NPTEL ONLINE CERTIFICATION COURSES

DIGITAL CONTROL IN SMPCs AND FPGA-BASED PROTOTYPING

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Module 01: Introduction to Digital Control in SMPCs

Lecture 07: Recap of Fixed and Variable Frequency Modulation Techniques

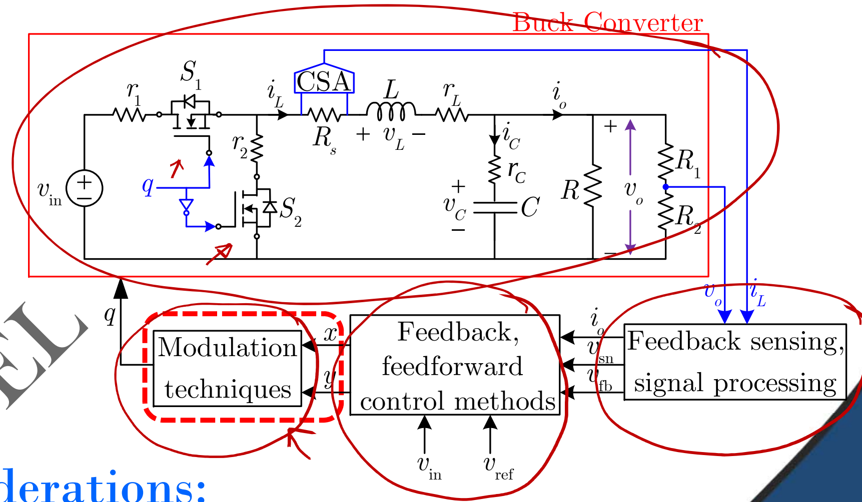
CONCEPTS COVERED

- Overview of fixed and variable frequency modulation techniques
- Summary of fixed frequency control methods
- Summary of variable frequency control methods
- Ripple parameters under fixed and variable frequency modulation
- Benefits and shortcomings in various modulation – Summary

Summary of Modulation Techniques

- Fixed frequency modulation
  - o Pulse width modulation
  - o Phase shift modulation
  - o Pulse skipping modulation

- Variable frequency modulation
  - o Constant on-time modulation
  - o Constant off-time modulation
  - o Hysteresis control



- Considerations:

ripple parameters, losses, stability, performance, switching frequency

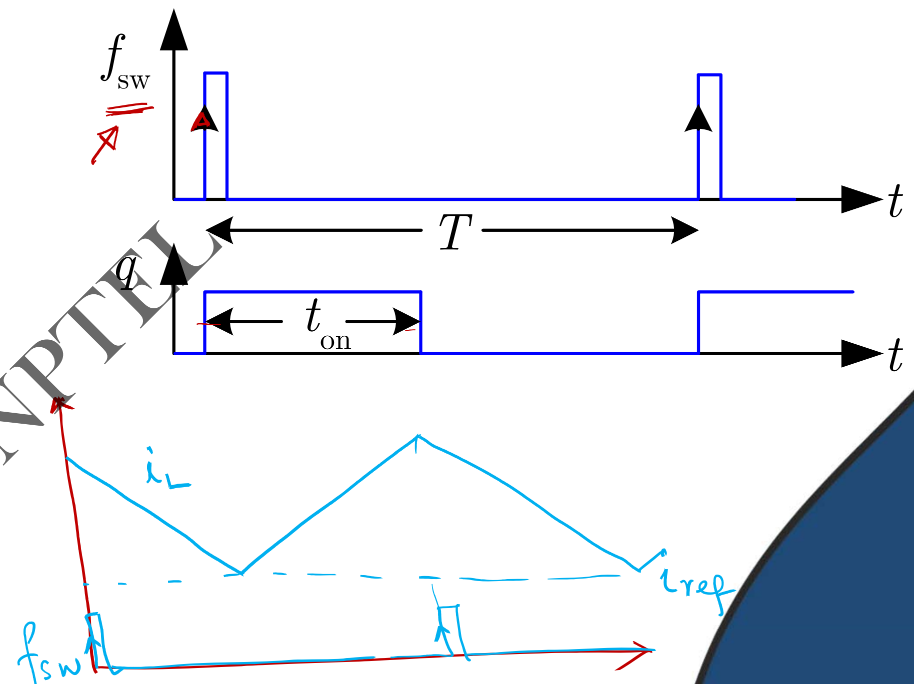
Why so many modulation techniques?

Fixed Frequency Control

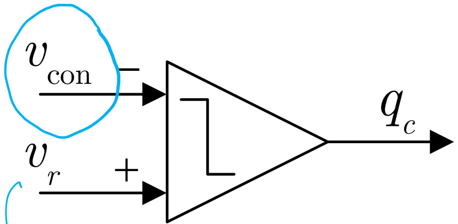
- Trailing-edge (TE) PWM
  - TE voltage mode control
  - Peak current mode control (CMC)
  - Average current mode control

- Leading-edge (LE) PWM
  - LE voltage mode control
  - Valley current mode control

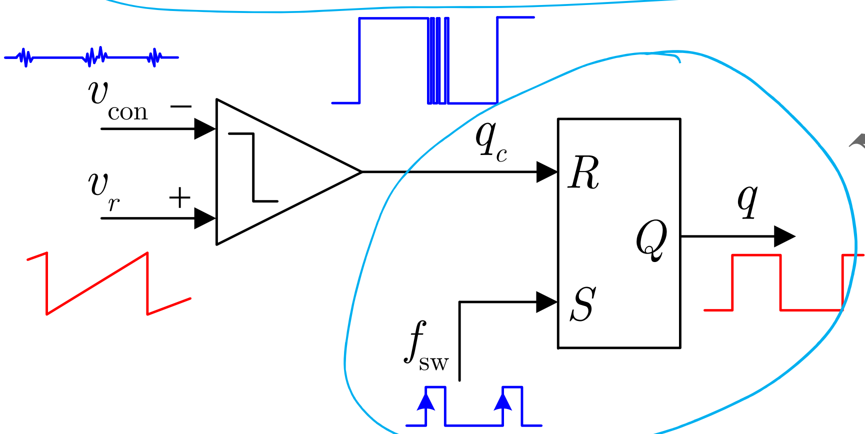
- Voltage mode or current mode pulse skip control



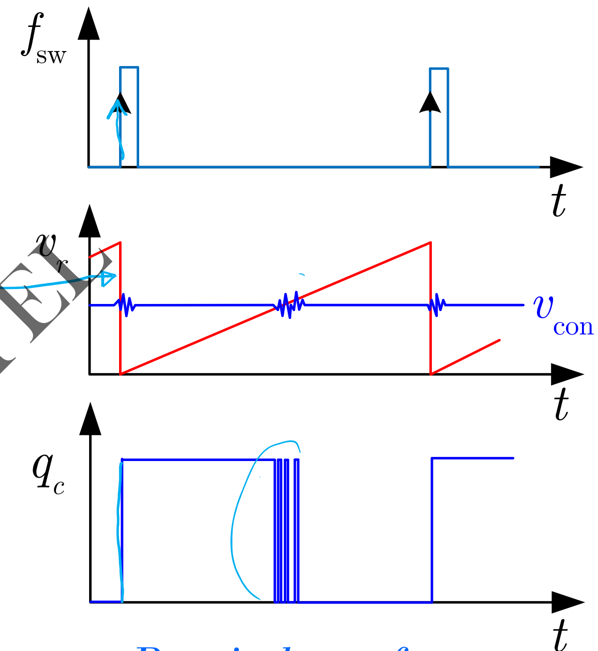
Trailing-edge PWM: Voltage Mode Control



Comparator

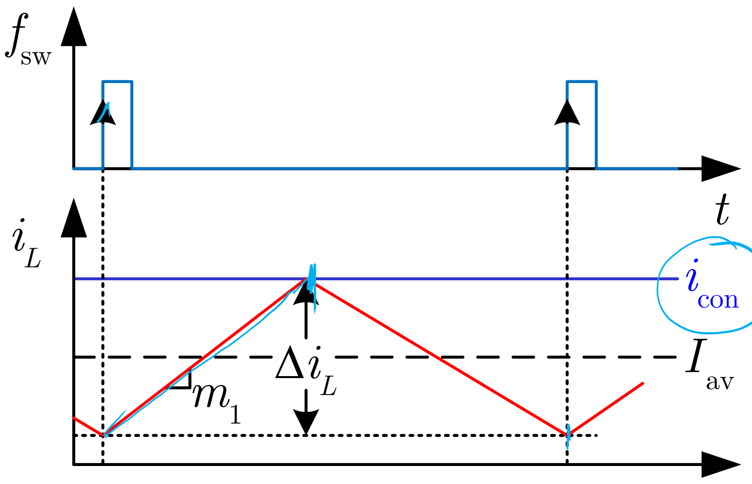


Noise Insensitive PWM operation

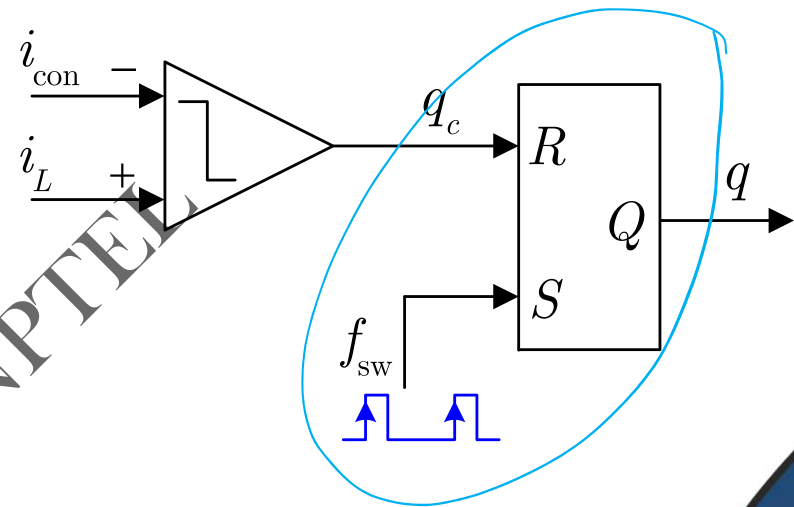


Practical waveforms

Trailing-edge PWM: Peak Current Mode Control

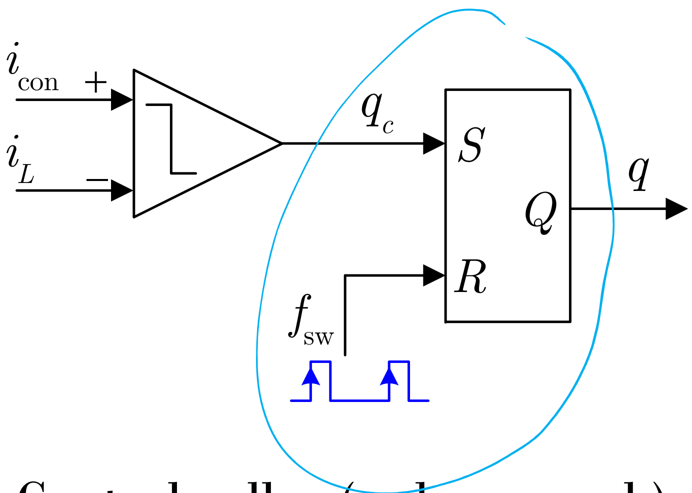


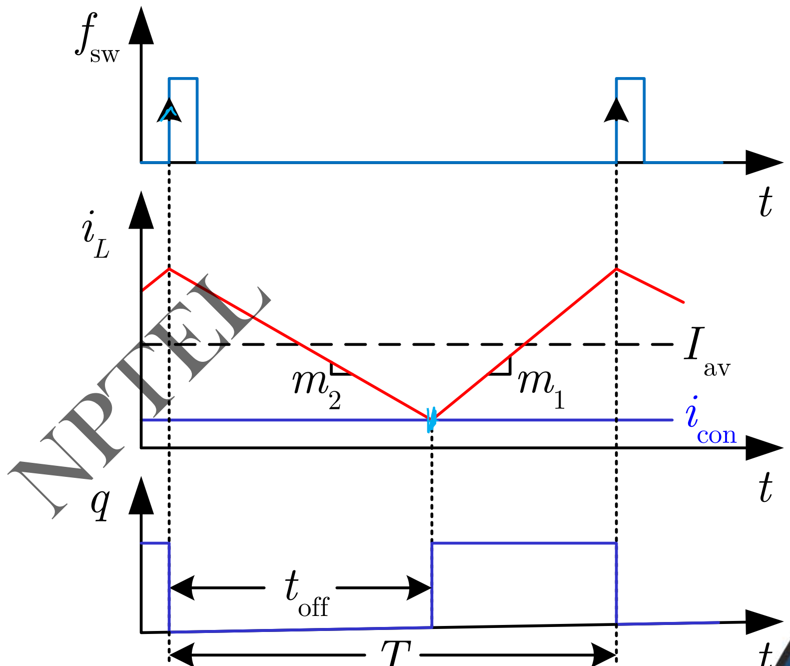
Control waveforms



- Control peak value of inductor current (known as Peak current mode control)

Leading-edge PWM: Valley Current Mode Control





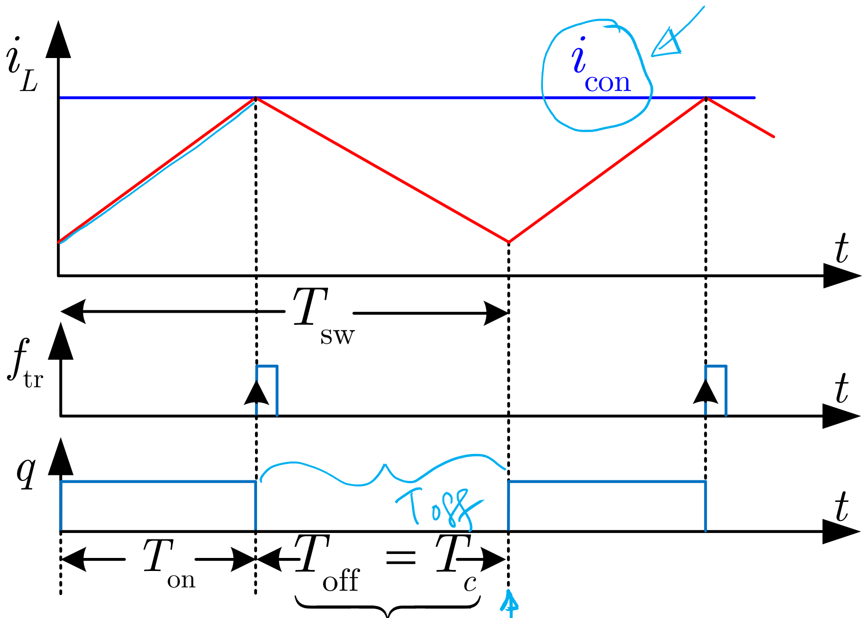
Control waveforms

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

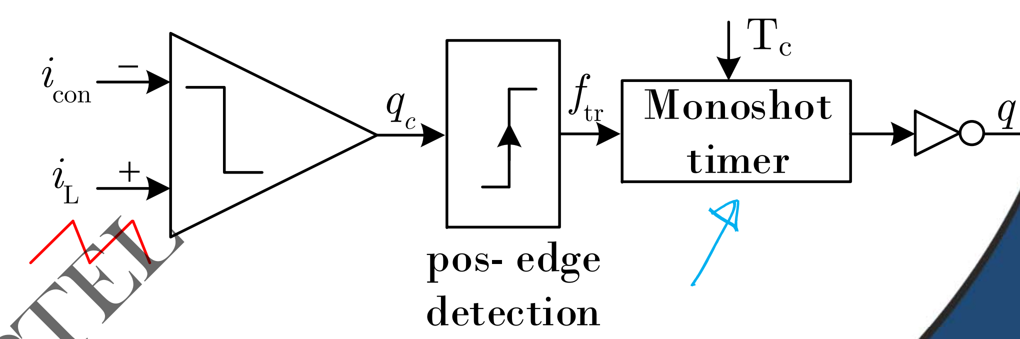
Variable Frequency Control

- Constant-off time (analogous to TE PWM)
    - Voltage control or peak current control
- Constant-on time (analogous to LE PWM)
    - Voltage control or valley current control
    - Current or voltage based adaptive on-time PFM control
- Hysteresis voltage or current control methods

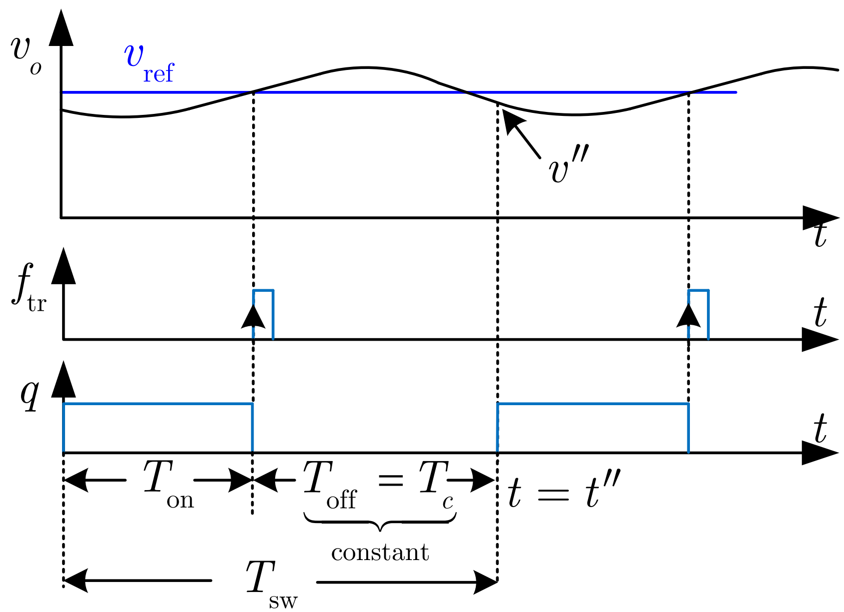
Constant Off-time Control

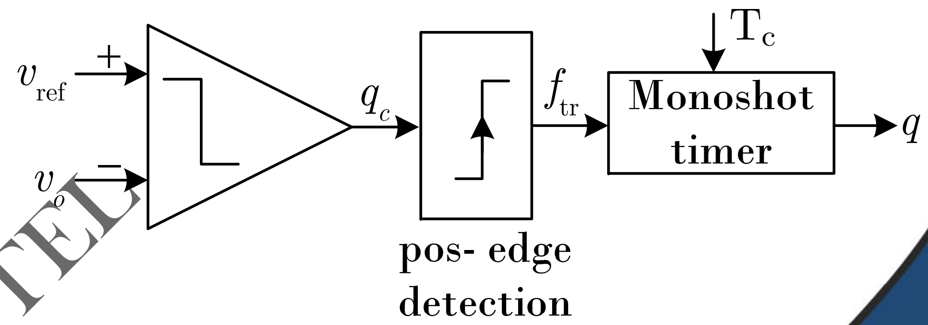


Control waveforms



Constant Off-time Control | *Voltage based implementation*

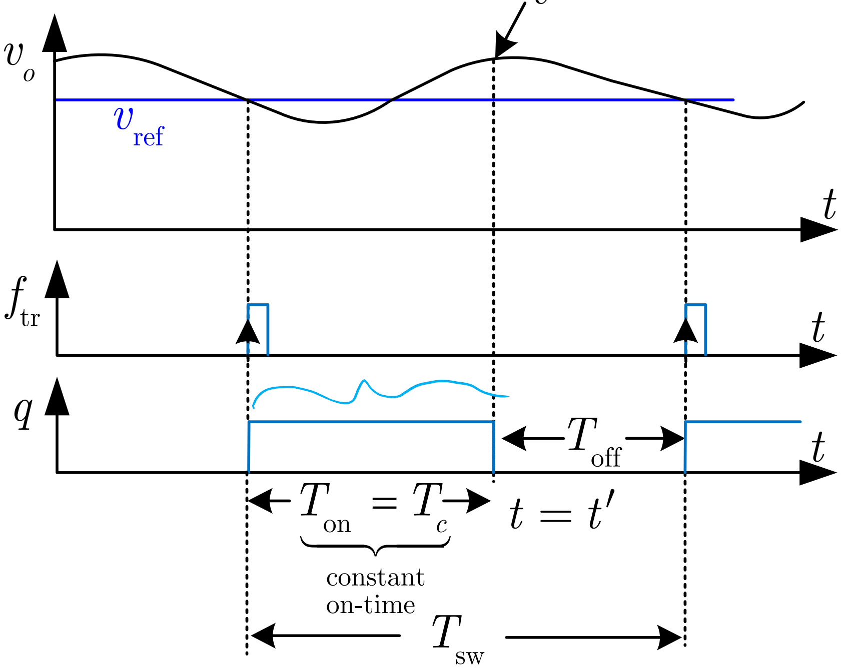


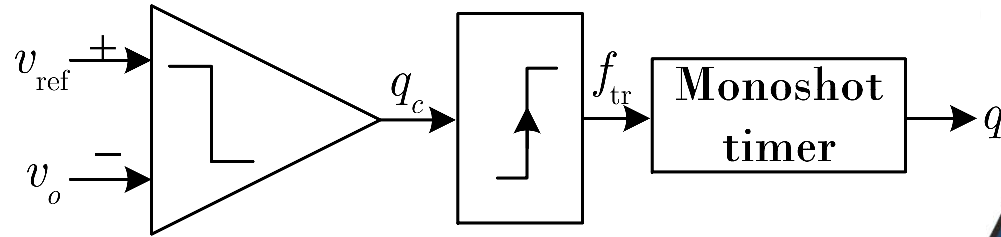


Why minimum on-time in constant off-time control ??

[For details, refer to Lecture~21, NPTEL "Control and Tuning Methods …" course (link)

Constant On-time Modulation

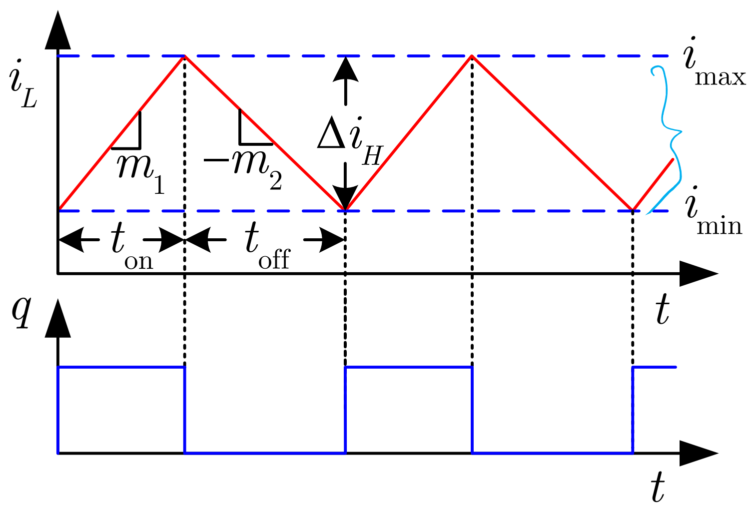


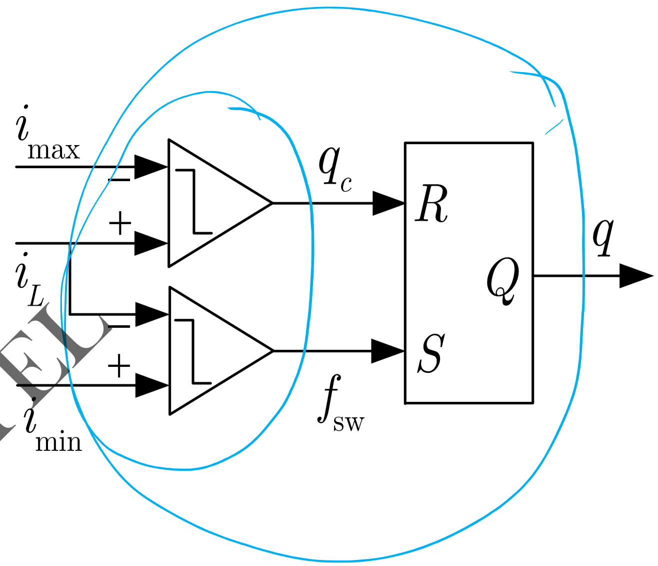


Why minimum off-time in constant on-time control ??

[For details, refer to Lecture~20, NPTEL "Control and Tuning Methods ..." course (link)

Current Hysteresis Control





[For details, refer to Lecture~22, NPTEL "Control and Tuning Methods ..." course (link)

Worst Case Inductor Current Ripple: Buck Converter in CCM

Modulation Technique	Current Ripple (Δi_L)	Worst case scenario
Pulse width modulation	$\frac{T}{L} \times V_o \left(1 - \frac{V_o}{V_{\text{in}}}\right)$	Highest input voltage
Constant on-time modulation	$\frac{T_{\text{on}}}{L} \times \left(V_{\text{in}} - V_o\right)$	Highest input voltage
Constant off-time modulation	$\frac{T_{\text{off}}}{L} \times V_o$	Insensitive to operating conditions

[For details, refer to Lecture~23, NPTEL "Control and Tuning Methods …" course (link)

Worst Case RMS Inductor Current: Buck Converter in CCM

Modulation Technique	RMS Current ($i_{L,\mathrm{rms}}$)	Worst case scenario
Pulse width modulation	$\sqrt{I_o^2 + \frac{1}{12}\left[\frac{TV_o}{L}\left(1 - \frac{V_o}{V_{\mathrm{in}}}\right)\right]^2}$	Highest input voltage and highest load current
Constant on-time modulation	$\sqrt{I_o^2 + \frac{1}{12}\left[\frac{T_{\mathrm{on}}}{L}\left(V_{\mathrm{in}} - V_o\right)\right]^2}$	Highest input voltage and highest load current
Constant off-time modulation	$\sqrt{I_o^2 + \frac{1}{12}\left(\frac{V_o T_{\mathrm{off}}}{L}\right)^2}$	Highest load current

[For details, refer to Lecture~23, NPTEL "Control and Tuning Methods …" course (link)

Switching Frequency: Buck Converter in CCM

Modulation Technique	Switching frequency (f_{sw})	Worst case scenario
Pulse width modulation	$f_{sw} = f_{ext}$	Insensitive to system and operating conditions
Constant on-time modulation	$f_{sw} = \frac{1}{T_{on}} \times \left(\frac{V_o}{V_{in}} \right)$	Highest switching frequency at lowest input voltage
Constant off-time modulation	$f_{sw} = \frac{1}{T_{off}} \times \left(1 - \frac{V_o}{V_{in}} \right)$	Highest switching frequency at highest input voltage

[For details, refer to Lecture~23, NPTEL "Control and Tuning Methods …" course (link)

Worst Case Inductor Current Ripple: Boost Converter in CCM

Modulation Technique	Current Ripple (Δi_L)	Worst case scenario
Pulse width modulation	$\frac{T}{L} \times \left[\frac{V_{in}}{V_o} \left(V_o - V_{in} \right) \right]$	Input voltage equals to half of the output voltage
Constant on-time modulation	$\frac{T_{on}}{L} \times V_{in}$	Highest input voltage
Constant off-time modulation	$\frac{T_{off}}{L} \times \left(V_o - V_{in} \right)$	Lowest input voltage

[For details, refer to Lecture~23, NPTEL "Control and Tuning Methods …" course (link)

Switching Frequency: Boost Converter in CCM

Modulation Technique	Switching frequency (f_{sw})	Worst case scenario
Pulse width modulation	$f_{sw} = f_{ext}$	Insensitive to system and operating conditions
Constant on-time modulation	$f_{sw} = \frac{1}{T_{on}} \times \left(1 - \frac{V_{in}}{V_o}\right)$	Highest switching frequency at lowest input voltage
Constant off-time modulation	$f_{sw} = \frac{1}{T_{off}} \times \frac{V_{in}}{V_o}$	Highest switching frequency at highest input voltage

[For details, refer to Lecture~23, NPTEL "Control and Tuning Methods …" course (link)

Fixed vs Variable Frequency Current Mode Control – Comparison

- Switching frequency
- Ripple parameters
- Transient performance
- Stability status

[For details, refer to Lecture~23, NPTEL "Control and Tuning Methods …" course (link)

CONCLUSION

- Overview of fixed and variable frequency modulation techniques
- Summary of fixed frequency control methods
- Summary of variable frequency control methods
- Ripple parameters under fixed and variable frequency modulation
- Benefits and shortcomings in various modulation – Summary

THANK YOU !