Electronic-Circuit II
Chap 3 Power Electronics

DC-DC Converters

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Course Homepage

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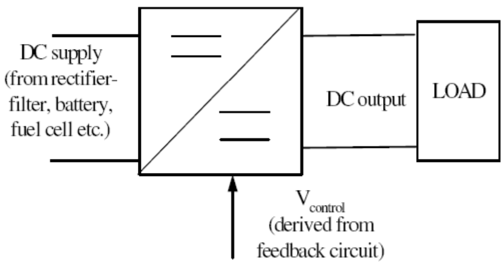
DC-DC Conversion



- Choppers: Converts the unregulated DC input to a controlled DC output with a desired voltage level

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DC-DC conversion contd

- Earlier, DC-DC converters were called choppers
- In modern power electronics, chopper refers to high power DC-DC converters & SMPS (switching regulators) refers to low power DC-DC converters
- Applications of DC-DC converters:
  - Switched-mode power supply (SMPS), DC motor control, battery chargers

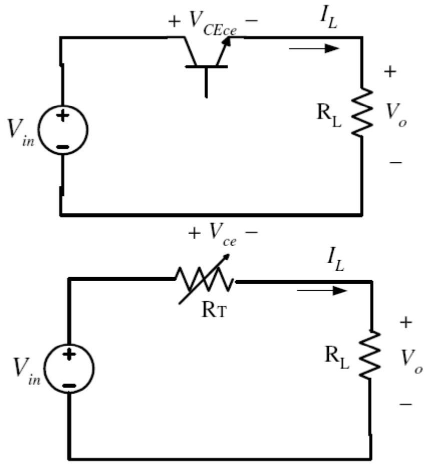
Linear Regulators Review

- Earlier, the linear regulators were the only reliable methods to meet all dc requirements
- Linear Regulator Problems
  - its size and weight
  - Large power dissipation & Low efficiency
  - Limited to low power applications

Example (Linear Regulator)

- Transistor operated in linear or active region
- Output voltage,

  Vo = Vin-Vce
- High power loss in BJT
- Low efficiency



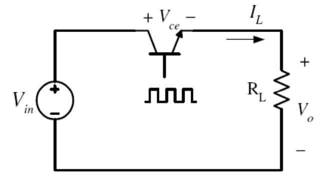
EQUIVALENT CIRCUIT

Switching Regulators

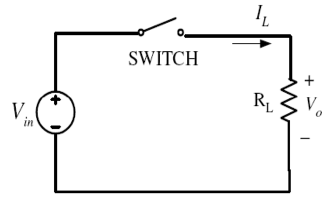
- Came into existence with the advent of power semiconductor devices
- the semiconductor devices are either **fully switched on** or **fully switched off**
- **Low power consumption** due to lower voltage drop across the semiconductor device
- High Efficiency
- Swiched on/off at high frequency so the relative **size** and **weight** of the components needed for its design is comparatively small

Switching Regulators contd..

- Transistor operated in switched mode
  - Switch closed: Fully on (saturated)
  - Switch opened: Fully off (cut-off)
  - When switch is open, no current flows through it
  - When switch is closed no voltage drop across it
- For an ideal switch power loss is zero since P=VI
- Practically, the loss is very small



SWITCHING REGULATOR



EQUIVALENT CIRCUIT

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Switching Regulators contd...

•The high voltage ripple can be controlled by placing a capacitor across the load

•The capacitor is large enough so that its voltage does not have any noticeable change during the time the switch is off

•Circuit can be optimized by placing an inductor in series to limit the current rush

> ➢Problem:- Since the current in the inductor cannot change suddenly, we have to provide at least one more switch, such as a freewheeling diode, to provide a path for the inductor current when the switch is off (open)

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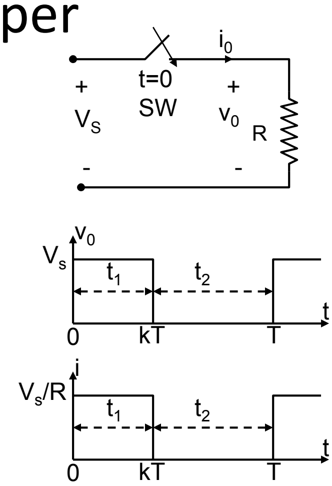
Switching Regulators contd...

- In summary, a good dc-to-dc converter may have, an inductor, a capacitor, a freewheeling diode and an electronic switch.
- The placement of these elements in a circuit dictates the performance of the circuit.
- The three configurations that utilize these circuit elements are:
  a) **Buck Converter** (lowering the output voltage, step-down application),
  b) **Boost Converter** (raising the output voltage, step-up application), and
  c) **Buck-Boost Converter** (lowering or raising the output voltage, step-down or step up application)

Choppers

- DC-DC converters used in high power applications
- Equivalent to transformers in ac
- By switching only a fraction of power is transferred
- Classification
  - Step Down chopper
  - Step Up chopper

Step Down Chopper



Average output voltage

$$V_a = \frac{1}{T}\int_0^{t_1} v_0 dt = \frac{t_1}{T}V_s = kV_s$$

Average load current

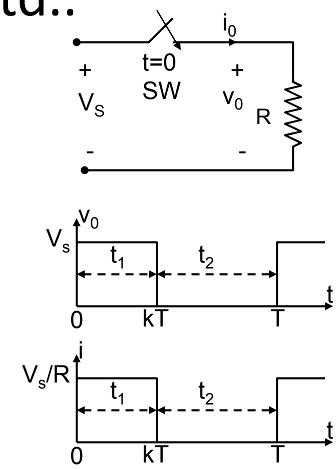
$$I_a = \frac{V_a}{R} = \frac{kV_s}{R}$$

T is the chopping period

k is duty cycle of chopper

f is the chopping frequency

Step Down Chopper contd..



rms output voltage

$$V_0 = \left(\frac{1}{T}\int_0^{kT} v_0^2 dt\right)^{1/2} = \sqrt{k}V_s$$

For lossless converter $P_{IN} = P_{OUT}$

$$P_{IN} = \frac{1}{T}\int_0^{kT} v_0 i dt = \frac{1}{T}\int_0^{kT} \frac{v_0^2}{R} dt = k\frac{V_s^2}{R}$$

Effective input resistance seen by source

$$R_i = \frac{V_s}{I_a} = \frac{V_s}{kV_s/R} = \frac{R}{k}$$

T is the chopping period

k is duty cycle of chopper

f is the chopping frequency

Step Down Chopper contd..

For lossy converter

$$P_{IN} = \frac{1}{T}\int_0^{kT} V_s i dt = \frac{1}{T}\int_0^{kT} \frac{V_s(V_s - V_{SW})}{R} dt = k\frac{V_s(V_s - V_{SW})}{R}$$

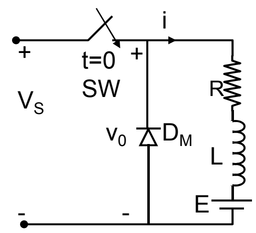
$$P_{OUT} = \frac{1}{T}\int_0^{kT} \frac{v_0^2}{R} i dt = \frac{1}{T}\int_0^{kT} \frac{(V_s - V_{SW})^2}{R} dt = k\frac{(V_s - V_{SW})^2}{R}$$

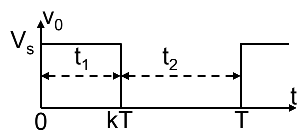
- Duty cycle can be varied from 0 to 1 by varying t_1, T or f
- Output voltage V_0 can be varied form 0 to V_s by varying k
- Power flow can be controlled by
- ➢ *Constant frequency operation*: f or T is kept constant and t_1 is varied → *pulse-width –modulation*
- ➢ *Variable frequency operation*: t_1 or t_2 is kept constant and f is varied. Operation needs to be carried out over wide range. Generates harmonics and unpredictable frequencies

Step Down Chopper (with RL load)

Operation in 2 modes

- Mode 1 → switch is closed & current flows from supply to load (0 →kT)
- Mode 2 → switch is open & current continues to flow though free wheeling diode D_M (kT →T)
- Assume current & voltage rises/falls linearly
  - Actually current rises/falls exponentially with time constant τ=L/R
  - If τ is very large compared to switching period T, linear assumption can be made





Step Down Converter With RL Load

For mode 1, $0 \le t \le t_1 (= kT)$

$$V_s = Ri_1 + L\frac{di_1}{dt} + E$$

Prove

$$i_1(t) = I_1 e^{-\frac{tR}{L}} + \frac{V_s - E}{R}(1 - e^{-\frac{tR}{L}})$$

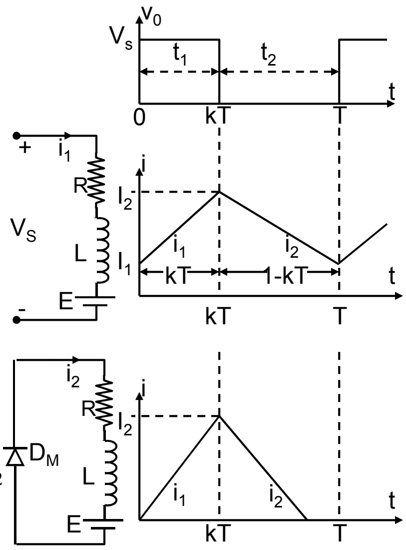
At $t = t_1 = kT \Rightarrow i_1(t = t_1) = I_2$

For mode 2, $0 \le t \le t_2 (= (1-k)T)$

$$0 = Ri_2 + L\frac{di_2}{dt} + E$$

$$i_2(t) = I_2 e^{-\frac{tR}{L}} + \frac{E}{R}(1 - e^{-\frac{tR}{L}}) \because i_2(t = 0) = I_2$$

At $t = t_2 = (1-k)T \Rightarrow i_2(t = t_2) = I_3$



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Step Down Converter With RL Load

- At the end of mode 2 converter is turned ON again in the next cycle, after time $T=t_1+t_2$
- Under steady state condition $I_1=I_3$

$$I_2 = I_1 e^{-\frac{kTR}{L}} + \frac{V_s - E}{R}(1 - e^{-\frac{kTR}{L}})$$

$$I_3 = I_1 = I_2 e^{-\frac{(1-k)TR}{L}} + \frac{E}{R}(1 - e^{-\frac{(1-k)TR}{L}})$$

Solving these two equations

$$I_1 = \frac{V_s}{R}\left(\frac{e^{\frac{kTR}{L}} - 1}{e^{\frac{TR}{L}} - 1}\right) - \frac{E}{R} \qquad I_2 = \frac{V_s}{R}\left(\frac{e^{-\frac{kTR}{L}} - 1}{e^{-\frac{TR}{L}} - 1}\right) - \frac{E}{R}$$

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Step Down Converter With RL Load

Peak-to-peak current is given by, $\Delta I = I_2 - I_1$

$$\Delta I = \frac{V_s}{R}\frac{1-e^{-\frac{kTR}{L}}+e^{-\frac{TR}{L}}-e^{-\frac{(1-k)TR}{L}}}{1-e^{-\frac{TR}{L}}}$$

For maximum ripple,

$$\frac{d(\Delta I)}{k}=0$$

$$\frac{V_s}{R\left(1-e^{-\frac{TR}{L}}\right)}\left(0+\frac{TR}{L}e^{-\frac{kTR}{L}}+0-\frac{TR}{L}e^{-\frac{(1-k)TR}{L}}\right)=0$$

$$\therefore \frac{TR}{L}e^{-\frac{kTR}{L}}-\frac{TR}{L}e^{-\frac{(1-k)TR}{L}}=0 \Rightarrow e^{-\frac{kTR}{L}}=e^{-\frac{(1-k)TR}{L}}$$

$$\Rightarrow k=1-k \Rightarrow k = 1/2$$

Step Down Converter With RL Load

$$\therefore \Delta I_{max}=\frac{V_s}{R}\frac{1-e^{-\frac{TR}{2L}}+e^{-\frac{TR}{L}}-e^{-\frac{TR}{2L}}}{1-e^{-\frac{TR}{L}}}=\frac{V_s}{R}\frac{1-2e^{-\frac{R}{2fL}}+e^{-\frac{R}{fL}}}{1-e^{-\frac{R}{fL}}}$$

$$\Delta I_{max}=\frac{V_s}{R}\frac{1-2e^{-\frac{R}{2fL}}+\left(e^{-\frac{R}{2fL}}\right)^2}{1-\left(e^{-\frac{R}{2fL}}\right)^2}=\frac{V_s}{R}\frac{\left(1-e^{-\frac{R}{2fL}}\right)^2}{1-\left(e^{-\frac{R}{2fL}}\right)^2}=\frac{V_s}{R}\frac{1-e^{-\frac{R}{2fL}}}{1+e^{-\frac{R}{2fL}}}$$

$$\Delta I_{max}=\frac{V_s}{R}\frac{e^{-\frac{R}{4fL}}\left[e^{\frac{R}{4fL}}-e^{-\frac{R}{4fL}}\right]}{e^{-\frac{R}{4fL}}\left[e^{\frac{R}{4fL}}+e^{-\frac{R}{4fL}}\right]}=\frac{V_s}{R}\frac{\sinh\left(\frac{R}{4fL}\right)}{\cosh\left(\frac{R}{4fL}\right)}=\frac{V_s}{R}\tanh\left(\frac{R}{4fL}\right)$$

$$\text{for } 4fL >> R \Rightarrow \tanh\theta \approx \theta \Rightarrow \Delta I_{max}=\frac{V_s}{4fL}$$

Step Down Converter With RL Load

- For discontinuous current flow
- low frequency, low output current & large off-time
- Current continuous if L/R>>T or Lf>>T
- For discontinuous current I_1=0

$$i_1(t)=\frac{V_s-E}{R}(1-e^{-\frac{tR}{L}}) \text{ but at } t=kT,\ i_1(t)=I_2$$

$$I_2=\frac{V_s-E}{R}(1-e^{-\frac{kTR}{L}})$$

$$i_2(t)=I_2e^{-\frac{tR}{L}}+\frac{E}{R}(1-e^{-\frac{tR}{L}}) \text{ for } 0\le t\le t_2$$

$$i_2(t=t_2)=I_3=I_1=0$$

$$\Rightarrow t_2=\frac{L}{R}\ln\left(1+\frac{RI_2}{E}\right)=\frac{L}{R}\ln\left(1+\frac{Vs-E}{E}\left(1-e^{-\frac{kTR}{L}}\right)\right)$$

Step Up Converter

Switch closed for time t_1

- Inductor current rises and energy is stored

Switch open for time t_2

- Energy transferred to load through diode

Voltage across the inductor when ON is

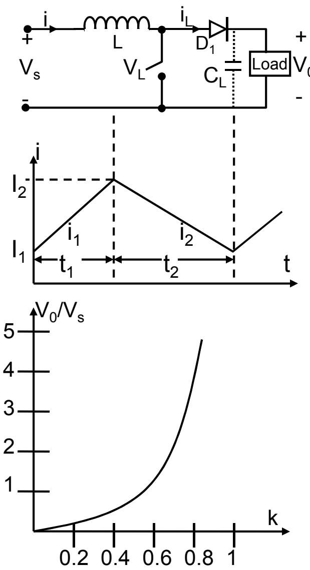
$$V_L=L\frac{di}{dt}$$

Peak – to – peak current in the inductor is

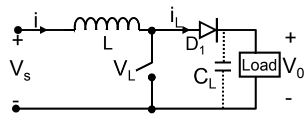
$$\Delta I=\frac{V_s}{L}t_1$$

Average output voltage

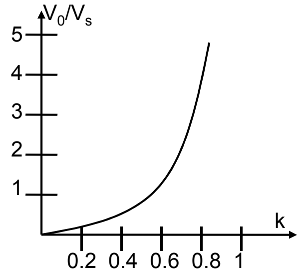
$$V_0=V_s+L\frac{\Delta I}{t_2}=V_s\left(1+\frac{t_1}{t_2}\right)=V_s\frac{1}{1-k}$$



Step Up Converter



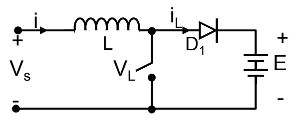
- Capacitor connected output is averaged
- Voltage can be varied by varying k
- As k increases sensitivity decreases
- Converter cannot work continuously for k=1
- ➢ Can be used to transfer voltage form one source to another



When switch is closed (mode 1)

$$V_S = L\frac{di_1}{dt}$$

$$i_1(t) = \frac{V_S}{L}t + I_1 \quad I_1 \equiv \text{Initial current for mode 1}$$



The current must rise,

$$\therefore \frac{di_1}{dt} > 0 \text{ or } V_S > 0$$

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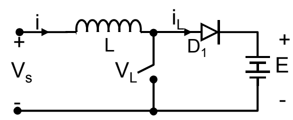
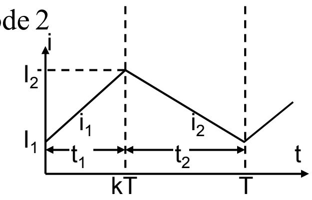
Step Up Converter

When switch is open (mode 2)



$$V_S = L\frac{di_2}{dt} + E$$

$$i_2(t) = \frac{V_S - E}{L}t + I_2 \quad I_2 \equiv \text{Initial current for mode 2}$$



The current must fall for stable operation,

$$\therefore \frac{di_2}{dt} < 0 \text{ or } V_S < E$$

- ➢ For controllable power transfer $0<V_S<E$

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Step Up Converter With Resistive Load

When switch is closed (mode 1)

$$V_S = L\frac{di_1}{dt}$$

$$i_1(t) = \frac{V_S}{L}t + I_1 \text{ for } 0 \le t \le kT$$

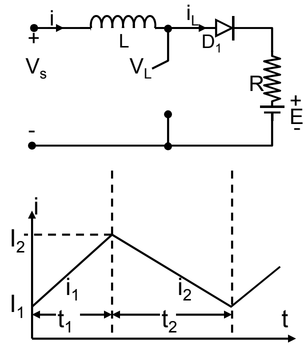
$$I_2 = i_1(t = kT) = \frac{V_S}{L}kT + I_1$$

When switch is open (mode 2)

$$V_S = Ri_2 + L\frac{di_2}{dt} + E$$

$$i_2(t) = \frac{V_S - E}{L}\left(1 - e^{-\frac{tR}{L}}\right) + I_2 e^{-\frac{tR}{L}} \quad \text{for } 0 \le t \le (1-k)T$$

$$I_1 = i_2(t = (1-k)T) = \frac{V_S - E}{L}\left(1 - e^{-\frac{(1-k)TR}{L}}\right) + I_2 e^{-\frac{(1-k)TR}{L}}$$



Step Up Converter With Resistive Load

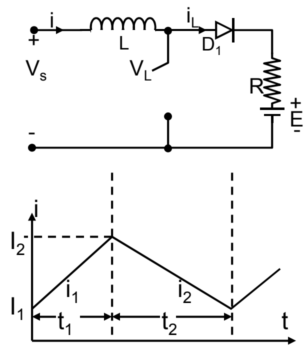
By solving the equations

$$I_1 = \frac{V_S kT}{L}\frac{e^{-\frac{(1-k)TR}{L}}}{1 - e^{-\frac{(1-k)TR}{L}}} + \frac{V_S - E}{R}$$

$$I_2 = \frac{V_S kT}{L}\frac{1}{1 - e^{-\frac{(1-k)TR}{L}}} + \frac{V_S - E}{R}$$

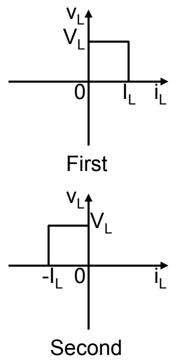
The ripple current is given by

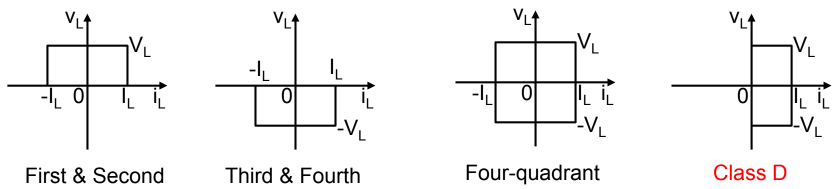
$$\Delta I = I_2 - I_1 = \frac{V_S kT}{L}$$



Chopper Classification

- On the basis of power flow, i.e. on the basis of current and voltage flows choppers can be divided into
  - First quadrant converter (Class A)
  - Second quadrant converter (Class B)
  - First & second quadrant converter (Class C)
  - Third & fourth quadrant converter (Class D)
  - Four-quadrant converter (Class E)





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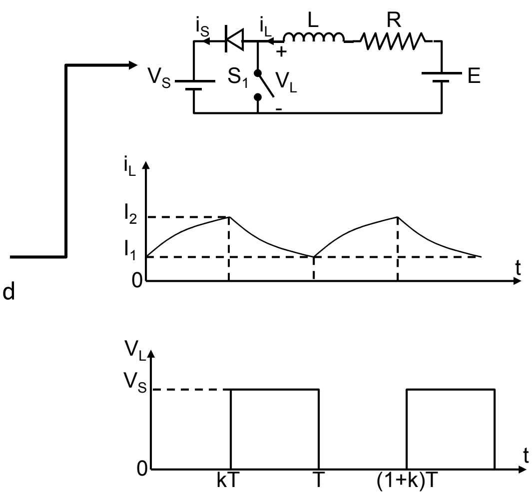
Chopper Classification contd..

First Quadrant Converter

- Current flows into the load
- Voltage & current positive
- Single Quadrant converter
- Acts as a rectifier

Second Quadrant Converter

- Current flows out of the load
- Load voltage positive
- Load Current Negative
- Single Quadrant converter
- Acts as an inverter
- Battery E is part of the load



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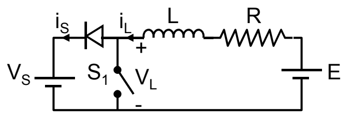
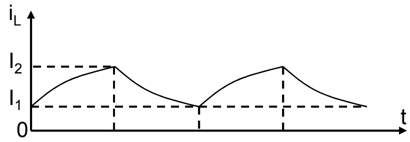
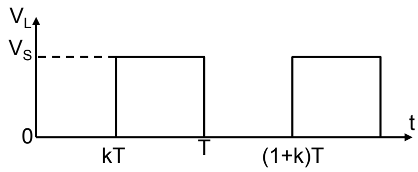
Chopper Classification

Second Quadrant Converter Operation

- When switch S_1 is ON voltage E drives current through inductor
- Voltage V_L becomes zero







$$0 = L\frac{di_L}{dt} + Ri_L + E$$

$$i_L = I_1 e^{-\frac{R}{L}t} - \frac{E}{R}\left(1 - e^{-\frac{R}{L}t}\right) \text{ for } 0 \le t \le kT$$

$$i_L(t=0) = I_1 \qquad i_L(t=kT) = I_2$$

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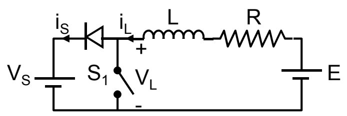
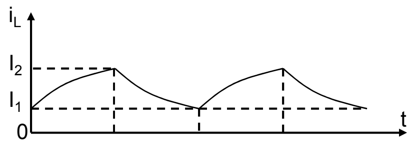
Chopper Classification

Second Quadrant Converter Operation

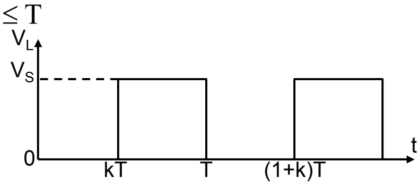
- When switch S_1 is OFF energy stored in inductor is returned to supply V_S via diode D
- Current i_L falls





$$V_S = L\frac{di_L}{dt} + Ri_L + E$$

$$i_L = I_2 e^{-\frac{R}{L}t} - \frac{V_S - E}{R}\left(1 - e^{-\frac{R}{L}t}\right) \text{ for } kT \le t \le T$$



$i_L(t=kT) = I_2$ Steady-state

$i_L(t=T) = I_1$ continuous current

$i_L(t=T) = 0$ dis-continuous current

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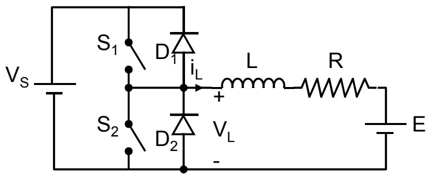
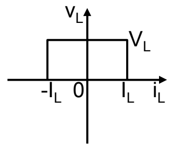
Chopper Classification





First & Second

First & Second Quadrant Converter

- Load current is either positive or negative
- Load voltage is always positive
- S_1 & D_2 operate as first quadrant converter
- S_2 & D_1 operate as second quadrant converter
- Firing of both switched must not occur together →to prevent short-circuit
- Can operate as a rectifier or inverter

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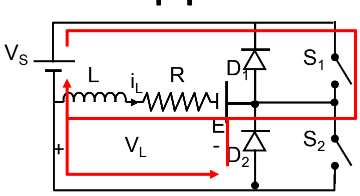
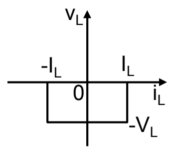
Chopper Classification





Third & Fourth

Third & Fourth Quadrant Converter

- Load current is either positive or negative
- Load voltage is always negative
- S_1 & D_2 operate to yield both negative voltage and load current
- When S_1 is closed a negative current flows through the load
- When S_1 is open current free wheels thought diode D_2

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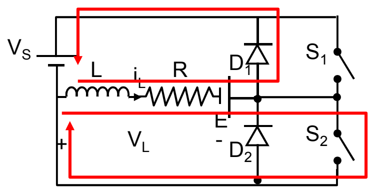
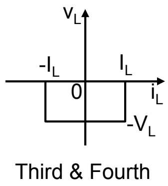
Chopper Classification

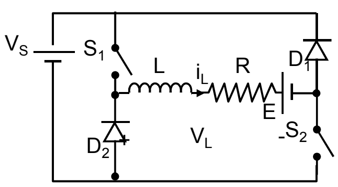


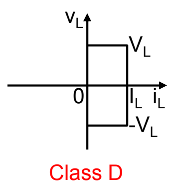


Third & Fourth Quadrant Converter

- S_2 & D_1 operate to yield negative voltage and positive load current
- When S_2 is closed a positive current flows through the load
- When S_2 is open current free wheels thought diode D_1
- This is a negative two-quadrant converter
- Can operate as a rectifier or inverter

Chopper Classification

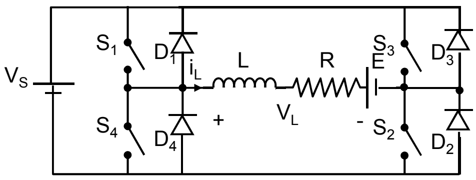


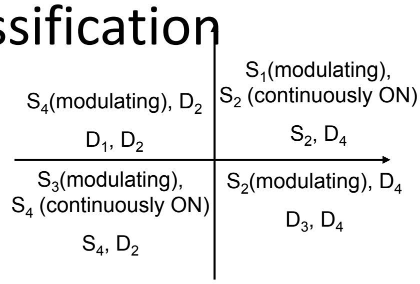


Class D Converter

- The load voltage is always positive
- The load current is either positive or negative
- S_1 & S_2 operate to yield positive voltage and load current
- D_1 & D_2 operate to yield positive load current and negative voltage
- Can operate as a rectifier or inverter

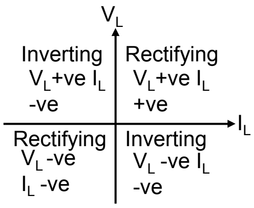
Chopper Classification





Four-Quadrant Converter

- Load current is either positive or negative
- Load voltage is either positive or negative
- One first & second quadrant converter and one third & fourth quadrant converter joined to form four-quadrant converter



DC-DC converters Electronic Circuit-II 33