1. Power Transistors

2. DC–DC Converters

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1.0 Outline – Power Transistors

- Power Electronic Devices
- Power Transistors
    - Power BJT
    - Power MOSFET
    - IGBT
- Comparison

Power semiconductor devices

Important feature

Controllability

- Power Diode – uncontrollable
- Thyristor (THYRatron tube & transISTOR)
  - **SCR (Silicon Controlled Rectifier)** – ON controllable
  - TRIAC (Triode ac switch) – ON controllable
  - GTO (Gate turn-off thyristor) – **ON/OFF controllable**
- Power Transistors – **ON/OFF controllable**
  - Power BJT
  - Power MOSFET
  - IGBT

Static induction transistor (SIT)

Not required

https://en.wikipedia.org/wiki/Power_semiconductor_device

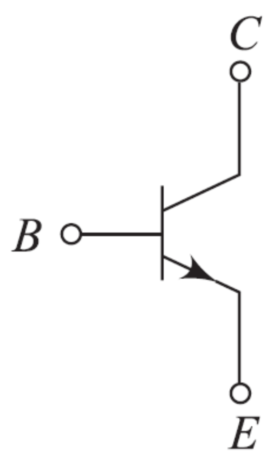
1.0 Power Transistors

- **Feature:**
  - Controlled characteristics: The transistor is turned ON when a current signal is given to base, or control terminal. It will remain in the ON-state as long as control signal is present – if the control signal is removed, the transistor is turned OFF.

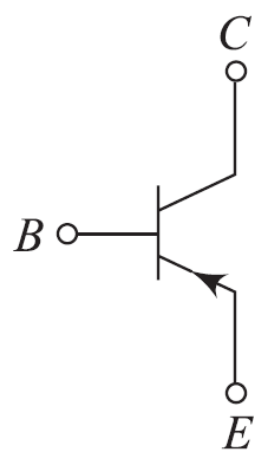
- **Applications**
  - In use from 1980s
  - GTR and GTO are seldom in use today
  - IGBT and power MOSFET are the two major power semiconductor devices nowadays

1.1 Power BJT (Bipolar Junction Transistor)

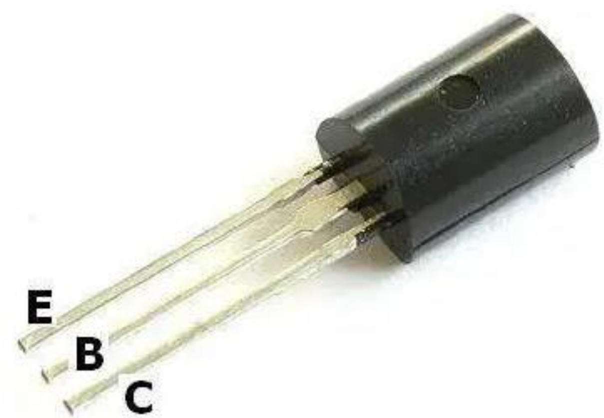
- Three terminals – collector (C), emitter (E), and base (B).
- Emitter with an *arrowhead* indicates the *direction* of emitter current.
- Three layer, two junction *NPN* or *PNP* semiconductor device.
- NPN type transistors are easy to manufacture, cheaper and very wide in high-voltage and high-current applications.
- *Bipolar* – the current flow in the device is due to the movement of both holes and electrons.



NPN type

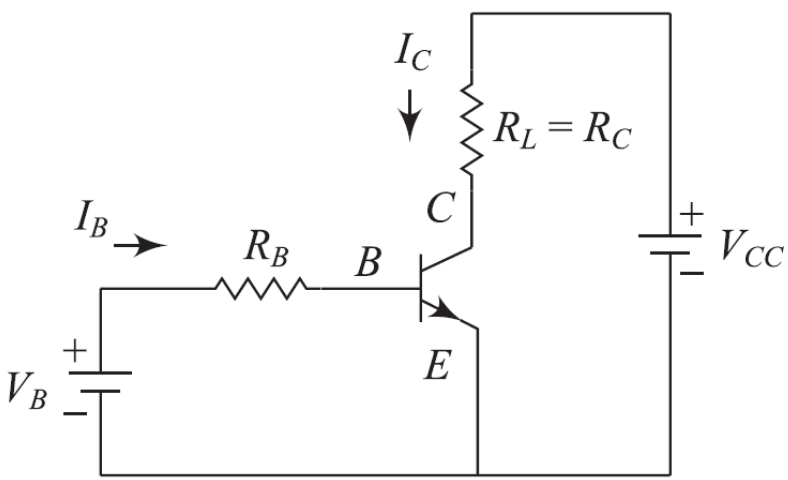


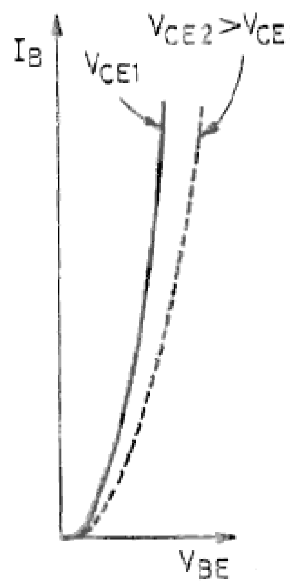
PNP type



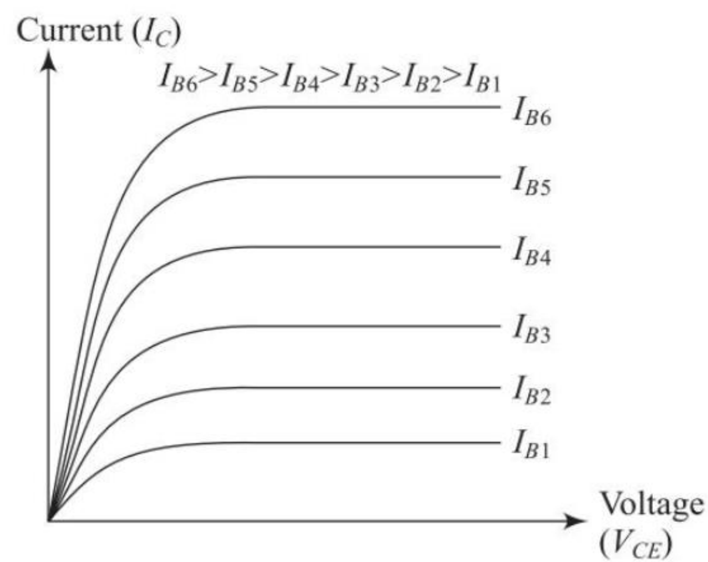
BJT I-V Characteristics

- Common-emitter (CE) is more common in switching applications.
- Output characteristics: Collector current (I_C) versus collector-emitter voltage (V_{CE}).
- For $I_B = 0$, as V_{CE} is increased, a small leakage current exists.
- As the base current is increased from $I_B = 0$ to I_{B1}, I_{B2} etc., collector current also rises as shown below:





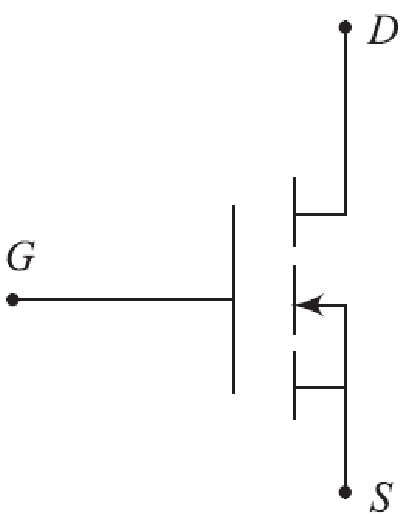
Input characteristics



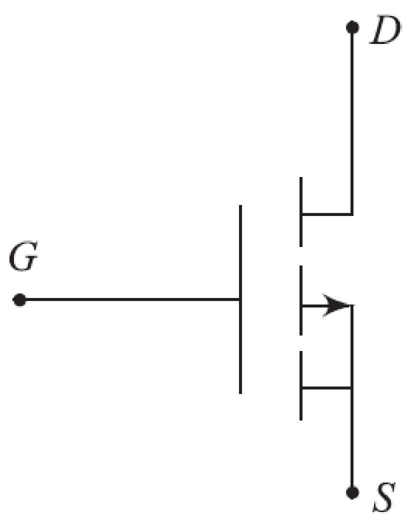
Output characteristics

1.2 Power MOSFET

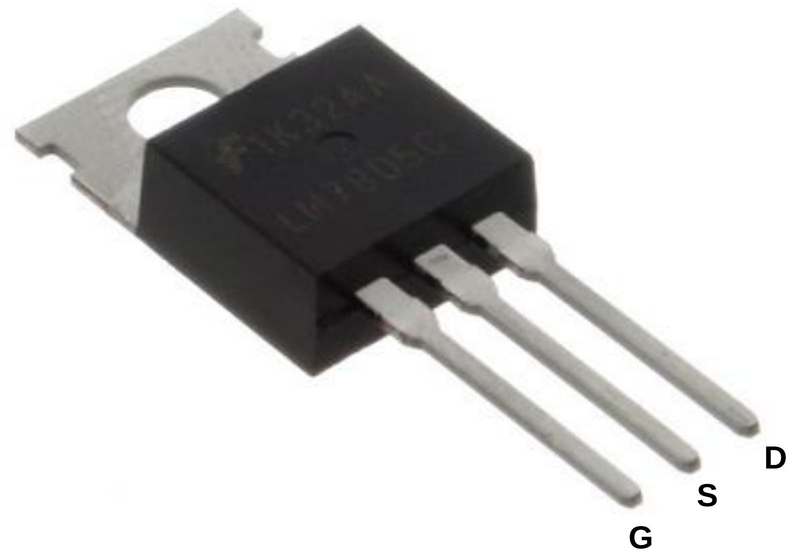
- Three-terminals – drain (D), source (S), and gate (G).
- Arrow indicates the direction of electron flow.
- BJT is current-controlled device whereas MOSFET is a voltage-controlled device.
- MOSFETs are used in low-power high-frequency converters.



n −channel MOSFET

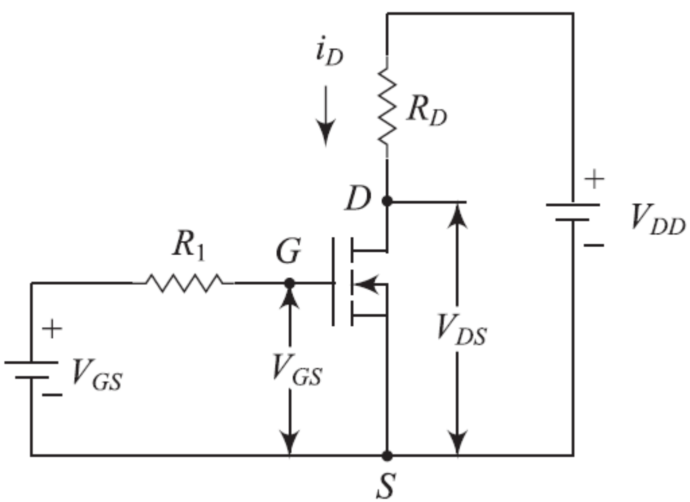


p −channel MOSFET

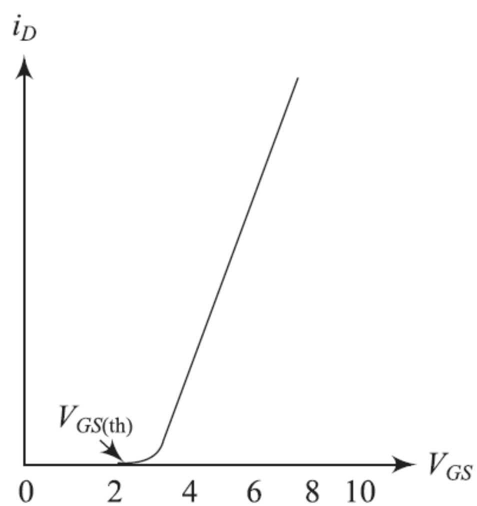


MOSFET I-V Characteristics

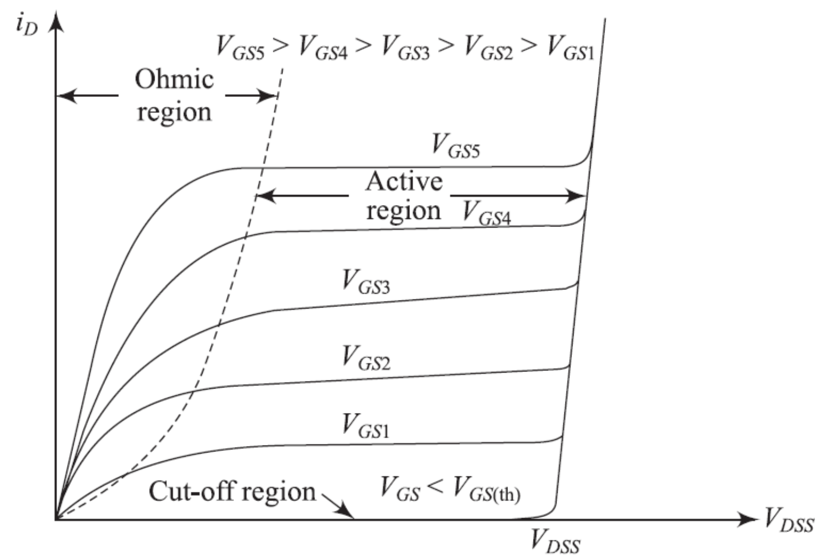
- Input signal V_{GS} is applied across gate to source & output signal V_{DS} is obtained from drain. Source terminal (S) is common between input & output of a MOSFET.
- *Transfer characteristics:* I_D is a function of V_{GS}. When $V_{GS} < V_{GS(th)}$, the device is in OFF-state. In general, the value of $V_{GS(th)}$ is about 2 to 3 V.
- *Output characteristics:* I_D is a function of V_{DS} with V_{GS} as a parameter. For given V_{GS}, if V_{DS} is increased, output characteristic is relatively flat indicating that drain current is nearly constant. It consists of cut-off, active and ohmic regions.



n −channel MOSFET



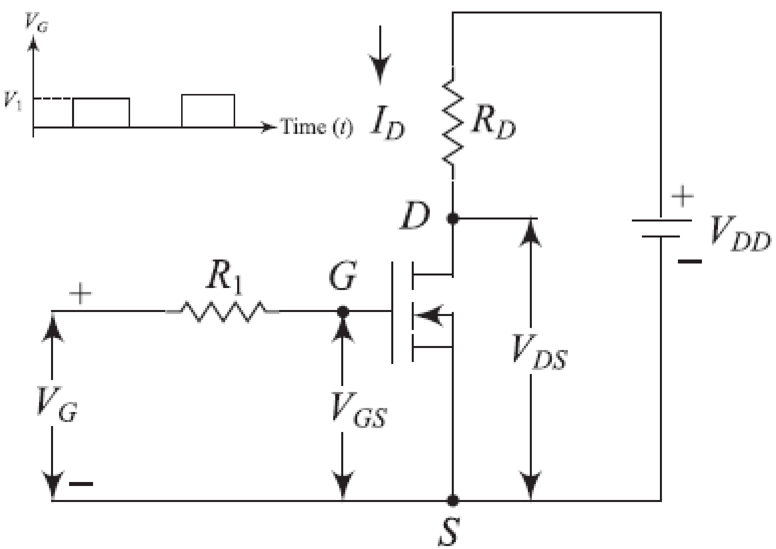
Transfer characteristics

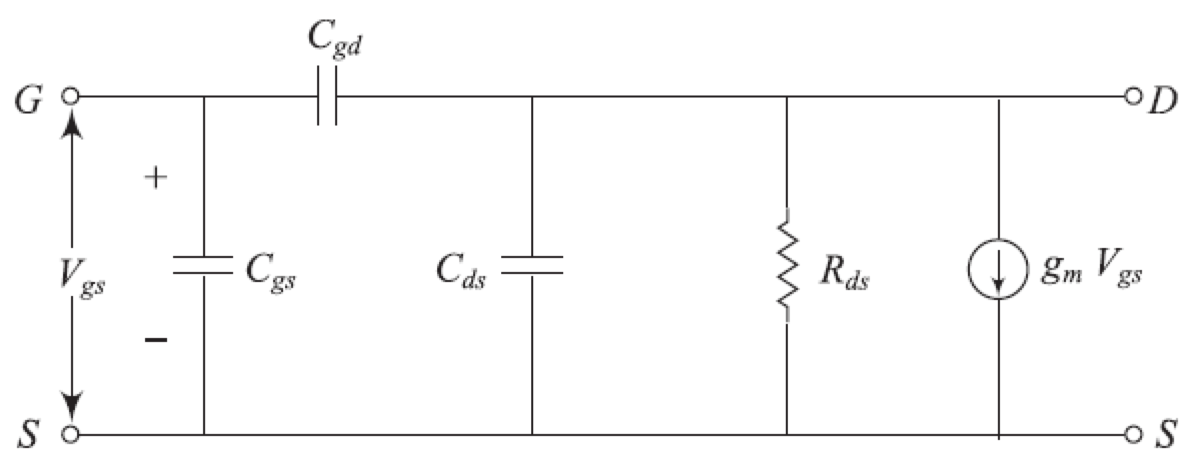


Output characteristics

Switching Characteristics

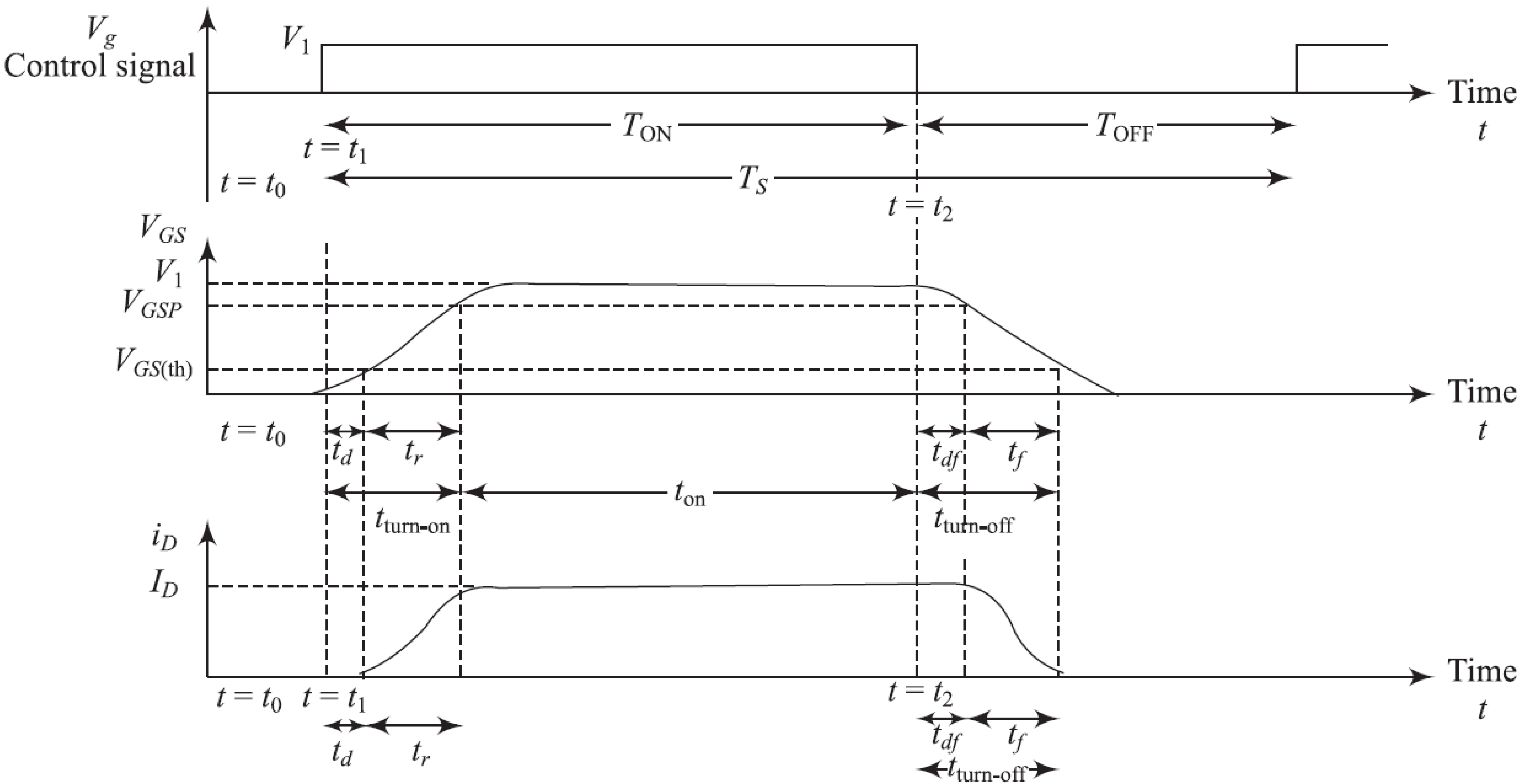
- When a pulse input voltage is applied to the gate of MOSFET, the device will turn-ON if $V_{GS} > V_{GS(th)}$.
- Switching characteristics' are influenced to large extent by internal capacitance.
- At $t = t_o$, input voltage $V_G = 0$ & $V_{GS} < V_{GS(th)} \rightarrow I_D = 0$, device in OFF state.
- At $t = t_1$, voltage starts to increase from 0 to $V_1 \rightarrow C_{gs}$ starts to charge. During t_d, C_{gs} is charged to $V_{GS(th)}$. During t_r, V_{GS} increases from $V_{GS(th)}$ to full gate voltage V_{GSP} to operate the transistor in linear region, also increases to I_D.





Switching model of MOSFET

Switching Characteristics

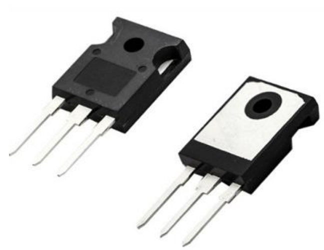


Applications and Features different from BJT

- High-frequency switching applications, varying from few W to kWs.
- Very popular in switch mode power supplies and inverters.
- Unipolar device whereas BJT is bipolar device.
- High input impedance whereas BJT has low impedance.
- Voltage controlled device whereas BJT is current controlled device.
- Conduction loss of MOSFET is larger than that of BJT due to a larger voltage drop for high-voltage applications.
- Lower switching losses whereas BJT has higher switching losses.

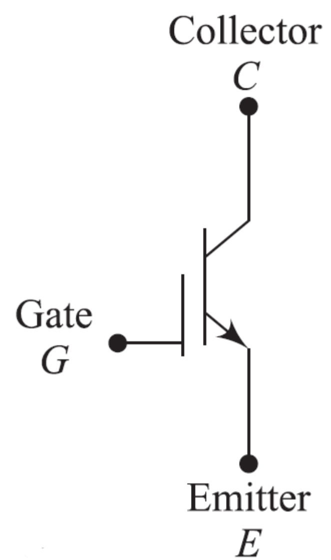
1.3 IGBT (Insulated Gate Bipolar Transistor)

- Combination of power transistors BJT and MOSFET.
- High input impedance like MOSFET and low on-state power loss as in BJT.
- Voltage controlled device.
- IGBT is very popular amongst power electronic engineers.
- MOSIGT ⟺ COMFET ⟺ GEMFET

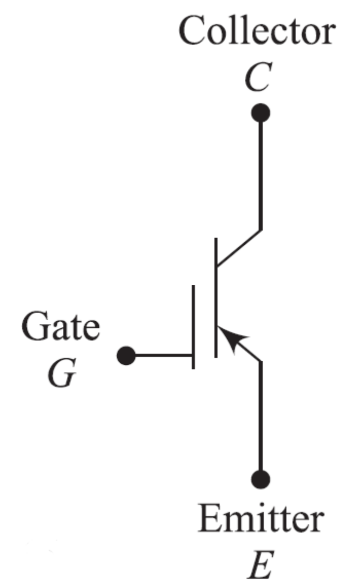


Features

- Low conduction loss (BJT)
  - High-speed turn-ON (MOSFET)
  - Low-power, easy drive (MOSFET)



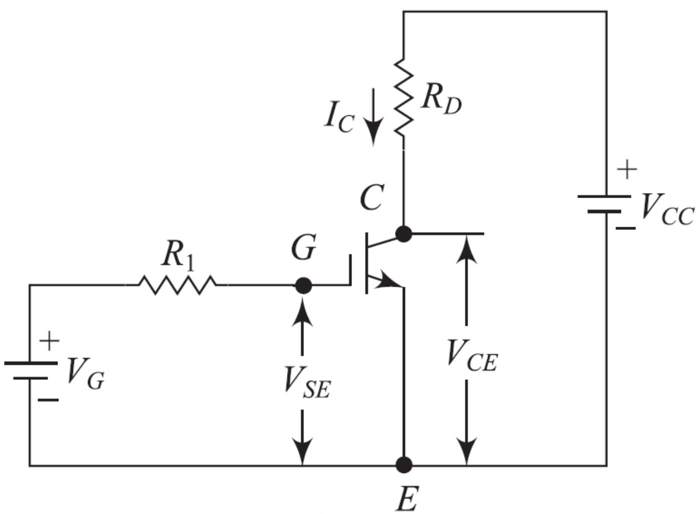
n –channel IGBT

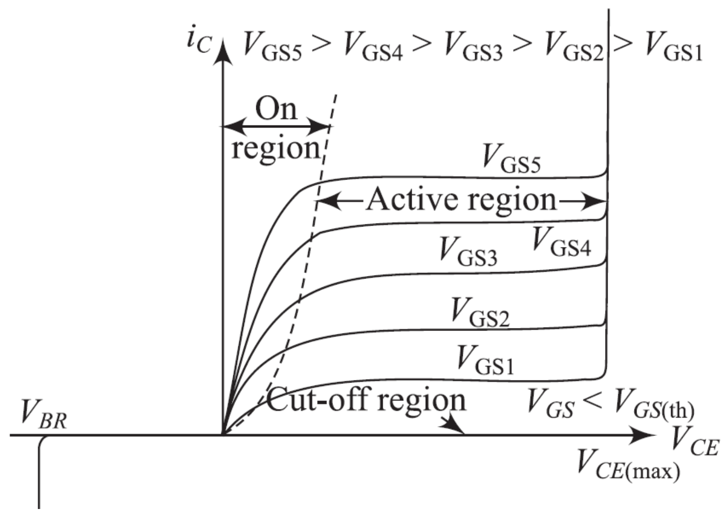


p –channel IGBT

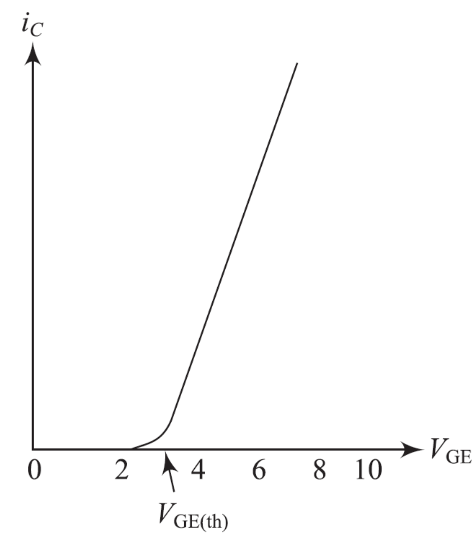
IGBT I-V Characteristics

- Emitter terminal is common between input and output of IGBT.
- *Transfer characteristics:* I_C versus the V_{GE} – similar to MOSFET.
- *Output characteristics:* I_C versus V_{CE} for various values of V_{GE1}, V_{GE2} etc., In the forward direction, the shape of the output characteristic is like that of BJT. But here the controlling parameter is V_{GE} because IGBT is voltage-controlled device.





Output characteristics



Transfer characteristics

Review of the classifications

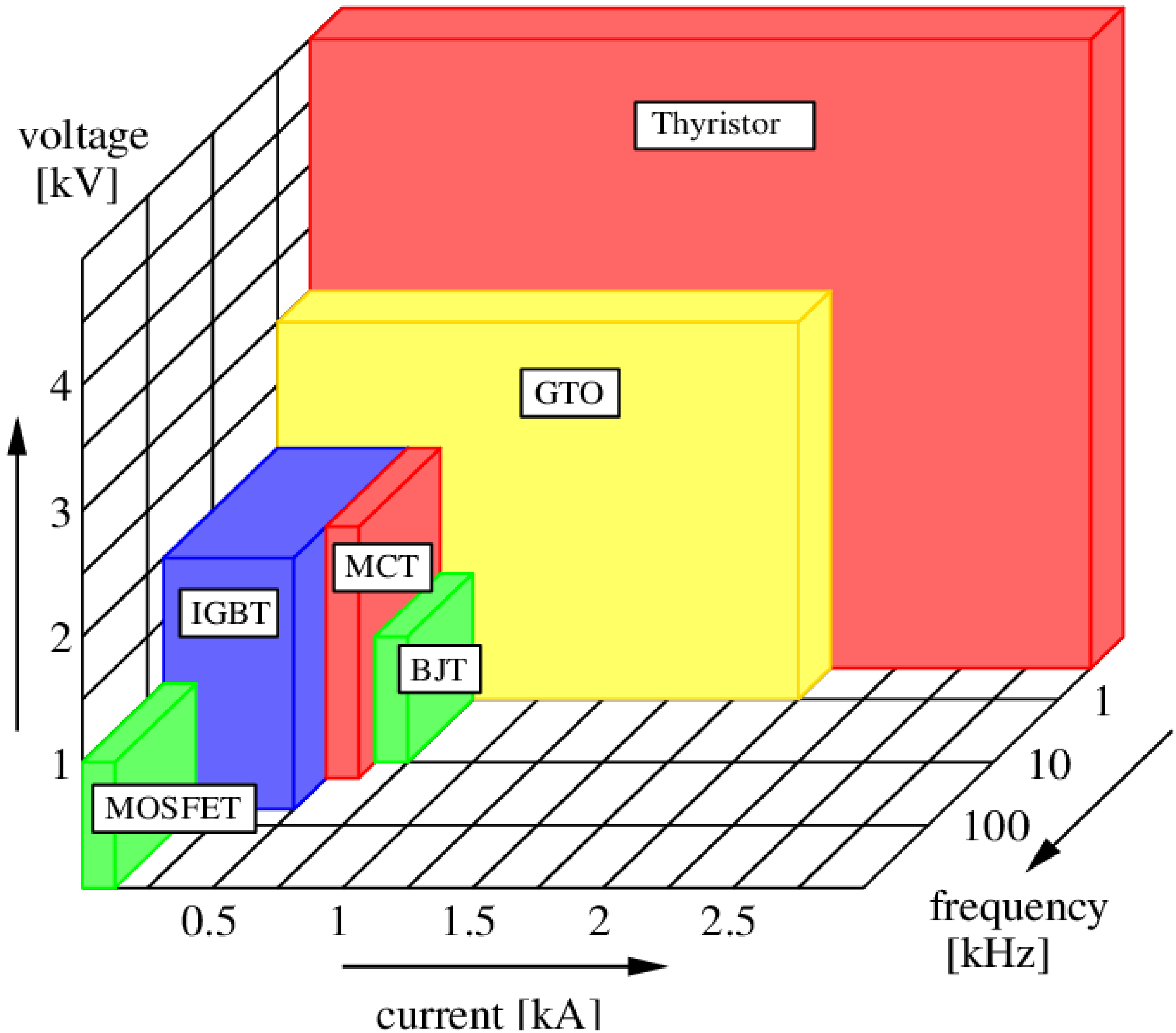
power electronic devices

- Current-driven (current-controlled) devices: thyristor, GTO, GTR
- Voltage-driven (voltage-controlled) devices (Field-controlled devices):power MOSFET, IGBT, SIT, SITH, MCT, IGCT

power electronic devices

- Pulse-triggered devices: thyristor, GTO
- Level-sensitive (Level-triggered) devices: GTR,power MOSFET, IGBT, SIT, SITH, MCT, IGCT

Comparison of power semiconductor devices



2.0 Outline – DC to DC Converters

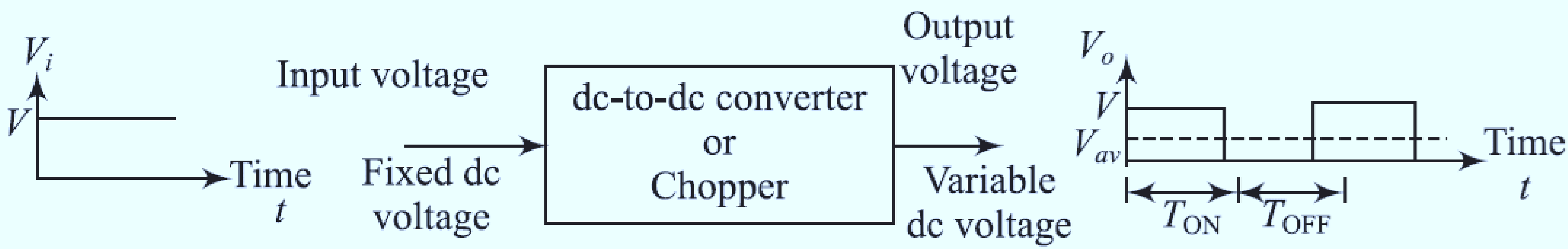
- ✓ Step-down operation
  - Duty cycle generation

- ✓ Types of DC-DC converter
  - Buck converters
  - Boost converters
  - Buck-Boost converter

- ✓ Closed-loop control of DC-DC converters

2.1 Types of DC-DC Converters

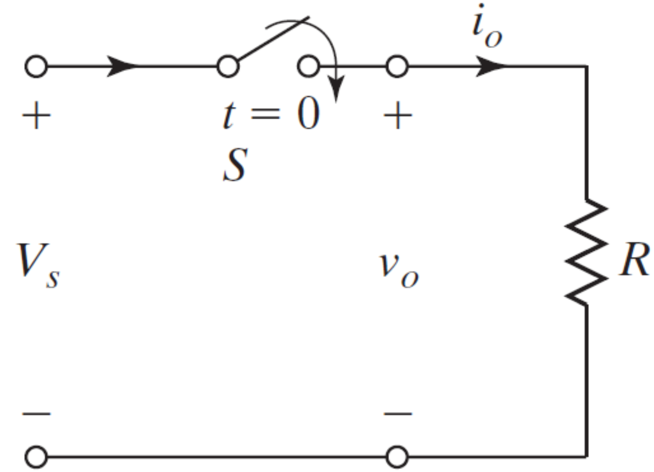
- DC-DC converters (also called *choppers*) can be used to obtain a *variable dc voltage from a fixed dc supply*.
- Step-down (*Buck converters*) – output voltage is less than input voltage.
- Step-up (*Boost converters*) – output voltage is higher than input voltage.
- Step-up/down: *Buck-boost converters*
  - the output voltage can be higher or less than the input voltage.



T_{ON} Is ON time of switch

T_{OFF} Is OFF time of switch

2.1.1 Step-down operation



- Operates in two modes:
  - Switch S is ON → $v_o = V_s$
  - Switch S is OFF → $v_o = 0$

- Average output voltage:

$$V_o = \frac{1}{T}\int_0^T v_o(t)dt = \frac{1}{T}\int_0^{t_1} V_s\, dt = \frac{t_1}{T}V_s = kV_s$$

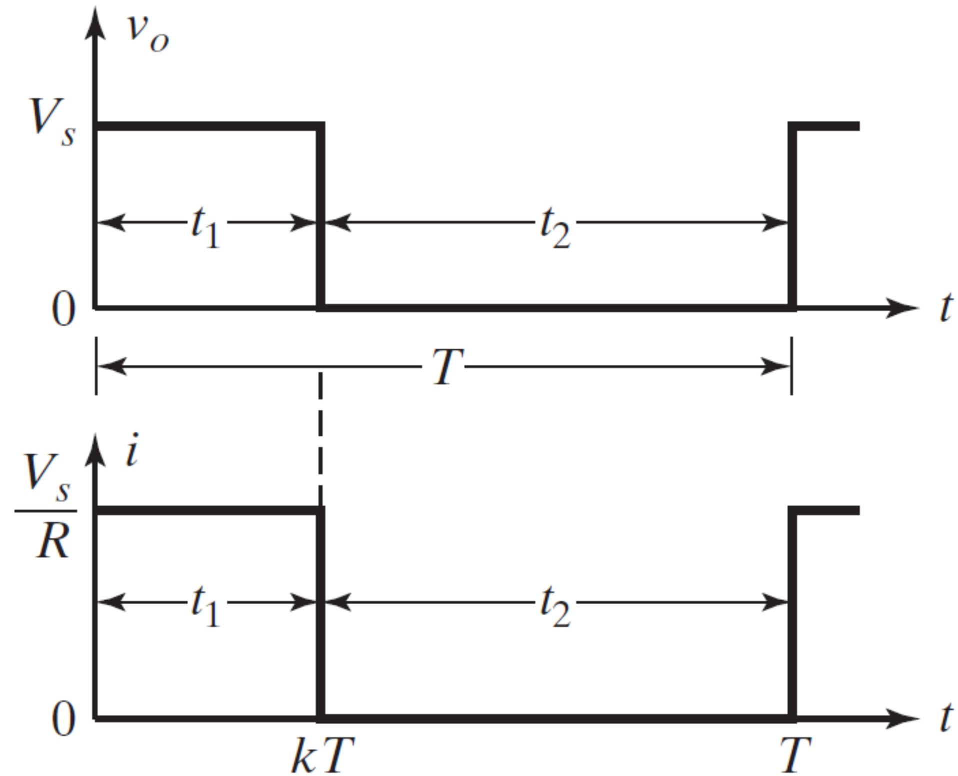
where k is the duty cycle;

t_1 – ON time period of switch.

t_2 – OFF time period of switch.

- RMS output voltage:

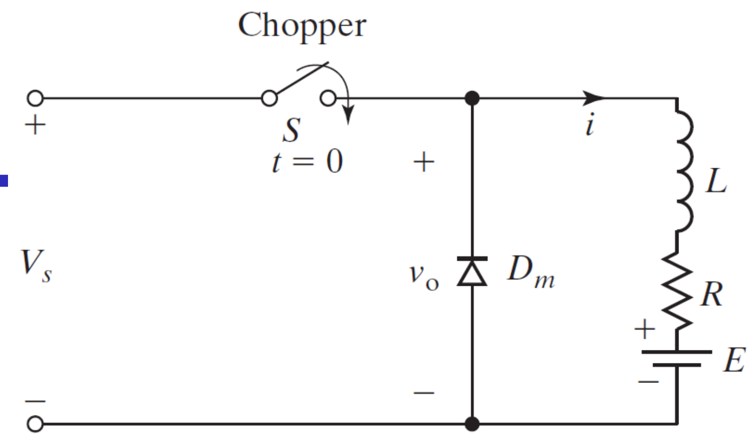
$$V_{RMS} = \left[\frac{1}{T}\int_0^T {v_o}^2(t)\, dt\right]^{1/2} = \sqrt{k}V_s$$



Switch ⟹ BJT, MOSFET, IGBT

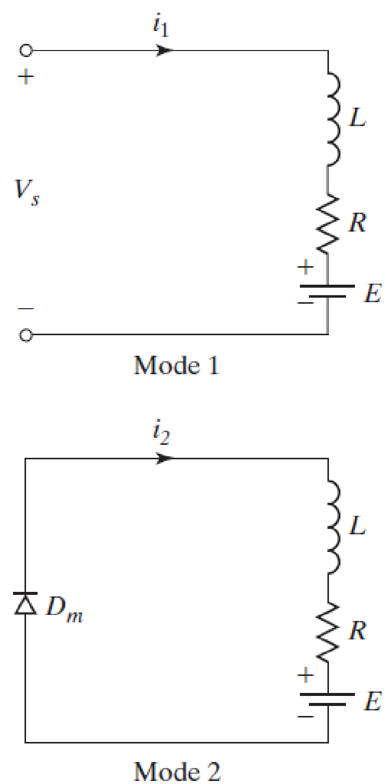
2.1.2 Step-down operation

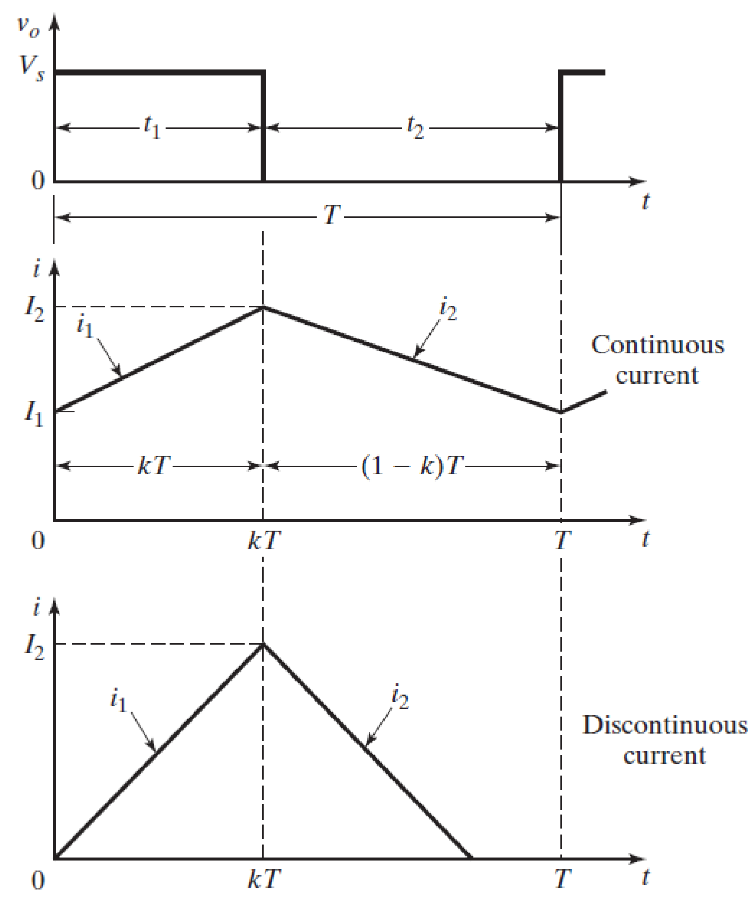
- Operates in two modes (RL –load):
  - Switch *S* is ON → current flows from supply to load
  - Switch *S* is OFF → load current continues to flow thru freewheeling diode.



- Assume that the load current rises linearly.

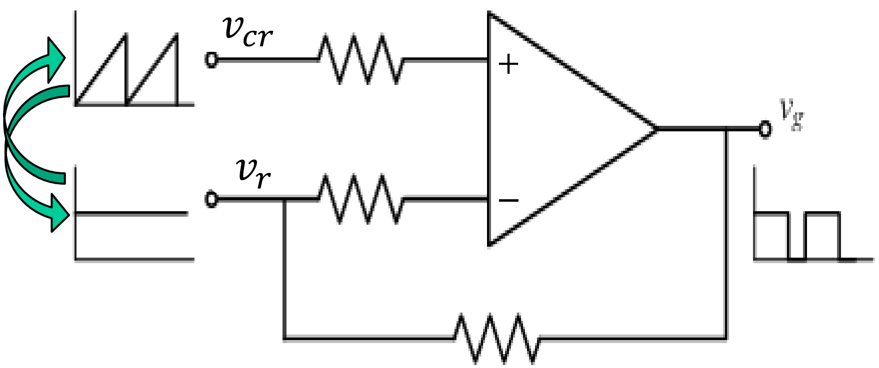
- However, the current flowing through an RL load rises or falls exponentially with a time constant ($\tau = L/R$), which is generally much higher than switching period T.

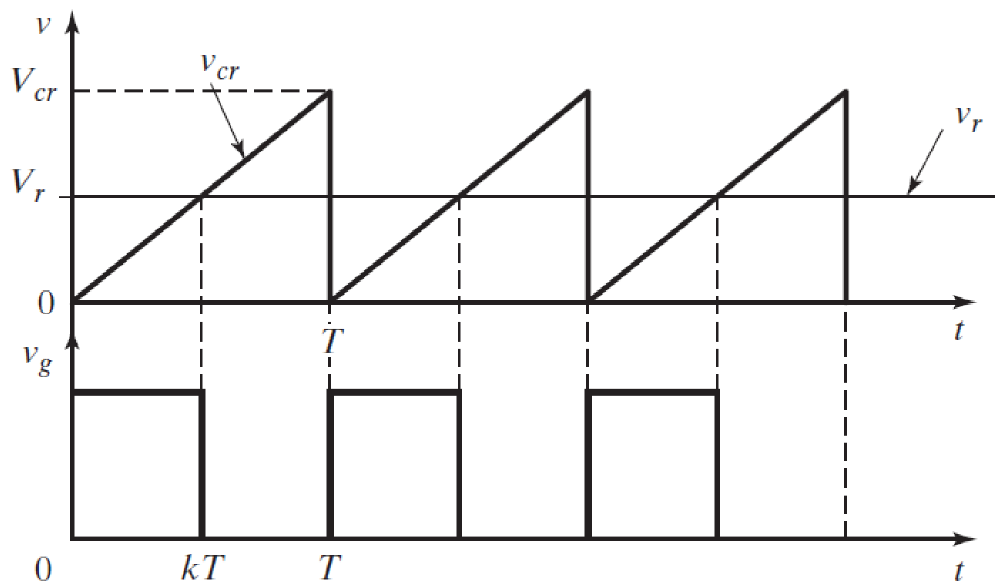




2.1.3 Generation of duty cycle

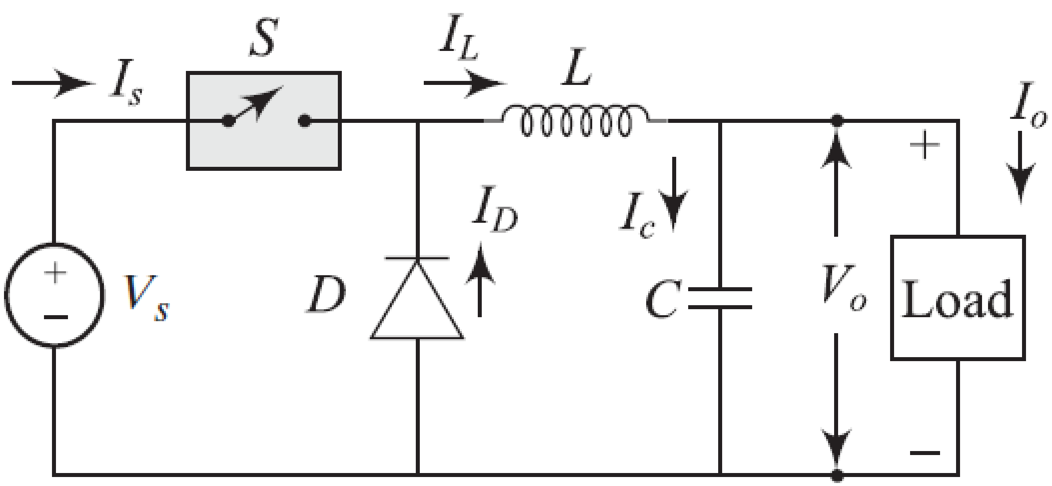
- If a saw-tooth signal v_{cr} and a DC reference signal v_r are supplied to a comparator, then the output of comparator is shown as v_g.
- The duty cycle of v_g is given as, $k = \frac{V_r}{V_{cr}}$
  - ✓ V_{cr} – is the peak value of v_{cr}; V_r – is the peak value of v_r.
  - ✓ By varying the carrier signal v_{cr} from 0 to V_{cr}, the k can be varied from 0 to 1.
- This is how we control the voltage of a DC-DC converter.

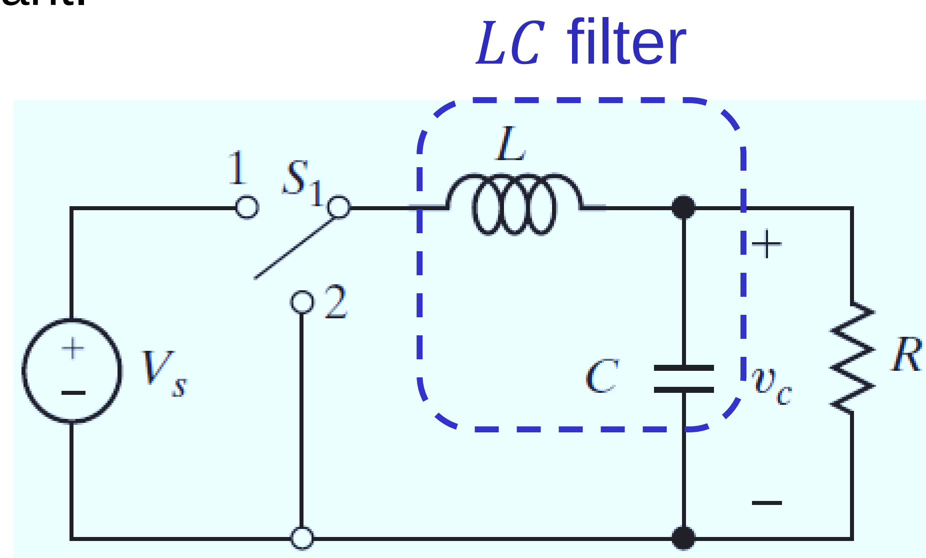




2.2 Buck Converter

- Average output voltage is *less than* input voltage – hence, called *buck* converter.
- One switch and one diode (to overcome the problem of stored inductive energy).
- Switch S can be a power BJT and acts as a controlled switch; diode D is uncontrolled switch – operate as *two* SPST bidirectional switches, shown below.
- LC filter to remove switching harmonics and to pass only the DC component so that the output voltage v_o is nearly a constant.





Buck converter → Two switches representation

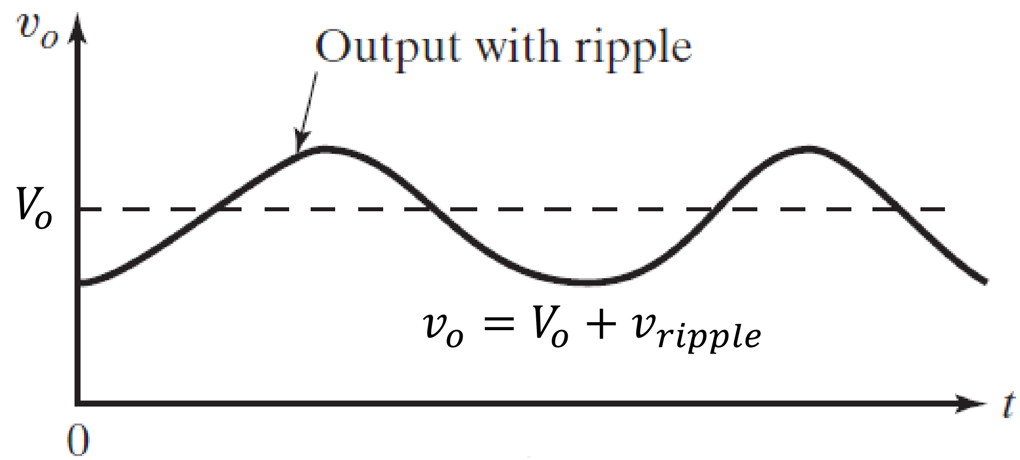
2.2.1 Small ripple approximation

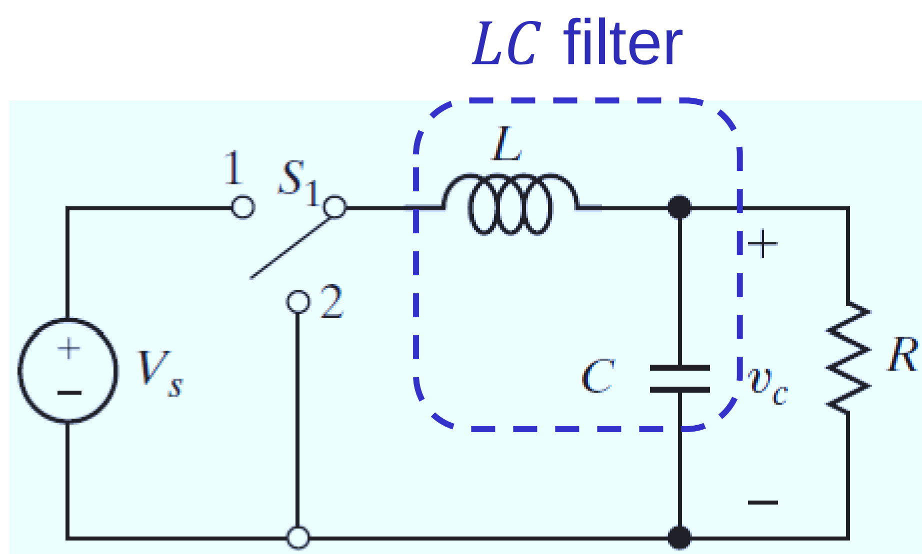
- The L-C form a practical low-pass filter.
- Actual output voltage waveform:

$$v_o = V_o + v_{ripple}$$

- In a well-designed converter, the output voltage ripple is small.
- Hence, the waveforms can be easily determined by ignoring the ripple: $\|v_{ripple}\| \ll V_o$

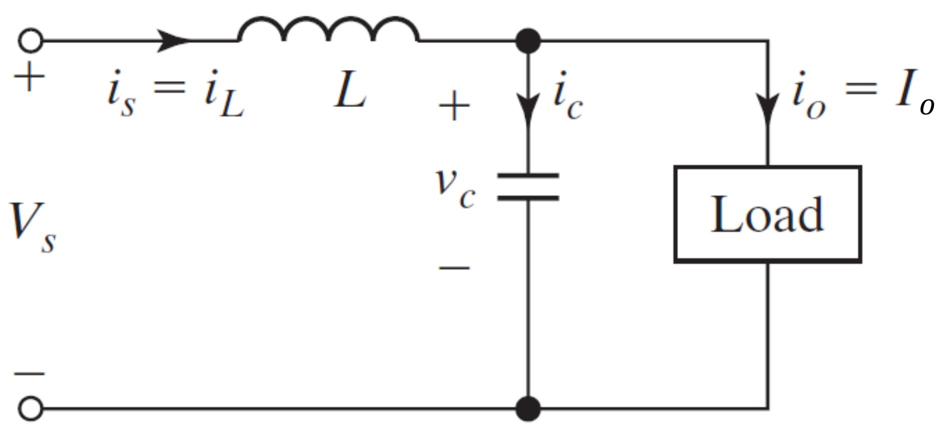
$$\therefore v_o \approx V_o$$



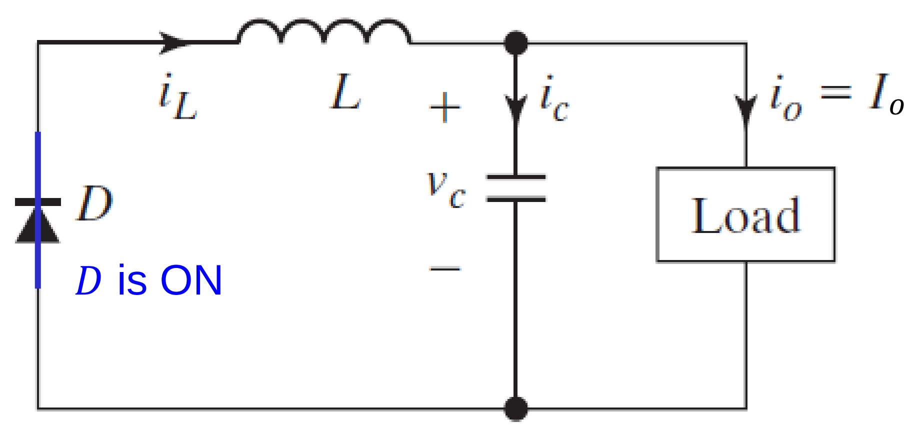


2.2.2 Operation modes

- Mode 1: Switch is ON (position 1 at $t = 0$)
  - Input current, rises, flows through L, C and load resistor R.
- Mode 2: Switch is OFF (position 2 at $t = t_1$)
  - Diode D conducts due to energy stored in the inductor & inductor current continues to flow through L, C, R, and D.
  - Inductor current falls until switch is ON again in the next cycle.



Mode 1



Mode 2

2.2.2 Operation modes

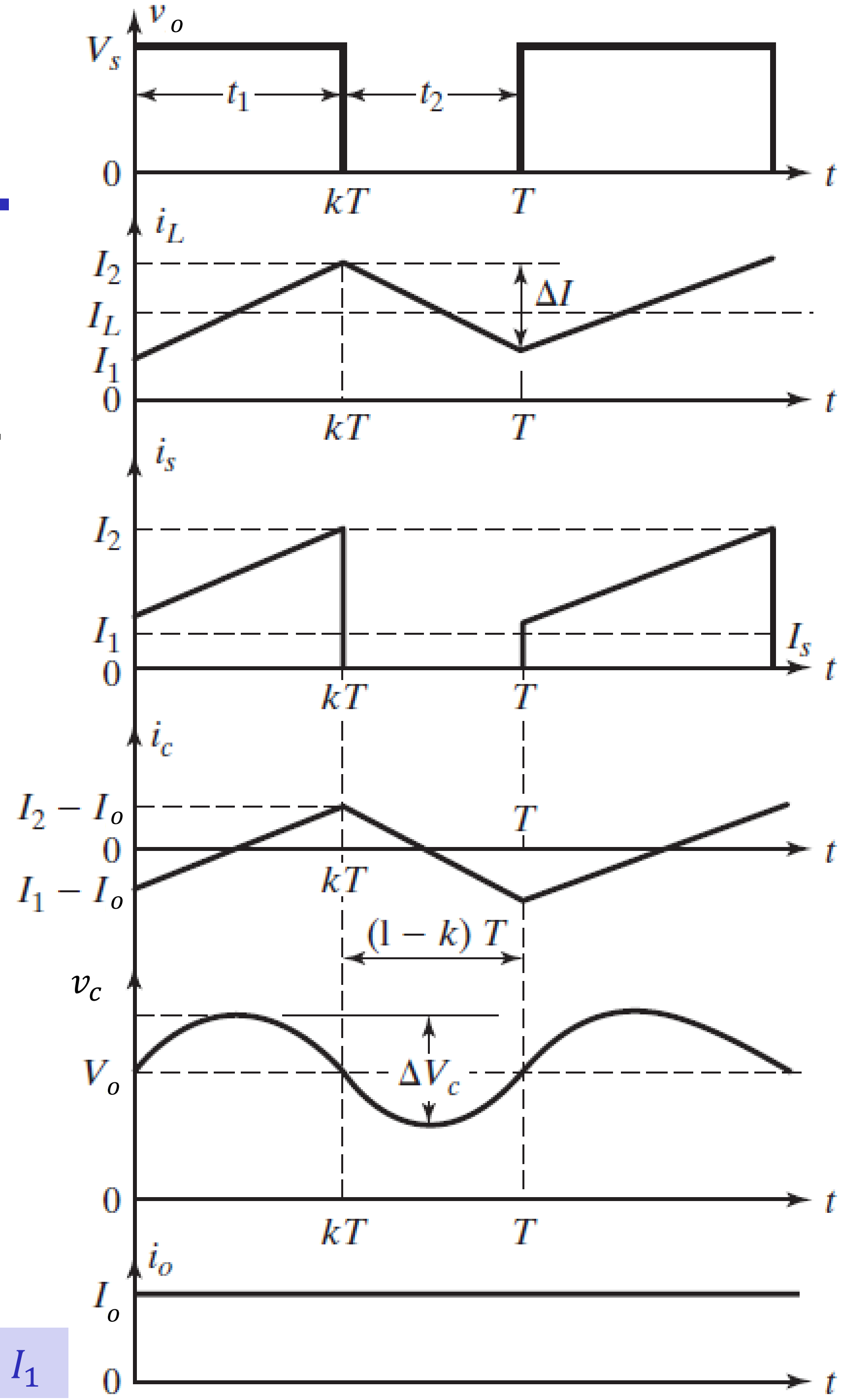
- The waveforms of voltages and currents are shown for a *continuous current flow in the L*.
- Assumed that the current rises and falls linearly.
- Depending on the *switching frequency*, filter inductance, capacitance, and inductor current could be *discontinuous*.
- Voltage across L, in general is, $v_L = L\frac{di_L}{dt}$

Mode 1: i_L rises linearly from I_1 to I_2 in time t_1

$$\therefore v_L = V_s - V_o = L\frac{I_2 - I_1}{t_1} = L\frac{\Delta I}{t_1} \quad \rightarrow t_1 = \frac{L\,\Delta I}{V_s - V_o}$$

Mode 2: i_L falls linearly from I_2 to I_1 in time t_2

$$\therefore v_L = -V_o = L\frac{I_1 - I_2}{t_2} \quad \rightarrow t_2 = \frac{L\,\Delta I}{V_o}$$



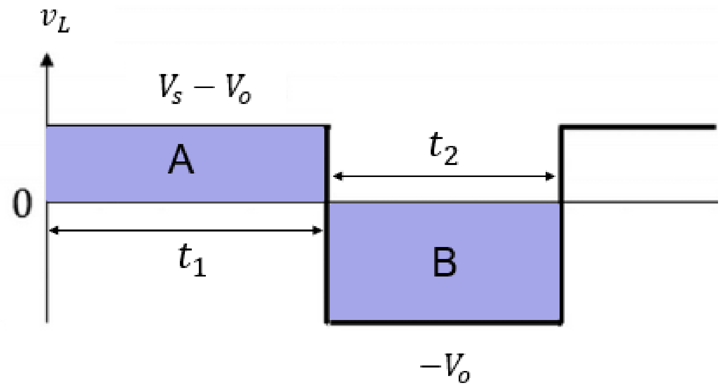
Peak-peak ripple current, $\Delta I = I_2 - I_1$

2.2.2 Operation modes

Volt-second balance

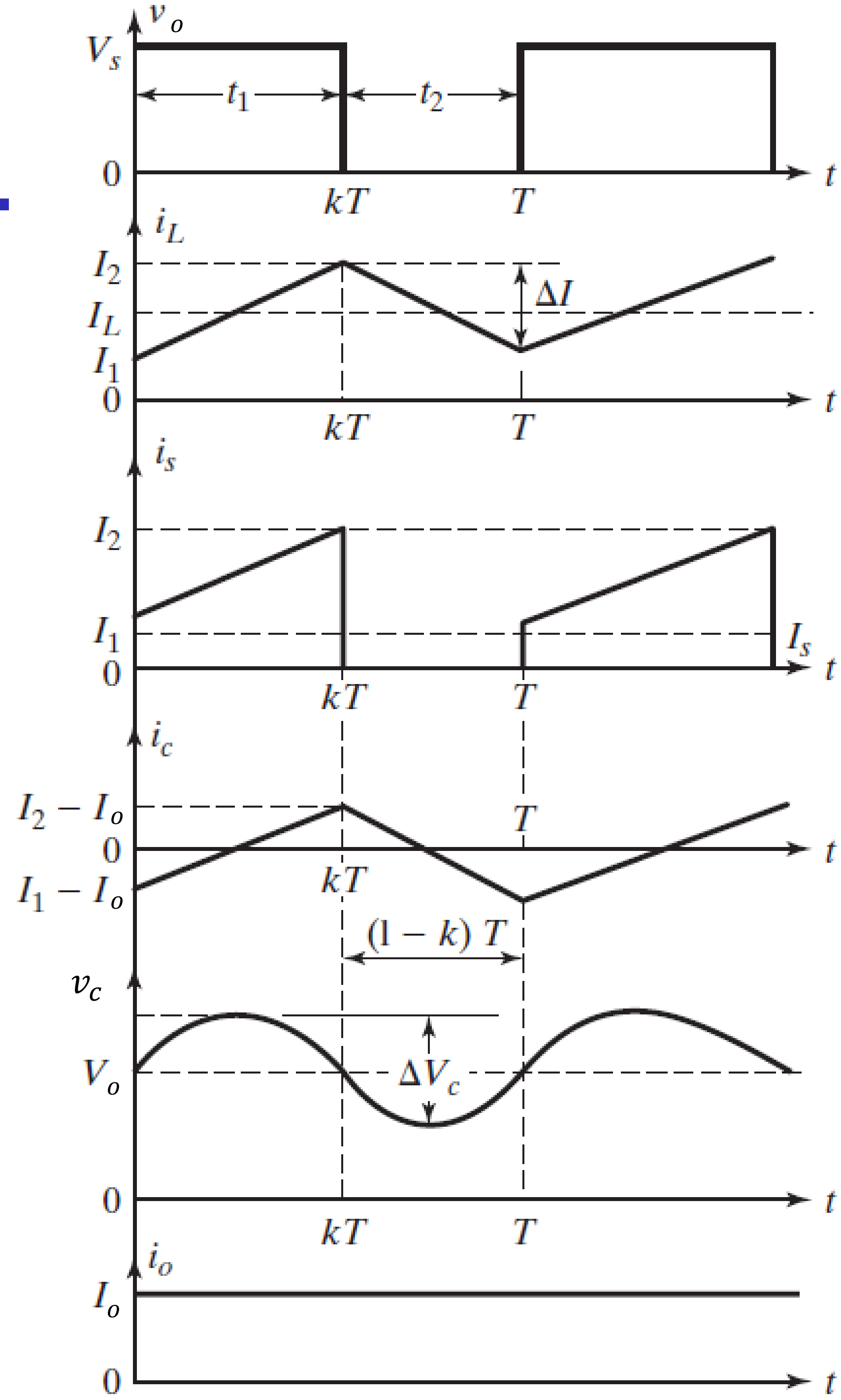
- Since in *steady-state operation*, the waveform must repeat from one time period to the next, the integral of the v_L over one time period must be zero, i.e., $\int_0^T v_L\,dt = \int_0^{t_1} v_L\,dt + \int_{t_1}^T v_L\,dt = 0.$

$$\therefore \quad (V_s - V_o)t_1 = V_o(T - t_1) \quad \rightarrow \quad \frac{V_o}{V_s} = \frac{t_1}{T} = k$$



- Neglecting power losses associated with all the circuit elements, the input power, $P_s = P_o$.

- Therefore, $V_sI_s = V_oI_o \;\; \rightarrow I_s = kI_o$.



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Peak-to-peak inductor ripple current

- Switching period can be expressed as

$$T = \frac{1}{f} \rightarrow f = \frac{1}{T} = \frac{1}{t_1 + t_2} = \frac{1}{\frac{L\,\Delta I}{V_s - V_o} + \frac{L\,\Delta I}{V_o}} = \frac{V_o(V_s - V_o)}{LV_s\Delta I}$$

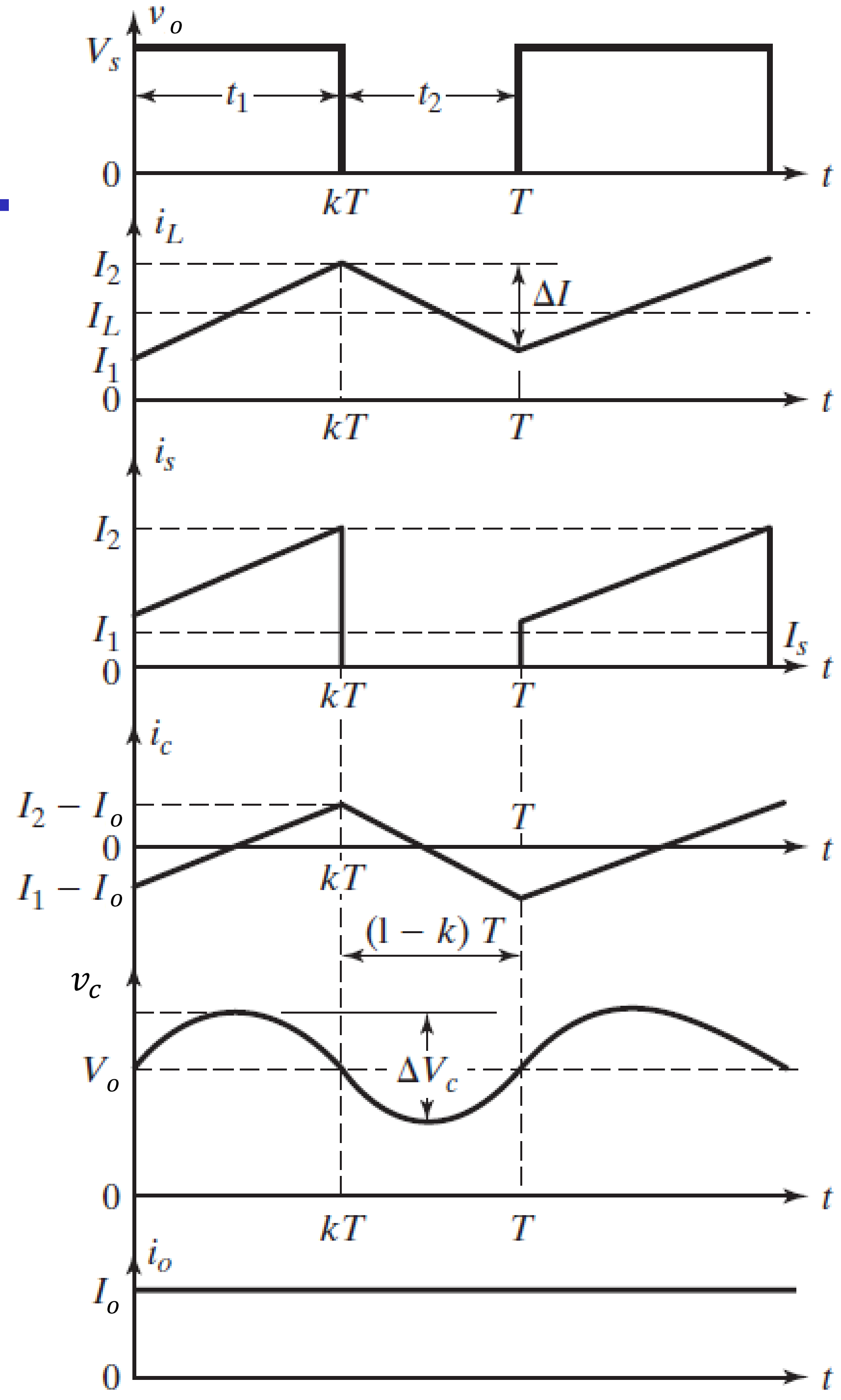
which gives the peak-to-peak ripple current as

$$\Delta I = \frac{V_o(V_s - V_o)}{fLV_s} \equiv \frac{kV_s(1-k)}{fL}$$

- Maximum and minimum values of inductor current are given by

$$I_2 = I_L + \frac{1}{2}\Delta I$$

$$I_1 = I_L - \frac{1}{2}\Delta I$$



Peak-to-peak capacitor ripple voltage

- Using KCL, $i_L = i_c + i_o$
- Assume load ripple current Δi_o is very small and negligible, i.e., $\Delta i_L = \Delta i_c$.
- The average capacitor current, which flows for $t_1/2 + t_2/2 = T/2$, is $I_c = \Delta I/4$ $\Longrightarrow$ Think!
- The voltage across capacitor is expressed as

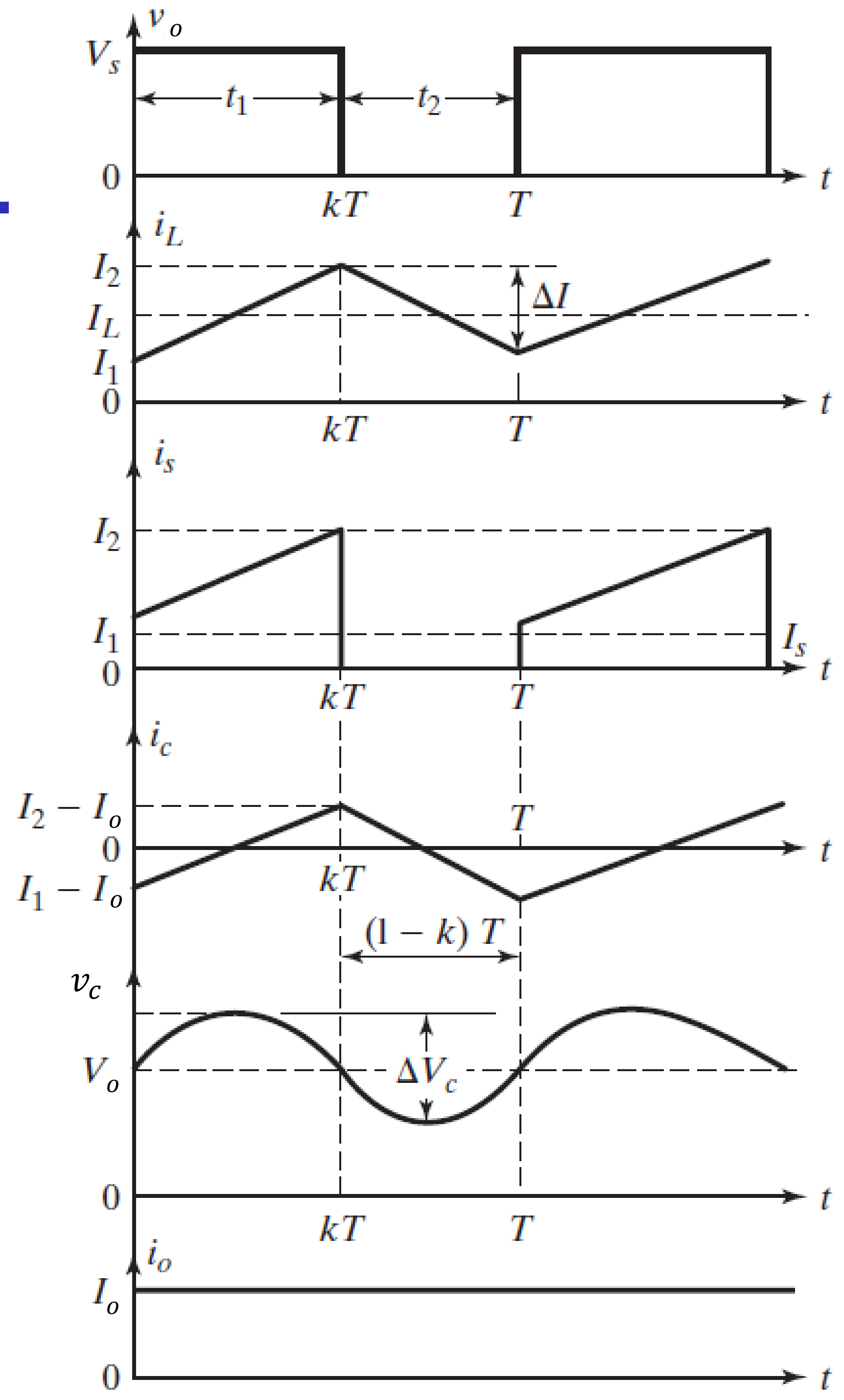
$$v_c = \frac{1}{C}\int i_c \, dt + v_c(t=0)$$

- The peak-to-peak ripple capacitor voltage is

$$\Delta V_c = v_c - v_c(t=0) = \frac{1}{C}\int_0^{\frac{T}{2}} \frac{\Delta I}{4} dt = \frac{\Delta I}{8fC}$$

- Substituting the value of ΔI from previous slide

$$\Delta V_c = \frac{V_o(V_s - V_o)}{8f^2 LCV_s} = \frac{kV_s(1-k)}{8f^2 LC}$$



Condition for continuous inductor current and capacitor voltage

- If I_L is the average inductor current, the inductor ripple current $\Delta I = 2I_L$.

$$\Delta I = \frac{kV_s(1-k)}{fL} = 2I_L = 2I_o = \frac{2kV_s}{R}$$

which gives the critical value of the inductor L_c as

$$L_c = L = \frac{(1-k)R}{2f}$$

- If V_c is the average capacitor voltage, the capacitor ripple voltage $\Delta V_c = 2V_o$.

$$\Delta V_c = \frac{kV_s(1-k)}{8f^2LC} = 2V_o = 2kV_s$$

which gives the critical value of the capacitor C_c as

$$C_c = C = \frac{1-k}{16Lf^2}$$

Example 1

A buck converter has an input voltage $V_s = 12V$. The required output voltage is $V_o = 5V$ at $R = 500\,\Omega$ and the peak-to-peak output ripple voltage is 20 mV. The switching frequency is 25kHz. If the peak-to-peak ripple current of inductor is limited to 0.8A, determine

(1) the duty cycle, k.

(2) the filter inductance L.

(3) the filter capacitance C.

(4) and the critical values of L and C.

Solution

$$V_s = 12\,V, \Delta V_c = 20mV, \Delta I = 0.8A, f = 25\,kHz, V_o = 5\,V$$

1) $\therefore \mathrm{V}_o = \mathrm{kV}_s \rightarrow \mathrm{k} = 0.4167 = 41.67\%$

2) $\Delta I = \frac{(1-k)kV_S}{fL} \rightarrow L = 145.83\ \mu H$

3) $\Delta \mathrm{V_c} = \frac{kV_S(1-k)}{8f^2LC} \rightarrow C = 200\ \mu F$

Solution

4) If I_L is average inductor current, the inductor ripple current

$$\Delta I = \frac{kV_S(1-k)}{fL} = 2I_L = 2I_o = \frac{2kV_S}{R}$$

gives critical value of inductor $L_C = L = \frac{(1-k)R}{2f} = 5.83\ mH$

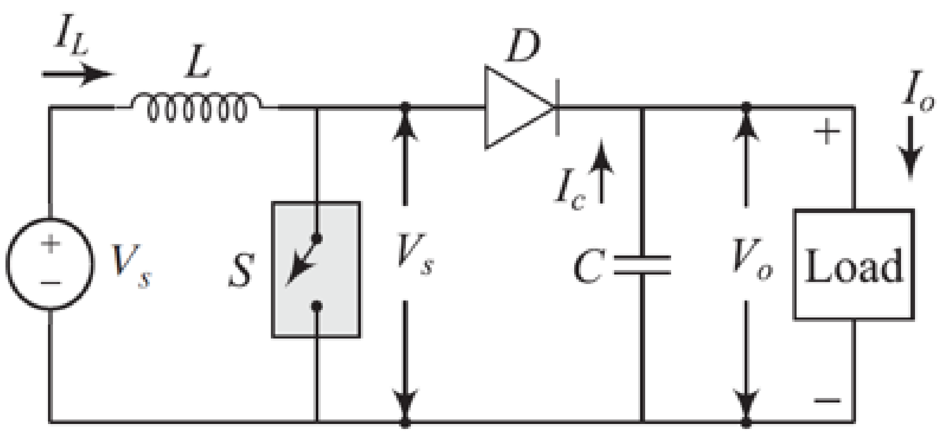
If V_c is average capacitor voltage, the capacitor ripple voltage

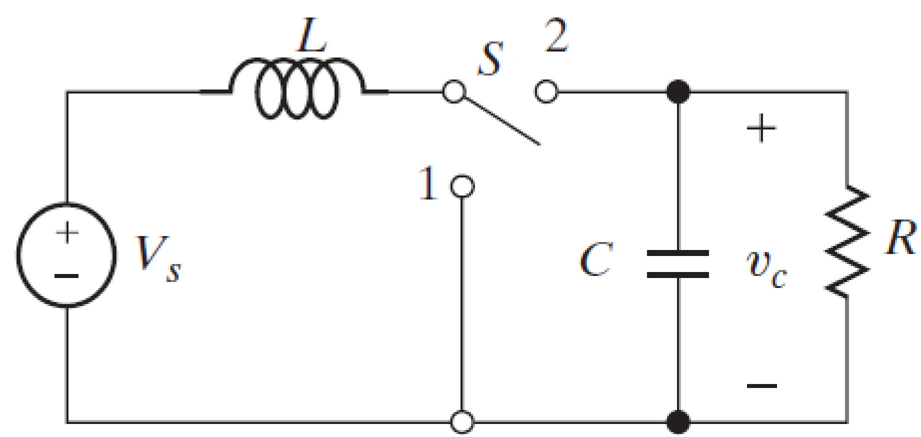
$$\Delta V_c = \frac{kV_s(1-k)}{8f^2LC} = 2V_o = 2kV_s$$

gives critical value of capacitor, $C_C = C = \frac{1-k}{16Lf^2} = 0.4\ \mu F$

2.3 Boost Converter

- Average output voltage is *greater than* input voltage – hence, called *boost* converter.
- One switch and one diode (to overcome the problem of stored inductive energy).
- Switch S can be a power MOSFET and acts as a controlled switch; diode D is uncontrolled switch – operate as *two* SPST bidirectional switches, shown below.

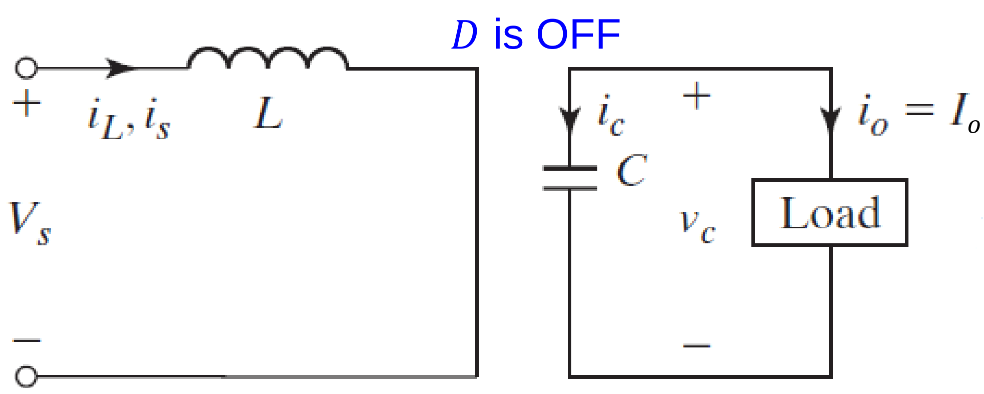




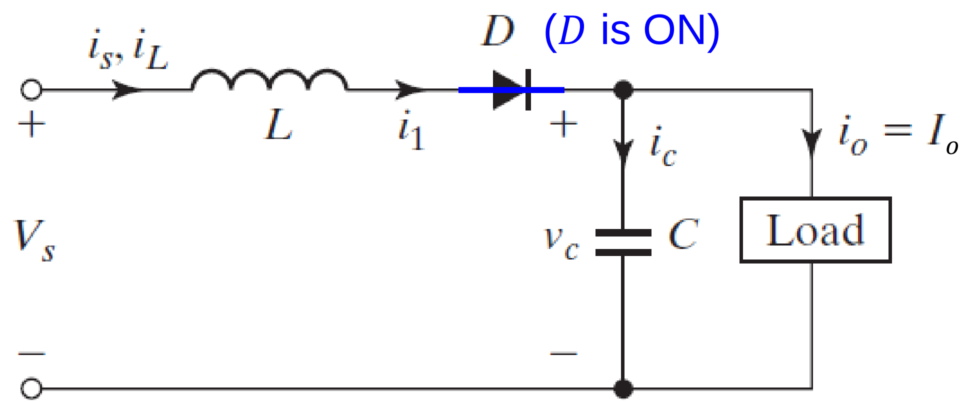
Boost converter → Two switches representation

2.3.1 Operation modes

- Mode 1: Switch is ON (position 1 at $t = 0$)
  - Input current, rises, flows through L and transistor (i.e., switch).
- Mode 2: Switch is OFF (position 2 at $t = t_1$)
  - Current that was flowing through transistor would now flow through L, C, R &D.
  - Inductor current falls until switch is ON again in the next cycle.
  - Energy stored in inductor L is transferred to the load.



Mode 1



Mode 2

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2.3.1 Operation modes

- The waveforms of voltages and currents are shown *for continuous load current*.
- Assumed that the *current rises and falls* linearly.
- Voltage across L, in general is, $v_L = L\frac{di_L}{dt}$

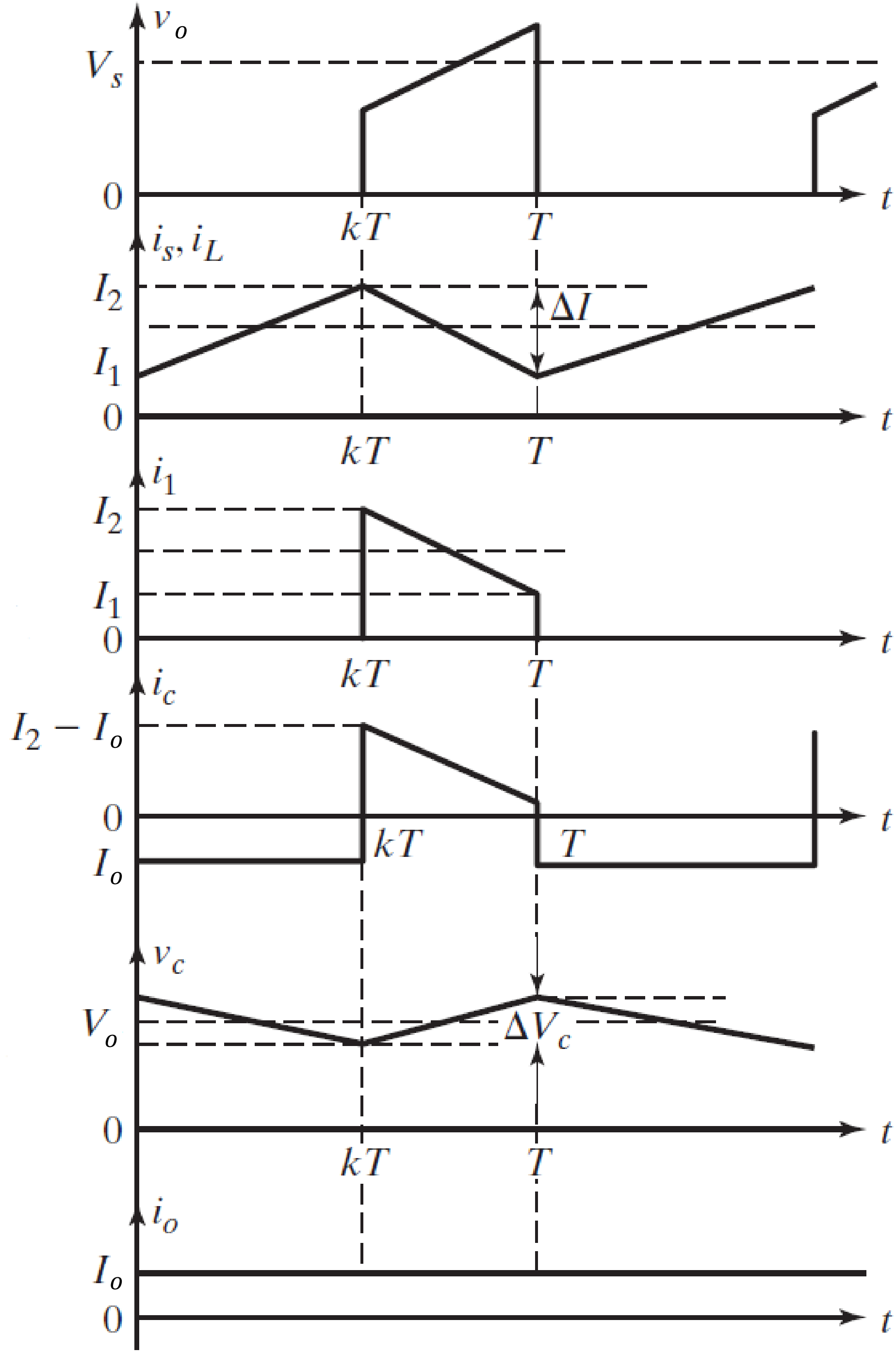
Mode 1: i_L rises linearly from I_1 to I_2 in time t_1

$$V_s = L\frac{I_2 - I_1}{t_1} = L\frac{\Delta I}{t_1} \quad \rightarrow t_1 = \frac{L\,\Delta I}{V_s}$$

Mode 2: i_L falls linearly from I_2 to I_1 in time t_2

$$V_s - V_o = L\frac{I_1 - I_2}{t_2} \quad \rightarrow t_2 = \frac{L\,\Delta I}{V_o - V_s}$$

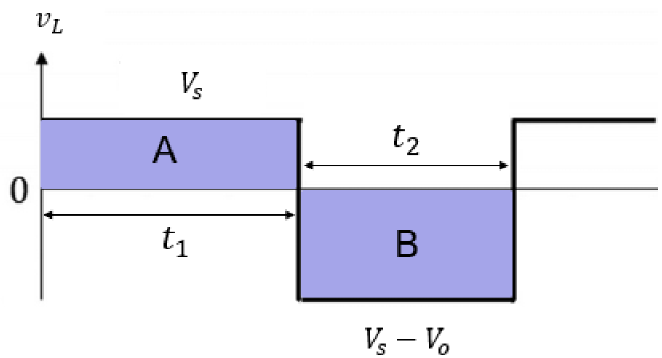
Peak-peak ripple current, $\Delta I = I_2 - I_1$



2.3.1 Operation modes

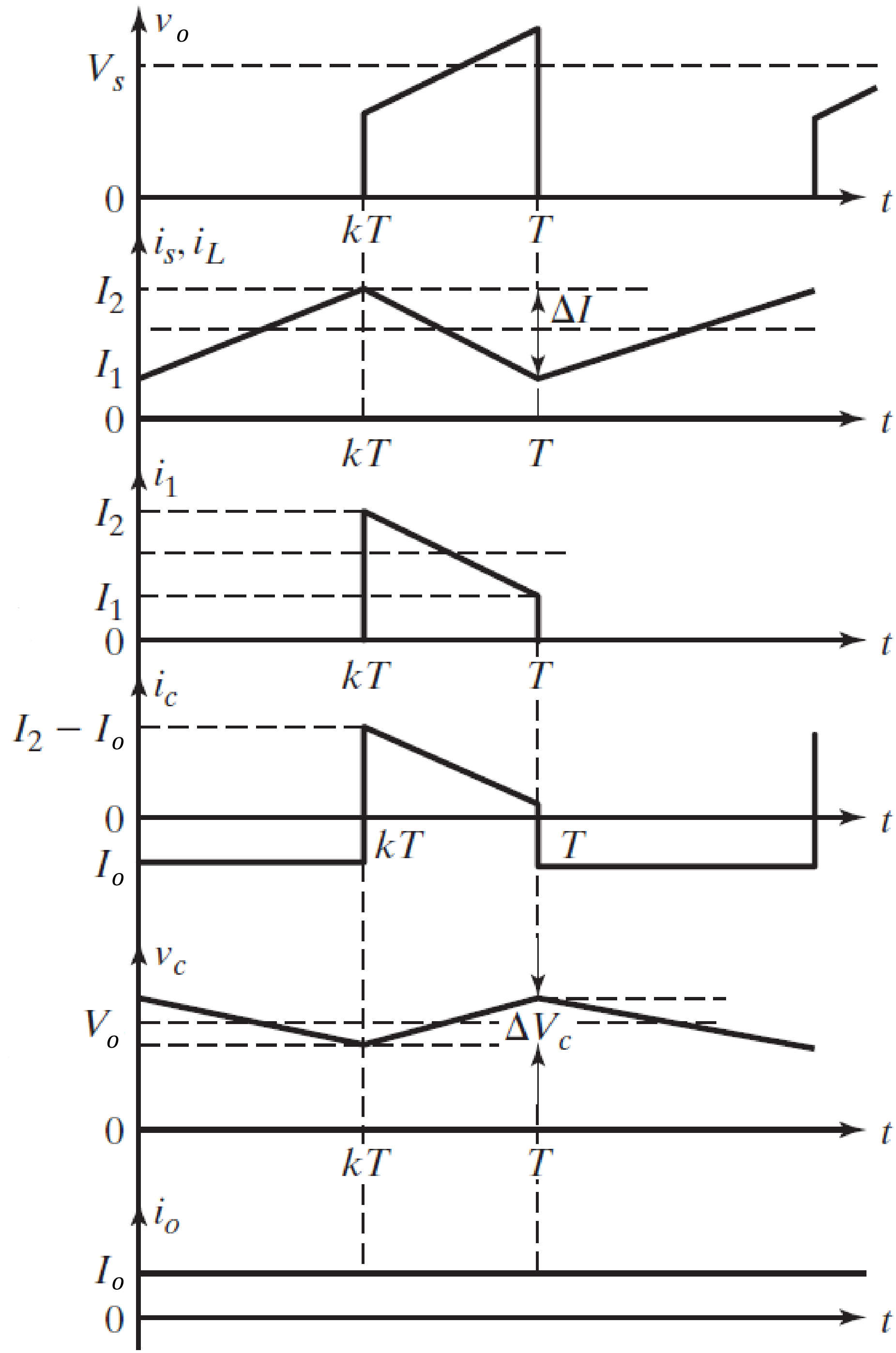
- Since in *steady-state operation*, the waveform must repeat from one time period to the next, the integral of the v_L over one time period must be zero, i.e., $\int_0^T v_L\,dt = \int_0^{t_1} v_L\,dt + \int_{t_1}^{T} v_L\,dt = 0.$

$$V_s\,t_1 + (V_s - V_o)(T - t_1) \;\rightarrow\; \frac{V_o}{V_s} = \frac{T}{T-t_1} = \frac{1}{1-k}$$



- Neglecting power losses associated with all circuit elements, input power, $P_s = P_o$.

- Therefore, $V_s I_s = V_o I_o \;\rightarrow I_s = \frac{I_o}{1-k}$



Peak-to-peak inductor ripple current

- Switching period can be expressed as

$$T = \frac{1}{f} \rightarrow f = \frac{1}{T} = \frac{1}{t_1 + t_2} = \frac{1}{\frac{L\,\Delta I}{V_s} + \frac{L\,\Delta I}{V_o - V_s}} = \frac{V_s(V_o - V_s)}{L V_o \Delta I}$$

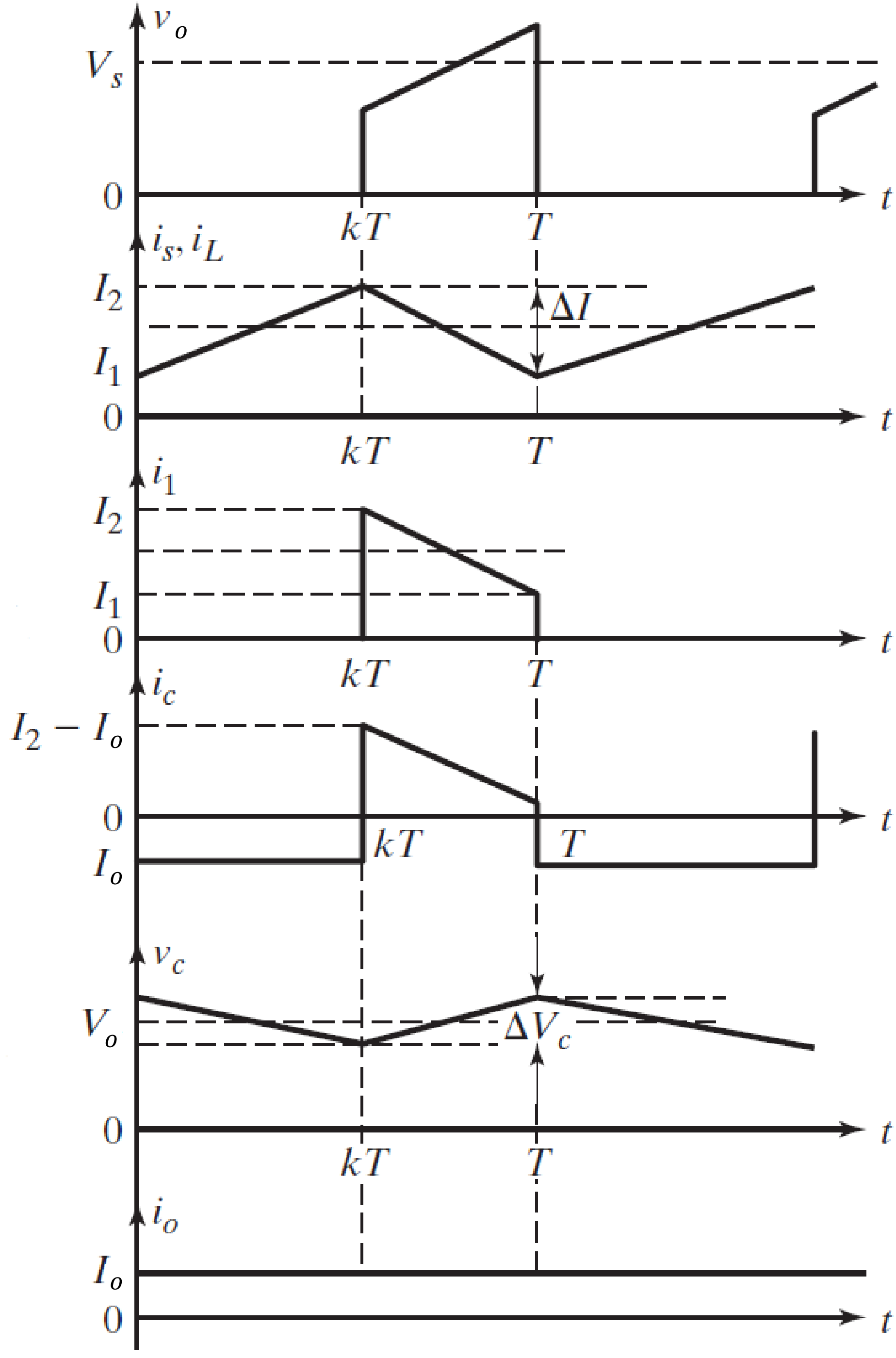
which gives the peak-to-peak ripple current as

$$\Delta I = \frac{V_s(V_o - V_s)}{f L V_o} \equiv \frac{k V_s}{f L}$$

- Maximum and minimum values of inductor current are given by

$$I_2 = I_L + \frac{1}{2}\Delta I$$

$$I_1 = I_L - \frac{1}{2}\Delta I$$



Peak-to-peak capacitor ripple voltage

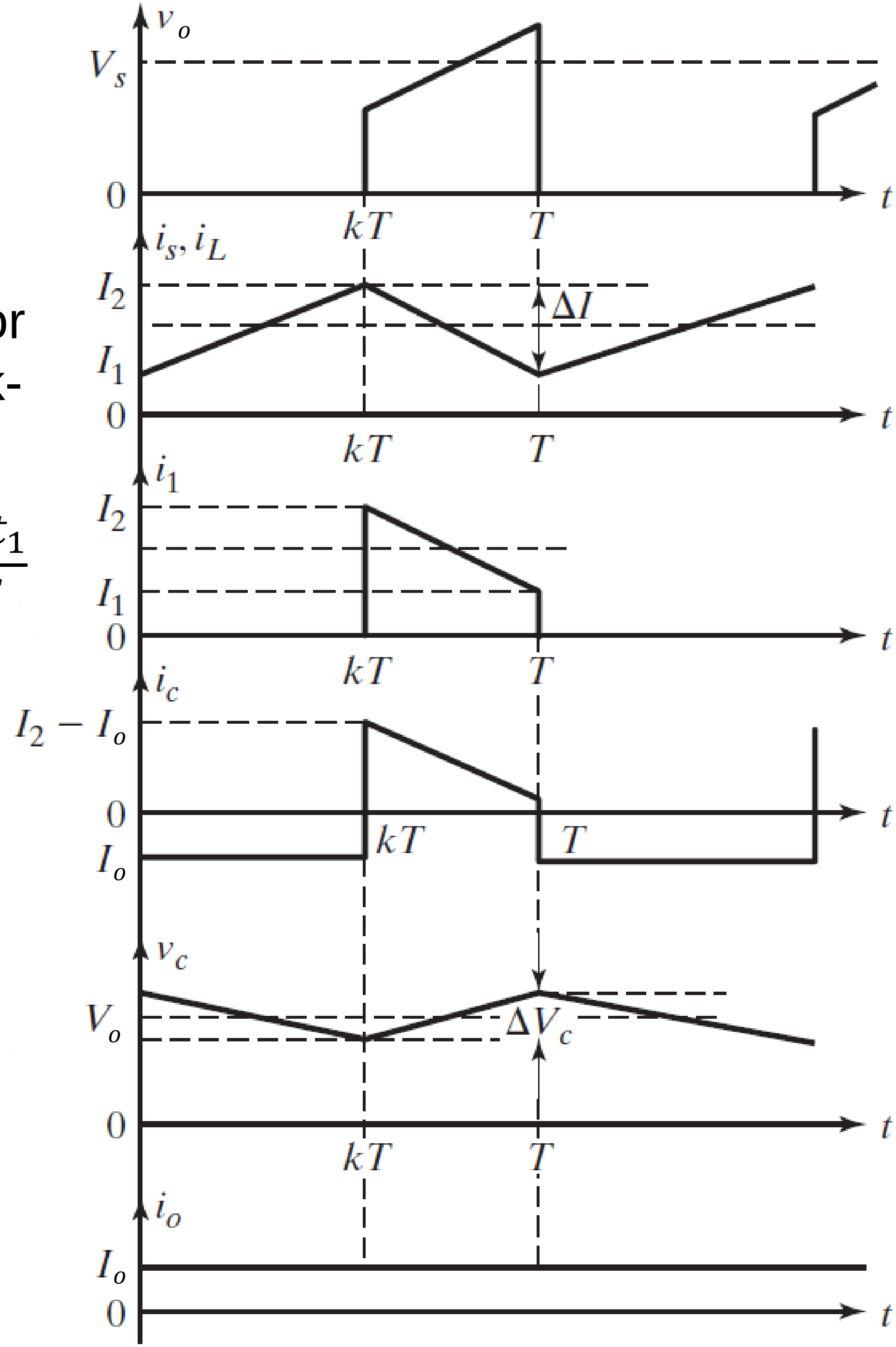
- When switch is ON, the capacitor supplies load current for $t = t_1$. The average capacitor current during time t_1 is $I_c = I_o$ and the peak-to-peak ripple voltage of capacitor is

$$\Delta V_c = v_c - v_c(t=0) = \frac{1}{C}\int_0^{t_1} I_c \, dt = \frac{1}{C}\int_0^{t_1} I_o \, dt = \frac{I_o t_1}{C}$$

Recall, $\frac{V_o}{V_s} = \frac{T}{T-t_1} = \frac{1}{1-k} \rightarrow t_1 = \frac{V_o - V_s}{V_o f}$

- Substituting the value of $t_1 = \frac{V_o - V_s}{V_o f}$ above,

$$\Delta V_c = \frac{I_o(V_o - V_s)}{V_o f C} = \frac{I_o k}{f C}$$



Condition for continuous inductor current and capacitor voltage

- If I_L is the average inductor current, the inductor ripple current $\Delta I = 2I_L$.

$$\Delta I = \frac{kV_s}{fL} = 2I_L = 2I_s = \frac{2I_o}{1-k} = \frac{2V_o}{(1-k)R} = \frac{2V_s}{R(1-k)^2}$$

which gives the critical value of the inductor L_c as

$$L_c = L = \frac{k(1-k)R}{2f}$$

- If V_c is the average capacitor voltage, the capacitor ripple voltage $\Delta V_c = 2V_o$.

$$\Delta V_c = \frac{I_o k}{fC} = 2V_o = 2I_o R$$

which gives the critical value of the capacitor C_c as

$$C_c = C = \frac{k}{2Rf}$$

Example 2

A boost converter has an input voltage of $V_s = 5V$. The average output voltage $V_o = 15V$ and the load current $I_o = 0.5A$. The switching frequency is 25 kHz. If $L = 150\ \mu H$ and $C = 220\ \mu F$, determine

(1) the duty cycle.

(2) the ripple current of inductor ΔI.

(3) The peak current of inductor I_2.

(4) the ripple voltage of filter capacitor ΔV_C.

Solution

$$V_s = 5\ V, V_o = 15\ V, f = 25\ kHz, L = 150\ \mu H, C = 220\ \mu F$$

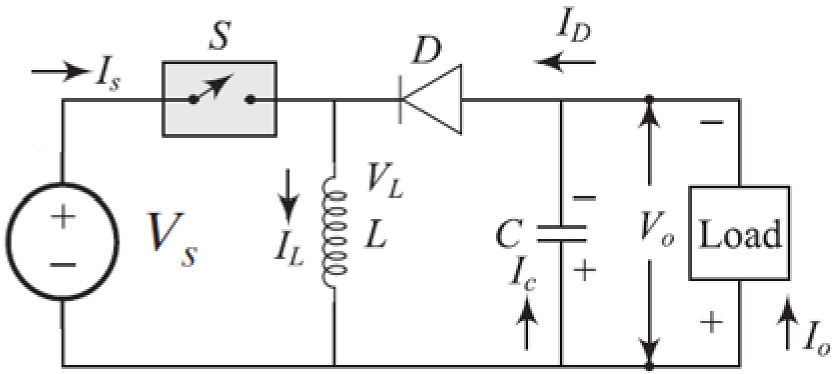
1) $\mathrm{V}_o = \frac{V_s}{1-k} \rightarrow k = 0.6667 = 66.67\%$

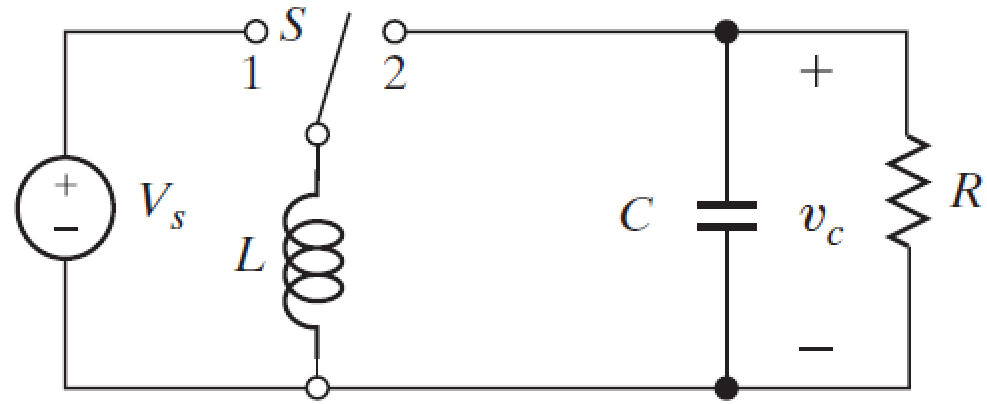
2) $\Delta I = \frac{kV_s}{fL} = 0.89\ A$

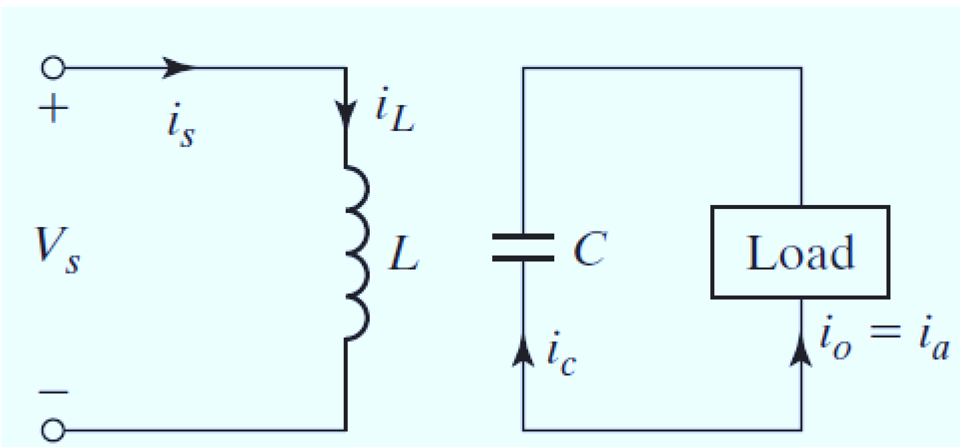
3) $\mathrm{I}_L = \frac{I_o}{1-k} = \frac{0.5}{1-0.667} = 1.5\ A \rightarrow I_2 = I_L + \frac{\Delta I}{2} = 1.945\ A$

4) $\Delta V_c = \frac{I_o k}{fC} = 60.61\ mV$

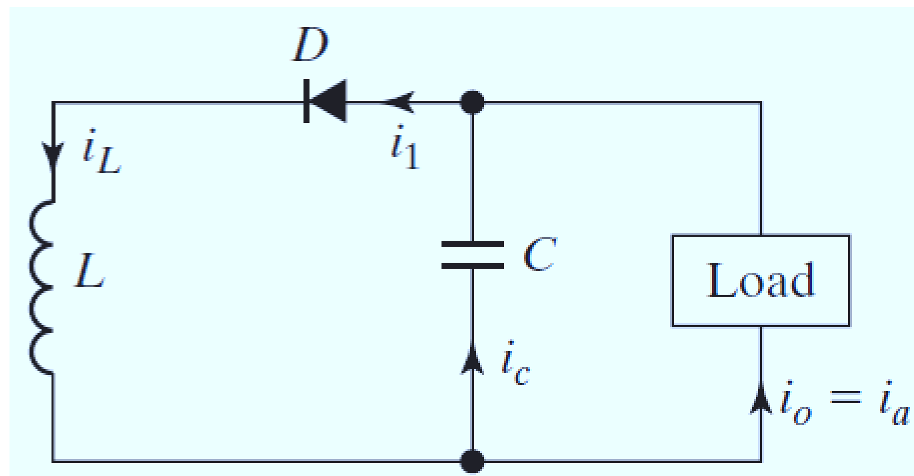
2.4 Buck-Boost converter







Mode 1



Mode 2

- Output voltage may be *less or greater than* input voltage; the output voltage polarity is *opposite* to that of input voltage.

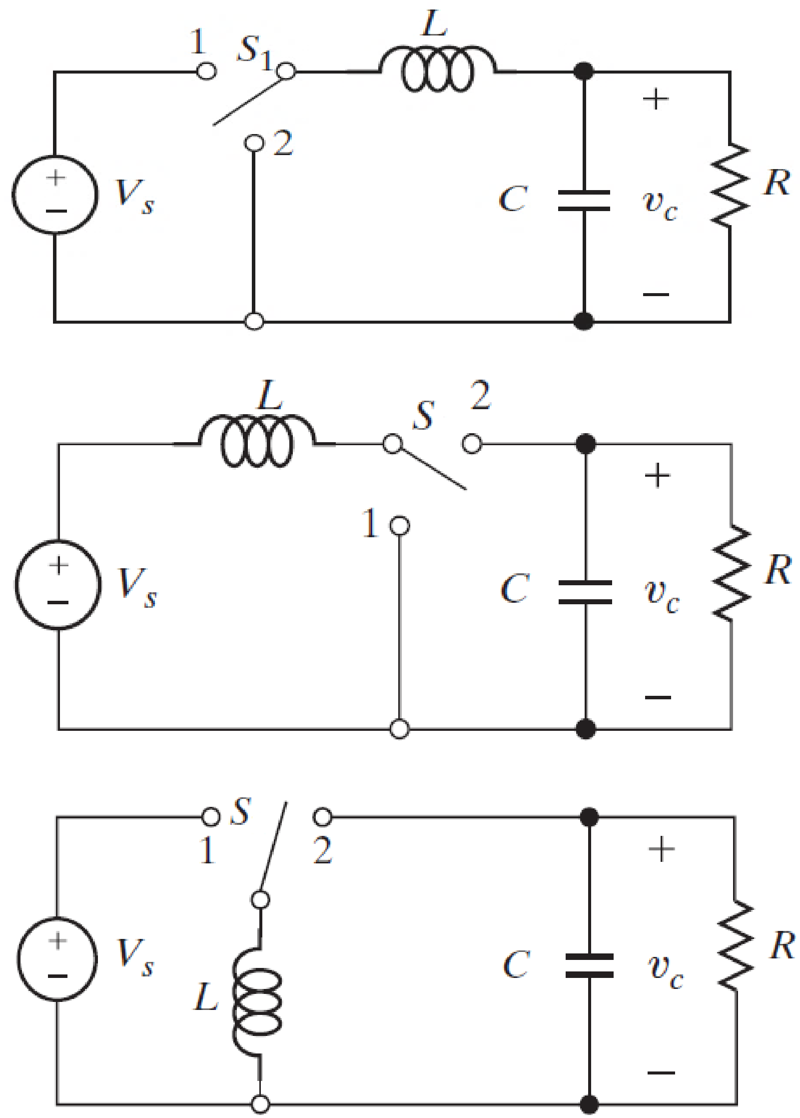
$$V_o = -\frac{V_s k}{1-k}$$

2.5 Comparison of basic Converters

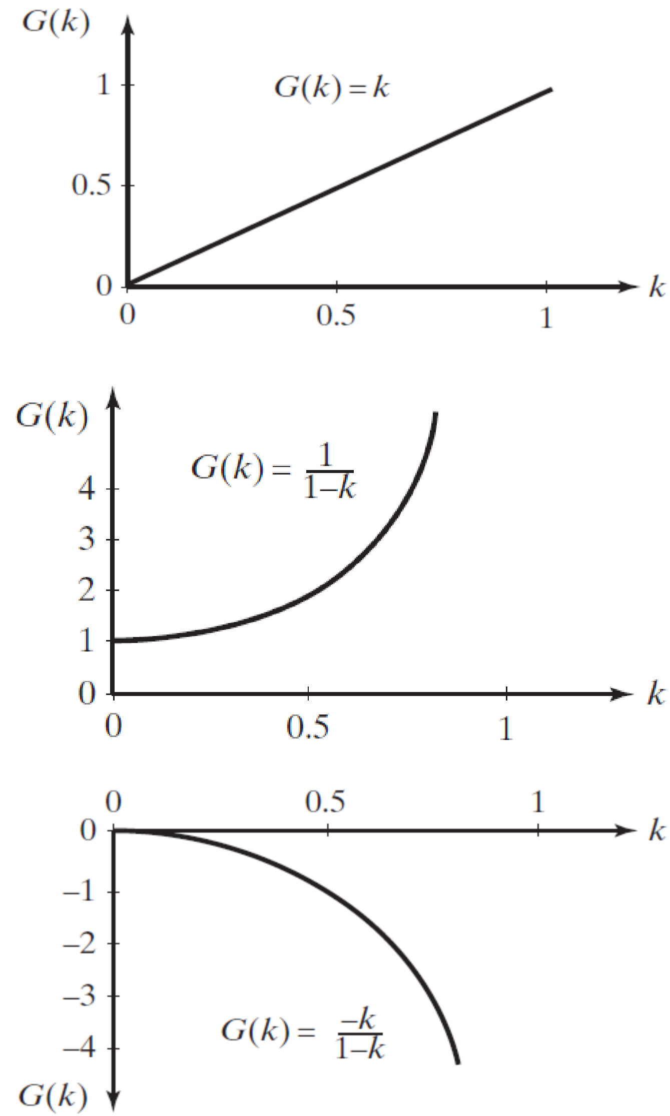
Buck

Boost

Buck-Boost



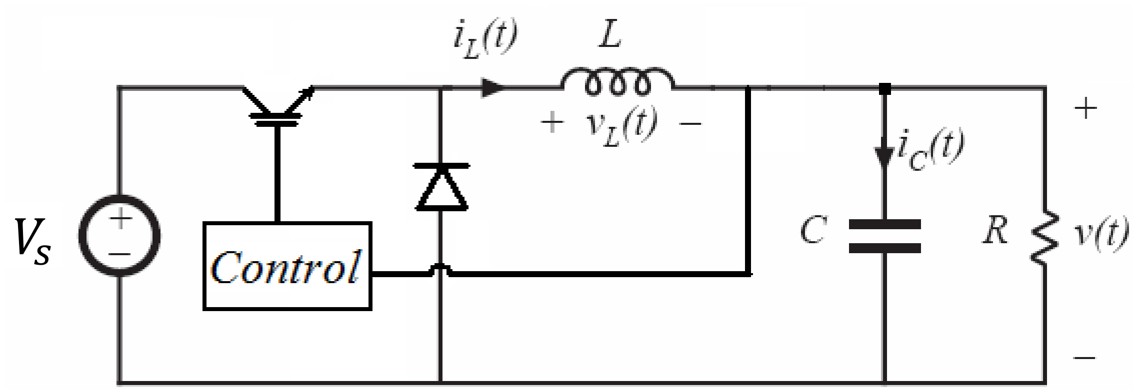
Switch representation



Comparison of voltage gains

2.6 Closed-loop control of DC-DC converters

- As have been seen, the output voltage of a DC-DC converter is related to the duty cycle k. In practice, one will never get an accurate output voltage if the duty cycle is fixed at the calculated value because
  - The components are not ideal: switching losses, diode voltage drop, inductor resistance etc
  - The load might change
  - There are fluctuations in the supply voltage V_s
  - …
- A closed-loop controller to regulate the output voltage is needed!



Summary – 1. Power Transistors

- ✓ Power transistors are mainly: BJTs, MOSFETs, and IGBTs.
- ✓ BJTs are current-controlled devices.
- ✓ MOSFETs are voltage-controlled devices and require very low-gating power.
- ✓ IGBTs (combine the advantages of BJTs and MOSFETs), are voltage-controlled devices.
- ✓ Transistors can be connected in series or parallel
  - – Parallel operation usually requires current-sharing elements
  - – Series requires matching of parameters during turn-on & off

Summary – 2. DC to DC Converters

- Converters (*duty cycle*):

  Buck (k), Boost $\left(\frac{1}{1-k}\right)$, Buck-boost $\left(\frac{-k}{1-k}\right)$

- A DC converter can be used as a *dc transformer* to step up or step down a fixed dc voltage.

- Filters are used to reduce the harmonics generated at the input and load side of the converter.

- Average output voltage is controlled by controlling the switch on and off durations.

See you in the next class (April 28th)

❖ **Reminder (Lab report deadline – April 25th, 23:55 PM)**

The End