Switched-mode DC-DC Converters

DC-DC Conversion

- **Why ?:**
  - To convert one DC voltage to another.
    - E.G. providing logic power supplied from a battery power source.
  - To control the current into a DC load.
    - E.G. controlled battery charging
  - Providing a regulated DC output.
    - DC power supplies

- **DC Power Source:**
  - battery
  - solar panel
  - fuel cell

- **Converter types:**
  - Step-down (or *buck*) converter
  - Step-up (or *boost*) converter
  - Step up/down (or *buck-boost*) converter

Principles

- Basic principle is **converting** a **fixed (or variable) DC source** and convert it **to a controllable DC output**.

- The DC source could be
  - battery
  - solar panel
  - fuel cell

- There are 3 basic classifications
  - Step-down (or *buck*) converter
  - Step-up (or *boost*) converter
  - Step up/down (or *buck-boost*) converter

- There are unidirectional and bidirectional variants, and isolated and non-isolated variants.

- The simplest dc-dc converters have one diode, switch, inductor and capacitor.

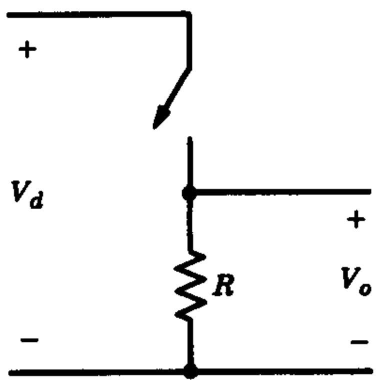
Why use switched-mode dc-dc conversion?

- Lower losses compared to linear conversion
  - Lower losses
  - Smaller heatsinks
  - Lower volume and weight
  - Step up and step down action.

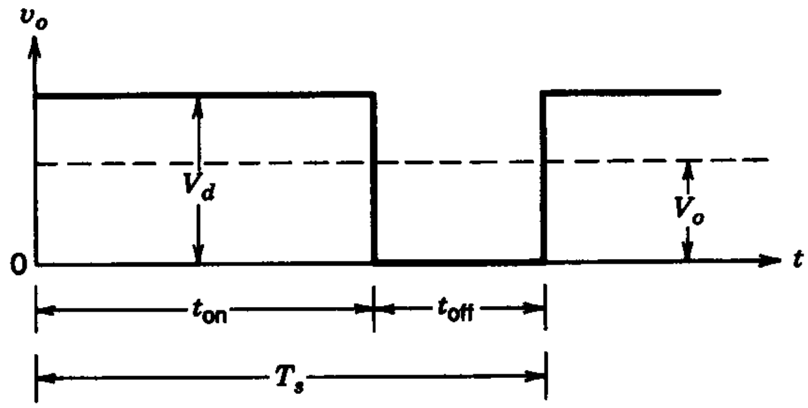
Step-down (Buck) Converter

• Basic step-down converter with load voltage waveform

$$\overline{V_o} = \frac{T_{on}}{T} V_d$$



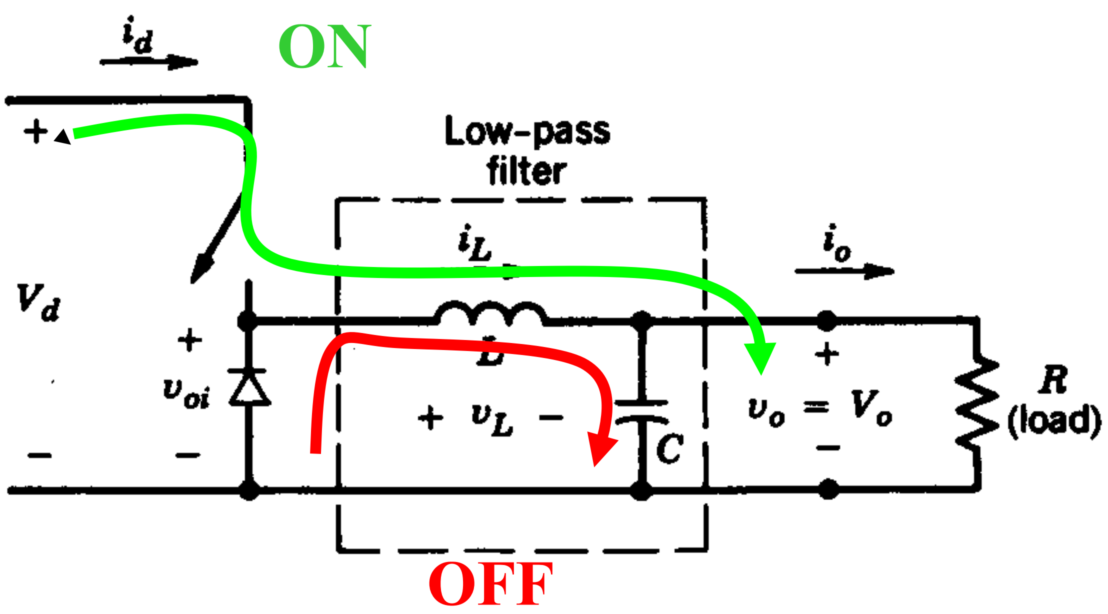
(a)



(b)

Practical Step-down Converter

- LC filter used to smooth output voltage from a stepped-waveform into a DC waveform.
- What values of L and C should be used?

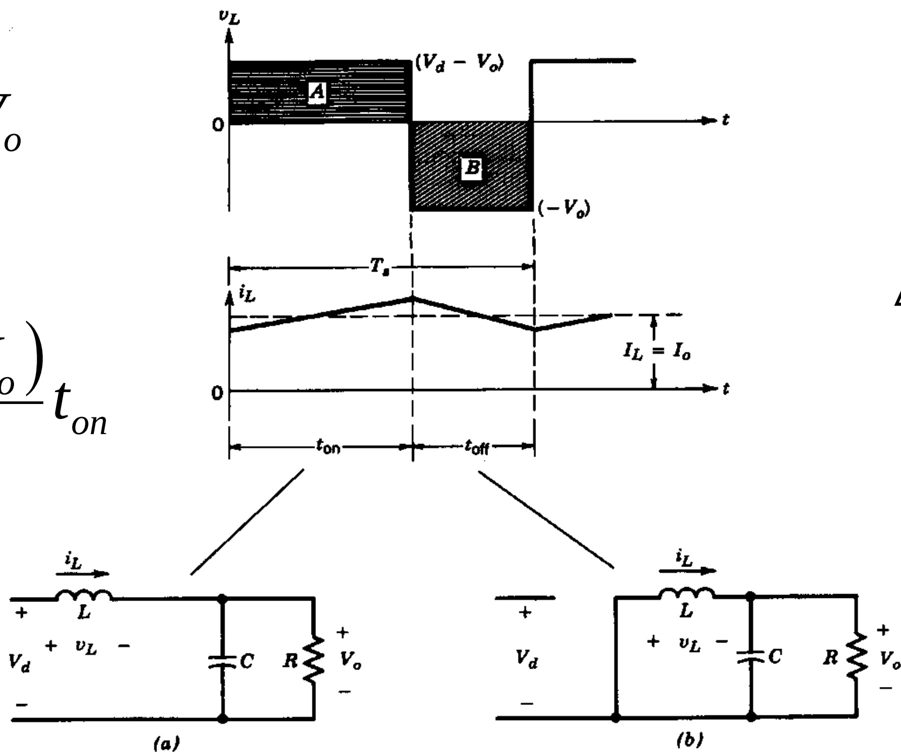


The circuit has two modes corresponding to ON and OFF states

$$V_L = V_d - V_o$$

$$L\frac{di}{dt} = V_d - V_o$$

$$\Delta i_{ON} = \frac{(V_d - V_o)}{L} t_{on}$$



$$V_L = -V_o$$

$$\Delta i_{OFF} = \frac{-V_o}{L} t_{off}$$

Switch ON

Switch OFF

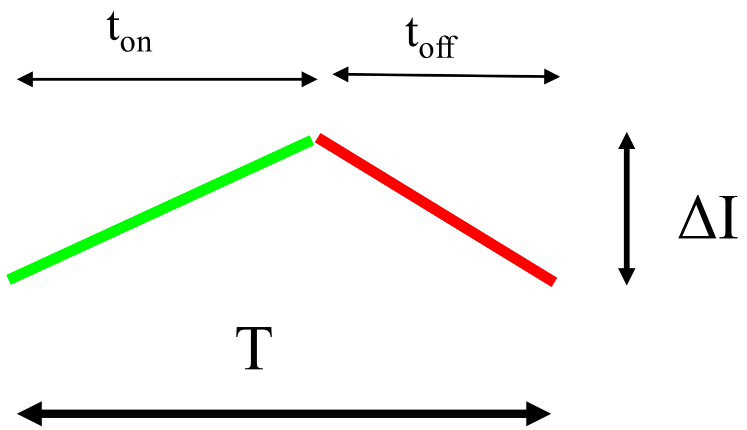
Steady State Output

In steady state the current rise in the ON period must match the current fall in the OFF period.

$$\Delta i_{ON} = \frac{(V_d - V_o)}{L} t_{on} = -\Delta i_{off} = \frac{V_o}{L} t_{off}$$

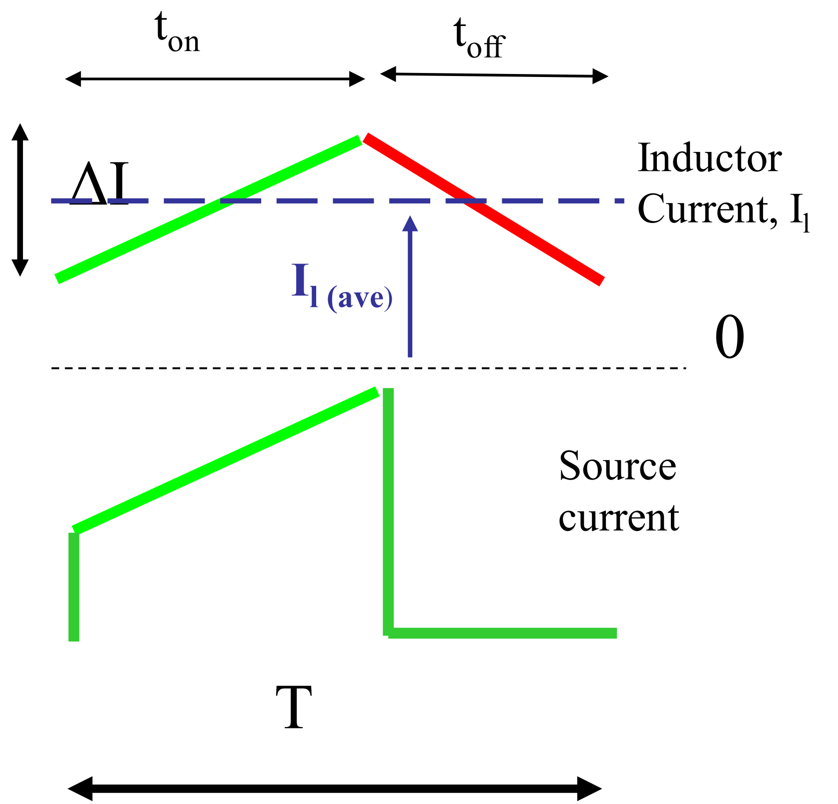
$$\Rightarrow$$

$$\frac{V_o}{V_d} = \frac{t_{on}}{T} = D$$



Source current

- The current drawn from the source is discontinuous.
- The current supplied to the load is **continuous** provided the **inductor** current **does not reach zero**.
- The inductor must be sized to limit current ripple ΔI
- If the **inductor current** reaches zero in the **OFF** period the converter operates in '**discontinuous**' mode and a different set of steady state equations apply.



Energy considerations. *(Energy from the source must match energy in the load)*

Energy supplied by the source during **ON** time is: $E_{on} = \int_0^{ton} V_d i_l(t)dt = V_d \bar{i}_d T_s$

Energy supplied to load during switching period is:

$$E_{period} = \frac{V_o^2}{R_o} T = I_o V_o T$$

$$V_d \bar{i}_d = I_o V_o$$

$$\bar{\bar{i}}_d = I_o \frac{V_o}{V_d}$$

$$\boxed{\bar{i}_d = I_o \frac{t_{on}}{T}}$$

As expected, the step-down converter steps down the voltage and steps up the current.

Component Sizing (Inductance)

The inductor must be sized according to the acceptable current ripple:

$$\Delta i = \frac{(V_d - V_o)}{L} t_{on} = \frac{V_o}{L} t_{off} \qquad \frac{V_o}{V_d} = \frac{t_{on}}{T} = D$$

$$\Rightarrow$$

$$\Delta I = \frac{V_d (1 - D)}{L} \cdot DT = \frac{V_d}{Lf} (D - D^2)$$

$$where \;\; f = \frac{1}{T}$$

The current ripple may be reduced by **increasing** the switching frequency **f** or **increasing** the **inductance**.

Component Sizing (Capacitance)

The previous analysis has assumed that the output capacitor voltage is constant over the switching period T.

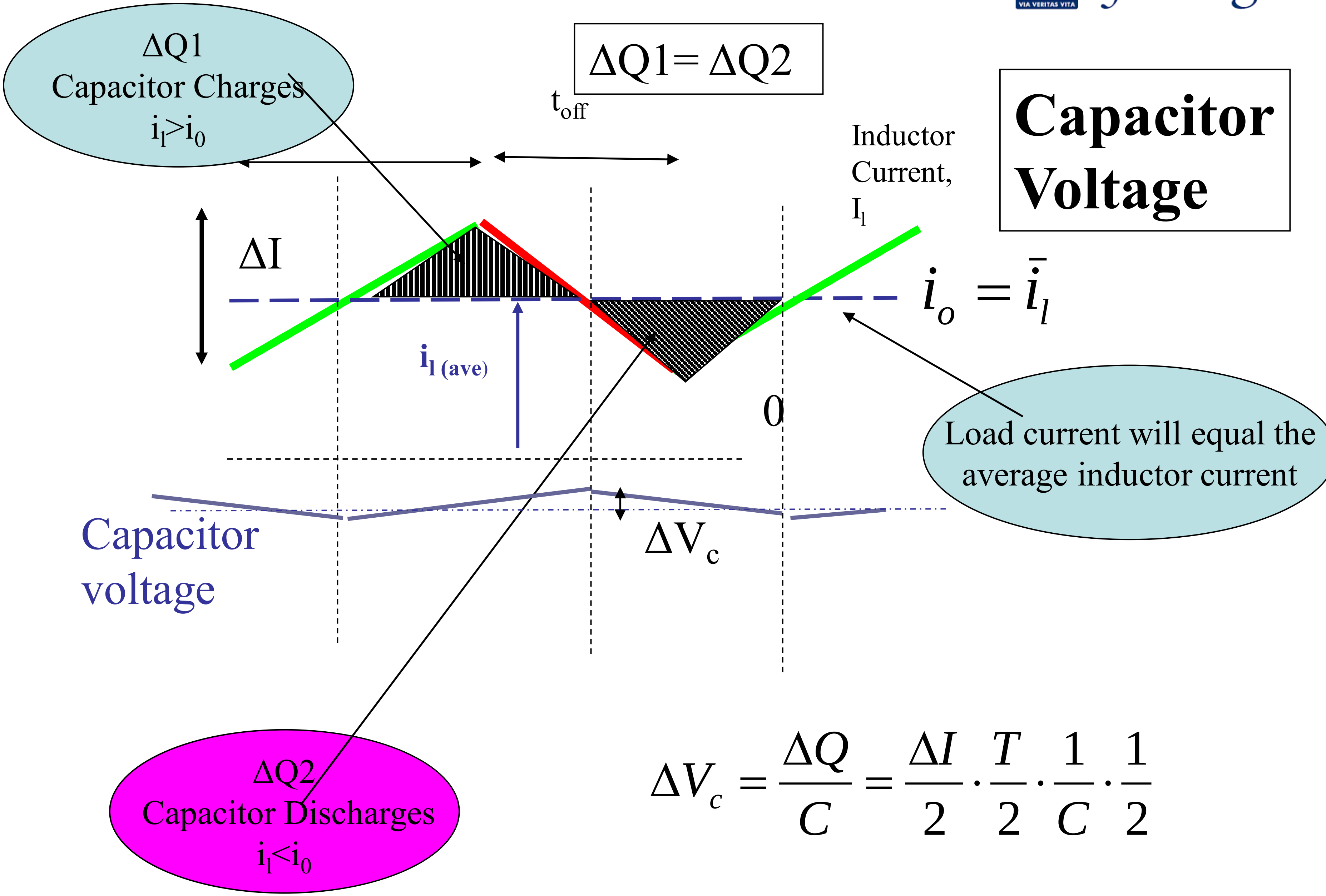
For this approximation to hold the output **capacitance must be sufficient large to limit the output voltage ripple**.

$$\Delta V_c = \frac{I_c \cdot \Delta t}{C}$$

$$i_c = i_l - i_o$$

The capacitor current is the difference between the inductor current i_l and the capacitor current i_o

Capacitor Voltage

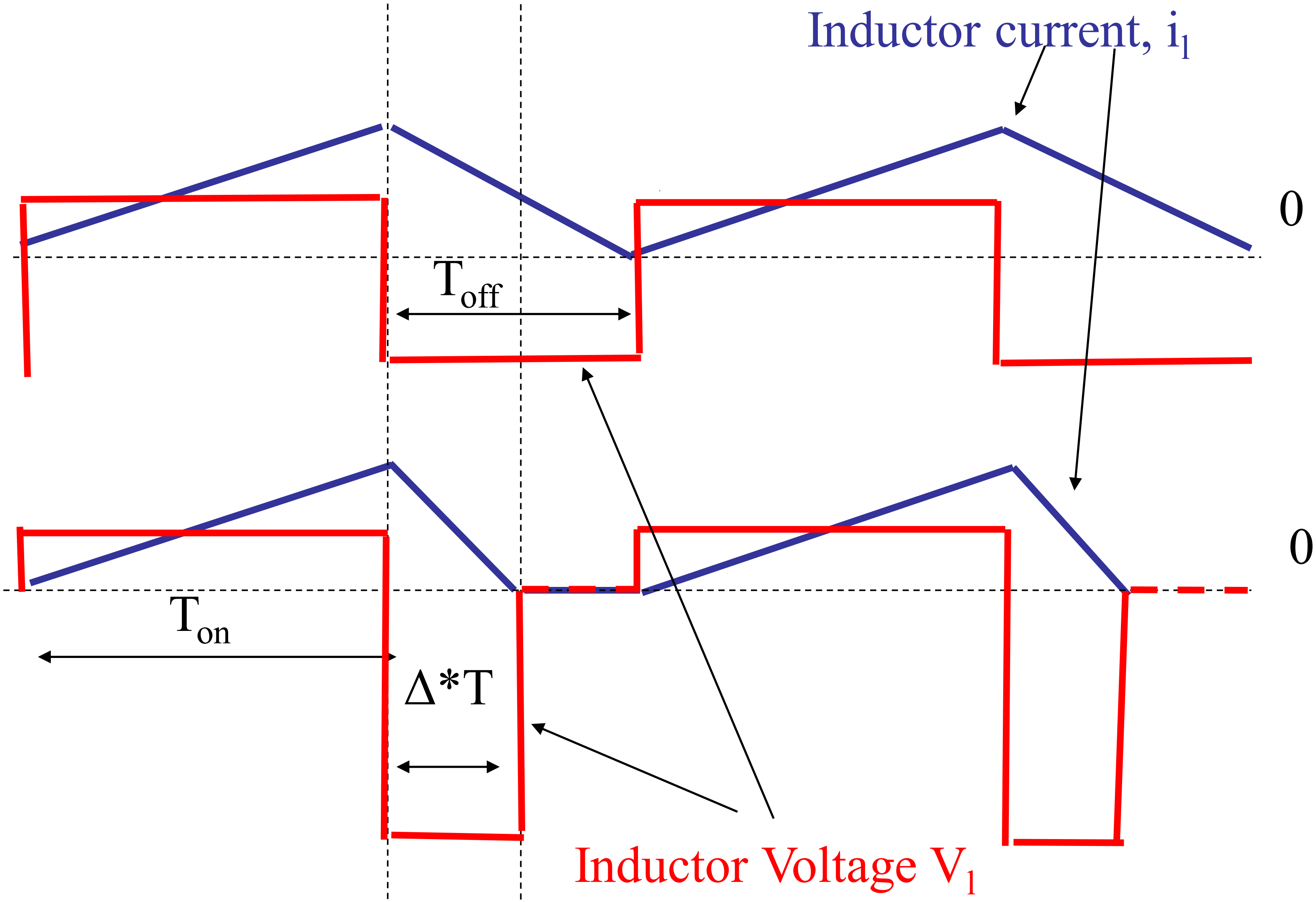


$$\Delta V_c = \frac{\Delta Q}{C} = \frac{\Delta I}{2} \cdot \frac{T}{2} \cdot \frac{1}{C} \cdot \frac{1}{2}$$

Efficiency

- If components are ideal they will be lossless (100% efficient)
- Practically losses occur in
  - Inductor (resistance and iron loss)
  - Capacitor (ESR)
  - Diode (On-state volt drop and reverse recovery)
  - Switch (Switching and conduction loss)
- But efficiencies of 96-98% common in high-power supplies.

Discontinuous Current (Buck Converter)



Discontinuous Current (Buck Converter)

As the load current decreases there comes a point where the inductor current reaches the end of the OFF period. The is the boundary current and is defined by the condition that the current ripple is equal to twice the average inductor current. For the boost converter:

$$\Delta i_l = 2 \cdot \bar{i}_l = 2 \cdot i_0$$

$$\Delta i_l = \frac{(V_d - V_o)T_{on}}{L} = \frac{(V_d - DV_d) \cdot D \cdot T}{L}$$

$$\Rightarrow$$

$$i_o = \frac{(D - D^2) \cdot V_d}{2L \cdot f}$$

$$Where: \quad T_{on} = DT \quad f = \frac{1}{T}$$

Discontinuous Current

Below the boundary current the conditions for the analysis of the output voltage of the converter are no longer valid. If the current in the inductor falls to zero in time ΔT, then the output voltage is defined by the conditions:

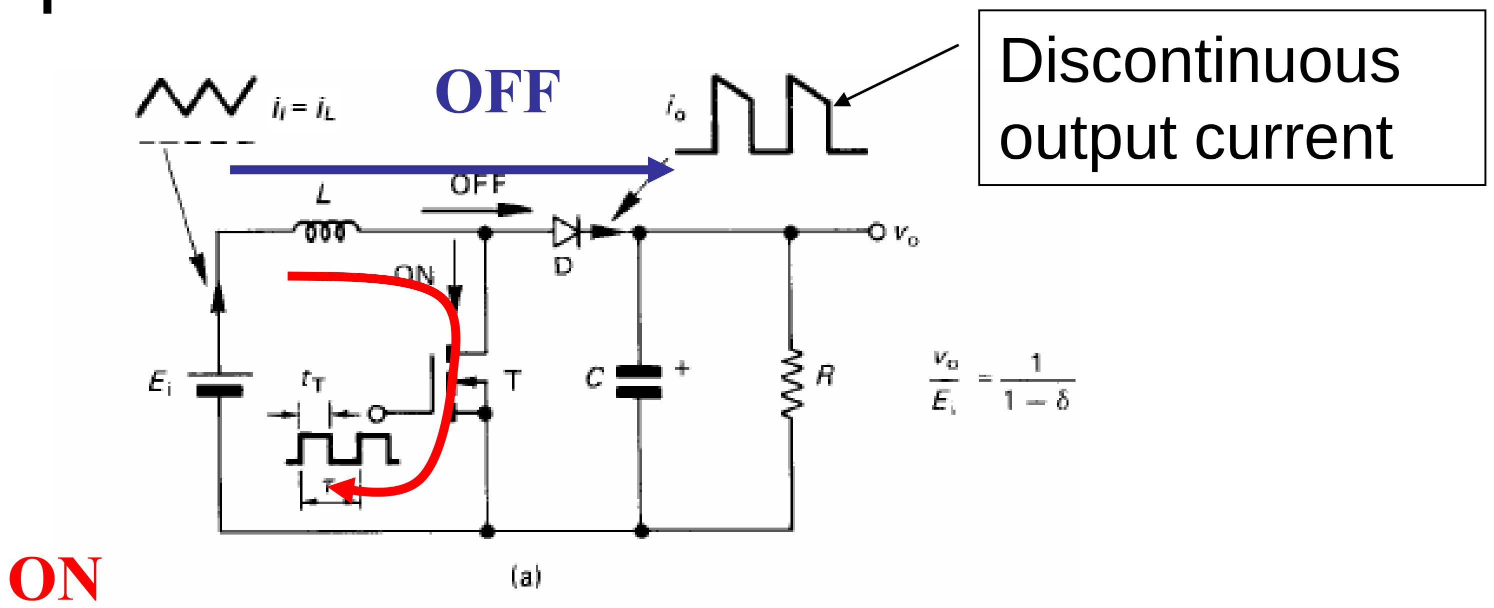
$$\Delta I_{off} = \frac{T_{on} \cdot (V_d - V_o)}{L}$$

$$\Delta I_{off} = \frac{\Delta T \cdot (-V_o)}{L}$$

$$\Rightarrow \quad \frac{T_{on} \cdot (V_d - V_o)}{L} = \frac{-\Delta T \cdot (-V_o)}{L}$$

$$\Rightarrow \quad \frac{V_o}{V_d} = \frac{T_{on} V_d}{(\Delta T + T_{on})} = \frac{D V_d}{(\Delta + D)}$$

Step-up Converter



- Step-up converter is a boost converter
- The output voltage is larger than the input.
- Switch is pulse-width modulated
- Supply current is near-continuous (inductor at input).
- Current can be uncontrolled when the output capacitor is fully discharged

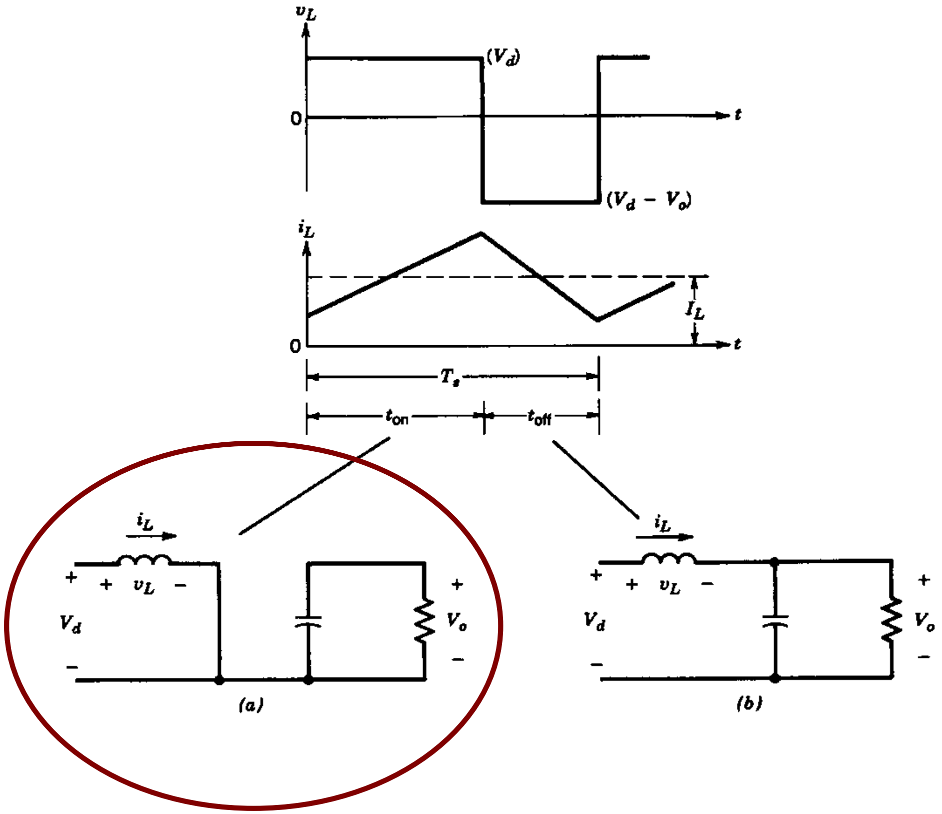
Switch ON

- Inductor current

$$\frac{di_L}{dt} = \frac{V_d}{L}$$

$$\Delta i_{LON} = \frac{V_d}{L} t_{on}$$

- During ON period, energy is stored in the inductor and the capacitor provides ALL of the energy to the load.



Switch ON

Switch OFF

Switch OFF

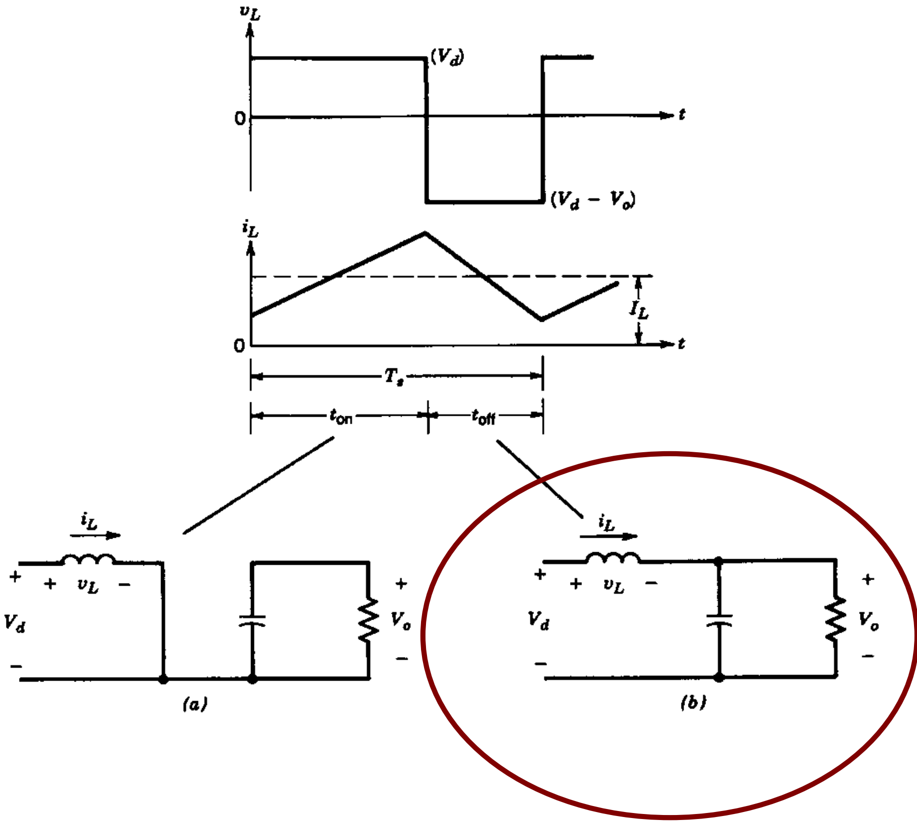
- At switch OFF, inductor current wants to keep current flowing.
- Inductor develops a voltage in same direction as *Vd*.
- This provides a voltage boost

$$V_o = \left(V_d + V_l\right)$$

- During OFF period, i_L falls

$$V_L = V_d - V_o$$

$$\Delta i_{L,OFF} = \frac{V_d - V_o}{L} t_{off}$$



Switch ON

Switch OFF

Switch OFF

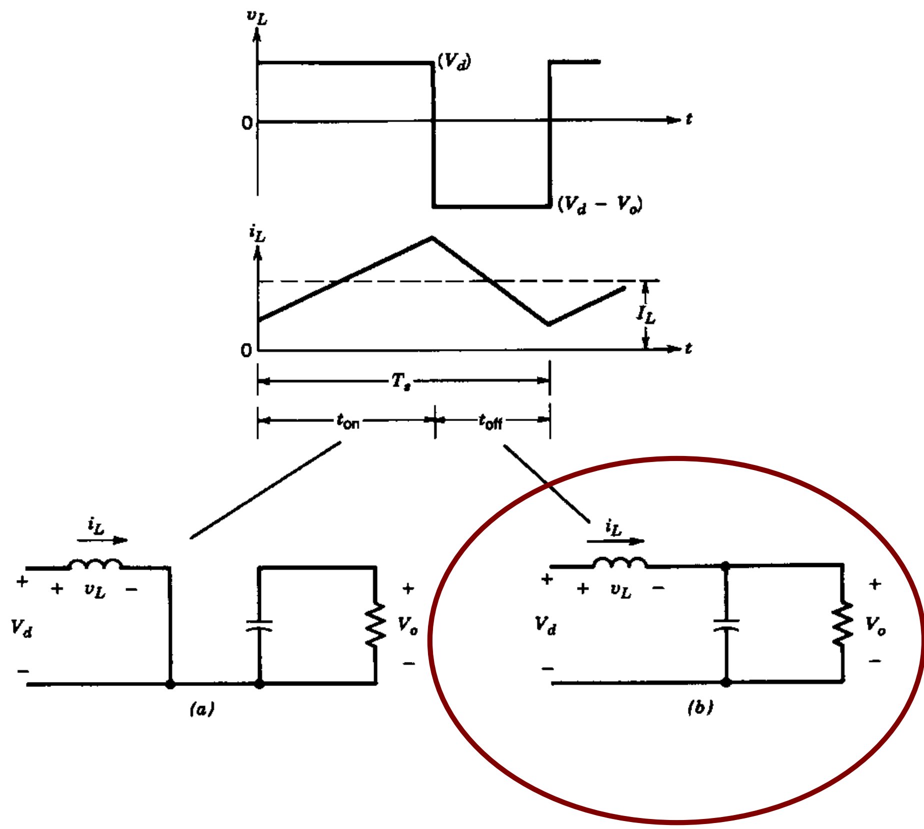
- In steady-state operation, the change in currents during ON and OFF periods must match.

$$\Delta i_{L,ON} = -\Delta i_{L,OFF}$$

$$V_d t_{on} = -(V_d - V_o) t_{off}$$

$$\boxed{\frac{Vo}{Vd} = \frac{1}{1-\left(\frac{t_{on}}{T_s}\right)} = \frac{1}{1-D}}$$

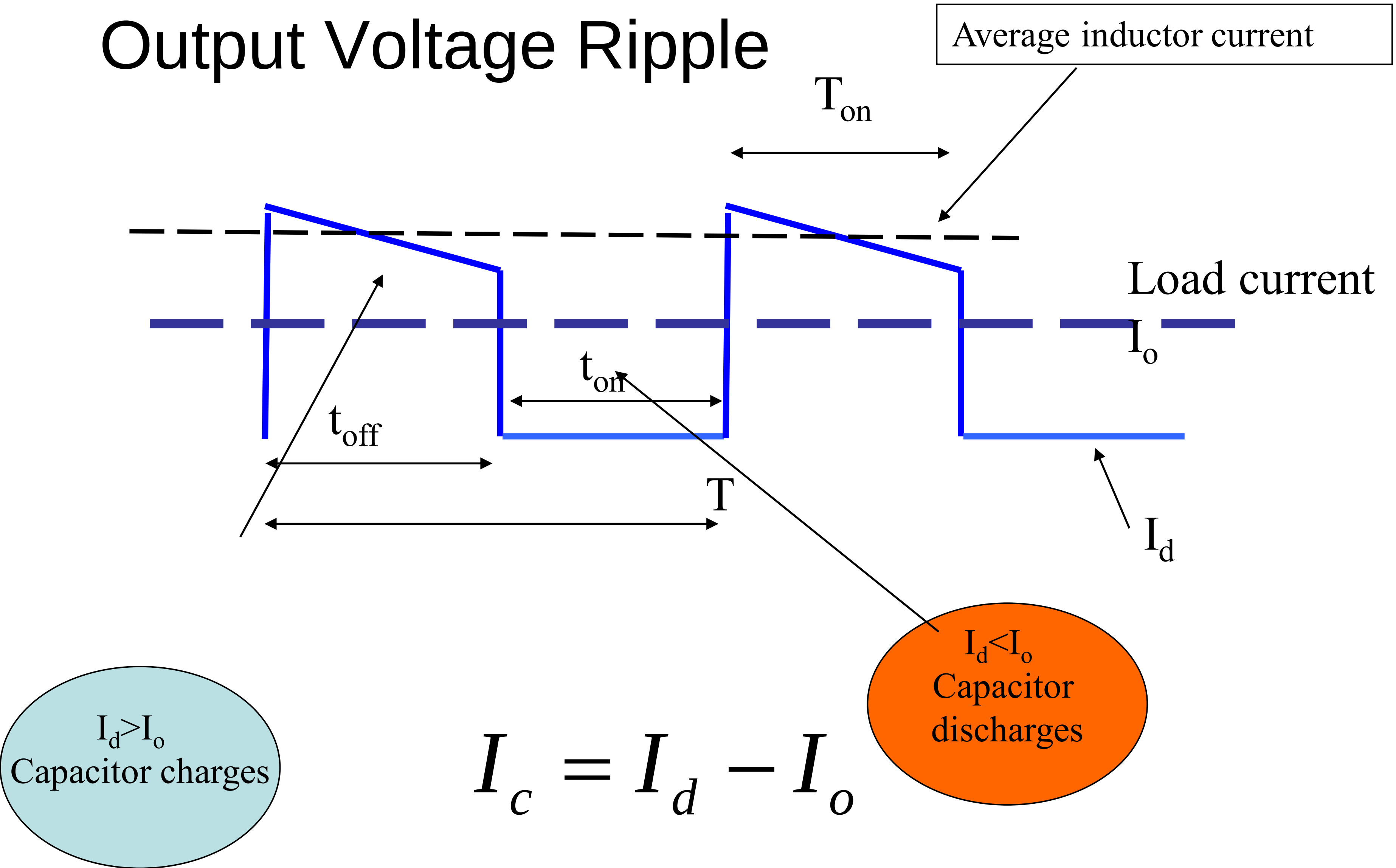
- Where $\boxed{D = \frac{t_{on}}{T_s}}$



Switch ON

Switch OFF

Boost Converter
Output Voltage Ripple



$$I_c = I_d - I_o$$

Boost Converter
Output Voltage Ripple

The current delivered via the diode to the load is discontinues
Charge is transferred to the capacitor when the switch is off

$$I_c = I_d - I_o$$

$$\Rightarrow$$

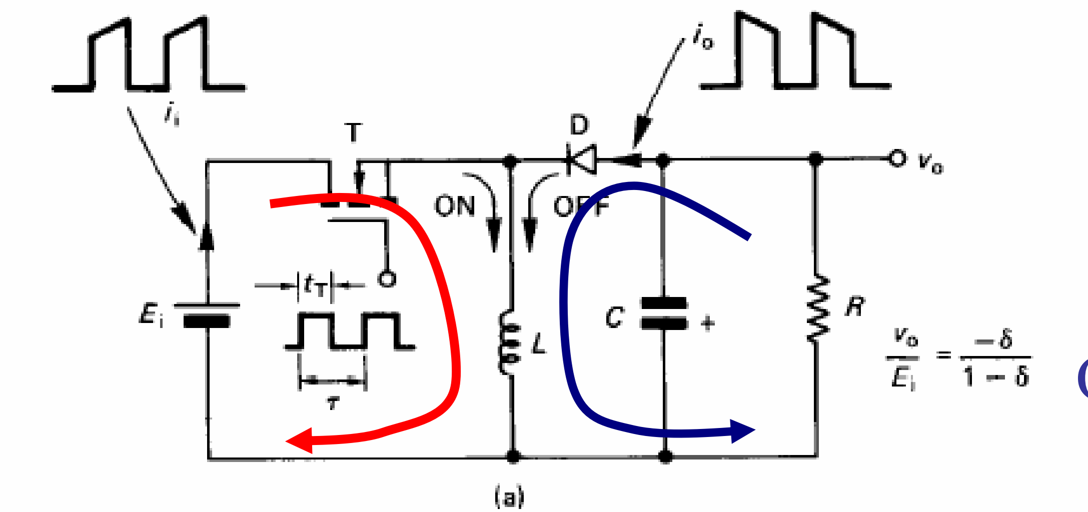
$$\Delta Q_{off} = \int_{o}^{t_{off}} I_d - I_o dt \approx (\bar{I}_l - I_o) \cdot t_{off}$$

$$\Delta Q_{on} = \int_{t_{off}}^{T} I_d - I_o dt \approx (0 - I_o) \cdot t_{on} = I_o \cdot t_{on}$$

Discontinuous output current will result in increased voltage ripple or larger output capacitance

Fly-Back Converter (Step Up/Step Down)

ON



OFF

$$\Delta I_{on} = \frac{V_d \cdot T_{on}}{L} \qquad \Delta I_{off} = \frac{V_o \cdot T_{off}}{L}$$

$$for\ steady - state$$

$$\Delta I_{on} = \frac{V_d \cdot T_{on}}{L} = -\Delta I_{off} = -\frac{V_o \cdot T_{off}}{L}$$

$$\Rightarrow \quad \frac{V_o}{V_d} = -\frac{T_{on}}{T_{off}} = -\frac{D}{(1-D)}$$

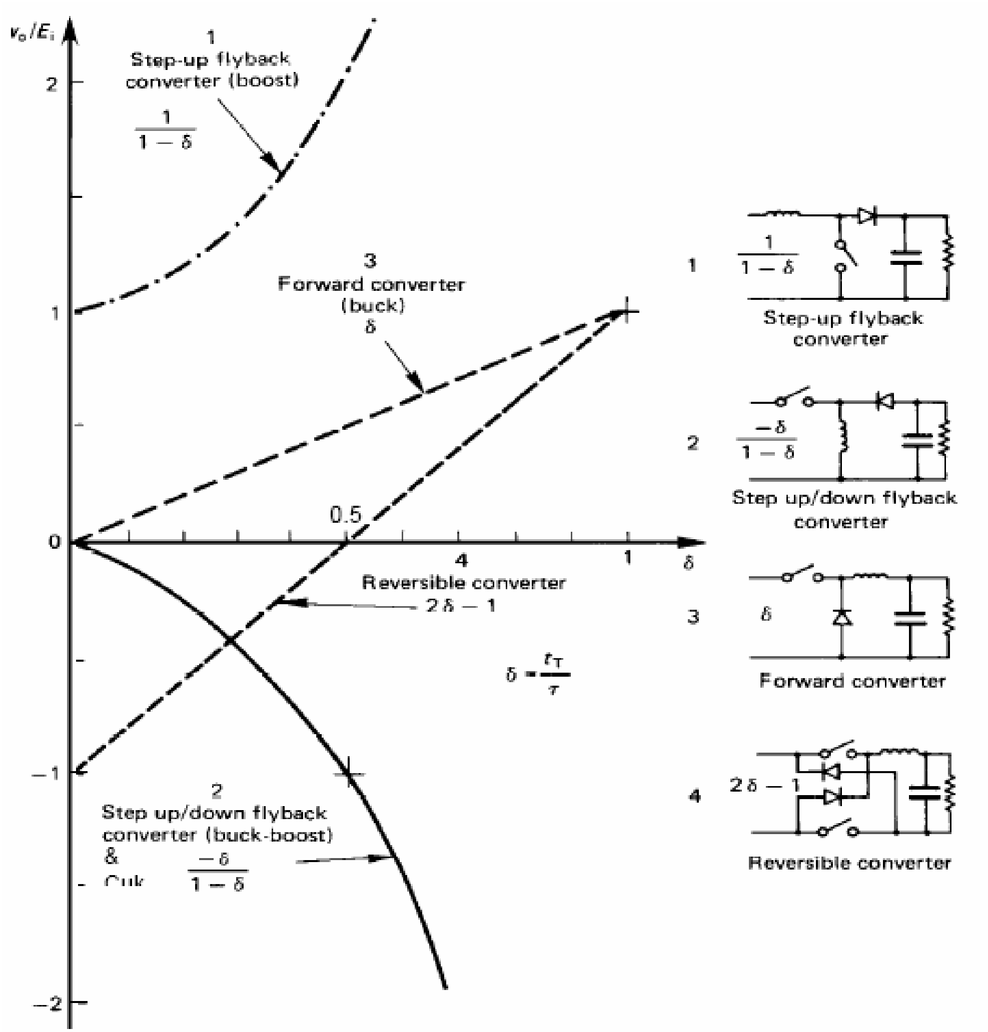


Figure 15.9. *Transformation voltage ratios for four converters when operated in the continuous inductor conduction mode.*

Voltage transformation ratios.