TAIWAN TECH
National Taiwan University of Science and Technology

Design and development practice of power electronic products

-Week 4

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Course content

- Principle of switching converter …1 week
- Understanding of components, materials and loss …2 weeks
- *Operation principle and application scope of common circuit architecture …2 weeks*
- Small signal model and stability analysis …3 weeks
- Basic control methods …1 week
- The stability of the cascade system …1 week
- Introduction and design of EMI conducted noise sources, coupling paths, and non-ideal filters …1 week

Course outline – Week 4

- **Take Buck as an example to illustrate the design and characteristics of the converter.**
  - Principles of converter derivation
    - Voltage/Ampere-second balance
  - Steps to derive converter conversion ratio based on the volt-second balance in C.C.M.
  - Buck converter under B.C.M and D.C.M operation
  - Component design process
  - The basic relationship between design parameters and efficiency performance
    - Effect of switching frequency
    - Effect of CCM/BCM/DCM operation
- **Basic non-isolated topology introduction**
  - Boost
  - Buck-Boost
  - SEPIC
- **Basic isolated topology introduction**
  - Reasons for electrical isolation requirement
  - Forward
  - Flyback
  - Half/Full bridge

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Voltage-second balance

Examine the voltage across an inductor that is operating in periodic steady state. The governing equation is

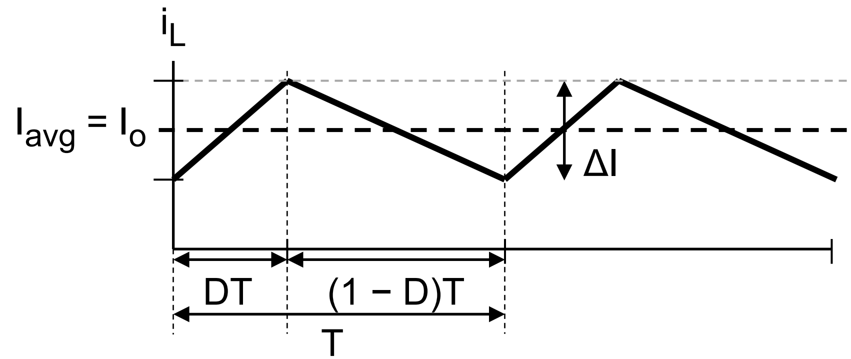
$$v(t) = L\frac{di(t)}{dt} \quad \text{which leads to} \quad i(t) = i(t_o) + \frac{1}{L}\int_{t_o}^{t_o+t} v(t)dt$$

Since the inductor is in periodic steady state, then the current at time t_o is the same as the current one period T later, so

$$i(t_o + T) = i(t_o),$$

or

$$i(t_o + T) - i(t_o) = 0 = \frac{1}{L}\int_{t_o}^{t_o+T} v(t)dt$$



The conclusion is that $\int_{t_o}^{t_o+T} v(t)dt = 0$ which means that

the average voltage across an inductor operating in periodic steady state is zero.

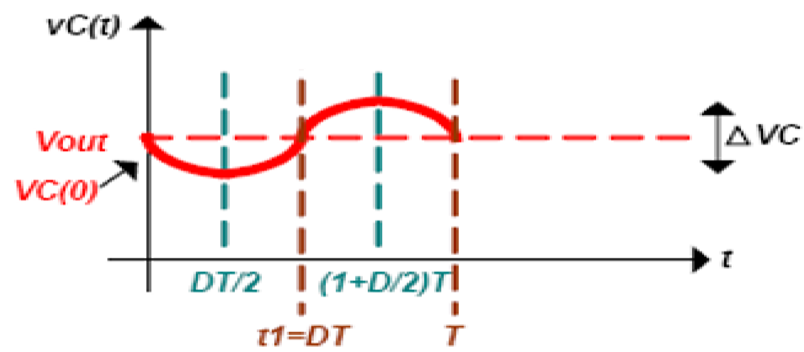
Amp-second balance

Examine the current passing through a capacitor that is operating in periodic steady state. The governing equation is

$$i(t) = C\frac{dv(t)}{dt} \quad \text{which leads to} \quad v(t) = v(t_o) + \frac{1}{C}\int_{t_o}^{t_o+t} i(t)dt$$

Since the capacitor is in periodic steady state, then the voltage at time t_o is the same as the voltage one period T later, so

$$v(t_o + T) = v(t_o),$$



or $$v(t_o + T) - v(t_o) = 0 = \frac{1}{C}\int_{t_o}^{t_o+T} i(t)dt$$

The conclusion is that $\int_{t_o}^{t_o+T} i(t)dt = 0$ which means that

the average current through a capacitor operating in periodic steady state is zero.

Inductor and Capacitor

In capacitors: $i(t) = C\dfrac{dv(t)}{dt}$ The voltage cannot change instantaneously

Capacitors tend to keep the voltage constant (voltage “inertia”). An ideal capacitor with infinite capacitance acts as a constant voltage source. Thus, a capacitor cannot be connected in parallel with a instantly changeable voltage source or a switch (otherwise KVL would be violated, i.e. there will be a short-circuit)

In inductors: $v(t) = L\dfrac{di(t)}{dt}$ The current cannot change instantaneously

Inductors tend to keep the current constant (current “inertia”). An ideal inductor with infinite inductance acts as a constant current source. Thus, an inductor cannot be connected in series with a instantly changeable current source or a switch (otherwise KCL would be violated)

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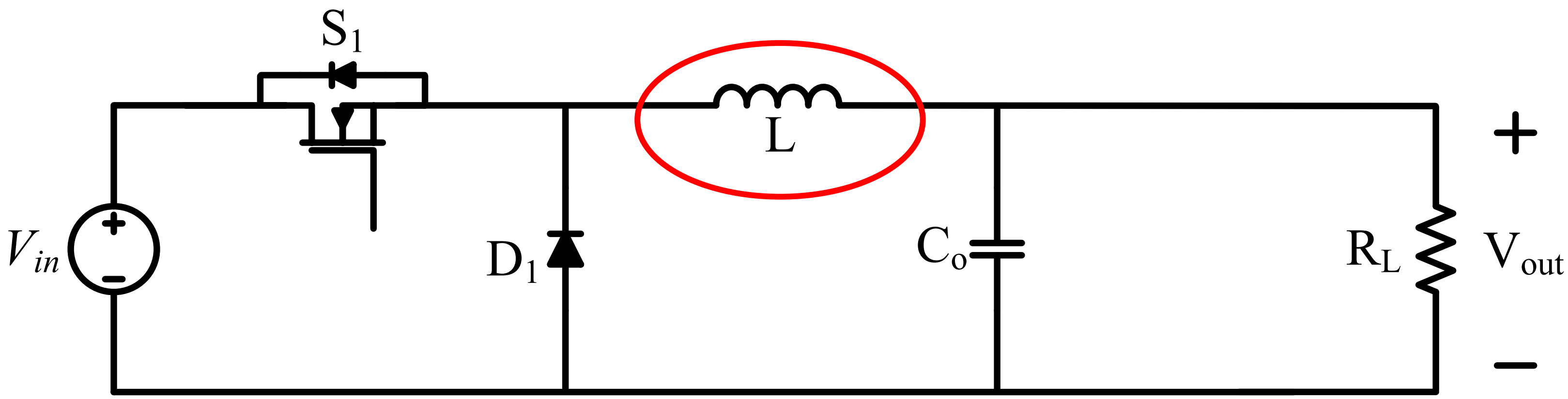
Principle of Buck converter



According to the current state can be divided into：

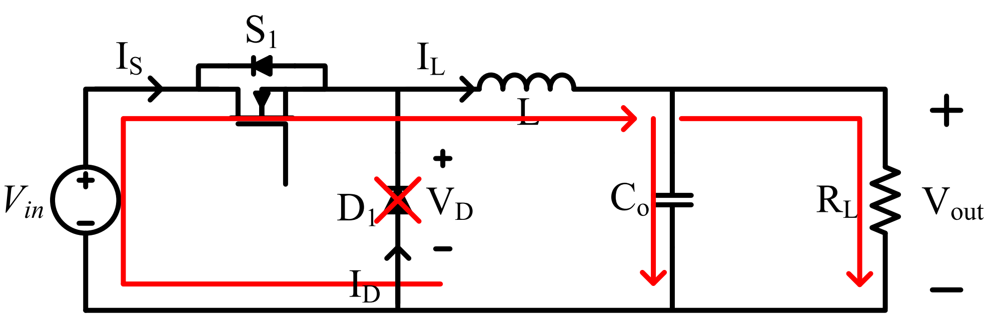
Continuous Conduction Mode (C.C.M.)

Boundary Conduction Mode (B.C.M.)

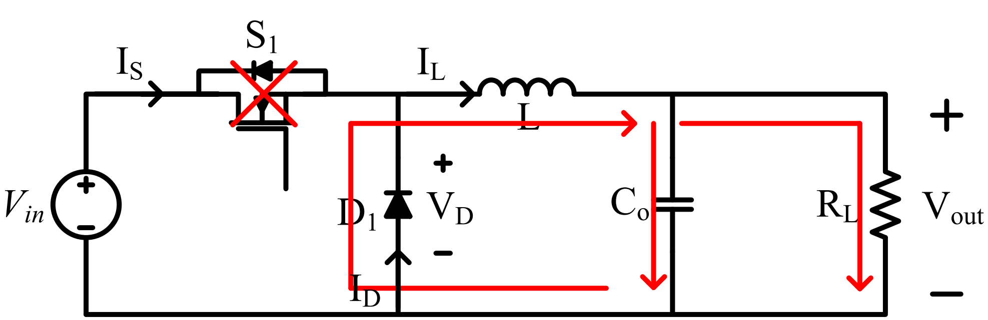
Discontinuous Conduction Mode (D.C.M.)

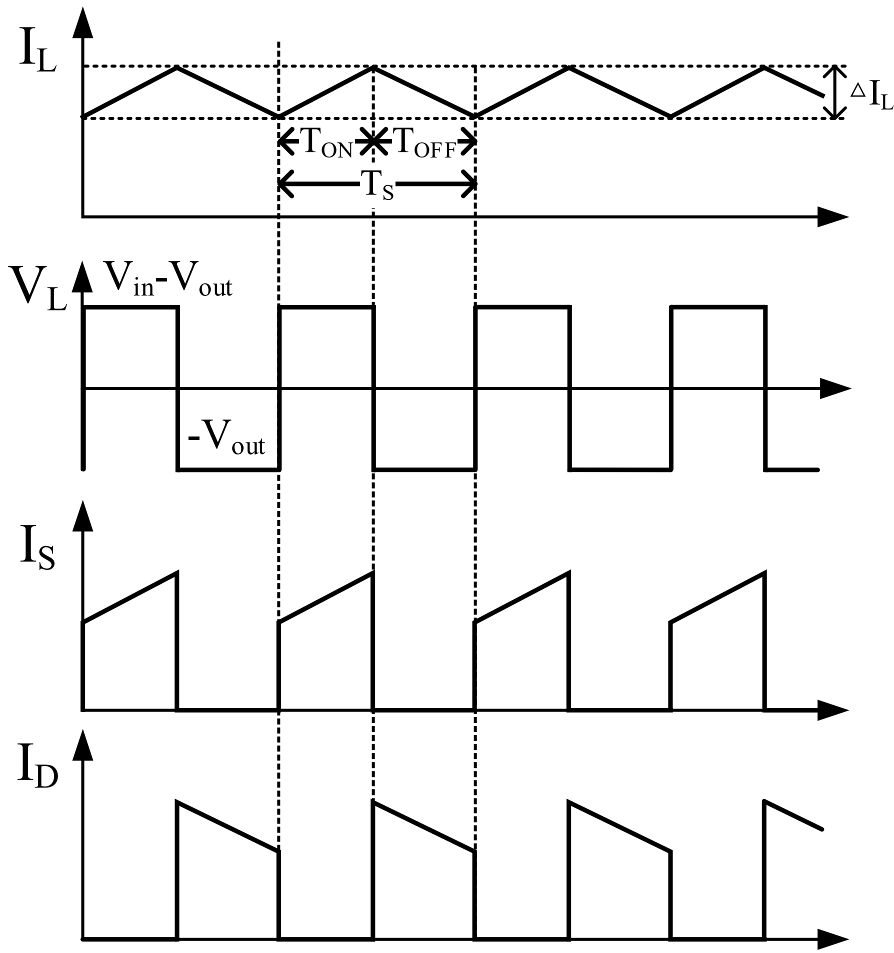
Buck converter operation modes - C.C.M.

S_1 turn on, D_1 turn off (T_{ON})：

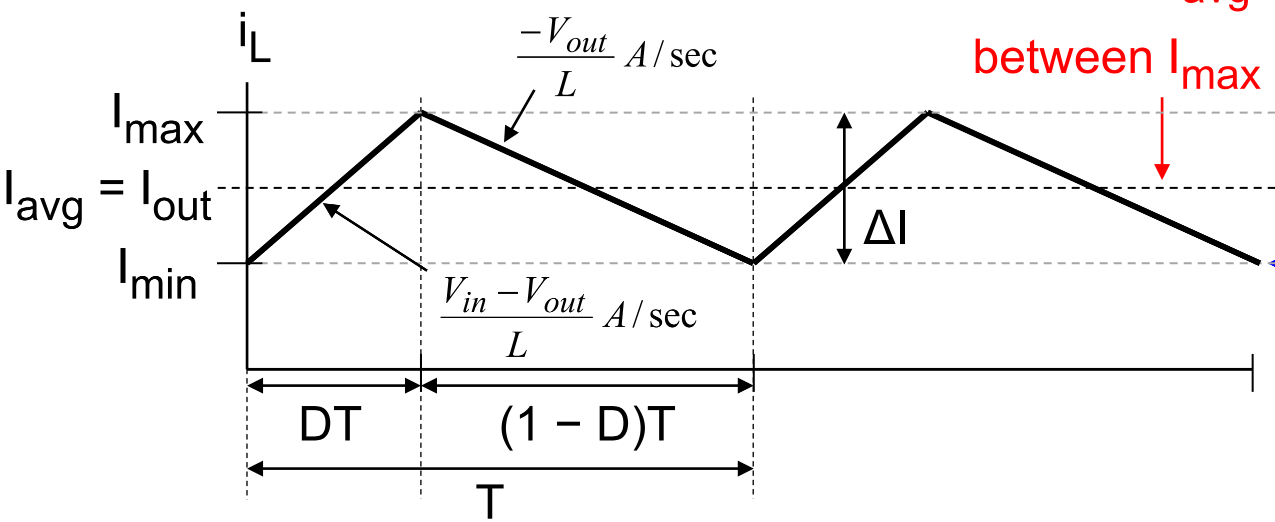


S_1 turn off, D_1 turn on (T_{OFF})：





Inductor's current waveform in buck converter



From geometry, $I_{avg} = I_{out}$ is halfway between I_{max} and I_{min}

Periodic – finishes a period where it started

Switch closed, $v_L = V_{in} - V_{out}, \frac{di_L}{dt} = \frac{V_{in} - V_{out}}{L}$

Switch open, $v_L = -V_{out}, \frac{di_L}{dt} = \frac{-V_{out}}{L}$

Derive the voltage conversion ratio from the volt-second balance-C.C.M.

Since the average voltage across L is zero

$$V_{Lavg} = D \cdot (V_{in} - V_{out}) + (1-D) \cdot (-V_{out}) = 0$$

$$DV_{in} = D \cdot V_{out} + V_{out} - D \cdot V_{out}$$

The input/output equation becomes

$$V_{out} = DV_{in}$$

From power balance, $V_{in} I_{in} = V_{out} I_{out}$, so

$$I_{out} = \frac{I_{in}}{D}$$

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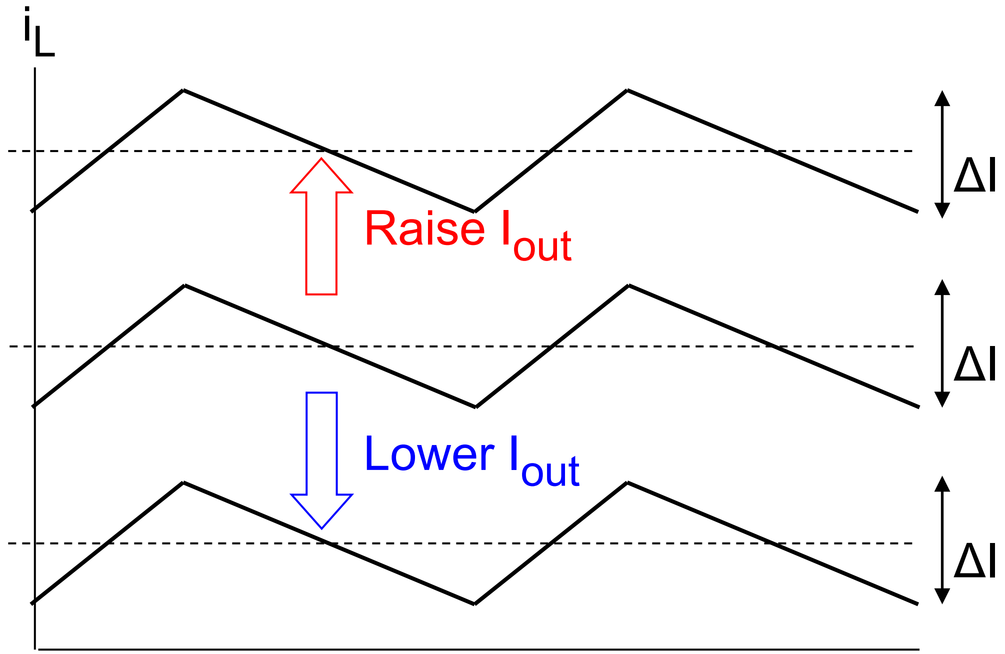
The process of inductor current from C.C.M to D.C.M

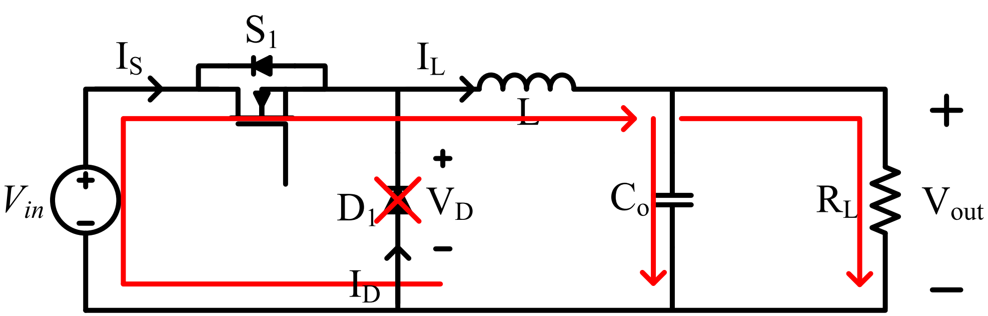
Effect of raising and lowering I_{out} while holding V_{in}, V_{out}, f, and L constant



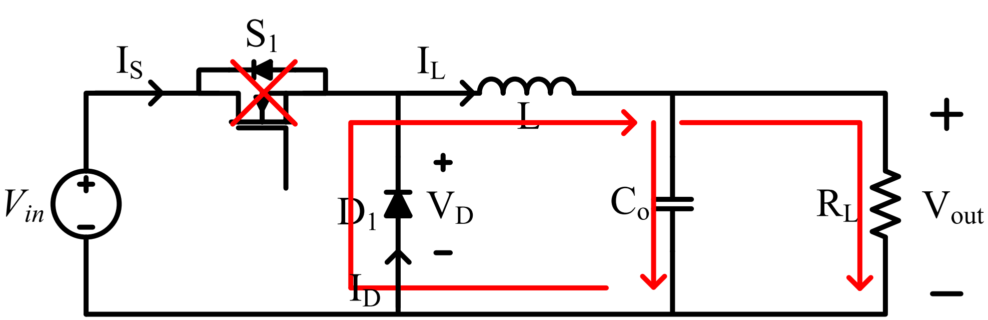
- V_{in} and V_o are constant, ΔI is unchanged.
- Lowering I_{out} (and, therefore, P_{out}) moves the circuit toward discontinuous operation.

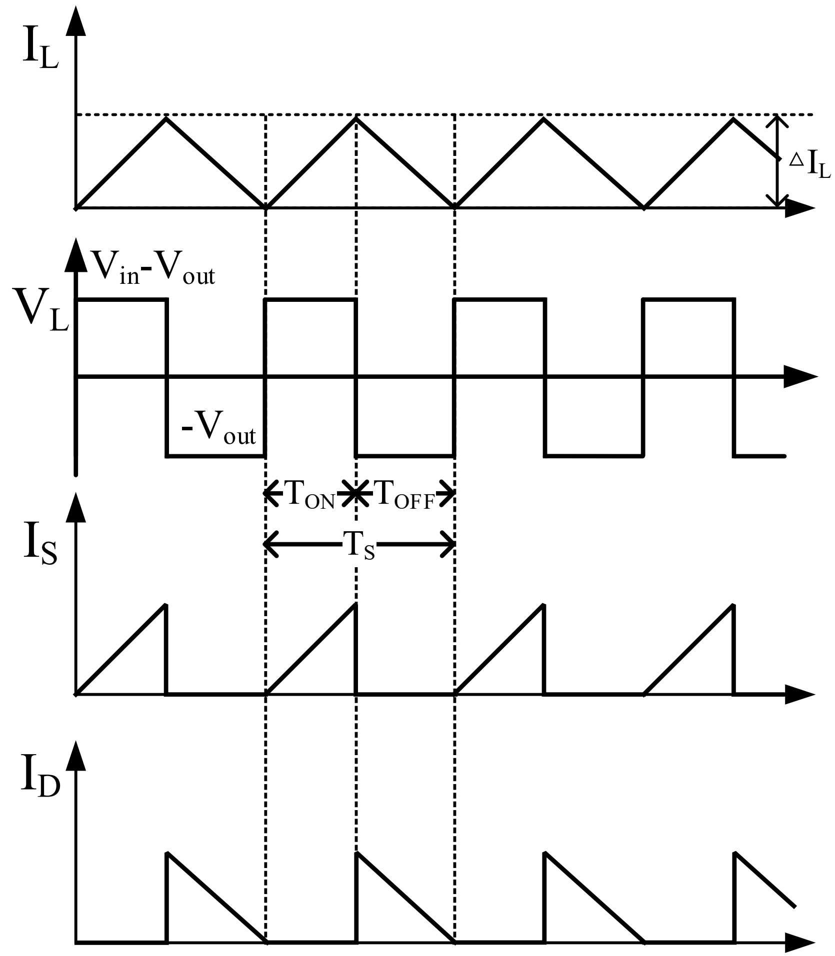
Buck converter operation modes - B.C.M.

S_1 turn on, D_1 turn off (T_{ON})：

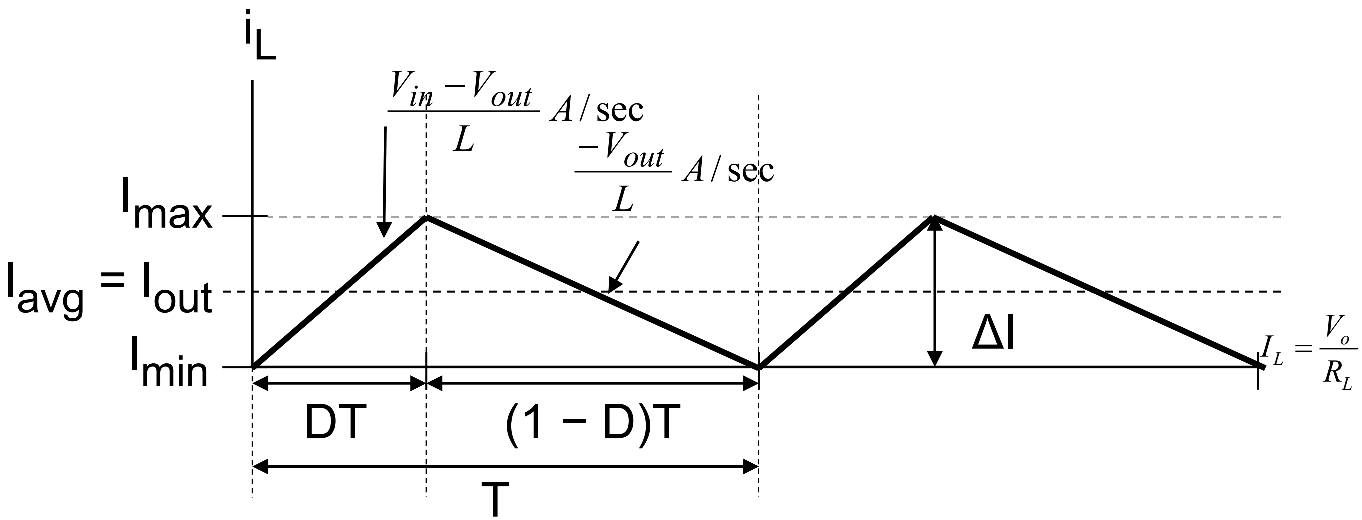


S_1 turn off, D_1 turn on (T_{OFF})：





Derive the voltage conversion ratio from the volt-second balance-B.C.M.



$$I_L = \frac{V_o}{R_L}$$

$$I_{L(\max)} = I_L + \frac{\Delta i_L}{2} = \frac{V_o}{R_L} + \frac{1}{2}\left[\frac{(V_{in}-V_O)}{L}(DT)\right] = \frac{V_o}{R_L} + \frac{1}{2}\left[\frac{V_O}{L}(1-D)T\right]$$

$$I_{L(\min)} = I_L - \frac{\Delta i_L}{2} = \frac{V_o}{R_L} - \frac{1}{2}\left[\frac{(V_{in}-V_O)}{L}(DT)\right] = \frac{V_o}{R_L} - \frac{1}{2}\left[\frac{V_O}{L}(1-D)T\right]$$

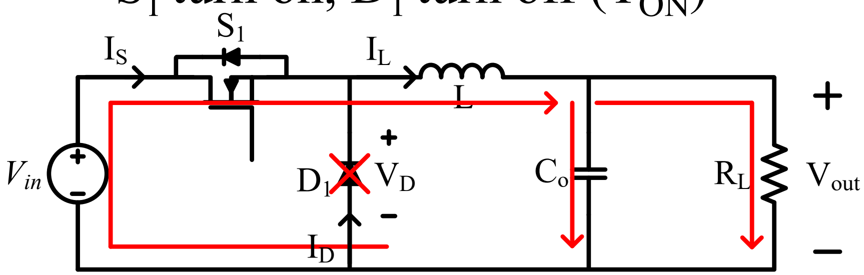
B.C.M. $I_{L(min)}$=0

$$L_B = \frac{R_L(1-D)}{2\cdot f} = \frac{V_O}{I_O}\frac{(1-D)}{2\cdot f}$$

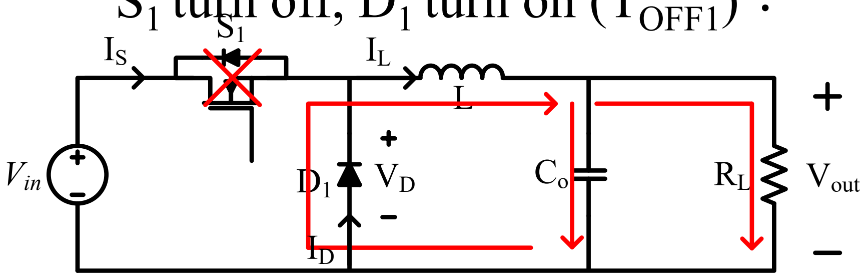
$$V_{out} = DV_{in}$$

Buck converter operation modes - D.C.M.

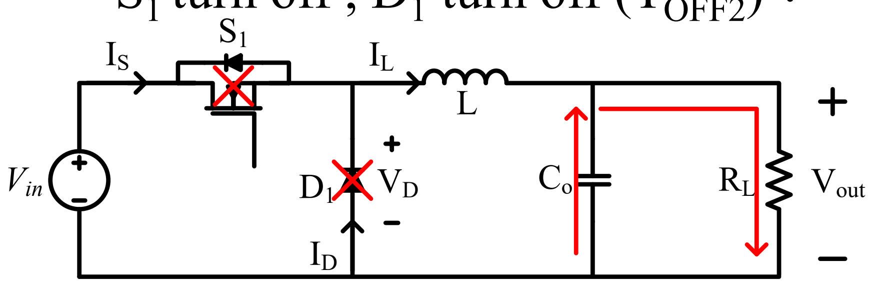
S_1 turn on, D_1 turn off (T_{ON})：

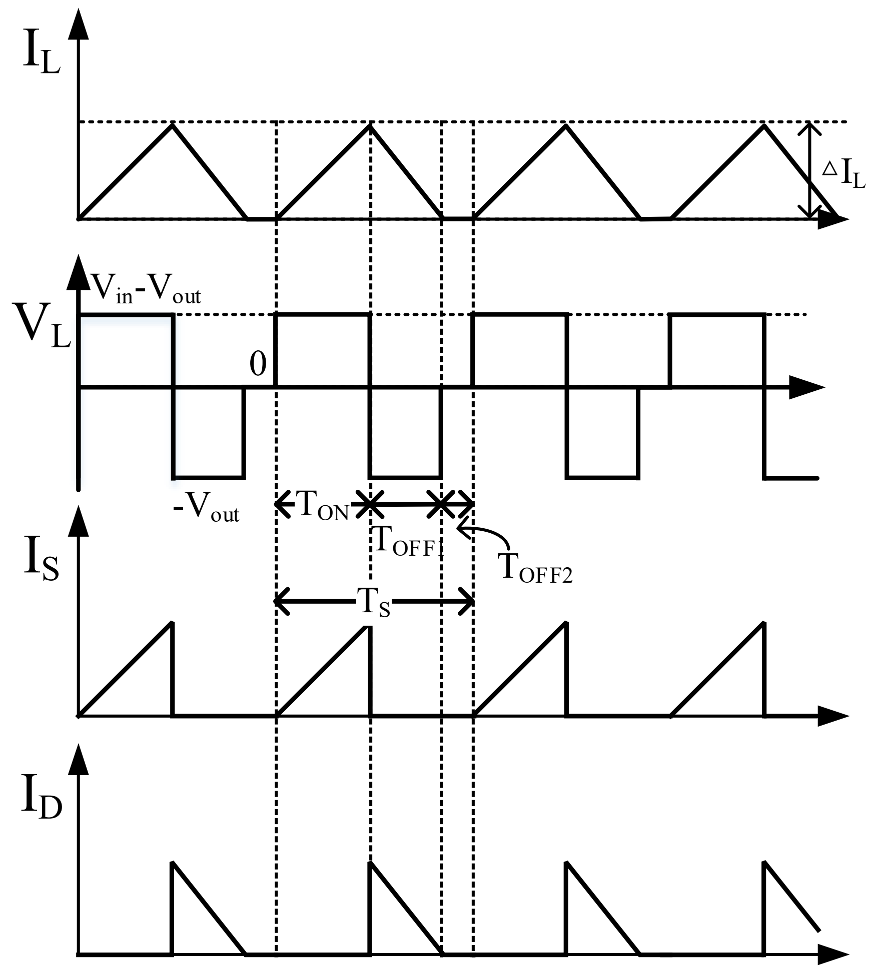


S_1 turn off, D_1 turn on (T_{OFF1})：

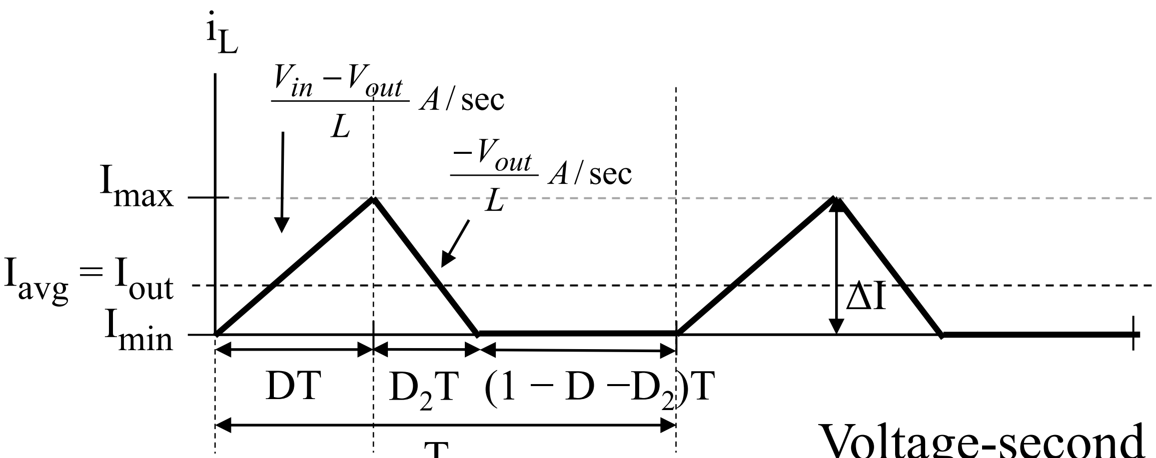


S_1 turn off , D_1 turn off (T_{OFF2})：





Derive the voltage conversion ratio from the volt-second balance-D.C.M.



S_1 turn on, D_1 turn off (T_{ON})：

$$\Delta I_L = \frac{V_{in} - V_o}{L_1} \times T_{on} = I_{PK}$$

S_1 turn off, D_1 turn on (T_{OFF1})：

$$\Delta I_L = -\frac{V_o}{L_1} \times T_{off1} = I_{PK}$$

$$V_o = V_{in} \times \frac{T_{on}}{T_{on} + T_{off1}} = V_{in} \times \frac{D}{D + D_2}$$

Voltage-second balance：

$$\frac{V_{in} - V_o}{L_1} DT - \frac{V_o}{L_1} D_2 T = 0$$

$$\frac{I_{PK}}{2} D + \frac{I_{PK}}{2} D_2 = I_o = \frac{V_o}{R_L} \leftarrow I_{PK} = \frac{V_{in} - V_o}{L_1} DT = \frac{V_o}{L_1} D_2 T$$

$$\frac{V_{in} - V_o}{2L_1} D^2 T + \frac{V_o}{2L_1} {D_2}^2 T = \frac{V_o}{R_L} \leftarrow D_2 = \left(\frac{V_{in}}{V_o} - 1\right) D$$

$$\rightarrow \frac{V_o}{V_{in}} = \frac{2}{1 + \sqrt{1 + \frac{8L_1 f_s}{R_L D^2}}}$$

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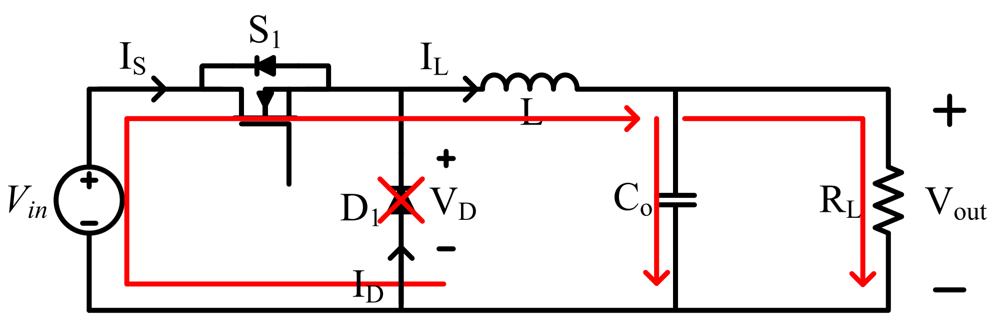
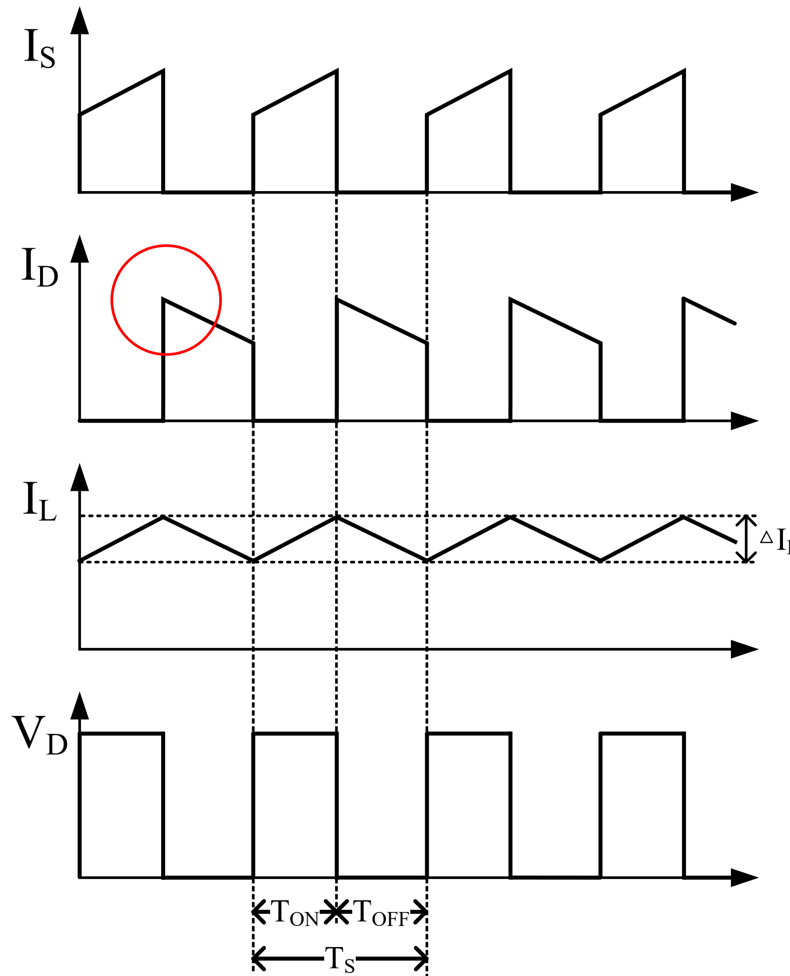
Component Design (I) - Diode

S_1 turn on, D_1 turn off (T_{ON})：





Diode

$$V_D = V_{in}$$

$$I_{D}\_\max = I_L + \frac{\Delta i_L}{2} = \frac{V_o}{R_L} + \frac{1}{2}\left[\frac{(V_{in} - V_O)}{L}(DT)\right]$$

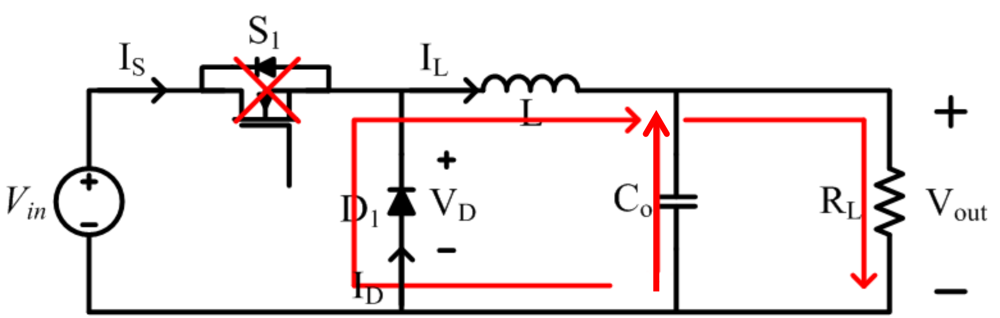
Component Design (II) - Switch

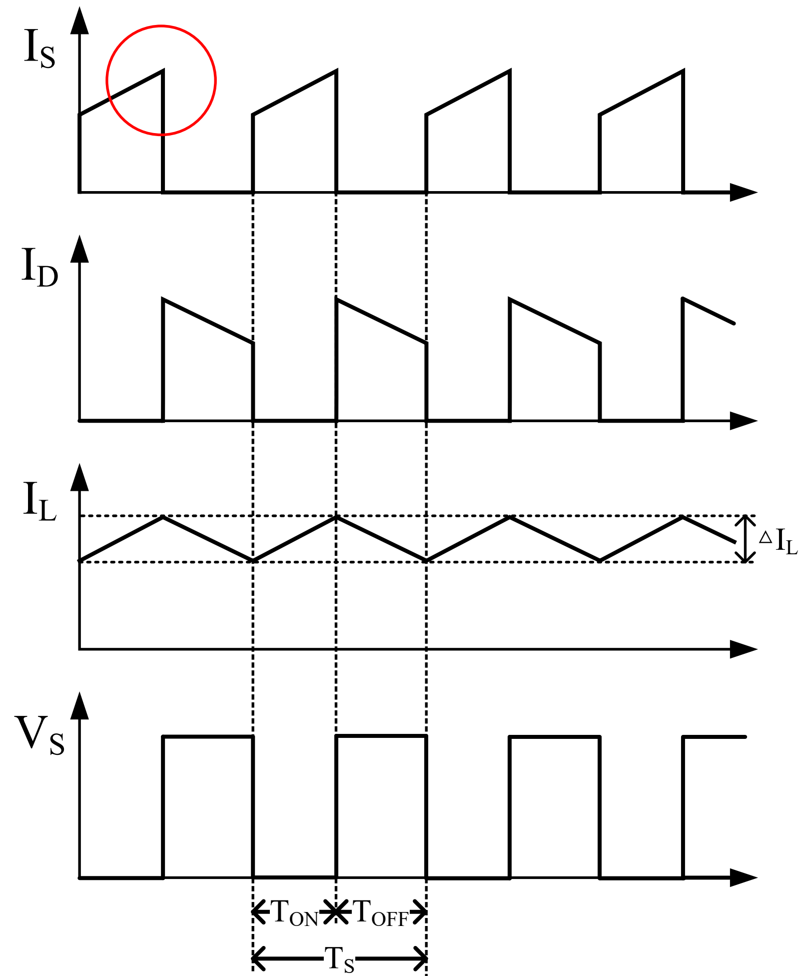
Switch

$$V_S = V_{in} + V_{Diode}$$

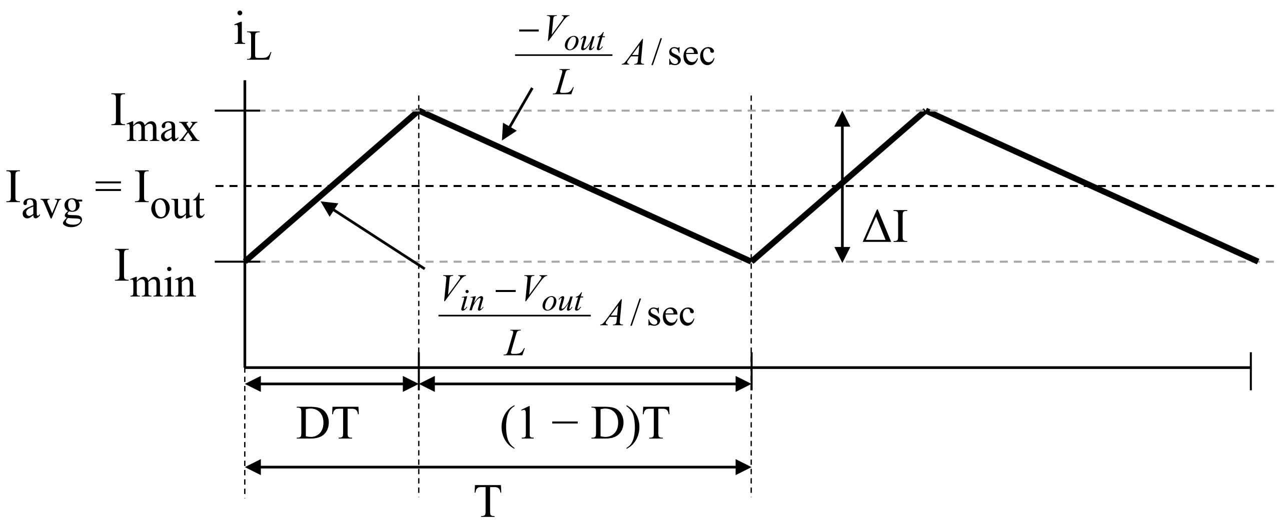
$$I_S\_\max = I_L + \frac{\Delta i_L}{2} = \frac{V_o}{R_L} + \frac{1}{2}\left[\frac{(V_{in} - V_O)}{L}(DT)\right]$$

S_1 turn off, D_1 turn on (T_{OFF}) :





Component Design (III) - Inductor



$$V_L = L\frac{di}{dt} = V_{in} - V_O$$

$$\Rightarrow L\frac{\Delta I}{DT} = V_{in}(1-D)$$

$$\boxed{\Rightarrow L\uparrow = \frac{V_{in}(1-D)D}{\downarrow\Delta I\downarrow \cdot f_S\uparrow}}$$

$$I_{L\_rms} = \sqrt{D\left[\mathrm{I}_{max}\,\mathrm{I}_{min} + \frac{1}{3}(\mathrm{I}_{max} - \mathrm{I}_{min})^2\right]}$$

Component Design (IV) - Capacitor

Output voltage ripple ：

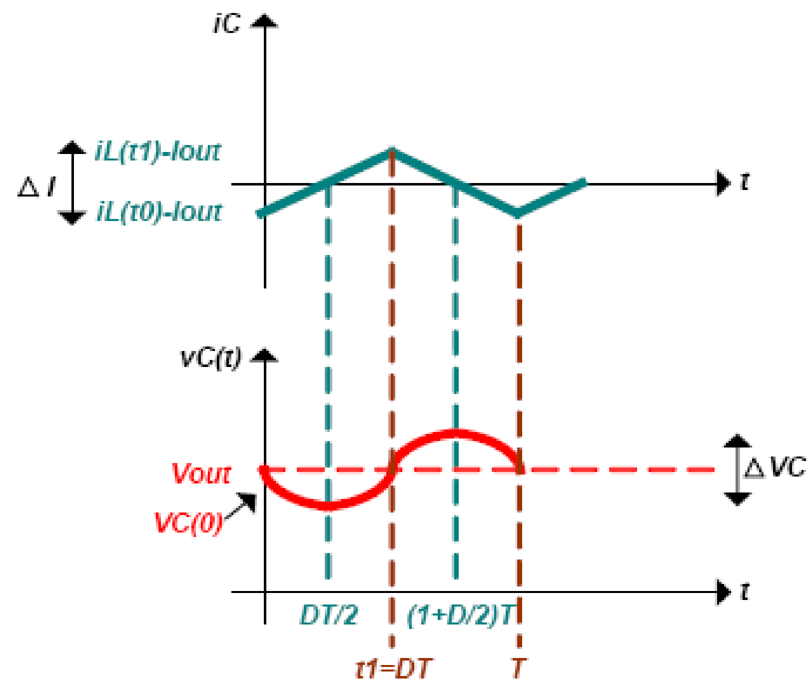
$$\Delta Q = C \cdot \Delta V = \Delta I \cdot T$$

$$\Delta Q = \frac{1}{2}\int_{\frac{DT}{2}}^{DT+\frac{DT}{2}} i dt = \frac{1}{2}\cdot\frac{T}{2}\cdot\frac{\Delta I}{2} = \frac{T\Delta I}{8}$$

$$\Rightarrow C = \frac{\Delta I}{8 \cdot f_S \cdot \Delta V}$$

And because $\Delta I = \frac{V_O}{L}(1-D)T$

$$\Rightarrow C\uparrow = \frac{V_O(1-D)}{8 \cdot f_S^{\,2} \cdot \Delta V\downarrow \cdot L}$$



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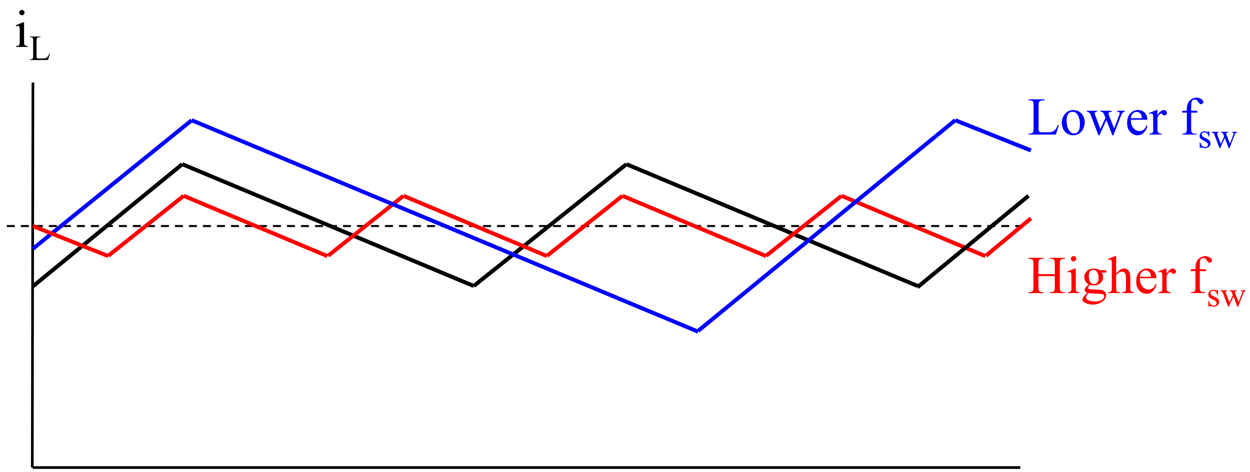
Basic relationship between switching frequency and inductance value to ripple current – Variable F_{sw}

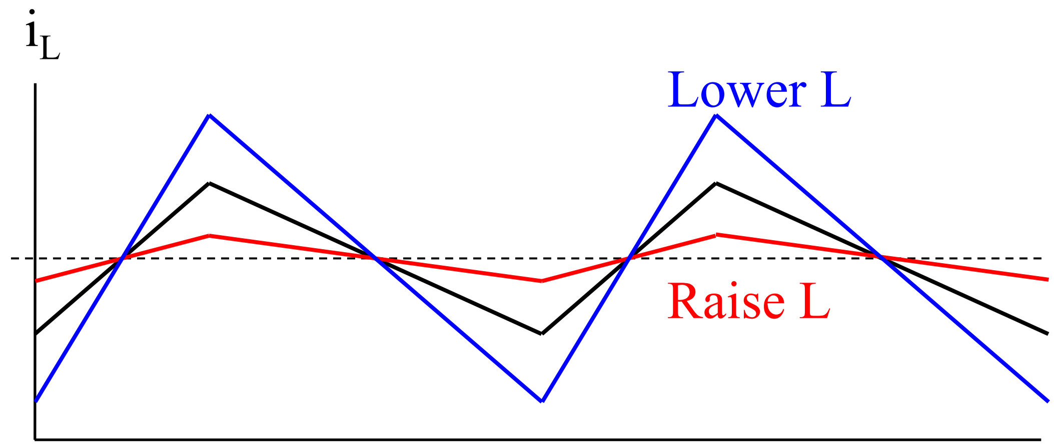
Effect of changing f_{sw} while holding V_{in}, V_{out}, I_{out}, and the inductor L is constant



- Slopes of i_L are unchanged.
- Lowering f_{sw} increases ΔI and moves the circuit toward discontinuous operation.
- Ripple current will be smaller with higher switching frequency

Basic relationship between switching frequency and inductance value to ripple current – Variable L

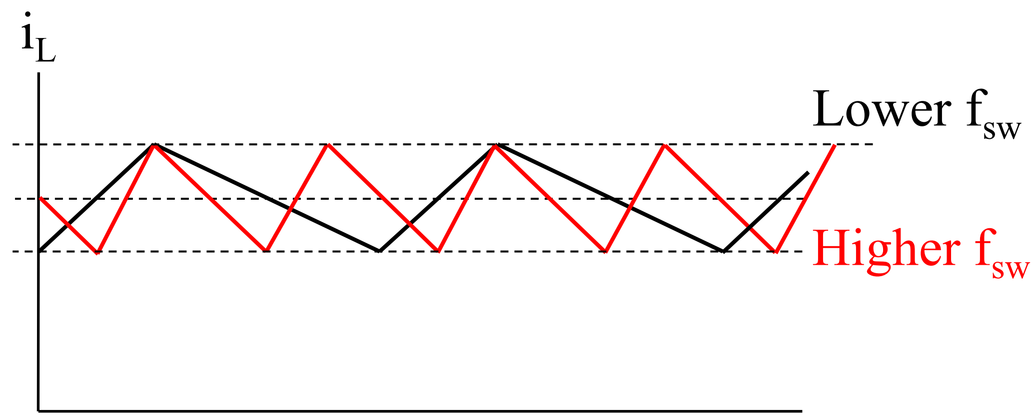
Effect of raising and lowering L while holding Vin, Vout, Iout and f_s constant

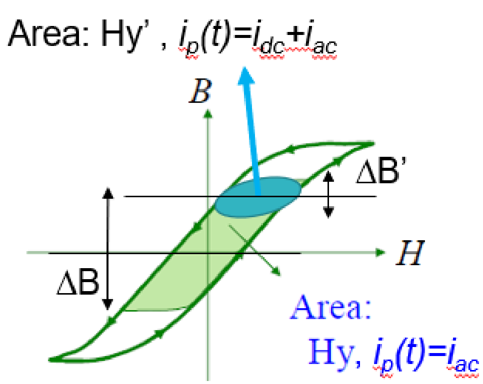


- Lowering L increases ΔI and moves the circuit toward discontinuous operation

The relationship between switching frequency and power composition

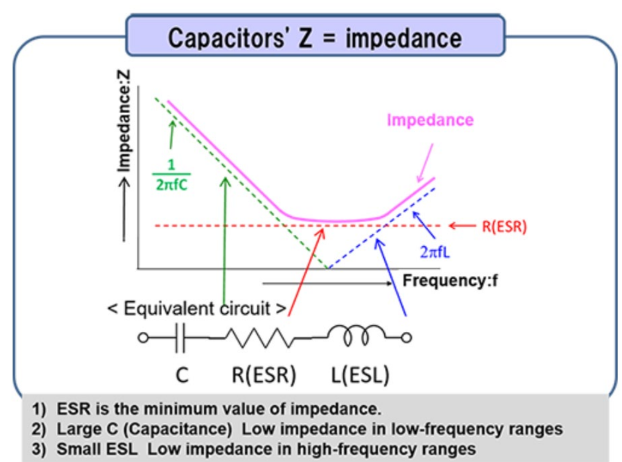
- Discuss switching frequency and inductance design under fixed current ripple specification:
- Switching frequency ⇧ inductor value ⇩
- Conduction loss of inductor? (ignore skin effect)
- Iron loss of inductor?
- ESR loss of output capacitor?





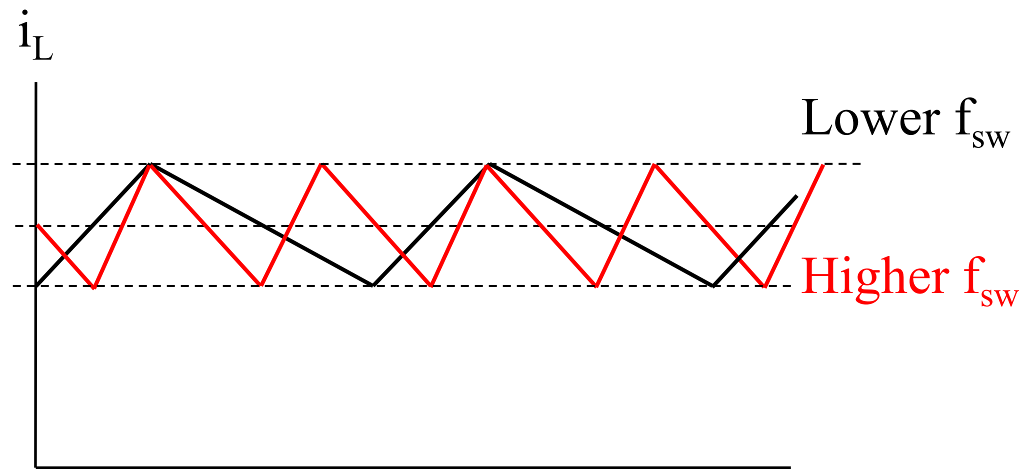
Steinmetz's equation,
sometimes called the **power equation**

$$P_v = k \cdot f^a \cdot B^b$$



The relationship between switching frequency and power composition

- Discuss switching frequency and inductance design under fixed current ripple specification:
- Switching loss of MOSFET?
- Switching loss of Diode?
- Switching loss of Driver?
- Conduction loss of MOSFET?
- Conduction loss of Diode?



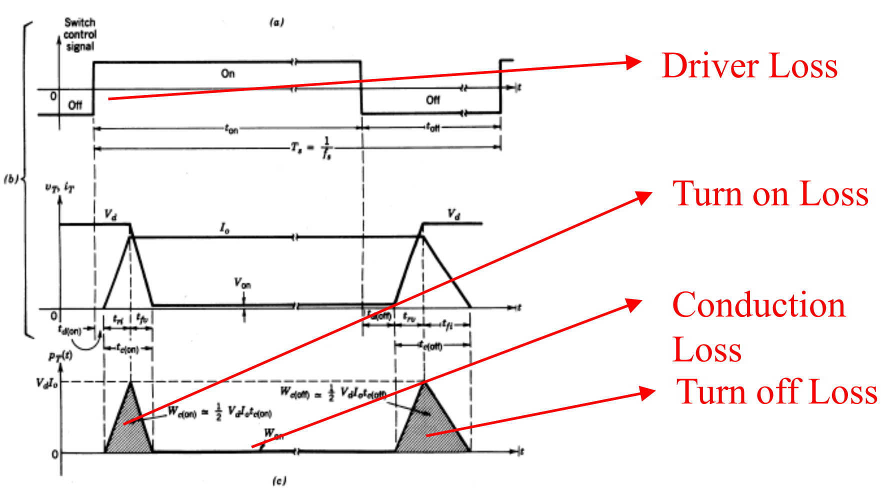
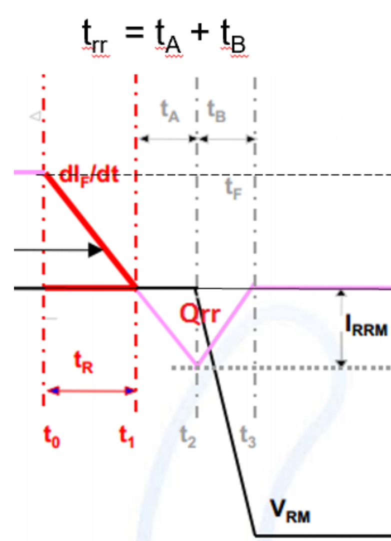
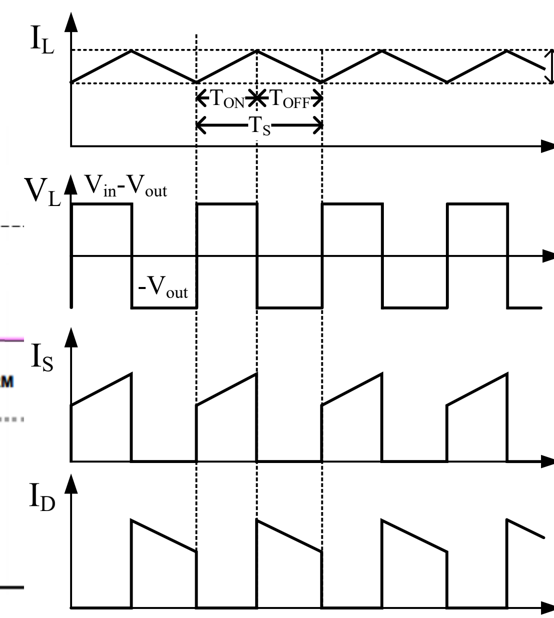


Figure 2-6 Generic-switch switching characteristics (linearized): (a) simplified clamped-inductive-switching circuit, (b) switch waveforms, (c) instantaneous switch power loss.





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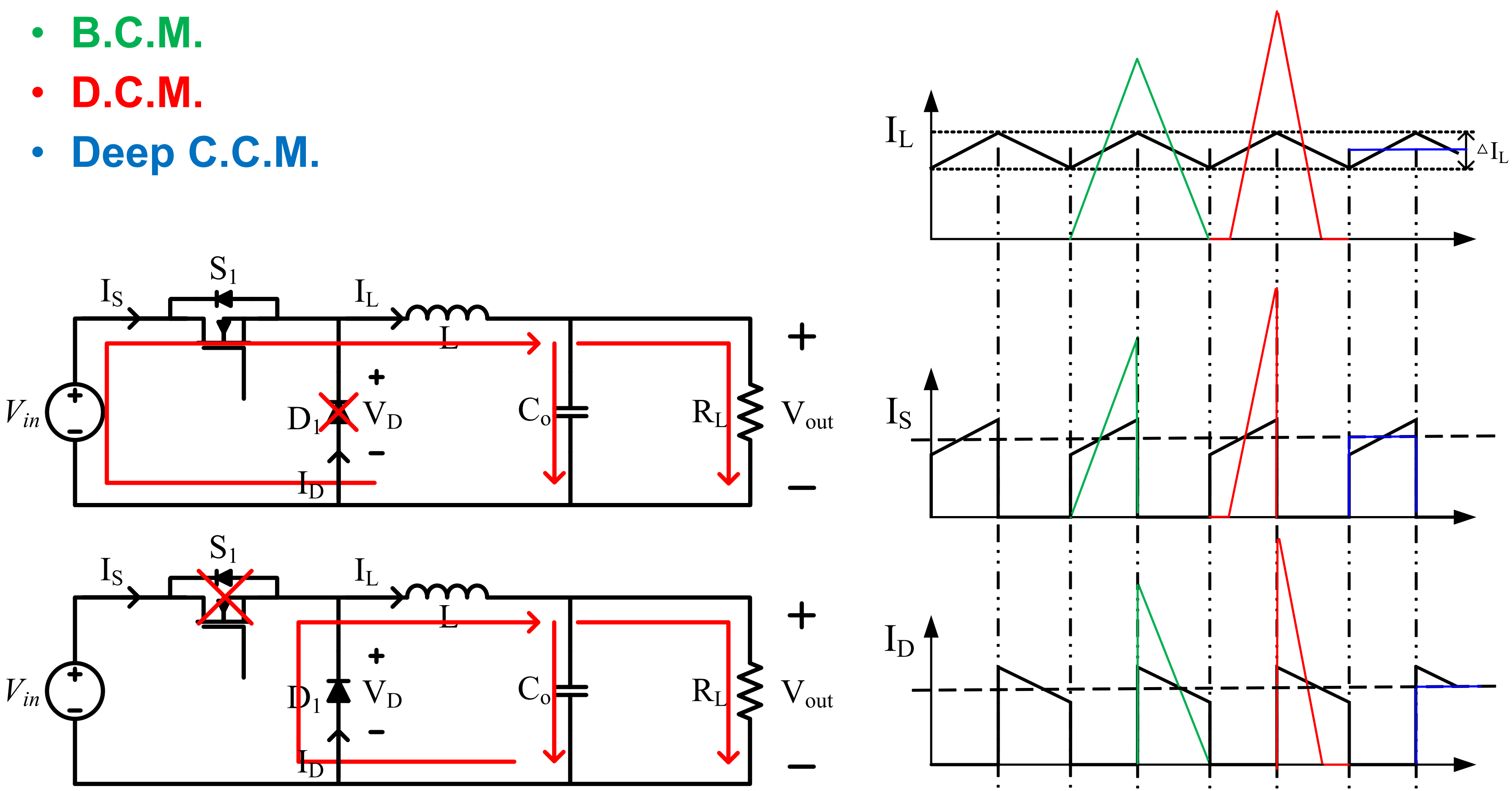
Three operation modes caused by changing the inductance under fixed-switching frequency and fixed load

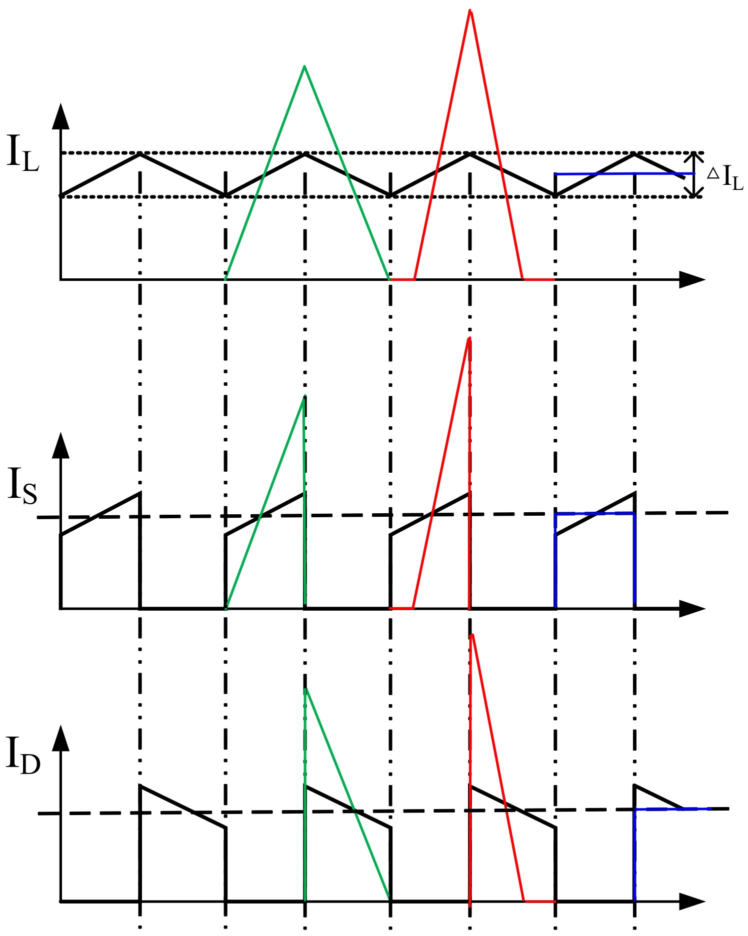
- C.C.M.
- B.C.M.
- D.C.M.
- Deep C.C.M.



Brain storming –
Comparison of losses in different operating modes

- **Deep C.C.M. v.s. C.C.M.**
- Switching loss of MOSFET?
- Switching loss of Diode?
- Switching loss of Driver?
- Conduction loss of MOSFET?
- Conduction loss of Diode?

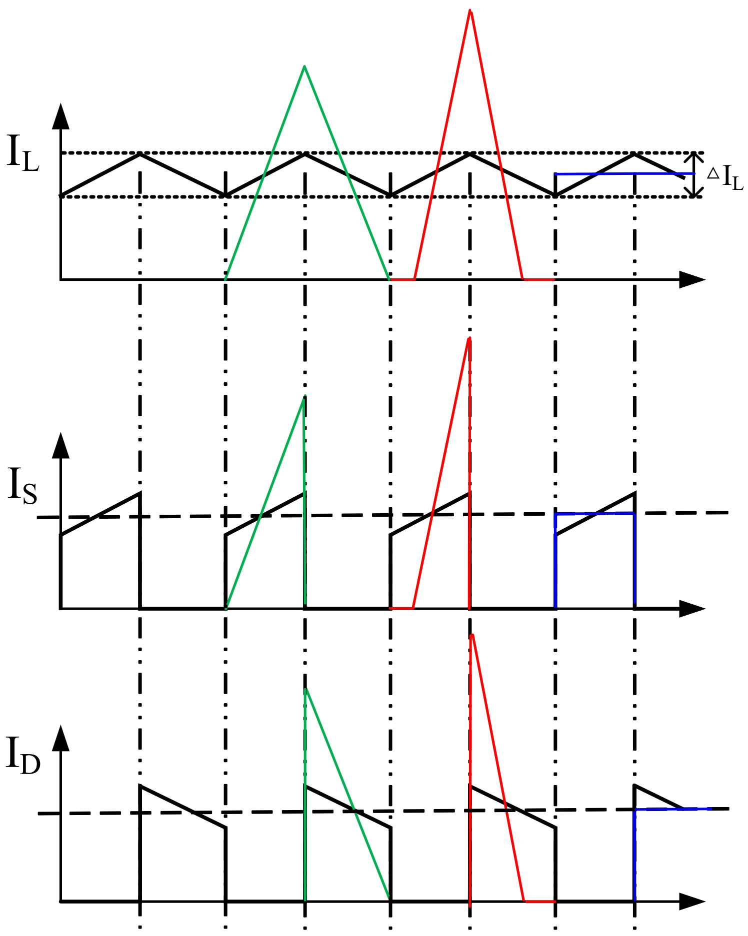
- Conduction loss of capacitor?
- Conduction loss of inductor?
- Iron loss of inductor?



Brain storming –
Comparison of losses in different operating modes

- **C.C.M. v.s. B.C.M.**
- Switching loss of MOSFET?
- Switching loss of Diode?
- Switching loss of Driver?
- Conduction loss of MOSFET?
- Conduction loss of Diode?

- Conduction loss of capacitor?
- Conduction loss of inductor?
- Iron loss of inductor?



Brain storming –
Comparison of losses in different operating modes

- **B.C.M.** **v.s.** **D.C.M.**
- Switching loss of MOSFET?
- Switching loss of Diode?
- Switching loss of Driver?
- Conduction loss of MOSFET?
- Conduction loss of Diode?

- Conduction loss of capacitor?
- Conduction loss of inductor?
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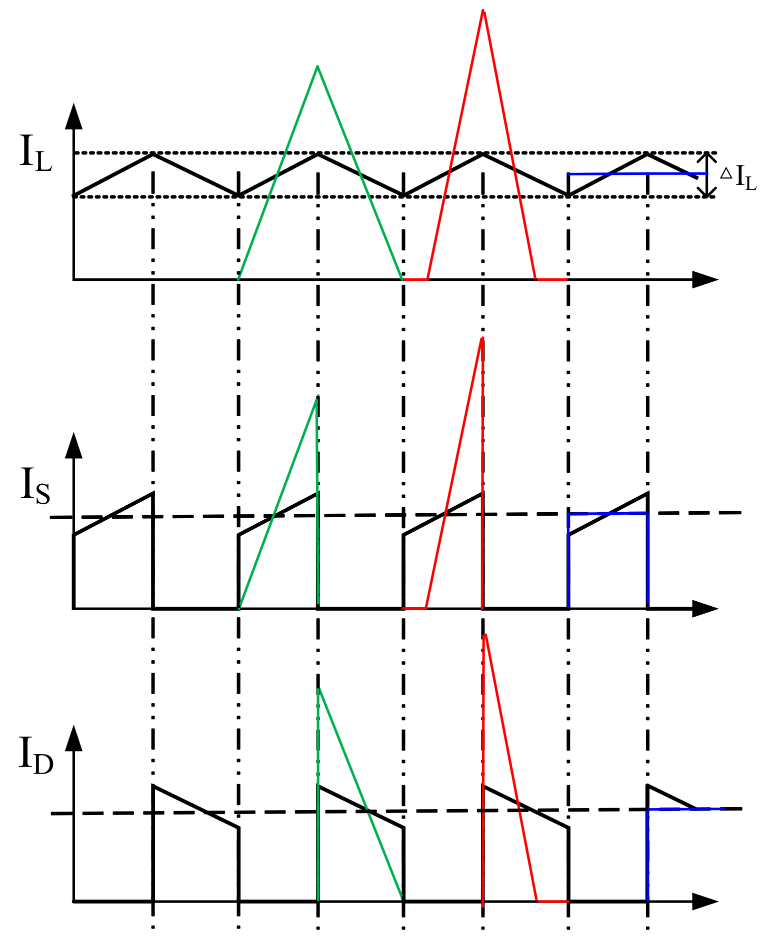

Brain storming –
Comparison of losses in different operating modes

- **B.C.M. v.s. D.C.M.**
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- Conduction loss of capacitor?
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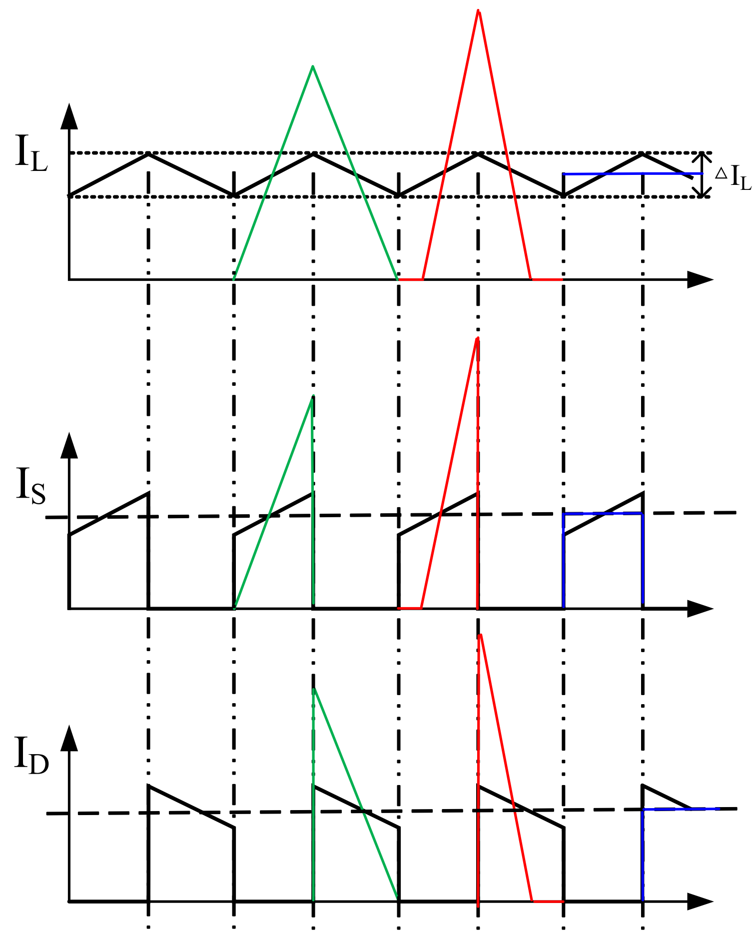

- Why the control method usually uses DCM operation instead of BCM operation under light load? (Tips: lower switching frequency cause…?)

Course outline – Week 4

- **Take Buck as an example to illustrate the design and characteristics of the converter.**
  - Principles of converter derivation
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  - SEPIC
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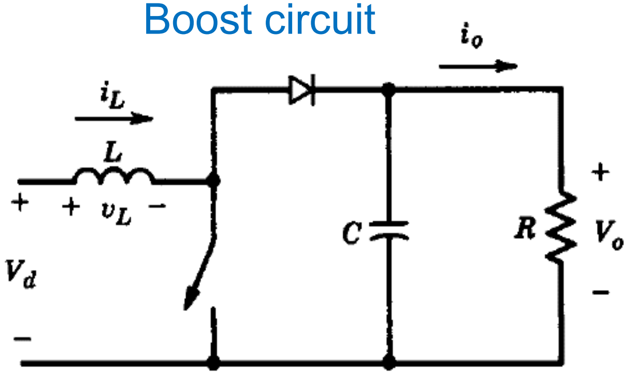
  - Forward
  - Flyback
  - Half/Full bridge

Characteristic of Boost converter

- Pos:
  - The output voltage is greater than the input voltage
  - Input current is equal to the inductor current (lower input current ripple)
  - The main application is in regulation dc power supplies, the regenerative braking of dc motors and PFC.
- Dis:
  - Discontinuous diode current cause high output noise and ripple

Boost circuit



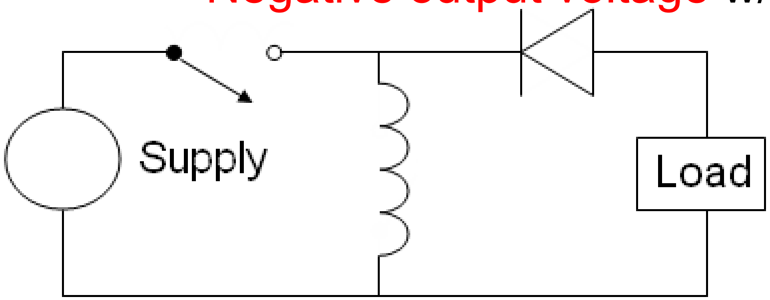
Voltage transfer function

$$\frac{V_o}{V_d} = \frac{1}{1-D}$$

$\boxed{\text{Duty} \propto \text{Vo}}$

Characteristic of Buck-boost converter

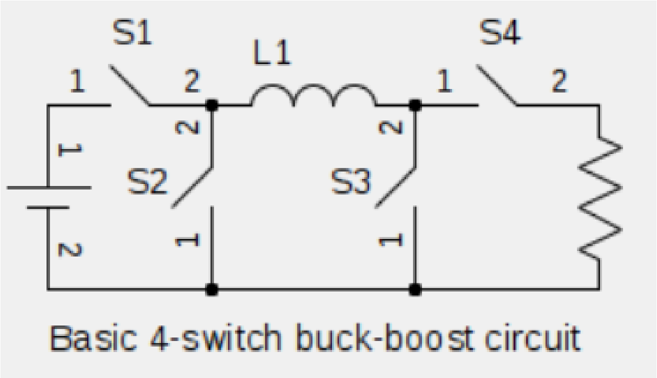
- Pos:
  - The output voltage can be greater or lower than the input voltage
- Dis:
  - Discontinuous switch & diode current cause high input & output noise and ripple
  - Negative output voltage w/i reverse type



Reverse type

Voltage transfer function

$$\frac{V_o}{V_d} = \frac{-D}{1-D}$$



4 switches type

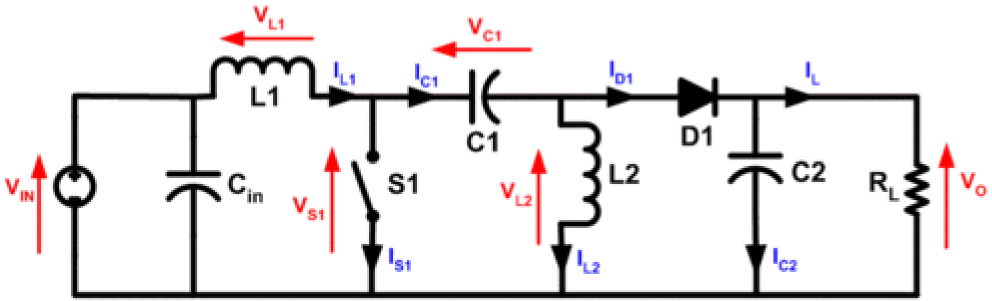
Voltage transfer function

$$\frac{V_o}{V_d} = \frac{1}{1-D}$$ OR $$\frac{V_o}{V_d} = D$$

[Ref]: https://zh.wikipedia.org/wiki/降壓-升壓變換器

Characteristic of SEPIC converter

- Pos:
  - The output voltage can be greater or lower than the input voltage
  - Positive output voltage
  - Input current continues, current stress and noise are lower
- Dis:
  - More components. Cost, volume problem
  - Hard to closed-loop compensation (nature high order transfer function w/i RHP)



Voltage transfer function

$$\frac{V_o}{V_d} = \frac{D}{1-D}$$

[Ref]: https://en.wikipedia.org/wiki/Single-ended_primary-inductor_converter

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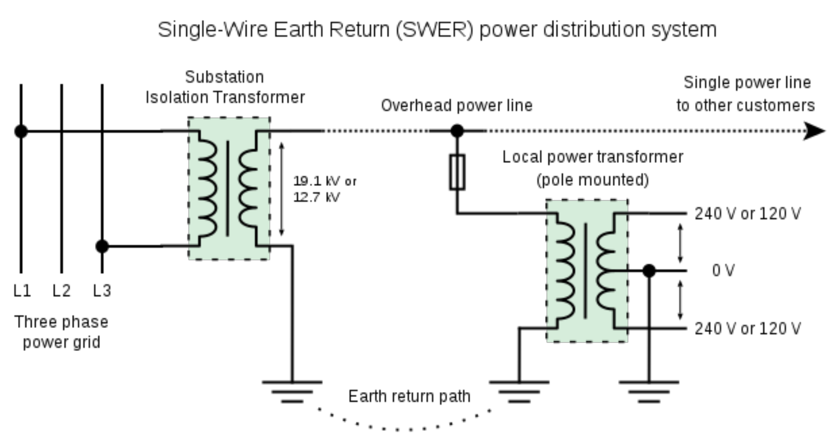
  - Half/Full bridge

Reasons for electrical isolation requirement

- Safety: to protect the operator from dangerous voltages
- Voltage level shifting
- To provide galvanic isolation in which the two isolated circuits communicate without a direct conduction path
- Prevent ground loops
- The isolation protects the equipment from the line-level events such as surges, lightning strikes, etc.



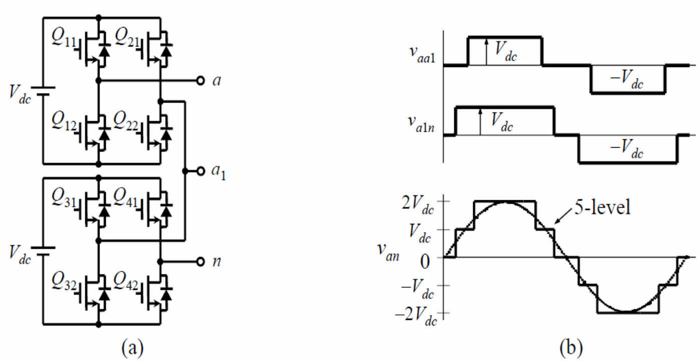


Figure 22. Cascaded inverter with two cells and five levels: (a) Circuit diagram; and (b) individual module output and the entire phase output waveforms.

[Ref]: https://commons.wikimedia.org/wiki/File:Swer_power_distribution.svg

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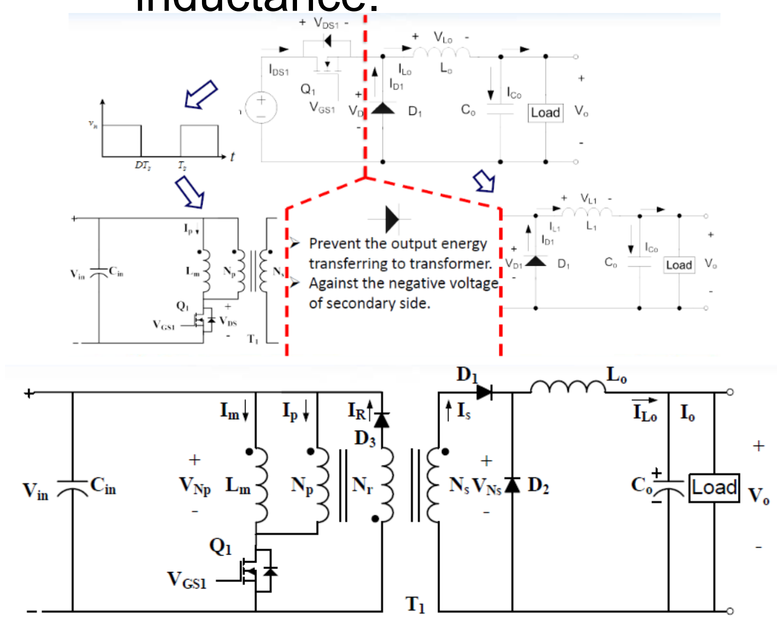
Characteristic of Forward converter

- Pos:
  - The output voltage is much lower than the input voltage w/i transformer turns ratio
  - Continues output current, low output noise and ripple
  - Suitable for medium power 150~300W application
- Dis:
  - Reset winding, increase winding cost and switch's voltage stress
  - The switch will have a voltage spike caused by transformer leakage inductance.



Forward circuit

Voltage transfer function

$$\frac{V_o}{V_{in}} = \frac{N_s}{N_p} D$$

[Ref]: Fundamentals of Power Electronics | Robert W. Erickson

Characteristic of Flyback converter

- Pos:
  - An isolated buck-boost converter with positive output voltage
  - Lowest number of components (cost) of isolated converter
- Dis:
  - Discontinues current of input and output
  - Energy is stored in the magnetizing inductance, which increases the volume of magnetic components
  - Only suitable for low power application
  - The switch will have a voltage spike caused by transformer leakage inductance.

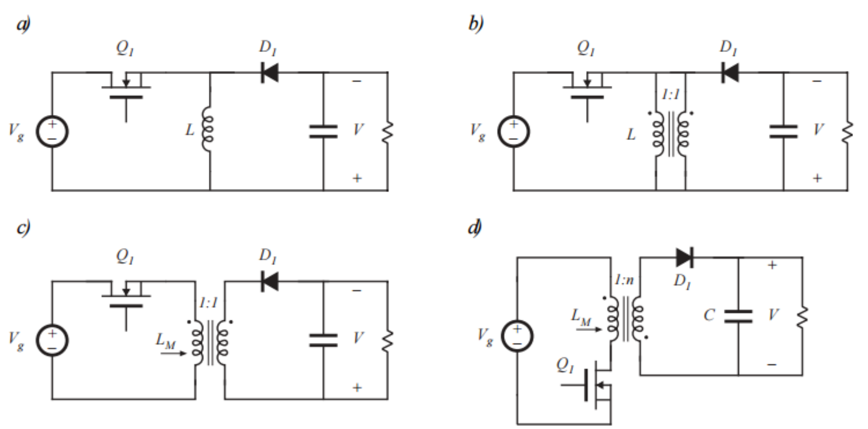


Fig. 1. Derivation of the flyback converter: (a) buck-boost converter, (b) inductor L is wound with two parallel wires, (c) inductor windings are isolated, leading to the flyback converter, (d) with a 1:n turns ratio and positive output.

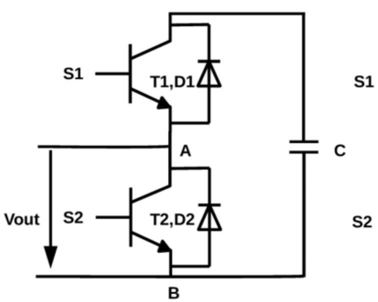
Voltage transfer function

$$\frac{V}{V_g} = \frac{n}{1}\frac{D}{1-D}$$

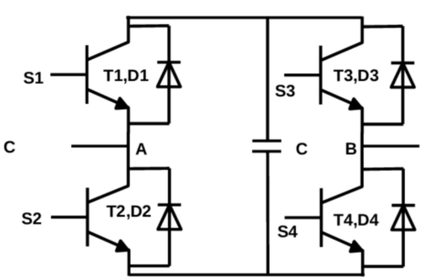
[Ref]: Fundamentals of Power Electronics | Robert W. Erickson

Characteristic of Half/Full bridge converter

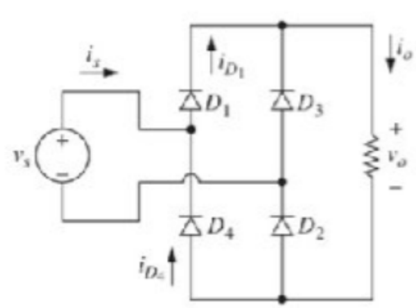
- Half / Full bridge:
  - 2 switches / 4 switches
  - Need DC blocking capacitor / No need DC blocking capacitor (ideal)
  - Transformer input voltage is +/- 0.5Vin / +/- 1Vin
- Full wave rectifier (Full bridge / Center Tapped):
  - 4 diodes / 2 diodes
  - Diode's voltage stress is 0.5Vo / 2Vo
  - 2 voltage drops pre half-cycle / 1 voltage drop pre half-cycle
  - No need center-tapped transformer / Need center-tapped transformer



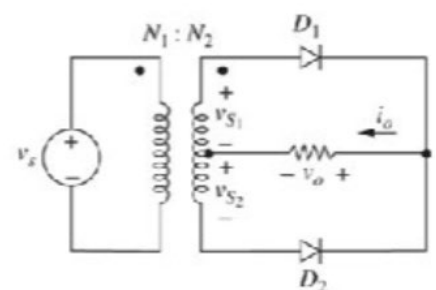
a) Half bridge submodule configuration



b) Full bridge submodule configuration
Vout=VAB



Full Bridge



Center-Tapped

[Ref]: Tsague, Nescelin. (2016). Analysis and development of a Modular Multi-level Converter for Traction Drives applications.
https://slidetodoc.com/chapter-4-half-wave-rectifiers-ac-dc-conversion/

THANK YOU