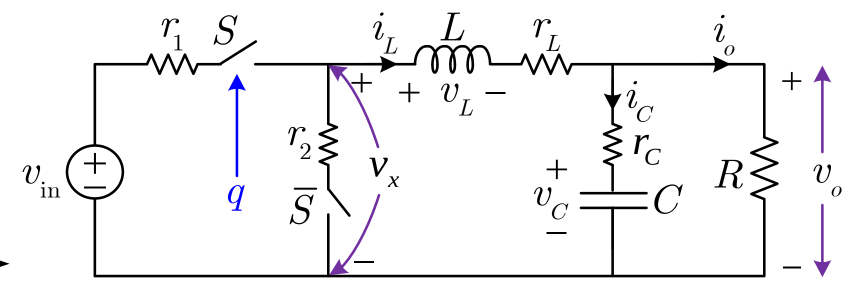
$$v_x = (-i_L r_2)$$

$$\boxed{v_x = q(v_{in} - i_L r_1) + (1-q)(-i_L r_2)}$$



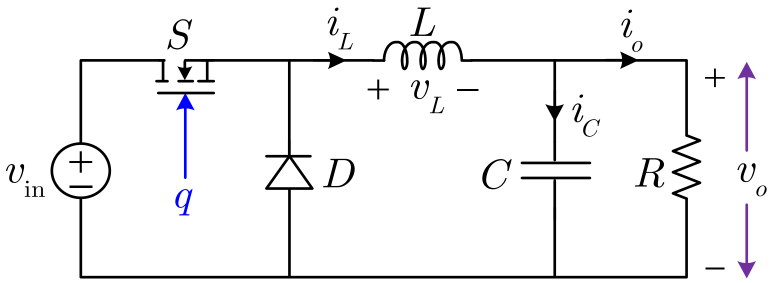
Synchronous Buck Converter – Complete Implementation



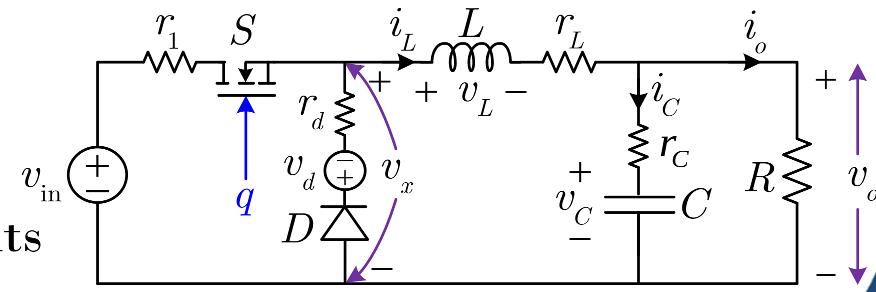


Complete block

Conventional Buck Converter



real components with parasitic



$$\frac{di_L}{dt} = \begin{cases} \frac{1}{L} \times (v_x - i_L r_L - v_o) & \text{for } i_L > 0 \\ 0 & \text{for } i_L \leq 0 \end{cases}$$

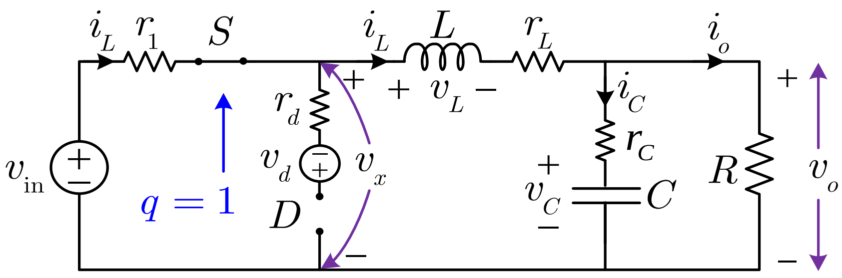
$$i_C = i_L - i_o$$

$$v_o = i_C r_C + v_C$$

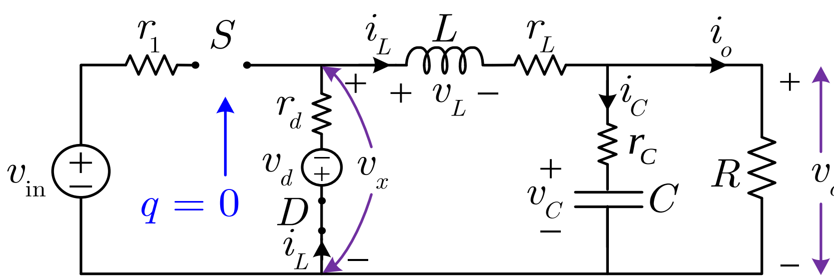
$$\frac{dv_C}{dt} = \frac{1}{C} \times i_C$$

$$v_x = q(v_{\text{in}} - i_L r_1) + (1-q)(-v_d - i_L r_d)$$

Conventional Buck Converter – Implementation

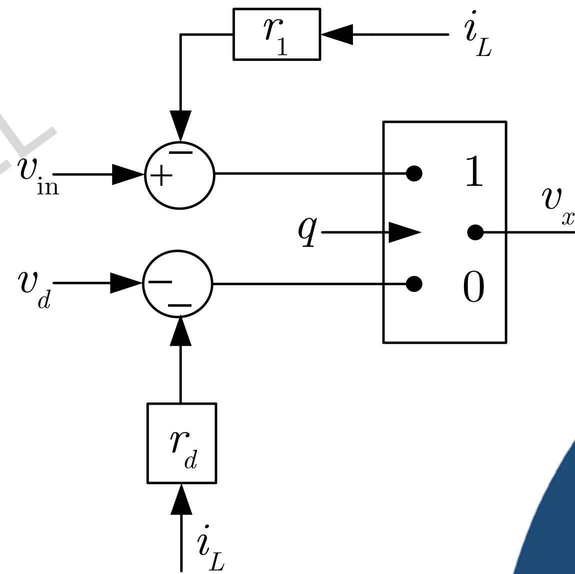


$$v_x = (v_{in} - i_L r_1)$$



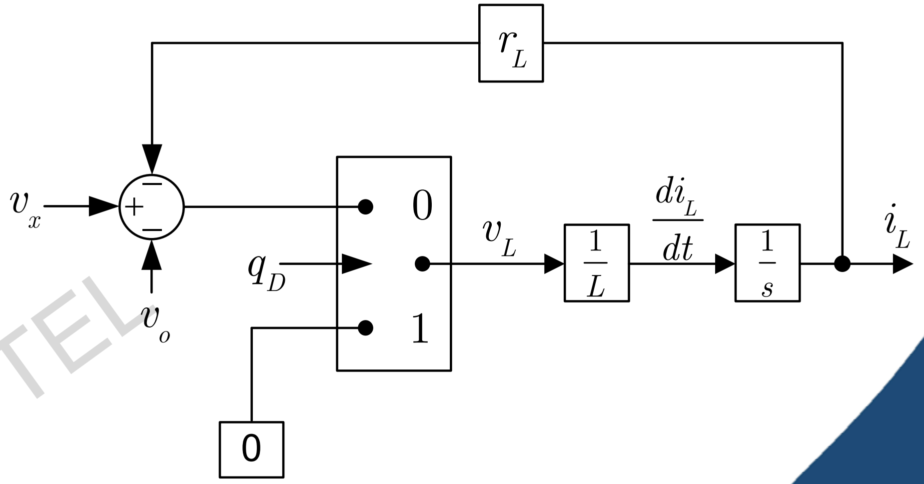
$$v_x = (-v_d - i_L r_d)$$

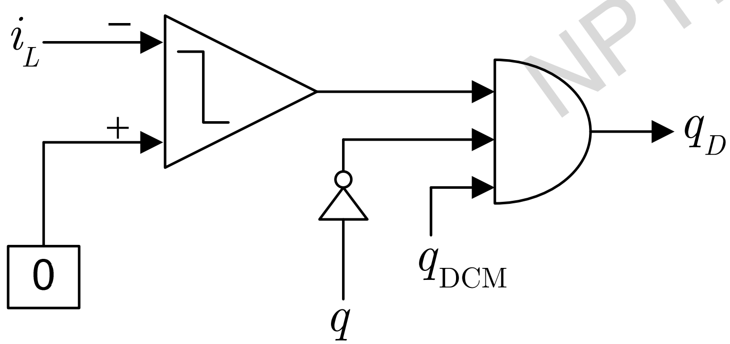
$$\boxed{v_x = q(v_{in} - i_L r_1) + (1-q)(-v_d - i_L r_d)}$$



Conventional Buck Converter – Implementation

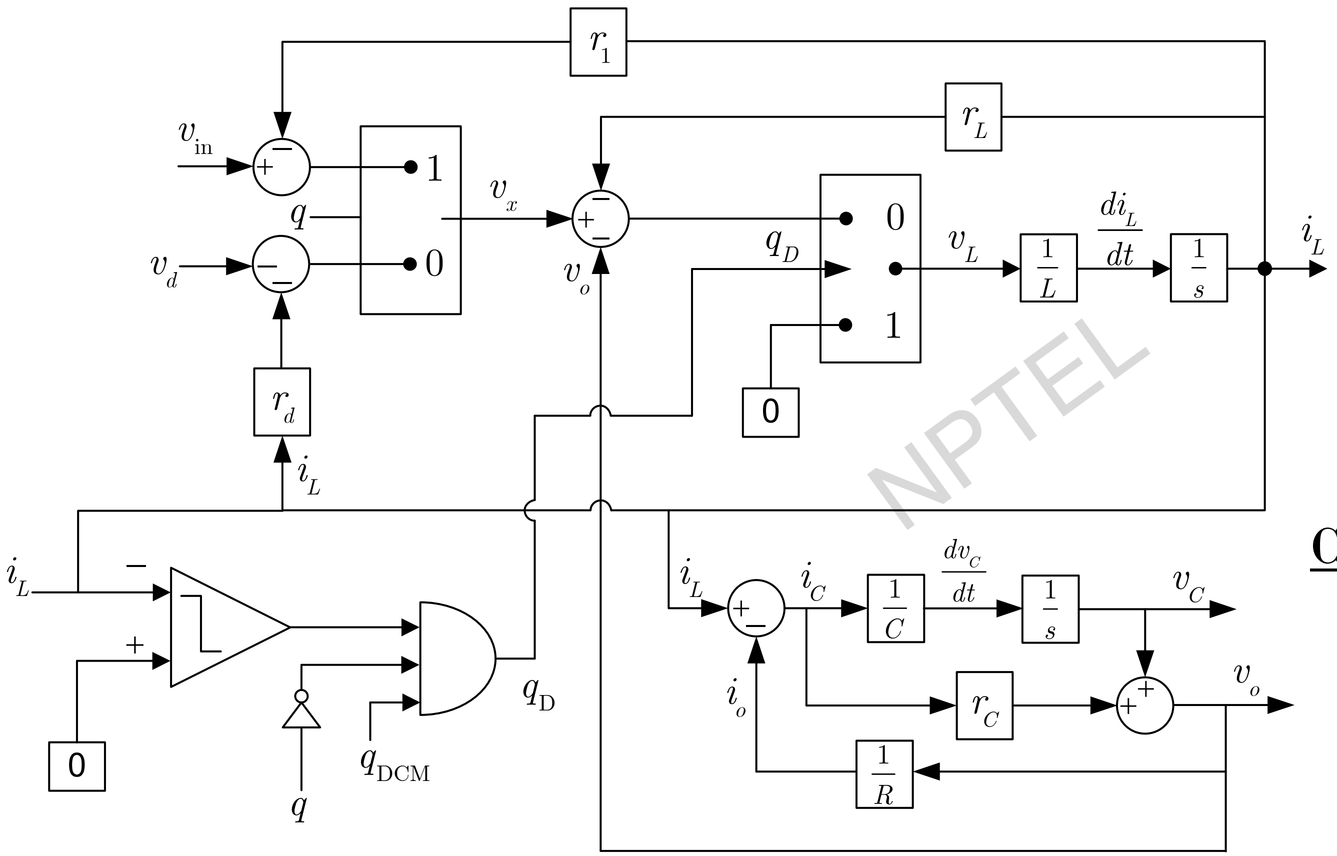
$$\frac{di_L}{dt} = \begin{cases} \frac{1}{L} \times (v_x - i_L r_L - v_o) & \text{for } i_L > 0 \\ 0 & \text{for } i_L \le 0 \end{cases}$$





DCM Enable Active high

Conventional Buck Converter – Implementation



Complete block

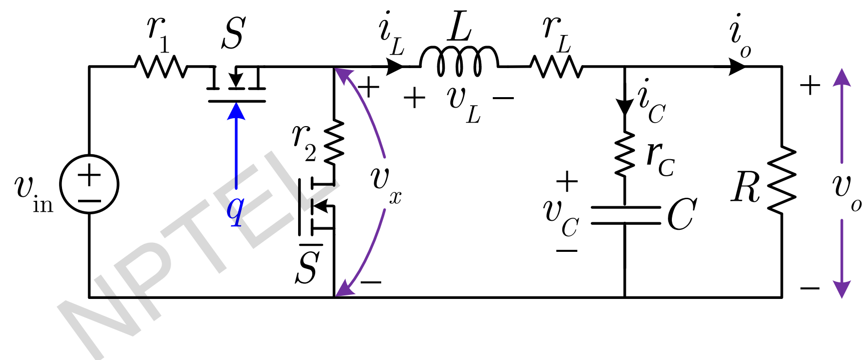
Model Generalization

- The previous block can be used for synchronous buck by setting

$$q_{\mathrm{DCM}} = 0$$

$$r_d = r_2$$

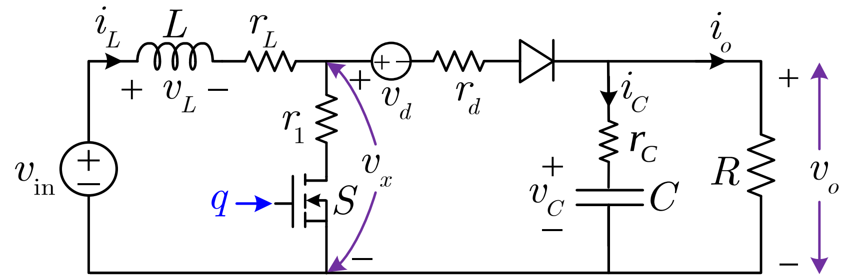
$$v_d = 0$$



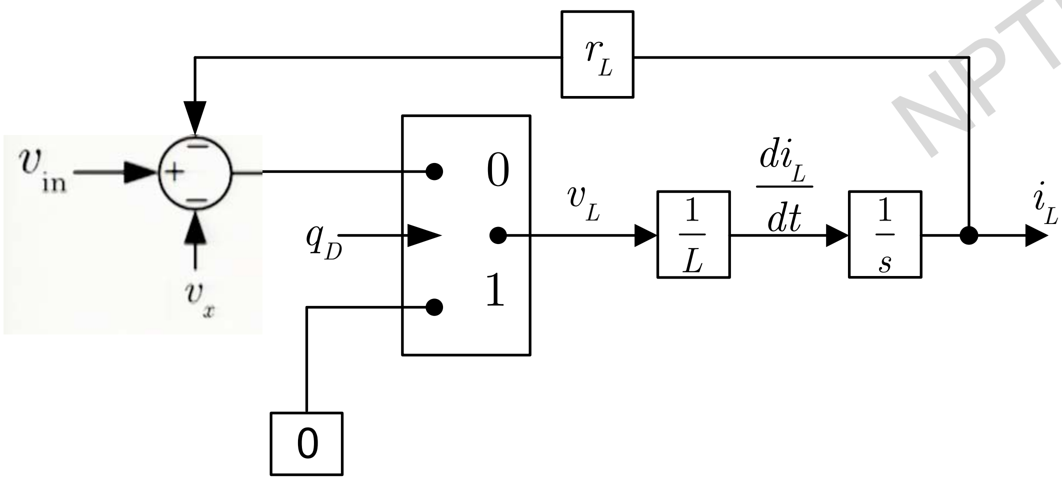
- For Constant current load,

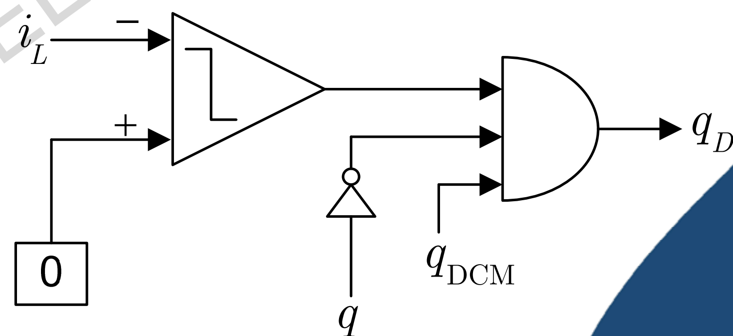
$i_o \rightarrow$ Can be directly used as a load current

Generic Form of a Boost Converter



$$\frac{di_L}{dt} = \begin{cases} \frac{1}{L} \times (v_{\text{in}} - i_L r_L - v_x) & \text{for } i_L > 0 \\ 0 & \text{for } i_L \leq 0 \end{cases}$$



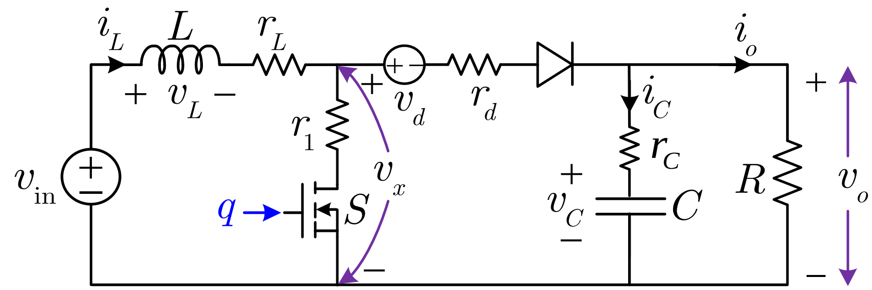


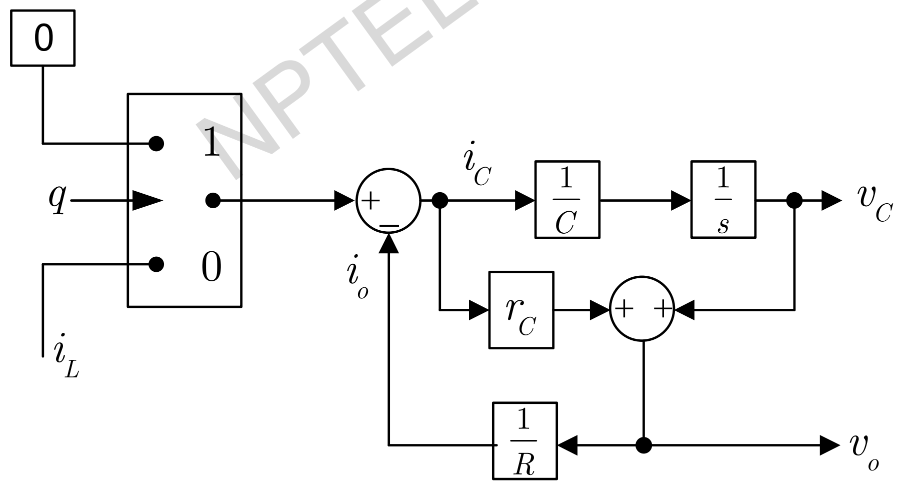
Boost Converter Implementation

$$\frac{dv_C}{dt} = \frac{1}{C} \times [(1-q)\times i_L - i_o] = \frac{1}{C} \times i_C$$

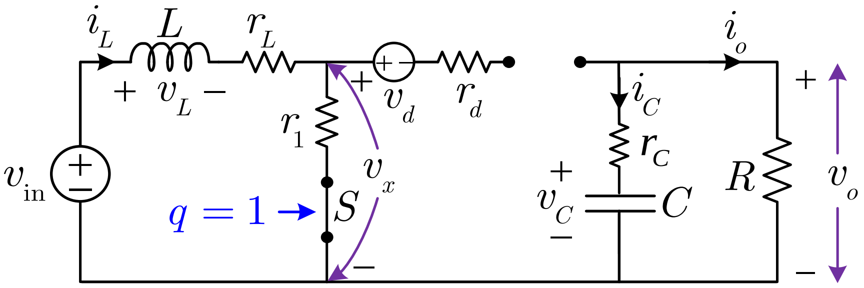
$$i_C = \left[(1-q)\times i_L\right] - i_o$$

$$v_o = (i_C \times r_C) + v_C$$

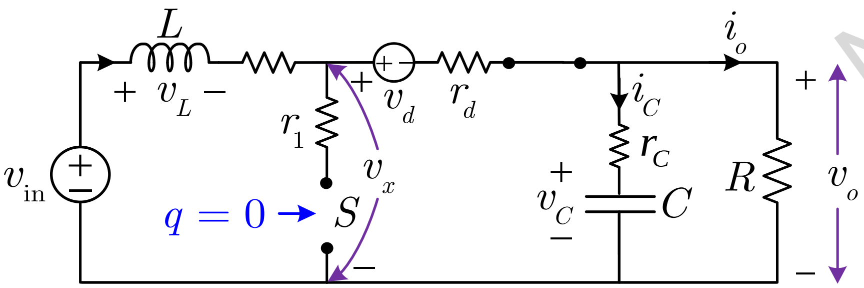




Boost Converter Implementation

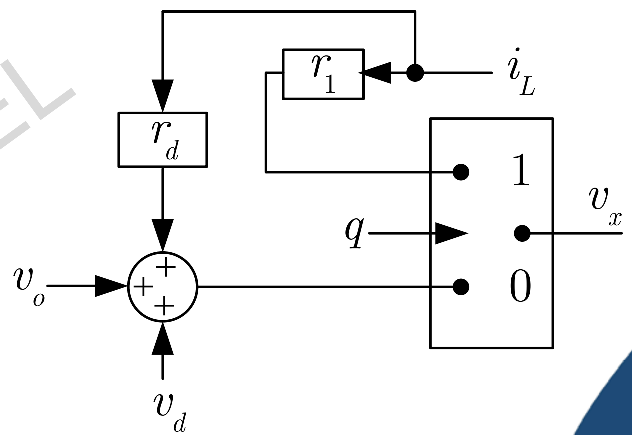


$$v_x = i_L r_1$$



$$v_x = (v_d + i_L r_d + v_o)$$

$$\boxed{v_x = q(i_L r_1) + (1-q)(v_d + i_L r_d + v_o)}$$



Summary

- Model development for simulation – versatile for reconfigurations
- MATLAB Simulink sufficient – no specialized toolbox needed
- Sync MATLAB code and Simulink – design oriented simulation
- Plug-and-play with modular configurations
- MATLAB demonstration to be shown

THANK YOU !

NPTEL ONLINE CERTIFICATION COURSES

CONTROL AND TUNING METHODS IN SMPCs

Dr. Santanu Kapat
Electrical Engineering Department, IIT KHARAGPUR

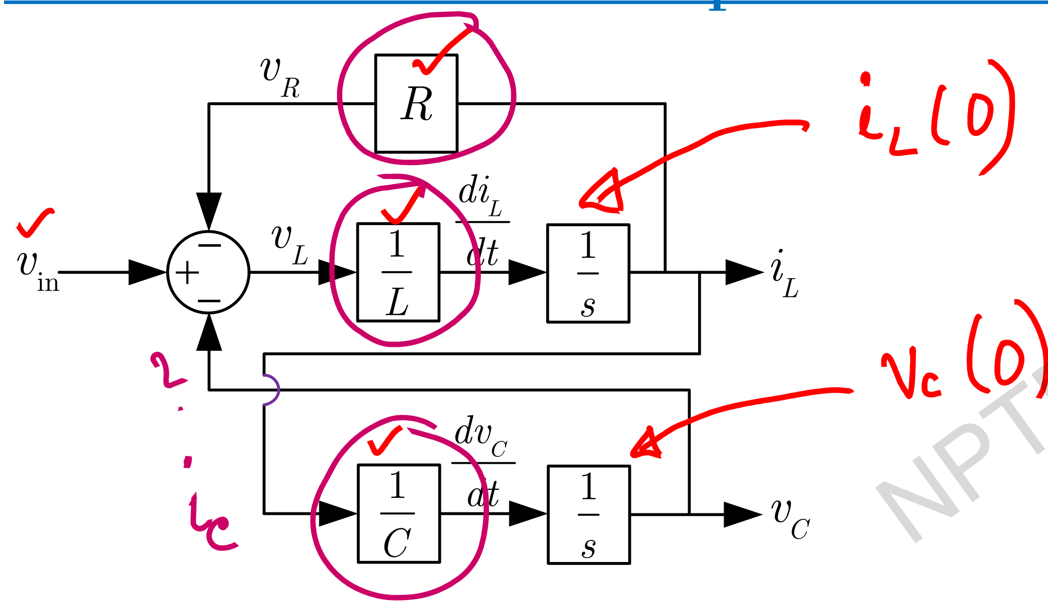
Module 01: Switched Mode Power Converters and Simulation

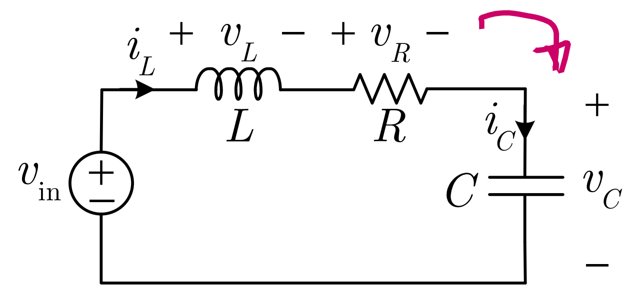
Lecture 05: Demonstration of MATLAB Simulation

Concepts Covered

- Introduction to MATLAB simulation
- Introduction to source, sink, dynamics, and ALU operations
- Development of Simulink models for various SMPCs
- Syncing with MATLAB coding and Simulink
- Data processing, data plotting, figure exporting – case studies

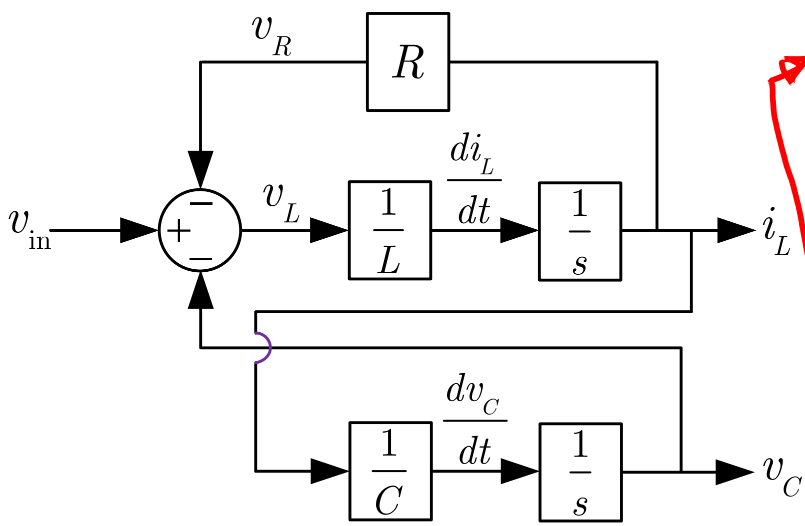
Series RLC Circuit – Implementation





- Select parameter symbols while building Simulink models
- Use a separate script (.m) file; define parameter notation, use consistent parameter symbols and specify parameter values

Series RLC Circuit – Implementation



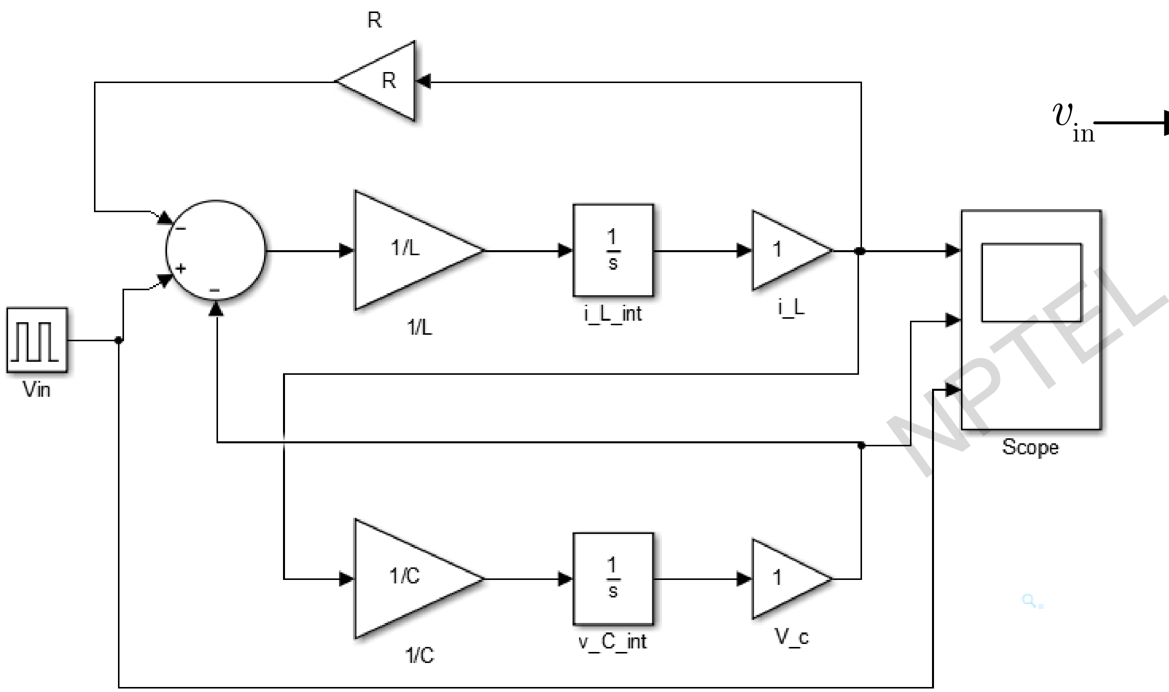

```
L=2e-6;        % Inductor in Henry
C=100e-6;      % Capacitor in Farad
R=1;           % Resistance in Ohm
I_L_int=0;     % Initial condition of inductor current
V_c_int=0;     % Initial condition of capacitor voltage
```

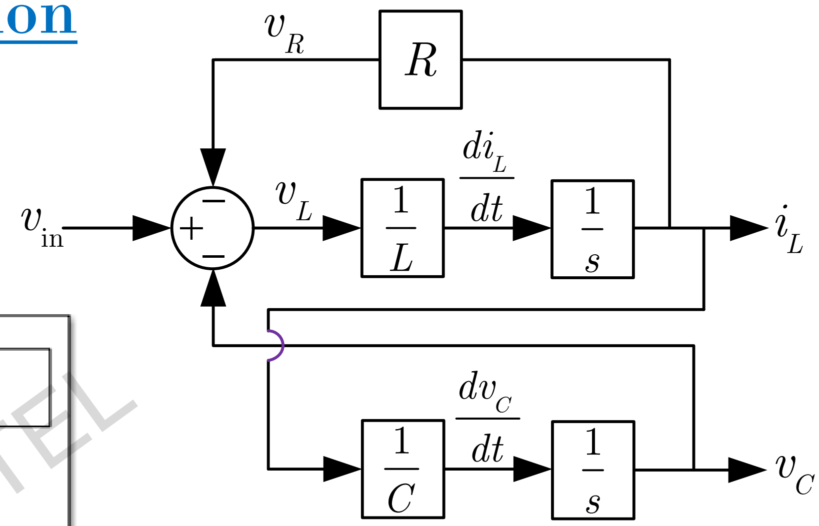
series_RLC_parameter.m

$= 2 \times 10^{-6}$ H

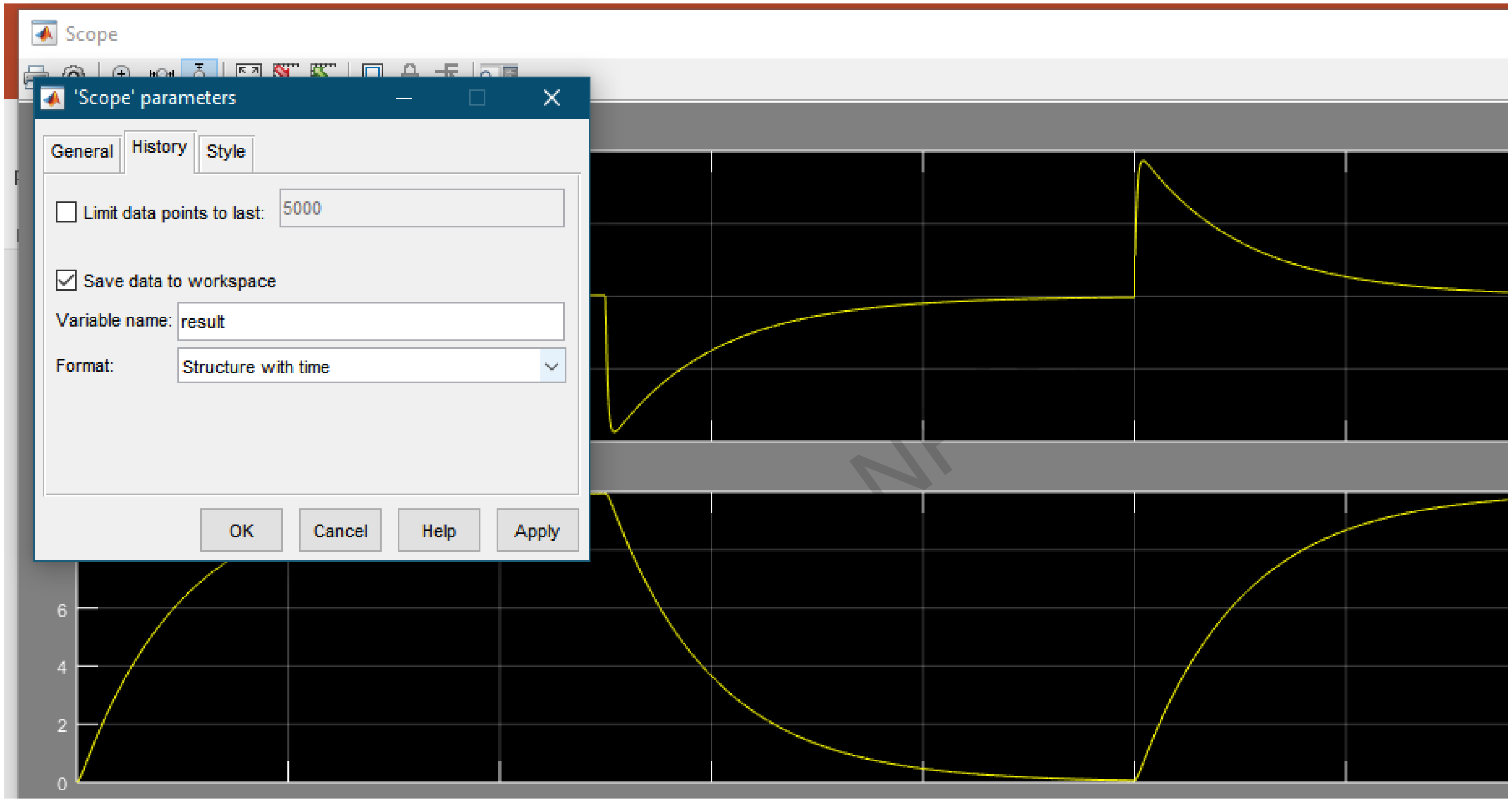
$= 2e-6$ H

Series RLC Circuit – Implementation



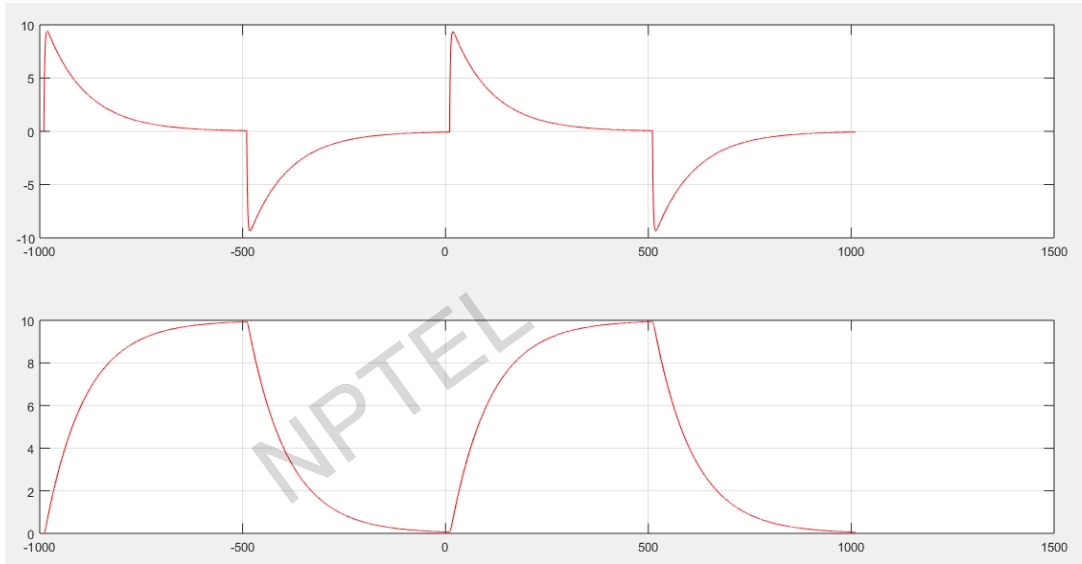


Data Processing and Plotting

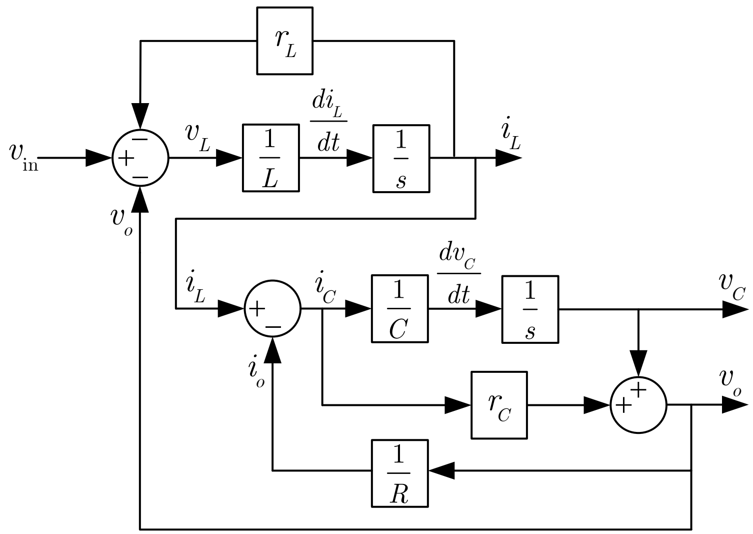


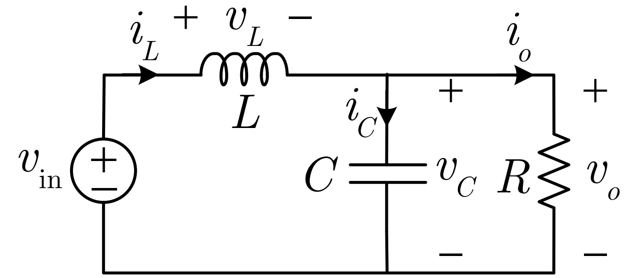
Data Processing and Plotting

```
t=result.time;
i_L=result.signals(1).values;
v_o=result.signals(2).values;
Vin=result.signals(3).values;

subplot(2,1,1)
plot(t,i_L,'r')
hold on;
grid;

subplot(2,1,2)
plot(t,v_o,'r')
hold on;
grid;
```



Parallel RLC Circuit – Implementation





- Select parameter symbols while building Simulink models
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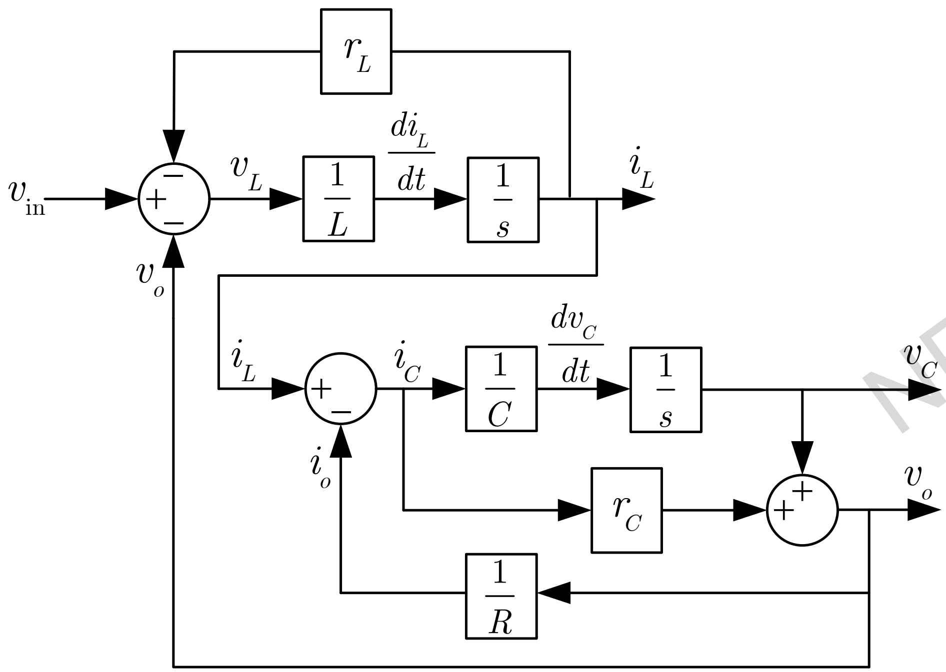
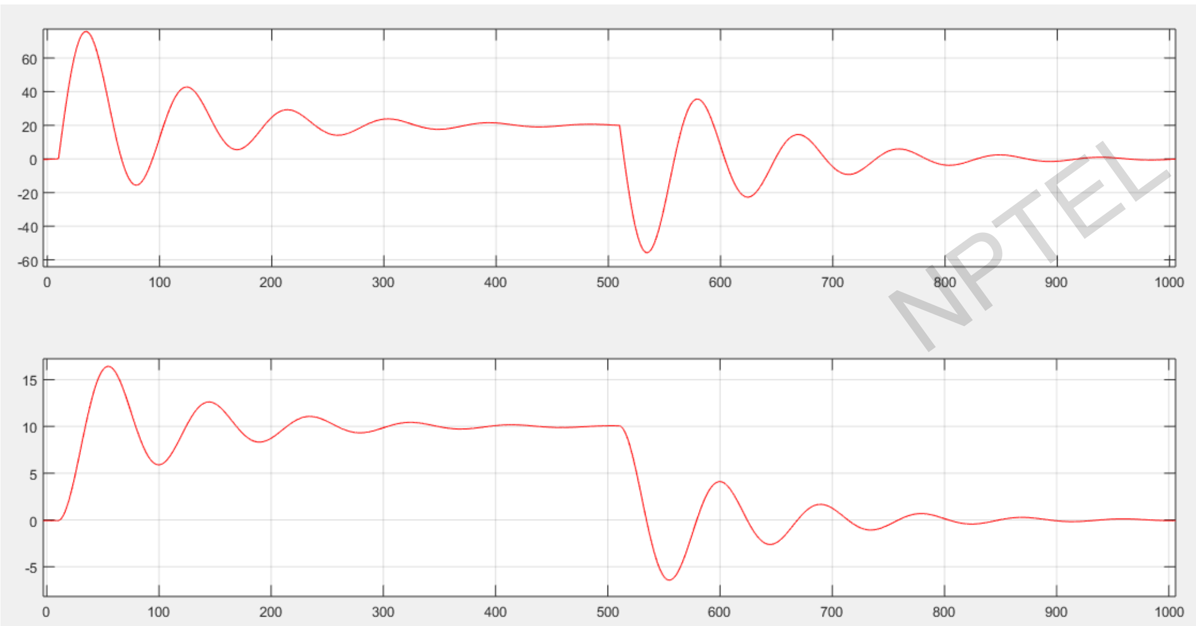
Parallel RLC Circuit with Parasitic

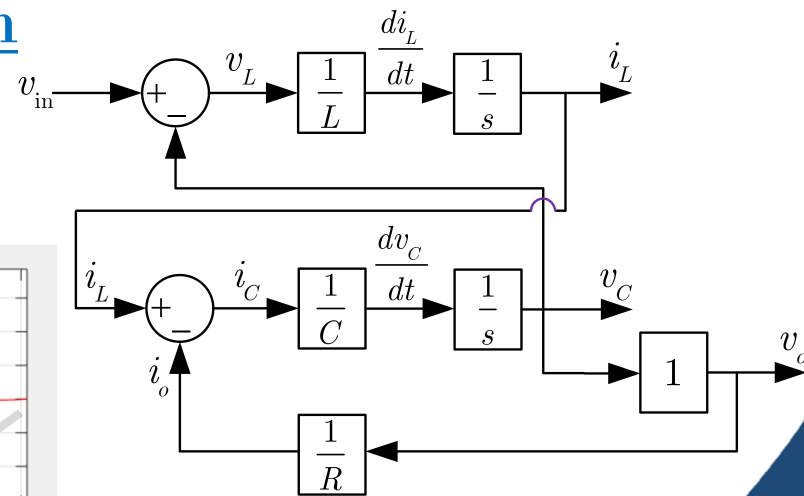


L=2e-6;
C=100e-6;
R=0.5;
r_L=10e-3;
r_C=5e-3;
I_L_int=0;
V_c_int=0;

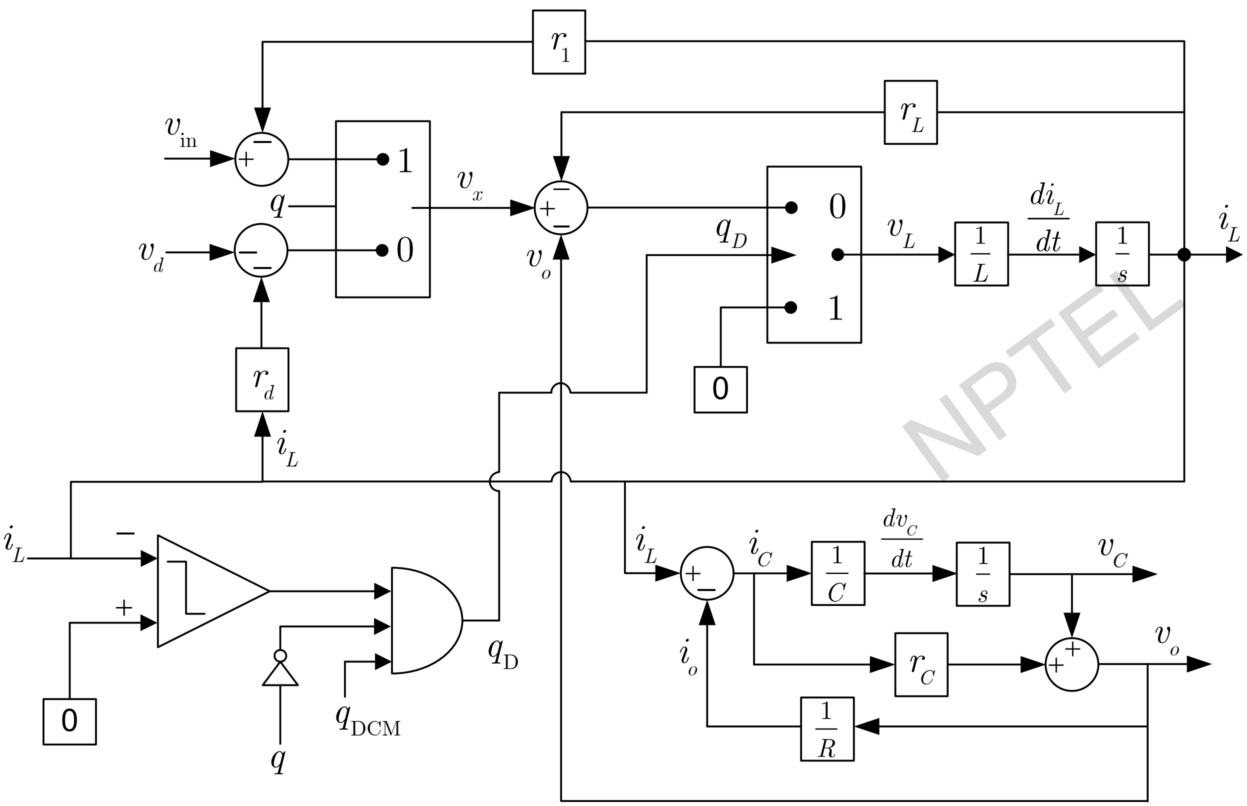
parallel_RLC_parameter.m

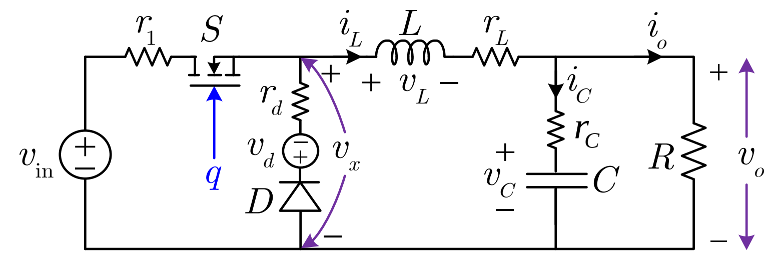
Parallel RLC Circuit – Implementation



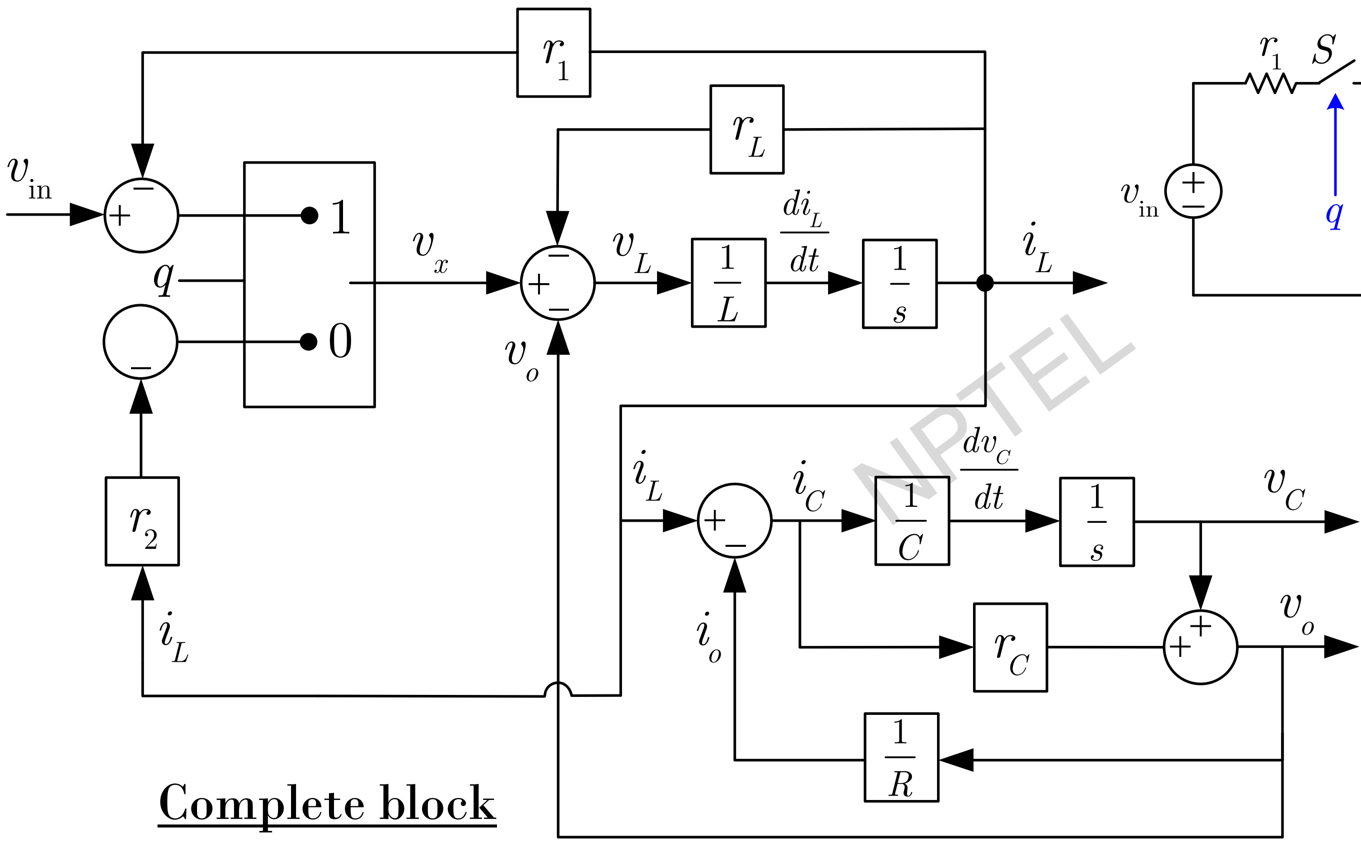


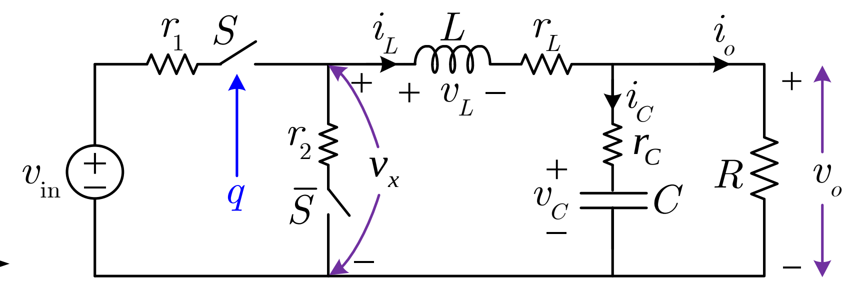
Conventional Buck Converter





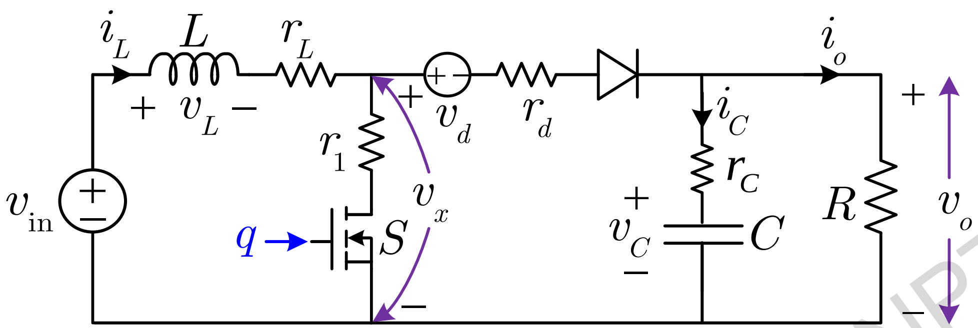
Synchronous Buck Converter – Complete Implementation





Complete block

Implementation of Boost Converter using Simulink



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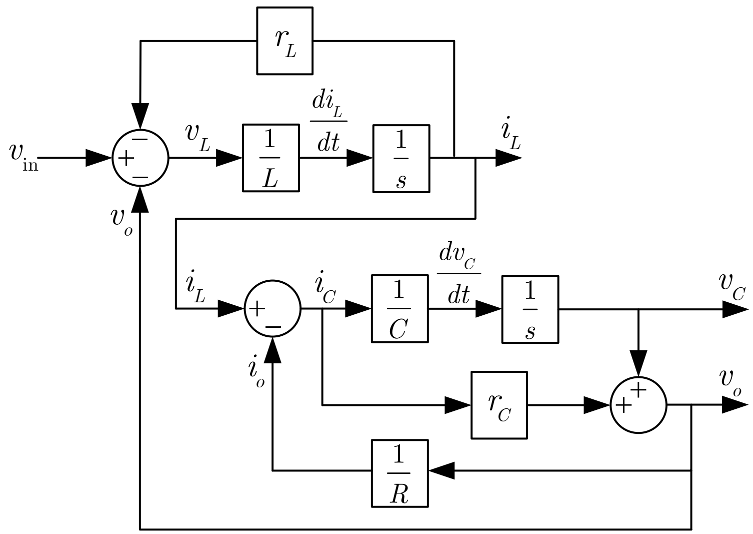
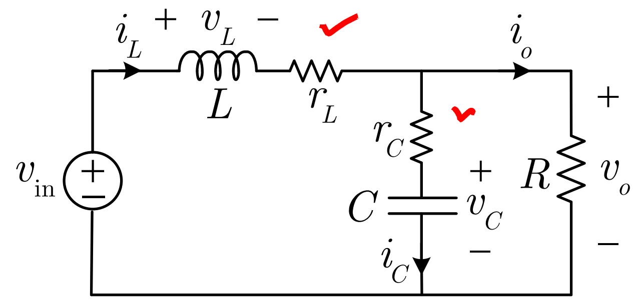
Module 01: Switched Mode Power Converters and Simulation

Lecture 06: Demonstration of MATLAB Simulation (Contd ...)

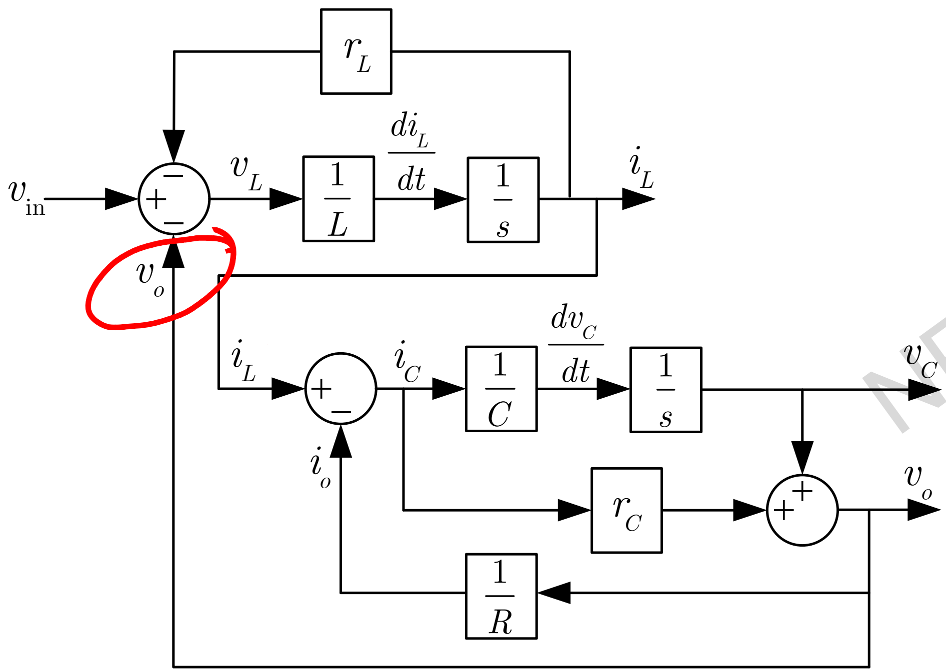
Parallel RLC Circuit – Implementation





- Select parameter symbols while building Simulink models
- Use a separate script (.m) file; define parameter notation, use consistent parameter symbols and specify parameter values

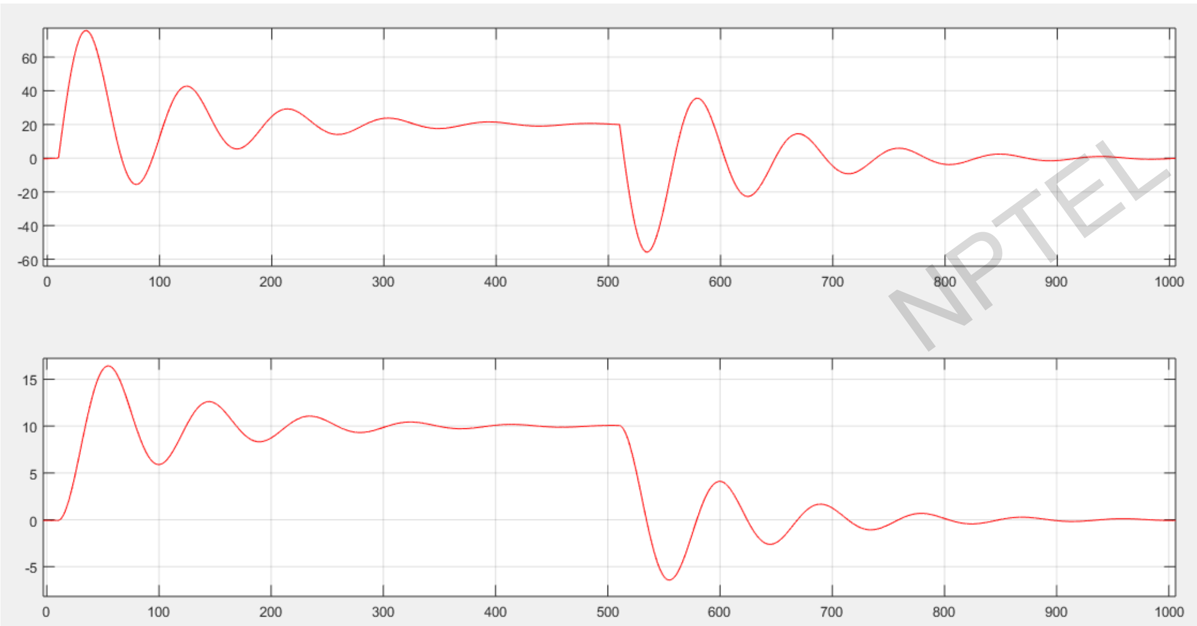
Parallel RLC Circuit with Parasitic

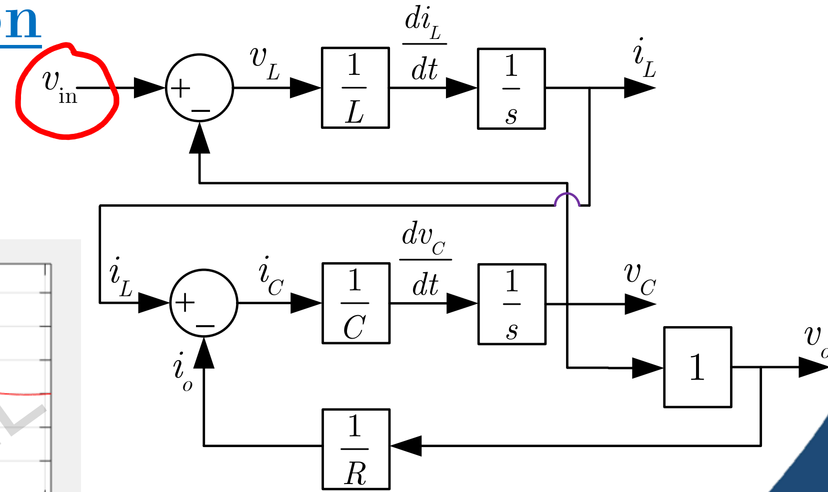


L=2e-6;
C=100e-6;
R=0.5;
r_L=10e-3;
r_C=5e-3;
I_L_int=0;
V_c_int=0;

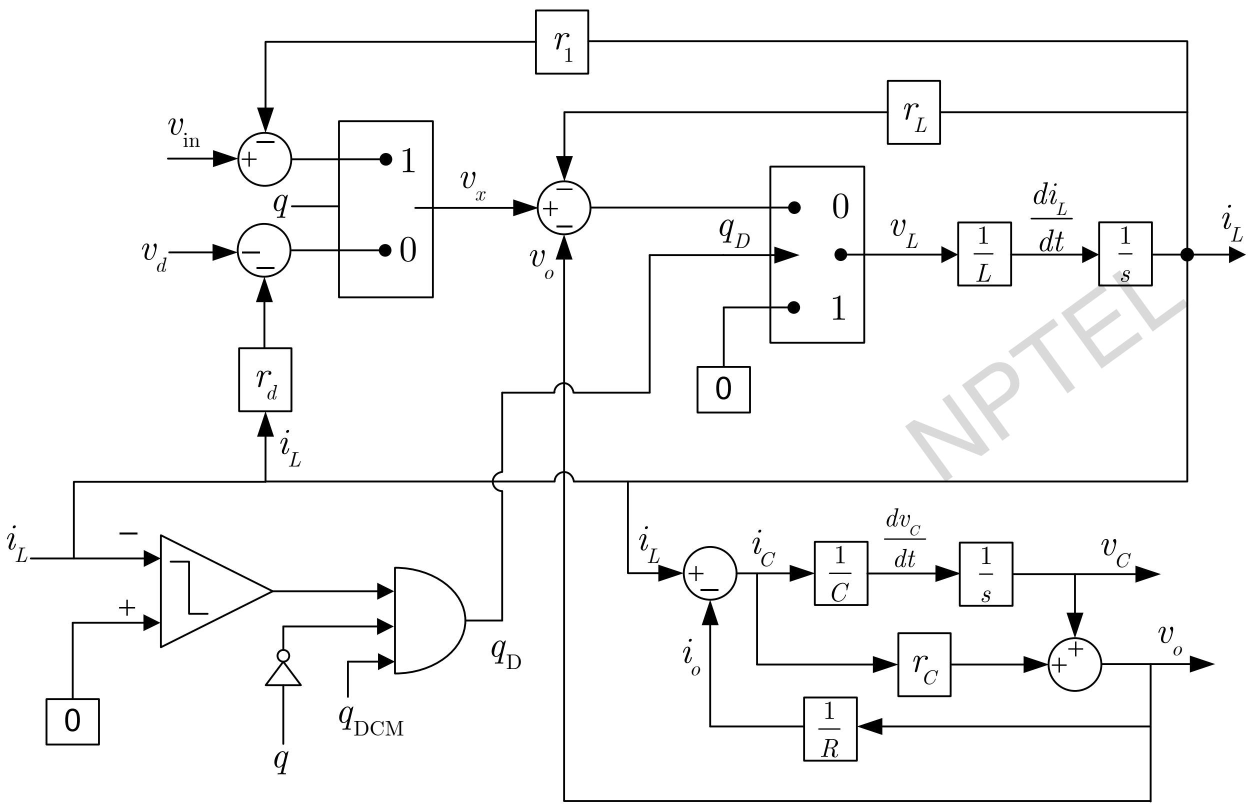
parallel_RLC_parameter.m

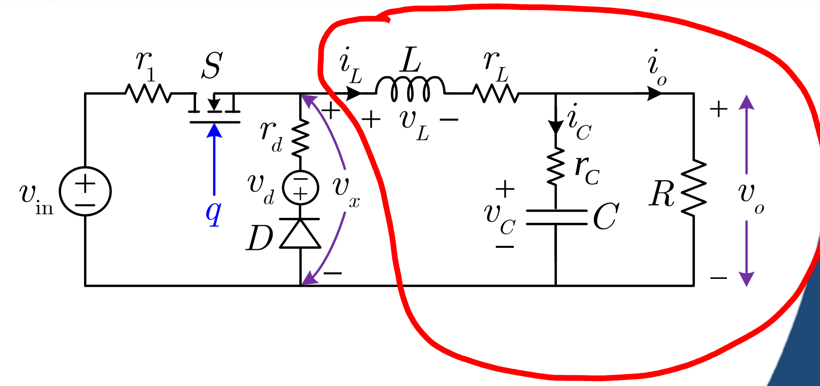
Parallel RLC Circuit – Implementation



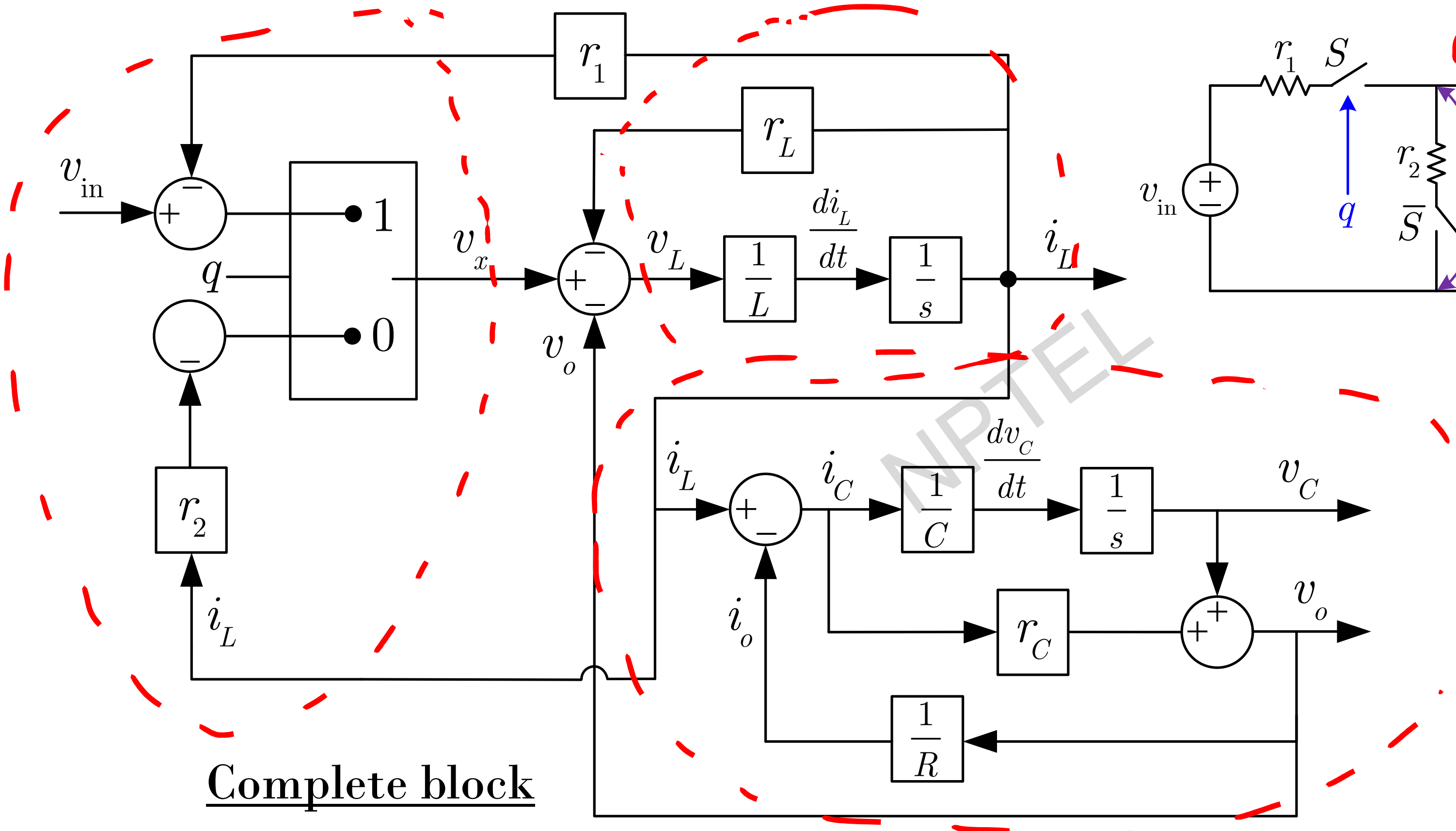


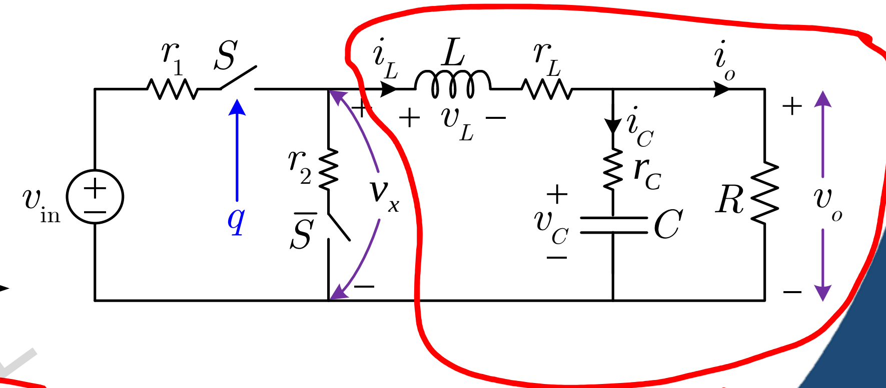
Conventional Buck Converter





Synchronous Buck Converter – Complete Implementation





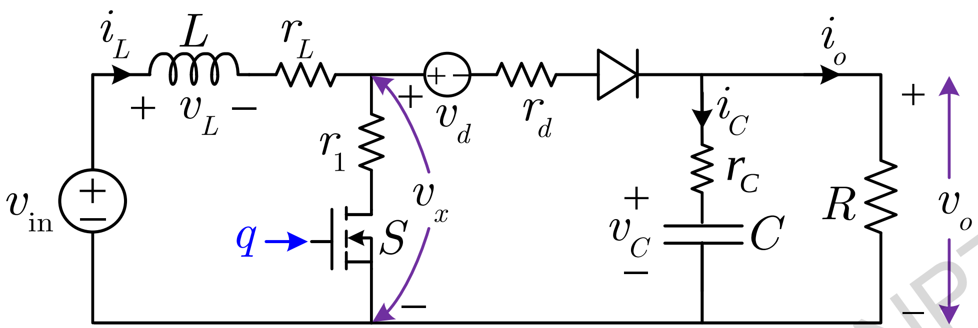
$V_x = V_{in} - r_1 i_L$

when

$q = 1$

<u>Complete block</u>

Implementation of Boost Converter using Simulink



Summary

- Model development for simulation – versatile for reconfigurations
- MATLAB Simulink sufficient – no specialized toolbox needed
- Sync MATLAB code and Simulink – design oriented simulation
- Plug-and-play with modular configurations
- MATLAB demonstration to be shown

THANK YOU !