NPTEL ONLINE CERTIFICATION COURSES

CONTROL AND TUNING METHODS IN SMPCs

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Module 02: Modulation Techniques in SMPCs

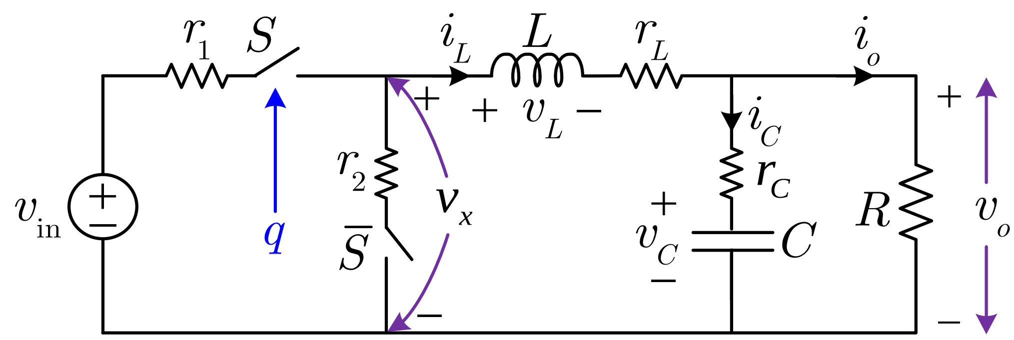
Lecture 07: Power Stage Design of Basic SMPCs: Summary

Concepts Covered

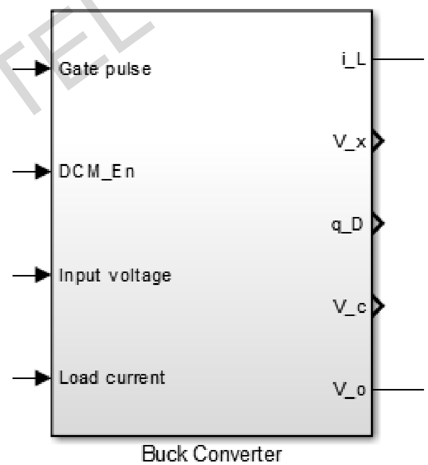
- Steady-state ripple parameters
- Derivation of RMS quantities
- Selection of inductor
- Selection of capacitor
- Simulation case studies

Synchronous Buck Converter

```
L=2e-6;          % output inductor
C=500e-6;        % output capacitor
T=1e-6;          % switching time period
r_L=10e-3;       % inductor DCR
v_d=0*0.7;       % diode voltage drop
r_1=5e-3;        % High-side MOSFET on resistance
r_2=5e-3;        % Low-side MOSFET on resistance
                 or diode resistance (in case diode)
r_C=5e-3;        % capacitor ESR
I_L_int=1;       % initial inductor current
V_c_int=3.4;     % initial capacitor voltage
V_up=10;         % ramp peak voltage
V_b=0;           % ramp base voltage
Vin=12;          % input voltage
Vref=3.3;        % reference output voltage
R=1;           % load resistance
```



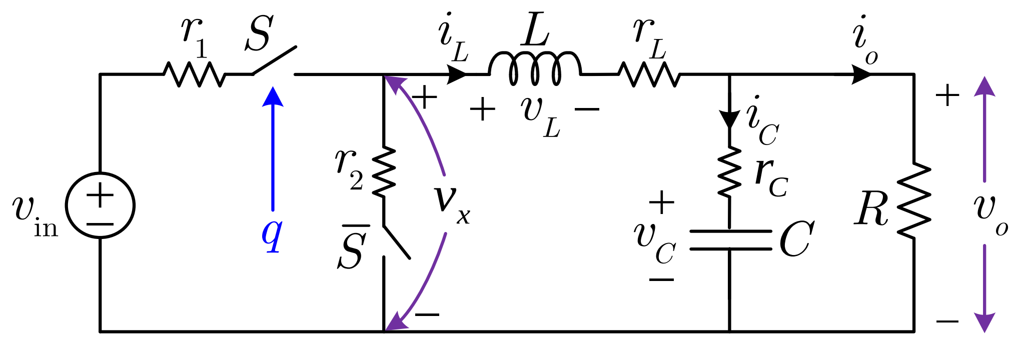
Synchronous buck converter



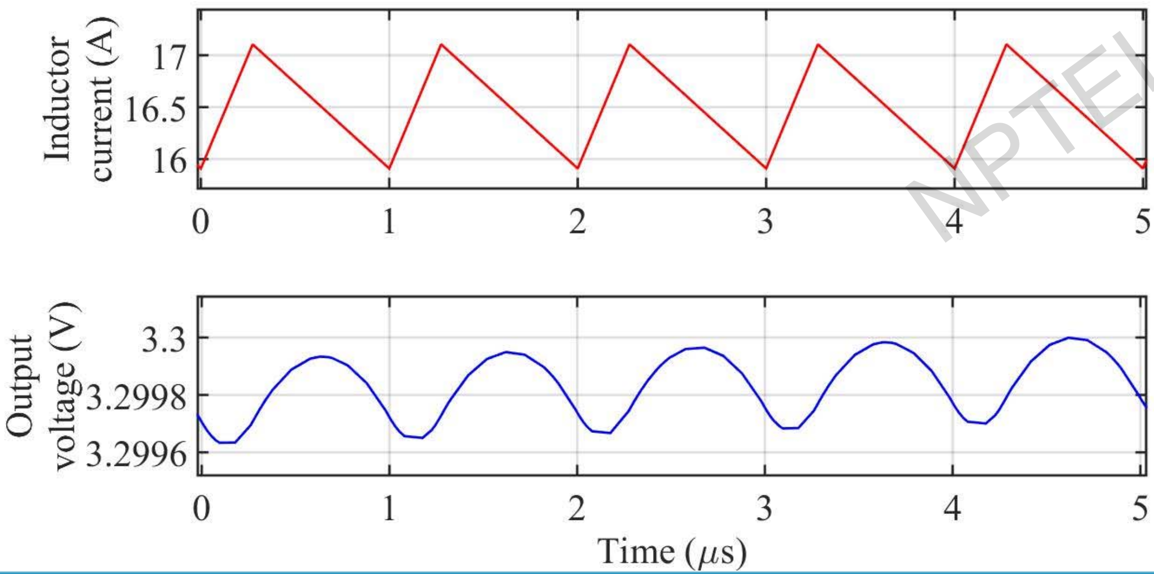
MATLAB model

Ideal Buck Converter Simulation

$$r_L = r_1 = r_2 = r_C = 0$$

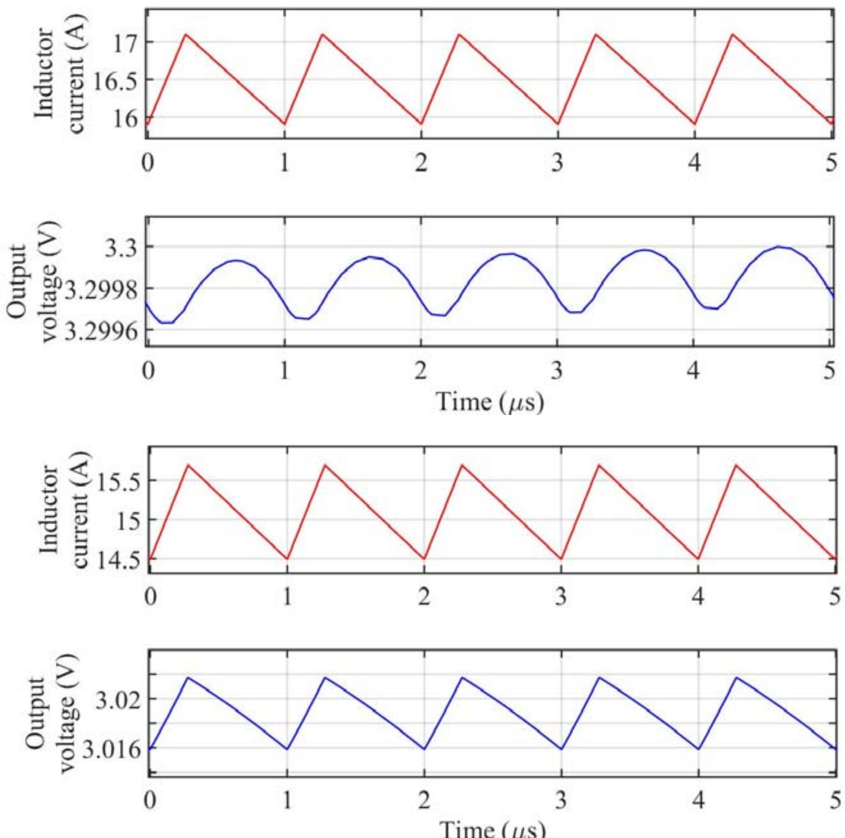


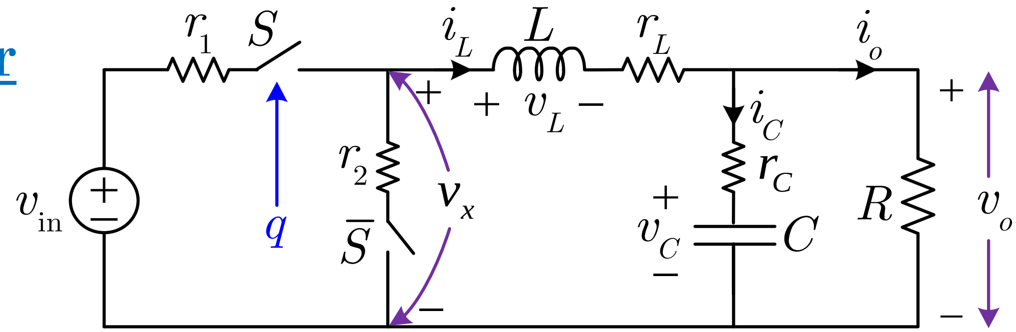
Synchronous buck converter



- ❑ Ripple current
- ❑ Ripple voltage
- ❑ Average current
- ❑ Average voltage

Ideal vs Practical Buck Converter

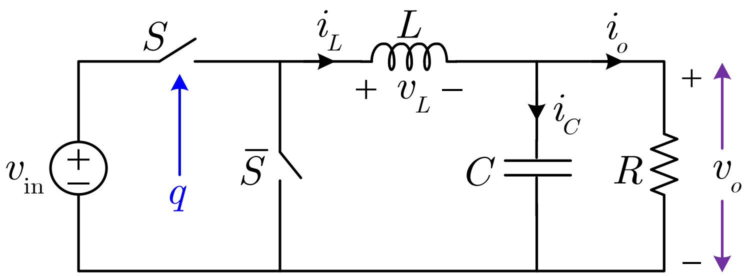




Synchronous buck converter

- ❑ Ripple current – **insignificant effect**
- ❑ Ripple voltage – **significant effect**
- ❑ Average current, average voltage – **significantly affected**

Buck Converter Ripple Parameters

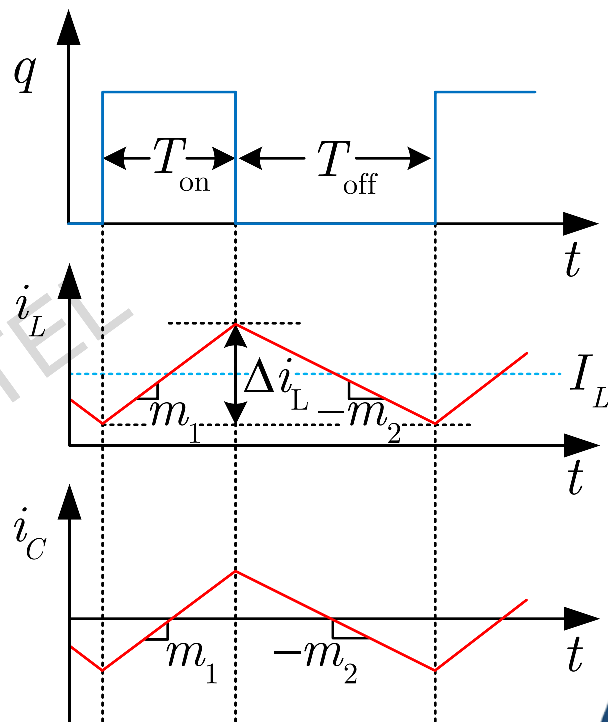


Buck Converter

- **Inductor current ripple (Δi_L) of a buck converter**

$$\Delta i_L = m_1 T_{on} \qquad \text{where } m_1 = \frac{V_{IN} - V_O}{L}$$

$$\therefore \Delta i_L = \frac{V_{IN} - V_O}{L} \times T_{on}$$



Steady-state waveforms

Buck Converter Ripple Parameters (contd…)

- Write ripple current in terms of $\boldsymbol{T_{on}}$, $\boldsymbol{T_{off}}$ and $\boldsymbol{V_o}$ ($\boldsymbol{V_o}$ is constant for a VR)
- Voltage gain $$K_V = \frac{V_O}{V_{IN}} = \frac{T_{on}}{T_{on} + T_{off}}$$

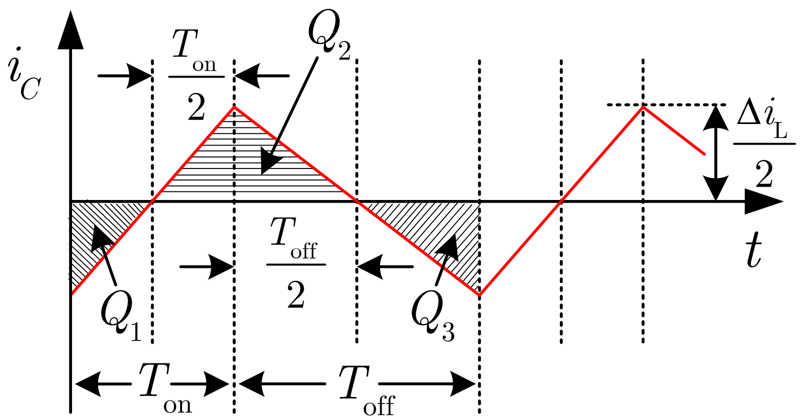
$$V_{IN} = \left(\frac{T_{on} + T_{off}}{T_{on}}\right) \times V_O = \left(1 + \frac{T_{off}}{T_{on}}\right) \times V_O$$

$$\therefore \Delta i_L = \frac{V_{IN} - V_O}{L} \times T_{on} = \frac{T_{on}}{L} \times \left[\left(1 + \frac{T_{off}}{T_{on}}\right) - 1\right] \times V_O$$

$$= \frac{V_O}{L} \times T_{off}$$

- Current ripple/off-time trade-off

Capacitor Voltage Ripple – Ideal Buck Converter



Capacitor current waveform

$$Q_2 = \frac{1}{2} \times \frac{\Delta i_L}{2} \times \left(\frac{T_{on} + T_{off}}{2} \right)$$

$$= \frac{1}{8} \times (T_{on} + T_{off}) \times \Delta i_L$$

Substituting $\Delta i_L = \frac{V_O}{L} \times T_{off}$

$$Q_2 = \frac{V_O}{8L} \times (T_{on} + T_{off}) \times T_{off}$$

Again $Q_2 = C \times \Delta v_o$

$$\Delta v_o = \frac{V_O}{8LC} \times (T_{on} + T_{off}) \times T_{off}$$

❑ Voltage ripple impact?

Ripple Parameters of a Buck Converter under PWM

- **Under PWM**

$$T_{\text{on}} + T_{\text{off}} = T_{\text{sw}} = \frac{1}{f_{\text{sw}}} \quad \textbf{(fixed)}$$

$$T_{\text{on}} = D \times T_{\text{sw}}$$

$$T_{\text{off}} = T_{\text{sw}} - T_{\text{on}} = (1-D) \times T_{\text{sw}}$$

$$\Delta v_o = \frac{V_O}{8LC} \times T_{sw} \times (1-D)T_{sw}$$

$$\boxed{\Delta v_o = \left(\frac{V_O}{8LCf_{\text{sw}}^{\,2}}\right) \times (1-D)}$$

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

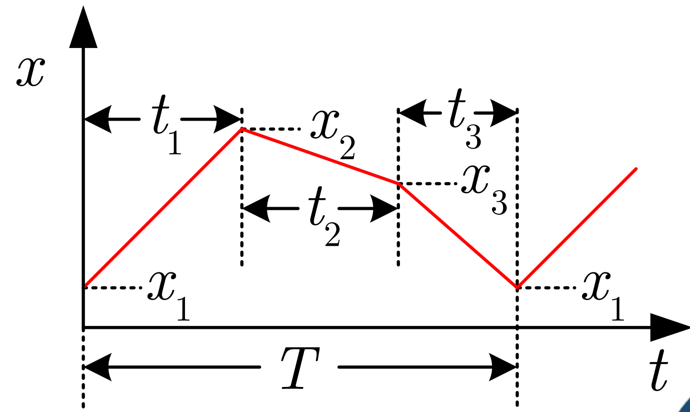
$$\Delta i_L = \frac{V_O}{L} \times (1-D)T_{\text{sw}}$$

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

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

RMS Value of a Periodic Piecewise Linear Waveform

$$\left(x_{\text{rms}}\right)^2 = \frac{1}{T}\left[\left(\frac{x_1^{\,2} + x_1 x_2 + x_2^{\,2}}{3}\right)t_1 + \left(\frac{x_2^{\,2} + x_2 x_3 + x_3^{\,2}}{3}\right)t_2 + \left(\frac{x_3^{\,2} + x_3 x_1 + x_1^{\,2}}{3}\right)\left(T - t_1 - t_2\right)\right]$$

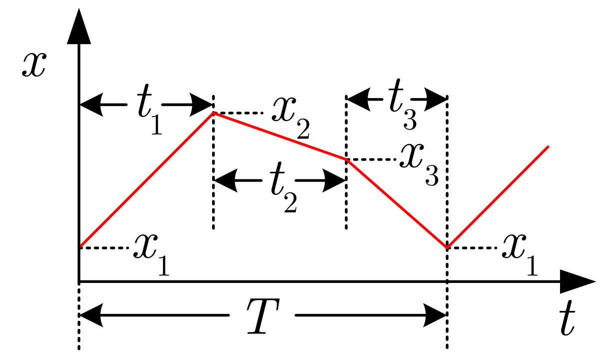


Prove it

Hint: $$\left(x_{\text{rms}}\right)^2 = \frac{1}{T}\left[\int_0^T x^2(t)dt\right] = \frac{1}{T}\left[\int_0^{t_1} x^2(t)dt + \int_{t_1}^{t_1+t_2} x^2(t)dt + \int_{t_1+t_2}^{T} x^2(t)dt\right]$$

$$= \frac{1}{T}\left[\int_0^{t_1} x^2(t)dt + \int_0^{t_2} x^2(t+t_1)dt + \int_0^{T-(t_1+t_2)} x^2(t+t_1+t_2)dt\right]$$

RMS Formulation – Proof



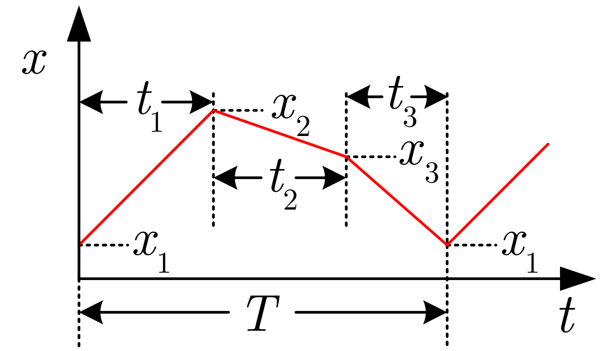
$$(x_{\text{rms}})^2 = \frac{1}{T}\left[\int_0^T x^2(t)dt\right]$$

$$= \frac{1}{T}\left[\int_0^{t_1} x^2(t)dt + \int_0^{t_2} x^2(t+t_1)dt + \int_0^{T-(t_1+t_2)} x^2(t+t_1+t_2)dt\right]$$

❑ **Define** $$I_k = \int_0^{t_k} x^2(t)dt = \int_0^{t_k}\left[x_k + \left(\frac{x_{k+1}-x_k}{t_k}\right)\tau\right]^2 d\tau$$

$$I_k = \int_0^{t_k}\left[x_k^2 + 2x_k\left(\frac{x_{k+1}-x_k}{t_k}\right)\tau + \left(\frac{x_{k+1}-x_k}{t_k}\right)^2\tau^2\right] d\tau$$

RMS Formulation – Proof Contd…



$$I_k = \int_0^{t_k} \left[x_k^2 + 2x_k \left(\frac{x_{k+1} - x_k}{t_k} \right) \tau + \left(\frac{x_{k+1} - x_k}{t_k} \right)^2 \tau^2 \right] d\tau$$

$$= \left[x_k^2 \tau + 2x_k \left(\frac{x_{k+1} - x_k}{t_k} \right) \frac{\tau^2}{2} + \left(\frac{x_{k+1} - x_k}{t_k} \right)^2 \frac{\tau^3}{3} \right]_0^{t_k}$$

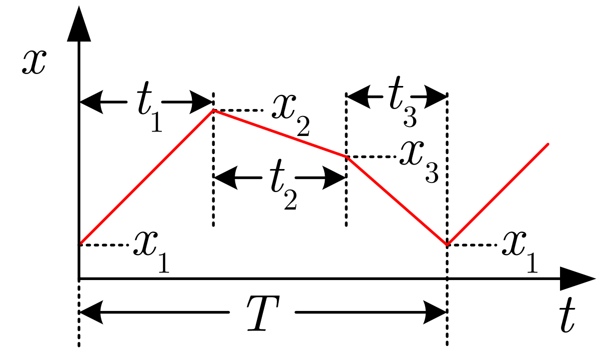
$$= \left(\frac{x_k^2 + x_k x_{k+1} + x_{k+1}^2}{3} \right) t_k$$

RMS Formulation – Proof Contd…

$$I_k = \left(\frac{x_k^2 + x_k x_{k+1} + x_{k+1}^2}{3}\right) t_k$$

$$(x_{\text{rms}})^2 = \frac{1}{T}\left[\int_0^T x^2(t)dt\right]$$

$$= \frac{1}{T}\left[\left(\frac{x_1^{\ 2} + x_1 x_2 + x_2^{\ 2}}{3}\right) t_1 + \left(\frac{x_2^{\ 2} + x_2 x_3 + x_3^{\ 2}}{3}\right) t_2 + \left(\frac{x_3^{\ 2} + x_3 x_1 + x_1^{\ 2}}{3}\right)(T - t_1 - t_2)\right]$$



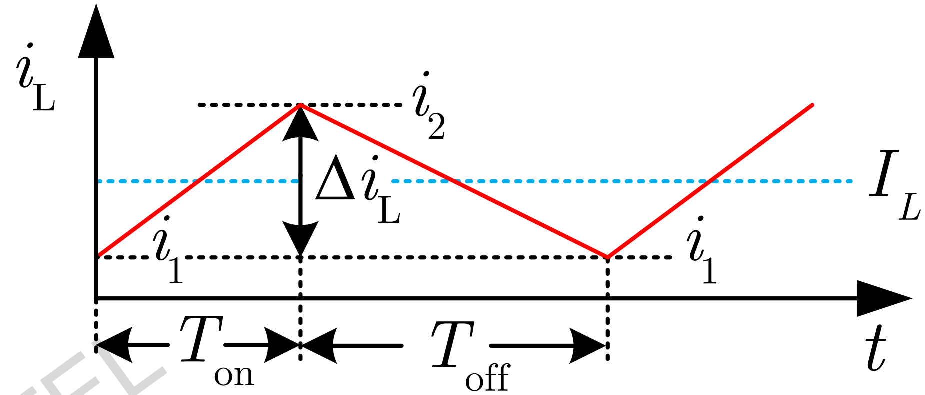
RMS Value of Inductor Current

$$\Delta i_L = i_2 - i_1 \Rightarrow i_2 - i_1 = \Delta i_L$$

$$I_L = \frac{i_1 + i_2}{2} \Rightarrow i_1 + i_2 = 2I_L$$

$$i_1 = I_L - \frac{\Delta i_L}{2}$$

$$i_2 = I_L + \frac{\Delta i_L}{2}$$

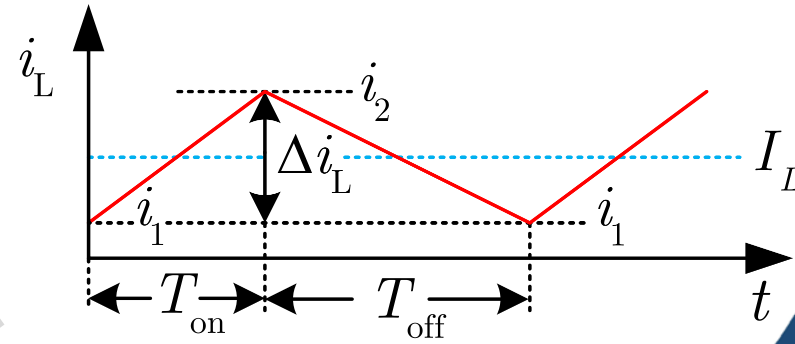


Inductor current waveform

RMS Value of Inductor Current (contd…)

$$\left(i_{L,\text{RMS}}\right)^2 = \frac{1}{T_{on}+T_{off}} \times \left[\left(\frac{i_1^2 + i_1 i_2 + i_2^2}{3}\right)\left(T_{on}+T_{off}\right)\right]$$

$$= \frac{i_1^2 + i_1 i_2 + i_2^2}{3}$$



Inductor current waveform

Substituting, $i_1 = I_L - \frac{\Delta i_L}{2}$ **and** $i_2 = I_L + \frac{\Delta i_L}{2}$

$$\left(i_{L,\text{RMS}}\right)^2 = I_L^2 + \frac{\Delta i_L}{12} = I_O^2 + \frac{\Delta i_L}{12}$$

Summary

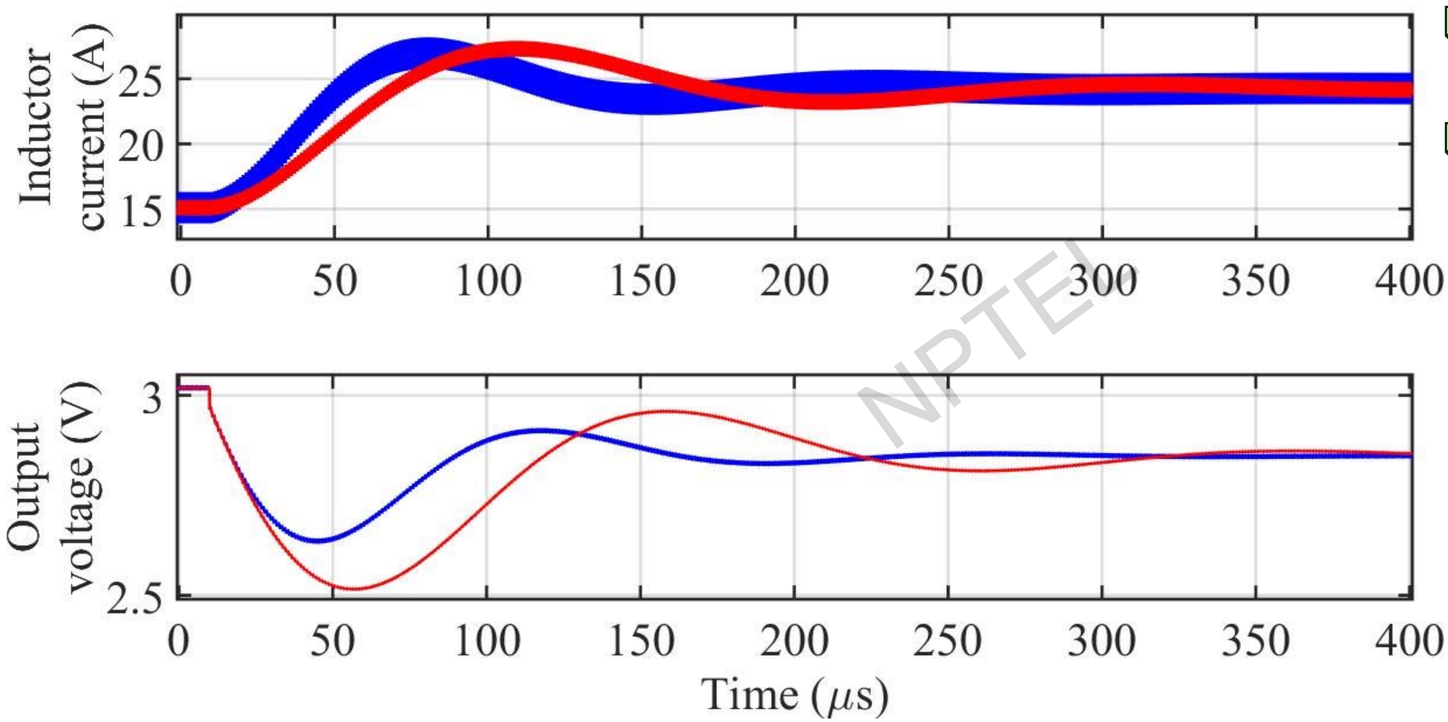
$$\left(i_{L,\mathrm{RMS}}\right)^2 = I_O^2 + \frac{\Delta i_L}{12}$$

- For a given load current,
  - $i_{L,\mathrm{RMS}}$ increases with increasing Δi_L
  - $i_{L,\mathrm{RMS}}$ is maximum at maximum v_{in}
  - Higher $i_{L,\mathrm{RMS}}$ implies higher conduction loss
- For a given input voltage,
  - $i_{L,\mathrm{RMS}}$ increases with increasing Δi_L
  - Higher conduction loss at higher load current

Worst case RMS current (also conduction loss) at

highest input voltage and highest load current

Design Consideration (Inductor)



- Larger inductor (red)
- Smaller inductor (blue)

Design Consideration (Inductor) Large Inductor

Advantages

Smaller ripple current

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

Smaller RMS current

$$\left(i_{L,\text{RMS}}\right)^2 = I_O^2 + \frac{\Delta i_L}{12}$$

Lower conduction loss

Smaller voltage ripple

$$\Delta v_o = \frac{V_O(1-D)}{8Cf_{\text{sw}}^2} \times \frac{1}{L}$$

Disadvantages

Larger size (bulky inductor)

Slower transient response!!

Higher voltage overshoot/ undershoot!!

Inductor should be carefully designed

Design Consideration (Capacitor) Large Capacitor

Advantages

Smaller output voltage ripple

$$\Delta v_o = \frac{V_o(1-D)}{8Cf_{sw}^2} \times \frac{1}{L}$$

Smaller output voltage undershoot/ overshoot

Disadvantages

Larger size and poor reliability

Higher time and energy overhead during reference voltage transient

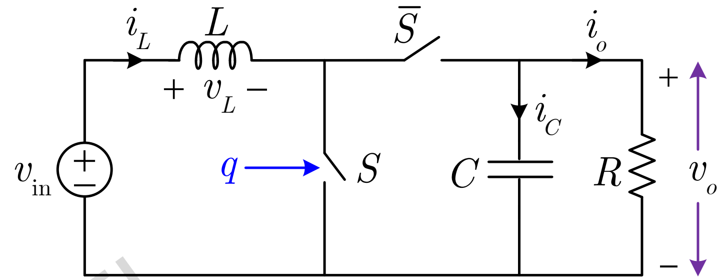
Capacitor should be carefully selected

Ripple Inductor Current- Boost Converter

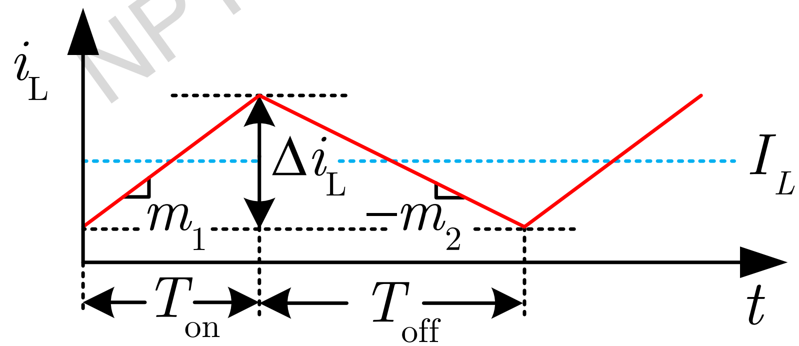
$$\Delta i_L = m_1 \times T_{on} = \frac{V_{IN}}{L} \times T_{on}$$

Express V_{IN} in terms of V_o

since V_o is constant for a VR



Boost converter



Inductor current waveform

For a Boost Converter

$$V_O = \frac{T_{\text{on}} + T_{\text{off}}}{T_{\text{off}}} V_{\text{IN}} \quad \Rightarrow V_{\text{IN}} = \frac{T_{\text{off}}}{T_{\text{on}} + T_{\text{off}}} V_O$$

$$\Delta i_L = \frac{V_{\text{IN}}}{L} \times T_{\text{on}} \quad \Rightarrow \Delta i_L = \frac{V_O}{L} \times \left(\frac{T_{\text{on}} T_{\text{off}}}{T_{\text{on}} + T_{\text{off}}} \right)$$

$$\therefore \Delta i_L = \frac{V_O}{L f_{\text{sw}}} \times \left[D(1-D) \right]$$

$$\frac{\partial \Delta i_L}{\partial D} = \frac{V_O}{L f_{\text{sw}}} \left(1 - 2D \right) = 0 \qquad \frac{\partial^2 \Delta i_L}{\partial D^2} = -\frac{2V_O}{L f_{\text{sw}}} < 0$$

$$\Rightarrow D = 0.5$$

Δi_L is maximum at D=0.5

Under PWM

$$T_{\text{on}} + T_{\text{off}} = T_{\text{sw}} = \frac{1}{f_{\text{sw}}}$$

$$T_{\text{on}} = D T_{\text{sw}}$$

$$T_{\text{off}} = (1-D) T_{\text{sw}}$$

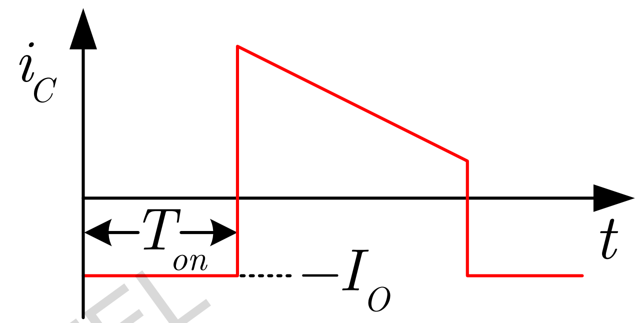
Ripple Output Voltage – Boost Converter

$$\Delta v_o \times C = I_O T_{\mathrm{on}}$$

$$\Delta v_o = \frac{I_O}{C} \times T_{\mathrm{on}}$$

Under PWM $\quad T_{\mathrm{on}} = D T_{\mathrm{sw}}$

$$\therefore \Delta v_o = \frac{I_O}{C f_{\mathrm{sw}}} \times D$$



Capacitor current waveform

- Voltage ripple is maximum when
  - Load current is maximum and
  - Duty ratio is maximum

Worst-case voltage ripple at

lowest input voltage and highest load current

Summary

- Steady-state ripple parameters – important design constraint
- RMS current – direct impact on efficiency
- Selection of inductor – ripple/RSM parameters vs transient response
- Selection of capacitor – ripple parameter, reliability, etc.
- Power stage design – critical for steady-state and transient

THANK YOU !

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CONTROL AND TUNING METHODS IN SMPCs

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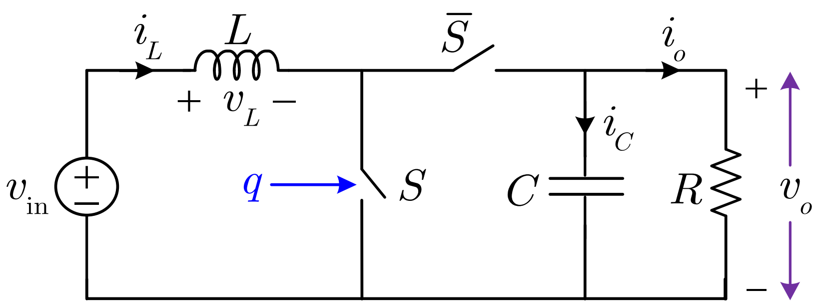
Module 02: Modulation Techniques in SMPCs

Lecture 08 : Fixed Frequency Modulation Techniques

Concepts Covered

- Pulse width modulation (PWM) techniques
- Trailing-edge PWM and implementation
- Leading-edge PWM and implementation
- Dual-edge PWM and implementation
- Phase shift modulation

Pulse Width Modulation

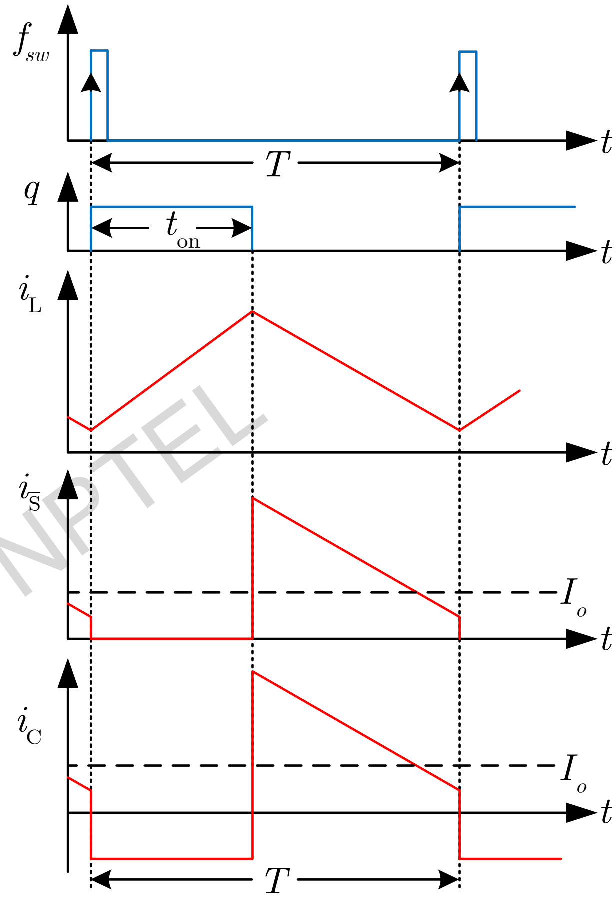


Ideal Synchronous Boost Converter

$$t_{on} = dT$$

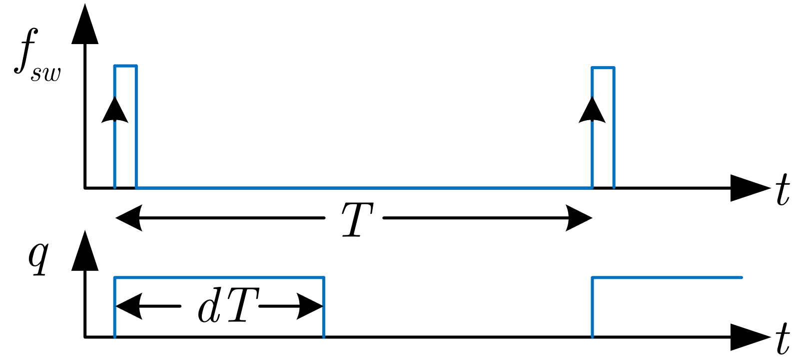
Duty ratio *d* is the control variable

Switching waveforms



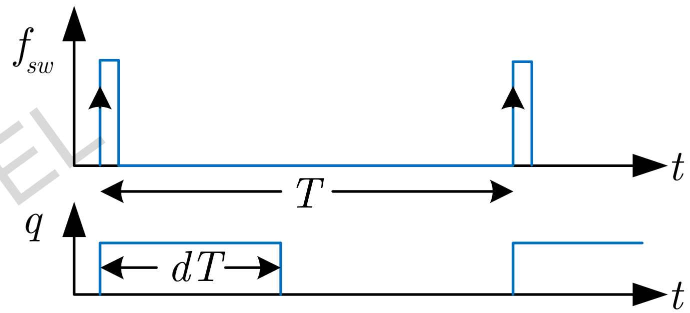
Features under PWM

- Switching period T is constant
  - Fixed frequency operation
  - Predictable ripple parameters throughout
  - Easy to design input filter
- Synchronized with an external fixed frequency clock f_{sw}
  - Switching frequency programmable using an external clock
  - Synchronization among other converters through clock sharing

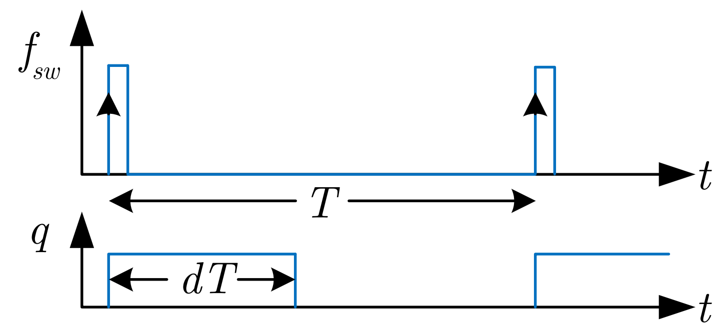


Features under PWM (contd…)

- Switch state cannot change its state more than once in between two subsequent edges of f_{sw}
  - Operation insensitive to switching noise
  - False triggering can be avoided
  - But introduces a transient detection delay



Possible Configurations under PWM



- Control on-time → duty ratio control

  $t_{on} = dt$ (known as trailing edge PWM)

- Control off-time → control $1\text{-}d$

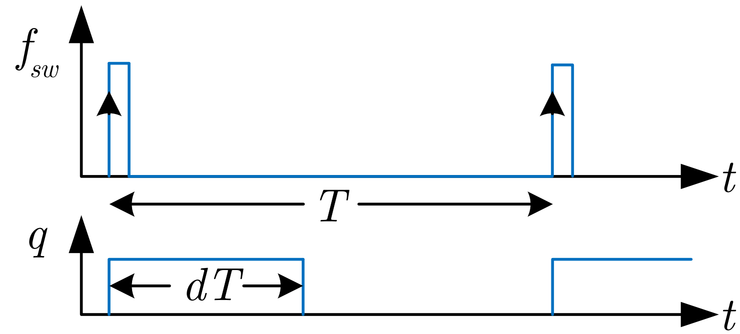
  $t_{off} = (1\text{-}d)t$ (known as leading edge PWM)

- Control both on and off-times t_{on} and t_{off} subject to the constraint

  $t_{on} + t_{off} = T$ (Example – dual edge PWM)

Possible Configurations under PWM

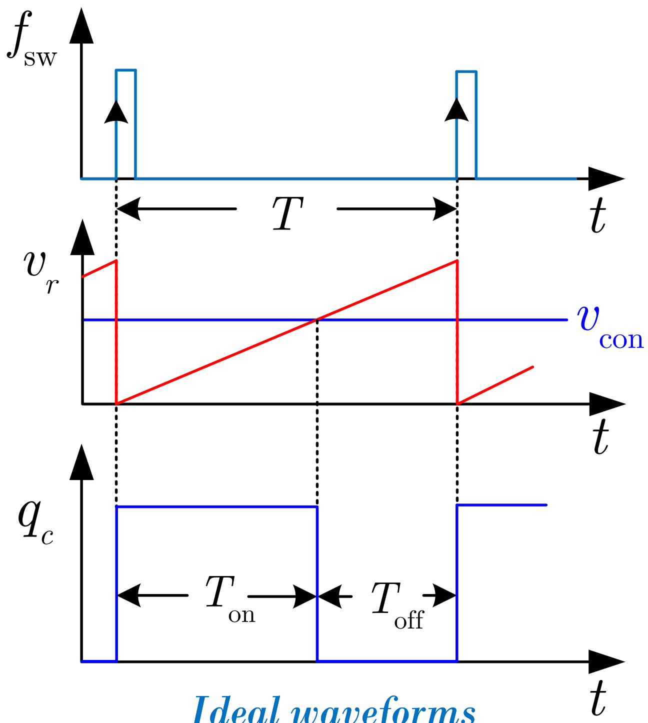
- In all cases the periodic operation is synchronized with the external fixed frequency clock f_{sw}



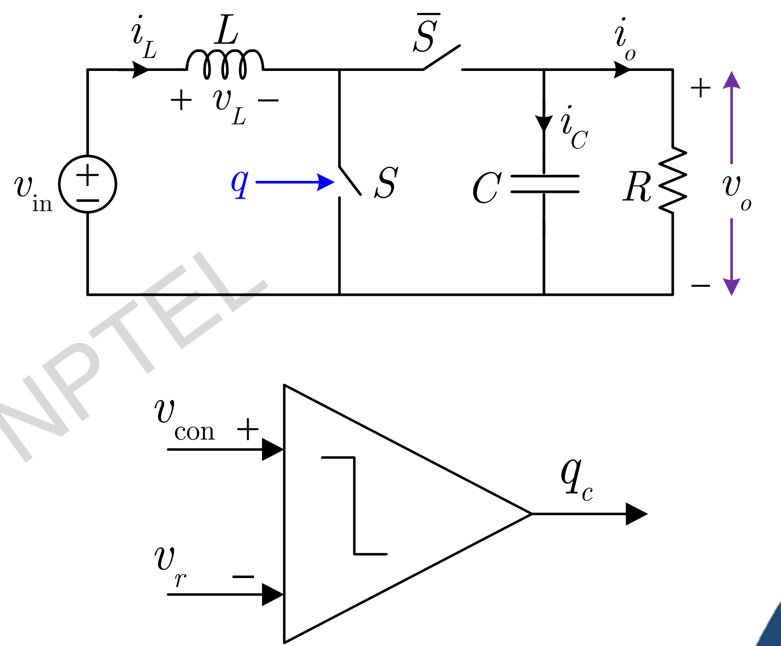
➢ How to implement different PWM techniques?

➢ What are the use of different PWM techniques?

Trailing – edge PWM and Implementation



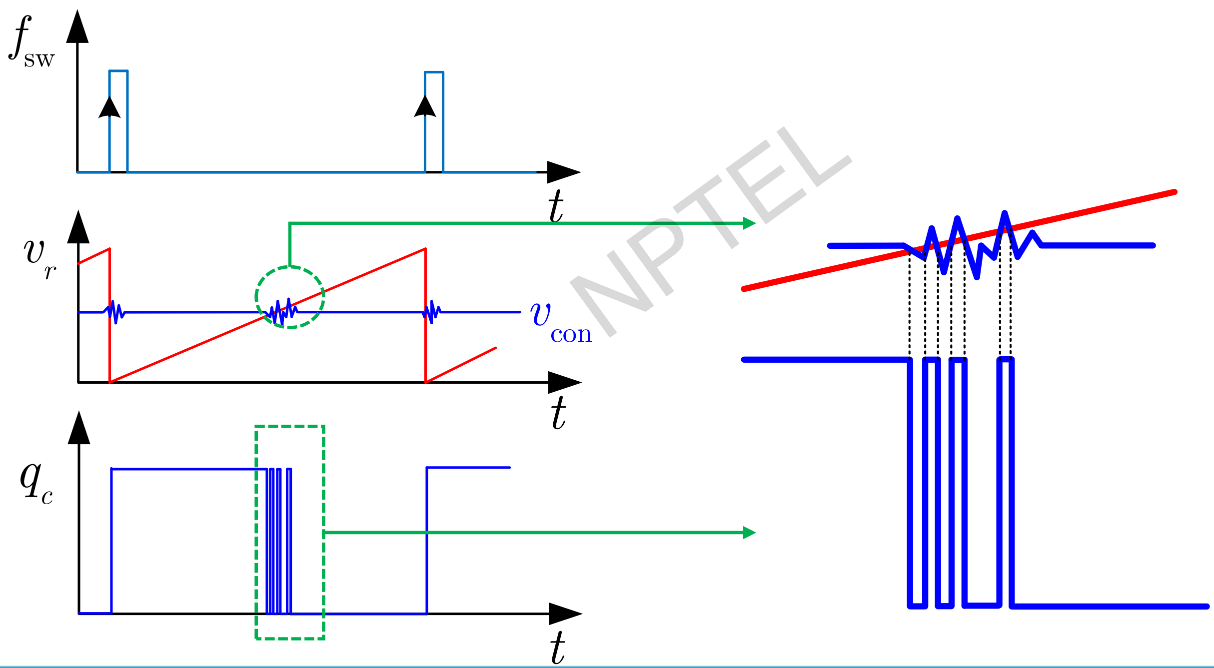
Ideal waveforms



Comparator

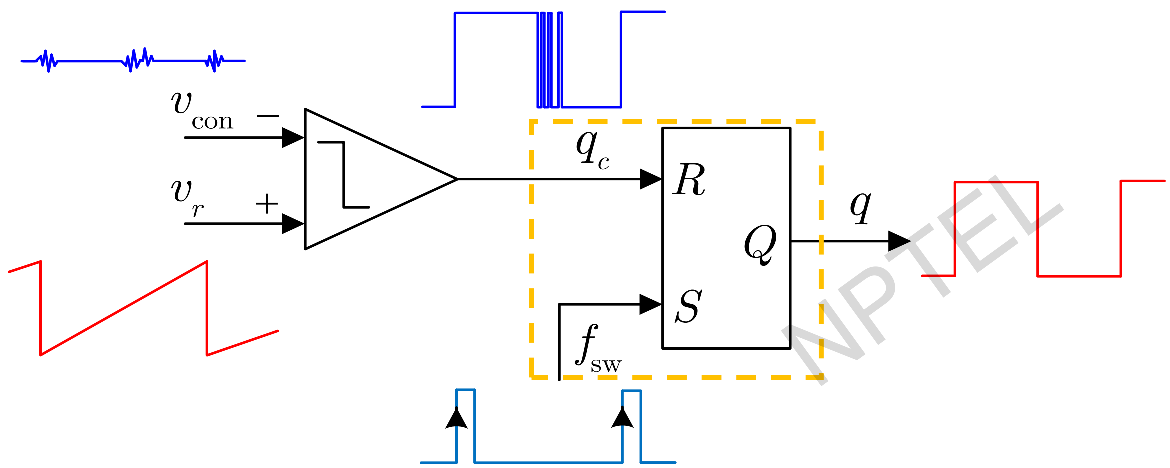
Impact of Switching Noise

- Question: What will be the impact on q_c for noisy v_{con} ?



Noise Insensitive PWM Operation

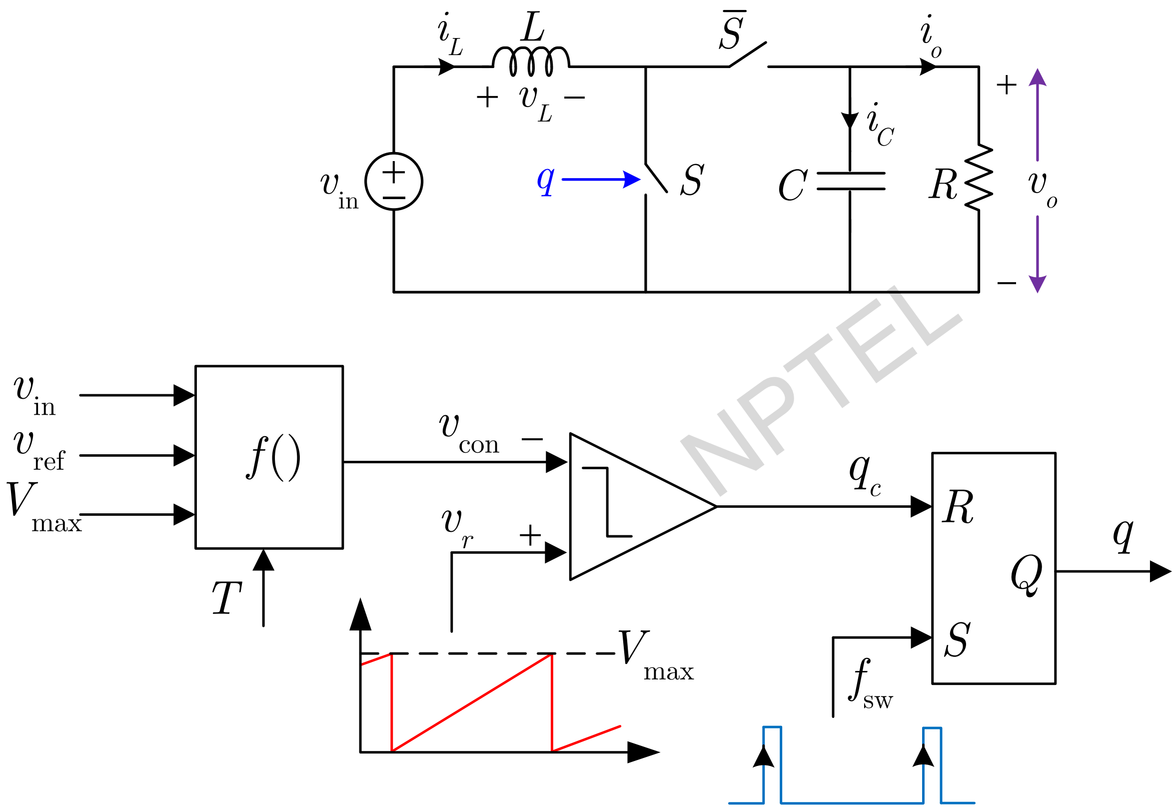
- Need to add a latch circuit



- For reset (R) dominated – full 0 to 100% duty ratio achievable

- For set (S) dominated – 0% duty ratio not achievable

Implementation



Setting Control Voltage for Open-Loop Simulation

- Using steady-state equations of an ideal boost converter, calculate v_{con} such that v_o can be maintained at v_{ref} (reference output voltage).

- Step 1:

$$V_O = \frac{V_{\text{IN}}}{(1-D)}$$

- Find D_r for given V_{IN} and V_{ref} .

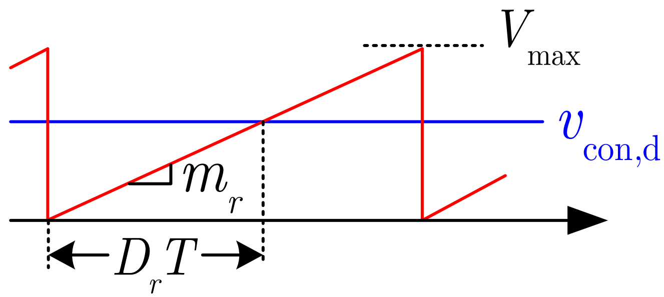
$$(1-D_r) = \frac{V_{\text{IN}}}{V_{\text{ref}}}$$

$$D_r = 1 - \frac{V_{\text{IN}}}{V_{\text{ref}}} = \left(\frac{V_{\text{ref}} - V_{\text{IN}}}{V_{\text{ref}}}\right)$$

$$\underbrace{D_r \times T}_{\text{Desired on-time (under trailing-edge PWM)}} = \left(\frac{V_{\text{ref}} - V_{\text{IN}}}{V_{\text{ref}}}\right) \times T$$

Desired on-time
(under trailing-edge PWM)

Setting Control Voltage Contd…



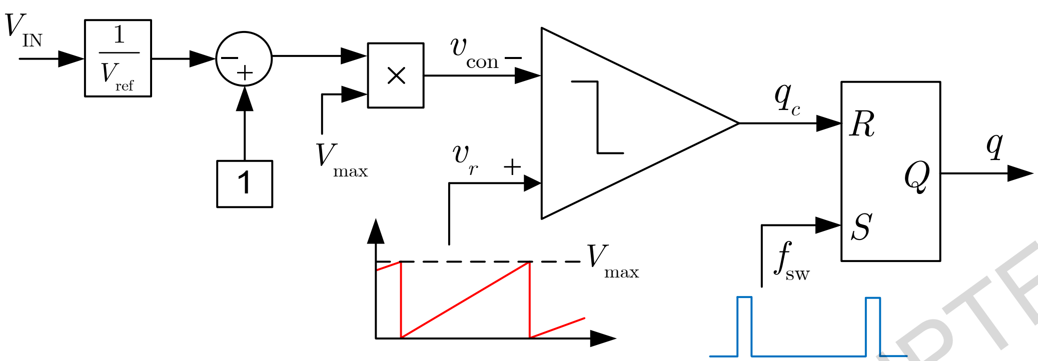
Desired constant voltage

$$v_{con,d} = m_r \times (D_r \times T) \qquad m_r = \frac{V_{max}}{T}, \qquad D_r \times T = \left(\frac{V_{ref} - V_{IN}}{V_{ref}}\right) \times T$$

$$v_{con,d} = V_{max} \times \left(\frac{V_{ref} - V_{IN}}{V_{ref}}\right)$$

$$\boxed{\therefore v_{con,d} = V_{max} \times \left(1 - \frac{V_{IN}}{V_{ref}}\right)}$$

MATLAB Simulation Case Study



- Implement this in a boost converter.

- <u>For a case study</u>

  With $V_{IN} = 4.5V$, $V_{ref} = 5V$

- Show steady-state results
- Apply a transient in v_{in}

  v_{in} changes from 4V to 3V

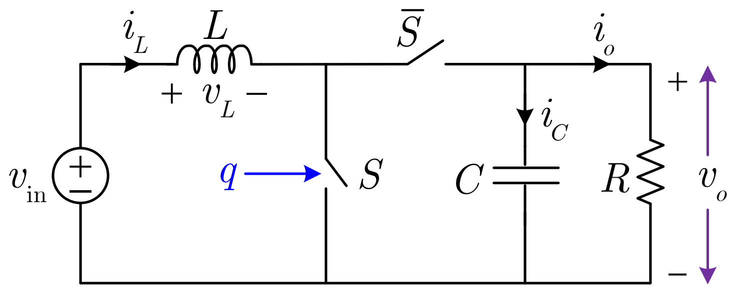
- Show the effect

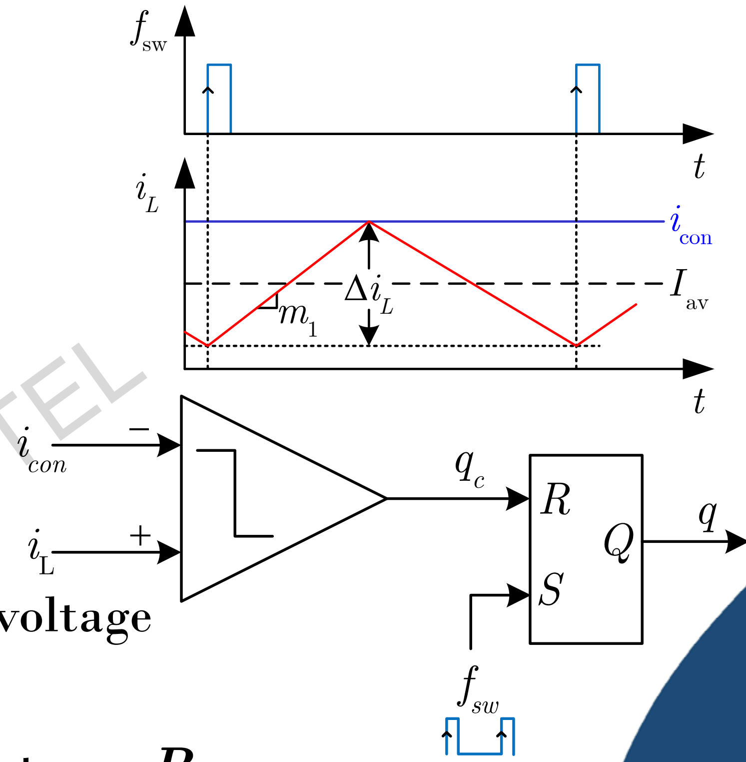
MATLAB Simulations

Trialing-edge vs Leading-edge Modulation a Boost Converter

MATLAB Simulations

Trailing Edge Current Control





- Control peak value of inductor current (known as Peak current mode control)
- $\boldsymbol{i}_{\textbf{con}}$ can be arbitrarily set
- How to set $\boldsymbol{i}_{\textbf{con}}$ to achieve desired output voltage ($\boldsymbol{V}_{\boldsymbol{o}}$) at $\boldsymbol{V}_{\textbf{ref}}$ for the following conditions?

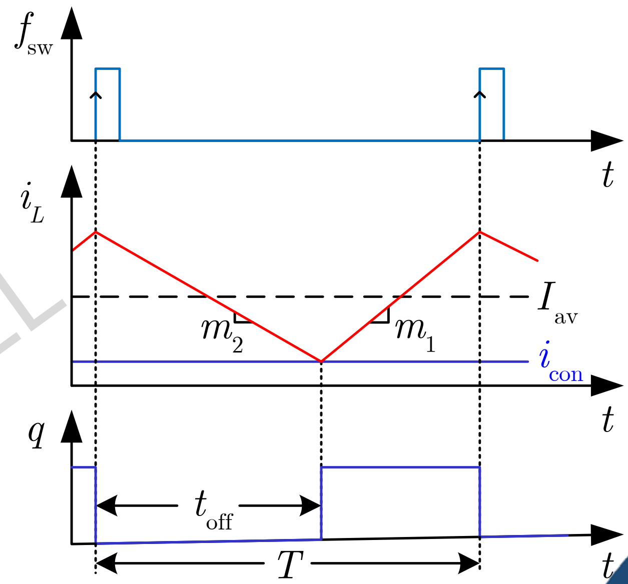
  $V_o = V_{\text{ref}}$ for a given $\boldsymbol{V}_{\textbf{in}}$ and the load resistance $\boldsymbol{R}$

  Will do it later !!!

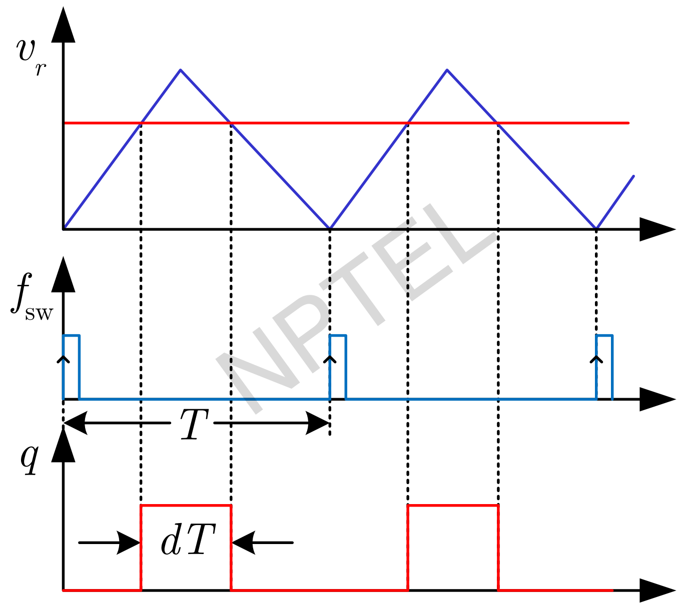
Leading Edge Current Control

- Control valley (or lower peak)current
- Also known as Valley current mode control

- Why and when is it used over Peak current mode control?



Dual Edge PWM



Steady State Parameters under PWM

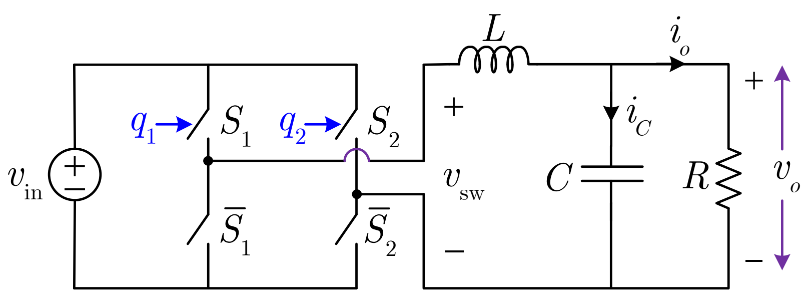
Buck converter in CCM

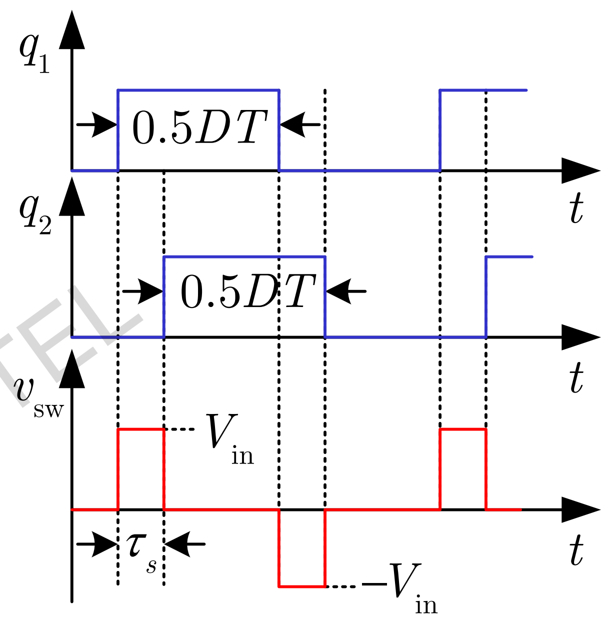
- Inductor current ripple Δi_L
- Output voltage ripple Δv_o
- RMS current
  - Inductor current RMS value
  - Input current RMS value
- Find worst case scenario

Boost converter in CCM

- Inductor current ripple Δi_L
- Output voltage ripple Δv_o
- RMS current
  - Inductor current RMS value
  - Diode current RMS value
- Find worst case scenario

Phase Shift Modulation

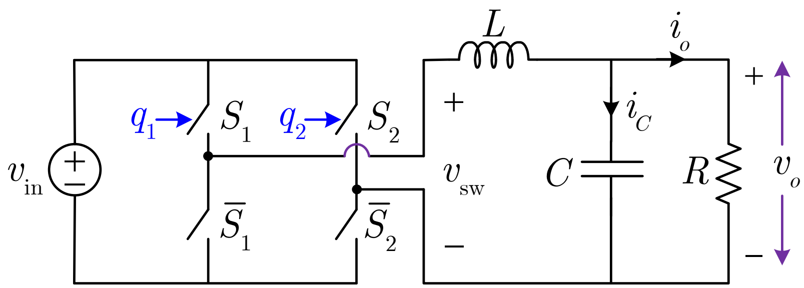


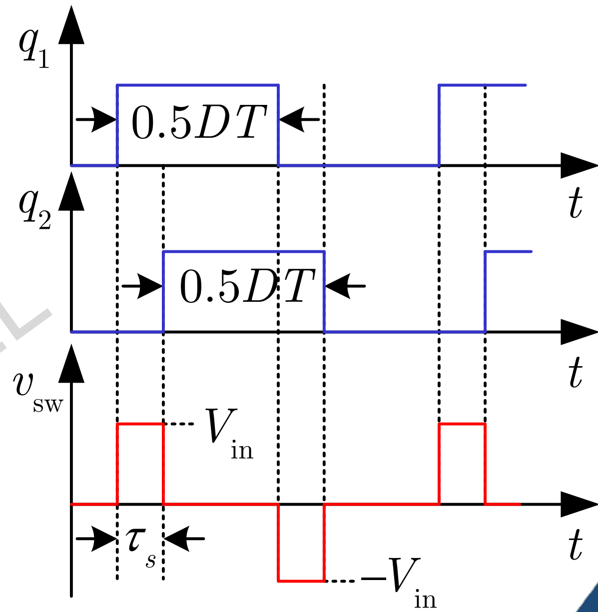


$$\tau_s = \underbrace{\phi_s}_{\text{phase shift}} T$$

- What will happen with v_o?
- How does it look like?

Phase Shift Modulation





- Where do you use such techniques?
  - Class-D audio
  - Inverter
  - Full bridge, dual active bridge converters
  - Switch cap converter

$$\tau_s = \underbrace{\phi_s}_{\text{phase shift}} T$$

Summary

- Pulse width modulation (PWM) techniques
- Trailing-edge PWM and implementation
- Leading-edge PWM and implementation
- Dual-edge PWM and implementation
- Phase shift modulation

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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 02: Modulation Techniques in SMPCs

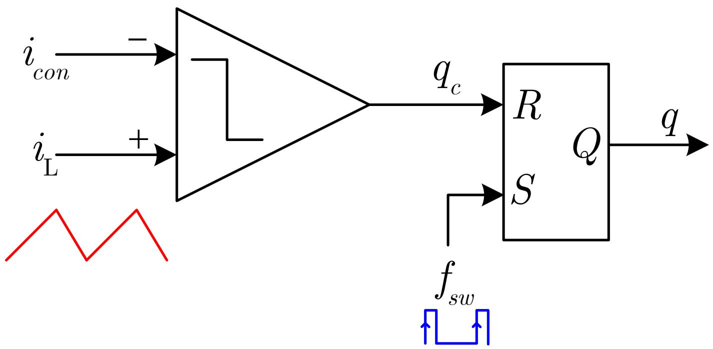
Lecture 09: Variable Frequency Modulation Techniques

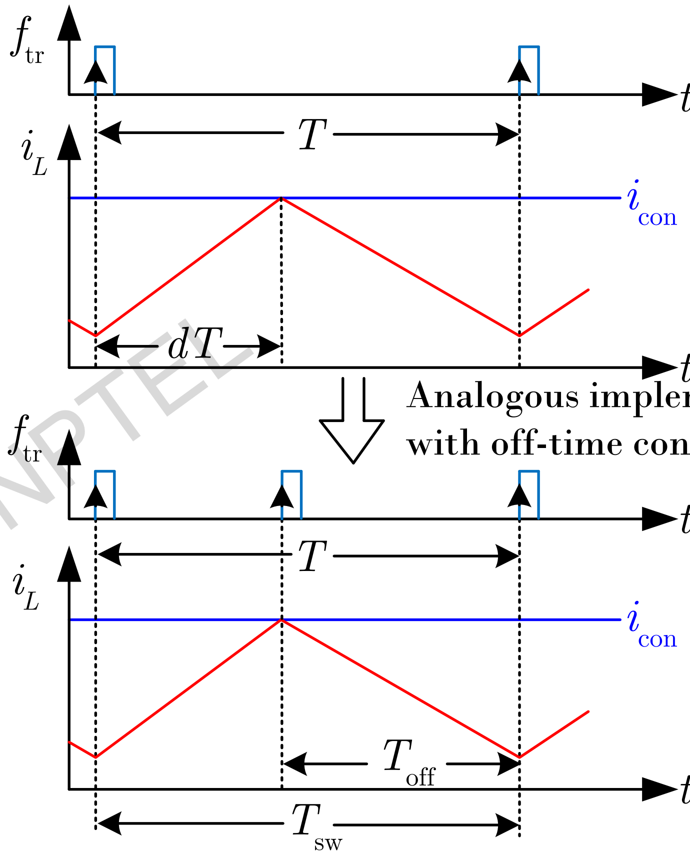
Concepts Covered

- Variable frequency control
- Constant on-time modulation
- Constant off-time modulation
- Hysteresis control
- Steady-state analysis

Variable Frequency Control Method

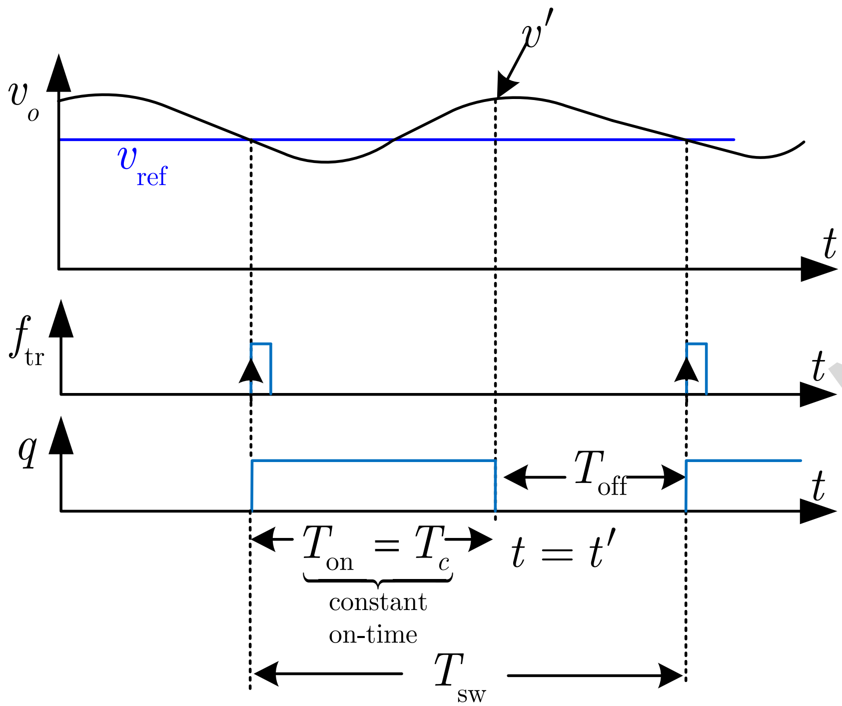
Recall fixed frequency Peak CMC

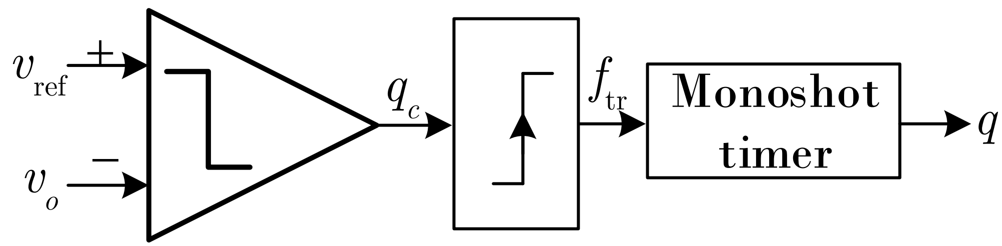




- T_{off} → constant, but unlike trailing-edge PWM, T_{sw} is not constant
- f_{tr} → trigger pulses (edge detection)
- Who generates f_{tr} ?

Constant ON-time Modulation





Problem with Constant ON-time Implementation

- What happens if $v_o < v_{ref}$ after the switch S turns off?

↓

$$v' < v_{ref} \quad \text{where } v' = v_o(t = t')$$

↓

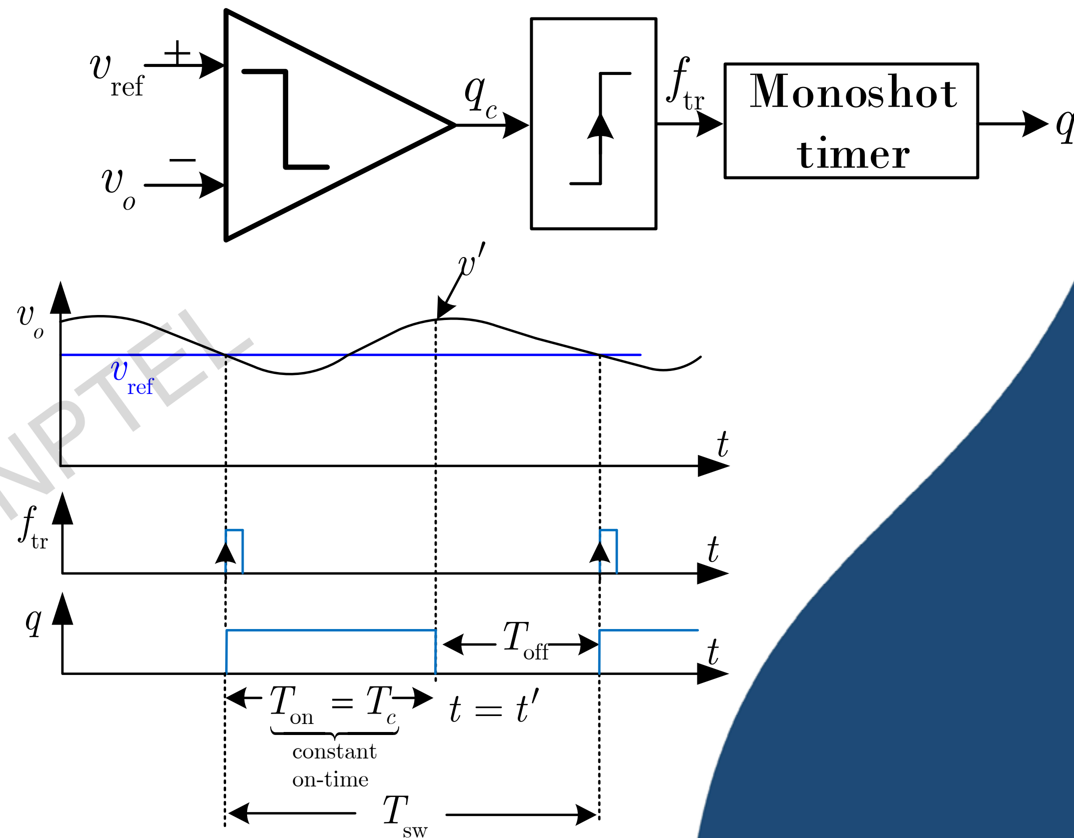
q_c continues to remain high and no rising-edge is detected at f_{tr}

↓

q - remains off and voltage v_o further decreases

↓

Output voltage completely collapses



Solving Implementation Problem

- Turn ON problem

  in Constant on-time

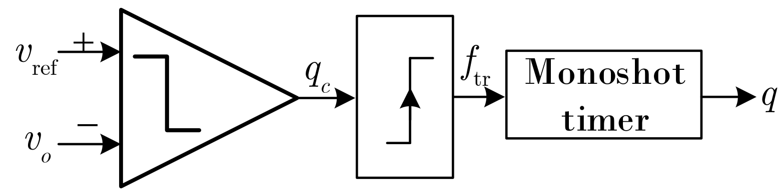
- Solution:

  Introduce a

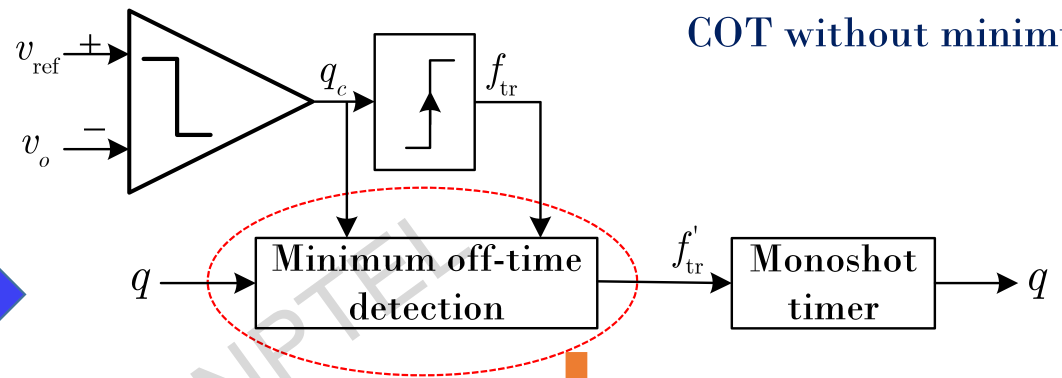
  minimum off-time

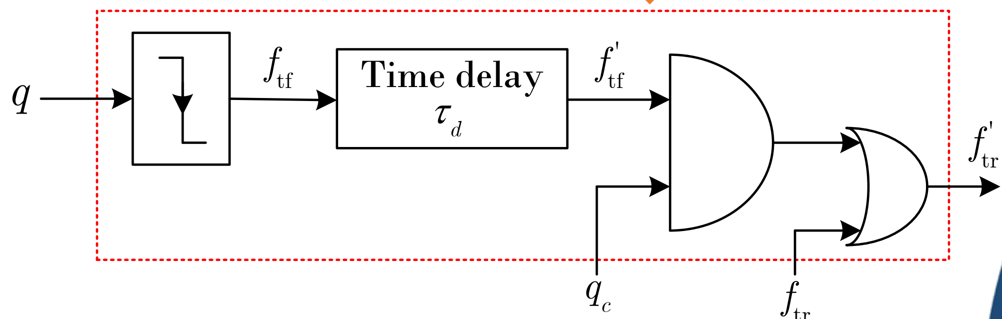
  in Constant on-time

  modulation



COT without minimum off-time





Minimum Off-Time in Constant On-Time Control

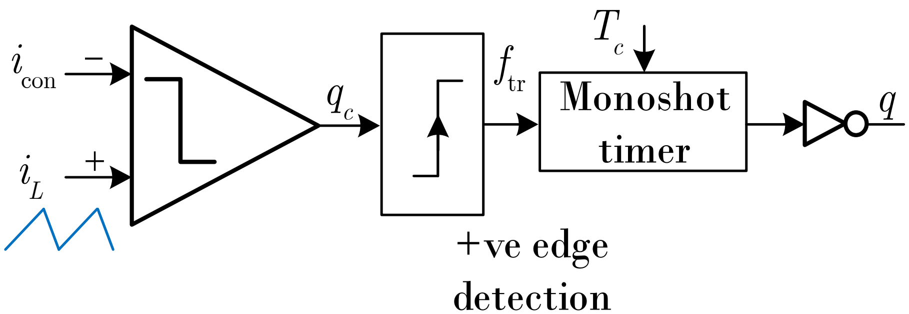
Objective: To solve turn ON problem in Constant on-time control

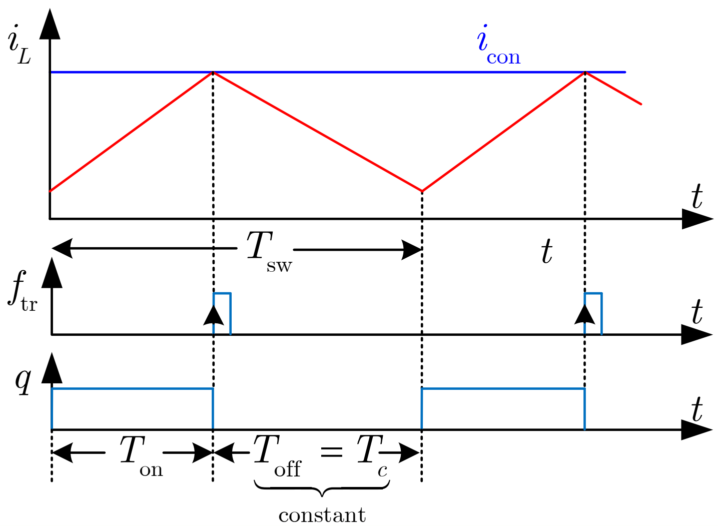
1. Identify the falling-edge (f_{tf}) of q (output of monoshot timer)
2. Delay f_{tf} by a time delay τ_d
3. Compare delayed-edge f_{tf}' with q_c (output of voltage comparator)

   Make an 'AND' operation
4. The output of 'AND' gate 'OR'-ed with f_{tr} to generate f_{tr}'
5. Use f_{tr}' as the trigger pulse for the monoshot timer

- Try a similar approach in Constant off-time

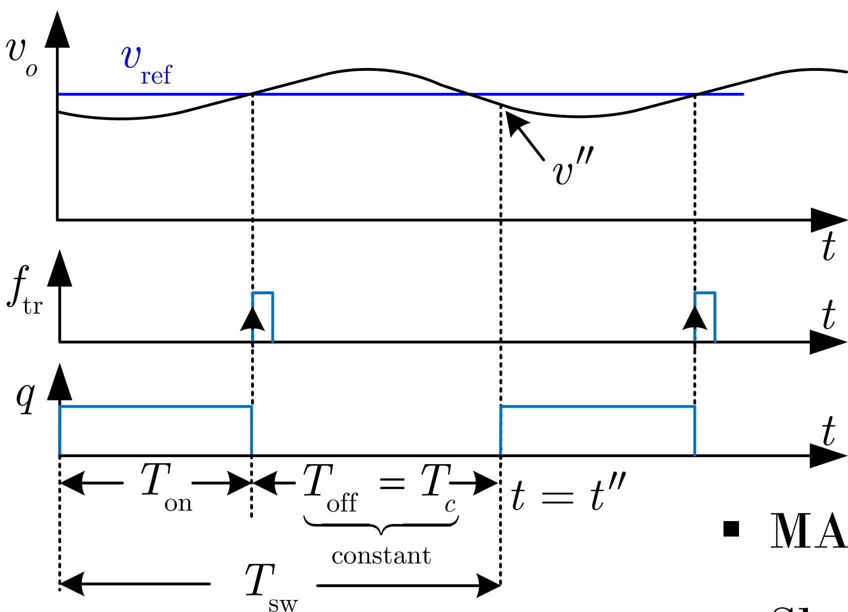
Constant Off-Time Modulation

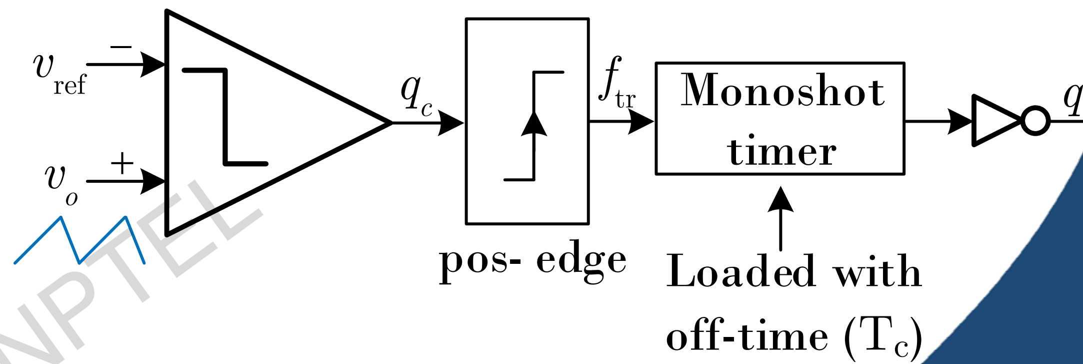




- Known as constant off-time modulation
- In constant off-time, off-time is constant, whereas in trailing-edge PWM, time period is constant
- Both techniques directly control peak inductor current

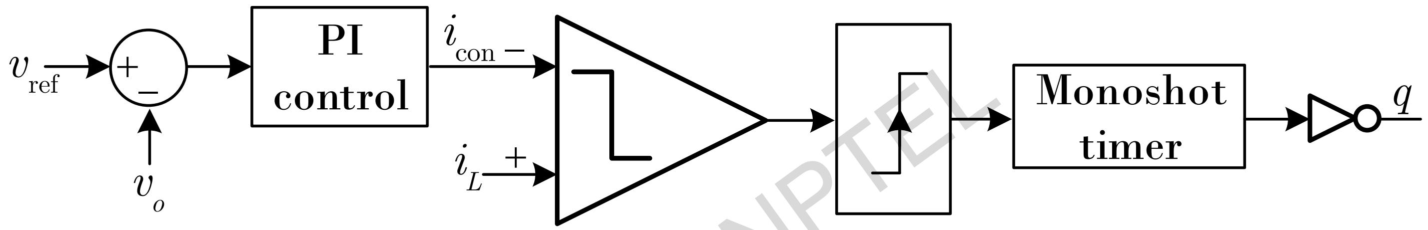
Constant OFF-time Modulation | Voltage based implementation





- MATLAB Implementation
- Show transient cases?
- Problems with frequency variations?

Constant OFF-time Control | Current based feedback control



Implement in MATLAB

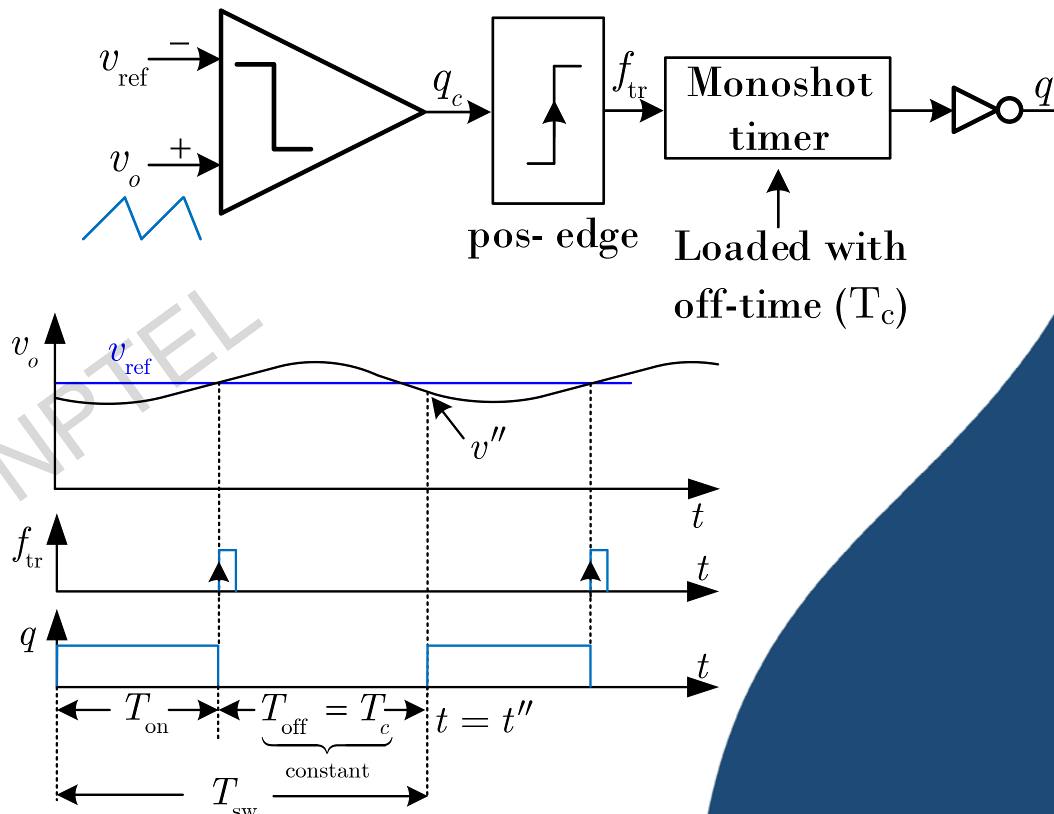
Problem with Constant OFF-time Implementation

- What happens if $v'' > v_{ref}$?

q_c remains high, no rising-edge of f_{tr} detected

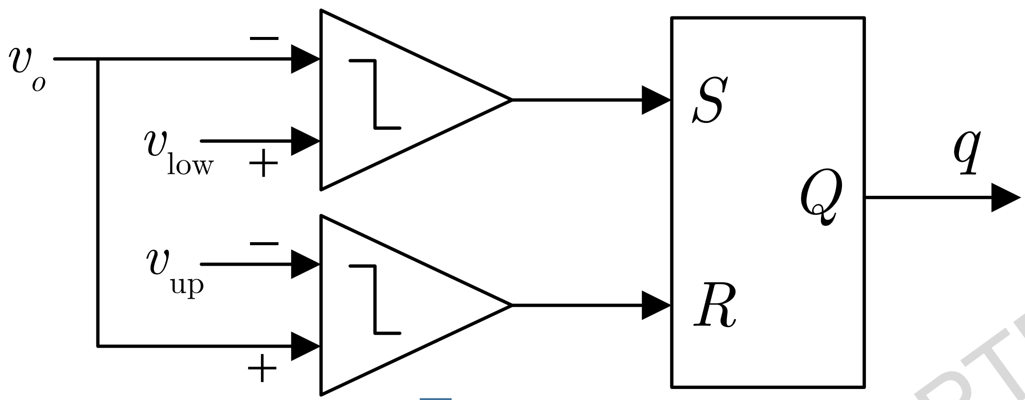
q – remains on and voltage v_o continues build

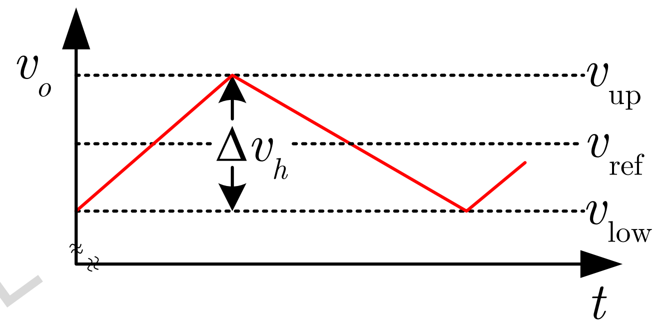
Voltage and current exceed limits !!



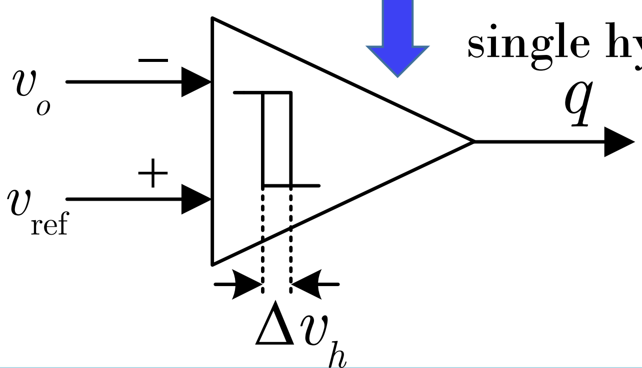
Voltage Regulation Issue – Simulation Case Study

Hysteresis Control Techniques





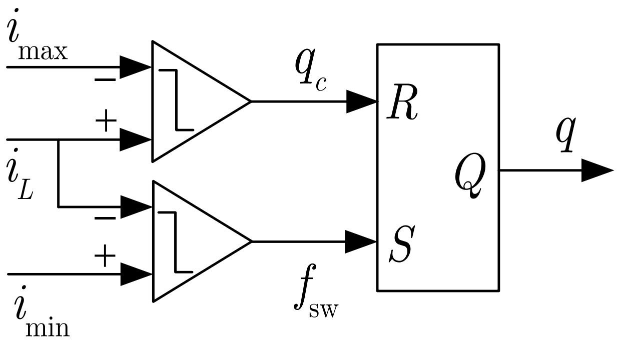
Can also be implemented using a single hysteresis comparator

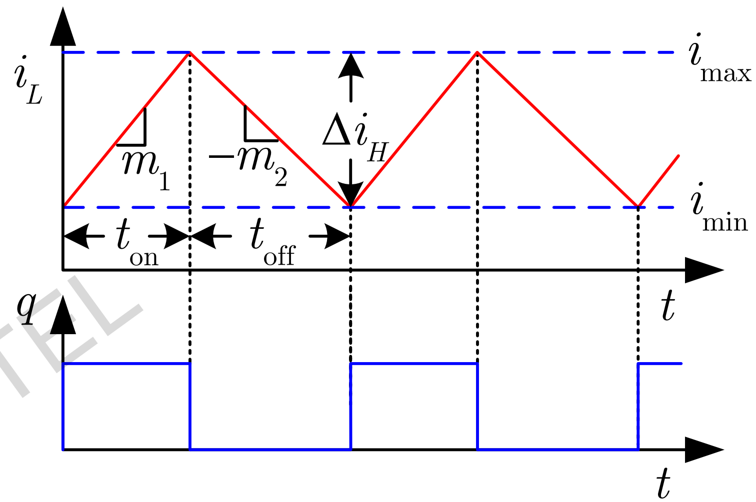


What happens for a Boost converter?

It may not work during a transient !!

Current Hysteresis Control





- For constant i_{min} and i_{max}

$$\underbrace{\Delta i_L}_{\text{Current ripple}} = \underbrace{\Delta i_H}_{\text{Current Hysteresis band}}$$

→ Current ripple independent of v_{in} , i_o

Current Hysteresis Control (contd…)

$$m_1 t_{\text{on}} = m_2 t_{\text{off}} \qquad \Rightarrow t_{\text{off}} = \left(\frac{m_1}{m_2}\right) t_{\text{on}}$$

$$m_1 t_{\text{on}} = \Delta i_H \qquad \Rightarrow t_{\text{on}} = \frac{\Delta i_H}{m_1}$$

$$T_{\text{sw}} = t_{\text{on}} + t_{\text{off}} \qquad = \left(1 + \frac{m_1}{m_2}\right) t_{\text{on}}$$

$$T_{\text{sw}} = \left(\frac{m_1 + m_2}{m_1 m_2}\right) \times \Delta i_H \qquad \boxed{f_{\text{sw}} = \left(\frac{m_1 m_2}{m_1 + m_2}\right) \times \frac{1}{\Delta i_H}}$$

Current Hysteresis Control

Buck converter

$$m_1 = \frac{V_{IN} - V_O}{L} \qquad m_2 = \frac{V_O}{L}$$

$$\frac{m_1 m_2}{m_1 + m_2} = \frac{\left(V_{IN} - V_O\right)V_O}{L\,V_{IN}}$$

$$\boxed{f_{sw} = \left(\frac{1}{L}\right)\times\left(\frac{1}{\Delta i_H}\right)\times\frac{\left(V_{IN} - V_O\right)V_O}{V_{IN}}}$$

- Switching frequency depends on
  - input/output voltages
  - hysteresis band
  - inductance value

sensitive to non-linear BH curve of inductor core!!!

Current Hysteresis Control in a Boost Converter

Boost converter

$$m_1 = \frac{V_{\mathrm{IN}}}{L} \qquad m_2 = \frac{V_O - V_{\mathrm{IN}}}{L}$$

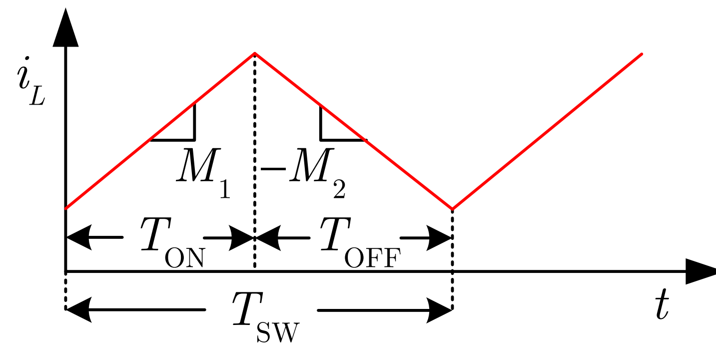
$$\frac{m_1 m_2}{m_1 + m_2} = \frac{V_{\mathrm{IN}}\left(V_O - V_{\mathrm{IN}}\right)}{L V_O}$$

$$\boxed{f_{\mathrm{sw}} = \left(\frac{1}{L}\right) \times \left(\frac{1}{\Delta i_H}\right) \times \frac{V_{\mathrm{IN}}\left(V_O - V_{\mathrm{IN}}\right)}{V_O}}$$

Steady-state Parameters under Constant ON-time

Buck converter

$$M_1 = \frac{V_{\text{IN}} - V_O}{L} \qquad M_2 = \frac{V_O}{L}$$



$$M_1 T_{\text{ON}} = M_2 T_{\text{OFF}}$$

$$\Rightarrow T_{\text{OFF}} = \left(\frac{M_1}{M_2}\right) T_{\text{ON}} = \frac{\left(V_{\text{IN}} - V_O\right)}{V_O} \times T_{\text{ON}}$$

$\boldsymbol{T_{\text{ON}}} \rightarrow$ **given**

$$\therefore T_{\text{OFF}} = \frac{\left(V_{\text{IN}} - V_O\right)}{V_O} \times T_C$$

$$T_{\text{ON}} = T_C$$

Constant ON-time – Buck Converter

$$T_{\mathrm{SW}} = T_{\mathrm{ON}} + T_{\mathrm{OFF}} = \frac{V_{\mathrm{IN}}}{V_O} \times T_C$$

$$f_{\mathrm{SW}} = \left(\frac{V_O}{V_{\mathrm{IN}}}\right) \times \frac{1}{T_C}$$

Varying switching frequency

$$\boxed{\Delta i_L = \left(\frac{V_{\mathrm{IN}} - V_O}{L}\right) \times T_C}$$

- Current ripple is maximum at $V_{\mathrm{IN,max}}$!!!
- Voltage ripple is maximum at $V_{\mathrm{IN,max}}$!!!

Steady-state Parameters under Constant ON-time

Boost converter

$$M_1 = \frac{V_{\mathrm{IN}}}{L} \qquad\qquad M_2 = \frac{V_O - V_{\mathrm{IN}}}{L}$$

$$T_{\mathrm{OFF}} = \left(\frac{M_1}{M_2}\right) T_{\mathrm{ON}} = \left(\frac{V_{\mathrm{IN}}}{V_O - V_{\mathrm{IN}}}\right) \times T_C$$

$$T_{\mathrm{SW}} = T_C + T_{\mathrm{OFF}} = \left(\frac{V_O}{V_O - V_{\mathrm{IN}}}\right) \times T_C$$

$$f_{\mathrm{SW}} = \left(\frac{V_O - V_{\mathrm{IN}}}{V_O}\right) \times \left(\frac{1}{T_C}\right)$$

Varying switching frequency

Constant ON-time – Boost Converter

$$\Delta i_L = M_1 \times T_C$$

$$\boxed{\Delta i_L = \frac{V_{IN}}{L} \times T_C}$$

- Current ripple is maximum at $V_{IN,max}$!!!
- Voltage ripple $\Delta v_o = \frac{-I_O}{C} \times T_C$
- Voltage ripple is maximum at $I_{O,max}$!!!

Steady-state Parameters under Constant OFF-time

- Calculate on-time T_{ON} in terms of T_C

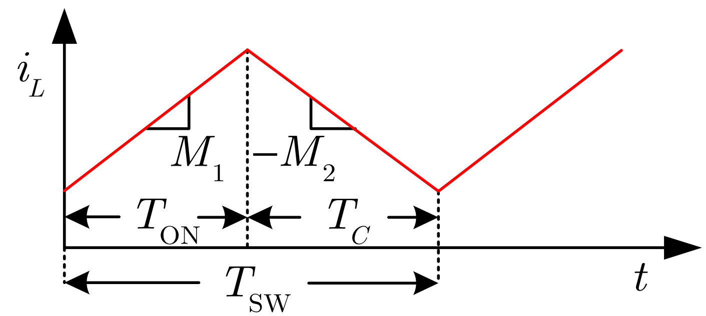
$$T_{\mathrm{ON}} = \left(\frac{M_2}{M_1}\right) T_C$$

- Calculate time-period T_{SW} in terms of T_C

$$T_{\mathrm{SW}} = T_{\mathrm{ON}} + T_C \Rightarrow T_{\mathrm{SW}} = \left(\frac{M_1 + M_2}{M_1}\right) T_C$$

- Calculate time-period T_{SW} in terms of T_C

$$\Delta i_L = M_2 \times T_C$$



- Off-time T_C is constant

Current Ripple under Constant Off-Time Modulation

Buck converter

$$M_1 = \frac{V_{IN} - V_O}{L} \qquad M_2 = \frac{V_O}{L}$$

$$f_{SW} = \left(\frac{V_{IN} - V_O}{V_{IN}}\right) \times \frac{1}{T_C}$$

Variable frequency

$$\boxed{\Delta i_L = M_2 \times T_C = \left(\frac{V_O}{L}\right) \times T_C}$$

Independent of $\boldsymbol{V_{IN}}$

Boost converter

$$M_1 = \frac{V_{IN}}{L} \qquad M_2 = \frac{V_O - V_{IN}}{L}$$

$$f_{SW} = \left(\frac{V_{IN}}{V_O}\right) \times \left(\frac{1}{T_C}\right)$$

Variable frequency

$$\boxed{\Delta i_L = M_2 \times T_C = \left(\frac{V_O - V_{IN}}{L}\right) \times T_C}$$

Maximum at $\boldsymbol{V_{IN,min}}$!!!

Summary

- Variable frequency modulation – alternatives to PWM
- Constant on-time modulation – gaining popularity
- Variable frequency modulation – switching frequency variations
- Minimum off/on-time required for constant on/off-time modulation
- Comparative simulation studies to be shown later!!

THANK YOU !

NPTEL ONLINE CERTIFICATION COURSES

COURSE NAME

Dr. Santanu Kapat
Electrical Engineering Department, IIT KHARAGPUR

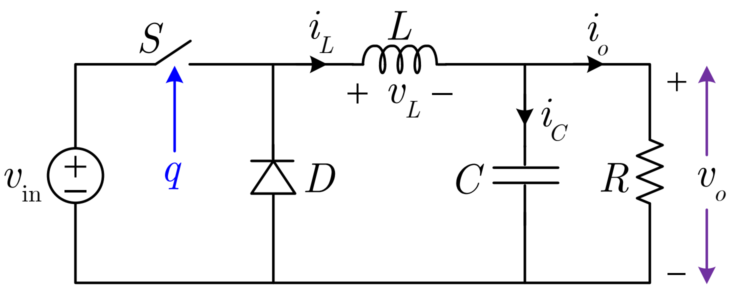
Module 02: Modulation techniques in SMPCs

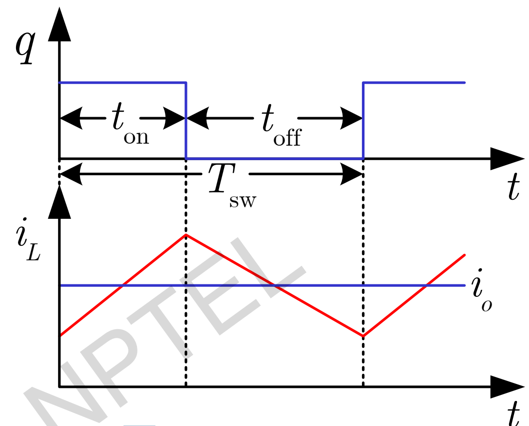
Lecture 10 : Modulation in Discontinuous Conduction Mode (DCM)

Concepts Covered

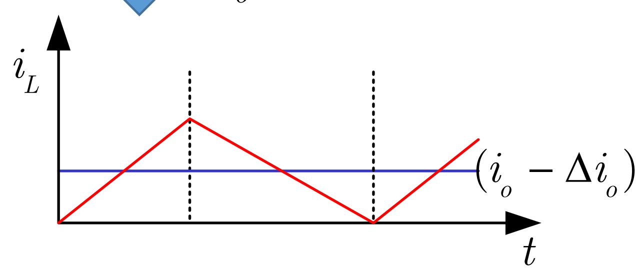
- Discontinuous mode (DCM) operation
- Steady-state analysis in DCM
- Pulse width modulation in DCM
- Pulse frequency modulation in DCM
- Pulse skip modulation in DCM

Critical Conduction Mode (CrM)

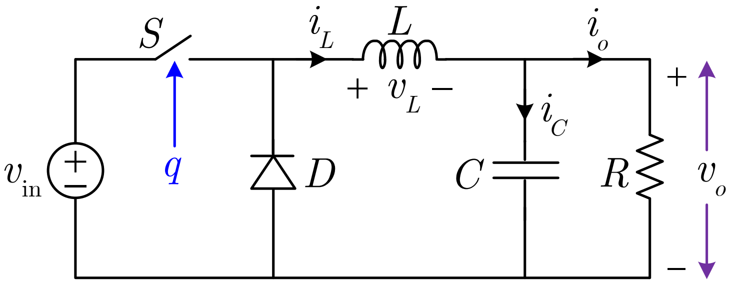


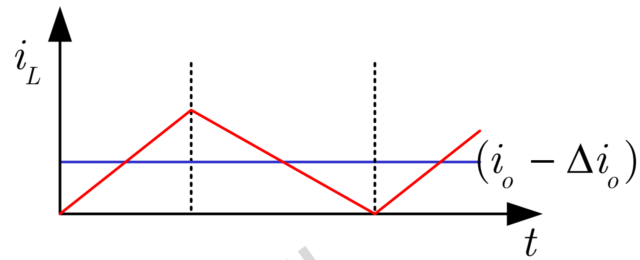


i_o **decreases to** $i_o - \Delta i_o$

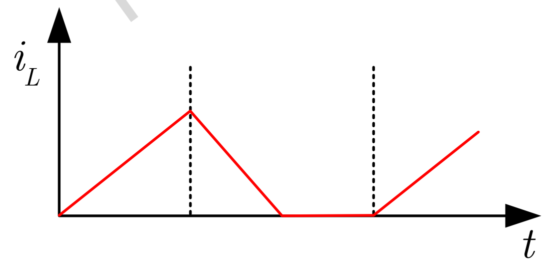


Discontinuous Conduction Mode (DCM)





i_o **further decreases to** $(i_o - 2\Delta i_o)$



Conditions for DCM in a Buck Converter

$$I_{av} = \frac{V_o}{R} = i_o \qquad \Delta i_L = m_1 t_{on} = \left(\frac{V_{in} - V_o}{L}\right) t_{on}$$

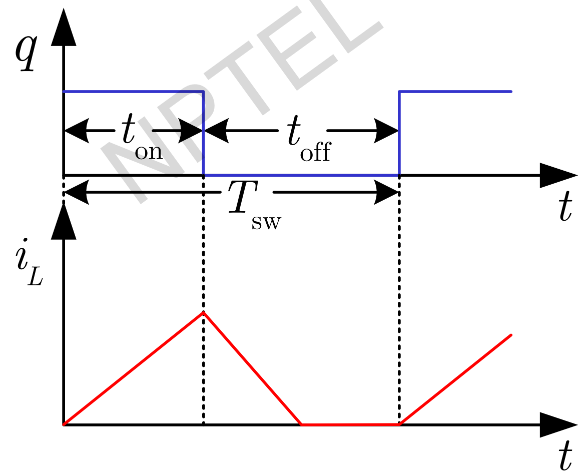
$I_{av} \rightarrow$ **Average value of i_L**

$\Delta i_L \rightarrow$ **ripple magnitude of i_L**

$$\left(I_{av} - \frac{\Delta i_L}{2}\right) > 0 \Rightarrow \textbf{CCM}$$

$$\left(I_{av} - \frac{\Delta i_L}{2}\right) = 0 \Rightarrow \textbf{CrM}$$

$$\left(I_{av} - \frac{\Delta i_L}{2}\right) < 0 \Rightarrow \textbf{DCM}$$



$$I_{\mathrm{av}} = \frac{V_o}{R} \qquad \Delta i_L = m_1 t_{\mathrm{on}} = \left(\frac{V_{\mathrm{in}} - V_o}{L}\right) t_{\mathrm{on}}$$

- Consider V_o to be constant – requirement for a voltage regulator
- Write V_{in} in terms of V_o $\Rightarrow$ $\frac{V_o}{V_{\mathrm{in}}} = \frac{t_{\mathrm{on}}}{t_{\mathrm{on}} + t_{\mathrm{off}}}$ $\Rightarrow$ $V_{\mathrm{in}} = \left(1 + \frac{t_{\mathrm{off}}}{t_{\mathrm{on}}}\right) V_o$

$$m_1 = \frac{V_{\mathrm{in}} - V_o}{L} = \frac{V_o}{L}\left[\left(1 + \frac{t_{\mathrm{off}}}{t_{\mathrm{on}}}\right) - 1\right] \Rightarrow \boxed{m_1 = \frac{V_o}{L} \times \frac{t_{\mathrm{off}}}{t_{\mathrm{on}}}}$$

$$\Delta i_L = m_1 t_{\mathrm{on}} = \frac{V_o}{L} \times t_{\mathrm{off}}$$

- **Now write** $\left(I_{av} - \frac{\Delta i_L}{2}\right)$ $\Rightarrow$ $\left(I_{av} - \frac{\Delta i_L}{2}\right) = \frac{V_o}{R} - \left(\frac{V_o}{L} \times t_{off}\right)$

$$\Downarrow$$

$$\left(I_{av} - \frac{\Delta i_L}{2}\right) = V_o\left(\frac{1}{R} - \frac{t_{off}}{L}\right)$$

- **For CrM:** $\frac{1}{R_C} - \frac{t_{off}}{L} = 0$ $\Rightarrow$ $R_C = \frac{L}{t_{off}}$ $\Rightarrow$ $R_C = \frac{L}{(T_{sw} - t_{on})}$

For DCM: $R > R_C$

For CCM: $R < R_C$

For CrM: $R = R_C$

DCM Operation of a Boost Converter

$$I_{av} = i_o \times \frac{T_{sw}}{t_{off}} = \frac{v_o}{R} \times \frac{T_{sw}}{t_{off}}$$

$$\Delta i_L = m_1 t_{on} = \frac{v_{in}}{L} t_{on}$$

- **Represent v_{in} in terms of v_o**

$$\frac{v_o}{v_{in}} = \frac{T_{sw}}{t_{off}} \Rightarrow v_{in} = \left(\frac{t_{off}}{T_{sw}}\right) v_o$$

$$\therefore \Delta i_L = \left(\frac{t_{on} t_{off}}{T_{sw} L}\right) v_o$$

- **Voltage gain K_V at CCM**

$$K_V = \frac{v_o}{v_{in}} = \frac{T_{sw}}{t_{off}}$$

DCM Operation of a Boost Converter (contd...)

Now write $\left(I_{\text{av}} - \frac{\Delta i_L}{2}\right)$

$$I_{\text{av}} - \frac{\Delta i_L}{2} = \left(\frac{v_o}{R} \times \frac{T_{\text{sw}}}{t_{\text{off}}}\right) - \left(\frac{t_{\text{on}} t_{\text{off}}}{2T_{\text{sw}} L} v_o\right)$$

$$= \left(\frac{v_o T_{\text{sw}}}{t_{\text{off}}}\right)\left(\frac{1}{R} - \frac{t_{\text{on}} t_{\text{off}}^2}{2L T_{\text{sw}}^2}\right)$$

Critical Resistance:

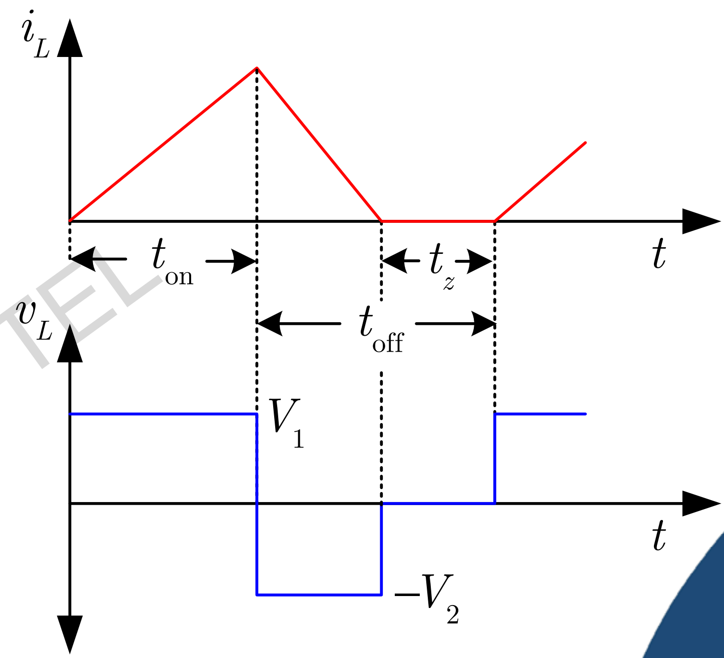
$$R_C = \left(\frac{2L}{t_{\text{on}}}\right) \times \left(\frac{T_{\text{sw}}}{t_{\text{off}}}\right)^2$$

Volt-second Balance in DCM

$$V_1 \times t_{\text{on}} - V_2 \times (t_{\text{off}} - t_z) = 0$$

$$V_1 = \begin{cases} (v_{\text{in}} - v_o) & \textbf{buck converter} \\ v_{\text{in}} & \textbf{boost converter} \end{cases}$$

$$V_2 = \begin{cases} v_o & \textbf{buck converter} \\ (v_o - v_{\text{in}}) & \textbf{boost converter} \end{cases}$$



Volt-second Balance in DCM (contd…)

Buck converter

$$\left(v_{\text{in}} - v_o\right)t_{\text{on}} = v_o\left(t_{\text{off}} - t_z\right)$$

$$\Rightarrow v_o\left(\underbrace{t_{\text{on}} + t_{\text{off}}}_{T_{\text{sw}}} - t_z\right) = v_{\text{in}} t_{\text{on}}$$

$$\Rightarrow K_V = \frac{v_o}{v_{\text{in}}} = \frac{t_{\text{on}}}{\left(T_{\text{sw}} - t_z\right)}$$

Boost converter

$$v_{\text{in}} t_{\text{on}} = \left(v_o - v_{\text{in}}\right)\left(t_{\text{off}} - t_z\right)$$

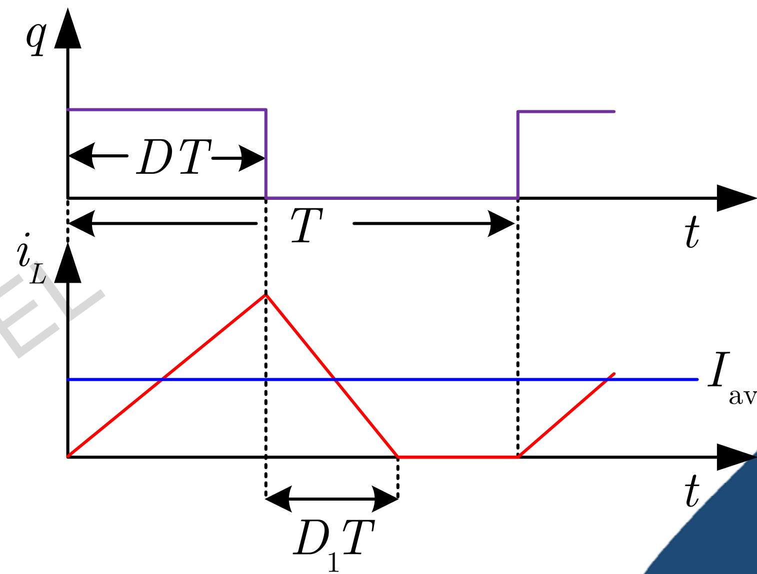
$$\Rightarrow v_o\left(t_{\text{off}} - t_z\right) = v_{\text{in}}\left(T_{\text{sw}} - t_z\right)$$

$$\Rightarrow K_V = \frac{v_o}{v_{\text{in}}} = \frac{\left(T_{\text{sw}} - t_z\right)}{\left(t_{\text{off}} - t_z\right)}$$

Pulse Width Modulation in DCM

$$I_{av} = \begin{cases} I_o & \textbf{buck converter} \\ I_o\left(1 + \dfrac{v_{in}D^2T}{2I_oL}\right) & \textbf{boost converter} \end{cases}$$

$$v_o = \begin{cases} \dfrac{v_{in}}{1 + \dfrac{2I_oL}{v_{in}D^2T}} & \textbf{buck converter} \\ v_{in}\left(1 + \dfrac{v_{in}D^2T}{2I_oL}\right) & \textbf{boost converter} \end{cases}$$



Pulse Width Modulation in DCM(contd…)

In DCM

Inductor voltage:

$$v_L = \begin{cases} V_1 & 0 < t \le DT \\ -V_2 & DT < t \le (D + D_1)T \\ 0 & (D + D_1)T < t \le T \end{cases}$$

Voltages	Buck	Boost
V_1	$(V_{IN} - V_O)$	V_{IN}
V_2	V_O	$(V_O - V_{IN})$

Capacitor current:

$$i_C = \begin{cases} I_1 & 0 < t \le DT \\ I_2 & DT < t \le (D + D_1)T \\ I_3 & (D + D_1)T < t \le T \end{cases}$$

Currents	Buck	Boost
I_1	$I_L - I_O$	$-I_O$
I_2	$I_L - I_O$	$I_L - I_O$
I_3	$-I_O$	$-I_O$

Pulse Width Modulation in DCM(contd…)

Using volt-second balance under PWM

$$V_1 D - V_2 D_1 = 0 \qquad \Rightarrow V_1 D = V_2 D_1$$

Buck converter

$$\left(V_{IN} - V_O\right) D = V_O D_1$$

$$\Rightarrow \frac{V_O}{V_{IN}} = \frac{D}{D + D_1}$$

Boost converter

$$V_{IN} D = \left(V_O - V_{IN}\right) D_1$$

$$\Rightarrow \frac{V_O}{V_{IN}} = \frac{D + D_1}{D_1}$$

Capacitor Charge Balance under DCM

$$m_1 DT = m_2 D_1 T \Rightarrow D_1 = \left(\frac{m_1}{m_2}\right) D$$

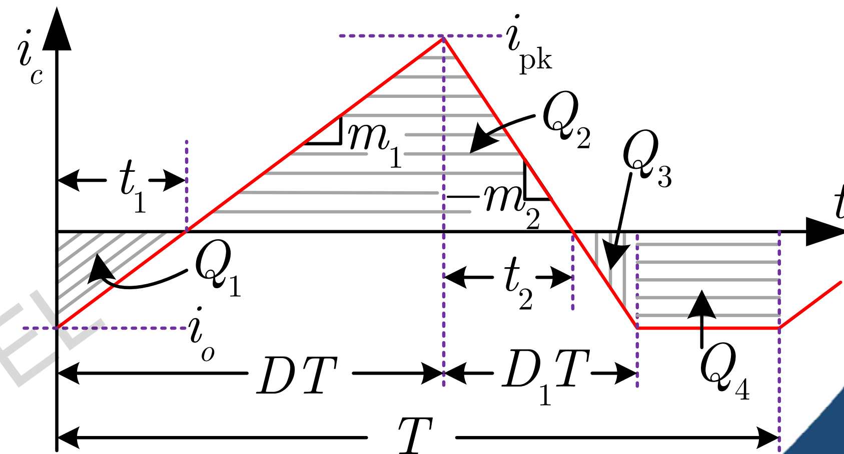
$$m_1 t_1 = i_o \Rightarrow t_1 = \frac{i_o}{m_1}$$

$$m_2 t_2 = i_o \Rightarrow t_2 = \frac{i_o}{m_2}$$

$$i_{\text{pk}} = -i_o + m_1 DT$$

$$Q_2 = \frac{1}{2}\left(i_{\text{pk}}\right) \times \left[\left(D_1 + D\right) - \left(t_1 + t_2\right)\right]$$

$$D_1 + D = \left(\frac{m_2}{m_1} + 1\right) D = \left(\frac{m_1 + m_2}{m_2}\right)$$

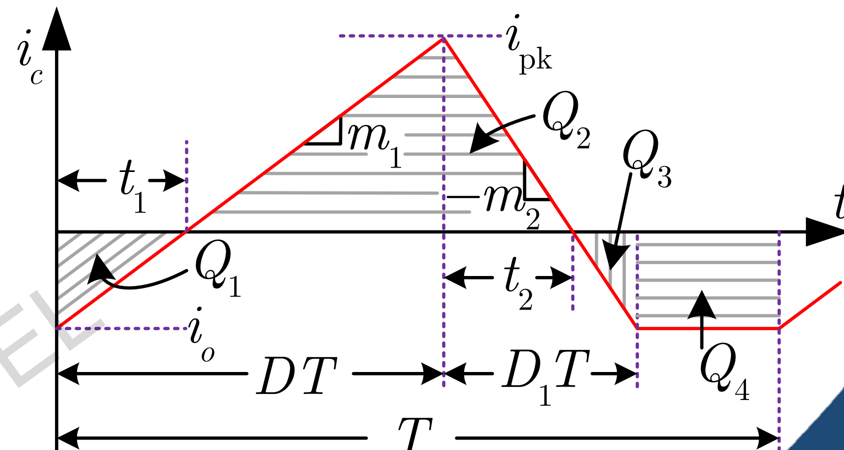


Capacitor Charge Balance under DCM (contd…)

$$t_1 + t_2 = i_o\left(\frac{1}{m_1} + \frac{1}{m_2}\right) = \left(\frac{m_1 + m_2}{m_1 m_2}\right) i_o$$

$$\therefore \left(D + D_1\right)T - \left(t_1 + t_2\right) = \left(\frac{m_1 + m_2}{m_2}\right)\left(DT - \frac{i_o}{m_1}\right)$$

$$= \left(\frac{m_1 + m_2}{m_1 m_2}\right)\left(m_1 DT - i_o\right)$$



$$Q_1 = -\frac{1}{2}t_1 i_o = -\frac{i_o^2}{2m_1} \qquad Q_2 = \frac{1}{2}\left(\frac{m_1+m_2}{m_1 m_2}\right)\times\left(m_1 DT - i_o\right)^2 \qquad Q_3 = -\frac{i_o^2}{2m_2}$$

$$Q_4 = -i_o\left(1-D-D_1\right)T$$

Charge balance $\sum Q = 0$

$$\Rightarrow \frac{1}{2}\left(\frac{m_1+m_2}{m_1 m_2}\right)\left(m_1 DT - i_o\right)^2 = \frac{1}{2}i_o^2\left(\frac{m_1+m_2}{m_1 m_2}\right) + i_o\left(1-D-D_1\right)T$$

$$\Rightarrow \frac{1}{2}\left(\frac{m_1+m_2}{m_1 m_2}\right)\left[\cancel{i_o^2} - 2m_1 DT i_o + m_1^2 D^2 T^2 - \cancel{i_0^2}\right] = i_o\left(1-D-D_1\right)T$$

$$\Rightarrow \left(\frac{m_1}{2m_2}\right)\left(m_1+m_2\right)D^2T^2 - \frac{\left(m_1+m_2\right)DT}{m_2}i_o = i_o\left(1-D-D_1\right)T$$

$$D + D_1 = \left(\frac{m_1 + m_2}{m_2}\right) D$$

$$\frac{(m_1 + m_2) m_1}{2m_2} D^2 T^2 - \cancel{\frac{(m_1 + m_2) m_1}{m_2}} i_o = i_o T - \cancel{\frac{(m_1 + m_2) m_1}{m_2}}$$

$$D^2 = \frac{2m_2}{m_1 (m_1 + m_2) T} i_o$$

For a Buck converter, $m_1 + m_2 = \frac{V_{\text{in}}}{L}, m_2 = \frac{V_o}{L}$

$$D^2 = \frac{2LV_o}{(V_{\text{in}} - V_o) V_{\text{in}} T} i_o \qquad \Rightarrow D = \sqrt{\frac{V_o i_o}{(V_{\text{in}} - V_o) V_{\text{in}}} \times \frac{L}{T}}$$

Constant ON-time Modulation in DCM

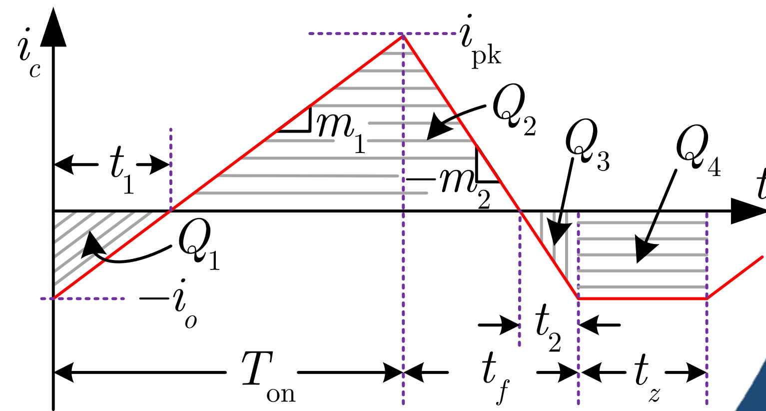
$$m_1 T_{\text{on}} = m_2 t_f \quad \Rightarrow t_f = \left(\frac{m_1}{m_2}\right) T_{\text{on}}$$

$$t_1 = \frac{i_o}{m_1} \qquad t_2 = \frac{i_o}{m_2}$$

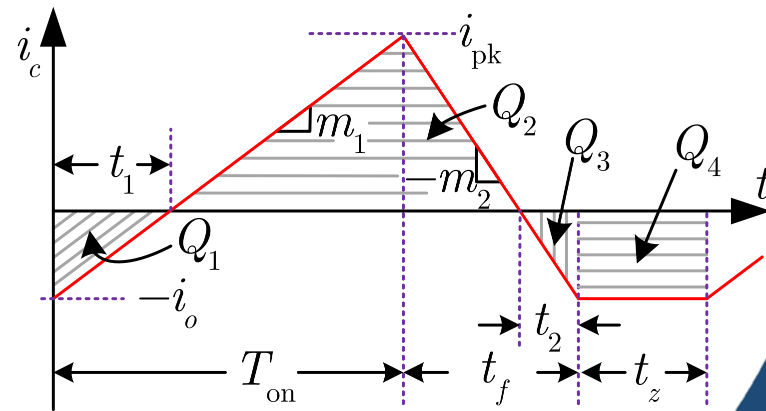
$$Q_2 = \frac{1}{2} i_{\text{pk}} \left(T_{\text{on}} + t_f - t_1 - t_2\right)$$

$$T_{\text{on}} + t_f = \left(1 + \frac{m_1}{m_2}\right) T_{\text{on}} = \left(\frac{m_1 + m_2}{m_2}\right) T_{\text{on}}$$

$$t_1 + t_2 = i_o \left(\frac{1}{m_1} + \frac{1}{m_2}\right) = \left(\frac{m_1 + m_2}{m_2}\right) i_o$$



$$T_{\text{on}} + t_f = \left(1 + \frac{m_1}{m_2}\right)T_{\text{on}} = \left(\frac{m_1 + m_2}{m_2}\right)T_{\text{on}}$$



$$t_1 + t_2 = i_o\left(\frac{1}{m_1} + \frac{1}{m_2}\right) = \left(\frac{m_1 + m_2}{m_2}\right)i_o$$

$$\left(T_{\text{on}} + t_f\right) - \left(t_1 + t_2\right) = \left(\frac{m_1 + m_2}{m_2}\right)\left(T_{\text{on}} - \frac{i_o}{m_1}\right) = \left(\frac{m_1 + m_2}{m_1 m_2}\right)\left(m_1 T_{\text{on}} - i_o\right)$$

$$i_{\text{pk}} = -i_o + m_1 T_{\text{on}} = \left(m_1 T_{\text{on}} - i_o\right)$$

$$Q_2 = \frac{1}{2}\left(\frac{m_1 + m_2}{m_1 m_2}\right)\left(m_1 T_{\text{on}} - i_o\right)^2$$

$$Q_1 = -\frac{i_o^2}{2m_1} \qquad Q_2 = \frac{1}{2}\left(\frac{m_1 + m_2}{m_1 m_2}\right)\left(m_1 T_{\text{on}} - i_o\right)^2 \qquad Q_3 = -\frac{i_o^2}{2m_2} \qquad Q_4 = -i_o t_z$$

$$Q_1 + Q_3 + Q_4 = -\frac{i_o^2}{2m_1 m_2}\left(m_1 + m_2\right) - i_o t_z$$

Charge balance $\sum Q = 0 \Rightarrow$

$$\frac{1}{2}\left(\frac{m_1 + m_2}{m_1 m_2}\right)\left(m_1 T_{\text{on}} - i_o\right)^2 = \left(\frac{m_1 + m_2}{2m_1 m_2}\right) i_o^2 + i_o t_z$$

$$\Rightarrow \left(\frac{m_1 + m_2}{2m_1 m_2}\right)\left(m_1^2 T_{\text{on}}^2 - 2m_1 T_{\text{on}} i_o + \cancel{i_o^2}\right) = \left(\frac{m_1 + m_2}{2\cancel{m_1} m_2}\right) i_o^2 + i_o t_z$$

$$t_z = T_{sw} - T_{on} - t_f \quad \Rightarrow t_z = T_{sw} - \left(\frac{m_1 + m_2}{m_2}\right) T_{on}$$

$$\frac{(m_1 + m_2) m_1}{2m_2} T_{on}^2 - \frac{(m_1 + \cancel{m_2})}{\cancel{m_2}} T_{on} i_o = i_o T_{sw} - \frac{(m_1 + \cancel{m_2})}{\cancel{m_2}} T_{on} i_o$$

$$T_{sw} = T_{on}^2 \times \frac{(m_1 + m_2) m_1}{m_2} \times \frac{1}{i_o}$$

$$f_{sw} = \frac{1}{T_{sw}} = \frac{2m_2}{\underbrace{(m_1 + m_2) m_1}} \times \frac{1}{T_{on}^2} \times i_o$$

$$\boxed{\frac{2V_o L}{V_{in}(V_{in} - V_o)}}$$

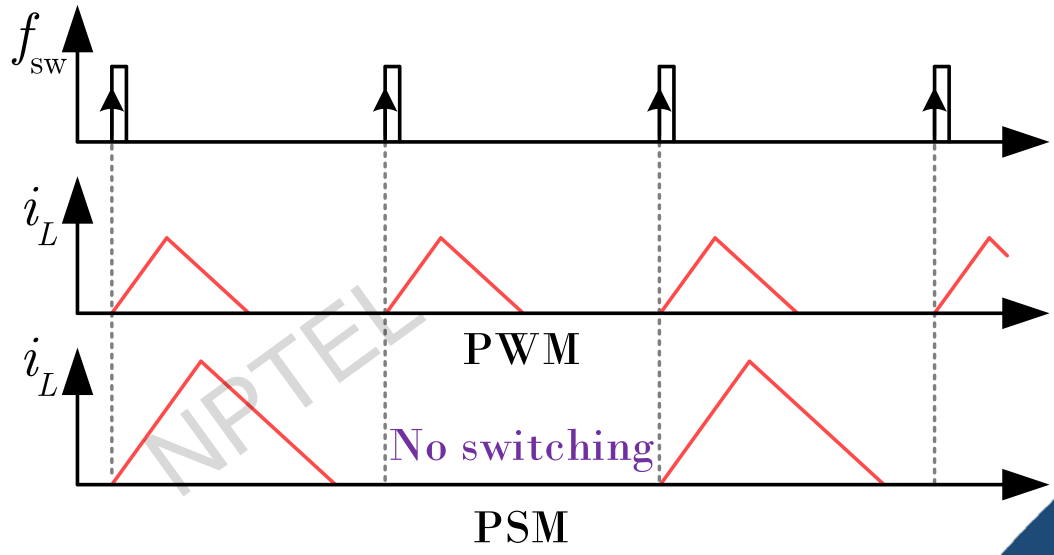
For a Buck converter, $m_1 + m_2 = \frac{V_{in}}{L}, m_2 = \frac{V_o}{L}$

$$f_{\mathrm{sw}} = \left[\frac{2V_o L}{V_{\mathrm{in}} \left(V_{\mathrm{in}} - V_o \right)} \right] \times \left(\frac{1}{T_{\mathrm{on}}} \right)^2 \times i_o$$

For given $V_{\mathrm{in}}, V_o, T_{\mathrm{on}}, L$

$$f_{\mathrm{sw}} \propto i_o$$

Pulse Skip Modulation



Summary

- Voltage gain in DCM – load dependent
- Under PWM, duty ratio decreases with load current in DCM
- Constant on-time – switching frequency decreases with load current
- Constant on-time modulation – frequently used under light load
- Pulse frequency modulation improves light load efficiency

THANK YOU !

NPTEL ONLINE CERTIFICATION COURSES

CONTROL AND TUNING METHODS IN SMPCs

Dr. Santanu Kapat
Electrical Engineering Department, IIT KHARAGPUR

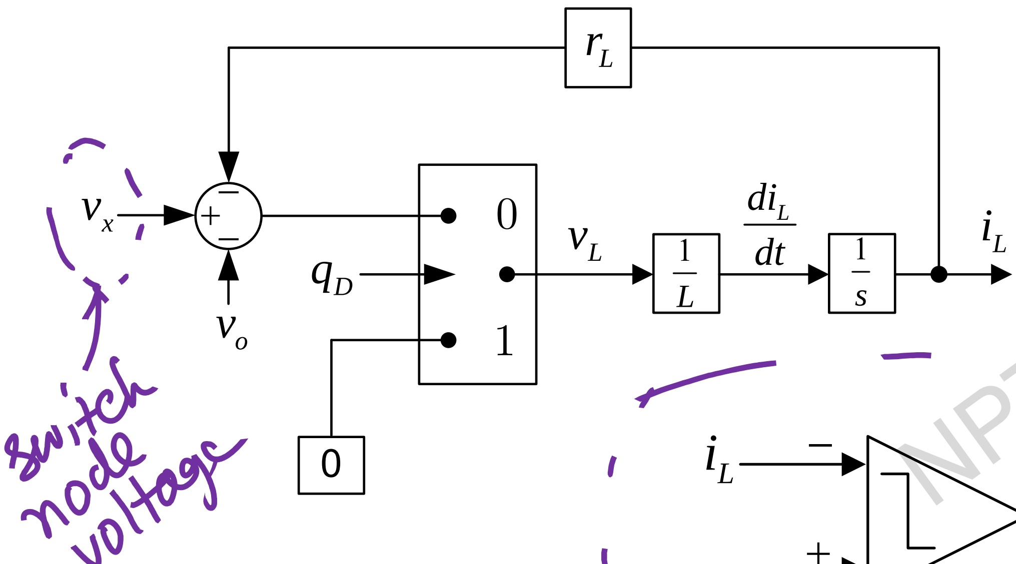
Module 02: Modulation techniques in SMPCs

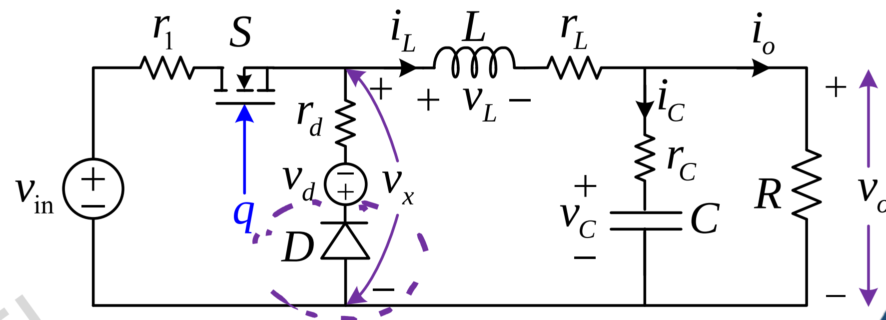
Lecture 11 : Synchronizing Simulation and Script files in MATLAB

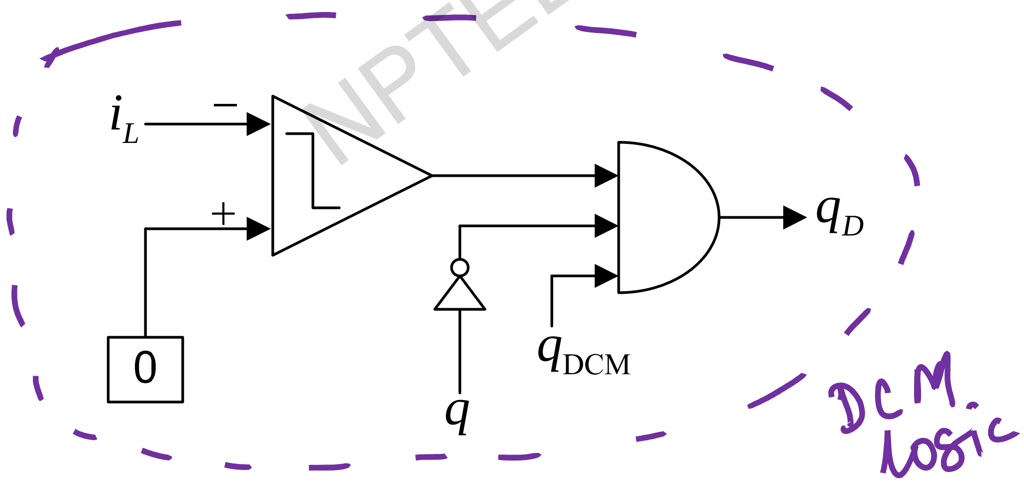
Concepts Covered

- Model development of SMPCs with DCM Enable
- Simulink model development of SMPCs with DCM Enable
- Synchronizing Simulink and script files in MATLAB
- Interactive simulation case studies

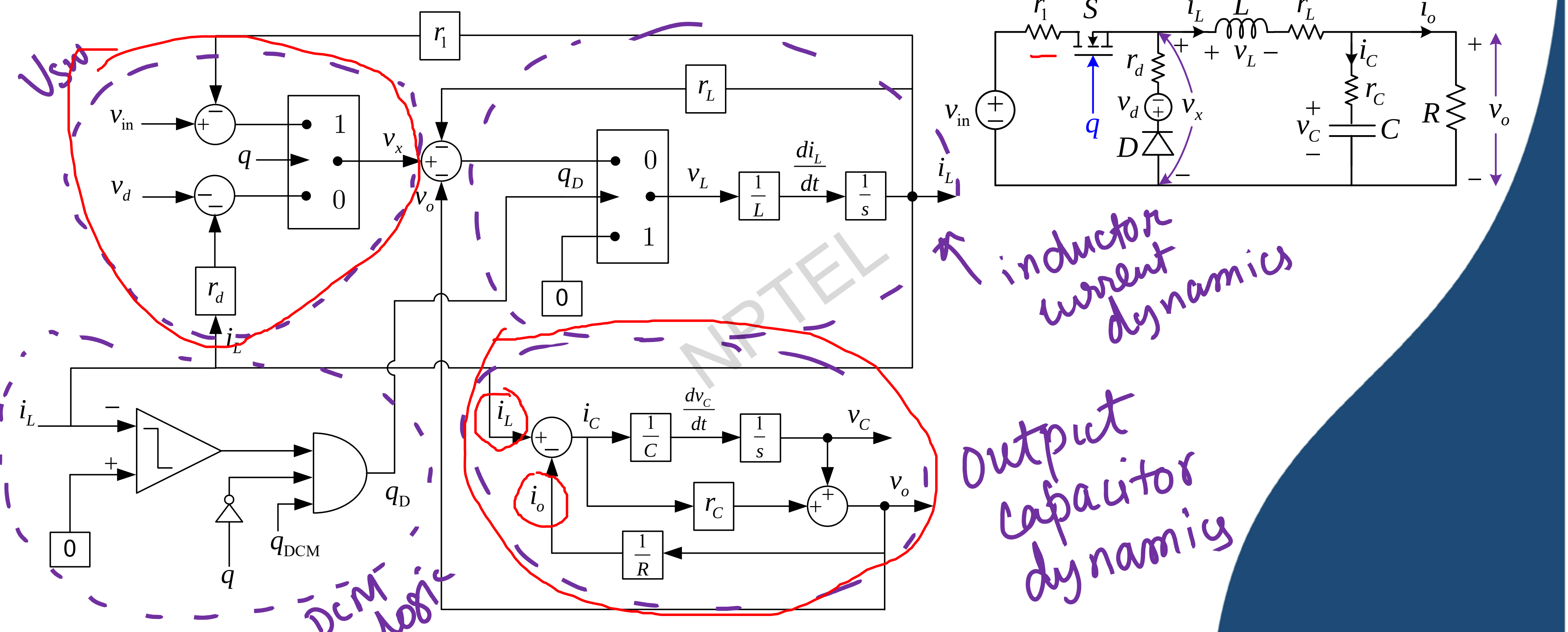
Block Diagram of a Conventional Buck Converter







Conventional Buck Converter – Complete Model

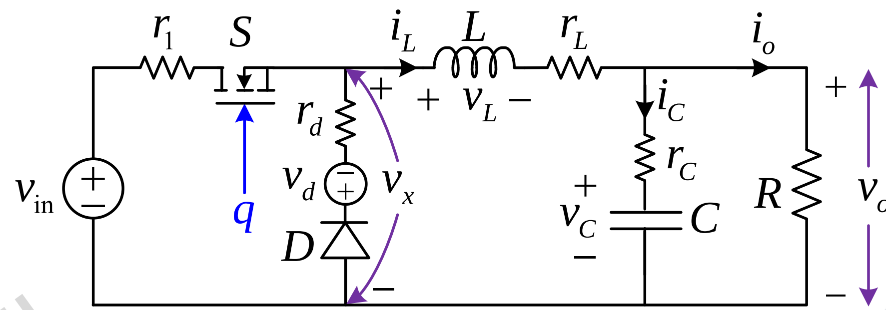


Conventional Buck Converter – Simulation Parameters

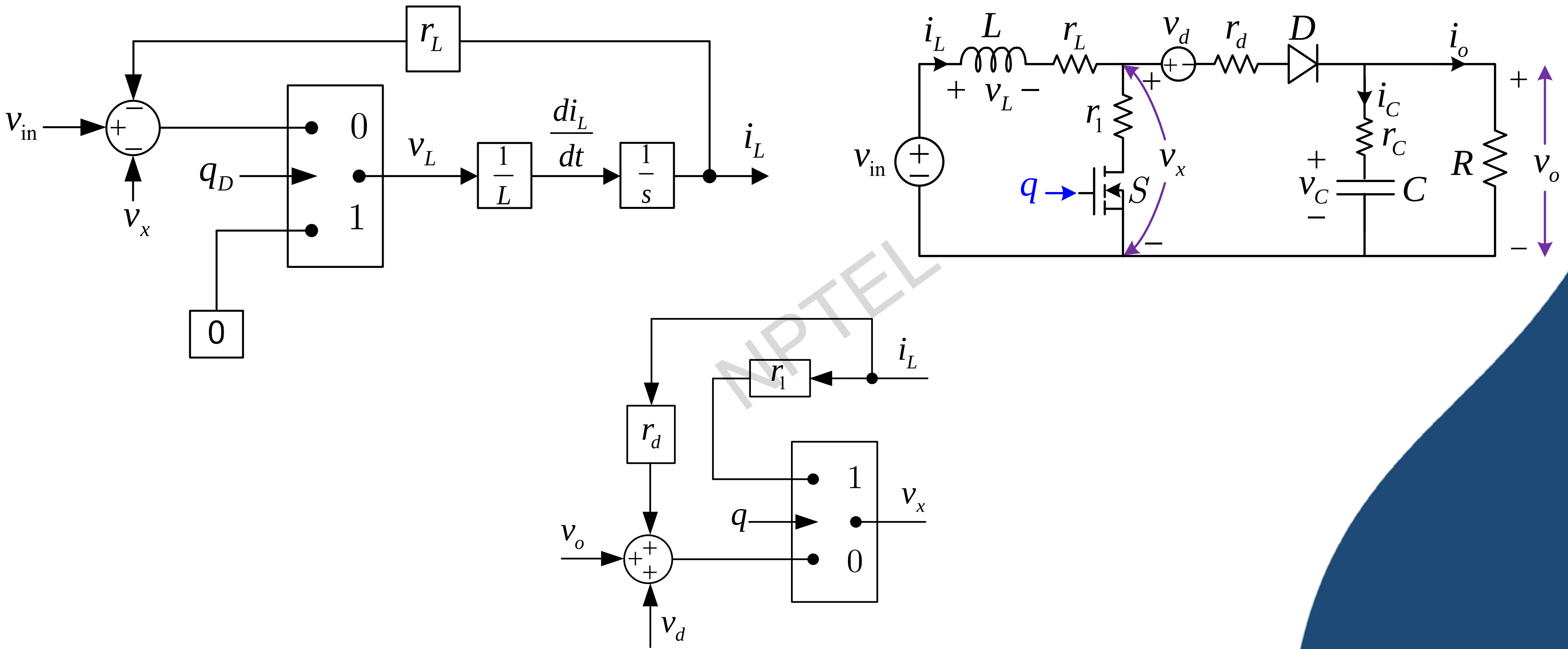
Output filter

Tsw

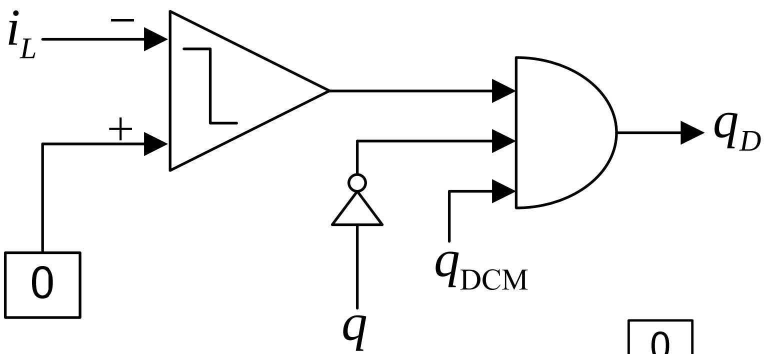
```
L=1e-6;         % output inductance
C=100e-6;       % output capacitance
T=1e-6;         % switching time period
r_L=10e-3;      % inductor DCR
r_d=10e-3;      % diode resistance
v_d=0*0.7;      % diode voltage drop
r_1=5e-3;       % Low-side MOSFET on resistance
r_2=5e-3;       % High-side MOSFET on resistance
r_C=5e-3;       % buck converter - capacitor ESR
V_up=10;        % Ramp peak voltage
V_b=0;          % Ramp base voltage
Vin=12;         % Input voltage
Vref=3.3;       % Reference output voltage in volt
```

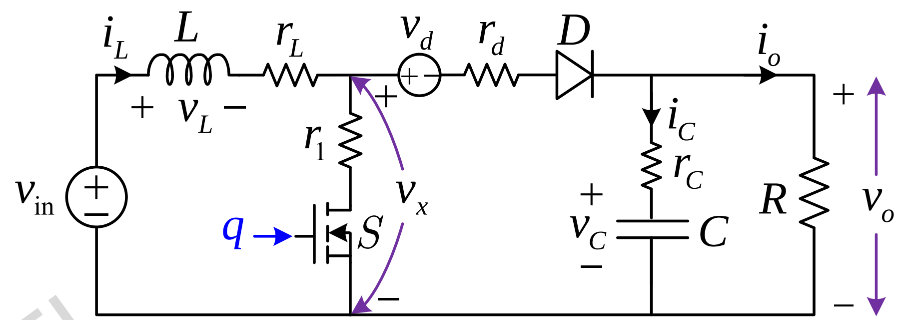


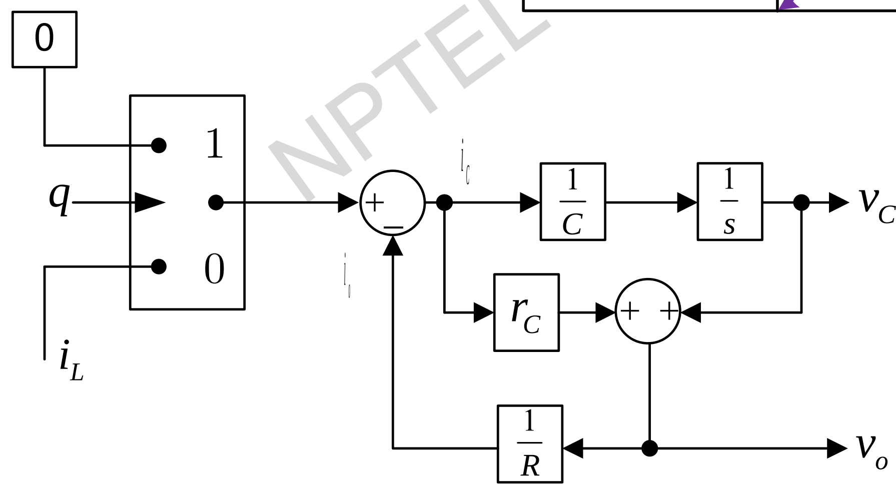
Block Diagram of a Conventional Boost Converter



Block Diagram of a Conventional Boost Converter







Summary

- Simulink models developed for conventional DC-DC converters
- Demonstrated DCM mode activation and deactivation features
- Demonstrated interactive MATLAB case studies
- Modulation techniques to be shown next

THANK YOU !

NPTEL ONLINE CERTIFICATION COURSES

CONTROL AND TUNING METHODS IN SMPCs

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Module 02: Modulation techniques in SMPCs

Lecture 12 : Interactive MATLAB Simulation and Case Studies

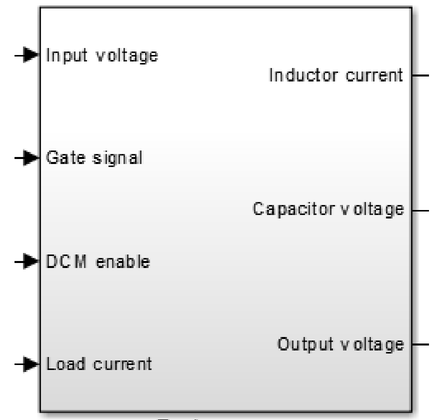
Concepts Covered

- Simulink and Script file Interactive Simulation
- Creation of Various Transient Test Cases
- Fixed Frequency and Variable Frequency Modulation

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
v_d=0.55; % diode voltage drop
r_1=5e-3; % High-side MOSFET on resistance
r_d=5e-3; % Low-side MOSFET on resistance
r_C=3e-3; % capacitor ESR
Vin=12; % input voltage
Vref=1; % reference output voltage
Io_max =20; % maximum load current

$f_{sw} = 500$ kHz

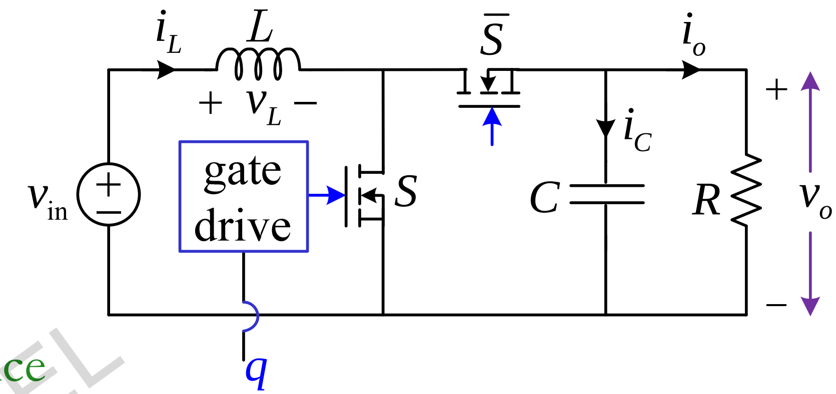


Buck converter

12 V to 1 V
PoL

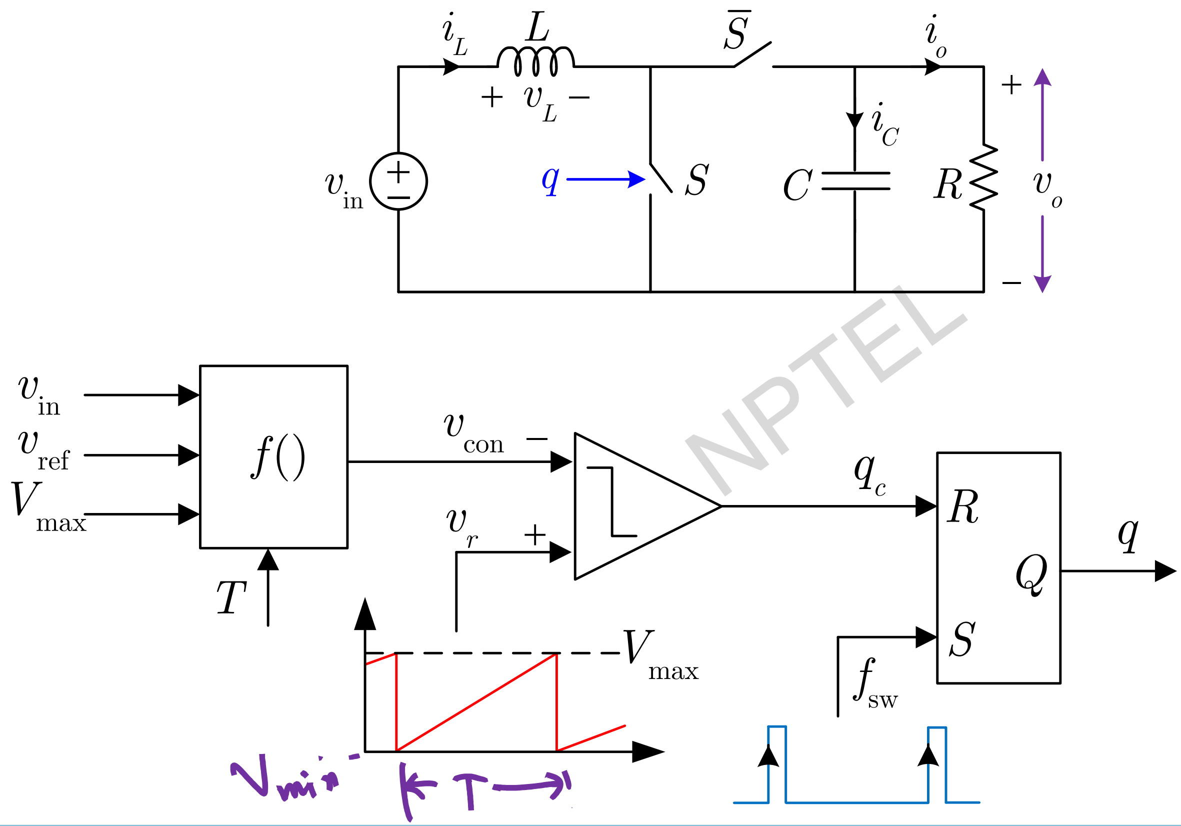
Boost Converter Parameters for Simulation

```
L=1e-6            % output inductance
C=47e-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_C=5e-3;         % capacitor ESR
Vin=3.3;          % input voltage (range – 2.5 to 4 V)
Vref=5;           % reference output voltage
Io_max =5;        % maximum load current
```



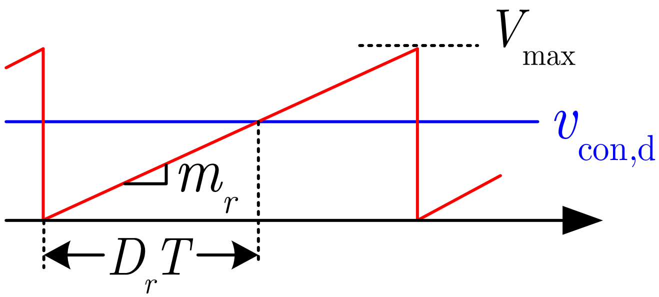
3.3 V to 5 V
boost converter

Trailing-edge PWM Control – Simulation



V_{max}

Setting Control Voltage Contd…



Desired constant voltage

$$v_{con,d} = m_r \times (D_r \times T) \qquad m_r = \frac{V_{max}}{T}, \qquad D_r \times T = \left(\frac{V_{ref} - V_{IN}}{V_{ref}}\right) \times T$$

$$v_{con,d} = V_{max} \times \left(\frac{V_{ref} - V_{IN}}{V_{ref}}\right)$$

$$\boxed{\therefore v_{con,d} = V_{max} \times \left(1 - \frac{V_{IN}}{V_{ref}}\right)}$$

Constant On-Time Modulation

- Turn ON problem

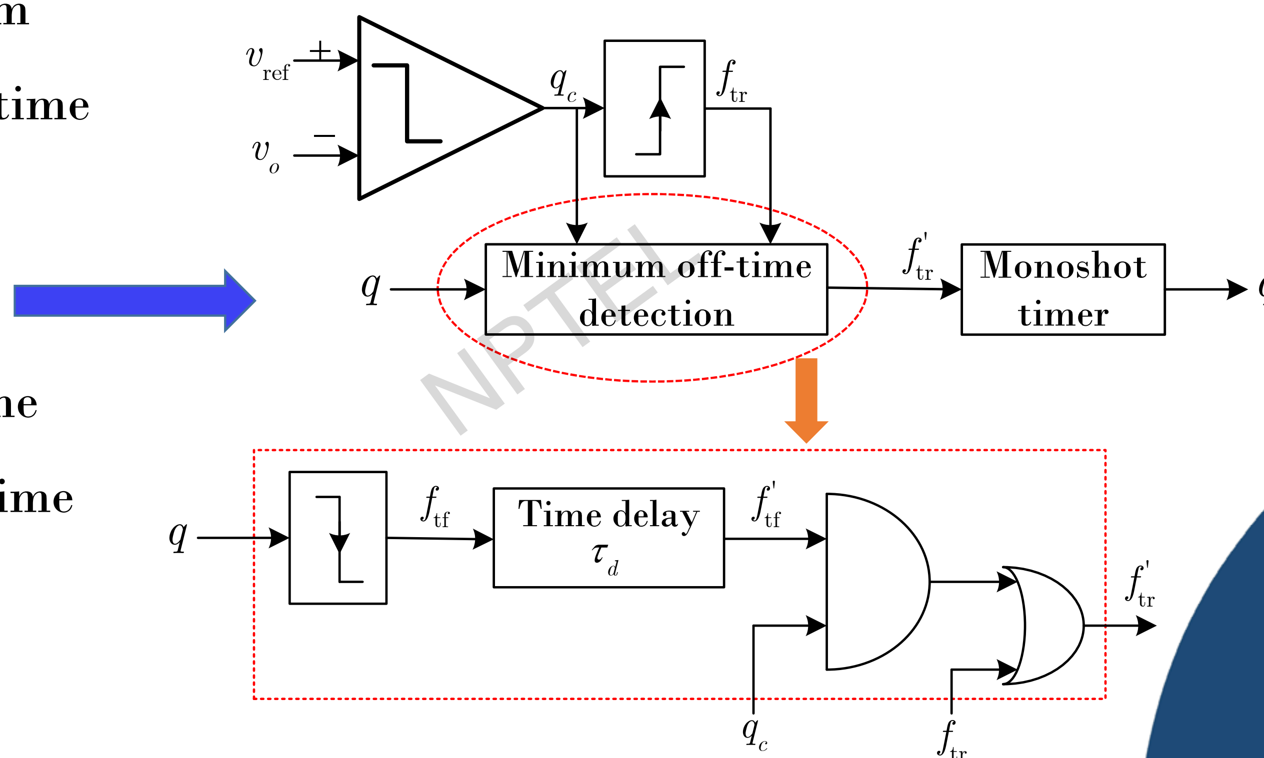
  in Constant on-time

- <u>Solution</u>:

  Introduce

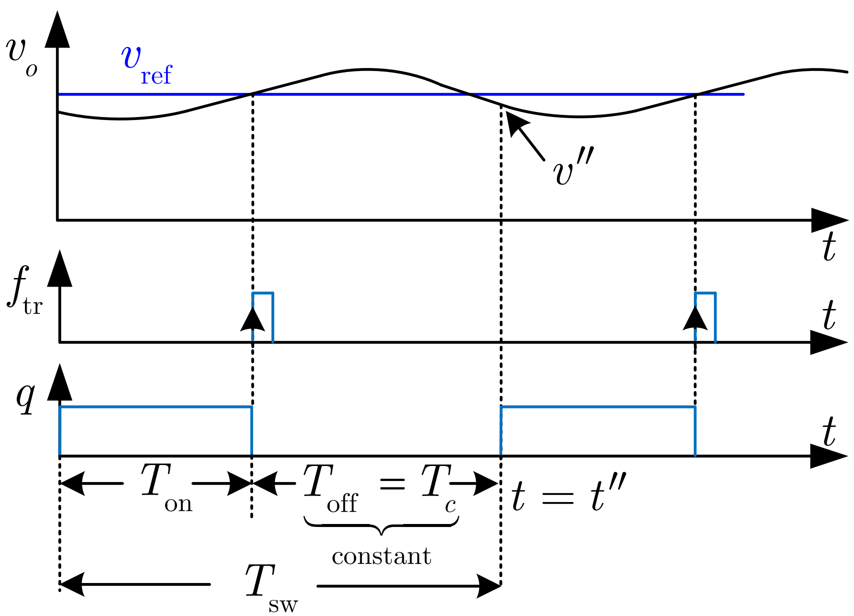
  minimum off-time

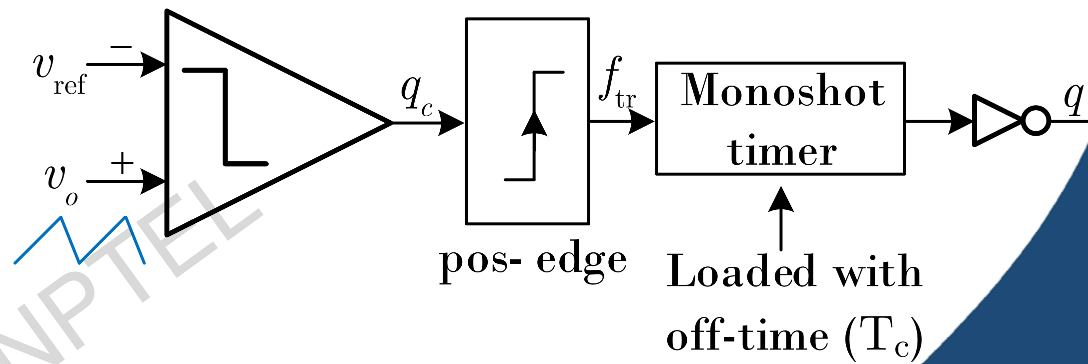
  in Constant on-time



Constant OFF-time Modulation

Voltage based implementation





Summary

- Simulink model development of fixed-frequency and variable-frequency modulators
- MATLAB simulation of buck and boost converters

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THANK YOU !