NPTEL ONLINE CERTIFICATION COURSES

CONTROL AND TUNING METHODS IN SMPCs

Dr. Santanu Kapat
Electrical Engineering Department, IIT KHARAGPUR

Module 03: Fixed Frequency Control Methods

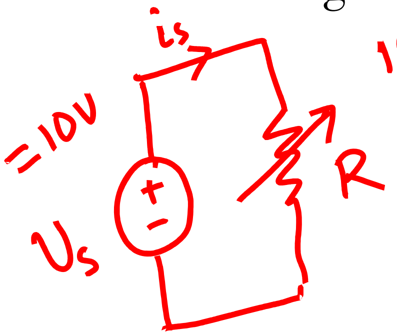
Lecture 13: Converter's Objectives and Control Implications using MATLAB Models

Concepts Covered

- Understanding behavior of a practical source while driving a SMPC
- Scalable MATLAB model development with a practical source
- Understanding converter objectives and control implications
- Power-stage design guidelines and few power designer tools
- MATLAB case studies to understand control requirements

Understanding a Voltage Source

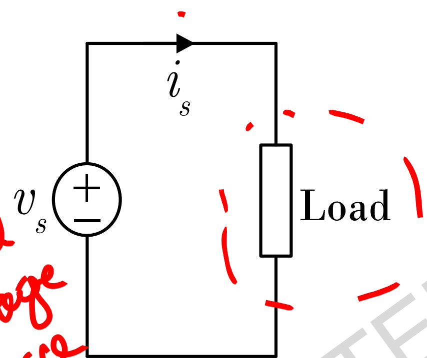
- Ideal voltage source



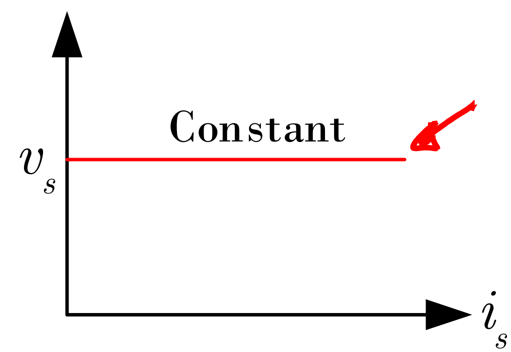
100Ω

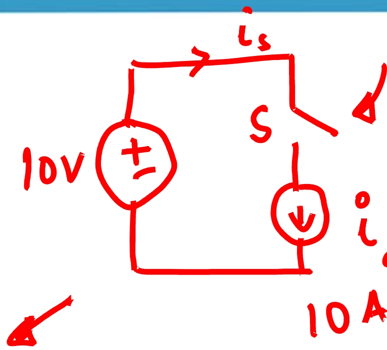
$i_s = \frac{V_s}{R}$

ideal voltage source



Characteristics

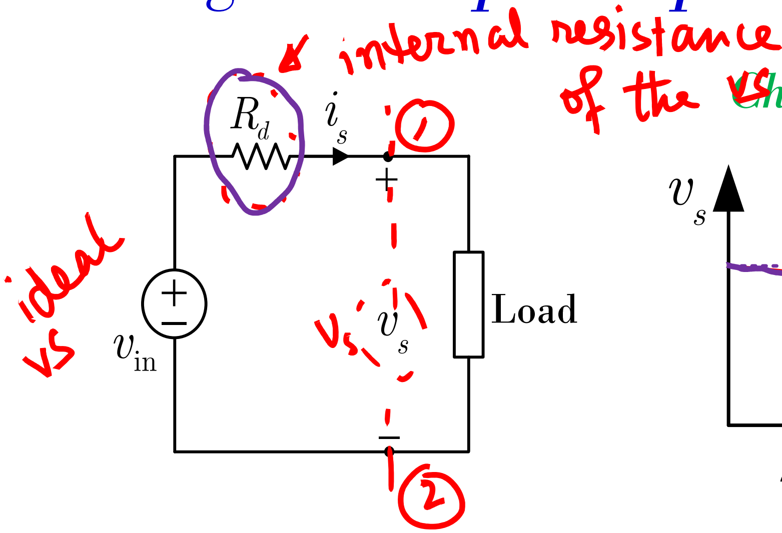




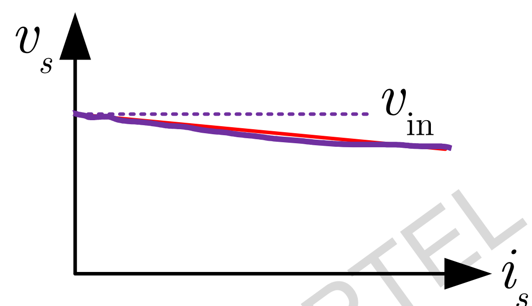
- Voltage remains constant
  - Irrespective of current magnitude ➢ Relates to DC output impedance
  - Irrespective of current profile ➢ Relates to AC output impedance

Ideal voltage source: Zero output impedance, infinite bandwidth!!

Adding DC Output Impedance (resistance)

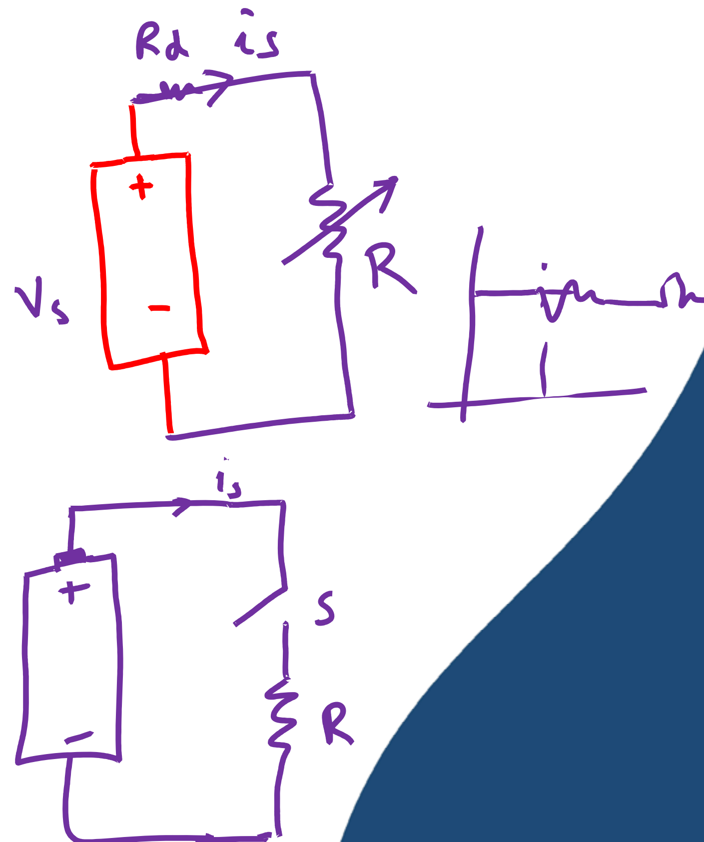


Characteristics

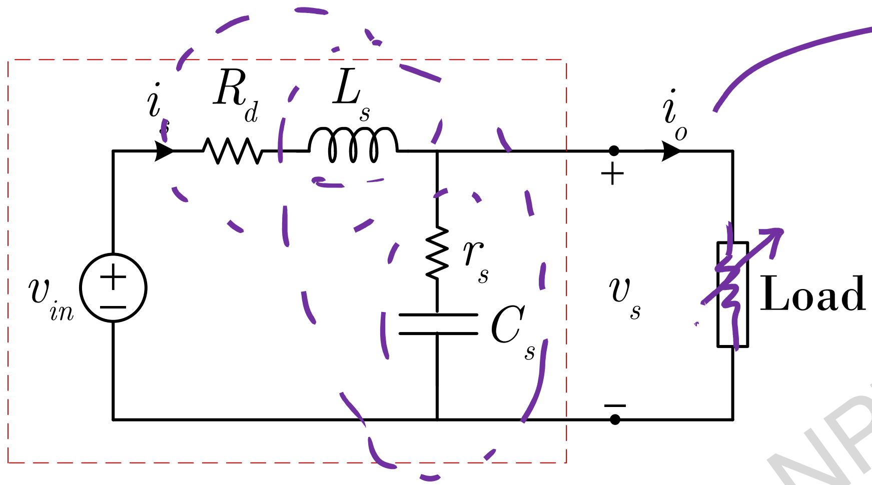


$$v_s = v_{in} - R_d i_s$$

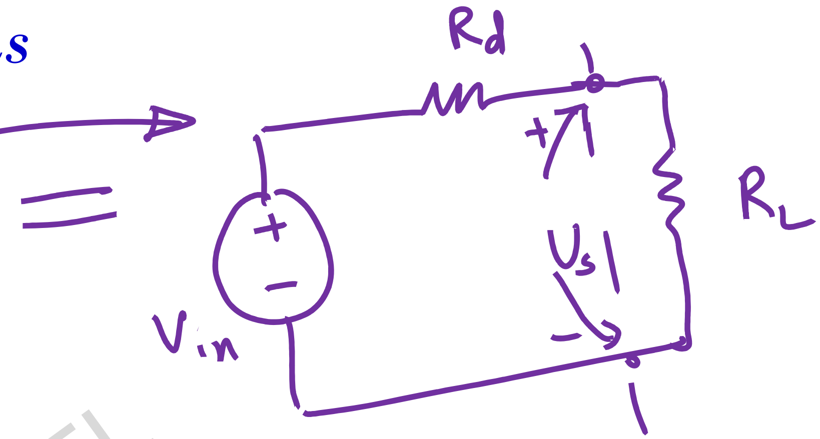
- This captures load regulation aspects.
- But, it does not capture transient effects.
- This model still assumes infinite bandwidth!!!



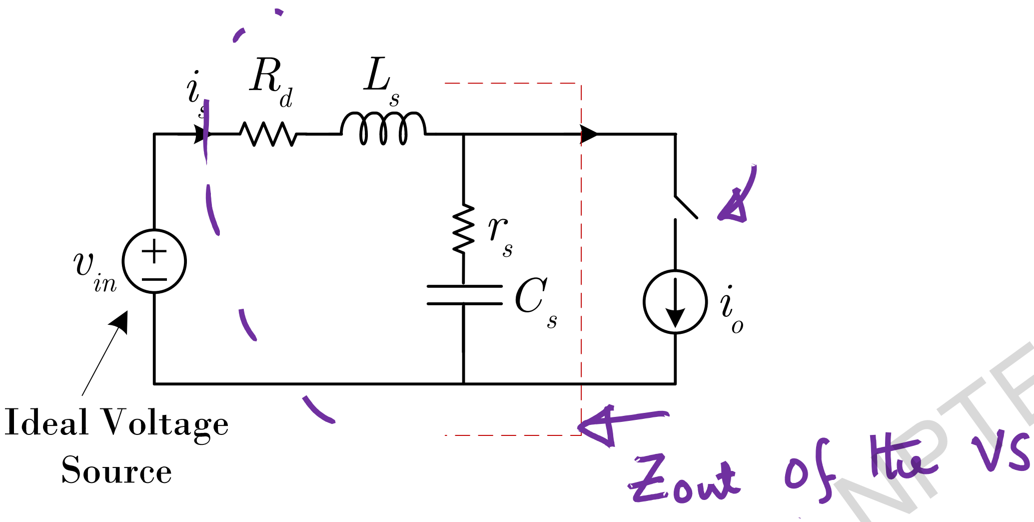
Adding Frequency Dependent Terms



Practical Voltage Source



AC Small-Signal Modeling Output Impedance of Voltage Source

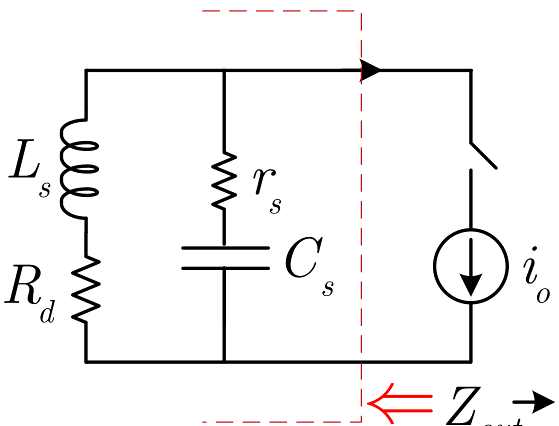


- For AC model, consider perturbations and replace DC quantities by zero

→ ideal voltage source: short circuited

→ ideal current source: open circuited

AC Small-Signal Modeling Output Impedance of ~~Voltage~~ Source



$\Leftarrow Z_{out} \rightarrow$ **Source output Impedance**

$s = j\omega$

$Z_{out}(0)$

$$Z_{out}(s) = R_d \times \frac{\left(1+\dfrac{s}{\omega_{zc}}\right)\left(1+\dfrac{s}{\omega_{zl}}\right)}{1+\dfrac{s}{Q_s\omega_s}+\dfrac{s^2}{\omega_s^2}}$$

$$\omega_{zc} = \frac{1}{r_s C_s}, \qquad \omega_{zl} = \frac{R_d}{L_s}$$

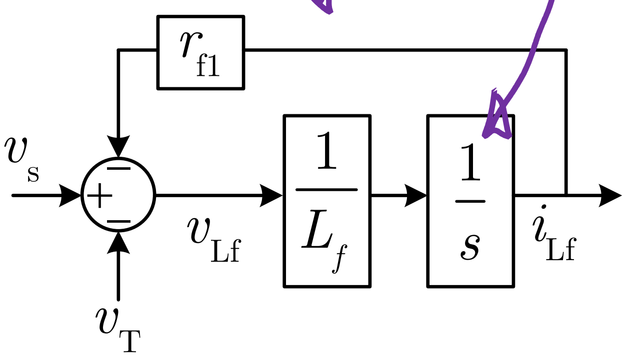
$$\omega_n = \sqrt{\frac{R_d}{r_s}} \times \frac{1}{\sqrt{L_s C_s}}, \qquad Q_s = \frac{Z_{cs}}{(R_d + r_s)}, \qquad Z_{cs} = \sqrt{\frac{L_s}{C_s}}$$

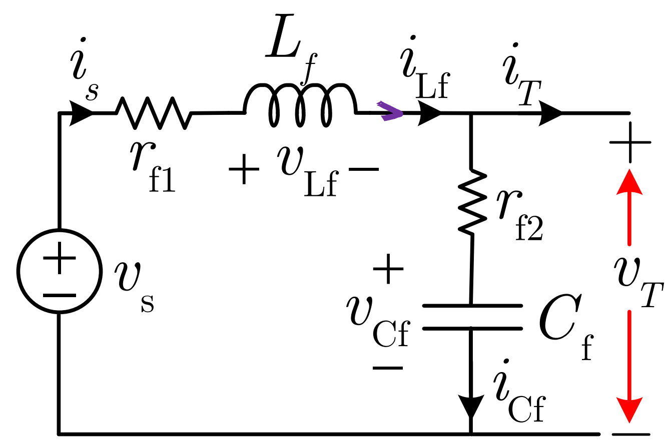
MATLAB Model Development of a Practical Voltage Source

$$v_{\mathrm{Lf}} = L_f \frac{di_{\mathrm{Lf}}}{dt}$$

$$= v_s - r_{\mathrm{f1}} i_{\mathrm{Lf}} - v_T$$

$i_{Lf}(0)$

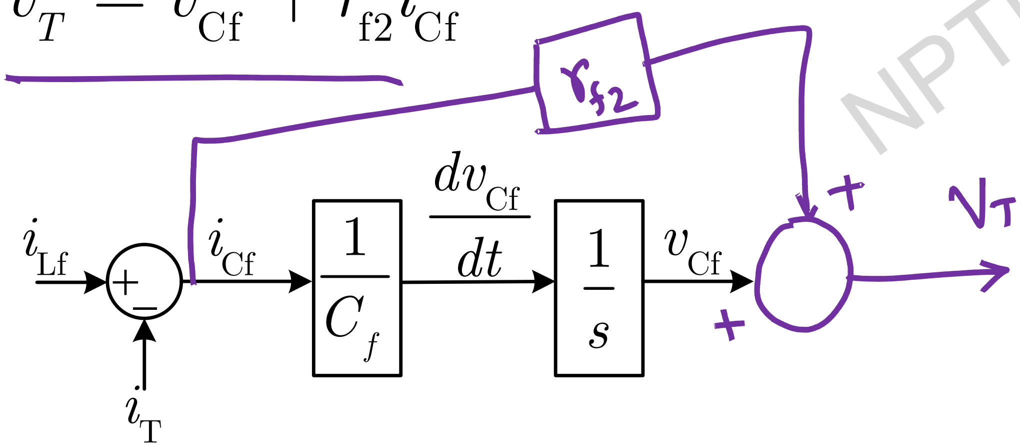


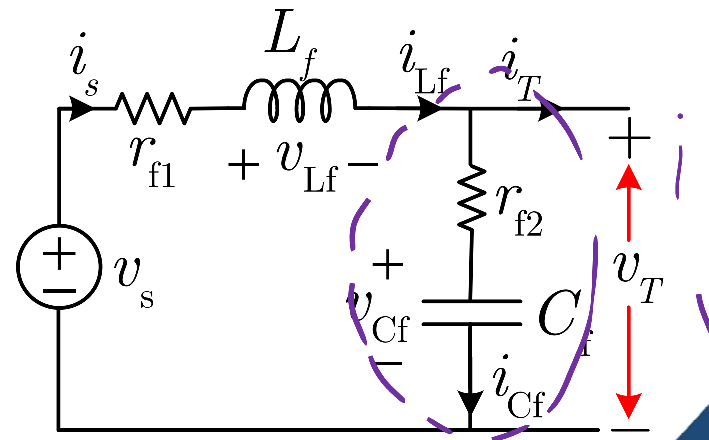


MATLAB Model Development of a Practical Voltage Source

$$C_f \frac{dv_{Cf}}{dt} = i_{Cf} = i_{Lf} - i_T$$

$$v_T = v_{Cf} + r_{f2} i_{Cf}$$





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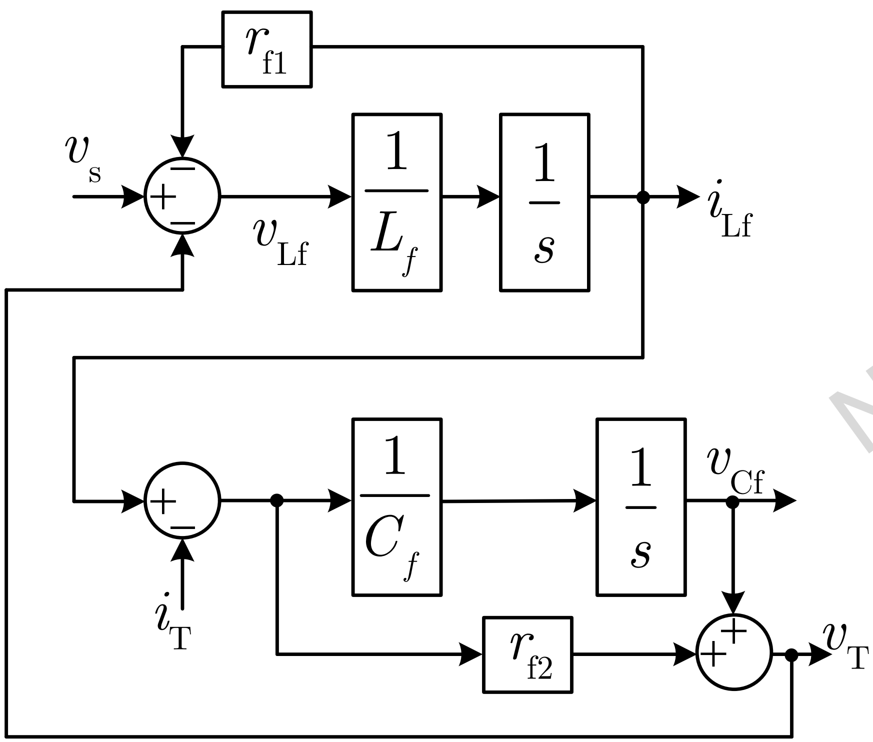
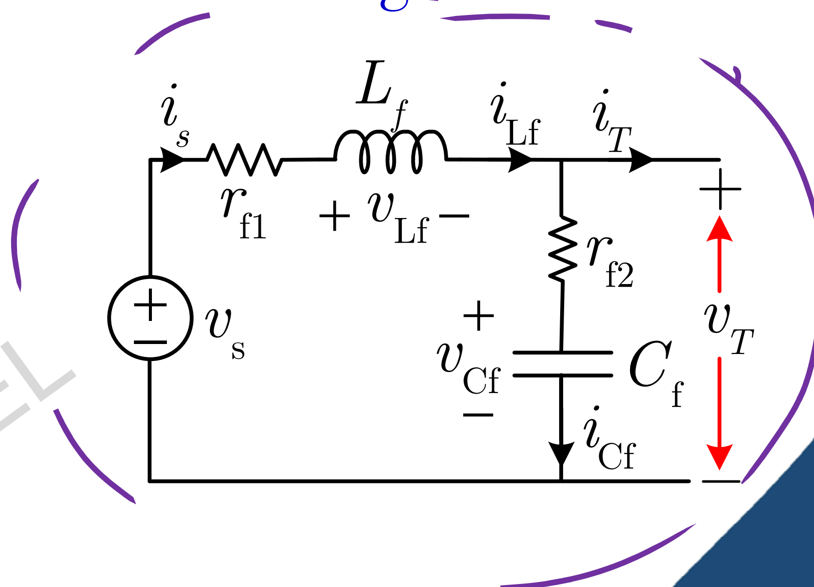
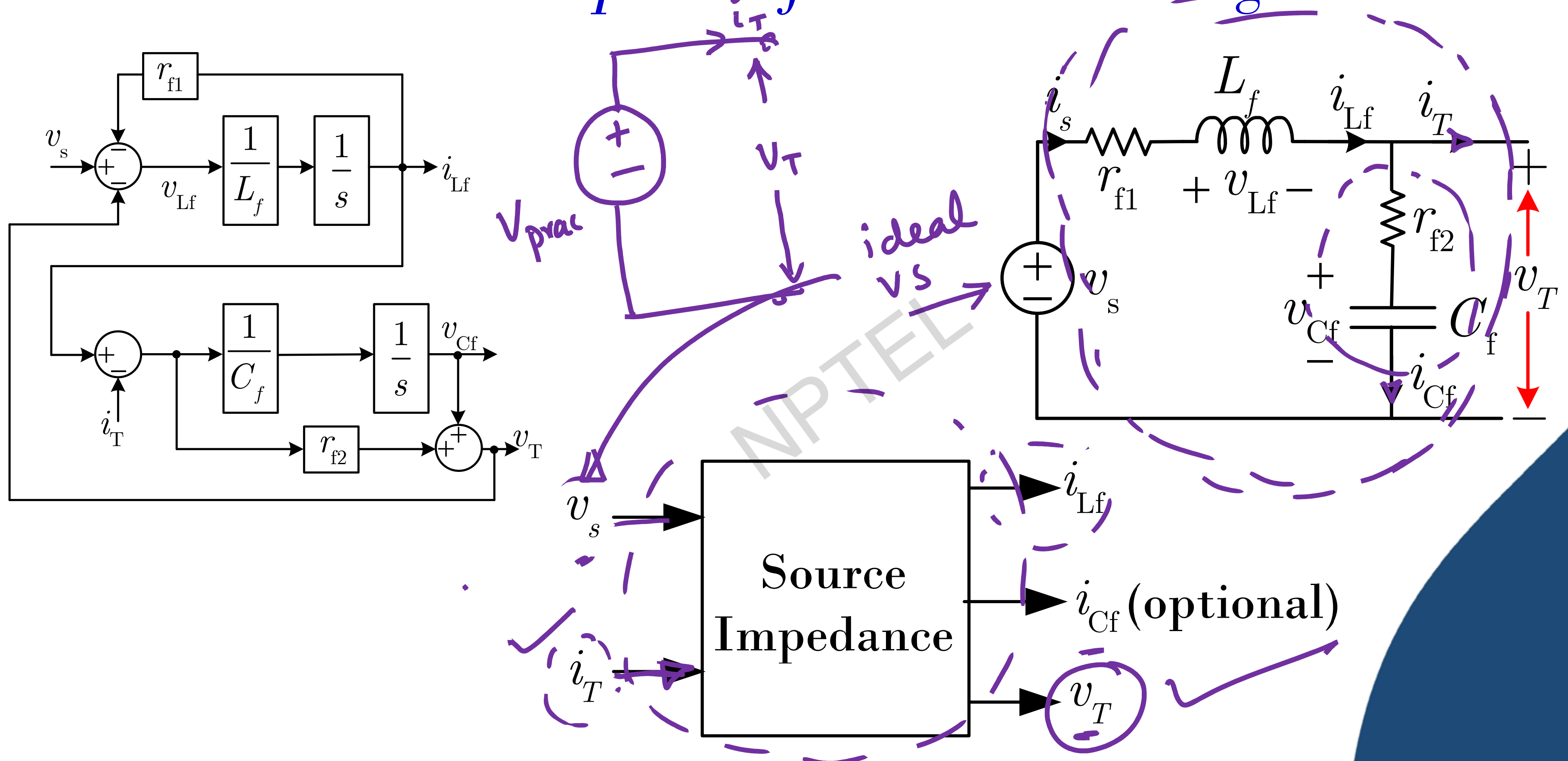
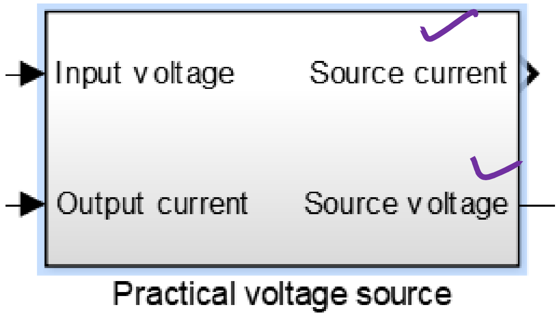


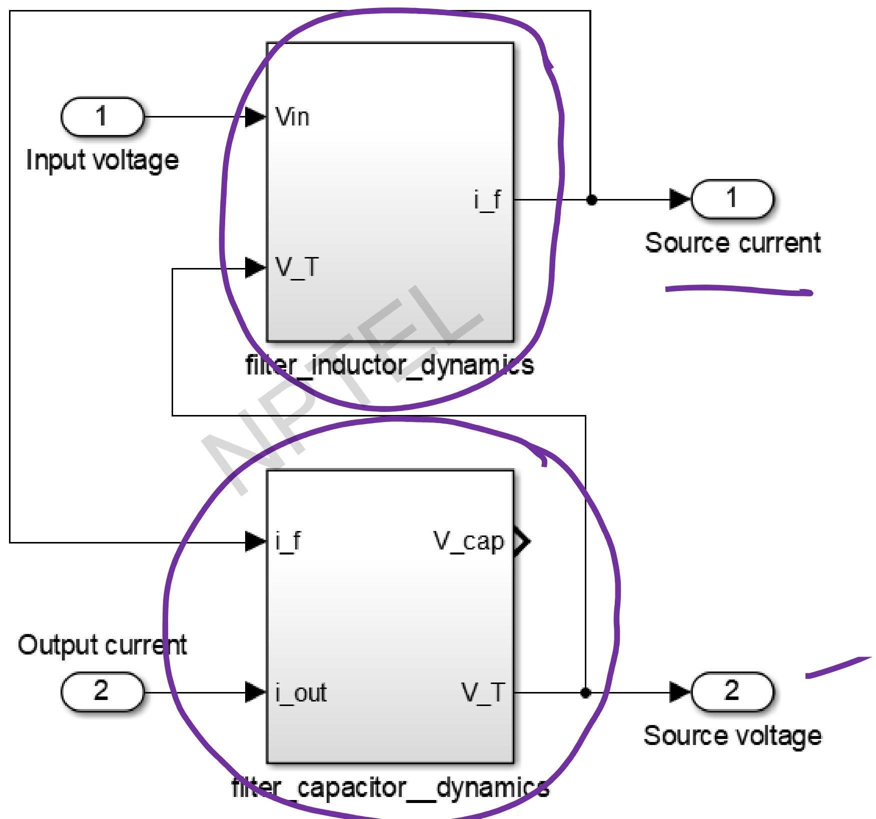


MATLAB Model Development of a Practical Voltage Source



Practical Voltage Source Parameters for Simulation

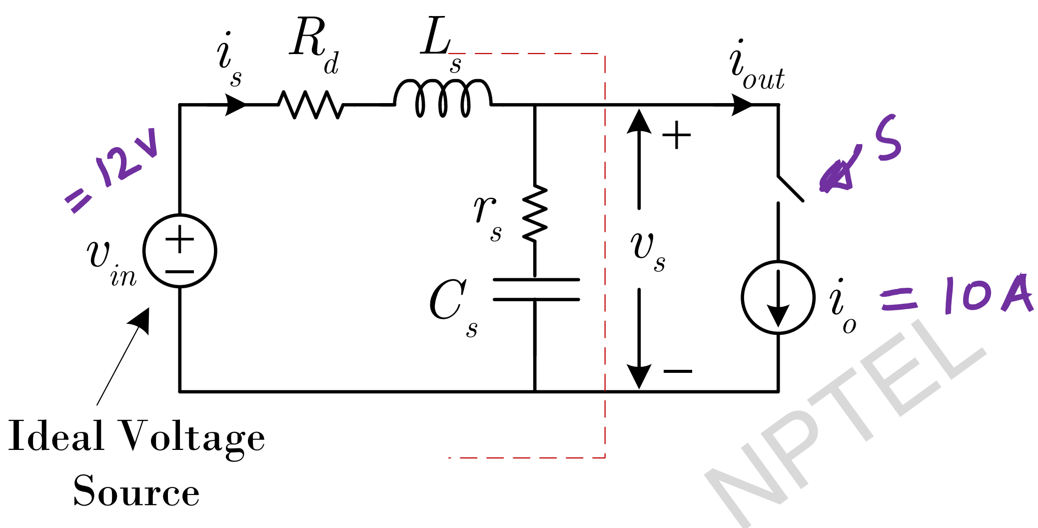




20 nH

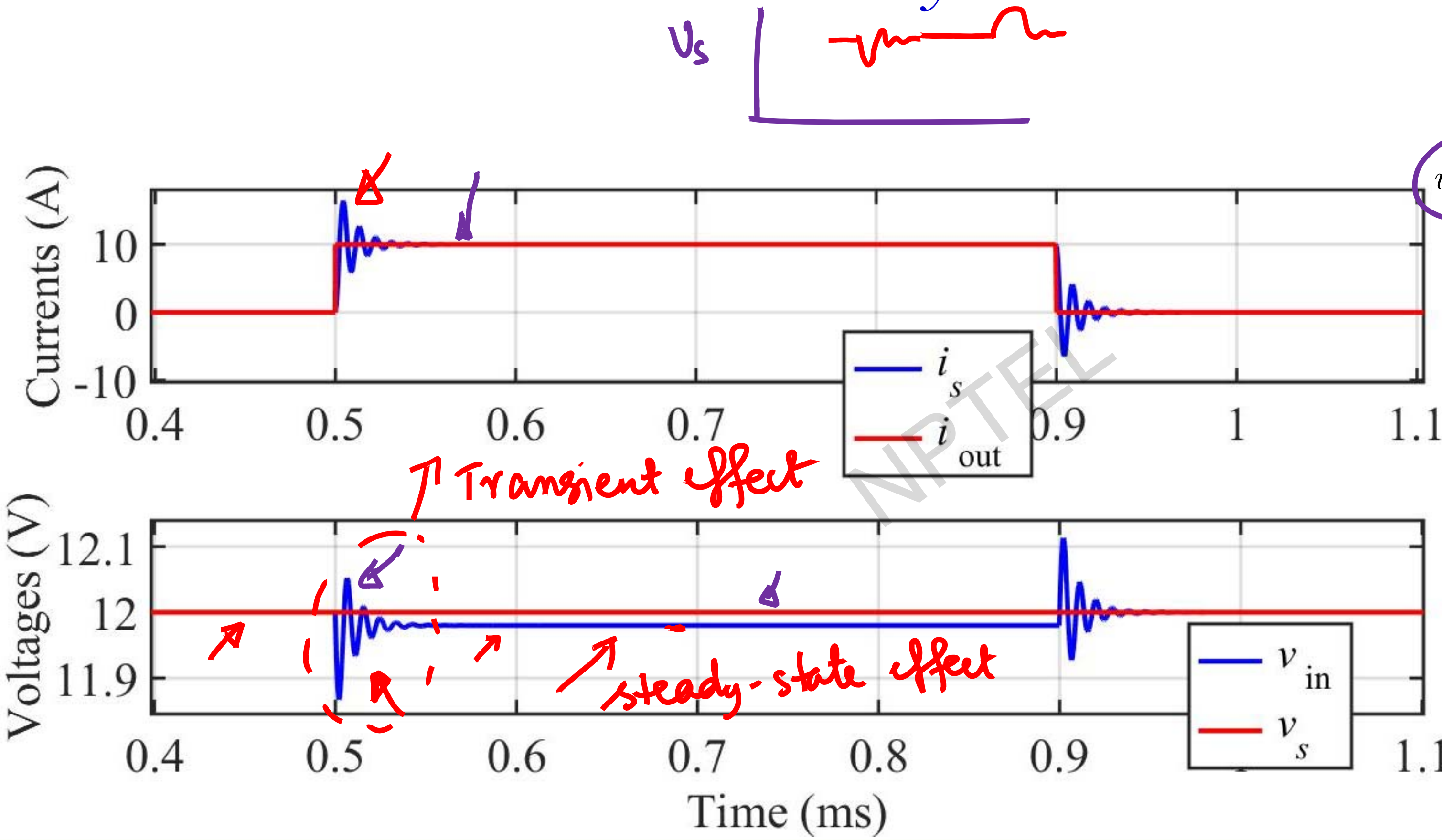
L_f=0.02e-6;
C_f=100e-6;
r_f1=2e-3;
r_f2=2e-3;

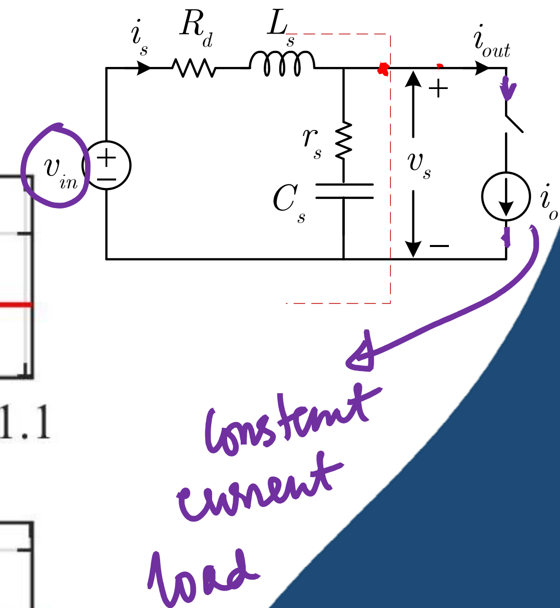
MATLAB Simulation Case Study – Practical Voltage Source



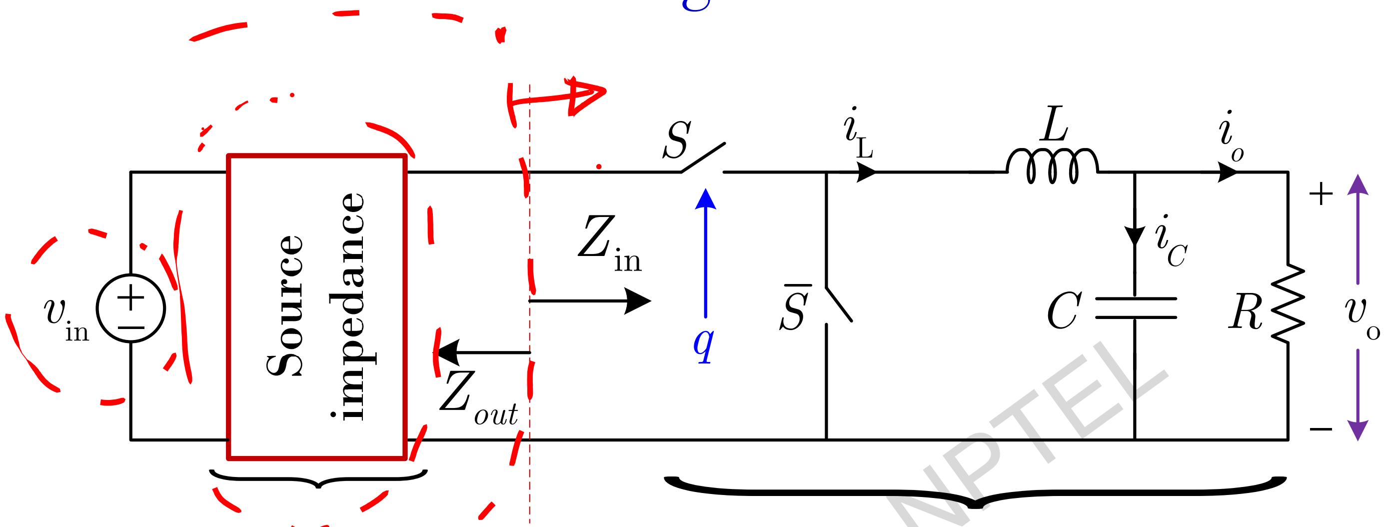
- Consider a pulsating load current profile
- Apply periodic load step-up and step-down

MATLAB Simulation Case Study – a Practical Voltage Source





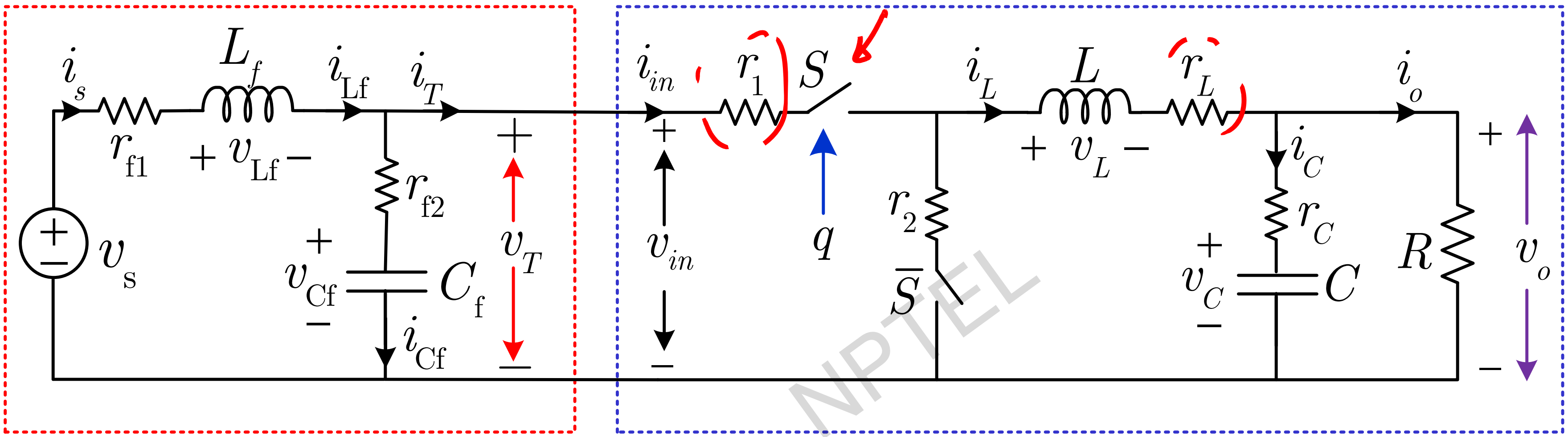
Practical Source Driving a Buck Converter



Output impedance of a practical voltage source

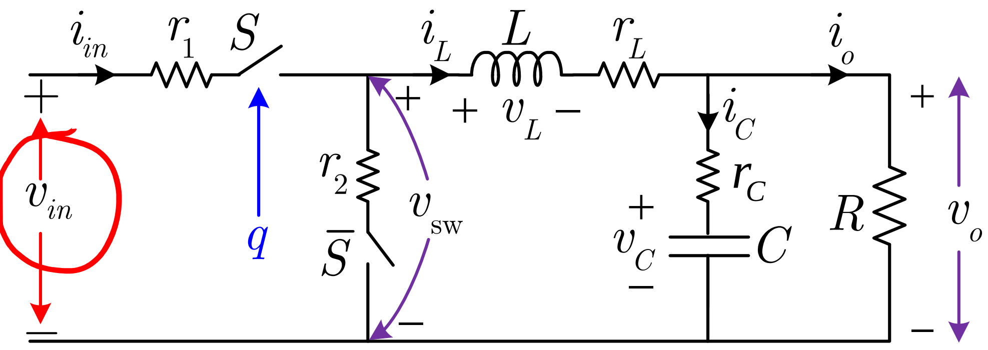
Practical buck converter in CCM

Practical Voltage Source Driving Practical Synchronous Buck Converter



Practical voltage source

Practical Synchronous Buck Converter



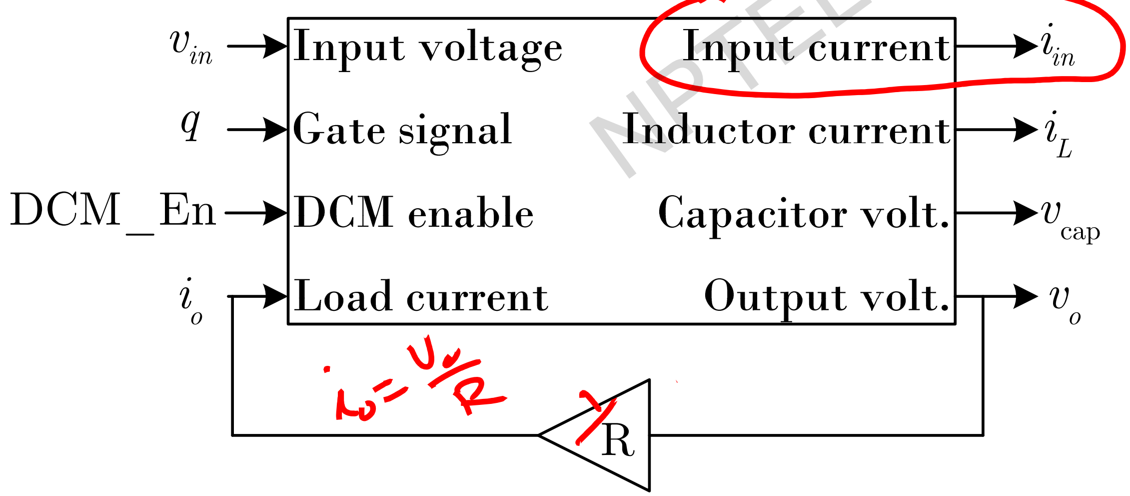
Synchronous buck converter

q = 1   q = 0

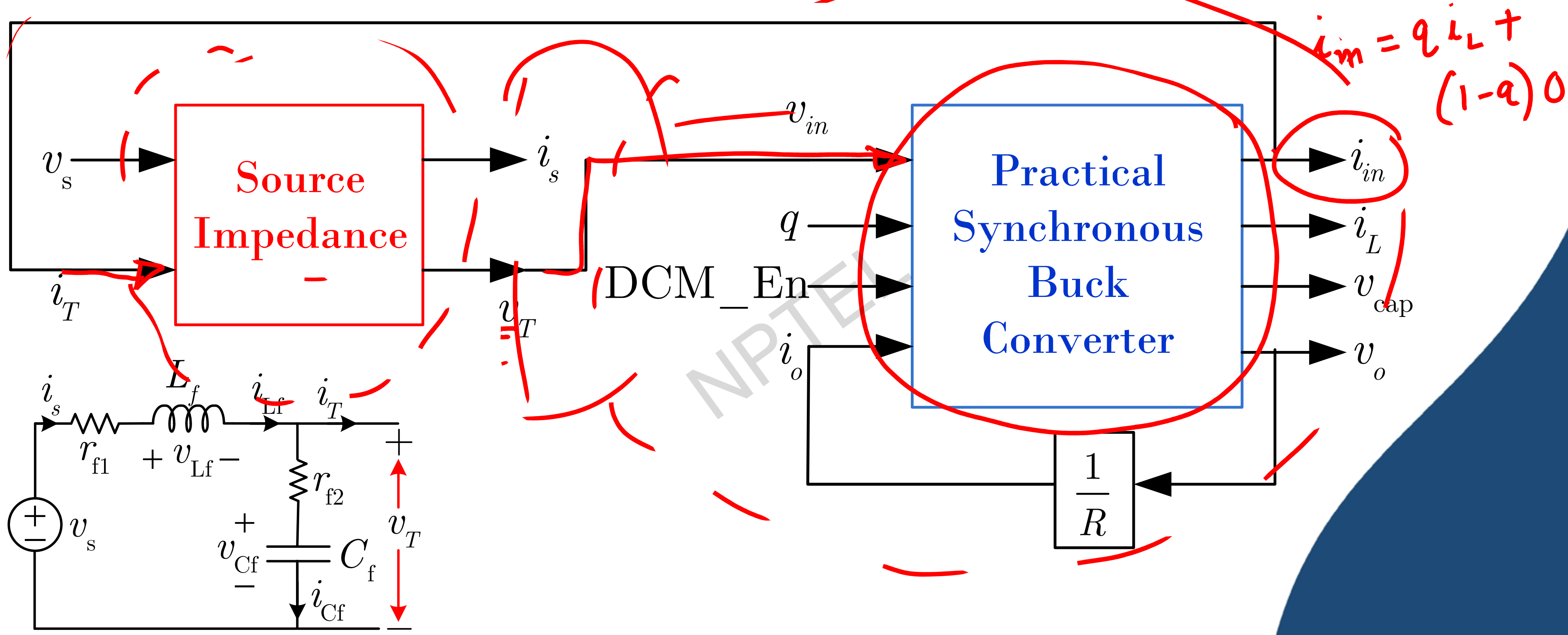
Input voltage v_{in} – source dependent

$$i_{in} = q \times (i_L) + (1-q) \times 0 = q \times i_L$$

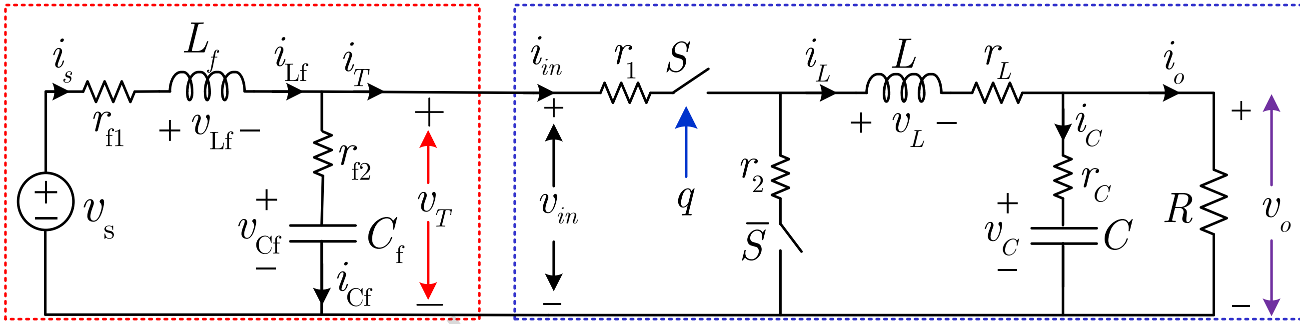
Input current i_{in} – dependent on i_L and q

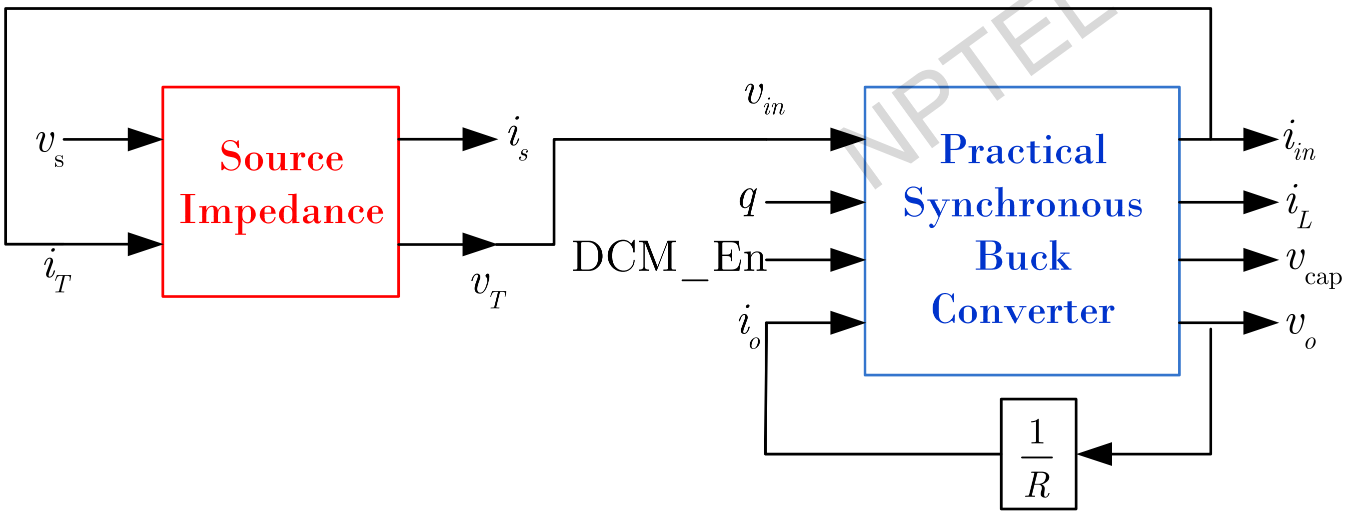


MATLAB Model Development of a Practical Voltage Source



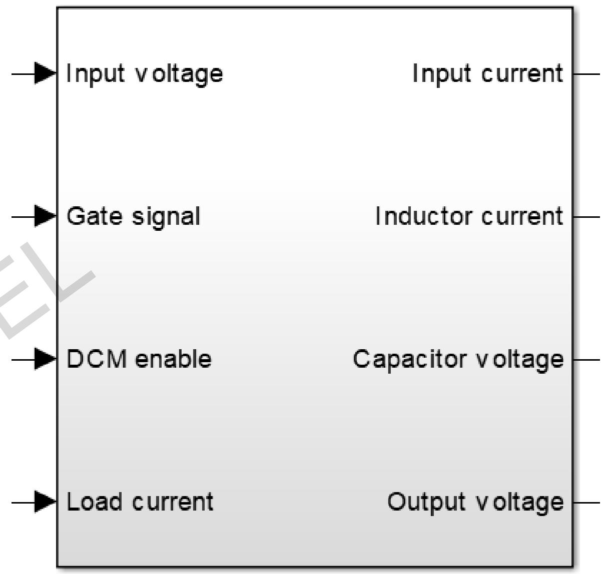
MATLAB Model Development of a Practical Voltage Source





Synchronous Buck Converter Parameters for Simulation

```
L=0.5e-6;        % output inductance
C=200e-6;        % output capacitance
T=2e-6;          % switching time period
r_L=5e-3;        % inductor DCR
r_1=5e-3;        % High-side MOSFET on resistance
r_2=5e-3;        % Low-side MOSFET on resistance
r_d=r_2;         % diode on resistance
v_d=0.55;        % diode voltage drop
r_C=3e-3;        % capacitor ESR
Vin=12;          % nominal input voltage
Vref=1;          % reference output voltage
Io_max =20;      % maximum load current
```



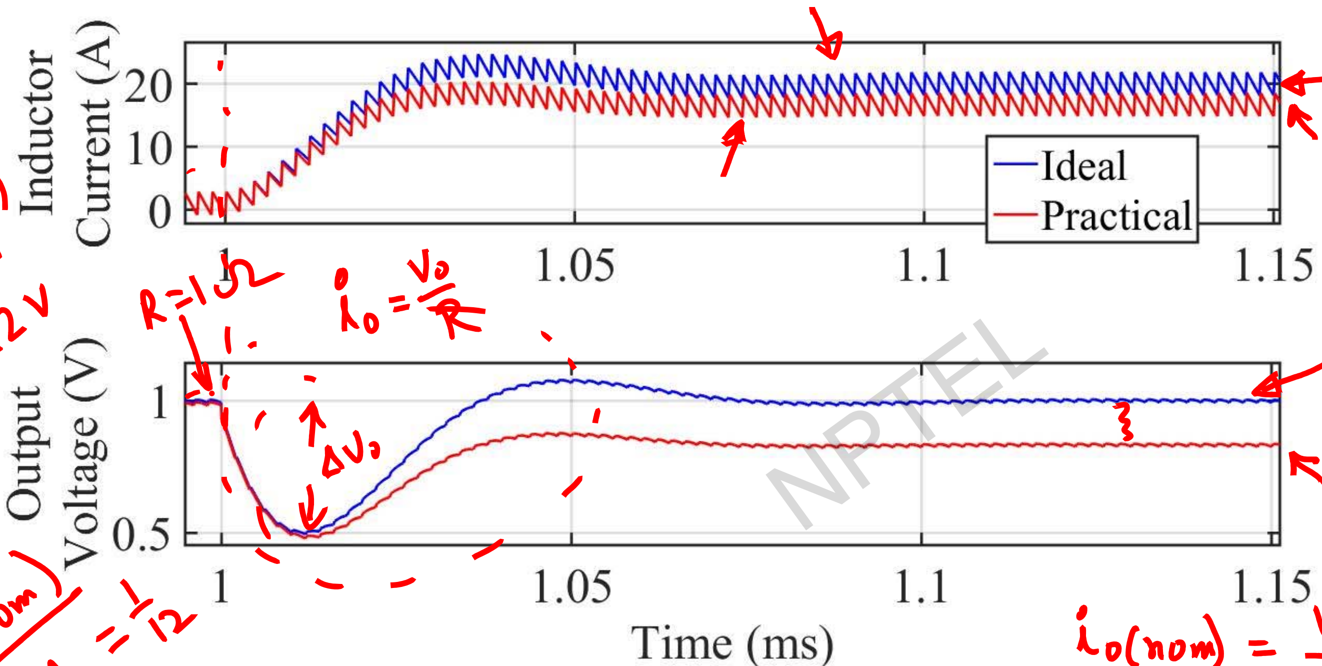
Buck converter

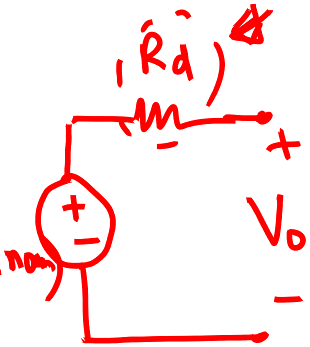
parameters for the buck conv.

Simulation Case Study – Understanding Performance Requirements

$V_{o(nom)} = 1\,V$

$V_{in} = 12\,V$





$D = \frac{V_{o(nom)}}{V_{in}} = \frac{1}{12}$

$i_{o(nom)} = \frac{V_{o(nom)}}{R} = \frac{1}{0.05} = 20A$

Load resistance changes from $R = 1$ to $R = 0.05\ \Omega$

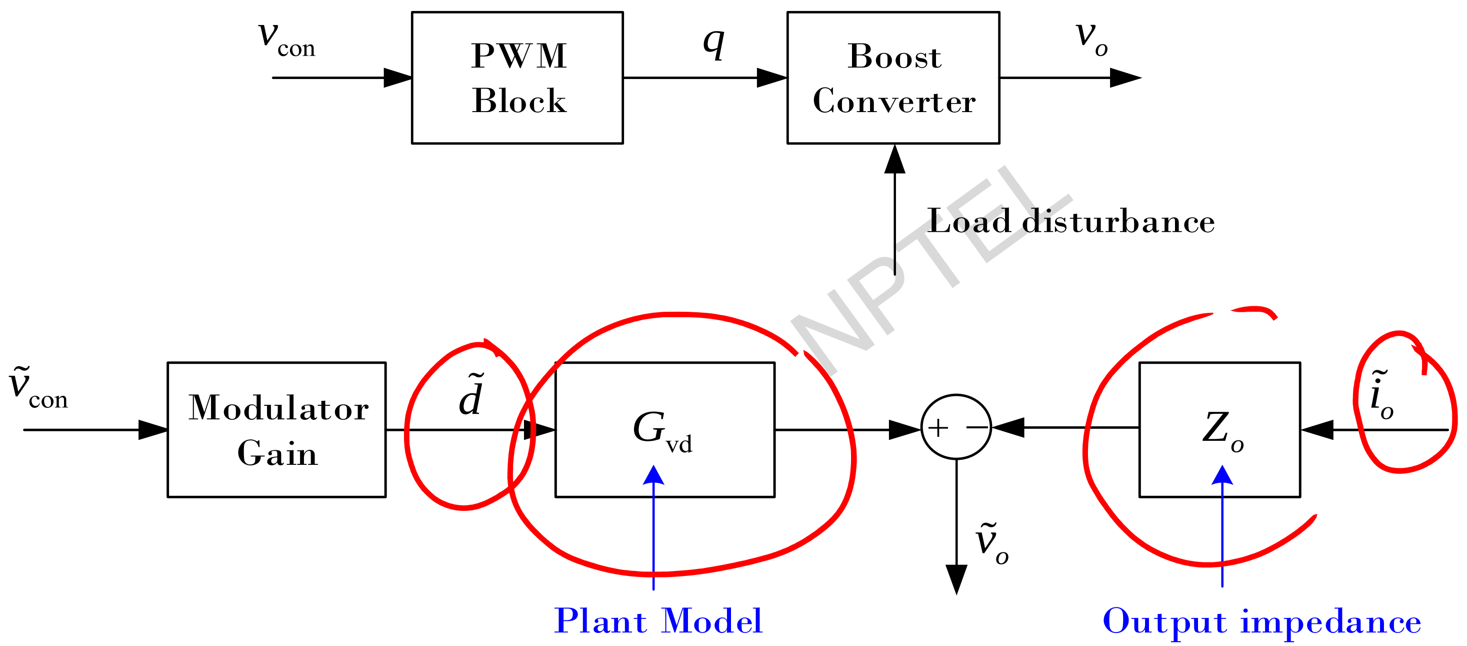
at $v_{in} = 12$ V and $D = \frac{1}{12}$

More Simulation Case Studies – Live Demonstration

- Buck converter operation using ideal and practical voltage sources
- Understanding conducted EMI effects
- Understanding transient response – supply, load, duty steps
- Understanding start-up behavior
- Understanding short circuit and open circuit behavior
- Understanding control requirements

Understanding Dynamic Requirements

<u>Conceptual understanding of load disturbance</u>



Understanding Converter's Objectives

<u>Types of objectives</u>

- Static objectives
- Dynamic objectives
- Operating requirements
- Fault management and protection

Understanding Converter's Objectives

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- Dynamic objectives
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Steady-state requirements and specifications

Understanding Converter's Objectives

Types of objectives

- Static objectives
- Dynamic objectives
- Operating requirements
- Fault management and protection

Transient requirements and specifications

Understanding Converter's Objectives

Types of objectives

- Static objectives
- Dynamic objectives
- Operating requirements
- Fault management and protection

- Conducted EMI compliance requirements and specifications
- Power-up sequencing – soft start, sequencing multiple converters
- Interrupt redundancy, hot swapping for fail-safe operations

Understanding Converter's Objectives

<u>Types of objectives</u>

- Static objectives
- Dynamic objectives
- Operating requirements
- Fault management and protection

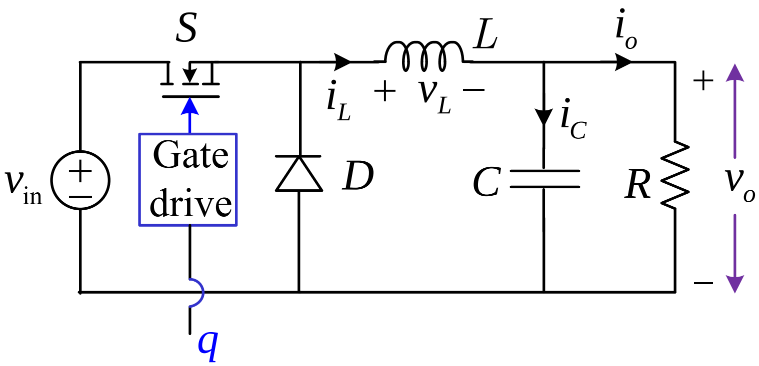
- Strat-up/inrush current limit – current protection circuit
- Mean-time-to-failure – reliability aspect
- Thermal protection and heat distribution
- Packaging and cooling (active/passive) techniques

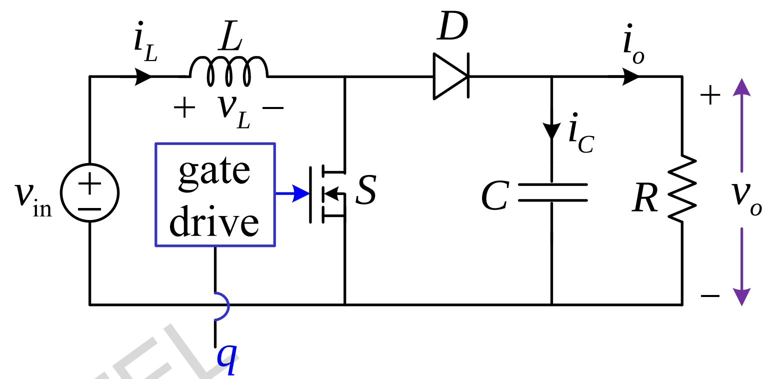
Important Steady-State Requirements

- Input voltage range
- Output voltage value
- Maximum load current
- Modulation technique under consideration

- *Range of input voltage* – worst-case current ripple, losses, device ratings
- *Nominal output voltage* – tolerable range, voltage regulation/ripple aspects
- *Maximum load current* – phase count, current ratings, losses, load step
- *Modulation technique* – frequency range, design rules, filter design

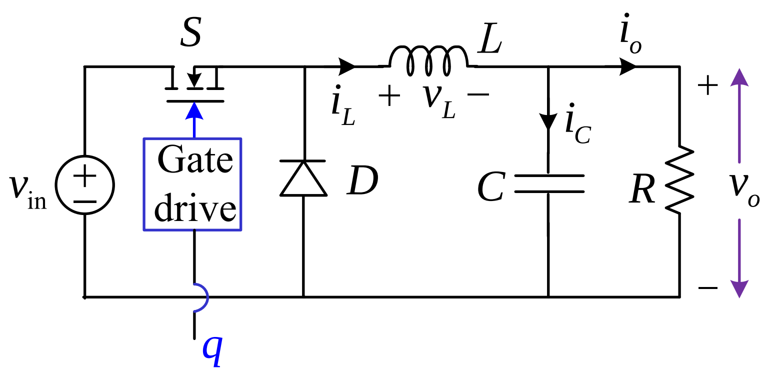
Power Stage Design Summary

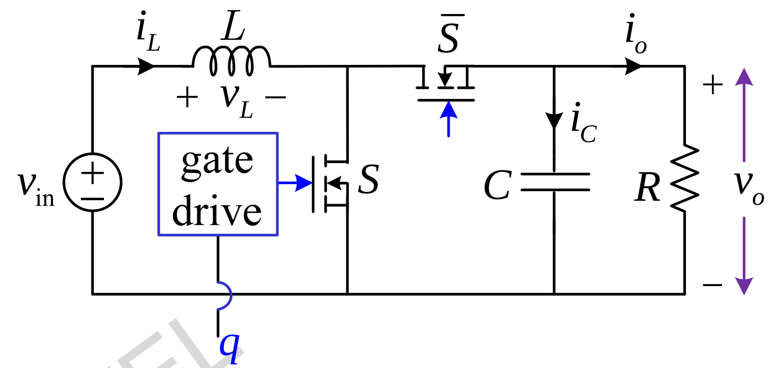




- *Range of input voltage* – worst-case current ripple, losses, device ratings
- *Nominal output voltage* – tolerable range, voltage regulation/ripple aspects
- *Maximum load current* – current ratings, phase count, losses, load step
- *Modulation technique* – frequency range, design rules, filter design

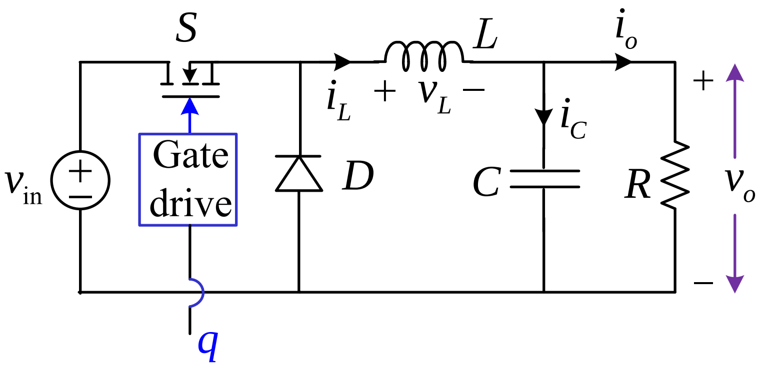
Few Commercial Power Stage Design Tools





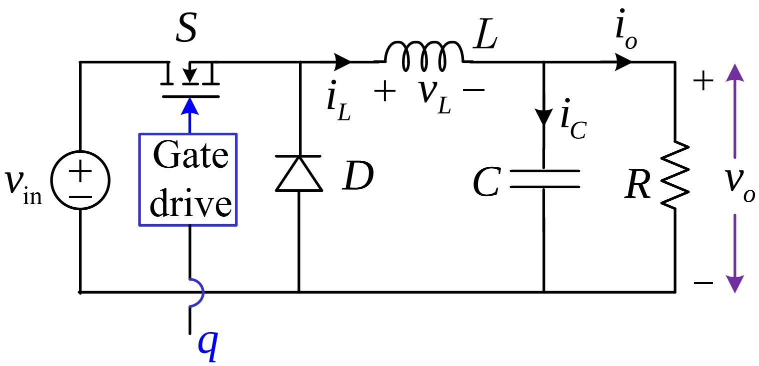
- *Texas Instruments Webench* – [link here]
- *STMicroelectronics eDesignSuite* – [link here]
- *Infineon Designer powered by TINA Cloud* – [link here]
- *On Semiconductor WebDesigner+Power* – [link here]

Example of Buck Converter Power Stage Design



- *Input voltage range* – 8 to 15 V with 12 V nominal
- *Nominal output voltage* – 1 V nominal with 2 % ripple limit
- *Maximum load current* – 20 A nominal and nearly 100 mA lower limit
- *Modulation technique* – single or combined multi-mode techniques

Buck Converter: Power Stage Inductor Design

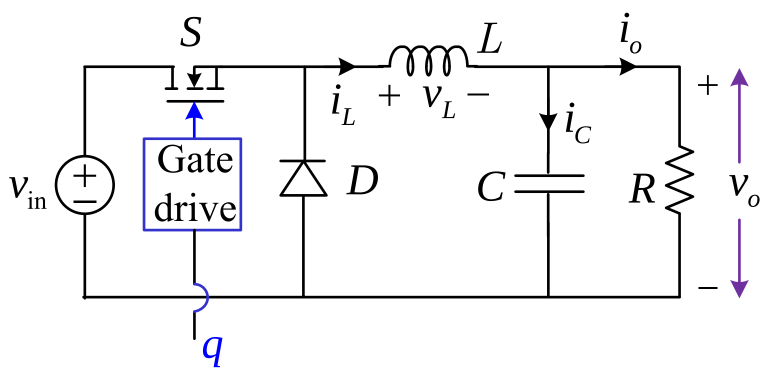


$$\Delta i_L = \frac{V_O}{Lf_{sw}} \times (1-D)$$

Current ripple is maximum at minimum $D \rightarrow$ highest v_{in}

- *Ripple inductor current* (20% of maximum load current) = 4 A
- *Minimum duty ratio* (at maximum input voltage) = 1/15= 0.067
- *Nominal switching frequency* (under high load) = 500 kHz
- *Minimum inductor value* (at 1 V output) = 467 nH

Buck Converter: Power Stage Design



$$\Delta v_o = \left(\frac{(1-D)V_O}{8LCf_{sw}^{2}} \right) + \underbrace{r_C \Delta i_L}_{ESR\ effect}$$

Current ripple is maximum at minimum $D \rightarrow$ highest v_{in}

- *Ripple output voltage* (2% of nominal output voltage) = 20 mV
- *Worst-case ripple at maximum input voltage*
- *Minimum output capacitor* (at 3 mΩ ESR) = 117 uF
- *Inductor and capacitor:* L = 0.5 uF, C=200 uF

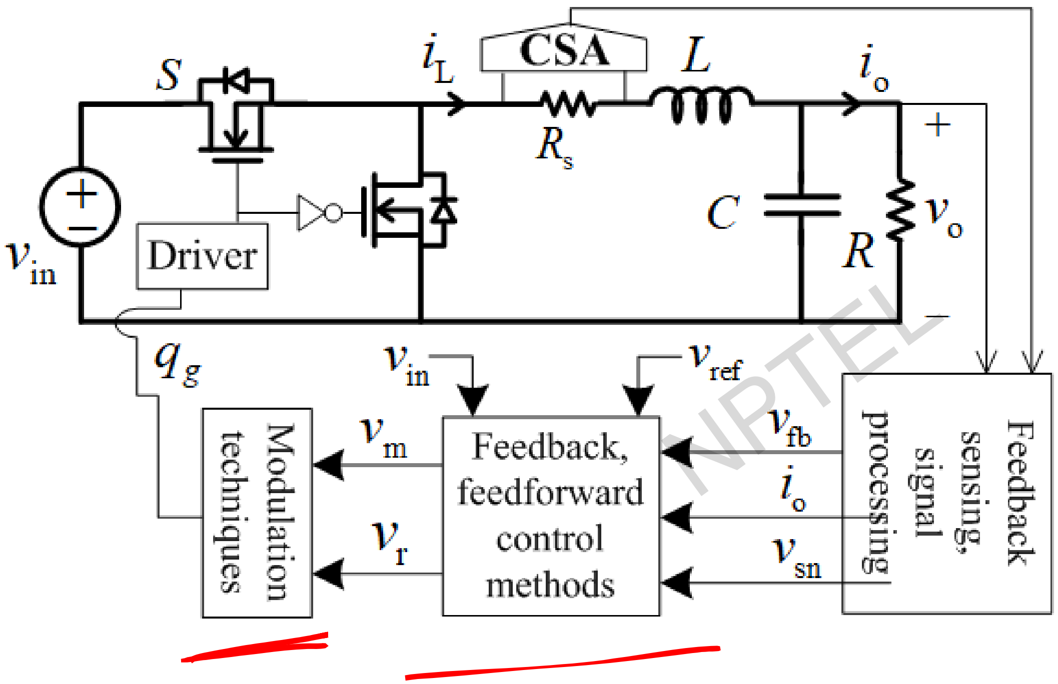
Understanding Operating Requirements

- Electromagnetic interference (EMI) – reference link
- Power-up sequencing – reference link
- Hot plugging – reference link

Fault Management and Protection

- Inductor (and switch) current limit
- Inrush/ start-up current limit
- Thermal protection
- Packaging and cooling requirements
- Health monitoring → Digital twin

Overview of Feedback/Feedforward Control Methods



S. Kapat & P. Krein, “A Tutorial and Review Discussions …”, *IEEE Open J. Power Electronics*

Summary

- Impedance aspects of a practical voltage source – discussed
- Scalable and plug-and-play MATLAB model development
- MATLAB case studies to demonstrate control requirements
- Power-stage design guidelines and few power designer tools


THANK
YOU !

NPTEL ONLINE CERTIFICATION COURSES

CONTROL AND TUNING METHODS IN SMPCs

Dr. Santanu Kapat
Electrical Engineering Department, IIT KHARAGPUR

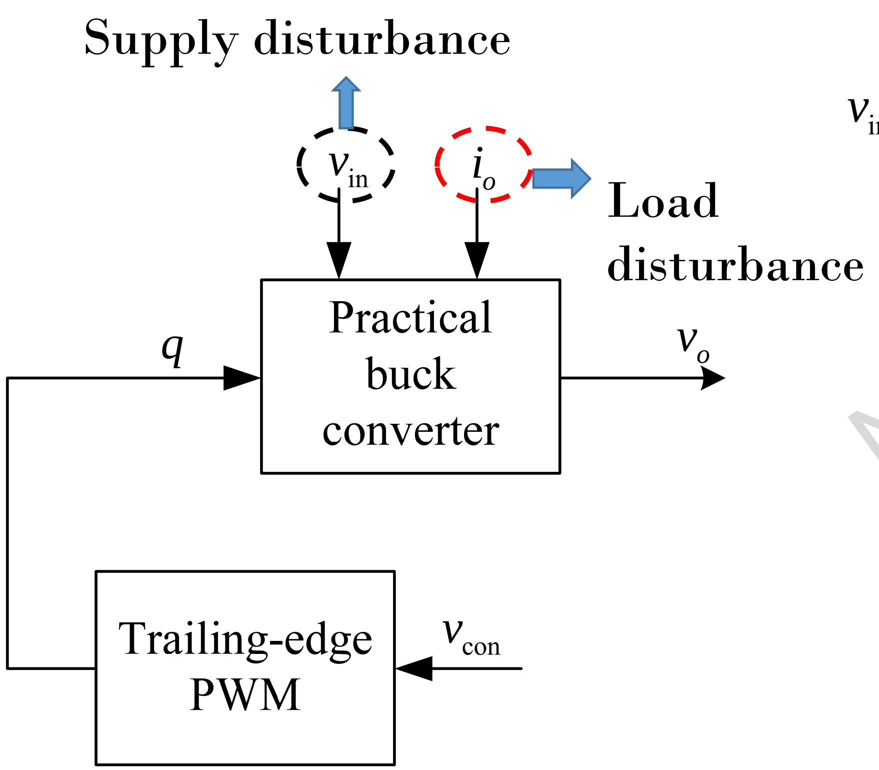
Module 03: Fixed Frequency Control Methods

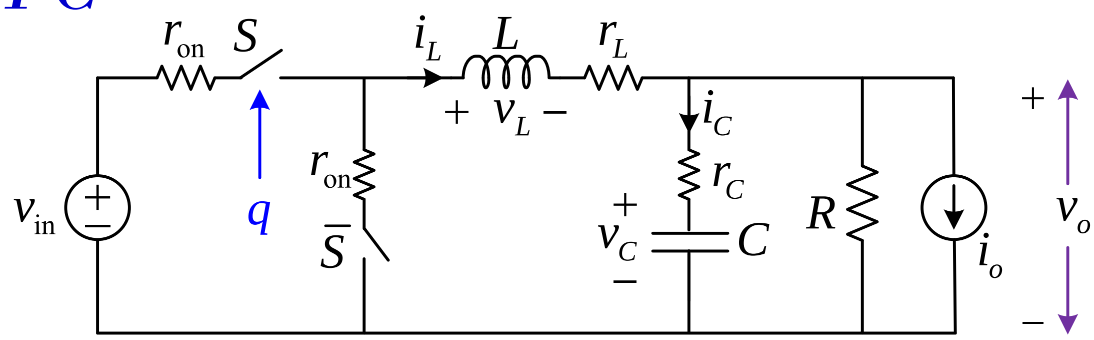
Lecture 14: Feedforward Control in SMPC and MATLAB Simulation

Concepts Covered

- Sources of disturbances in SMPCs
- Disturbance rejection using feedforward action
- Supply disturbance rejection and MATLAB simulation
- Load disturbance rejection and MATLAB simulation
- Understanding need for feedback control

Sources of Disturbance in SMPC





Synchronous Buck Converter Parameters for Simulation

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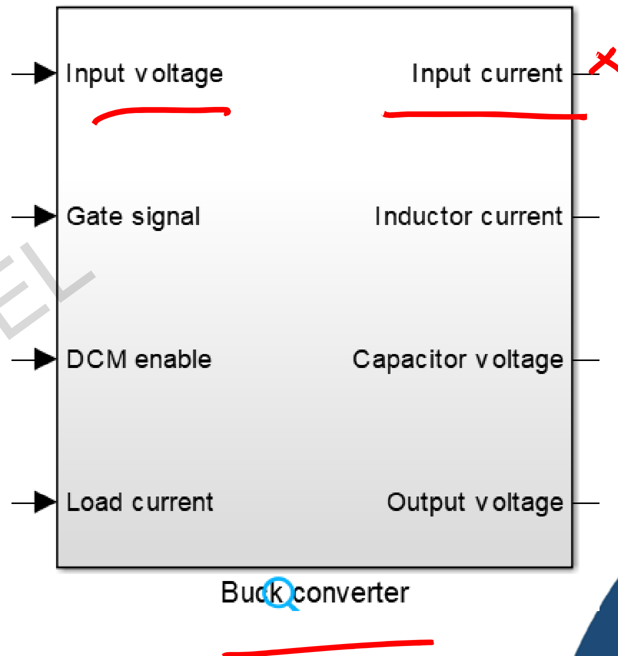
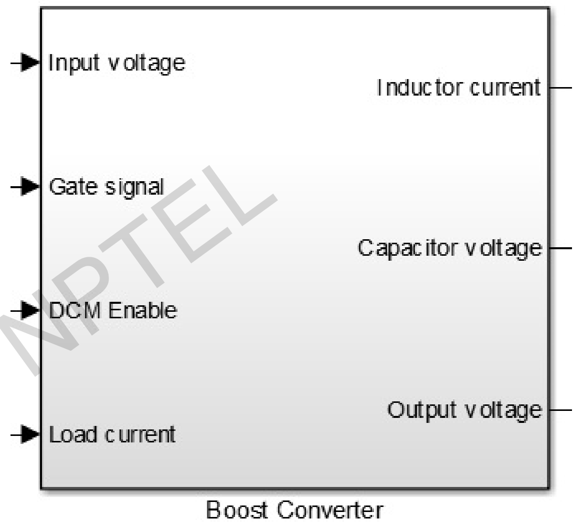
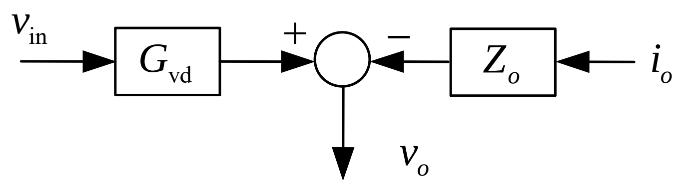


Synchronous Boost Converter Parameters for Simulation

```
L=2e-6;
C=100e-6;
T=2e-6;
r_L=0*10e-3;
r_d=0*10e-3;
v_d=0*0.7;
r_1=0*5e-3;
r_2=0*5e-3;
r_C=0*5e-3;
Vin=3.6;
Vref=5;
```



Effects of Supply and Load Disturbances – MATLAB Simulation



Buck converter

Observations:

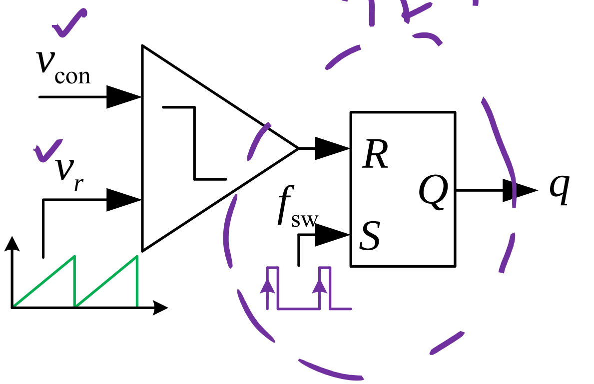
Supply step transient

Significant impact on output voltage as well as inductor current

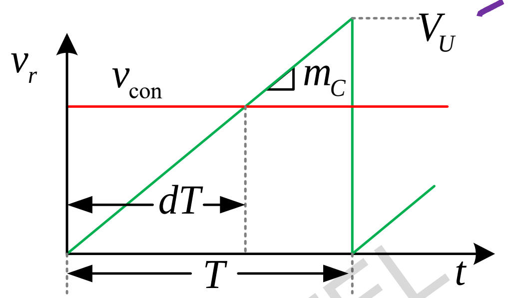
Impact is visible even for sinusoidal excitation

Input Voltage Disturbance Rejection in a Buck Converter

TE PWM



- max volt.



$$m_c = \frac{V_U - V_L}{T}$$

$$= \frac{V_U}{T} \quad (\because V_L = 0)$$

$$\frac{dT}{T} = \frac{v_{con}}{V_U} \Rightarrow d = \left(\frac{1}{V_U}\right) \times v_{con}$$

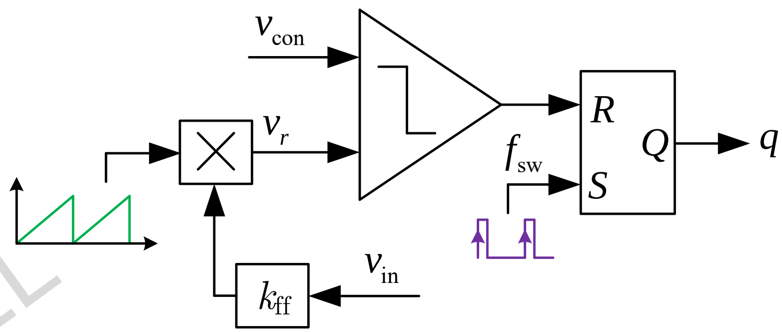
$v_{in} \rightarrow v_{in} + \Delta v_{in}$

- Objective is to reject disturbance of v_{in} change

Input Voltage Disturbance Rejection (contd…)

$$v_o = dv_{\text{in}} = \underbrace{\left(\frac{1}{V_U}\right)}_{F_{\text{m}}} \times v_{\text{con}} \times v_{\text{in}}$$

(modulator gain)



- Objective is to make Δv_o even without changing v_{con}

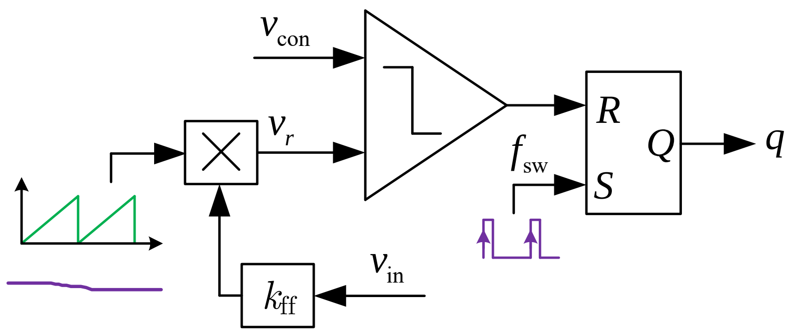
Let, $V_U = k_{\text{ff}} v_{\text{in}}$

$$v_o = \frac{1}{k_{\text{ff}} v_{\text{in}}} \times v_{\text{in}} \times v_{\text{con}} \quad \Rightarrow v_o = \frac{v_{\text{con}}}{k_{\text{ff}}} \longrightarrow$$

Insensitive to input voltage variation

Input Voltage Disturbance Rejection in a Boost Converter

Simple extension of the previous input voltage feedforward



$$v_{in} \rightarrow v_{in} + \Delta v_{in}$$

$$v_o = \frac{1}{1-d} \times v_{in}$$

$$v_o = \frac{1}{1 - \dfrac{v_{con}}{V_U}} \times v_{in}$$

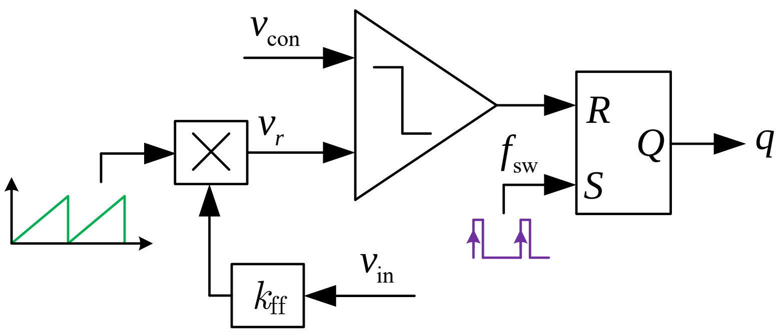
$$d = \frac{V_{con}}{V_m}$$

$V_m = V_U$

- Objective: Supply disturbance rejection using $V_U = k_{ff} \times v_{in}$

Input Voltage Disturbance Rejection in a Boost Converter

Simple extension of the previous input voltage feedforward



$$v_o = \frac{1}{1 - \frac{v_{con}}{V_U}} \times v_{in} = \frac{V_U}{V_U - v_{con}} \times v_{in}$$

$$\boxed{v_o = \frac{k_{ff} v_{in}}{k_{ff} v_{in} - v_{con}} \times v_{in}}$$

- Observation: Supply disturbance cannot be rejected!!

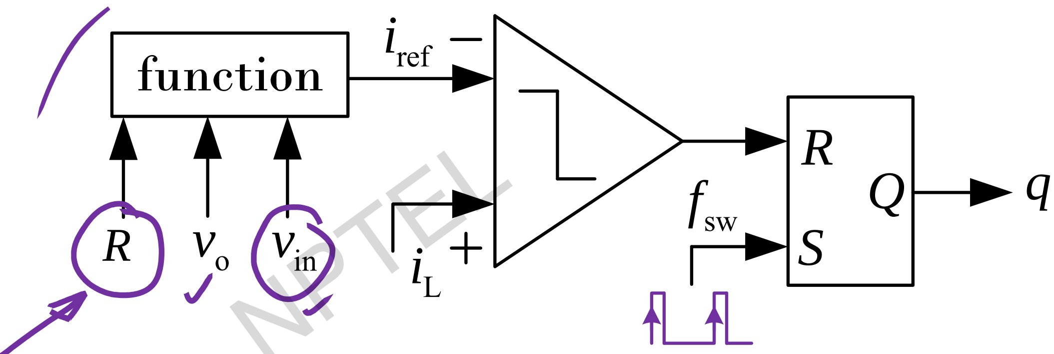
Input Voltage Disturbance Rejection in a Boost Converter

<u>Alternative method using current control and power balance</u>

$v_o i_o$

$$P_{in} = P_o \;\Rightarrow\; v_{in} i_{in} = \frac{v_o^2}{R}$$

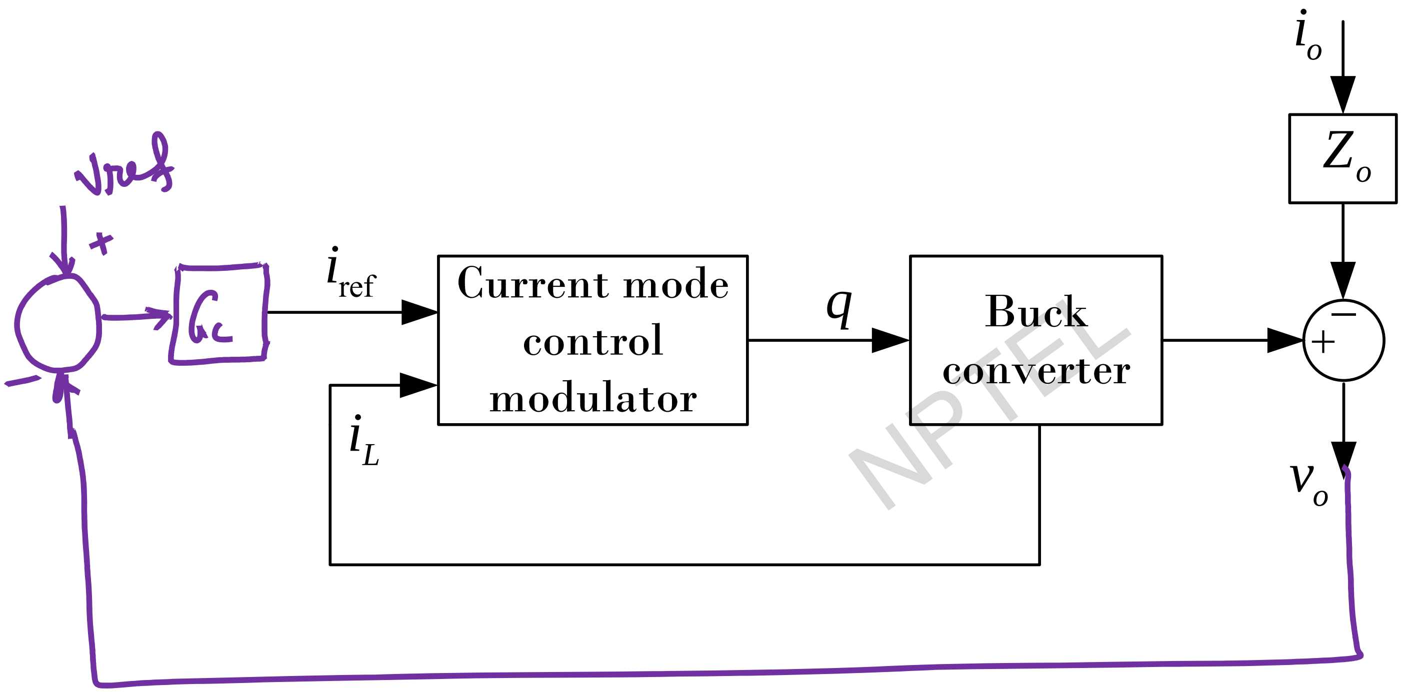
$$i_{ref} = \frac{v_o^2}{v_{in} R}$$



or i_o

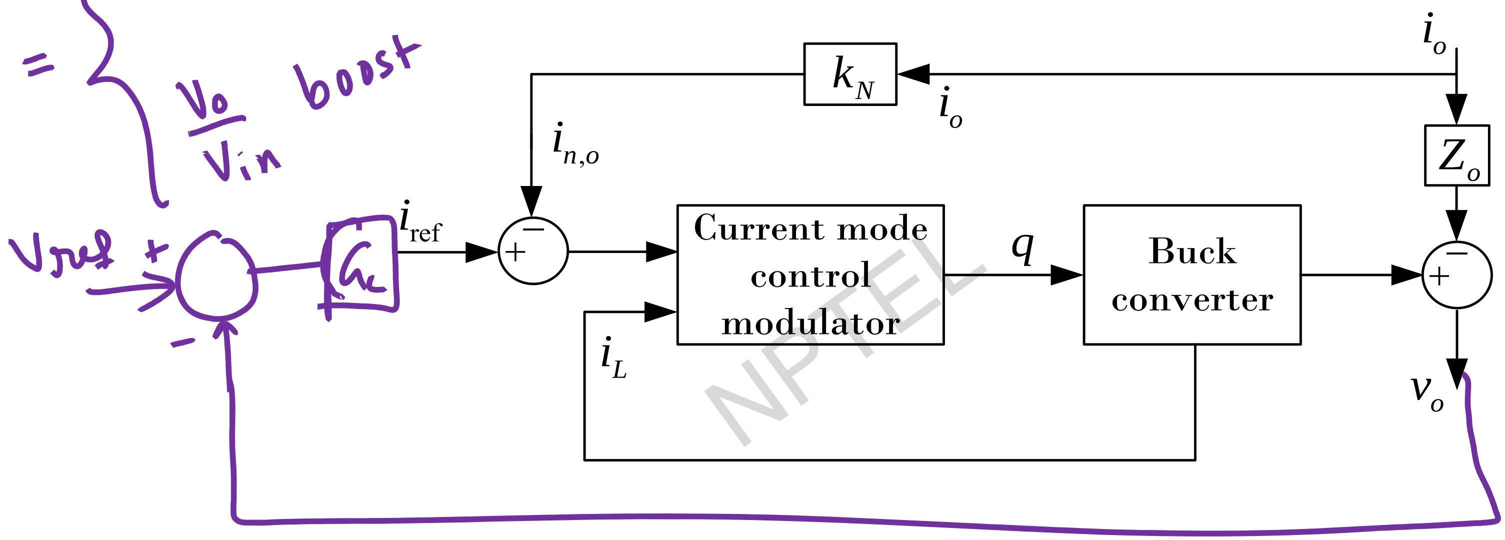
- Limitation: Non-robust due to difficulty in measuring *R*!!

Load Disturbance in CMC



Load Current Feedforward in CMC

$K_N = \begin{cases} 1 & \text{buck} \\ \frac{V_o}{V_{in}} & \text{boost} \end{cases}$



- Repeat the earlier simulation using CMC using load feedforward

Limitations of Feedforward Control in SMPC

- Feedforward control offers excellent disturbance rejection
- Requires accurate parameter information – non-robust
- Poor regulation performance with practical parasitic
- Unmodelled dynamics may be problematic
- Feedforward control alone is not suitable for SMPCs

Summary

- Sources of disturbances in SMPCs – identified
- Effects of supply and load disturbance – discussed
- Input voltage and load current feedforward – demonstrated
- Feedforward control non-robust, feedback control seems essential
- Combined feedback and feedforward control – to be discussed

THANK YOU !

NPTEL ONLINE CERTIFICATION COURSES

CONTROL AND TUNING METHODS IN SMPCs

Dr. Santanu Kapat
Electrical Engineering Department, IIT KHARAGPUR

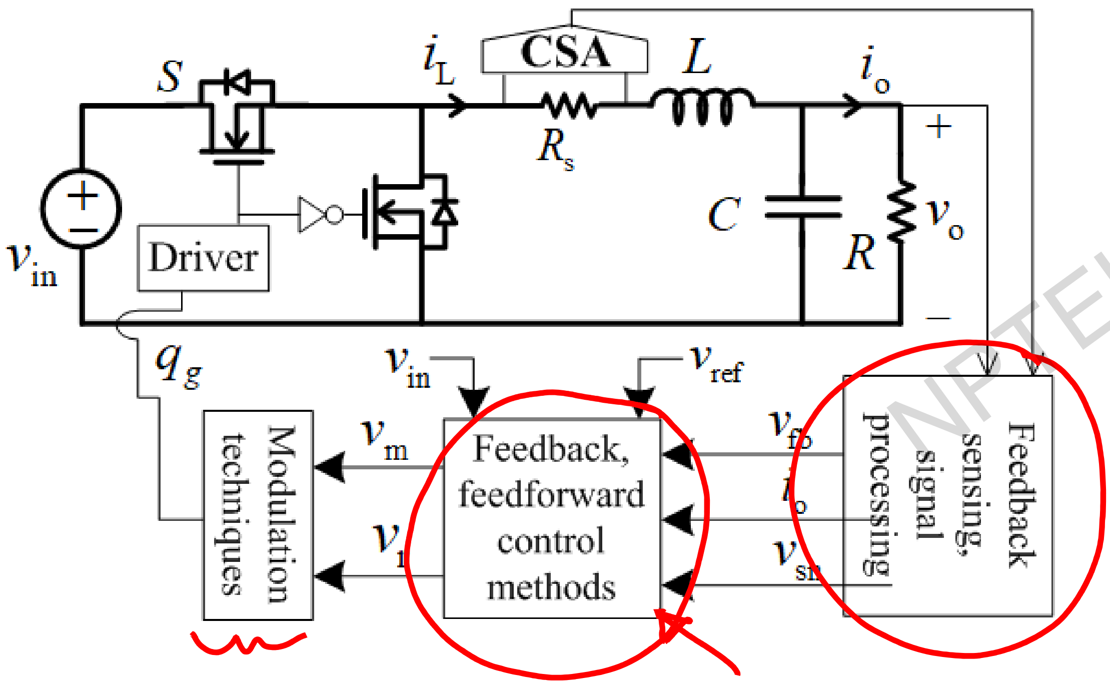
Module 03: Fixed Frequency Control Methods

Lecture 15: Single and Multi Loop Feedback Control Methods

Concepts Covered

- Conventional negative feedback control
- Link with voltage feedback control in SMPC
- PWM voltage mode control – single loop feedback control
- PWM current mode control – two-loop feedback control
- Discussions on advantages and limitations

Overview of Feedback/Feedforward Control Methods

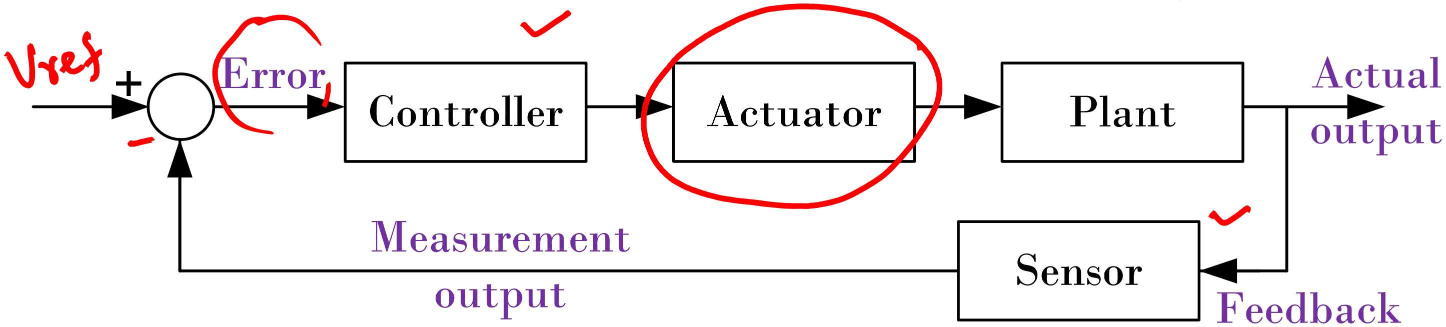


<u>Objectives</u>

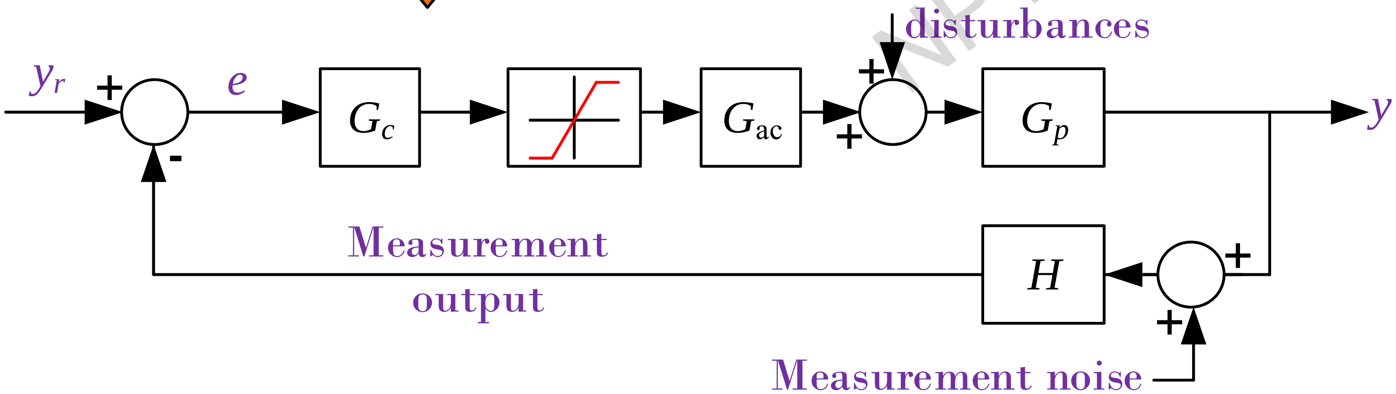
- Well-damped and fast response
- Good disturbance rejection
- Tight voltage regulation
- Soft-start at power-up

S. Kapat & P. Krein, "A Tutorial and Review Discussions …", *IEEE Open J. Power Electronics*

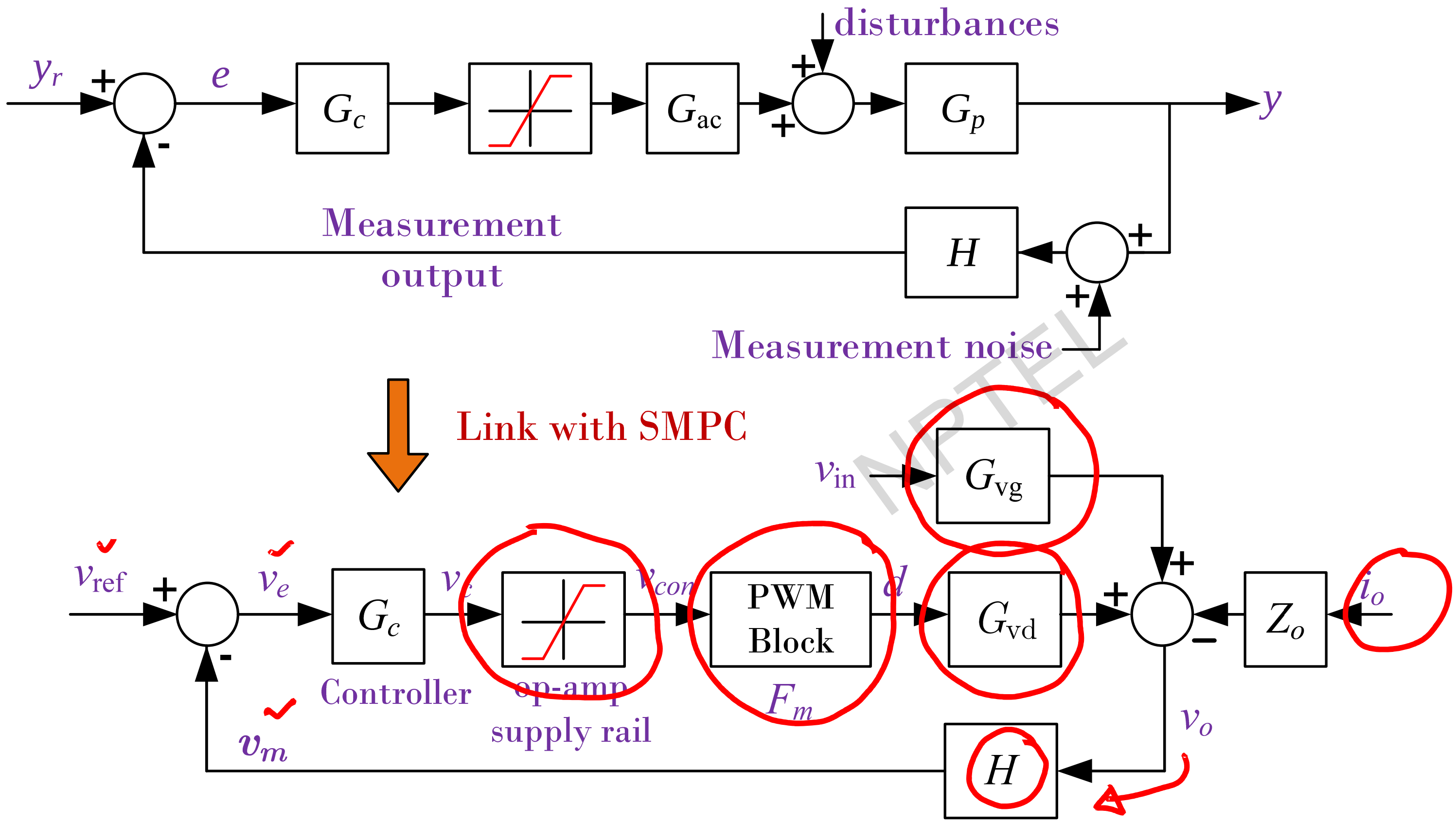
Single Loop Feedback Control – Sources of Disturbance



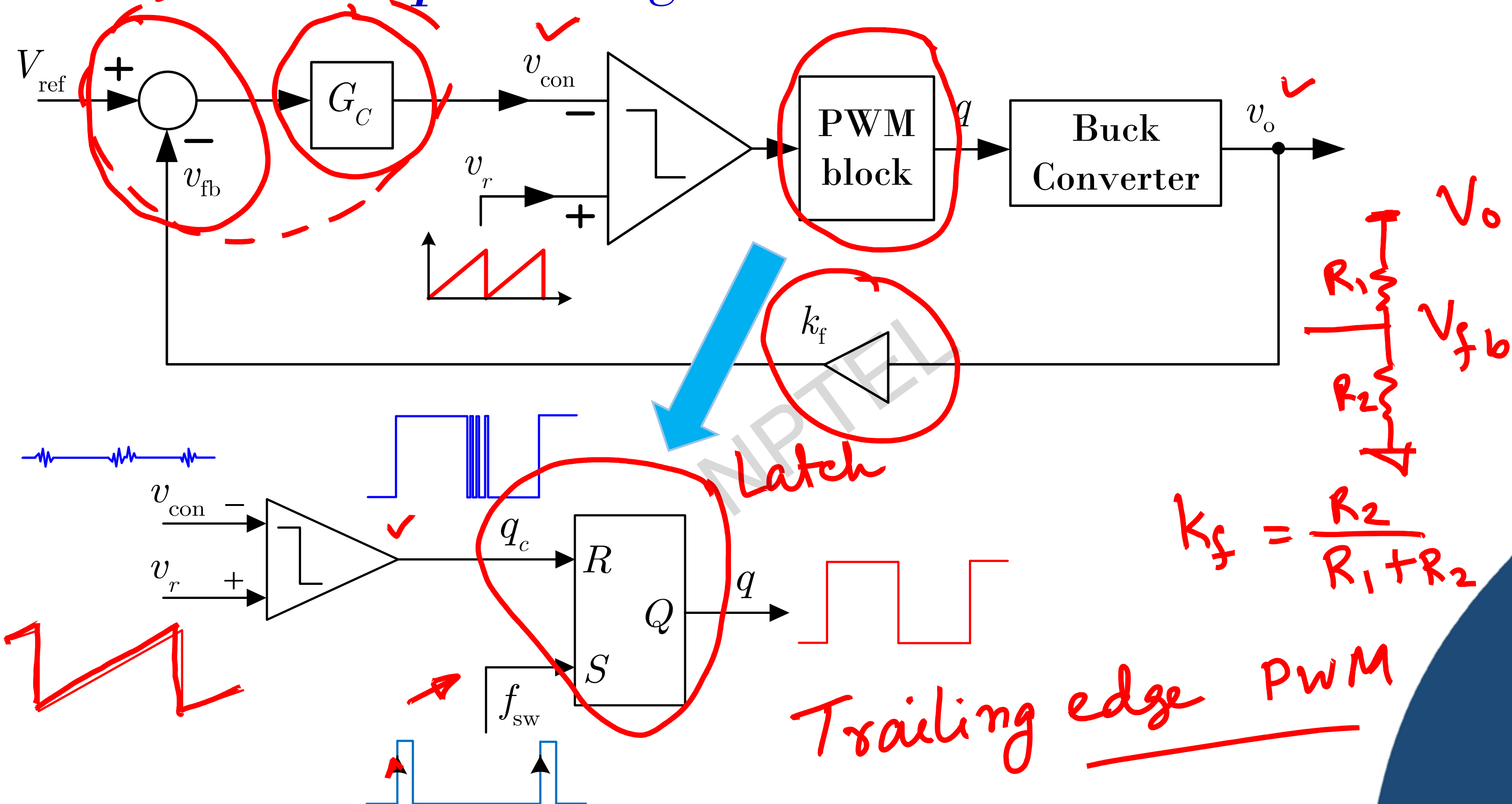
Source of disturbance and noise



Single Loop Feedback Control – Link with SMPC



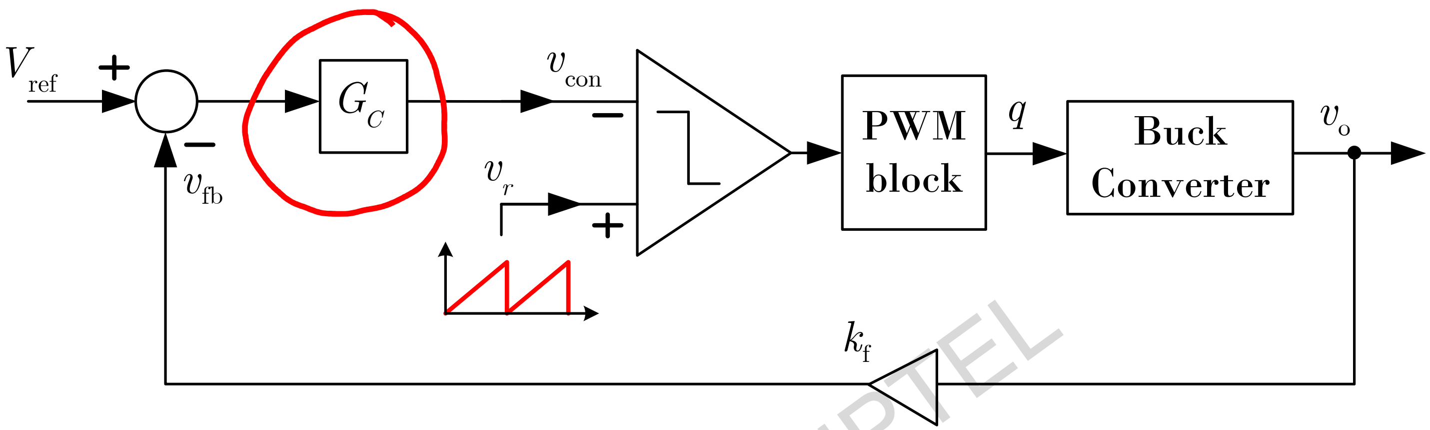
Single Feedback Loop – Voltage Mode Control



$k_f = \frac{R_2}{R_1 + R_2}$

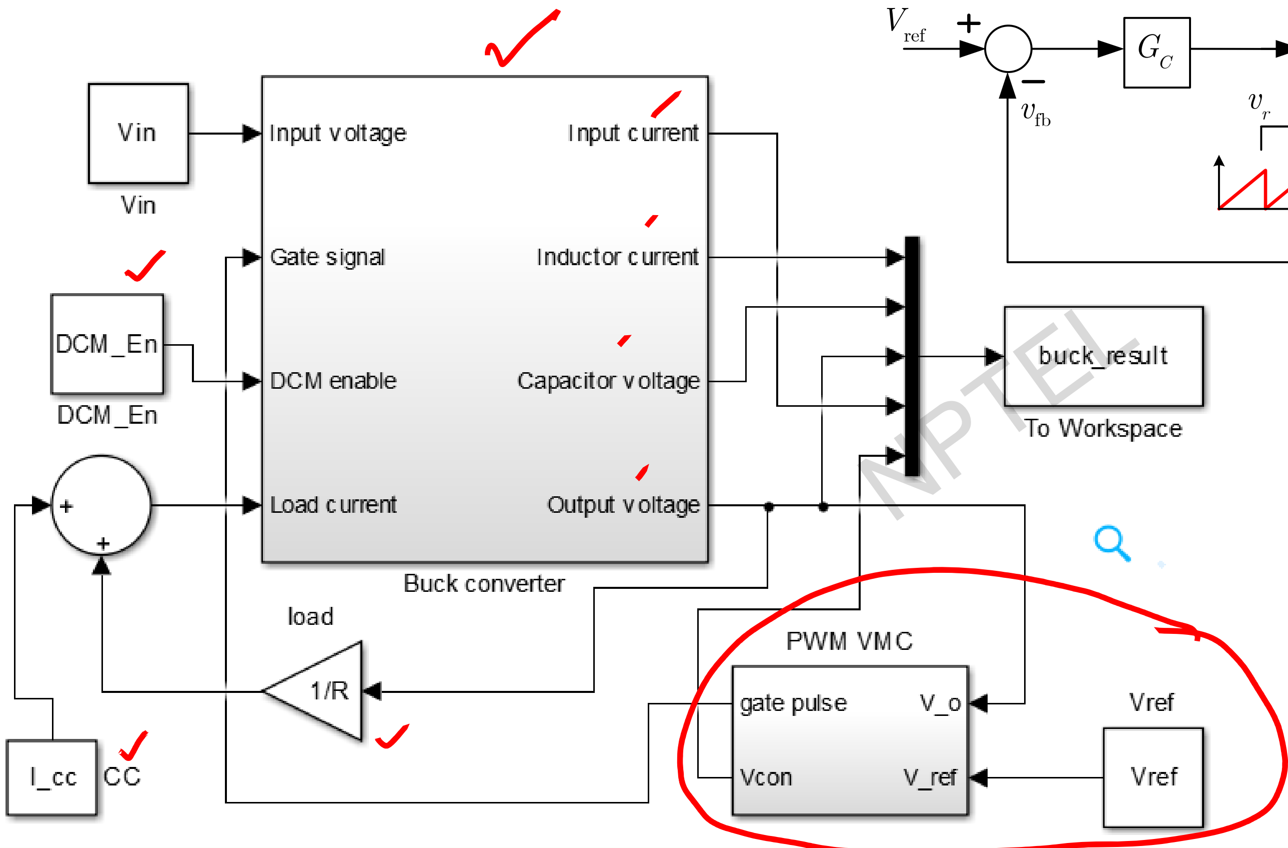
Trailing edge PWM

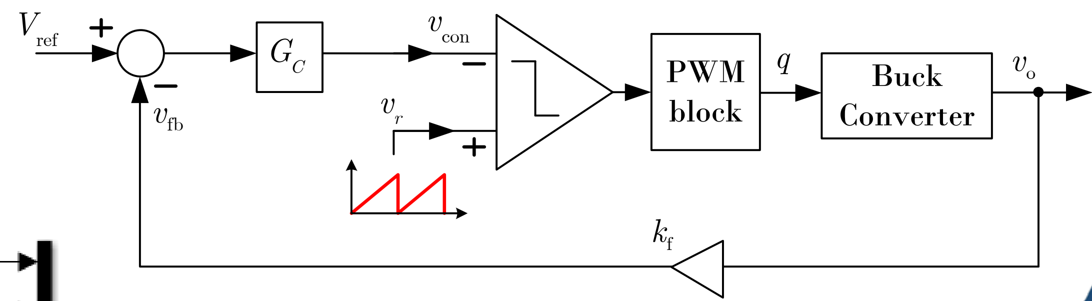
Voltage Mode Control (VMC) – A Start-up Case Study



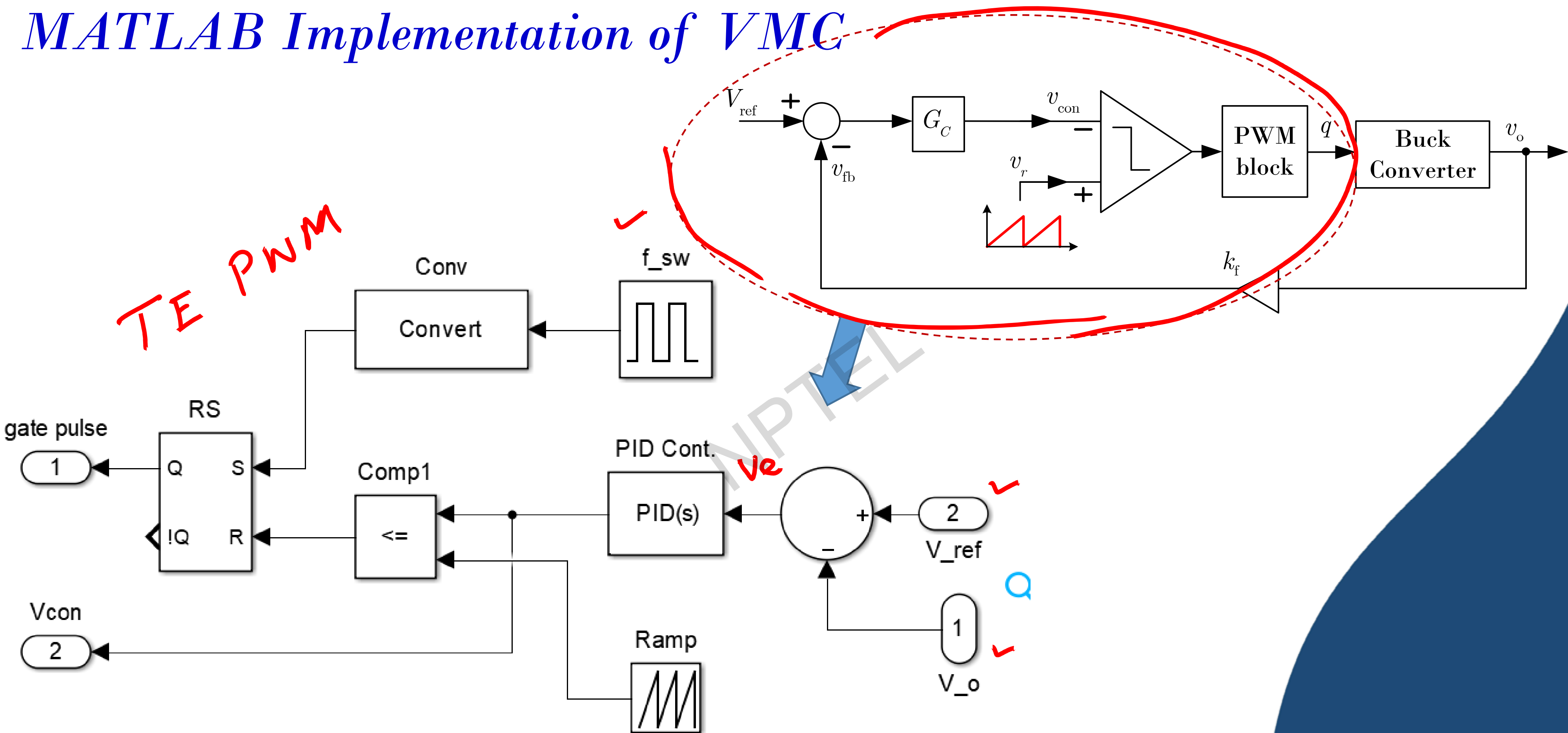
- Consider a PID controller $$G_C(s) = K_P + \frac{K_I}{s} + \frac{K_D s}{\tau_D s + 1}$$
- Implement VMC in MATLAB and simulate a start-up case study

MATLAB Implementation of VMC

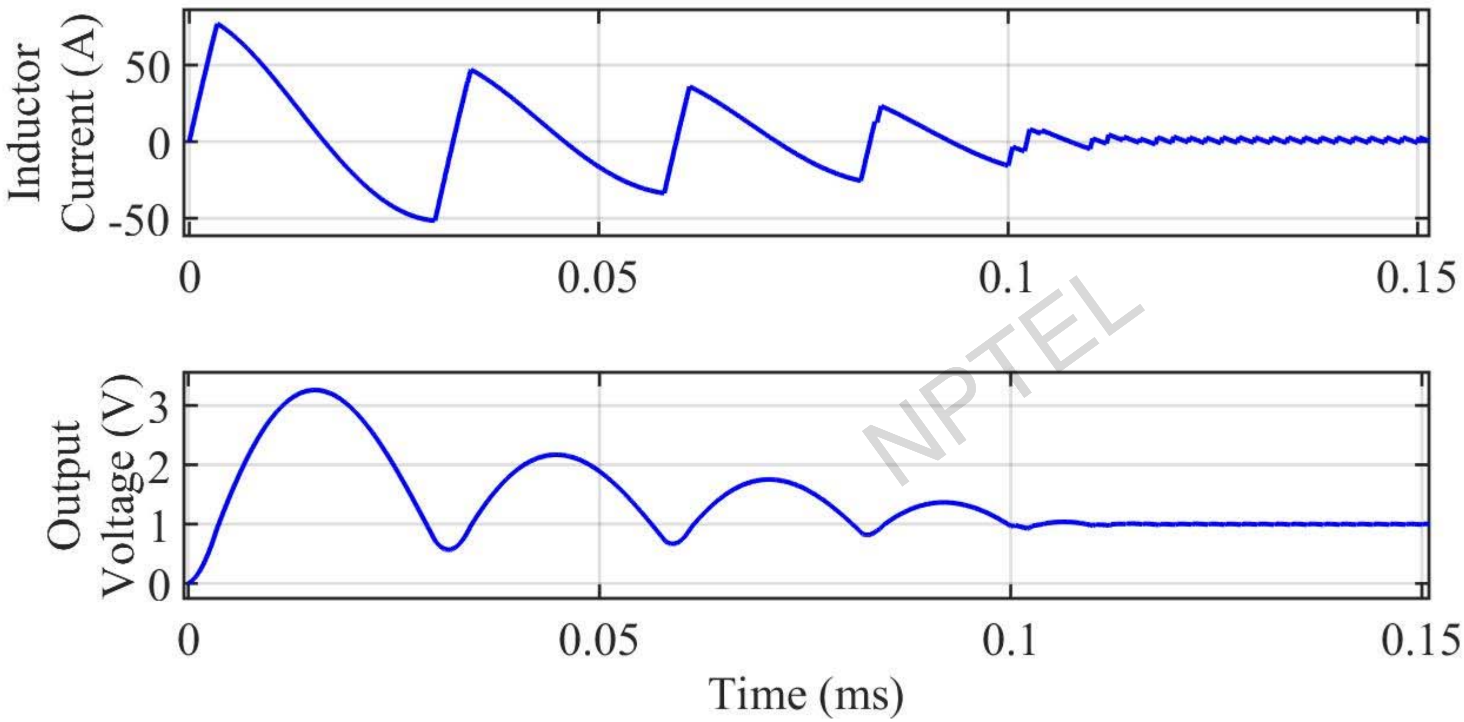




MATLAB Implementation of VMC



Simulating a Start-up Case Study under VMC

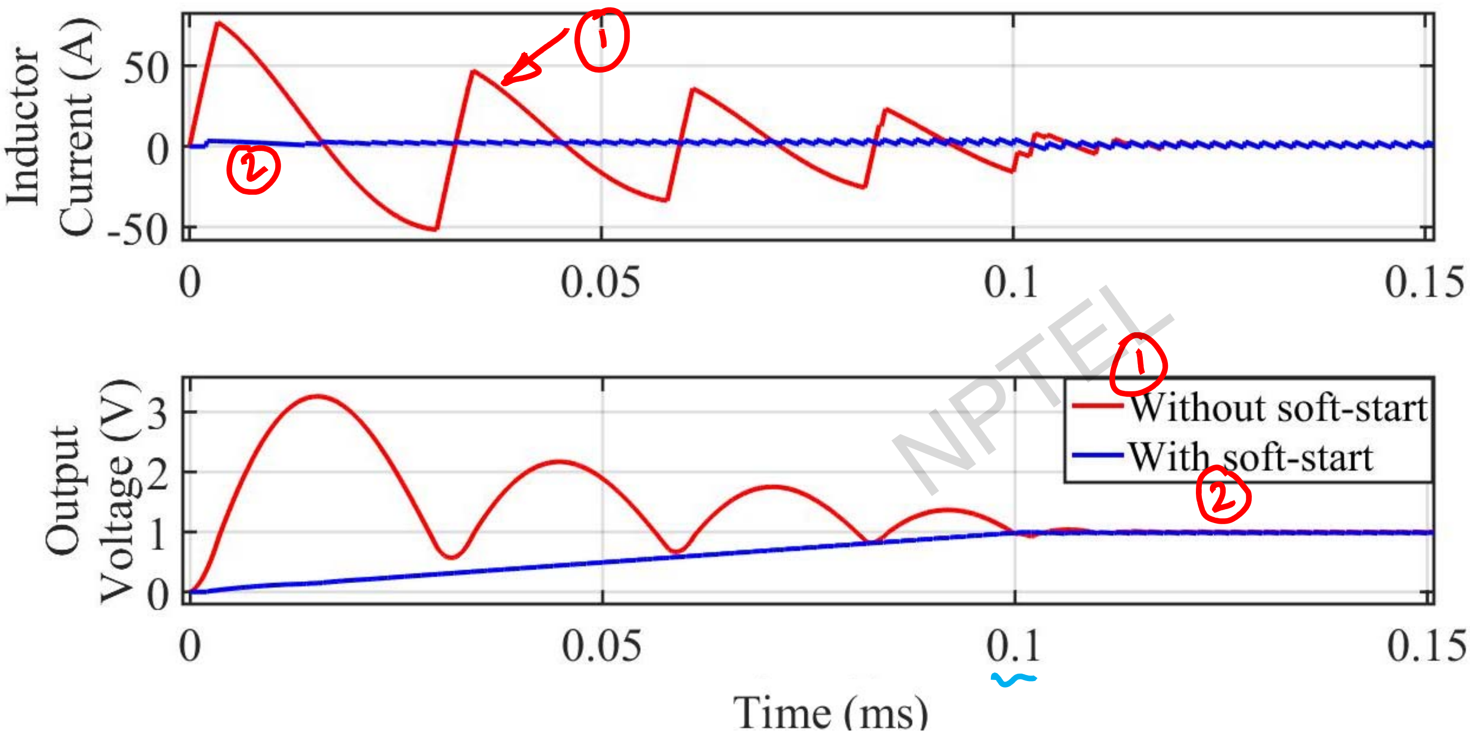


Vin=12; R=1; V_m=10; K_p=30; K_i=20000; K_d=0.04

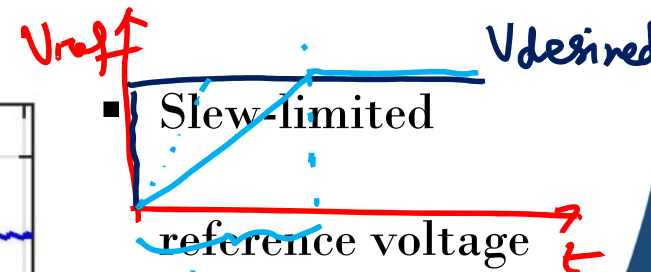
PID Controller – Functionality

PID Gain	Percentage Overshoot	Settling Time	Steady-state Error
Increasing K_P	Increases	Minimal impact	Decreases
Increasing K_I	Increases	Increases	Zero steady-state error
Increasing K_D	Decreases	Decreases	No impact

Simulating using a Soft-Start Logic in VMC



Vin=12; R=1; V_m=10; K_p=30; K_i=20000; K_d=0.04



- Slew-limited reference voltage

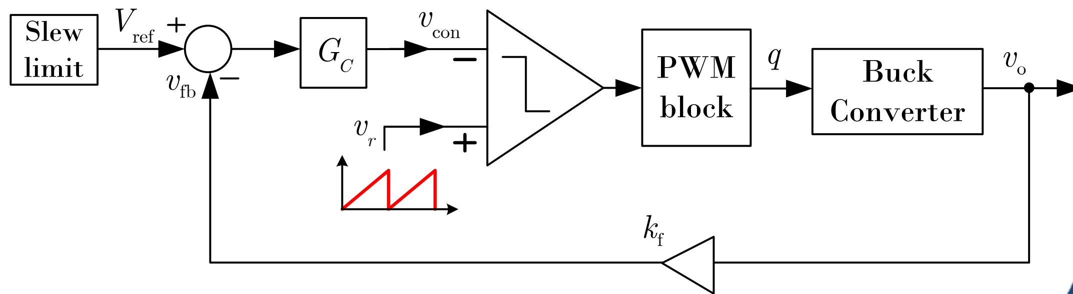
t_{slew}

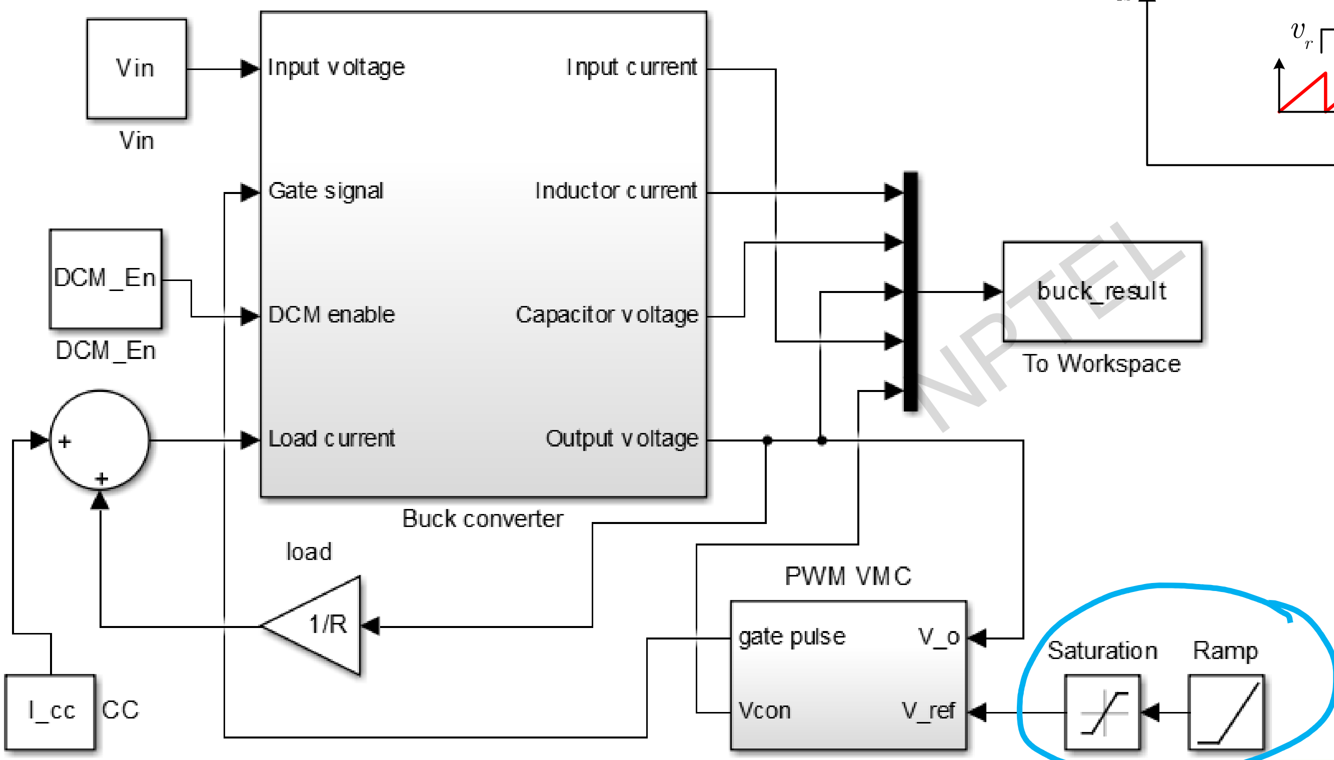
- Slew: 1 V/0.1 ms

slew rate $= \frac{V_{ref}}{t_{slew}}$

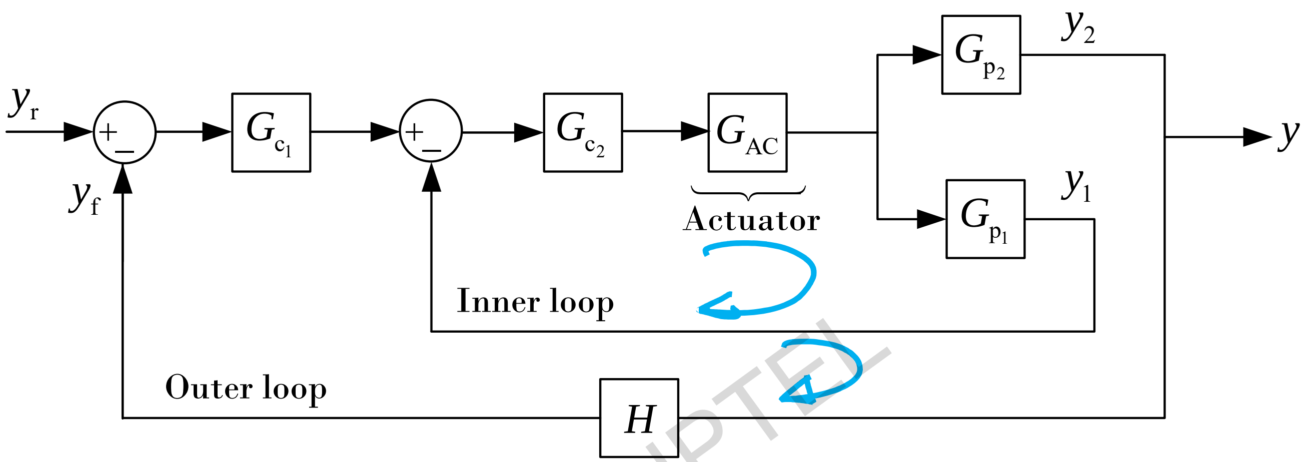
$\frac{1\ V}{0.1\ ms}$

MATLAB with Soft-Start in VMC





Basic Two Loop Output Feedback

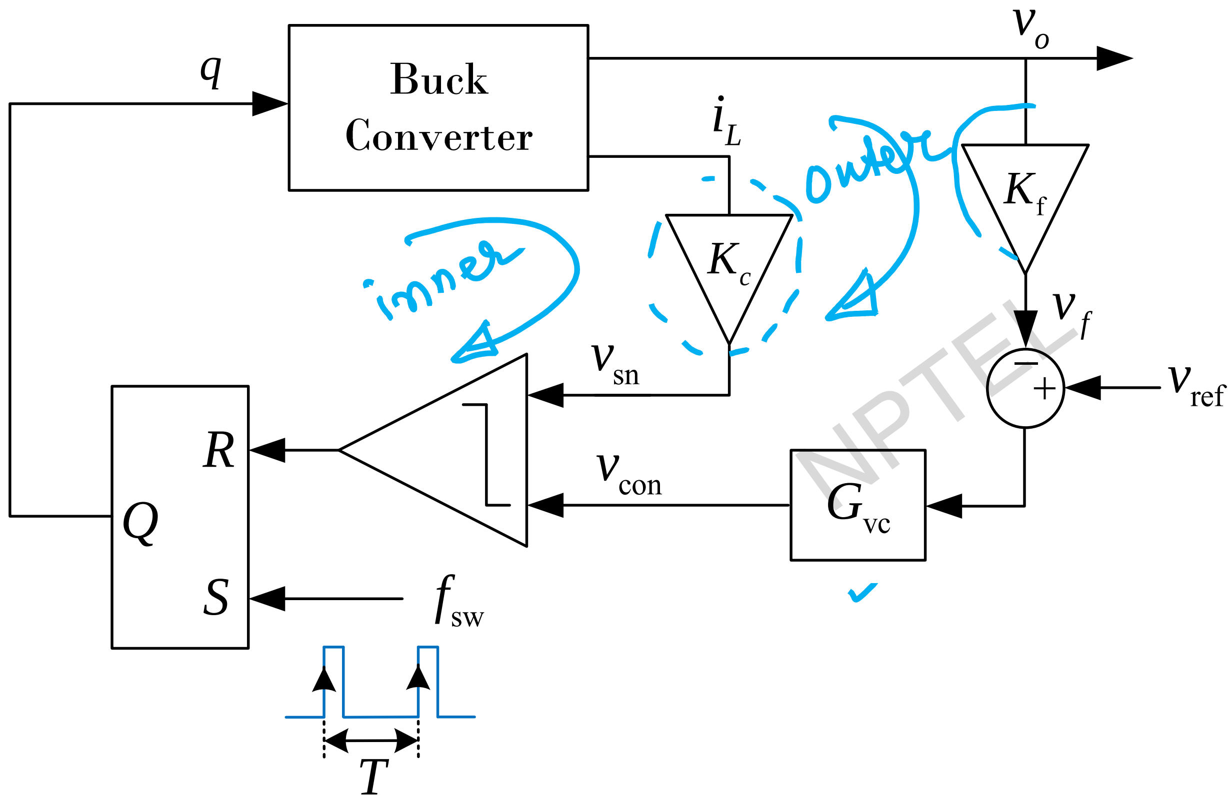


- Two loop control
- Master / slave control
- Cascade control

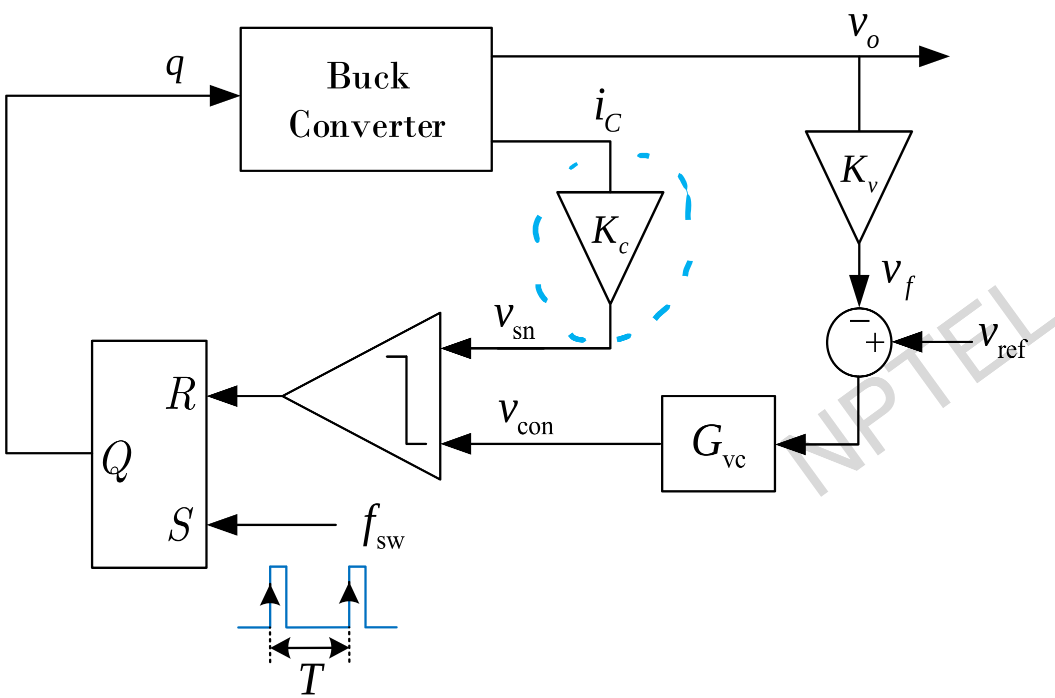
Two Loop Control in SMPC

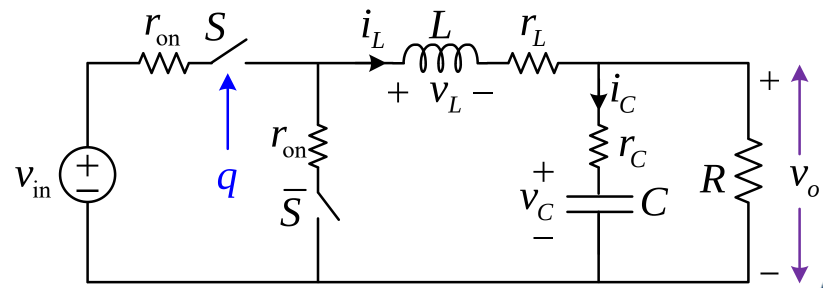
- Outer loop → generally (output) voltage loop
- Inner loop:
    - Inductor current
    - Capacitor current
    - Derivative of output voltage
    - Ripple output voltage

Current Mode Control

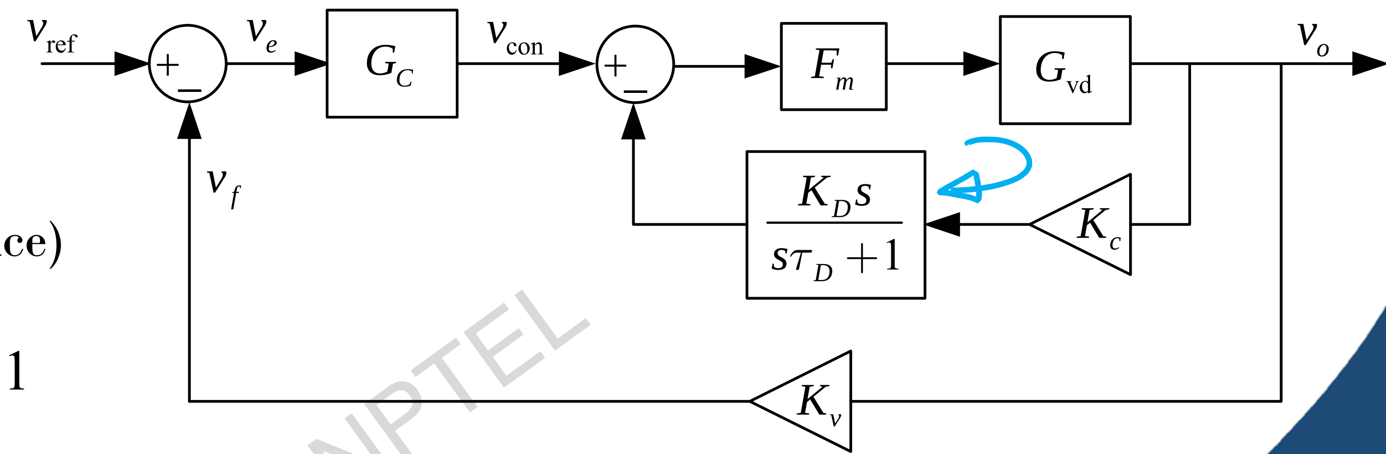


Capacitor current based Two Loop Control





Two loop Control using Voltage Derivative inner loop



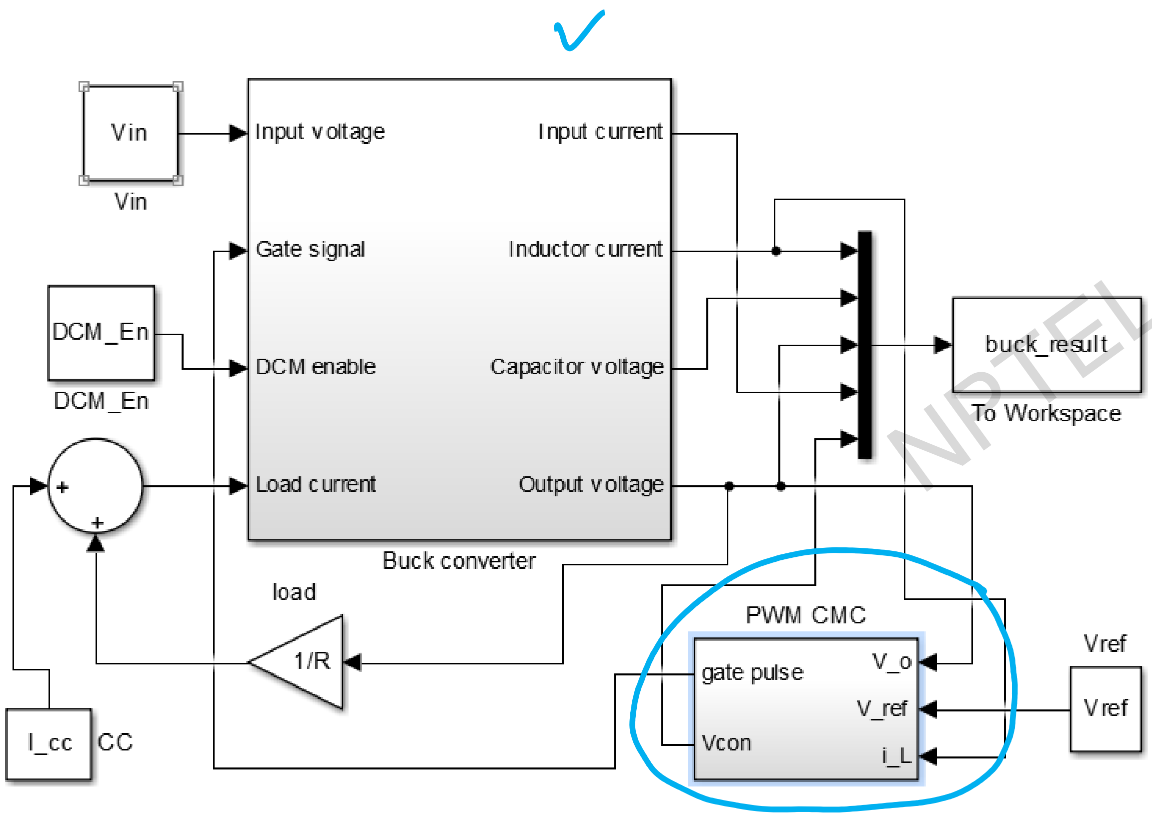
→ $K_D = C$

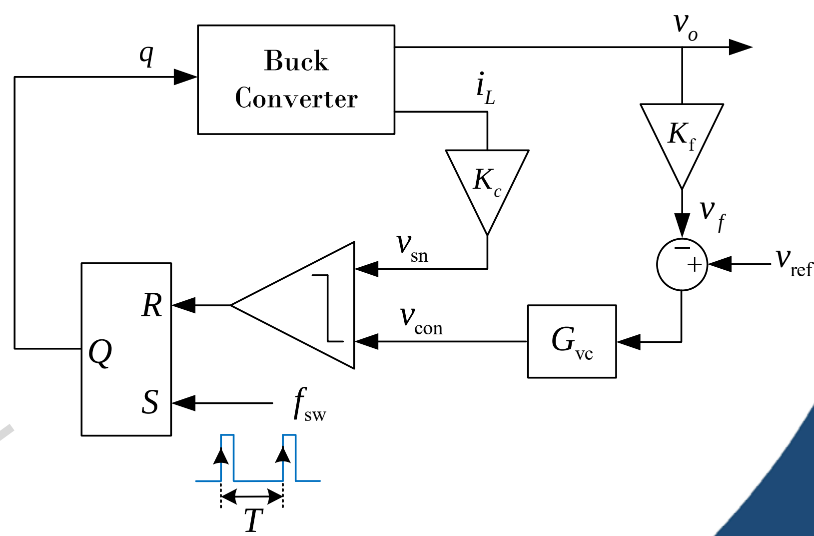
(Output Capacitance)

$$\tau_D = \frac{T}{50} \text{ (say)},\ K_c = 1$$

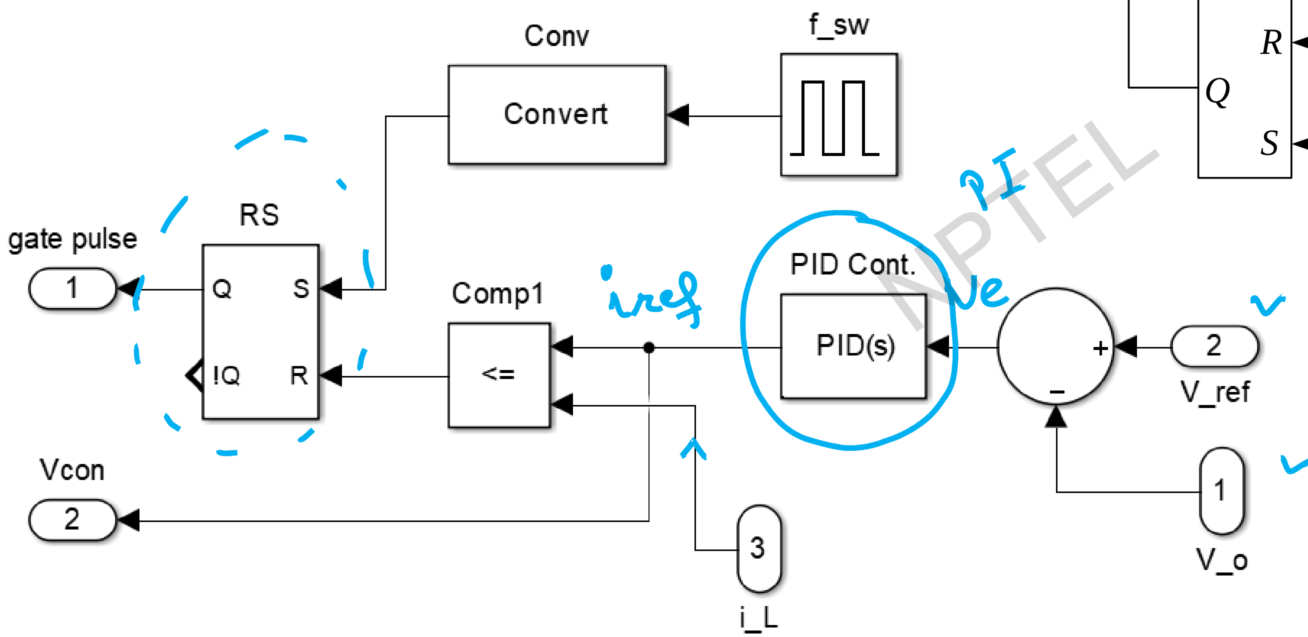
→ Use same voltage controller parameters as capacitor current and compare responses

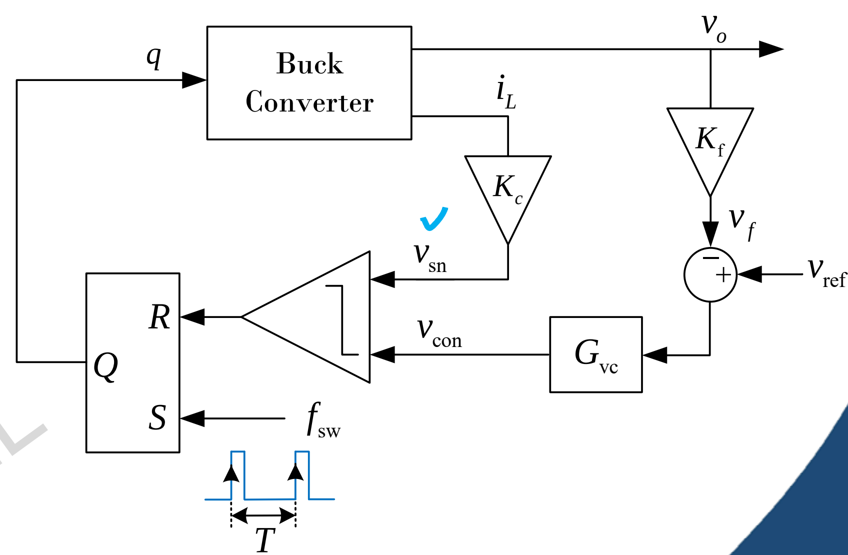
MATLAB – Current Mode Control



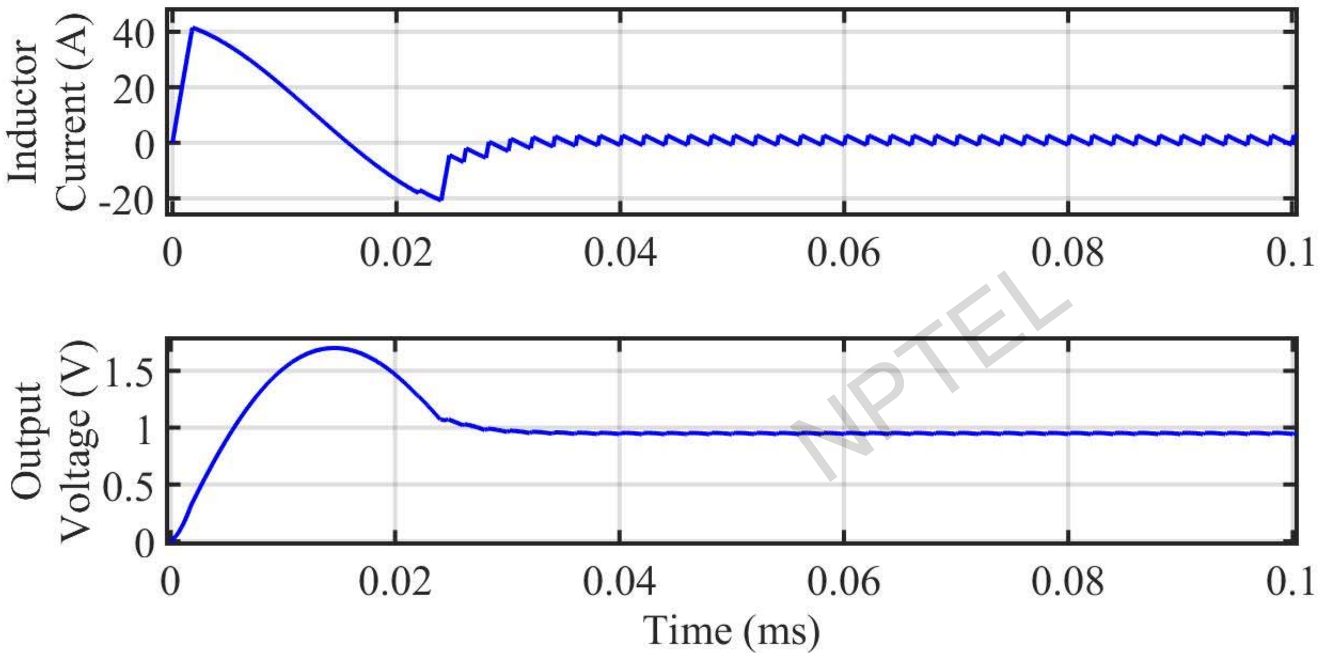


MATLAB – Current Mode Control





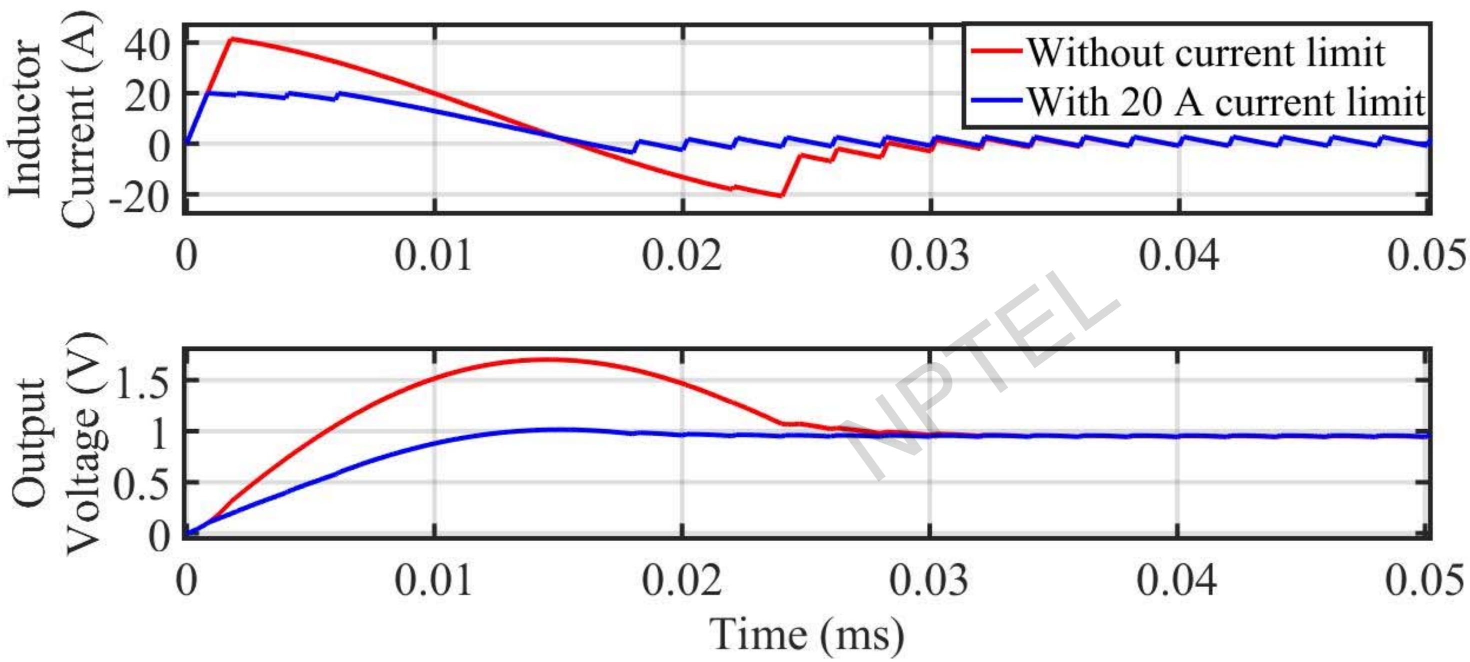
Simulating a Start-up Case Study under CMC



$$G_{vc}(s) = K_P + \frac{K_I}{s}$$

Vin=12; R=1; K_p=60; K_i=20000

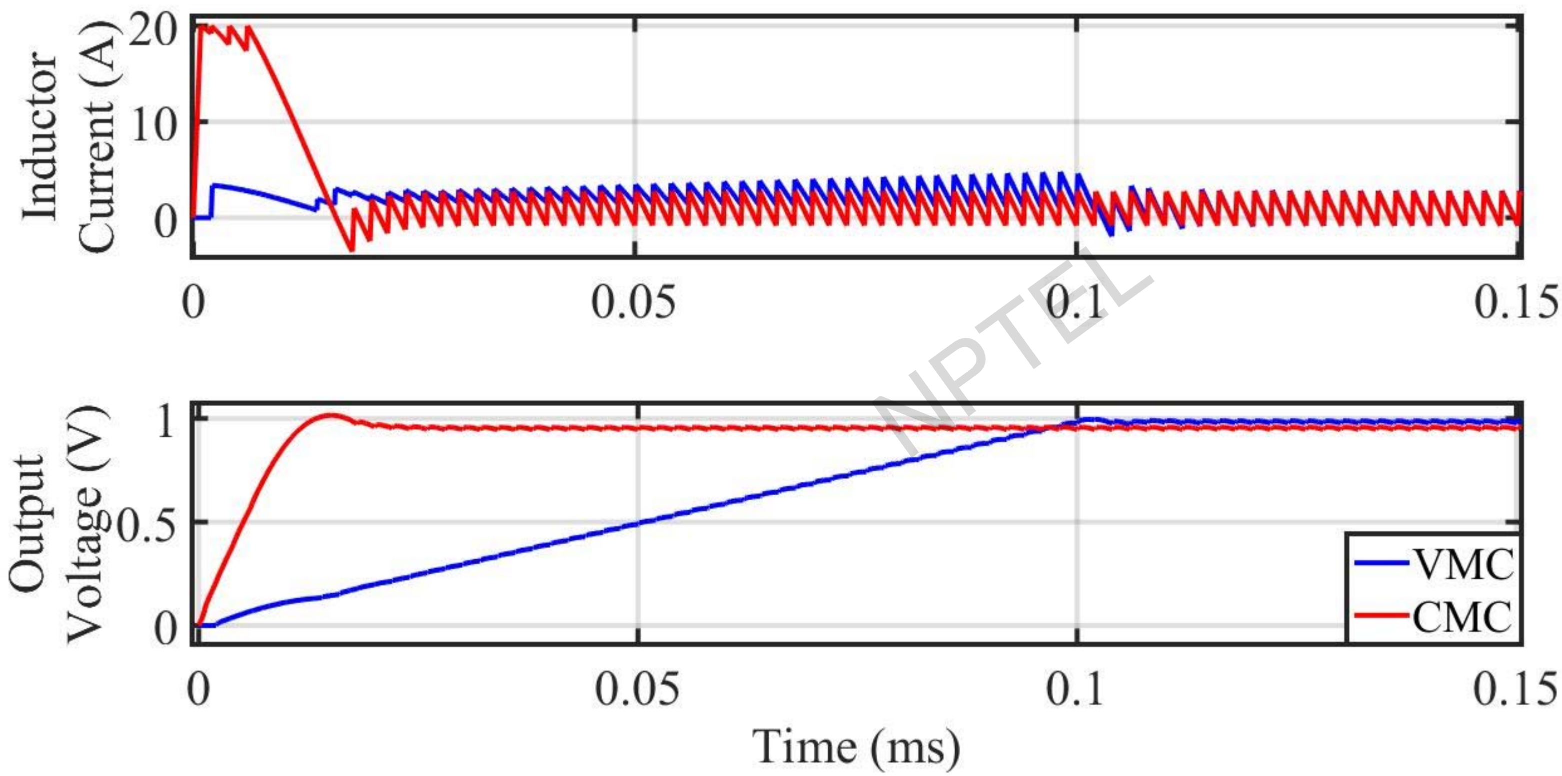
Simulating a Start-up with Current Limit under CMC



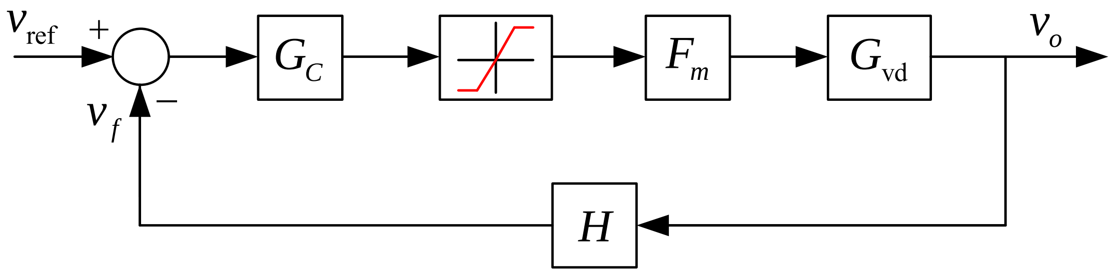
$$G_{vc}(s) = K_P + \frac{K_I}{s}$$

Vin=12; R=1; K_p=60; K_i=20000

Strat-up Logic Comparison – VMC vs. CMC



Limitations of Single Loop VMC



Single Loop Control

- No control over current !!!
- Compensation sensitive to operating conditions
- Fault protection and start-up logics separately needed
- Difficult to optimize transient and start-up performance

Advantages of Two-Loop CMC

- Possibility of reduced-order system dynamics using time-scale separation
- Simplified controller design with improved robustness
- Higher bandwidth can be achieved without compromising phase margin
- But, sensor requirement increases in current based implementation
- Existence of sub-harmonic instability over wide duty ratio range

Summary

- Fixed-frequency single loop control – discussed
- Fixed-frequency two loop control methods – discussed
- MATLAB based implementation – demonstrated
- Advantages/limitations of feedback control methods – discussed

THANK YOU !

NPTEL ONLINE CERTIFICATION COURSES

CONTROL AND TUNING METHODS IN SMPCs

Dr. Santanu Kapat
Electrical Engineering Department, IIT KHARAGPUR

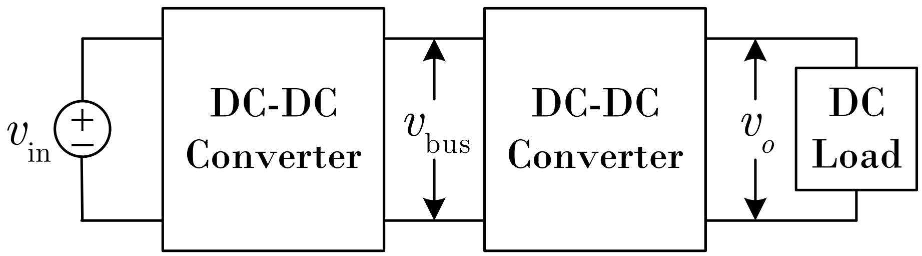
Module 03: Fixed Frequency Control Methods

Lecture 16: Feedback Control of Cascaded SMPCs

Concepts Covered

- Cascaded converter – intermediate bus architecture
- Concept of constant power load
- Instability and limit cycle oscillation
- Feedback control for active damping

Cascaded Converters and Applications



<u>Examples</u>

- LED driving

$$v_{\text{in}} = 12\,\text{V}$$
$$v_{\text{bus}} \in [30, 48]\,\text{V}$$
$$v_o = 12\,\text{V}$$

Head lamp load

- Data center

$$v_{\text{in}} = 48\,\text{V}$$
$$v_{\text{bus}} \in [6, 18]\,\text{V}$$
$$v_o = 1\,\text{V}$$

48
12
1

Processor load

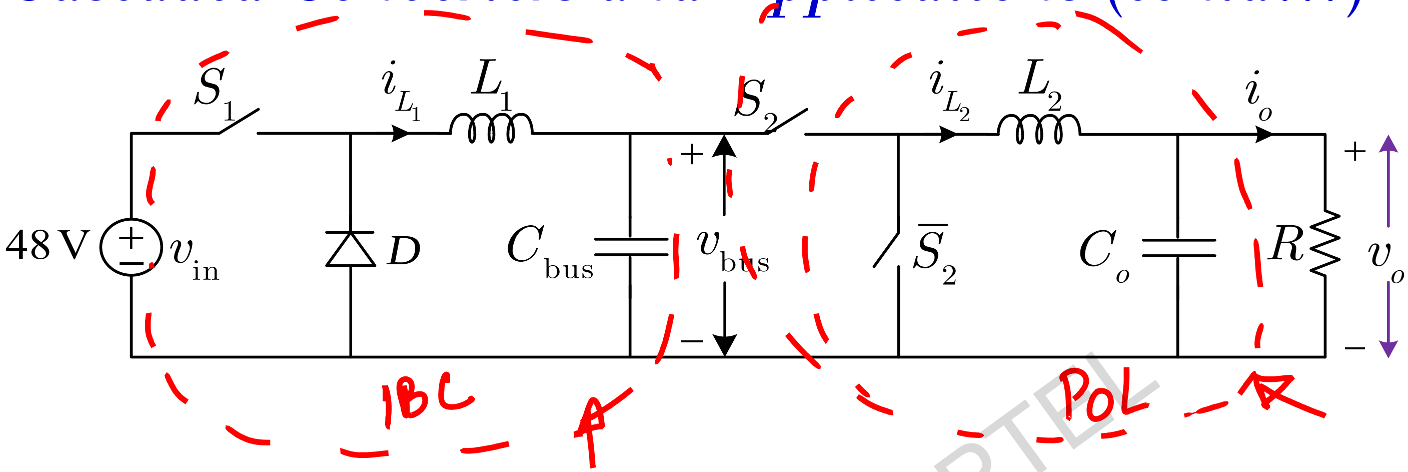
Cascaded Converters and Applications (contd…)

- Consider the data center example

  (intermediate bus architecture)

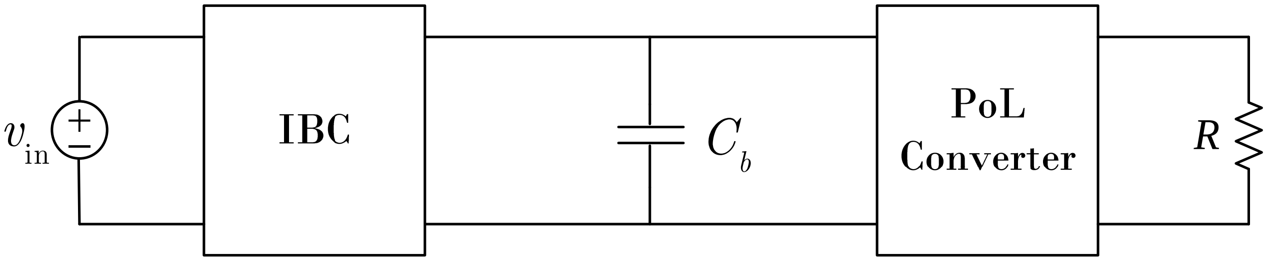
- Two cascaded buck converters
  - Input side buck → known as intermediate bus converter (IBC)
  - Output side buck → known as point of load (PoL) converter

Cascaded Converters and Applications (contd…)



- Use earlier simulation models of a conventional buck converter and a synchronous buck converter
- Configure the above files to show a cascaded converter

Dynamics of Cascaded Converter



High voltage, low current

Need to be efficient
and reliable

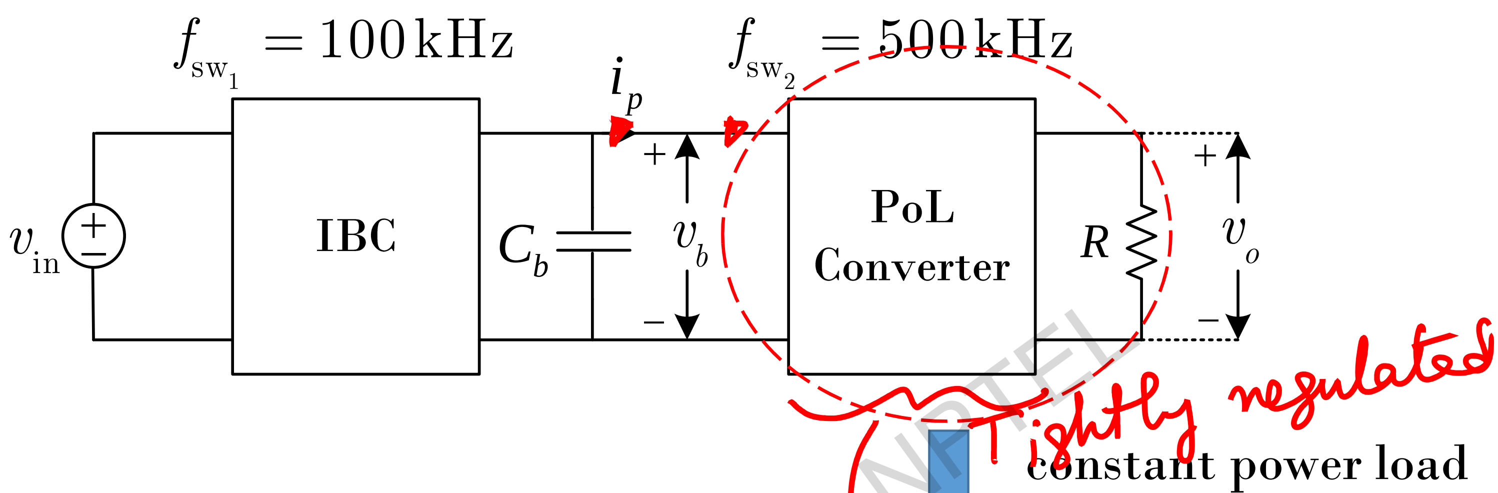
Operates at a relatively
lower switching frequency

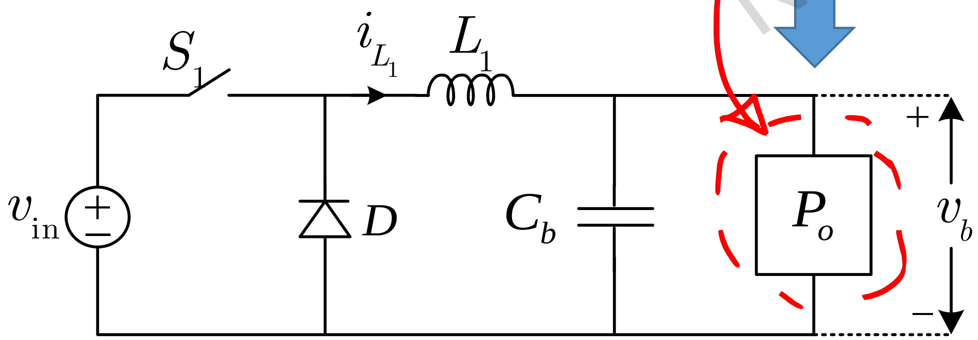
Low voltage, high current

Need to be very fast to meet
stringent performance requirement

Operates at a much higher
switching frequency

Constant Power Load



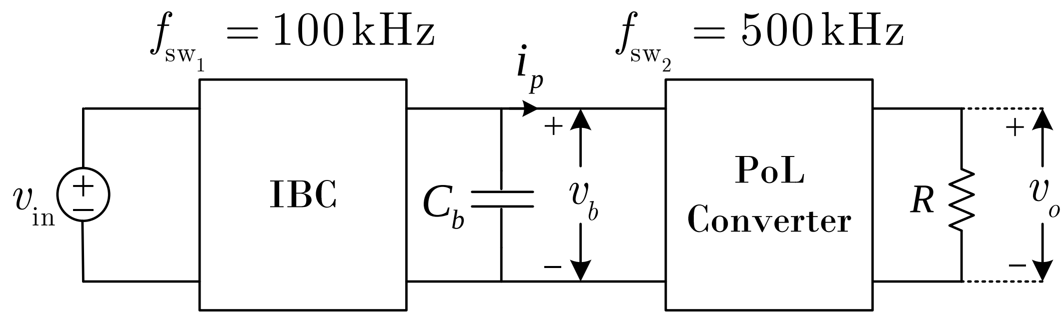


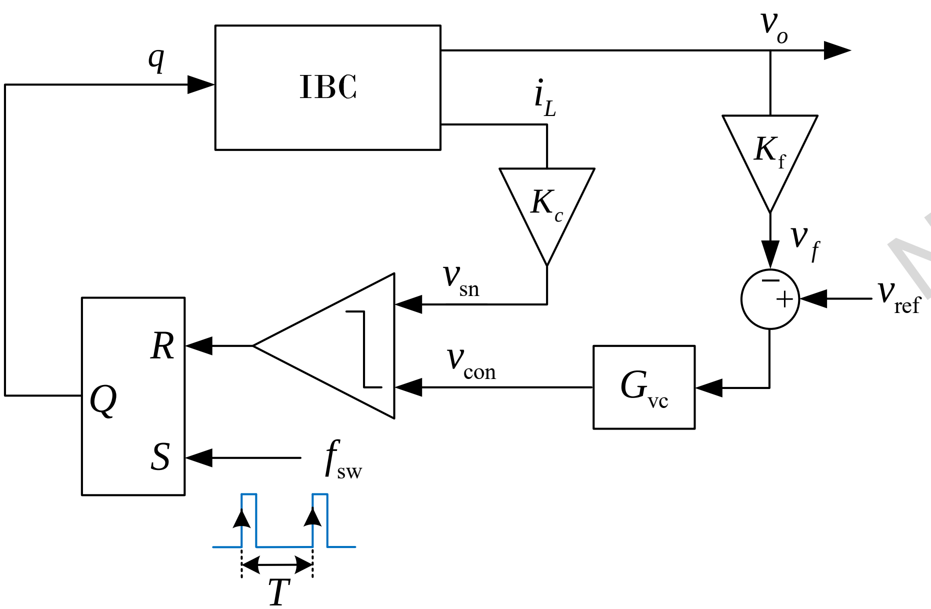
Simulation Case Study

- Case 1:
  - Use two separate converters (IBC and PoL converter)
  - Operate IBC in open loop at $f_{\mathrm{sw}_1} = 100\,\mathrm{kHz}$
  - Operate PoL converter under CMC at $f_{\mathrm{sw}_2} = 500\,\mathrm{kHz}$

- Case 2:
  - Keep the same IBC configuration
  - Replace PoL converter using a CPL where $P_o = v_o i_o$

Current Mode Control of IBC





Summary

- Cascaded dc-dc converters – Plug and play MATLAB model
- Origin of constant power load
- Nature of damping and existence of limit cycle oscillations
- Active damping using current mode control

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योगः कर्मसु कौशलम्

THANK YOU !

NPTEL ONLINE CERTIFICATION COURSES

CONTROL AND TUNING METHODS IN SMPCs

Dr. Santanu Kapat
Electrical Engineering Department, IIT KHARAGPUR

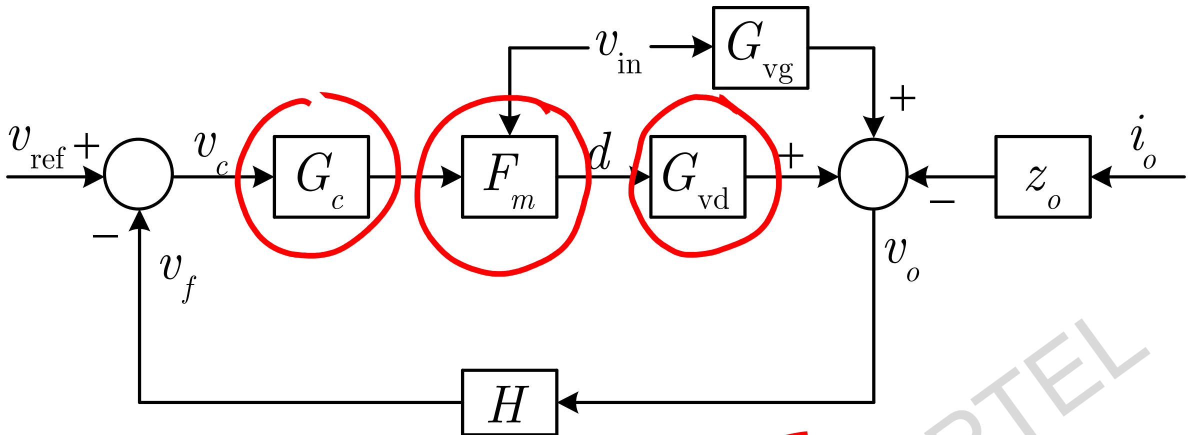
Module 03: Fixed Frequency Control Methods

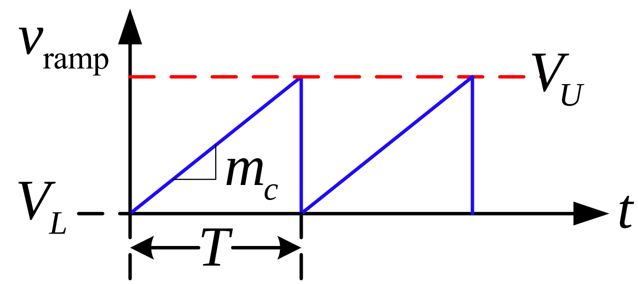
Lecture 17: Combined feedback/feedforward control

Concepts Covered

- Input voltage feedforward in VMC
- Load current feedforward in CMC
- Droop control and applications

Input Voltage Feedforward in VMC

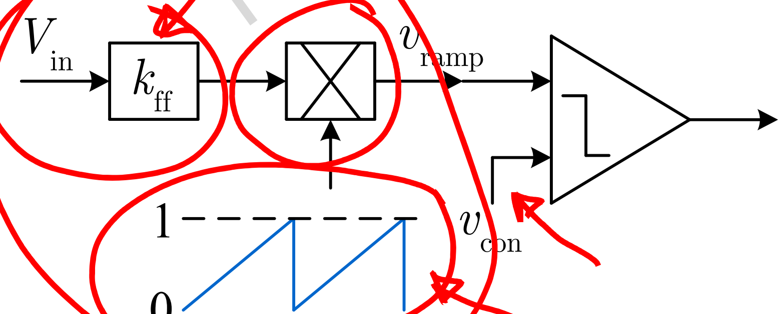




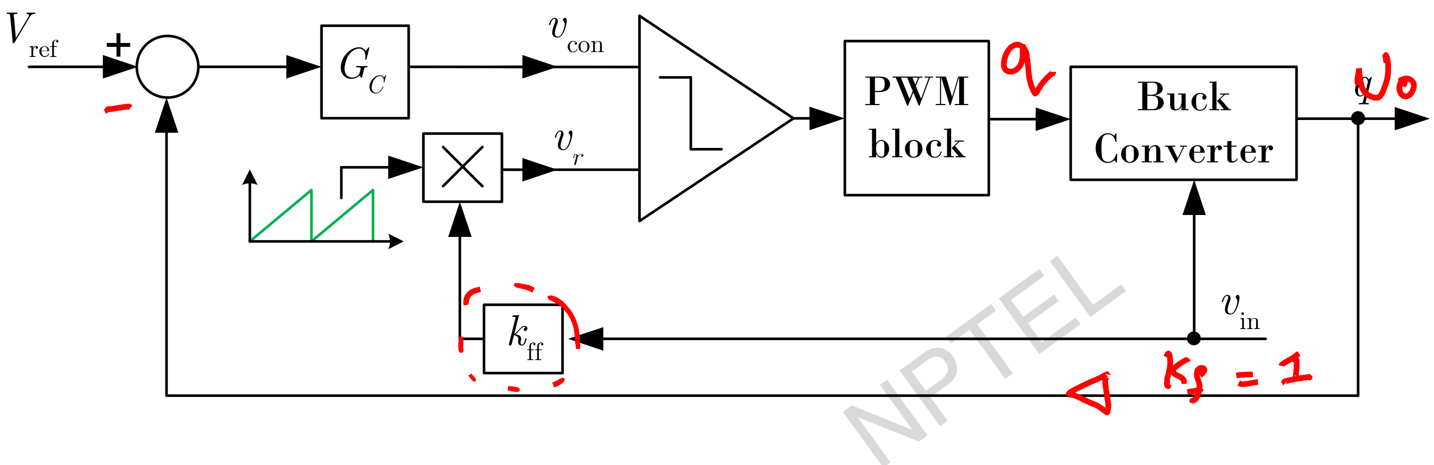
$$V_U = k_{ff} V_{in}$$

$$F_m = \left(\frac{1}{m_c T}\right)$$

$$m_c = \frac{V_U - V_L}{T}$$



Input Voltage Feedforward in VMC



- Simulate Line Transient Response with and without feedforward

Simulate DC-DC converter

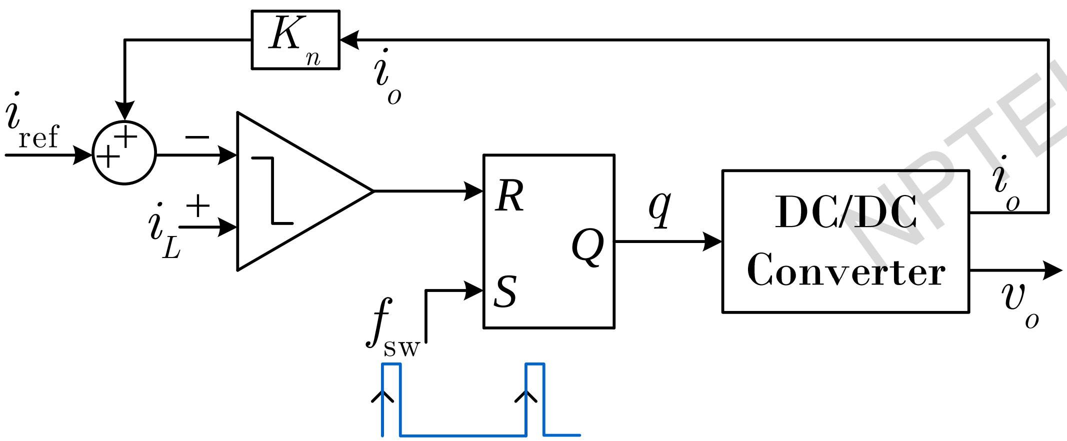
- Without feedforward
- With feedforward

$\left.\begin{array}{l} \text{Without feedforward} \\ \text{With feedforward} \end{array}\right\}$ Under VMC

- Show that CMC offers inherent input voltage feedforward by virtue of using inductor current

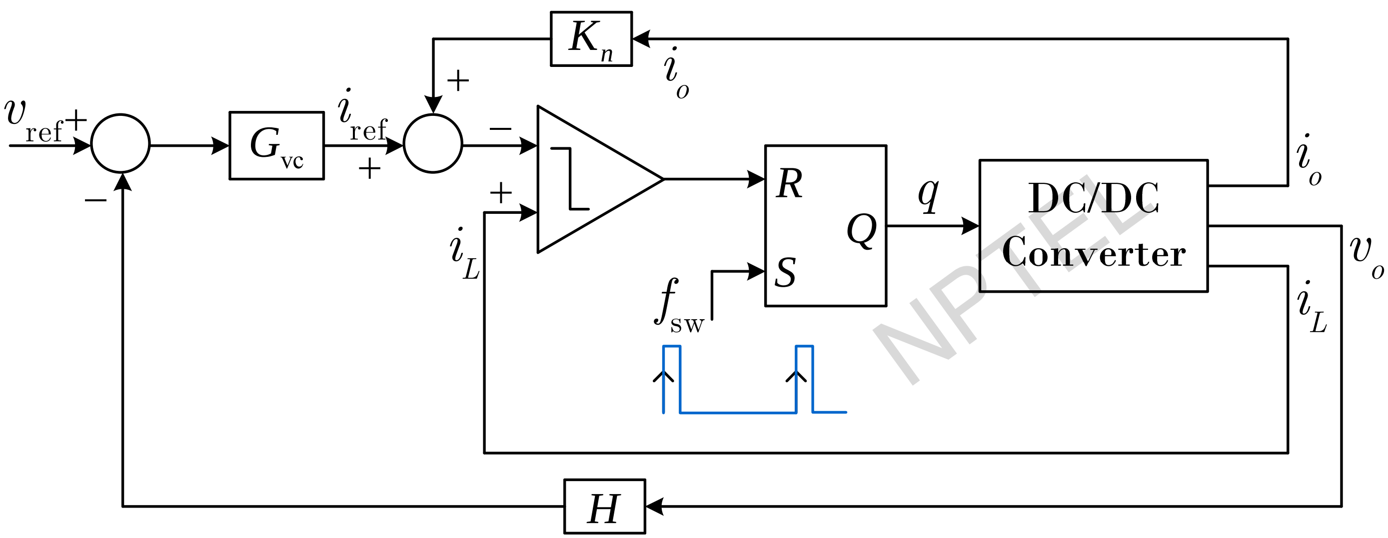
Load Current Feedforward in CMC

<u>Open outer-loop</u>

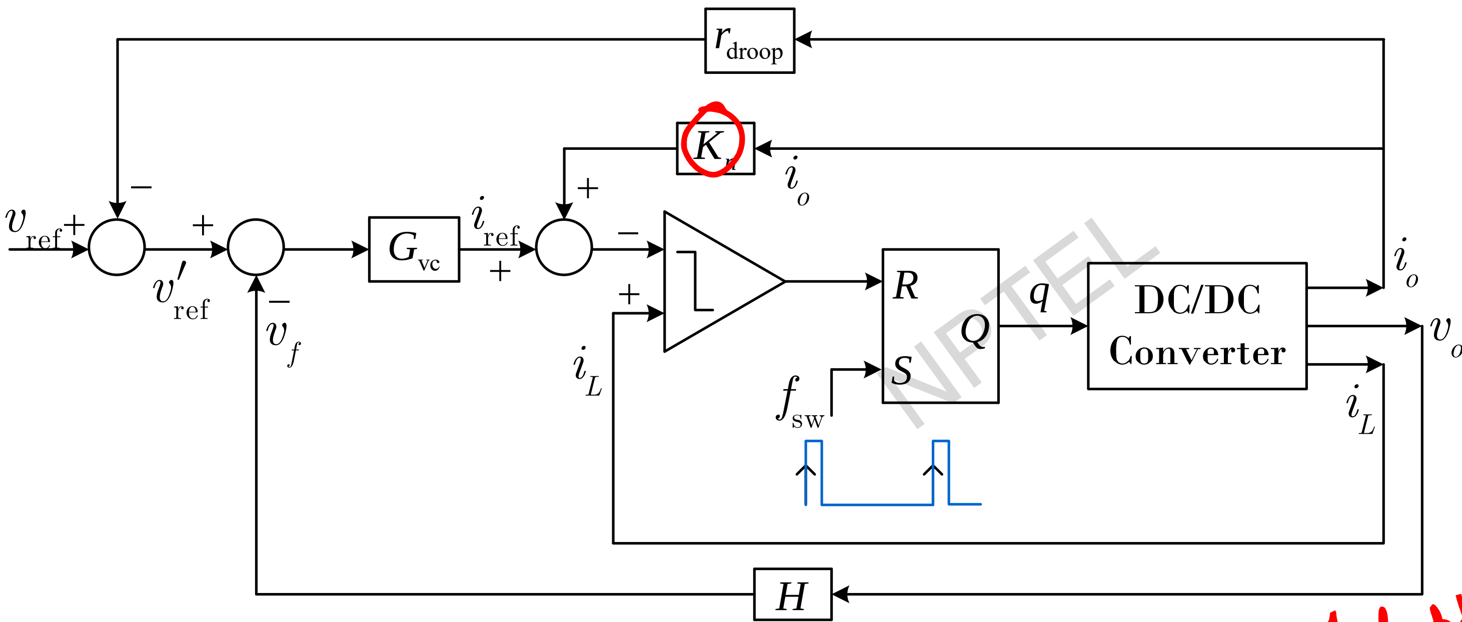


Load Current Feedforward in CMC

Step 1



Step 2



$k_n = 1$ buck

$k_n = \frac{V_{mf}}{V_{in}}$ boost

AVP → Adaptive voltage positioning

Droop Control and Applications

Cut down transient effect

Reduces current overshoot undershoot

- Adaptive voltage positioning in VRM application
- Nearly resistive output impedance
- DC microgrid applications
- Energy optimization in IBA

Summary

- Combined feedback and feedforward control offers excellent disturbance rejection and fast transient performance
- Suitable circuits needed either to sense or estimate load current
- More design aspects to be discussed later

THANK YOU !

NPTEL ONLINE CERTIFICATION COURSES

CONTROL AND TUNING METHODS IN SMPCs

Dr. Santanu Kapat
Electrical Engineering Department, IIT KHARAGPUR

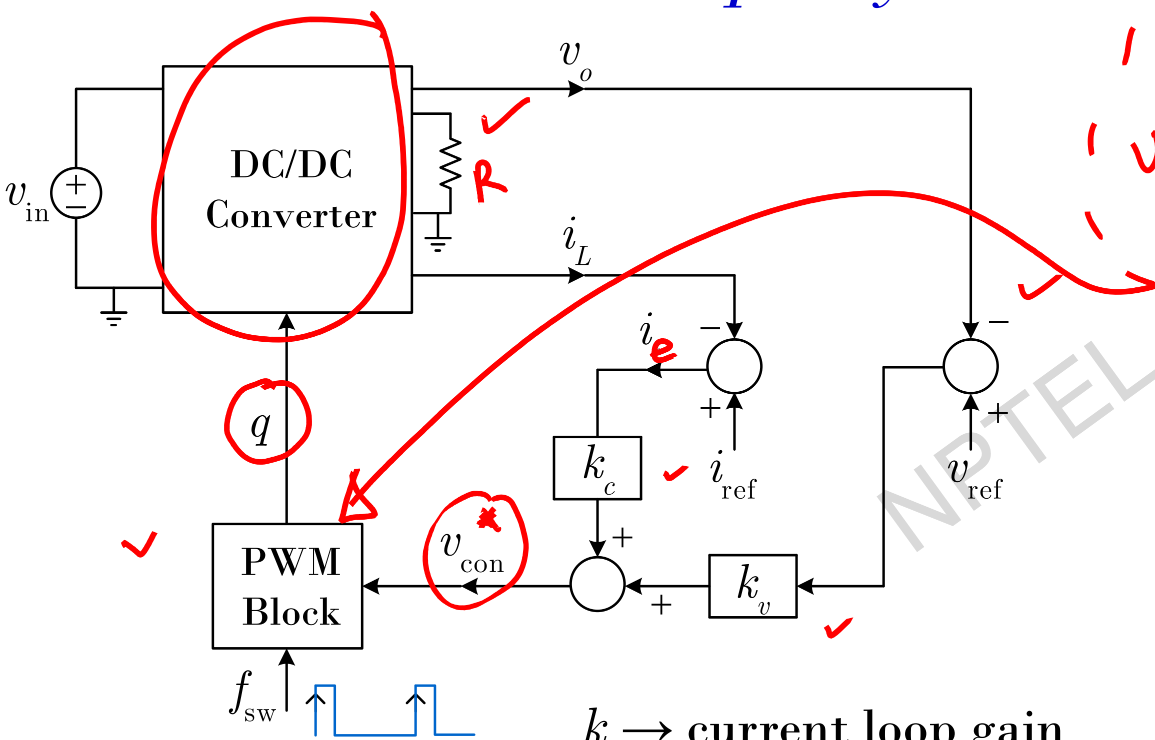
Module 03: Fixed Frequency Control Methods

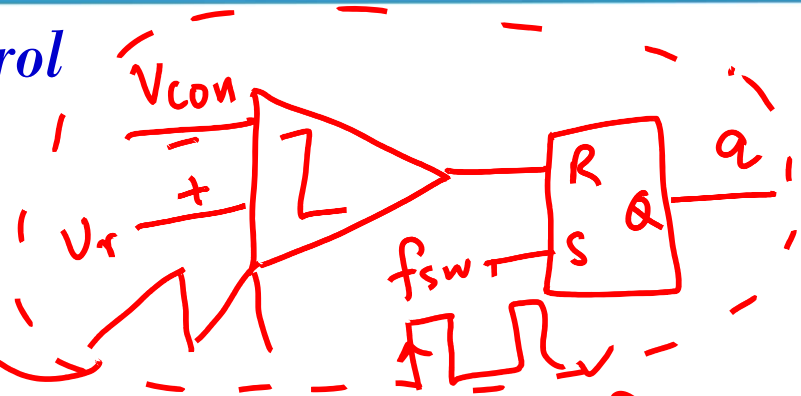
Lecture 18: State feedback control

Concepts Covered

- Implementation of state feedback PWM control
- Linking CMC and state feedback control
- Alternative form of state feedback
- Multivariable state feedback control in IBA
- Observer based state feedback control

State Feedback Fixed Frequency Control



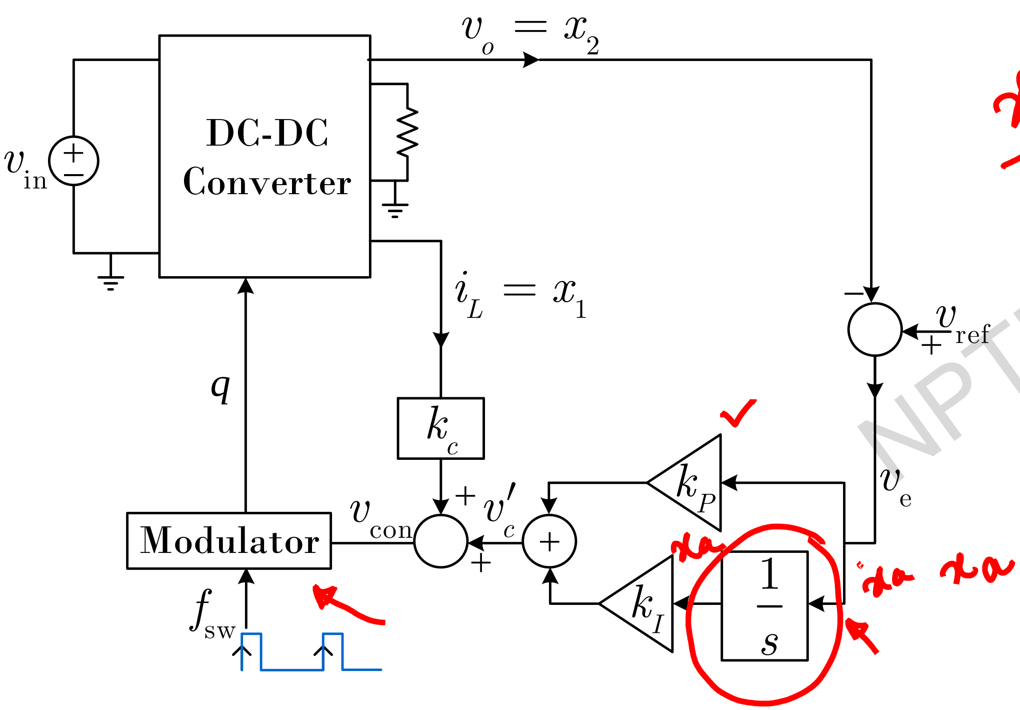


$$V_{con} = k_c(i_{ref} - i_L) + k_v(V_{ref} - V_o)$$

$k_c \rightarrow$ current loop gain

$k_v \rightarrow$ voltage loop gain

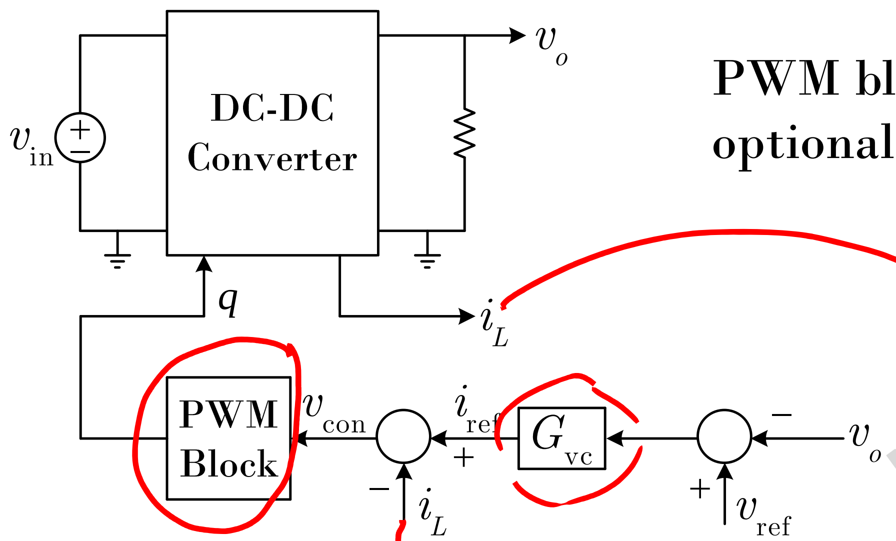
Augmented State Feedback Control



$\underline{x \in R^3}$

$\dot{x}_a = v_e$

Current Mode Control (CMC) Implementation



PWM block is added for optional ramp compensation

For a PI voltage controller

$$G_{vc} = k_{vp} + \frac{k_{vi}}{s}, \qquad i_{ref} = k_{vp}(v_{ref} - v_o) + k_{vi}\int (v_{ref} - v_o)\,dt$$

Analogy between state feedback control and CMC

State feedback control

$$v_{con} = k_v\left(v_{ref} - v_o\right) + k_c\left(i_{ref}^{*} - i_L\right)$$

Set

$$k_v = k_P; \quad k_c = 1$$

$$i_{ref}^{*} = k_I \int \left(v_{ref} - v_o\right) dt$$

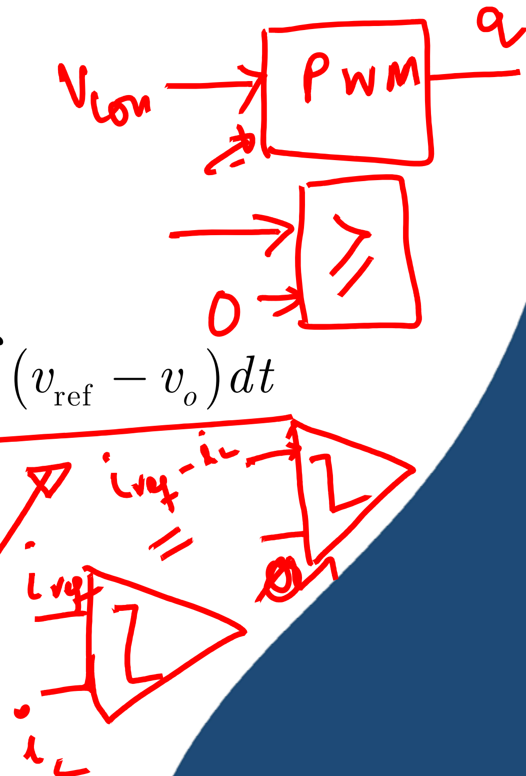
CMC

$$v_{con} = i_{ref} - i_L$$

$$i_{ref} = k_{vp}\left(v_{ref} - v_o\right) + k_{vi} \int \left(v_{ref} - v_o\right) dt$$

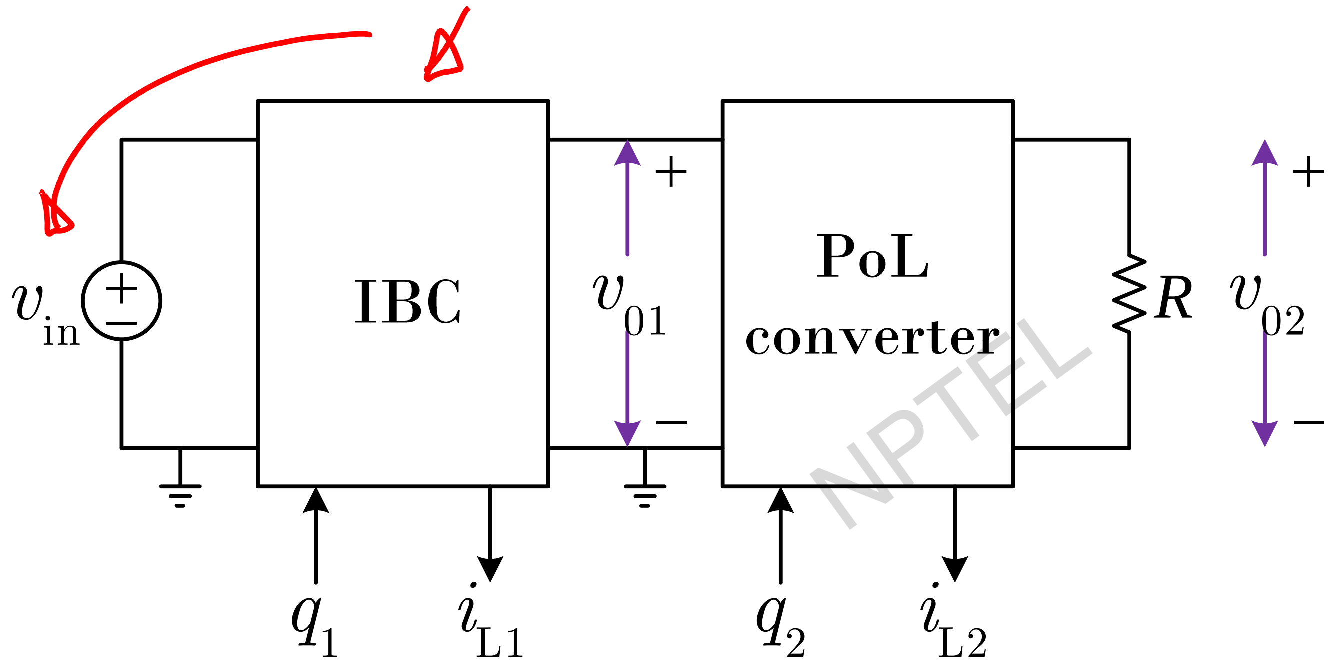
$$k_{vp} = k_P$$

$$k_{vi} = k_I$$

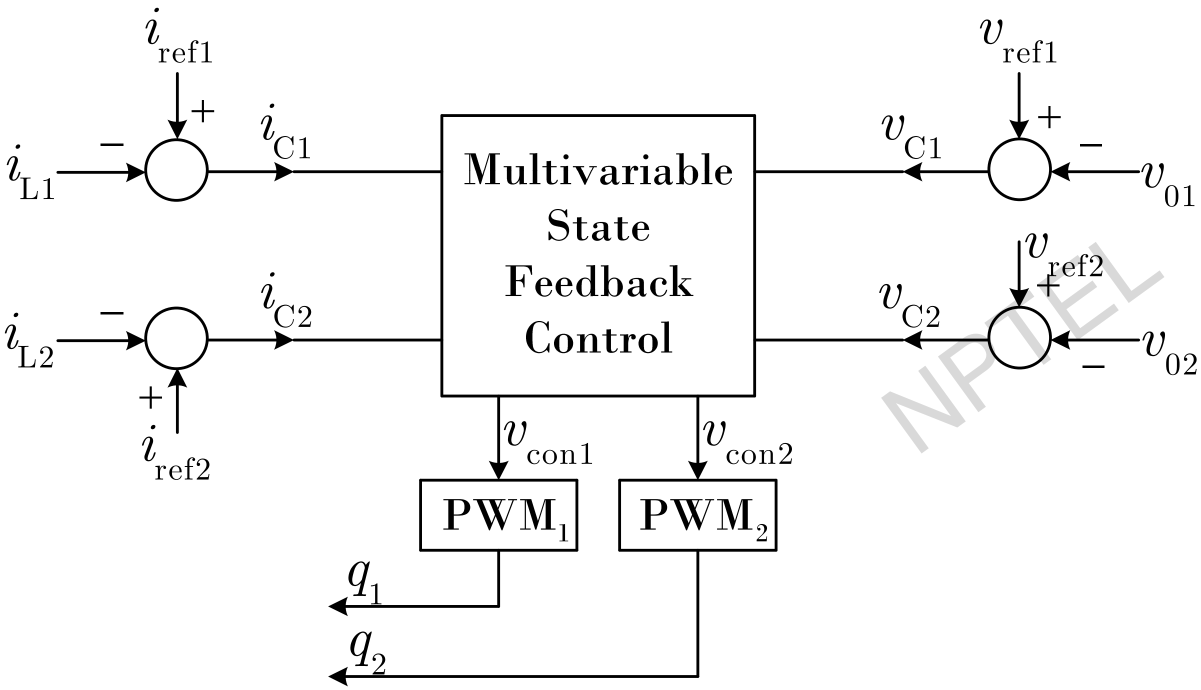


S. Kapat & P. Krein, "A Tutorial and Review Discussions …", *IEEE Open J. Power Electronics*

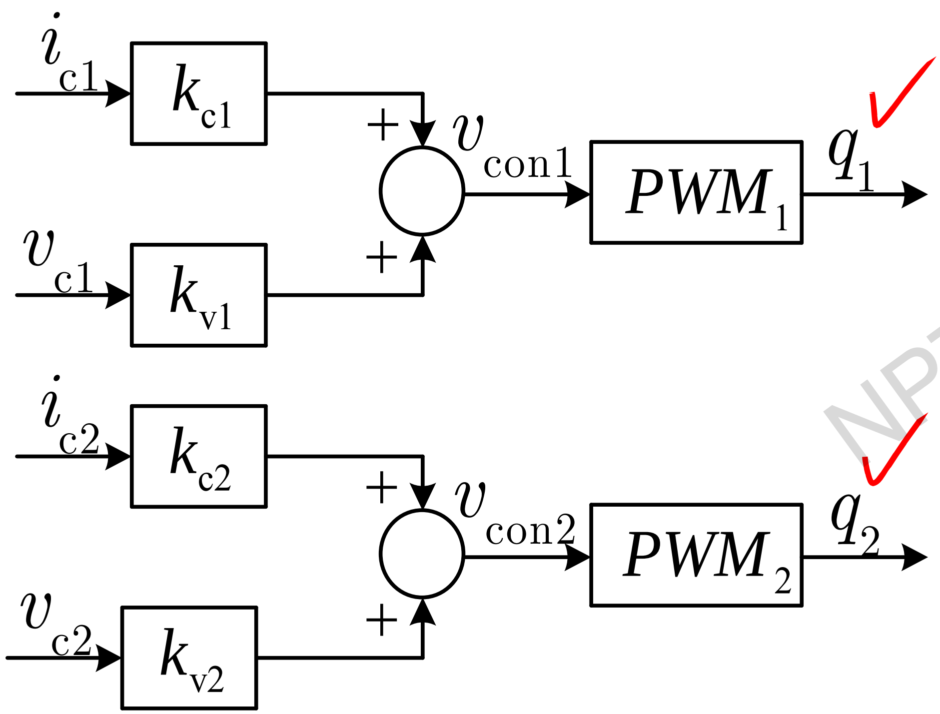
Multivariable State Feedback Control



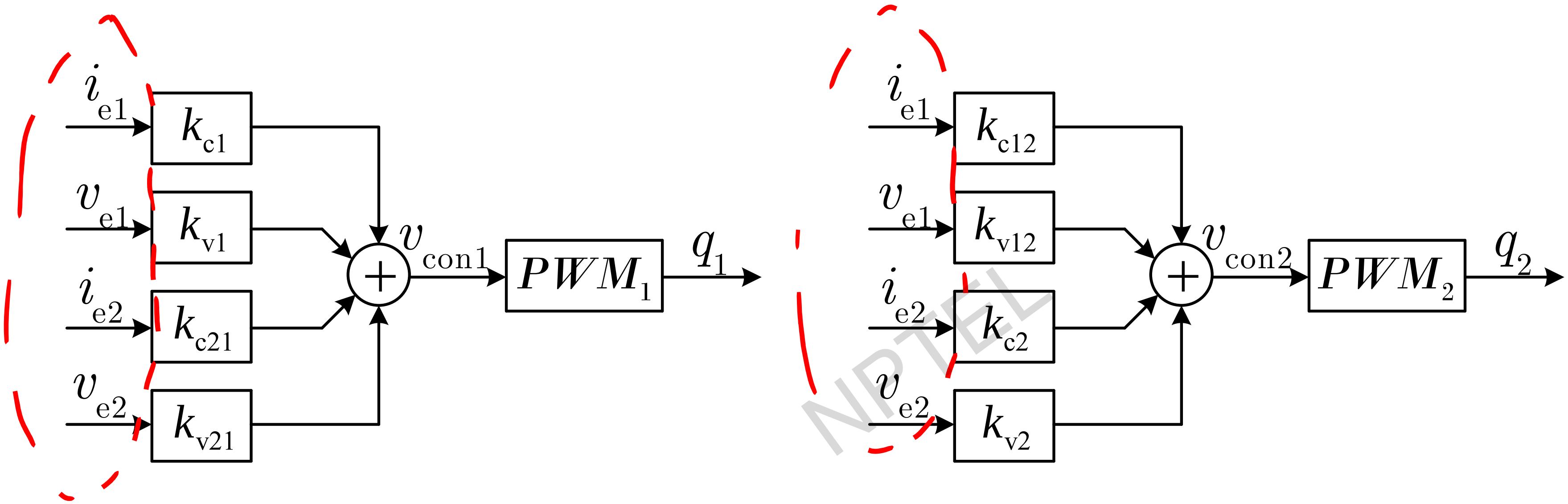
Multivariable State Feedback Control



Two Single Degree of Freedom Control



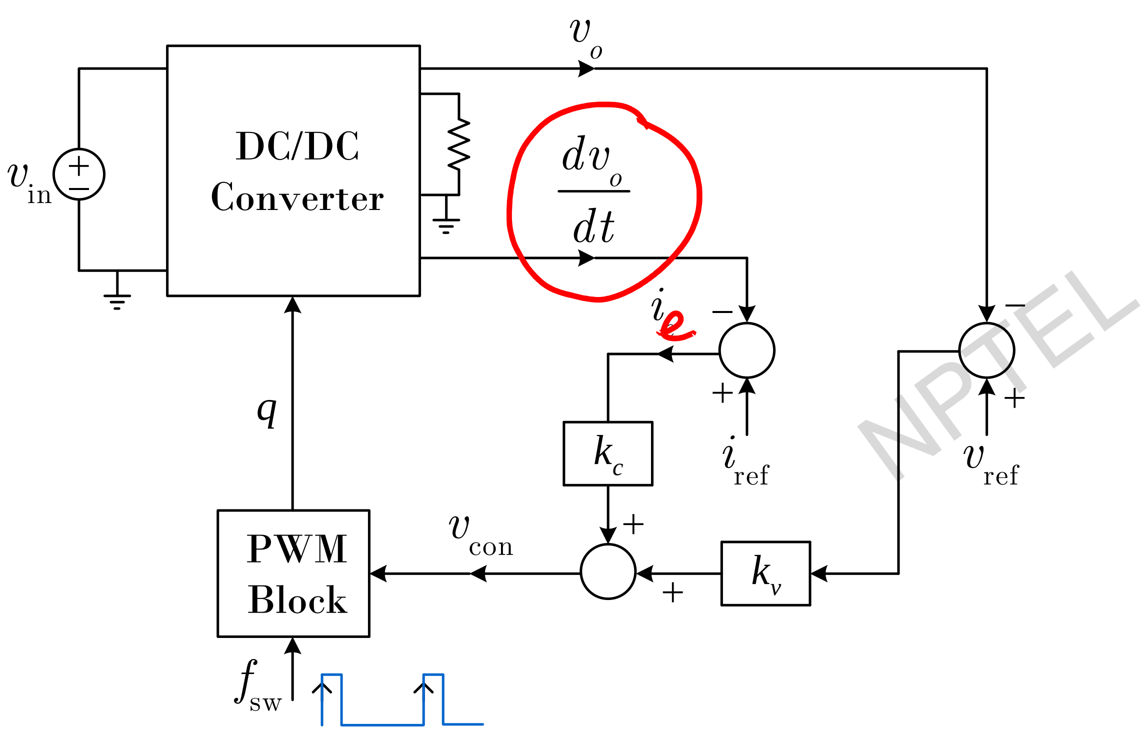
Multivariable Control



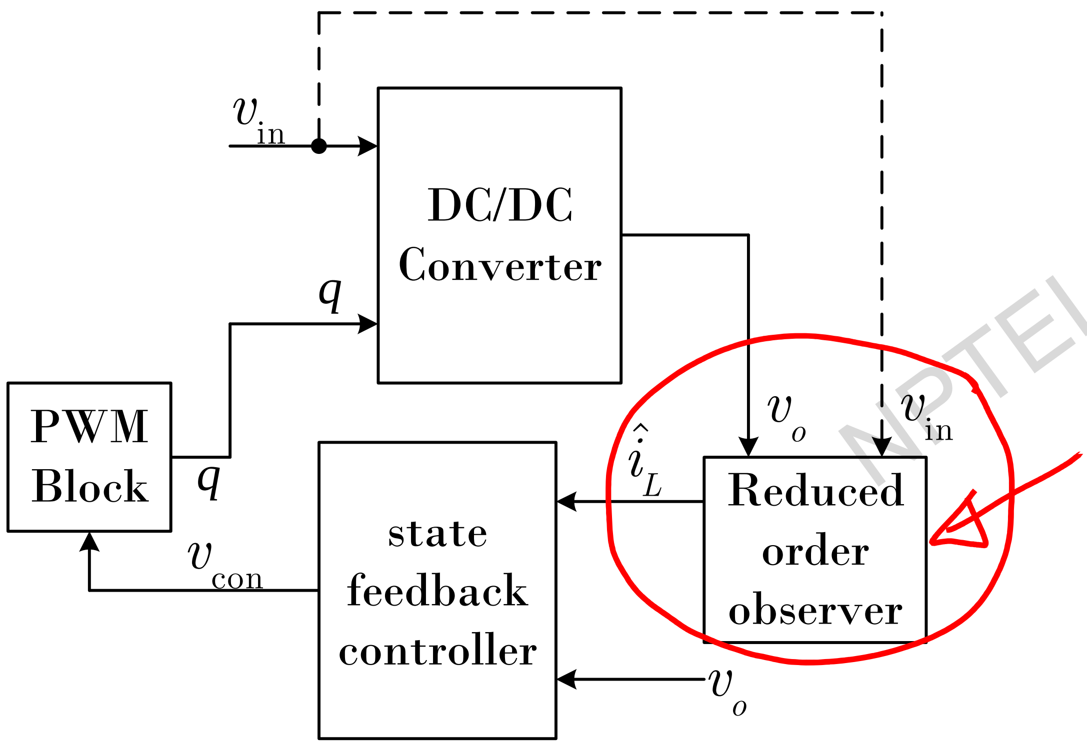
$\left.\begin{array}{l} k_{c21} \\ k_{v21} \end{array}\right\}$ **cross terms**

$\left.\begin{array}{l} k_{c12} \\ k_{v12} \end{array}\right\}$ **cross terms**

Alternative Form of State Feedback Control



Observer Based State Feedback Control



Summary

- Introduction to state feedback control
- Linking state feedback control with CMC
- State feedback control in cascaded converters
- Multivariable state feedback control
- Alternative state feedback control structures

THANK YOU !