NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

Process Control: Part II- Model Predictive Control (EE6225, AY2019/20, S1)

Dr Xin Zhang

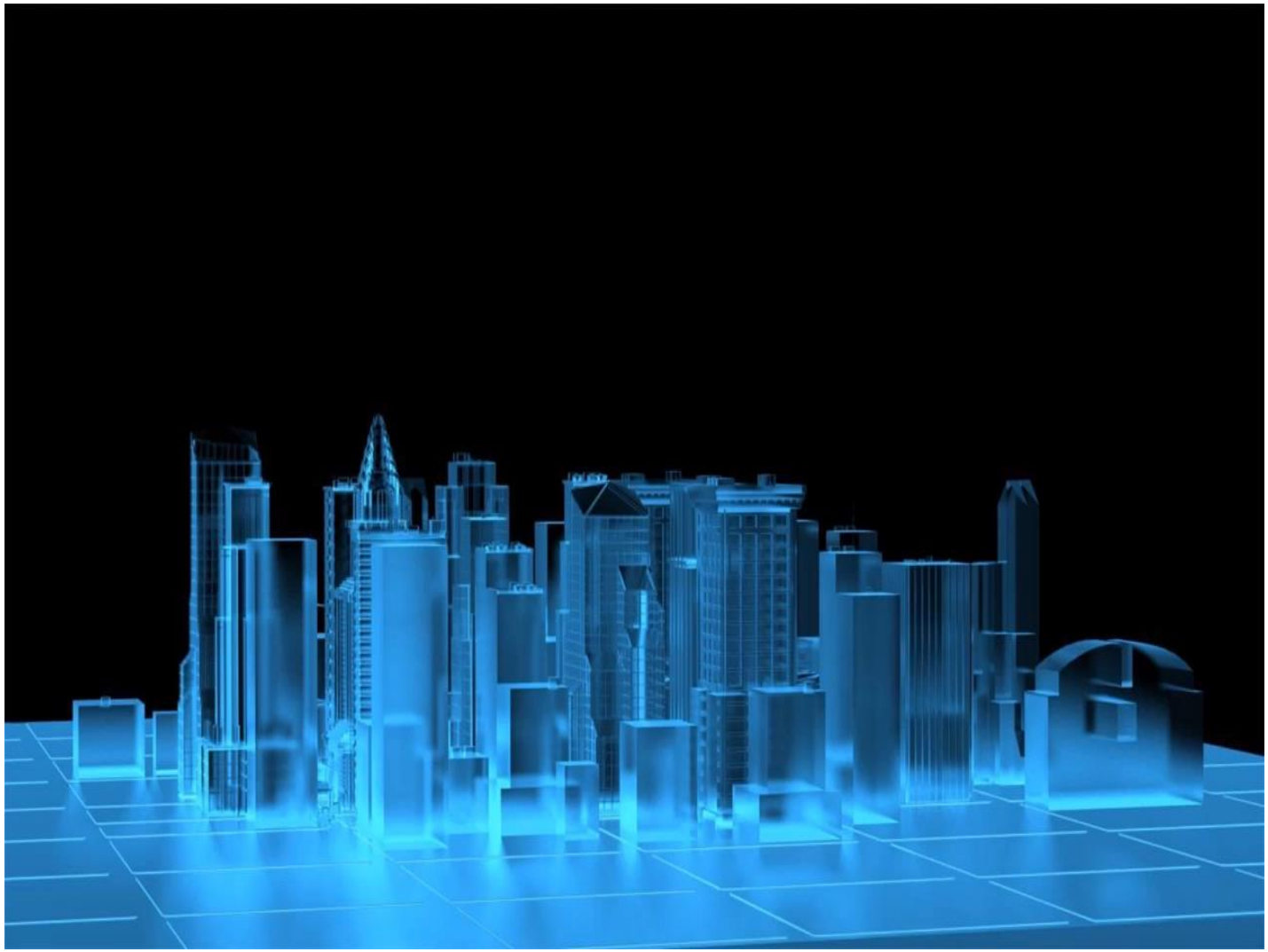
Assistant Professor

Office: NTU S2-B2c-95, Tel: 67905419

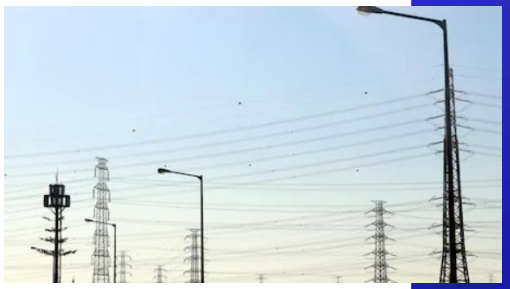
Lab: S2.2-B4-03

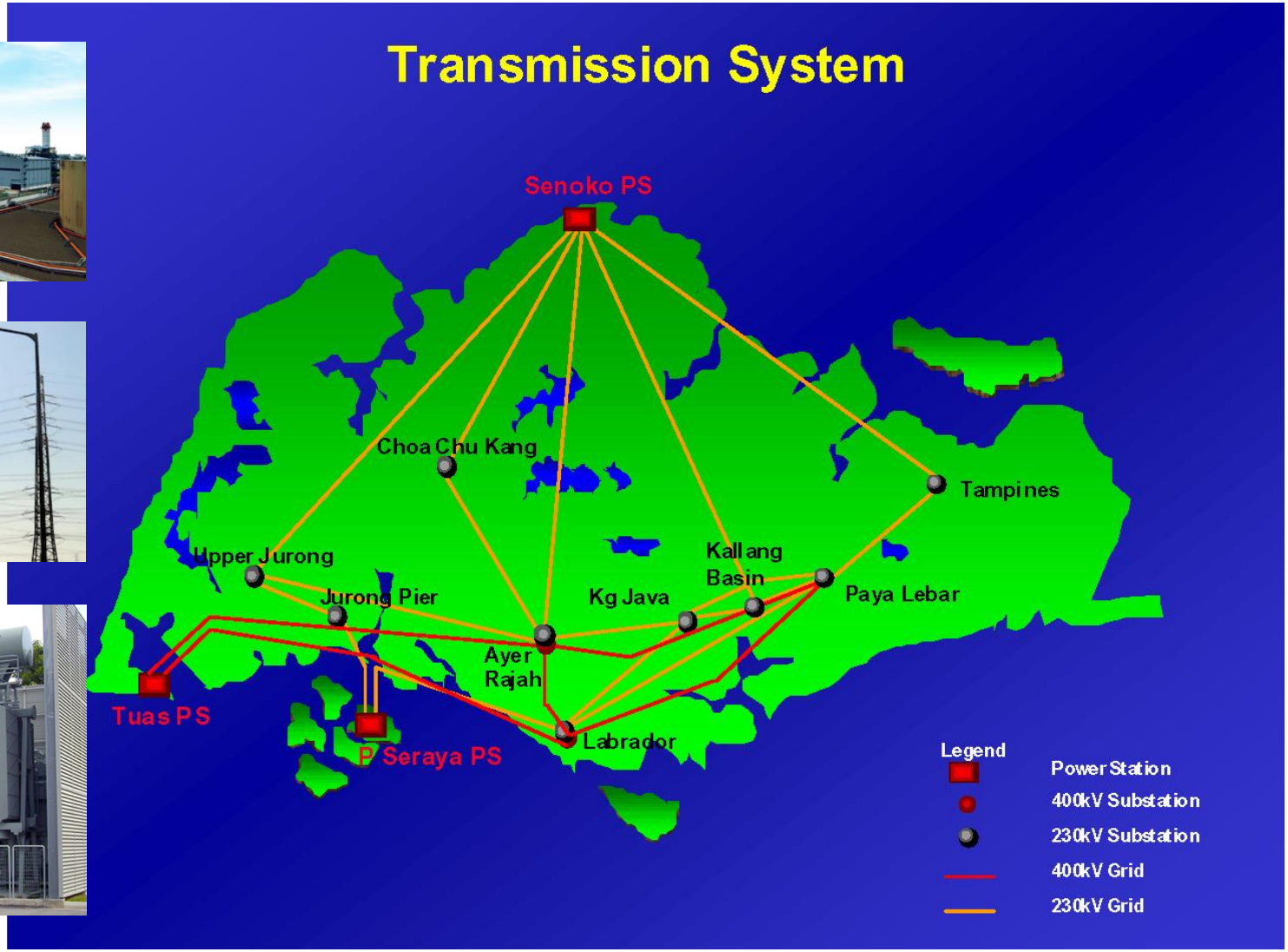
Email: Jackzhang@ntu.edu.sg

Application of power electronics

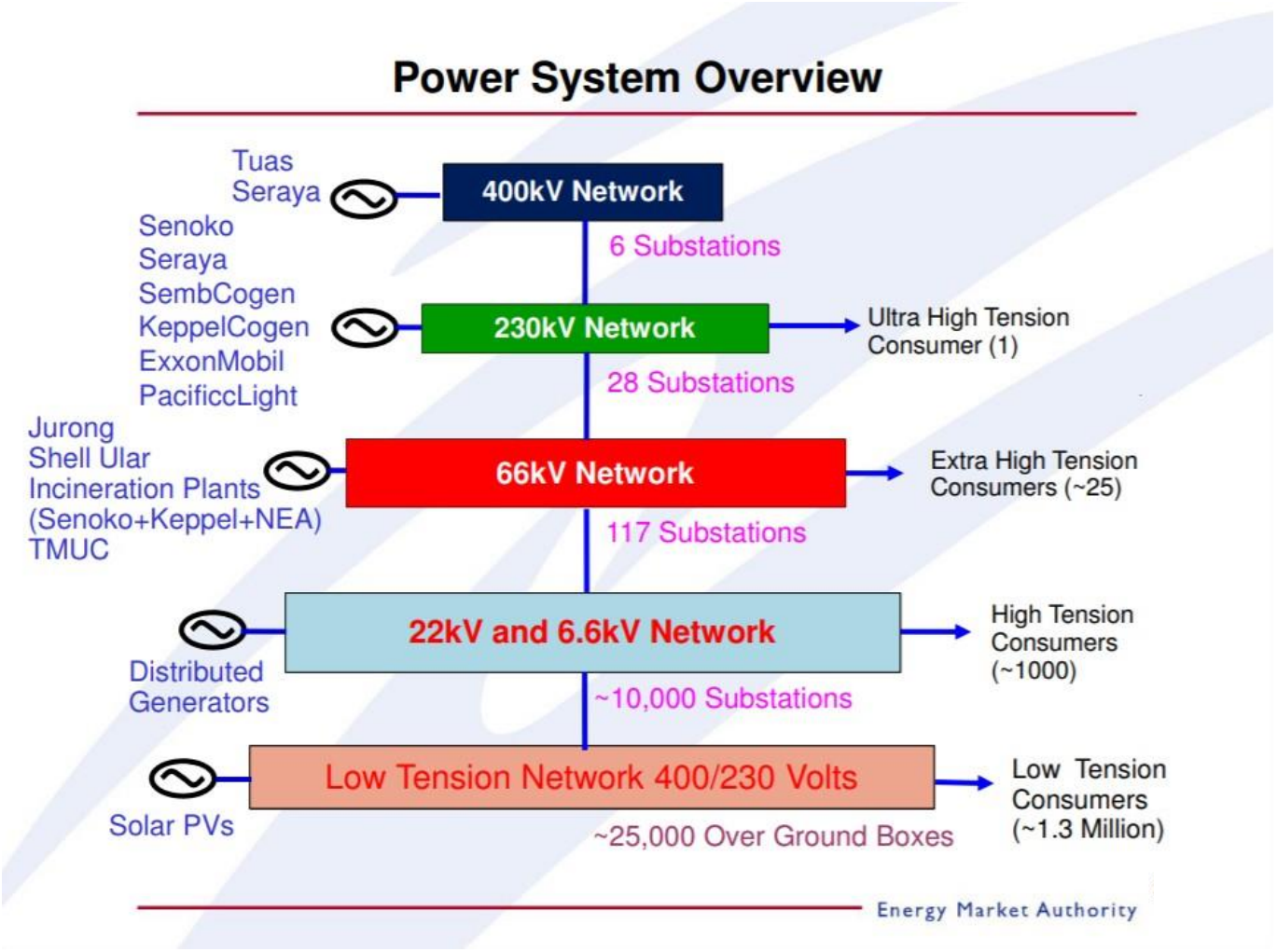


Grid of Singapore

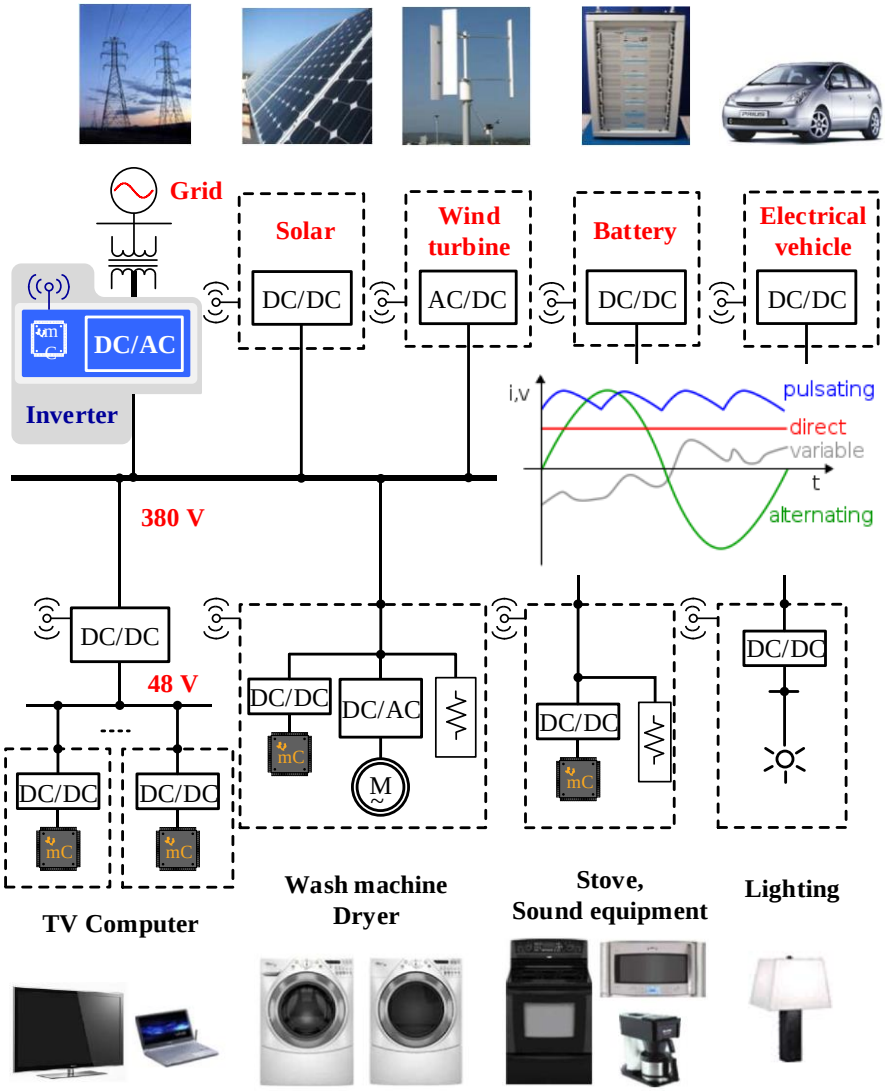


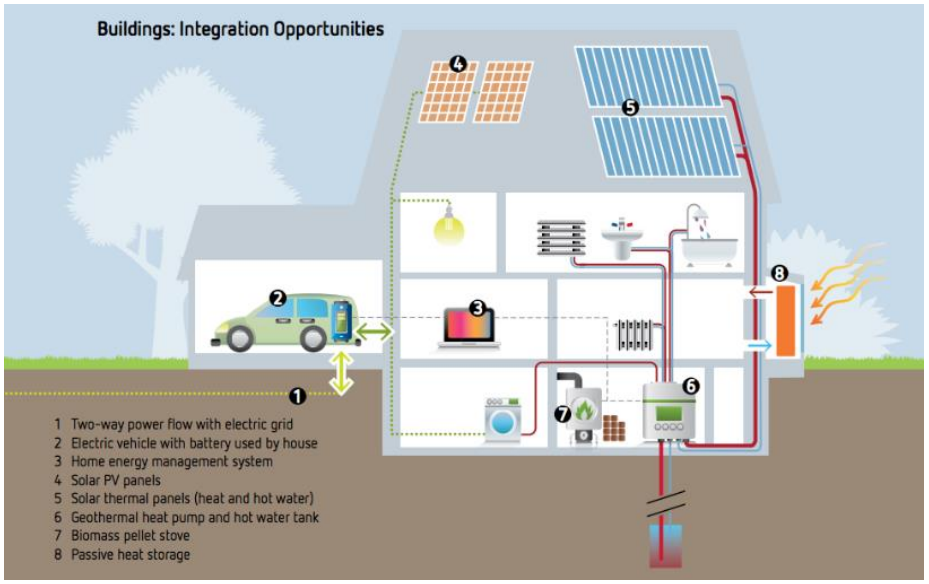


Grid of Singapore



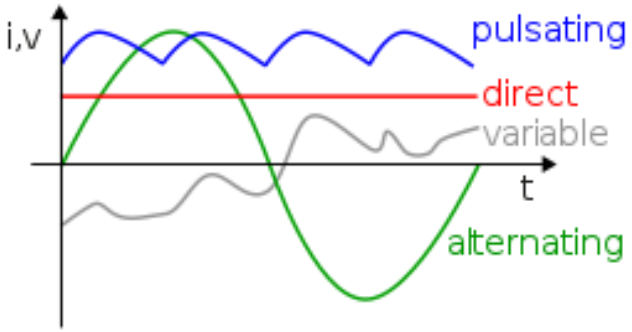
Future renewable energy sources-based building





OPERATION PRINCIPLE OF THE POWER CONVERTERS

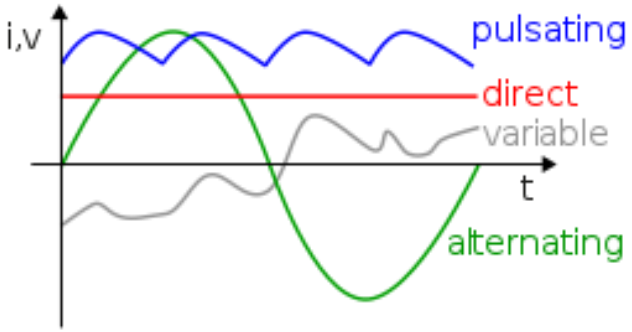
[31/10/2019]



- Operation principle of the DC/DC converter
- Operation principle of the DC/AC inverter

OPERATION PRINCIPLE OF THE POWER CONVERTERS

[31/10/2019]



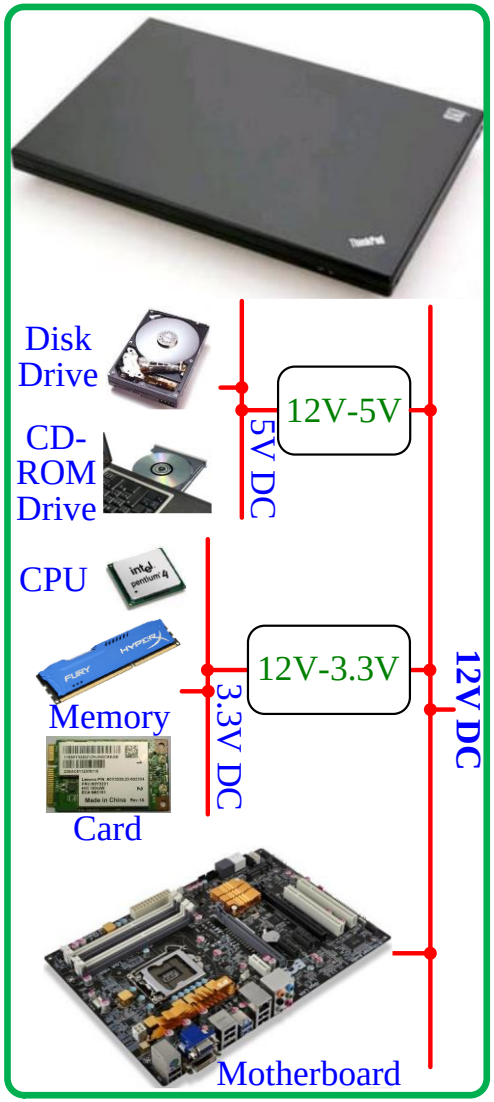
- Operation principle of the DC/DC converter
- Operation principle of the DC/AC inverter

DC/DC CONVERTER

- Buck converter
- Boost converter
- Buck-Boost converter

DC/DC CONVERTER

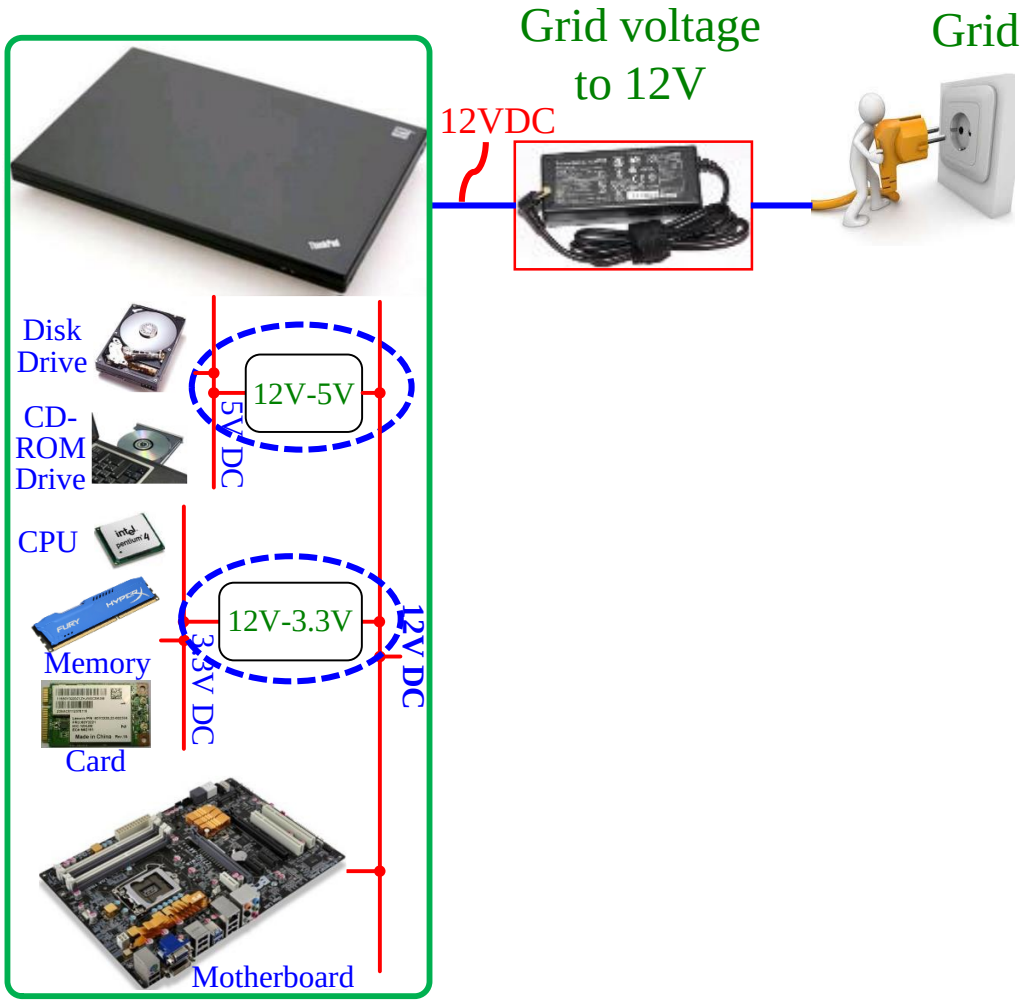
- Buck converter
- ~~Boost converter~~
- ~~Buck-Boost converter~~



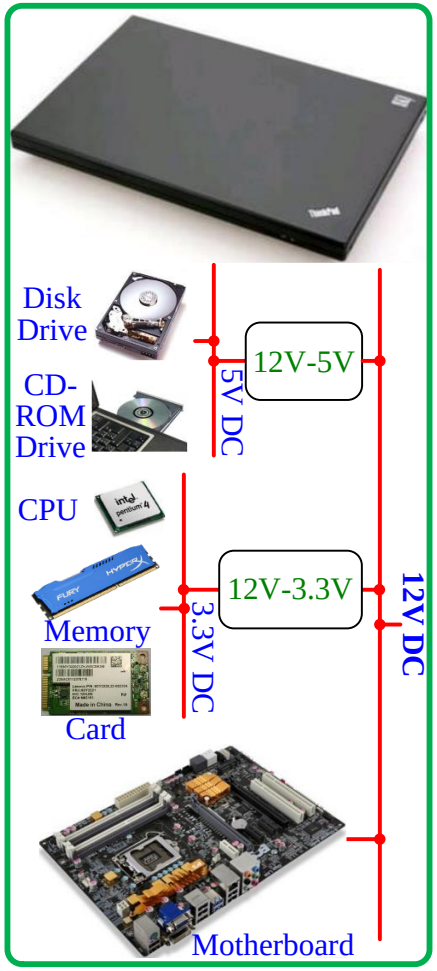
BUCK CONVERTER (STEP DOWN DC/DC CONVERTER)

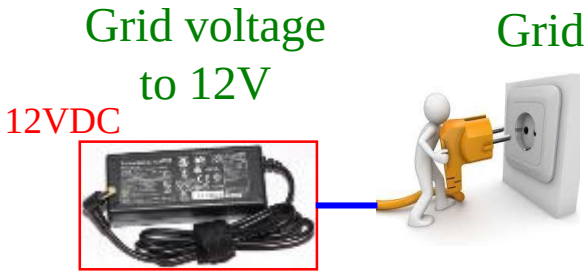
Input voltage → **Step down** → **Output voltage**

Application of step-down DC/DC power supplies in Laptop

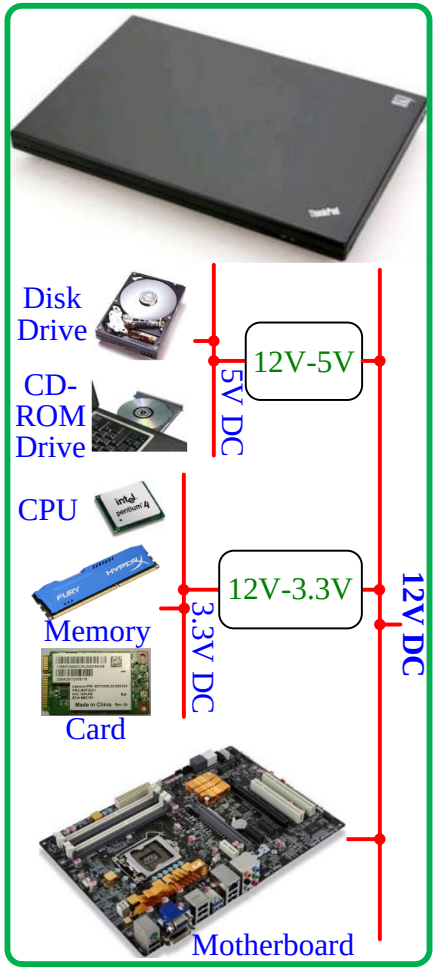


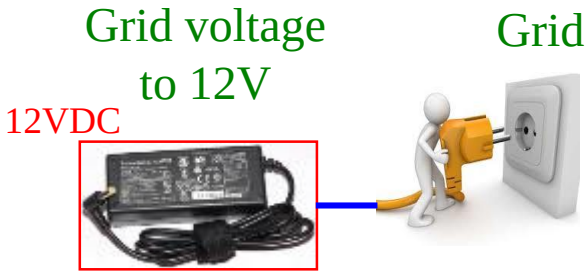
Other applications of step-down DC/DC power supplies: Aircraft

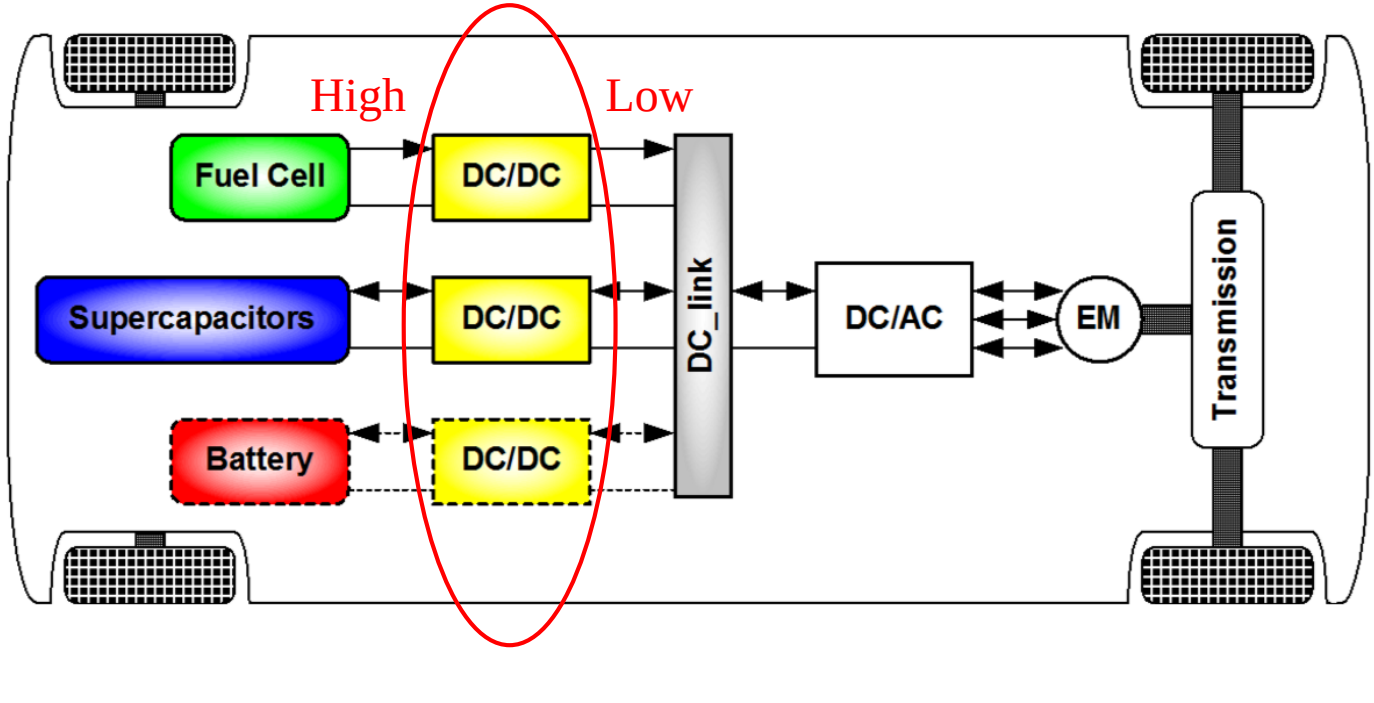




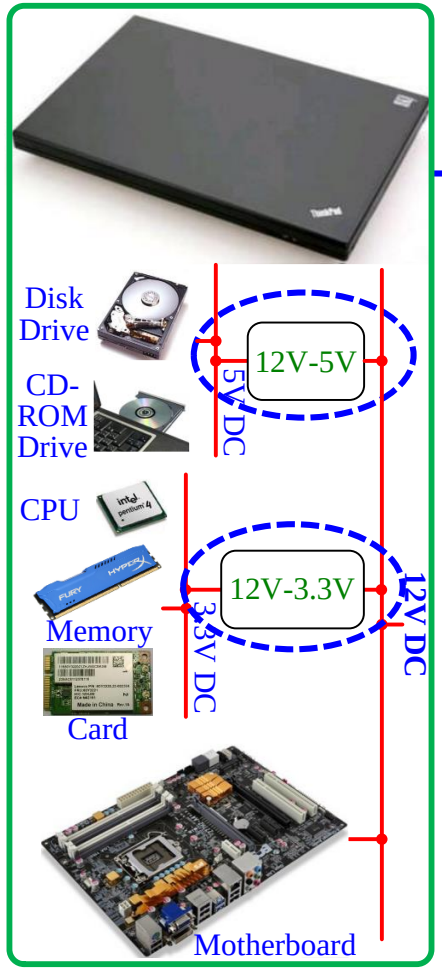
Other applications of step-down DC/DC power supplies: Electric vehicle

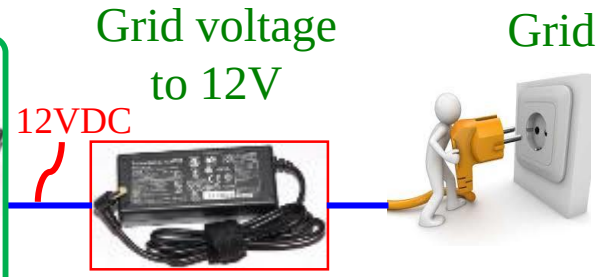


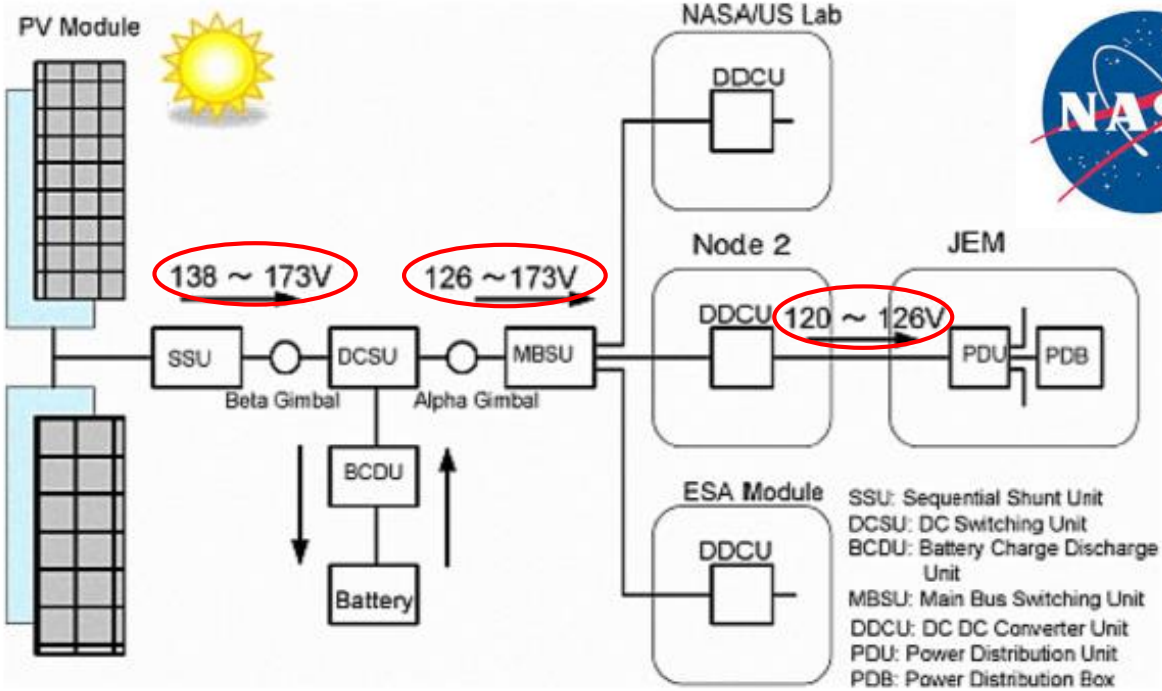




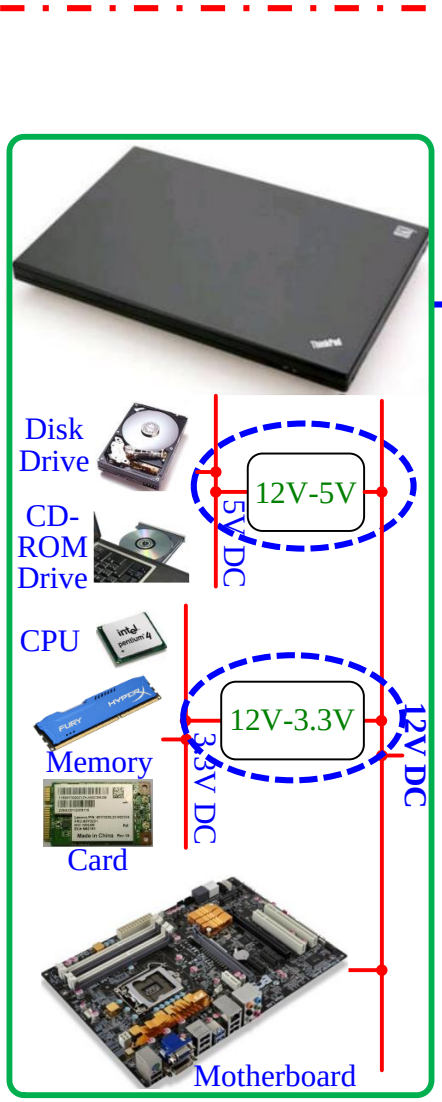
Other applications of step-down DC/DC power supplies: Space station

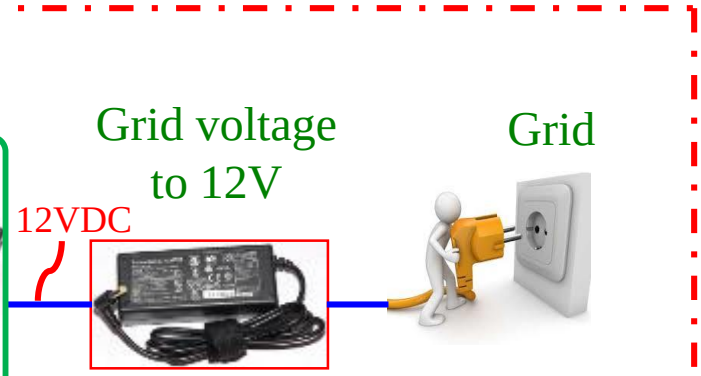


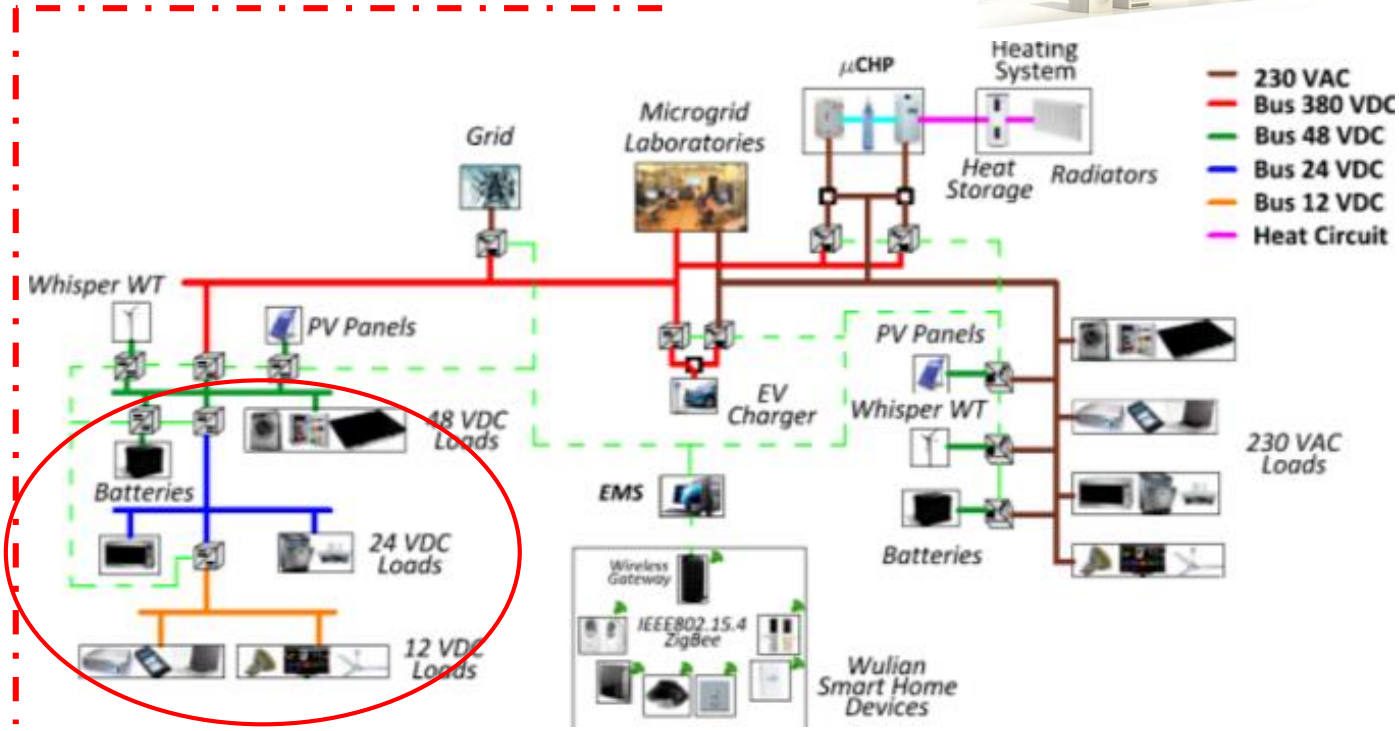




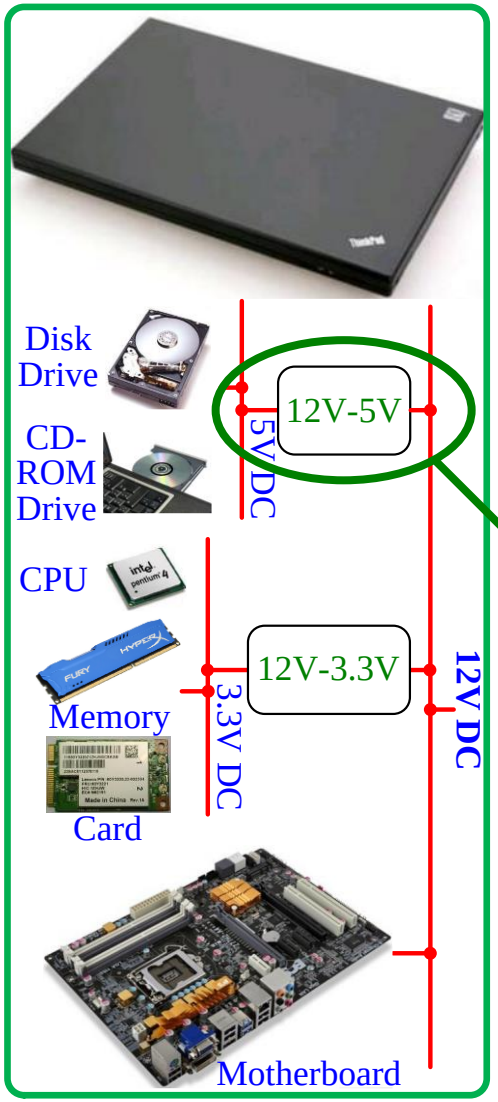
Other applications of step down DC/DC power supplies: Renewable energy system in the house







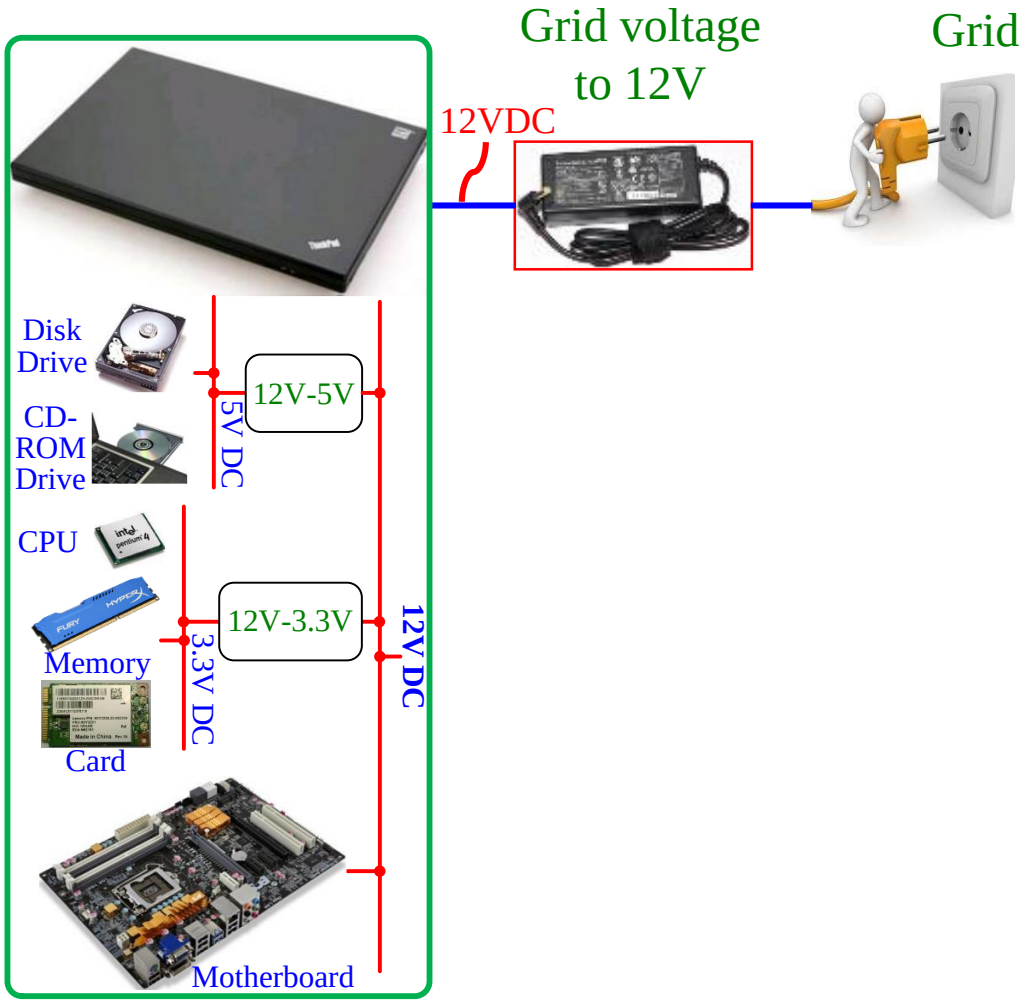
Example



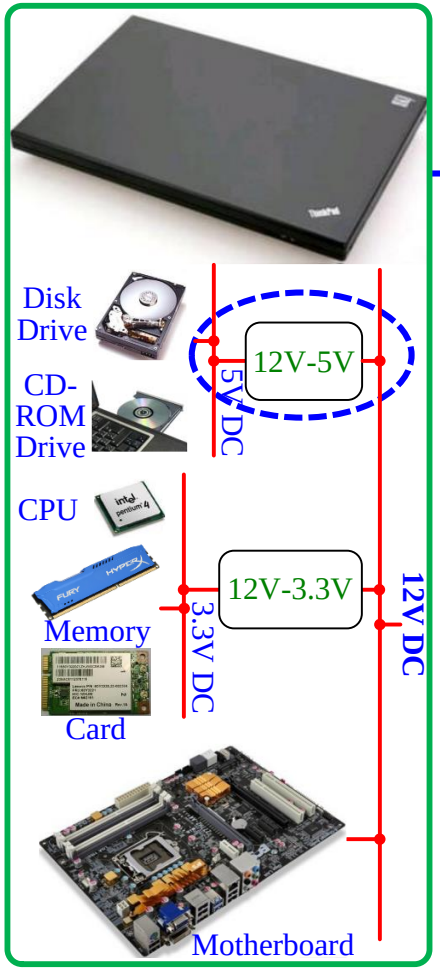
BUCK CONVERTER (STEP DOWN DC/DC CONVERTER)

How to design a 12 V to 5 V DC/DC converter

How to design step down DC/DC power supply?



How to design a 12 V – 5 V power supply?



Grid voltage to 12V

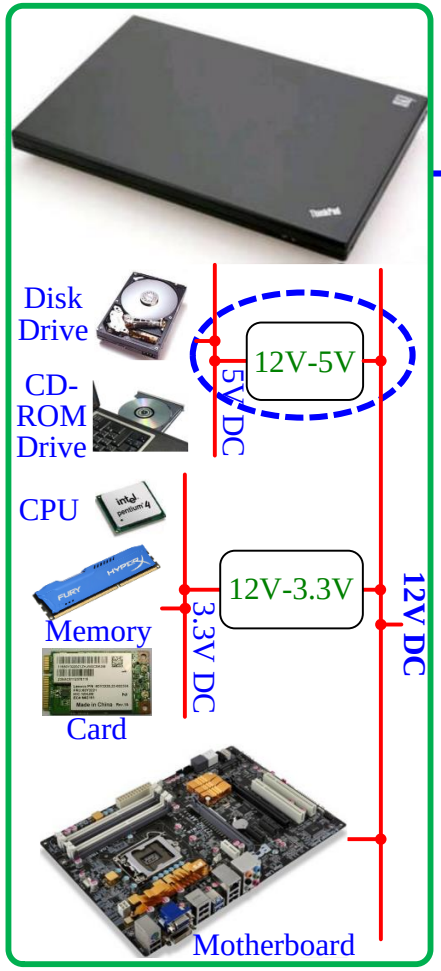
Grid

12VDC

How to get 5V from 12V?

12V DC — **DC-DC Conversion** — 5V DC

How to design a 12 V – 5 V power supply?



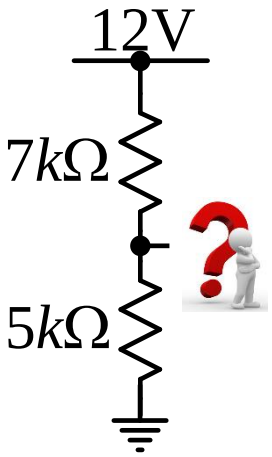
Grid voltage to 12V

Grid

12VDC

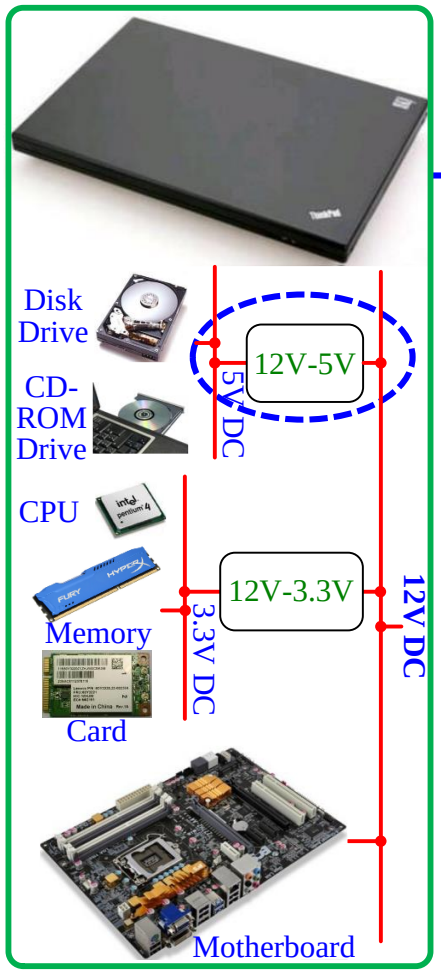
How to get 5V from 12V?

12V DC — **DC-DC Conversion** — 5V DC



$$\frac{5(k\Omega)}{5(k\Omega)+7(k\Omega)}\cdot 12V = 5V$$

How to design a 12 V – 5 V power supply?



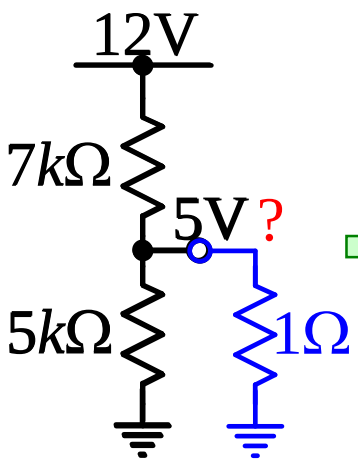
Grid voltage to 12V

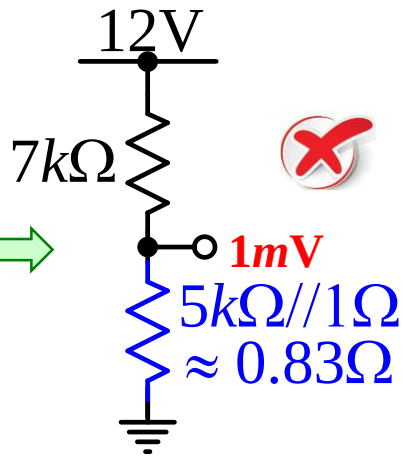
Grid

12VDC

How to get 5V from 12V?

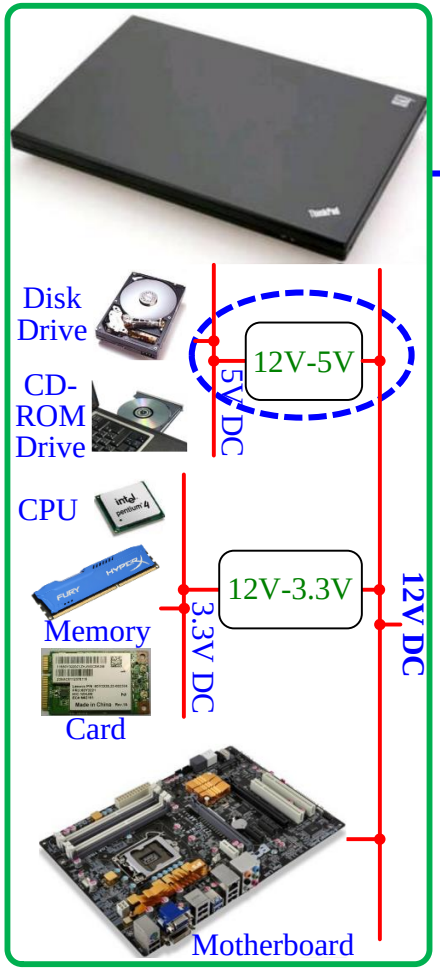
12V DC — **DC-DC Conversion** — 5V DC





$$\frac{0.83(k\Omega)}{0.83(k\Omega)+7(k\Omega)}\cdot 12V = 1mV$$

How to design a 12 V – 5 V power supply?



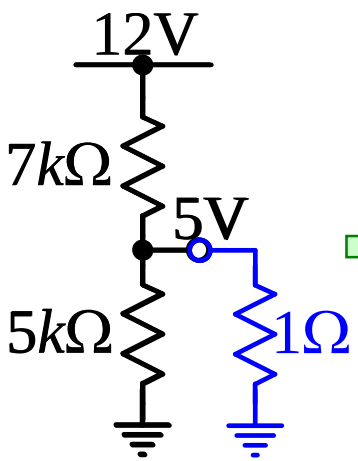
Grid voltage to 12V

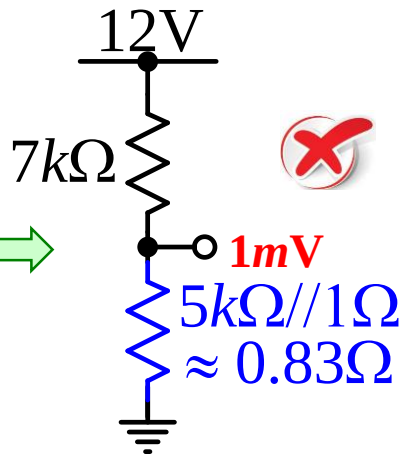
Grid

12VDC

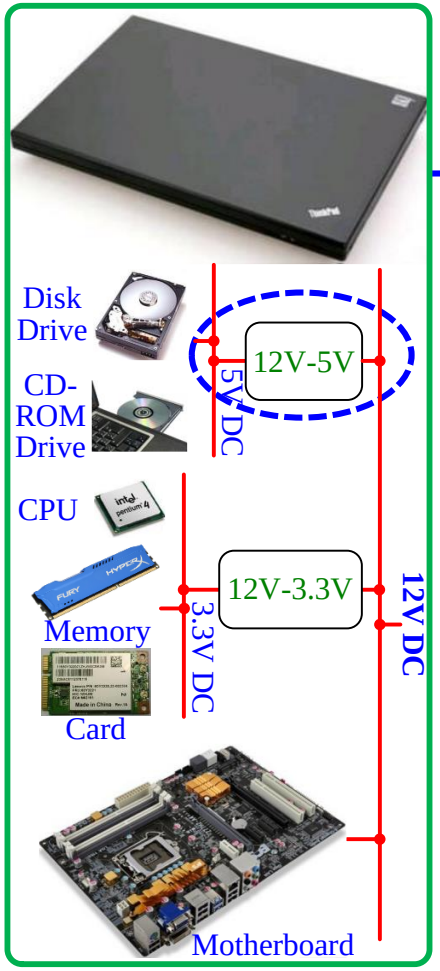
How to get constant 5V from 12V with load?

12V DC → **DC-DC Conversion** → 5V DC





How to design a 12 V – 5 V power supply?



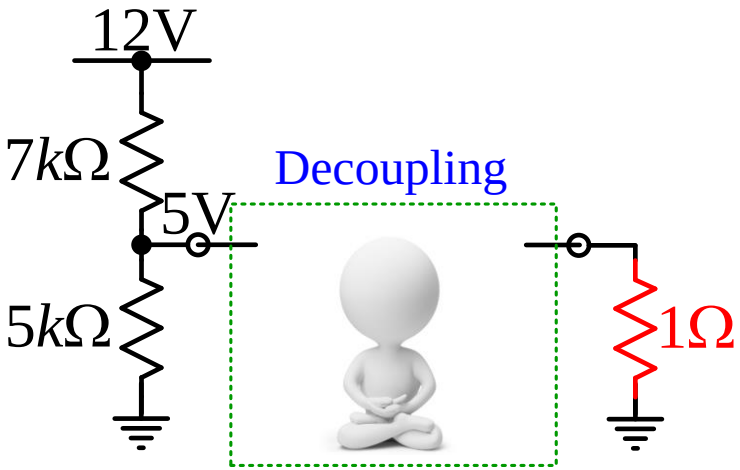
Grid voltage to 12V

Grid

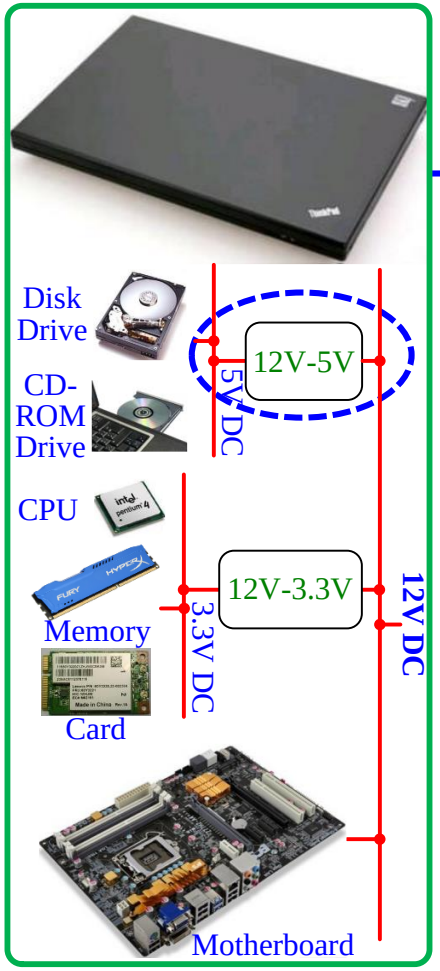
12VDC

How to get constant 5V from 12V with load?

12V DC — **DC-DC Conversion** — 5V DC



How to design a 12 V – 5 V power supply?



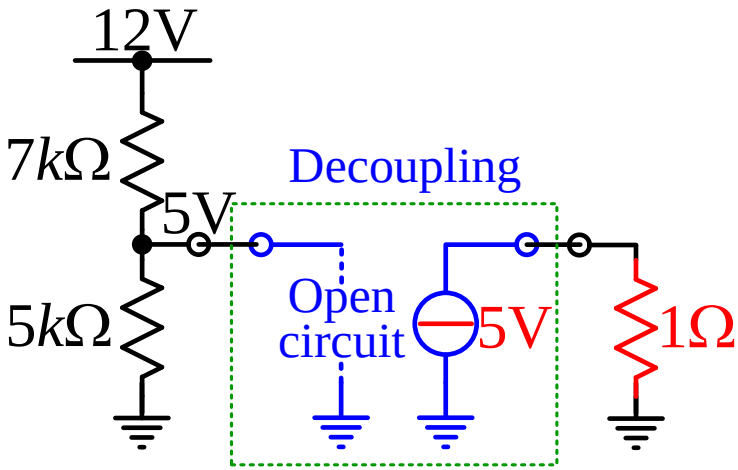
Grid voltage to 12V

Grid

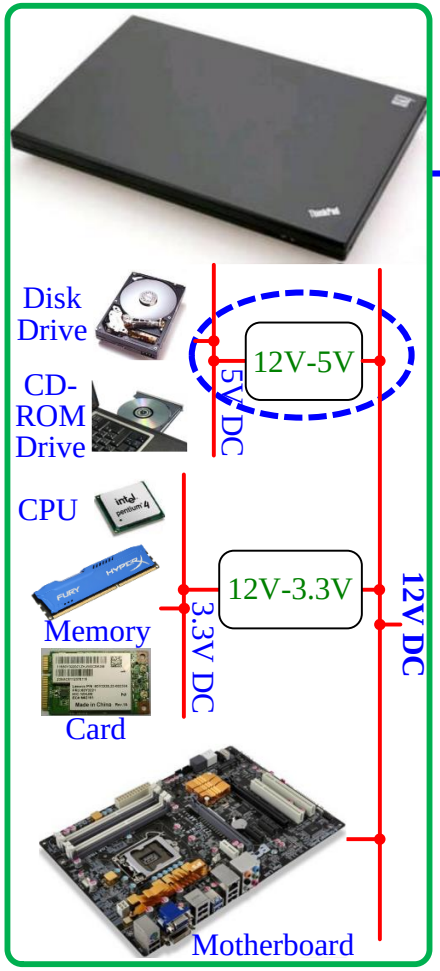
12VDC

How to get constant 5V from 12V with load?

12V DC — **DC-DC Conversion** — 5V DC



How to design a 12 V – 5 V power supply?



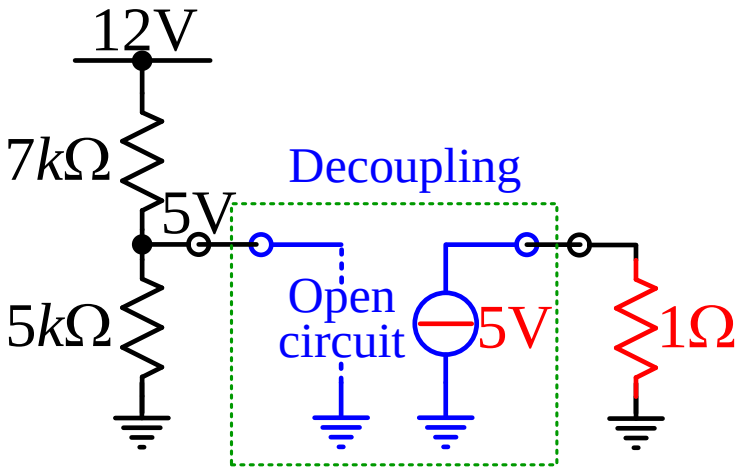
Grid voltage to 12V

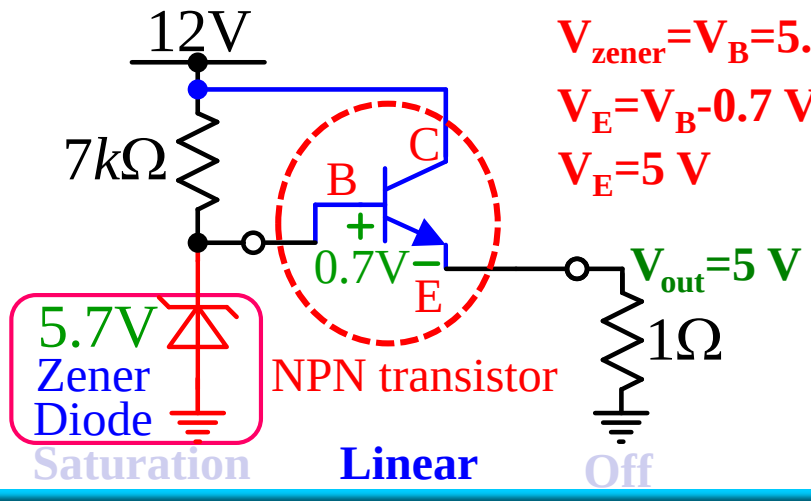
Grid

12VDC

How to get constant 5V from 12V with load?

12V DC → **DC-DC Conversion** → 5V DC



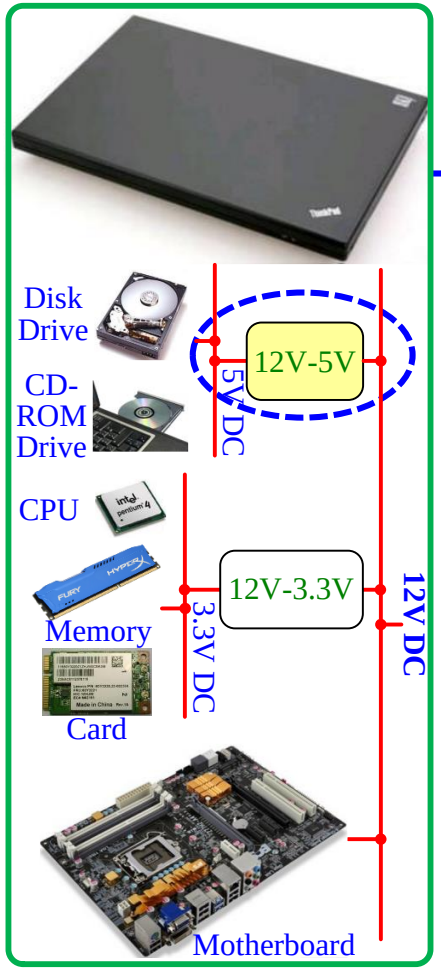


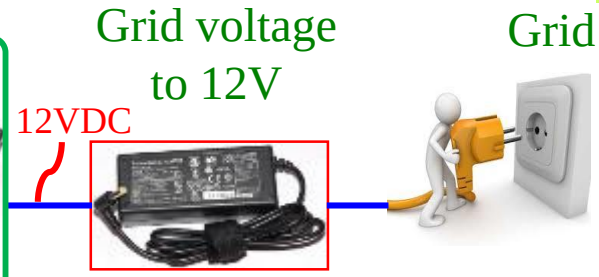
$V_{zener}=V_B=5.7$ V

$V_E=V_B-0.7$ V

$V_E=5$ V

Traditional step down DC/DC power supply

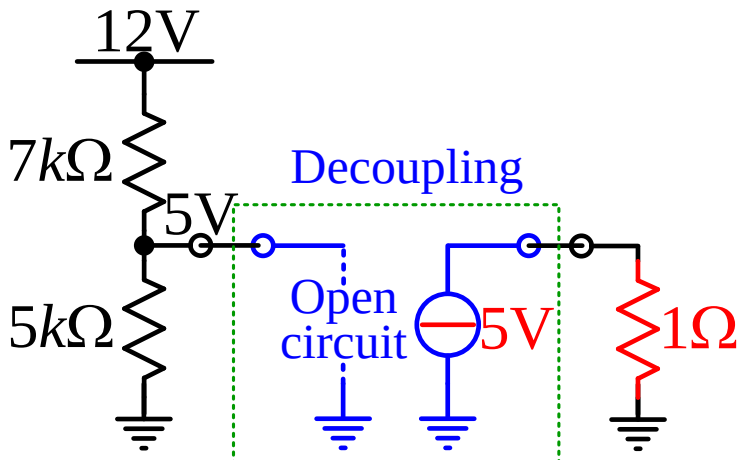


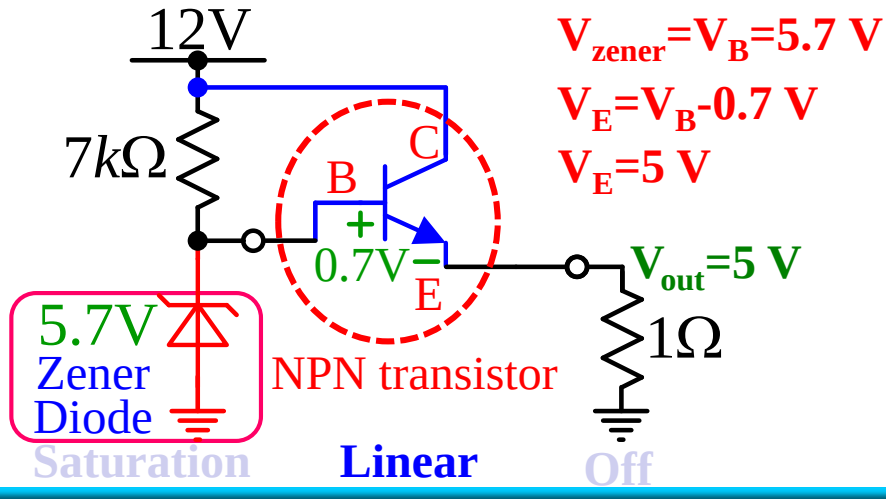


How to get constant 5V from 12V with load?

12V DC → **DC-DC Conversion** → 5V DC

Traditional step down DC/DC power supply



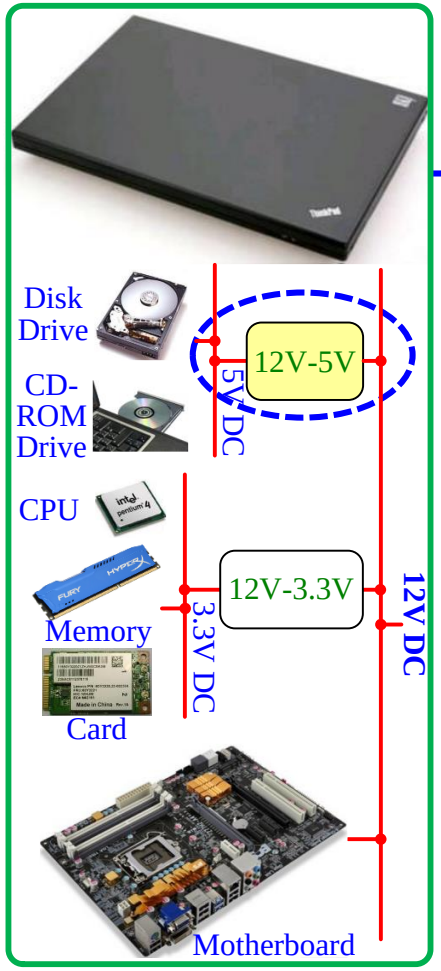


$V_{zener}=V_B=5.7$ V

$V_E=V_B-0.7$ V

$V_E=5$ V

Traditional step down DC/DC power supply: Linear voltage regulator



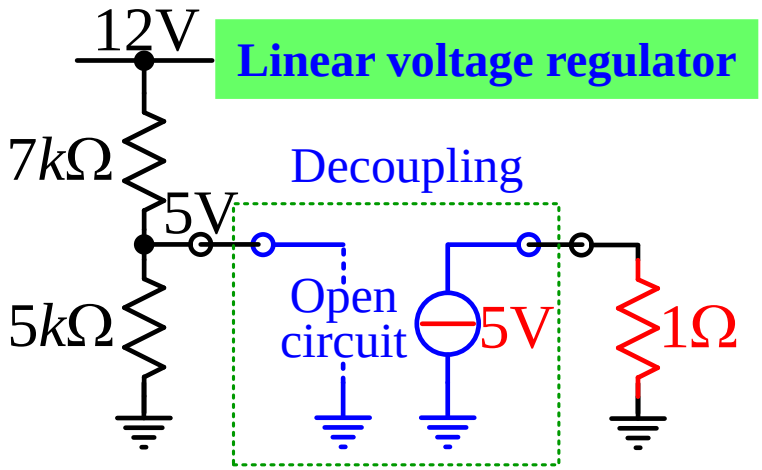
Grid voltage to 12V

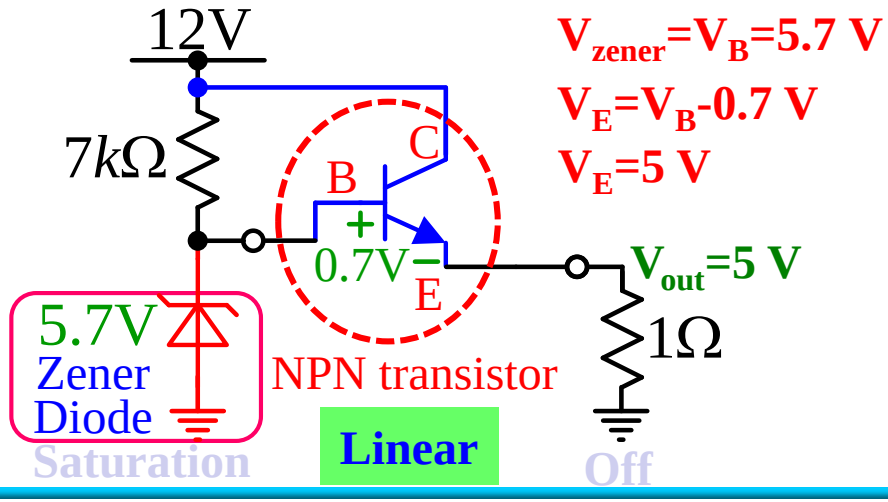
How to get constant 5V from 12V with load?

12V DC → **DC-DC Conversion** → 5V DC

Traditional step down DC/DC power supply

Linear voltage regulator





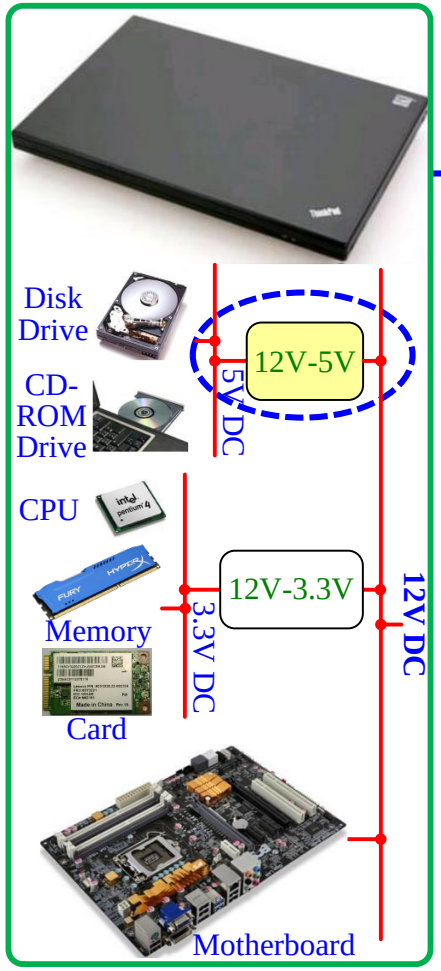
$V_{zener}=V_B=5.7$ V

$V_E=V_B-0.7$ V

$V_E=5$ V

$V_{out}=5$ V

The first linear voltage regulator IC: 7805



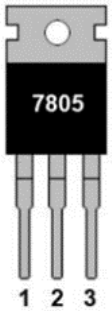
Grid voltage to 12V

Grid

12VDC

How to get constant 5V from 12V with load?

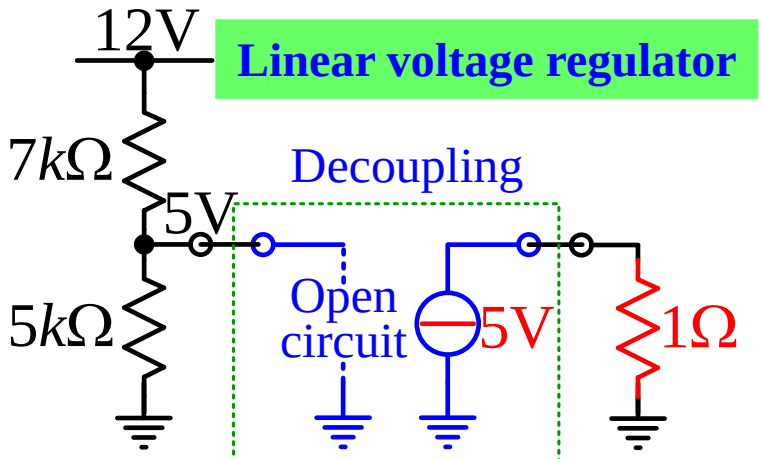
12V DC — **DC-DC Conversion** — 5V DC

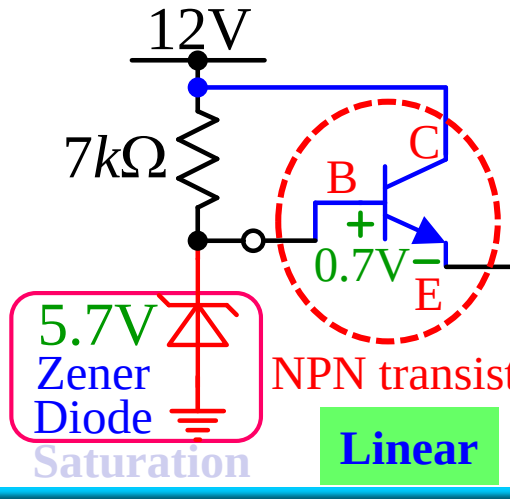


IC: 7805

V_{in}: 6-40V
V_o: 5V

Traditional step down DC/DC power supply



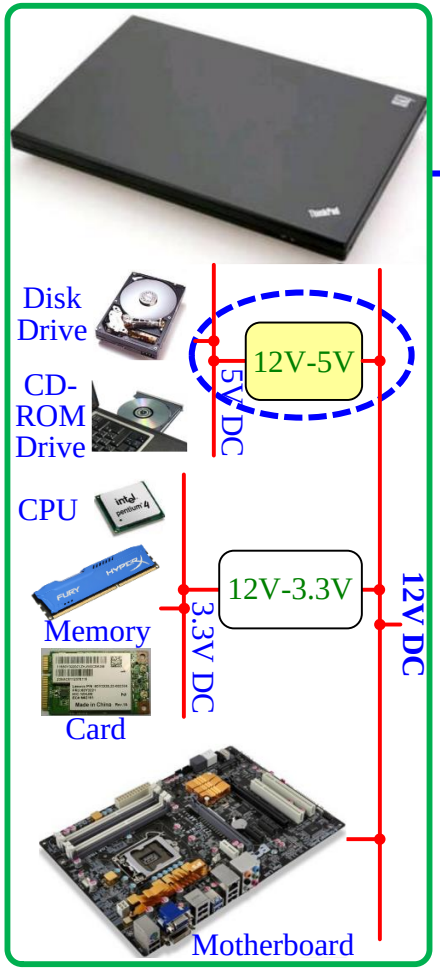


$V_{zener}=V_B=5.7$ V

$V_E=V_B-0.7$ V

$V_E=5$ V

The first linear voltage regulator IC: 7805



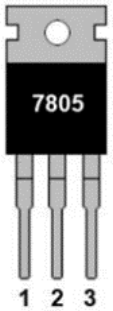
Grid voltage to 12V

12VDC

Grid

How to get constant 5V from 12V with load?

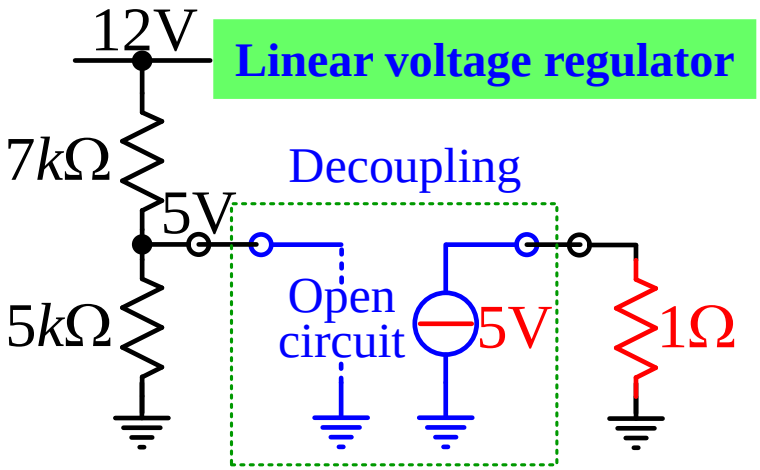
12V DC — **DC-DC Conversion** — 5V DC



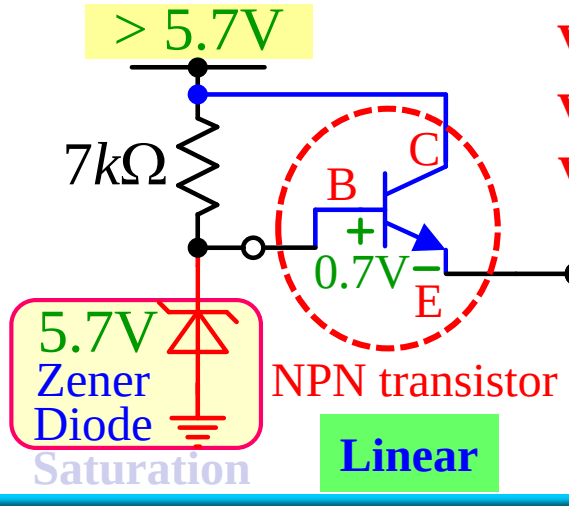
IC: 7805

V_{in}: 6-40V
V_o: 5V

Traditional step down DC/DC power supply



Linear voltage regulator



V_{out}=5 V

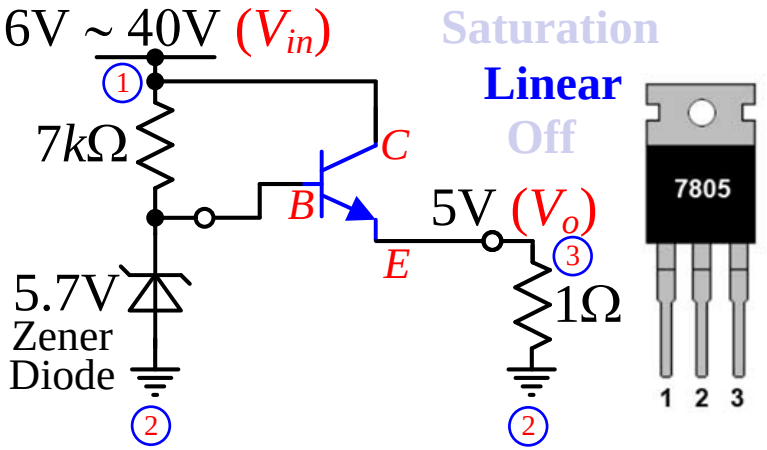
V_{zener}=V_B=5.7 V

V_E=V_B-0.7 V

V_E=5 V

Advantages of the linear voltage regulator: Take 7805 as an example

Linear voltage regulator 7805



Advantages of Linear voltage regulator 7805

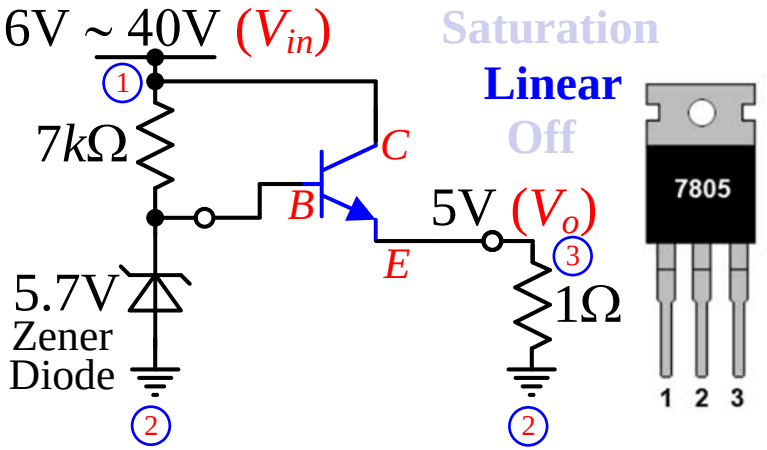
1. Cheap price < $ 0.1;
2. Simple circuit;
3. Wide input voltage: 6V ~ 40V DC.

No need to control it

Are there any disadvantages for linear voltage regulator?

Disadvantages of the Linear Voltage Regulator: Efficiency Problem

Linear voltage regulator 7805



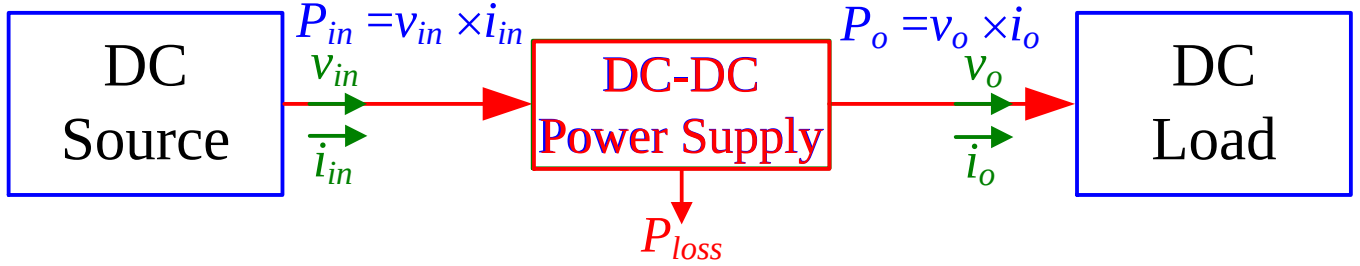
Advantages of Linear voltage regulator 7805

1. Cheap price < $ 0.1;
2. Simple circuit;
3. Wide input voltage: 6V ~ 40V DC.

Efficiency

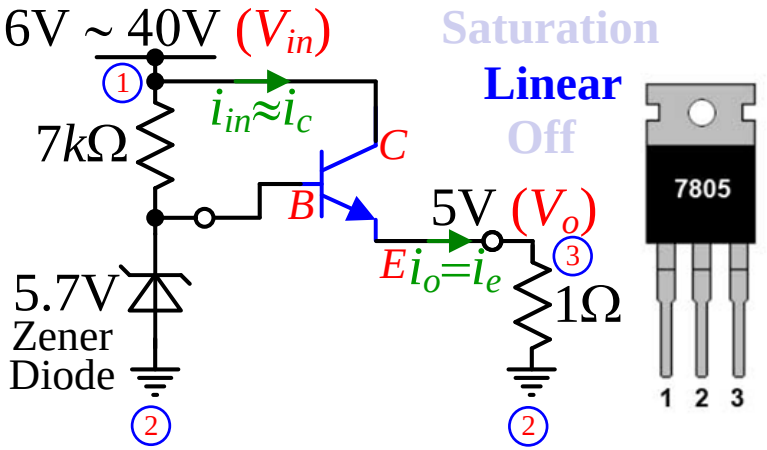
$$\eta = \frac{p_o}{p_{in}} = \frac{v_o \cdot i_o}{v_{in} \cdot i_{in}}$$

Efficiency Problem:



Disadvantages of the Linear Voltage Regulator: Efficiency Problem

Linear voltage regulator 7805



Advantages of Linear voltage regulator 7805

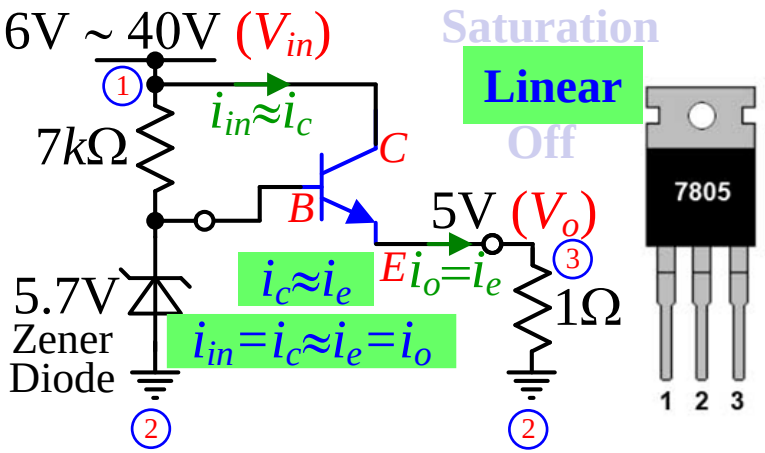
1. Cheap price < $ 0.1;
2. Simple circuit;
3. Wide input voltage: 6V ~ 40V DC.

Efficiency

$$\eta = \frac{p_o}{p_{in}} = \frac{v_o \cdot i_o}{v_{in} \cdot i_{in}}$$

Disadvantages of the Linear Voltage Regulator: Efficiency Problem

Linear voltage regulator 7805



Advantages of Linear voltage regulator 7805

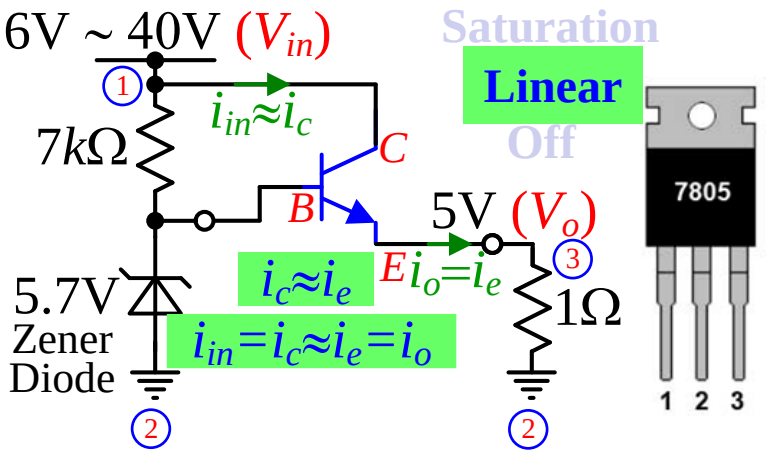
1. Cheap price < $ 0.1;
2. Simple circuit;
3. Wide input voltage: 6V ~ 40V DC.

Efficiency

$$\eta = \frac{p_o}{p_{in}} = \frac{v_o \cdot i_o}{v_{in} \cdot i_{in}}$$

Disadvantages of the Linear Voltage Regulator: Efficiency Problem

Linear voltage regulator 7805



Efficiency

$$\eta = \frac{p_o}{p_{in}} = \frac{v_o \cdot i_o}{v_{in} \cdot i_{in}} = \frac{v_o \cdot \cancel{i_e}}{v_{in} \cdot \cancel{i_c}} \approx \frac{v_o}{v_{in}}$$

1: If V_{in} = 6 V:

$$\eta \approx (5\text{ V})/(6\text{ V}) = 83.3\%$$

2: If V_{in} = 40 V:

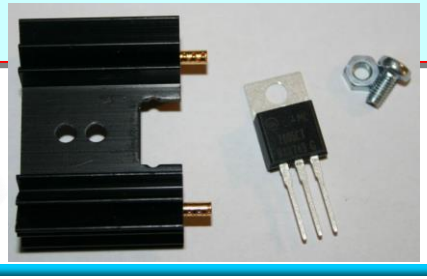
$$\eta \approx (5\text{ V})/(40\text{ V}) = 12.5\%$$

Advantages of Linear voltage regulator 7805

1. Cheap price < $ 0.1;
2. Simple circuit;
3. Wide input voltage: 6V ~ 40V DC.

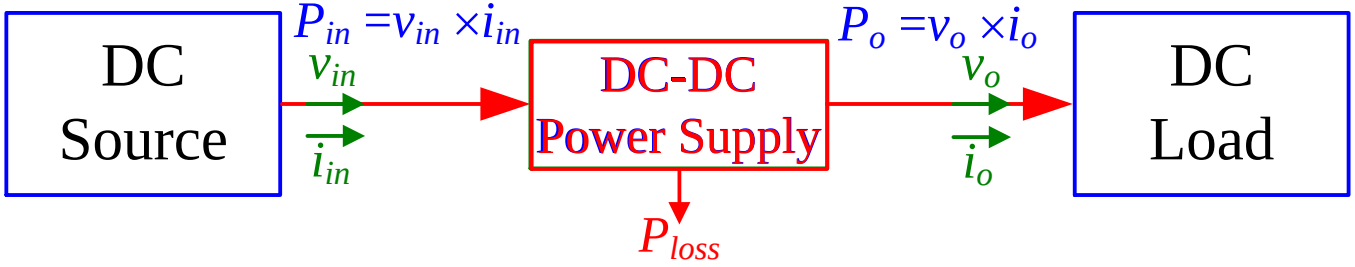
Disadvantages of Linear voltage regulator

1. Efficiency is low if the input voltage is high;
   - 83% @ 6V - 5V;
   - 12.5% @ 40V - 5V;
2. Large power loss → Need large heatsink → Large size.



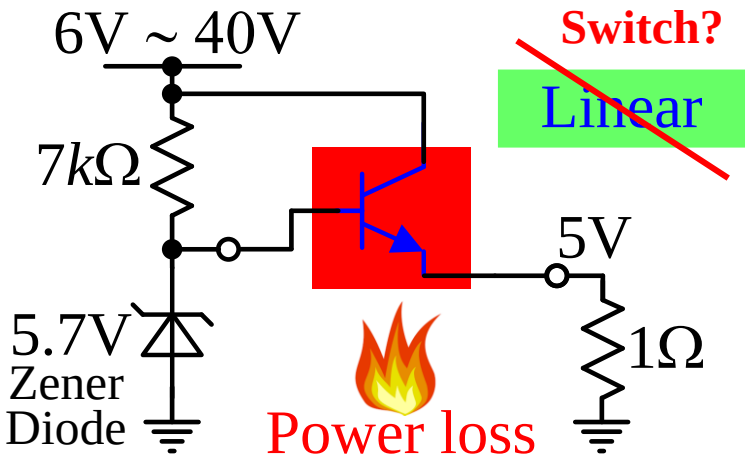
Improved step-down DC/DC power supplies: Switch-Mode Power Supplies (Buck converter)

Efficiency Problem:



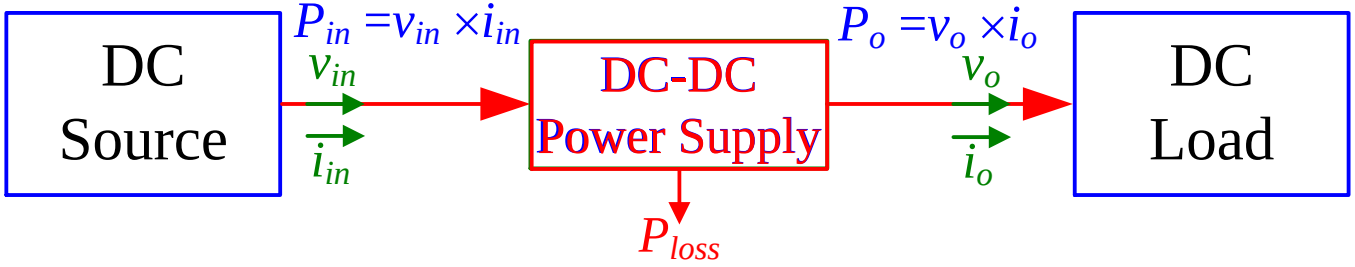
$$p_{in} = p_o + p_{loss} \Rightarrow \eta = \frac{p_o}{p_{in}} = \frac{p_o}{p_o + p_{loss}} \Rightarrow$$

High efficiency requires low power loss



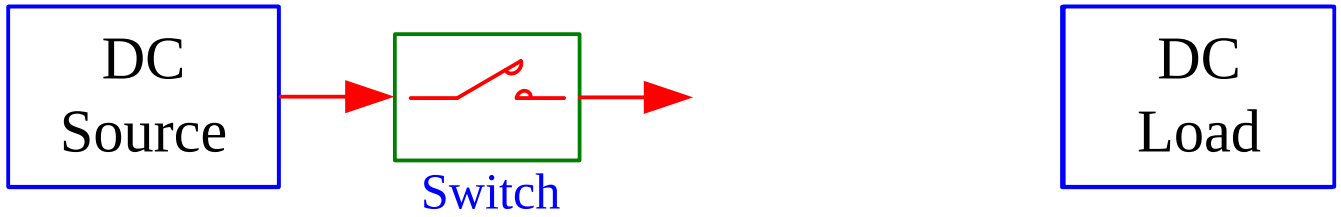
Improved step-down DC/DC power supplies: Switch-Mode Power Supplies (Buck converter)

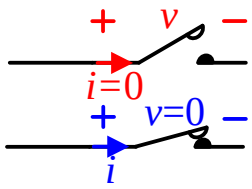
Efficiency Problem:



$$p_{in}=p_o+p_{loss} \Rightarrow \eta=\frac{p_o}{p_{in}}=\frac{p_o}{p_o+p_{loss}} \Rightarrow$$

High efficiency requires low power loss



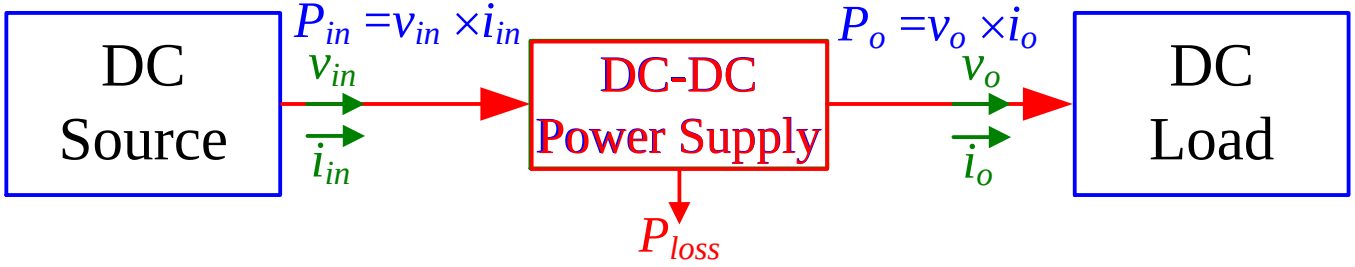


Off state: P_{loss}=i×v=0, No power loss

On state: P_{loss}=i×v=0, No power loss

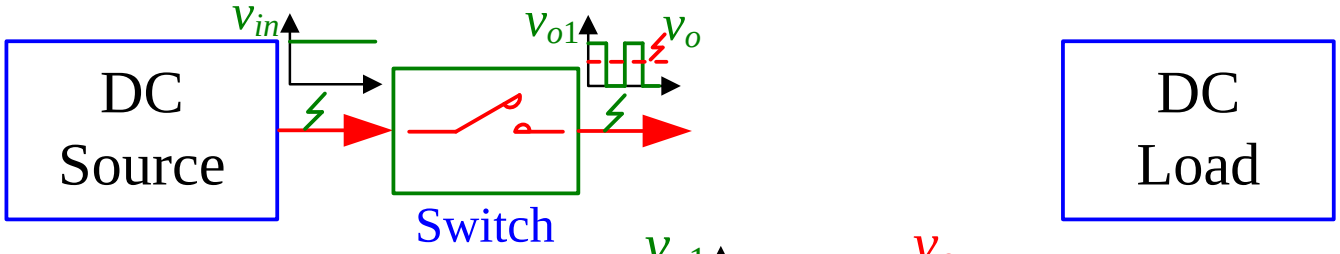
Improved step-down DC/DC power supplies: Switch-Mode Power Supplies (Buck converter)

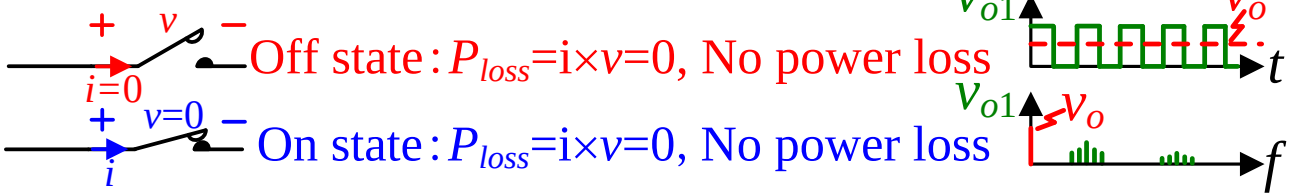
Efficiency Problem:



$$p_{in}=p_o+p_{loss} \Rightarrow \eta=\frac{p_o}{p_{in}}=\frac{p_o}{p_o+p_{loss}} \Rightarrow$$

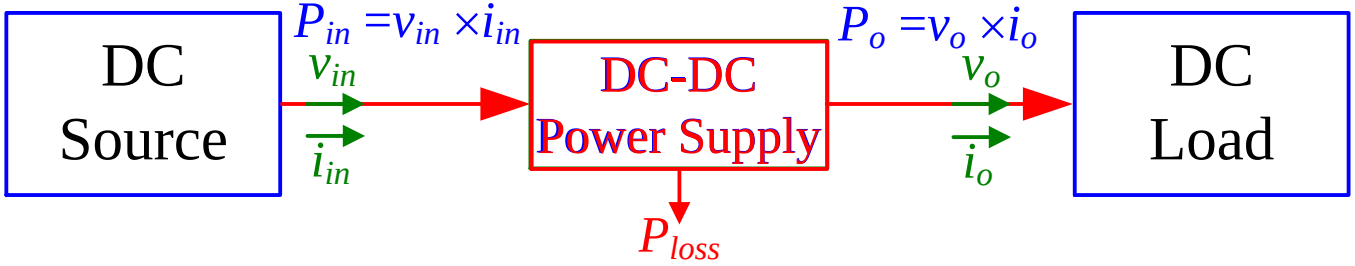
High efficiency requires low power loss





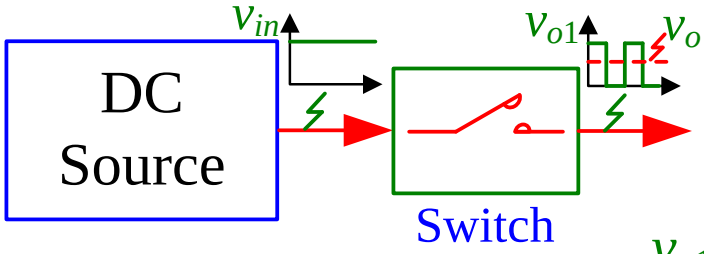
Improved step-down DC/DC power supplies: Switch-Mode Power Supplies (Buck converter)

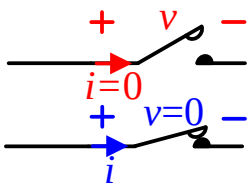
Efficiency Problem:



$$p_{in}=p_o+p_{loss} \Rightarrow \eta=\frac{p_o}{p_{in}}=\frac{p_o}{p_o+p_{loss}} \Rightarrow$$

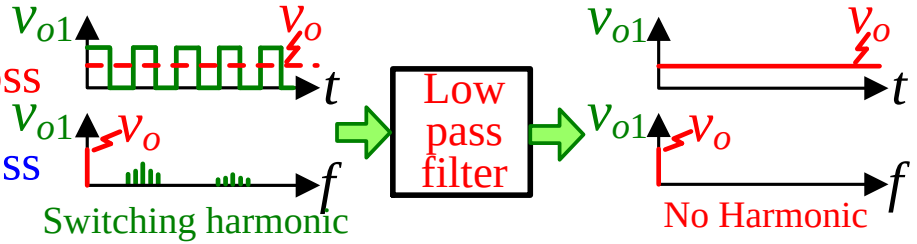
High efficiency requires low power loss





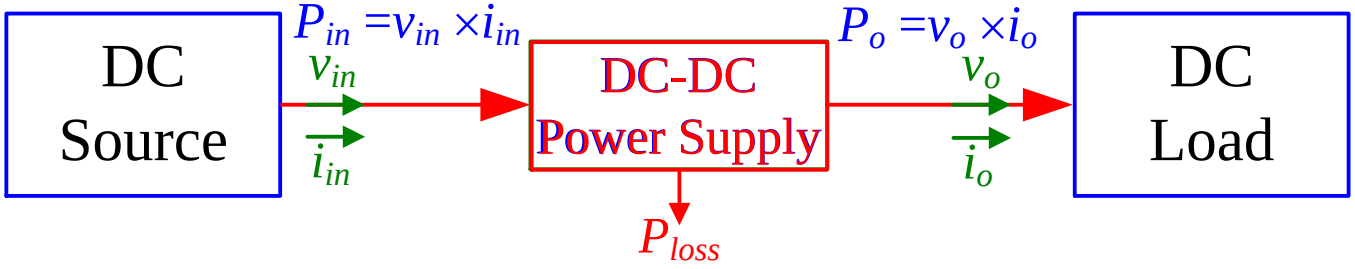
Off state: P_{loss}=i×v=0, No power loss

On state: P_{loss}=i×v=0, No power loss



Improved step-down DC/DC power supplies: Switch-Mode Power Supplies (Buck converter)

Efficiency Problem:



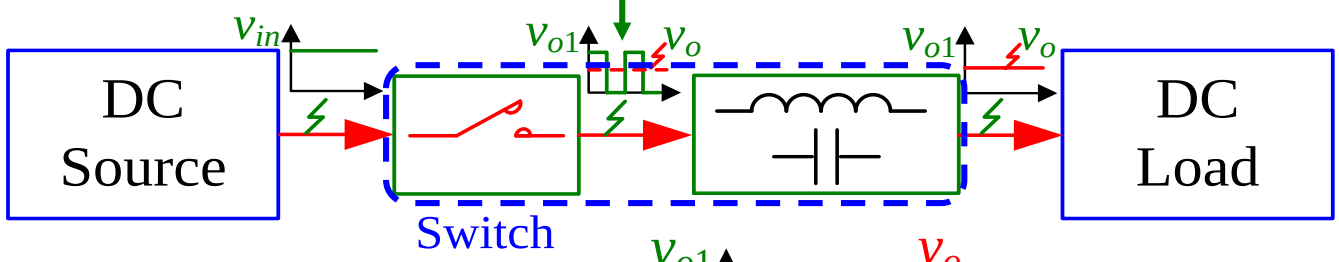
$$p_{in} = p_o + p_{loss} \Rightarrow \eta = \frac{p_o}{p_{in}} = \frac{p_o}{p_o + p_{loss}} \Rightarrow$$

High efficiency requires low power loss

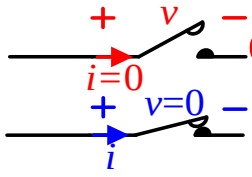
Efficiency

We can control the on/off time

Buck converter

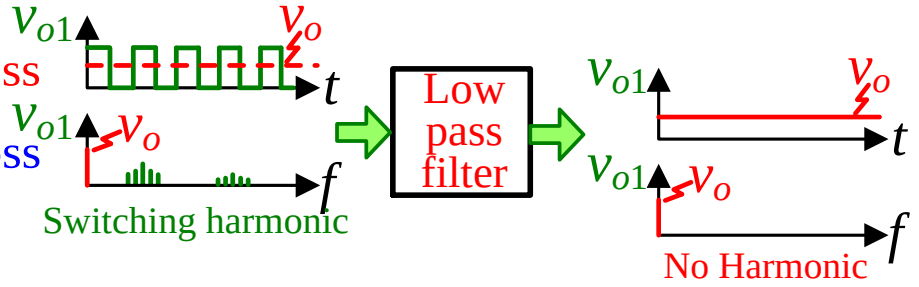


SMPS

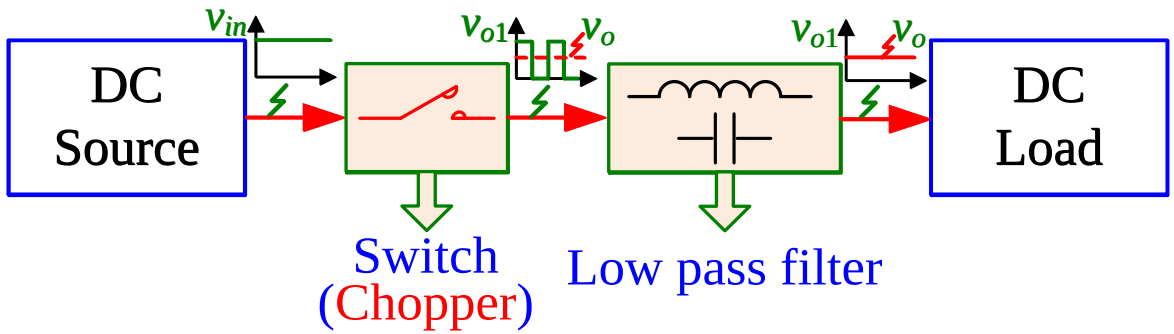


Off state: P_{loss}=i×v=0, No power loss

On state: P_{loss}=i×v=0, No power loss

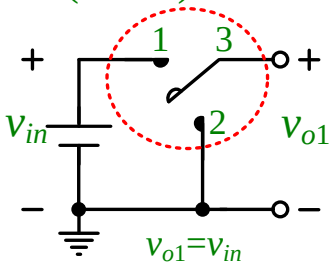


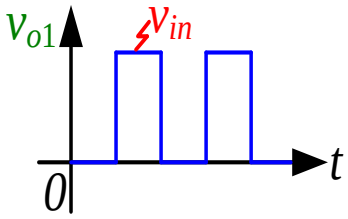
Derive the practical circuit of Buck Converter

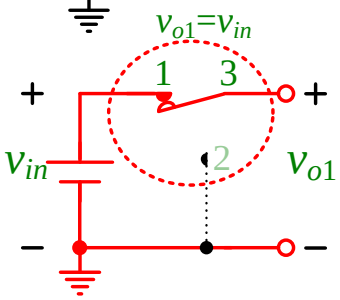


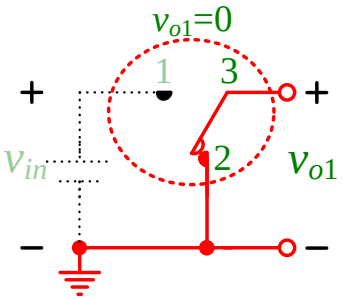
1. Chopper

Single-pole-double-throw (SPDT) Switch

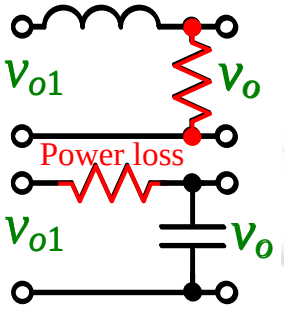


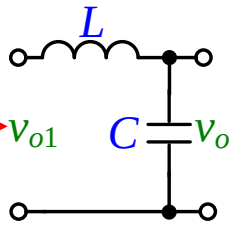


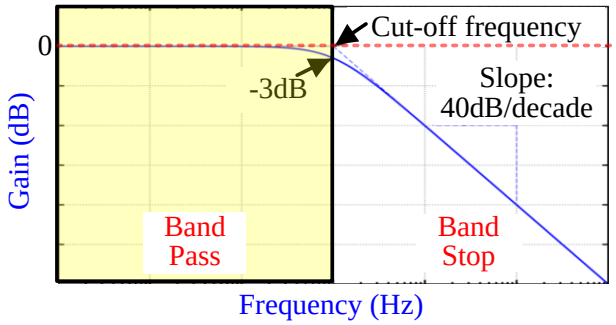




2. Low pass filter

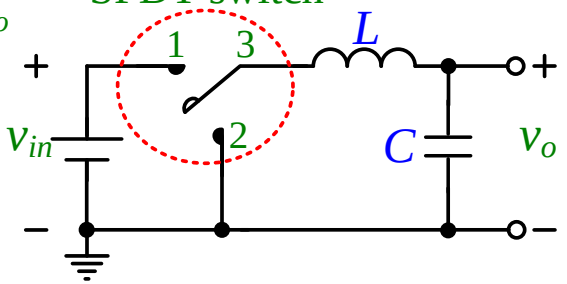






Buck Converter Version 1.0

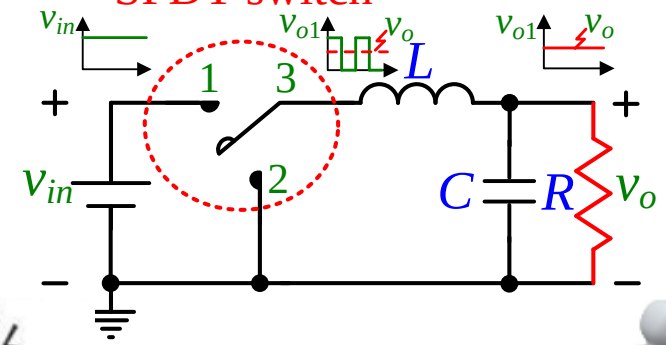
SPDT switch



Derive the practical circuit of Buck Converter

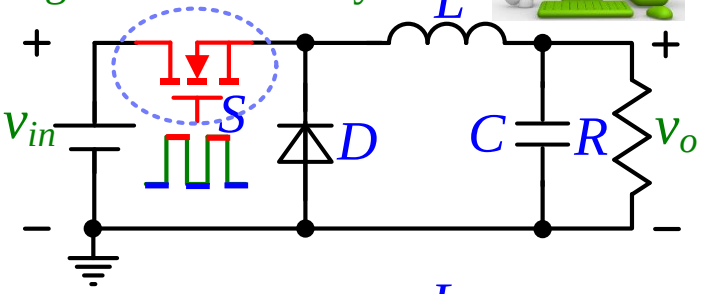
Buck Converter Version 1.0

SPDT switch

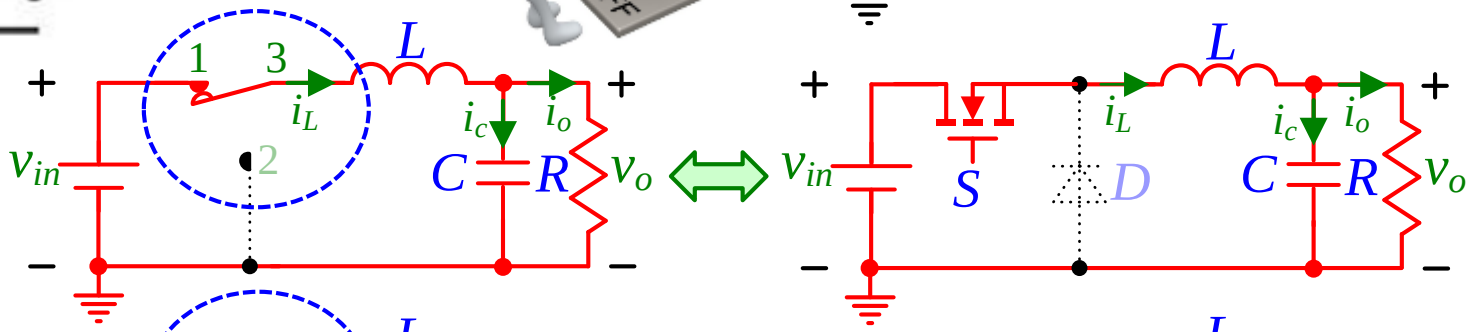


Final version of Buck converter

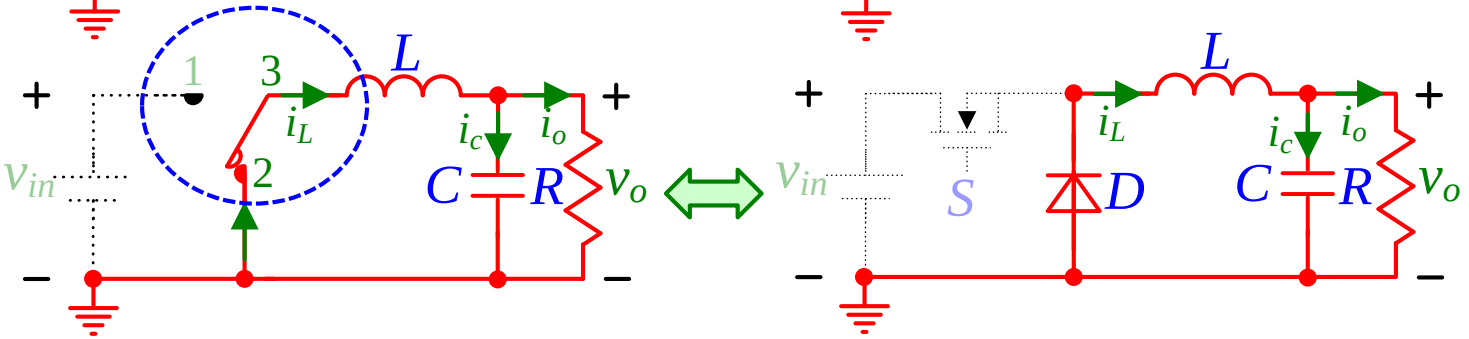
Turned on/off by drive signal automatically



Mode 1:

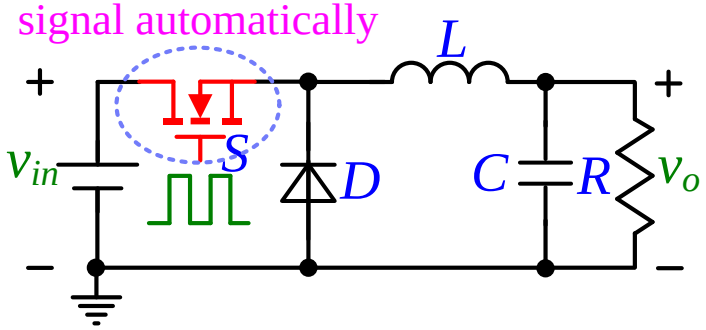


Mode 2:



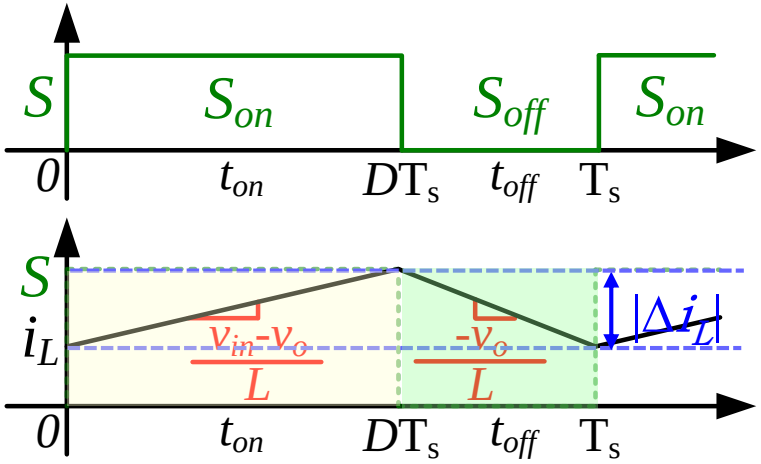
Relationship between v_o and v_{in}: Voltage Transfer Ratio of Buck Converter

Turned on/off by drive signal automatically

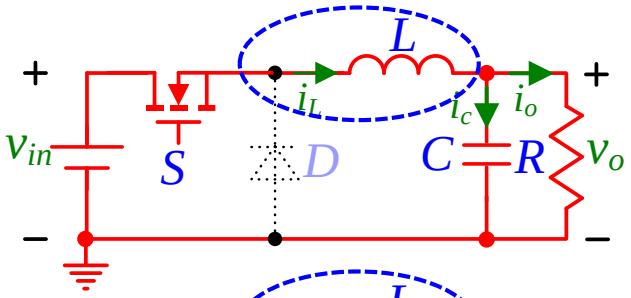


T_s:Switching periold t_{on}:Turn on time

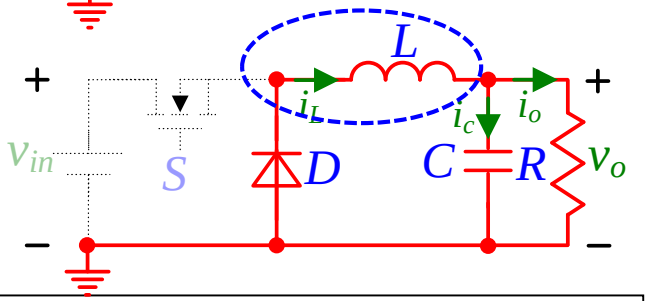
D=$\frac{t_{on}}{t_{on}+t_{off}}$:Duty cycle t_{off}:Turn off time



Turn on S: ($t_{on}=DT_s$)



Turn off S: ($t_{off}=T_s-DT_s$)



Derive voltage transfer ratio according to $|\Delta i_L|$:

$$\left|\Delta i_L \uparrow\right| = \left(\frac{v_{in}-v_o}{L}\right)\cdot DT_s \qquad \left|\Delta i_L \downarrow\right| = \left(\frac{v_o}{L}\right)\cdot(1-D)T_s$$

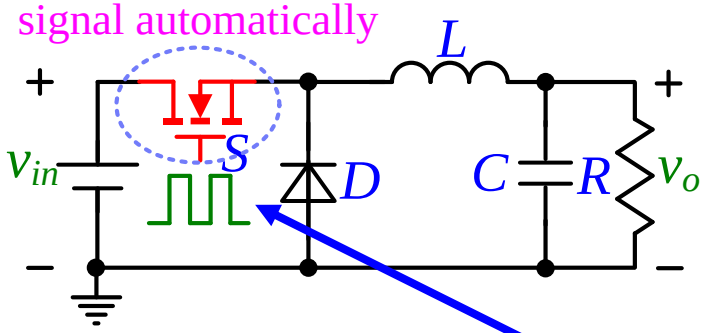
$$\left|\Delta i_L\right| = \left|\Delta i_L \uparrow\right| = \left|\Delta i_L \downarrow\right|$$

$$v_o = v_{in}\cdot D$$

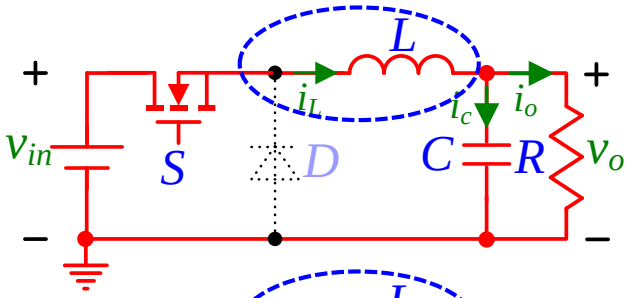
Derivation Preconditions:
- Buck converter is in steady state
- i_L keeps continuous

Operation principle of Buck Converter

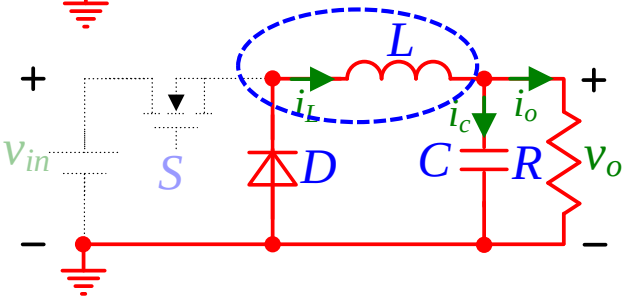
Turned on/off by drive signal automatically



Turn on S:
(t_{on}=DT_s)

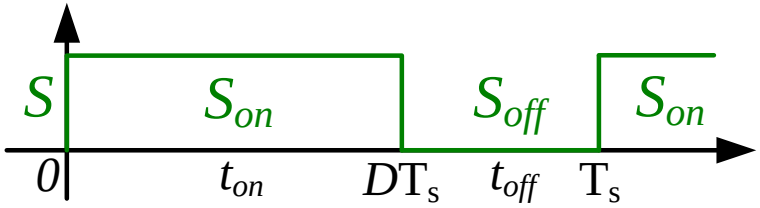


Turn off S:
(t_{off}=T_s-DT_s)



T_s:Switching periold t_{on}:Turn on time

D=$\frac{t_{on}}{t_{on}+t_{off}}$:Duty cycle t_{off}:Turn off time



We can control the on/off time

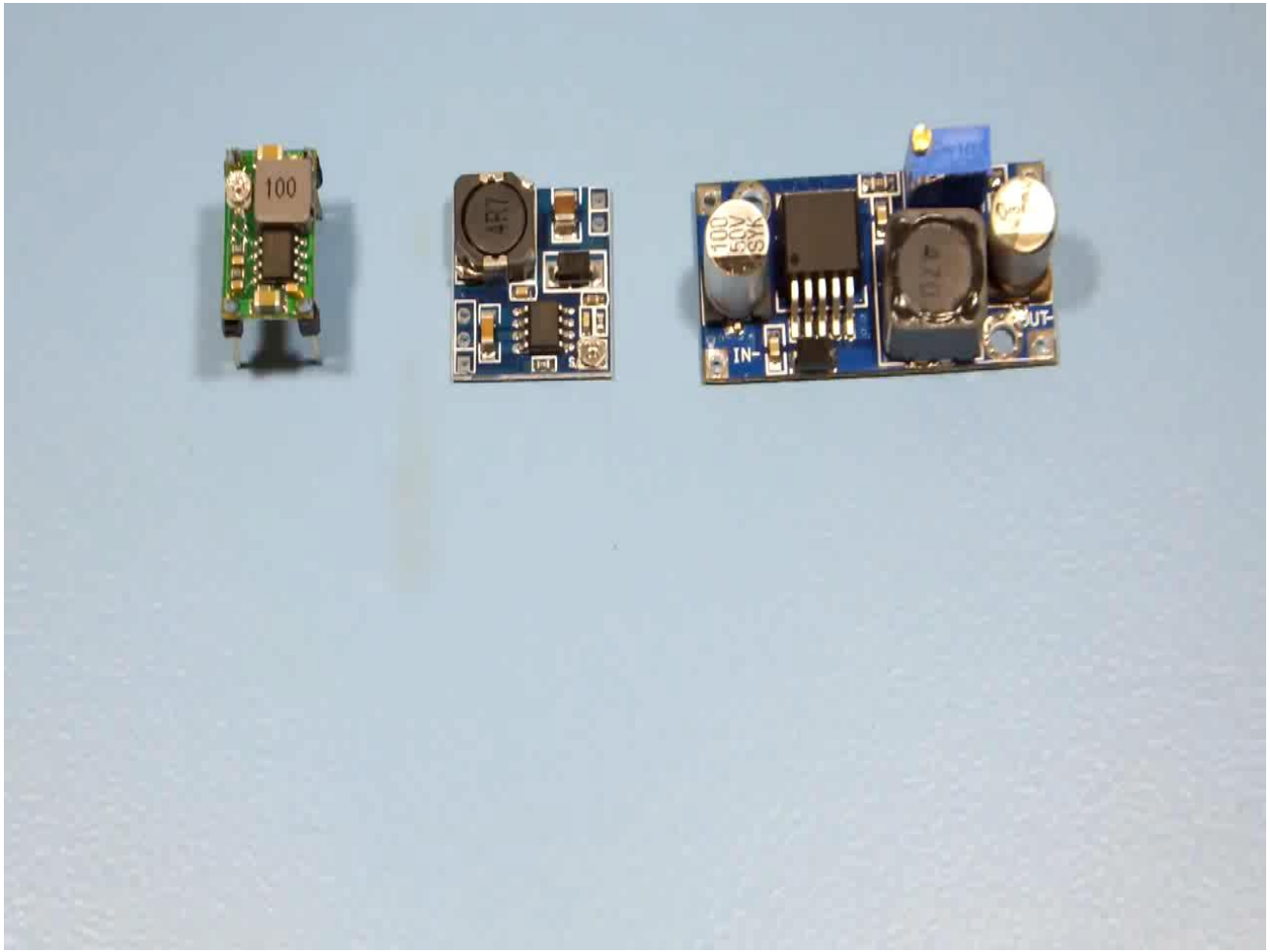
$$v_o = v_{in} \cdot D$$

If input voltage is 12 V,

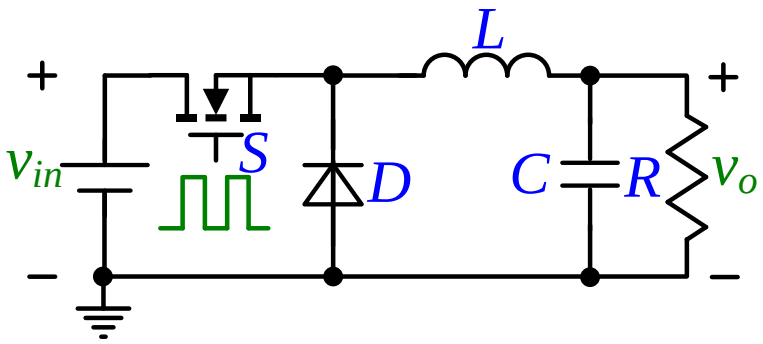
If output voltage is required to 5 V,

$$D = \frac{5}{12}$$

Comparison between Buck converter and linear voltage regulator



Benefits from this lecture



amazon

1W = 0.1 $

uxcell

uxcell New BIG-Size Voltage Converter Regulator DC/DC DC 48V Step-Down to DC 12V 30A 360W Buck Transformer Waterproof

24 customer reviews | 13 answered questions

Price: $36.76 & **FREE Shipping**. Details

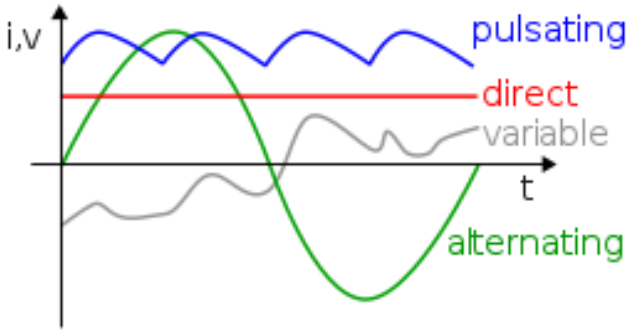
In Stock.

Sold by uxcell and Fulfilled by Amazon. Gift-wrap available.

Size: **48V to 12V 30A 360W**

OPERATION PRINCIPLE OF THE POWER CONVERTERS

[31/10/2019]



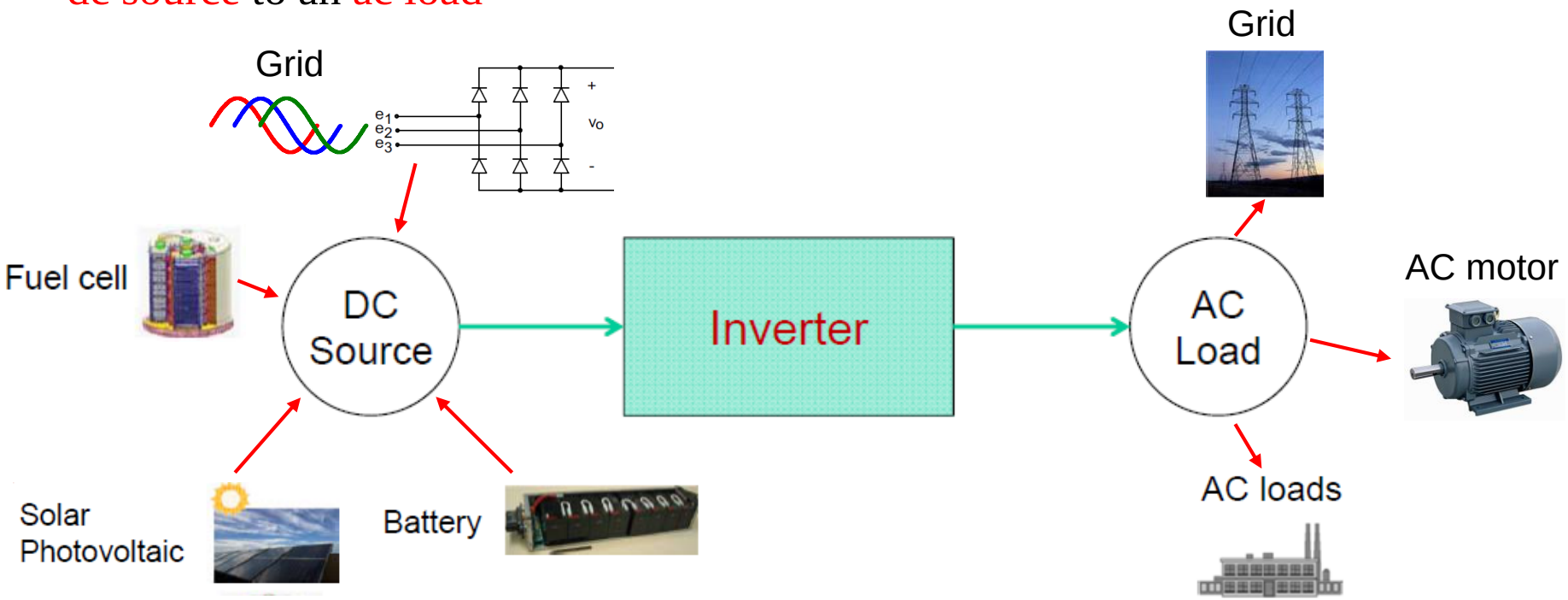
- Operation principle of the DC/DC converter
- Operation principle of the DC/AC inverter

How does inverter work?

Inverter basics: Definition of the inverter

- A device used to convert direct current into alternating current – Merriam-Webster Dictionary.

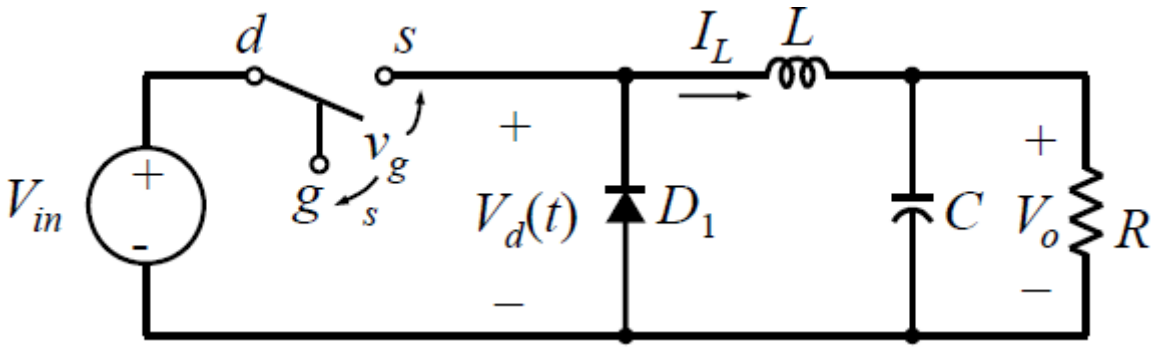
- More precisely: inverter is to convert or transfer power from a dc source to an ac load

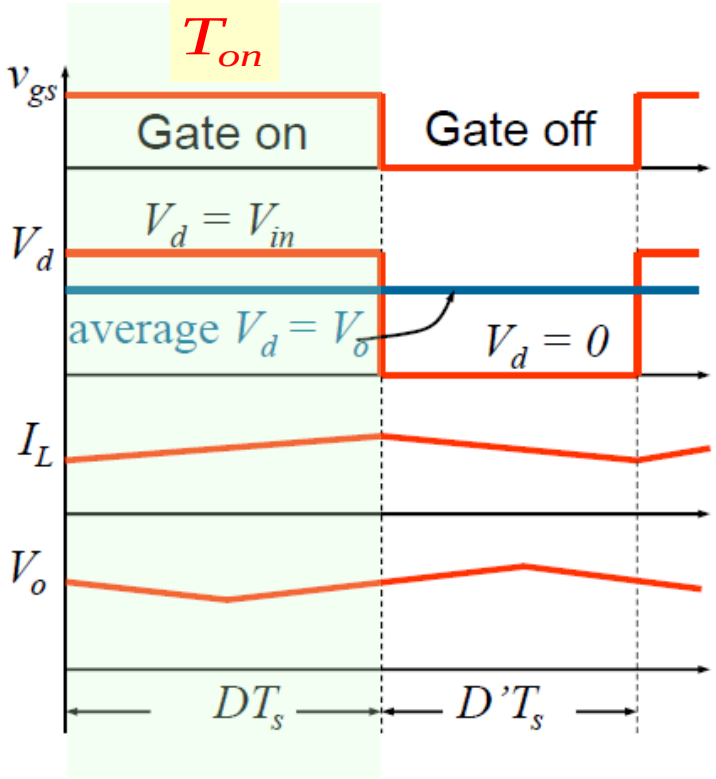


Preliminary of the operation principle of the inverter

BEFORE STUDY THE OPERATION OF THE INVERTER, LET US REVISIT THE DC TO DC CONVERTER.

DC-DC buck converter circuit





Average output voltage:

$$\bar{V}_o = D \cdot V_{in}$$

Where $D = T_{on}/T_s$ is the duty ratio.

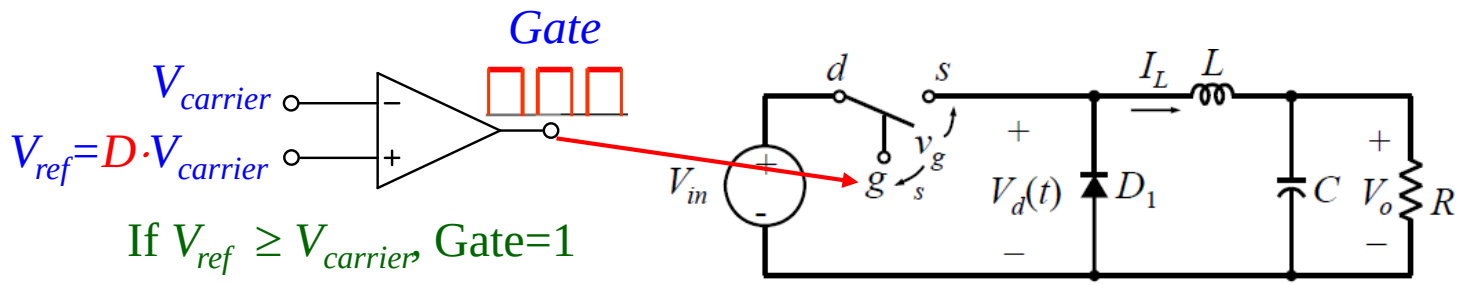
Because $D < 1$, V_o is always less than V_{in}

→ buck converting

T_s: switching period (unit: s) = $1/f_s$

f_s: switching frequency (unit: Hz)

How the gate signal generated for the switcher?

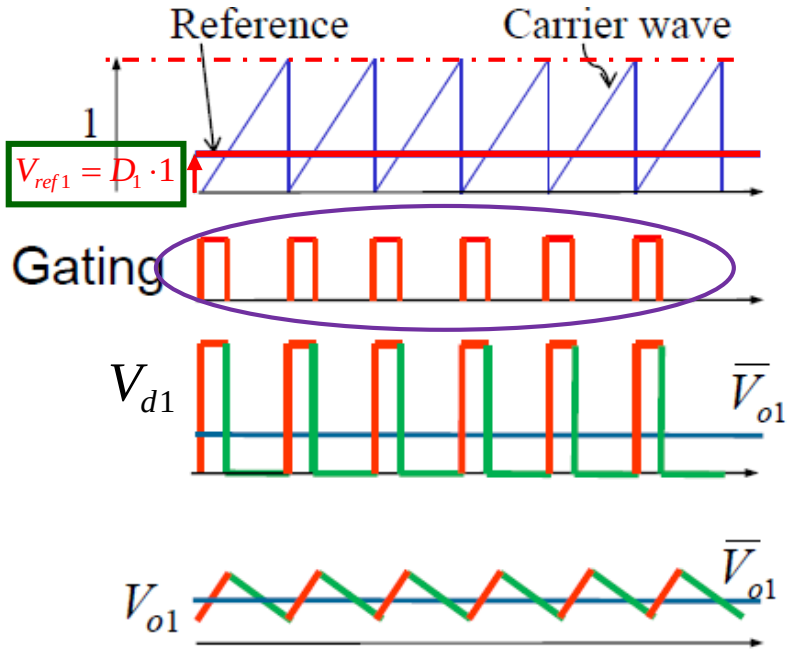


$$\bar{V}_o = D \cdot V_{in}$$

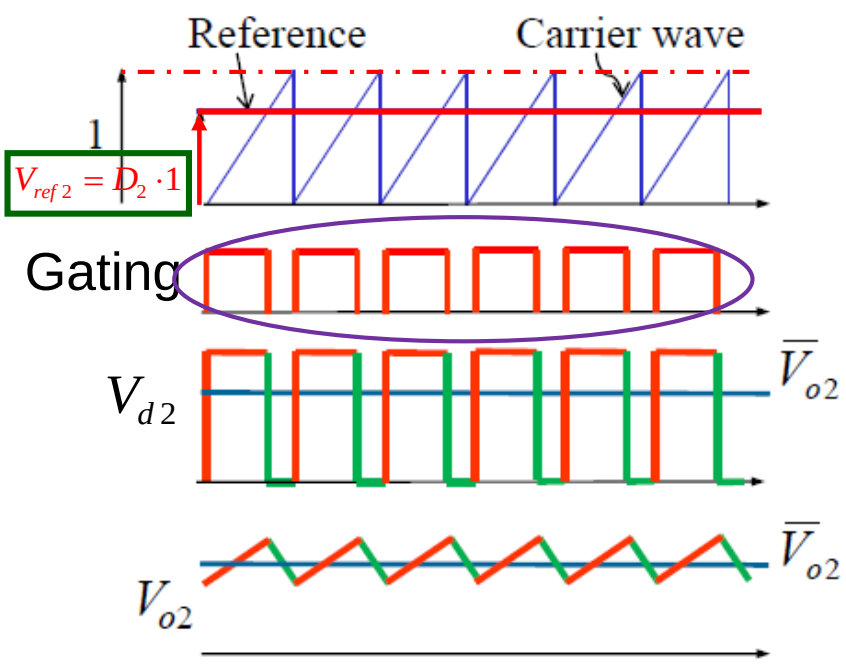
If $V_{ref} \geq V_{carrier}$, Gate=1

If $V_{ref} < V_{carrier}$, Gate=0

Get a small output voltage



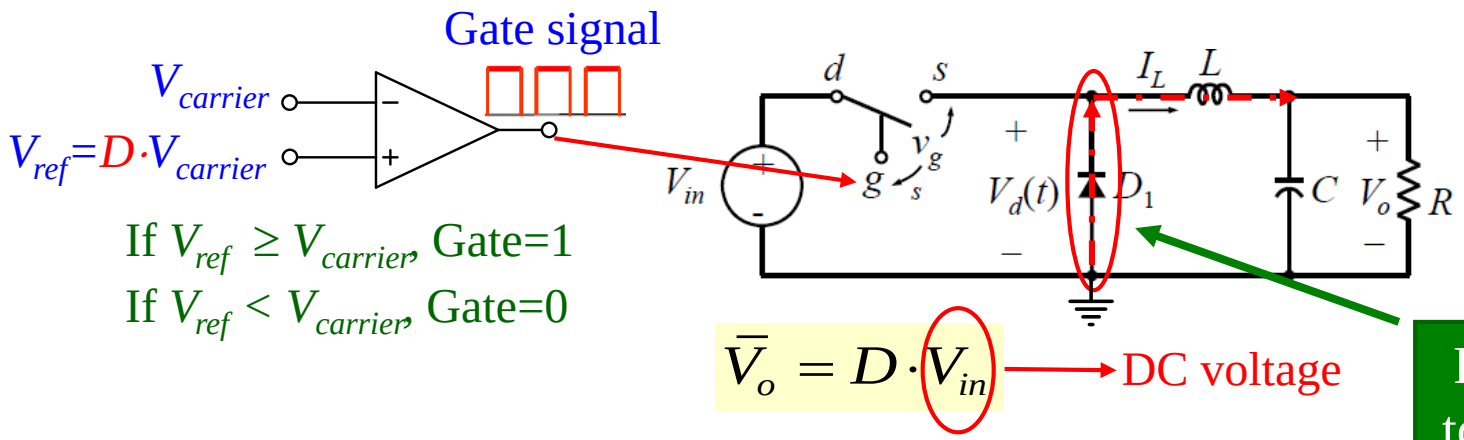
Get a large output voltage



Average output voltage: $\bar{V}_{o1} = D_1 \cdot V_{in}$

$\bar{V}_{o2} = D_2 \cdot V_{in}$

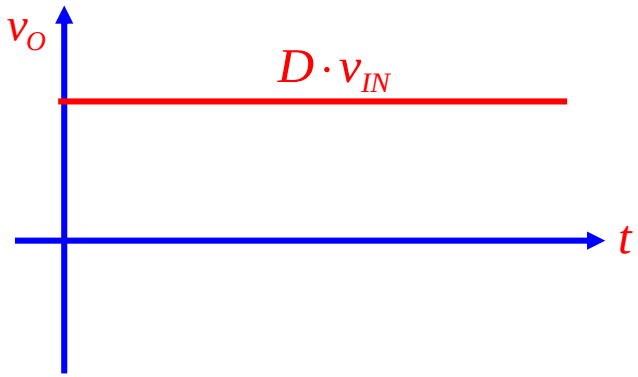
Question: Can we change the duty cycle to a sinusoidal AC waveforms ?



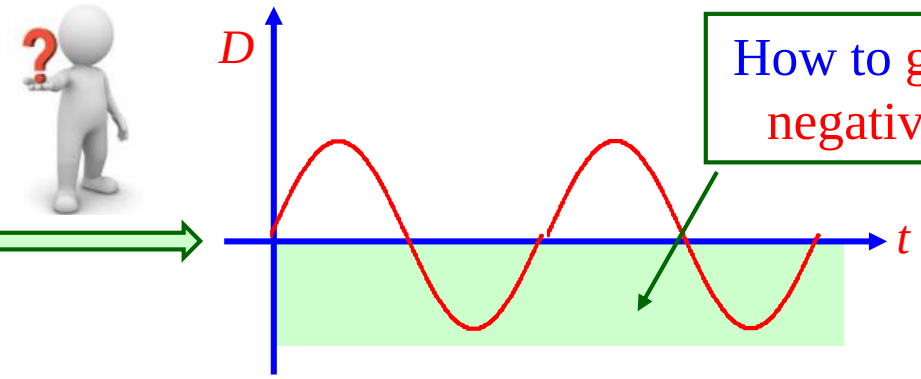
$$\bar{V}_o = D \cdot V_{in}$$ → DC voltage

Replace to switch

DC to DC converter



DC to AC converter?



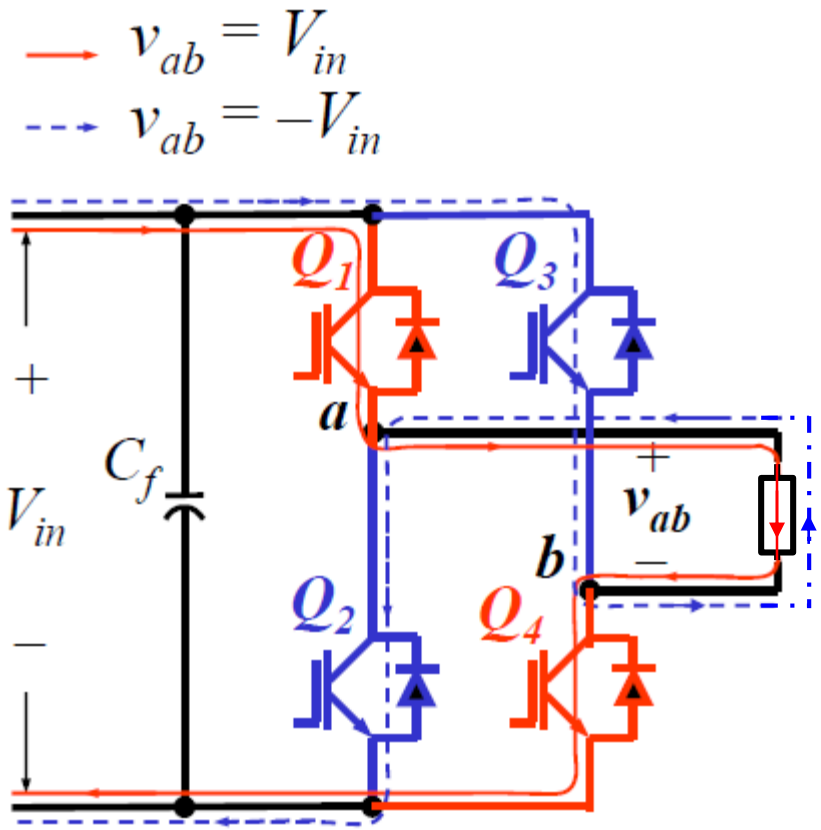
How to generate this negative voltage?

V_o cannot be smaller than 0 V due to the diode block

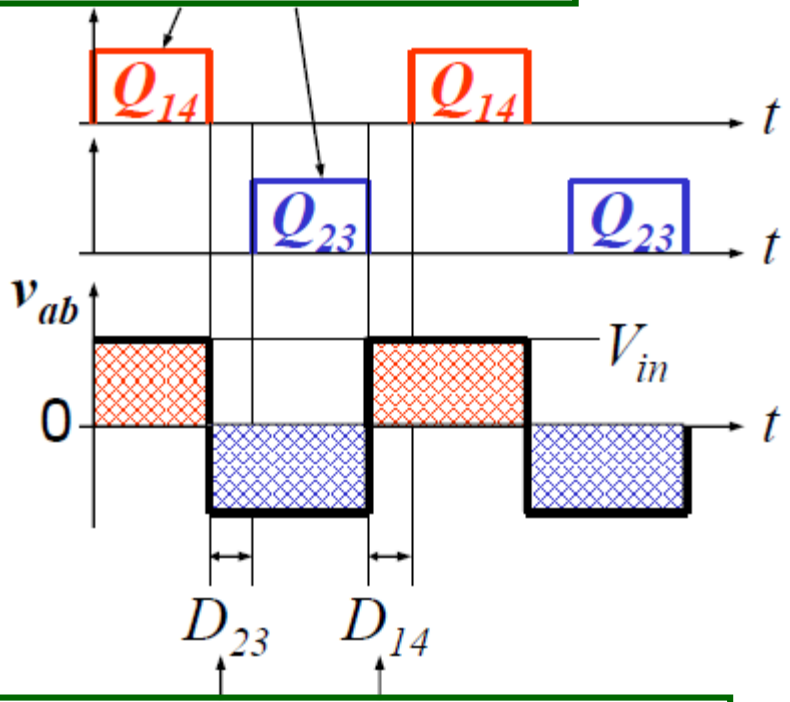
Operation principle of the inverter

LET US COME BACK TO THE INVERTER

Full bridge circuit can generate both positive and negative voltages

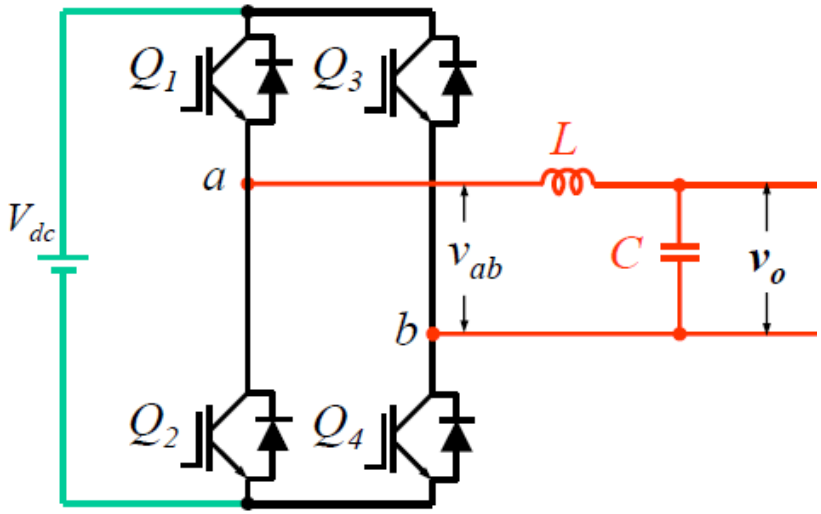


Switches conduct alternately



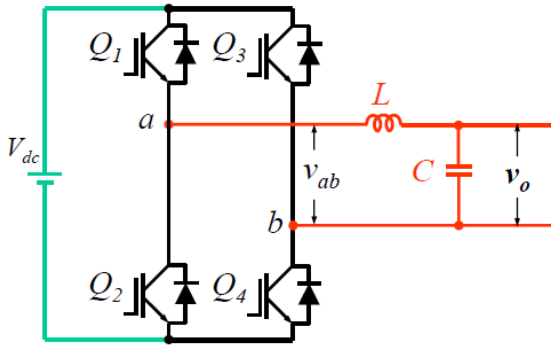
Dead-time, current circulating through anti-paralleled diodes

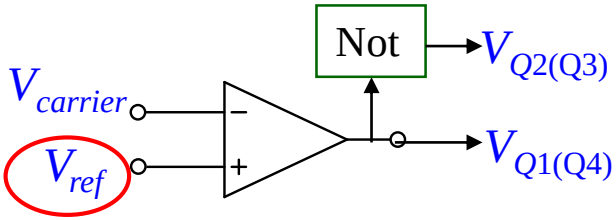
Single phase DC/AC inverter

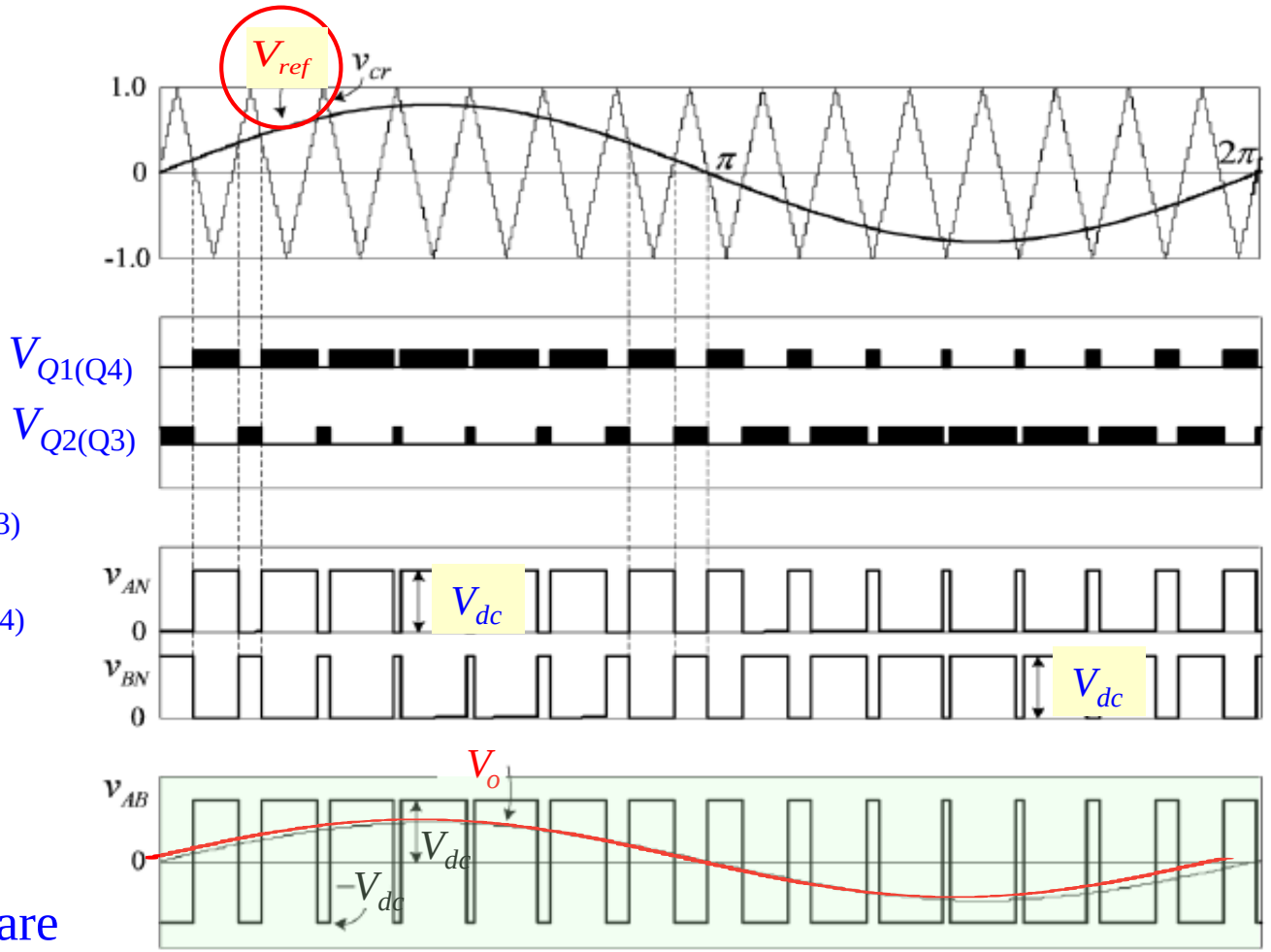


- Q_1-Q_2 and Q_3-Q_4 pairs are switched complementarily.
- The total average output voltage v_o = average(v_{ab}).
- Output across a and b looks like a square wave.
- LC circuit to smooth out the waveform to be sinusoidal.

Bipolar modulation of the single phase DC/AC inverter



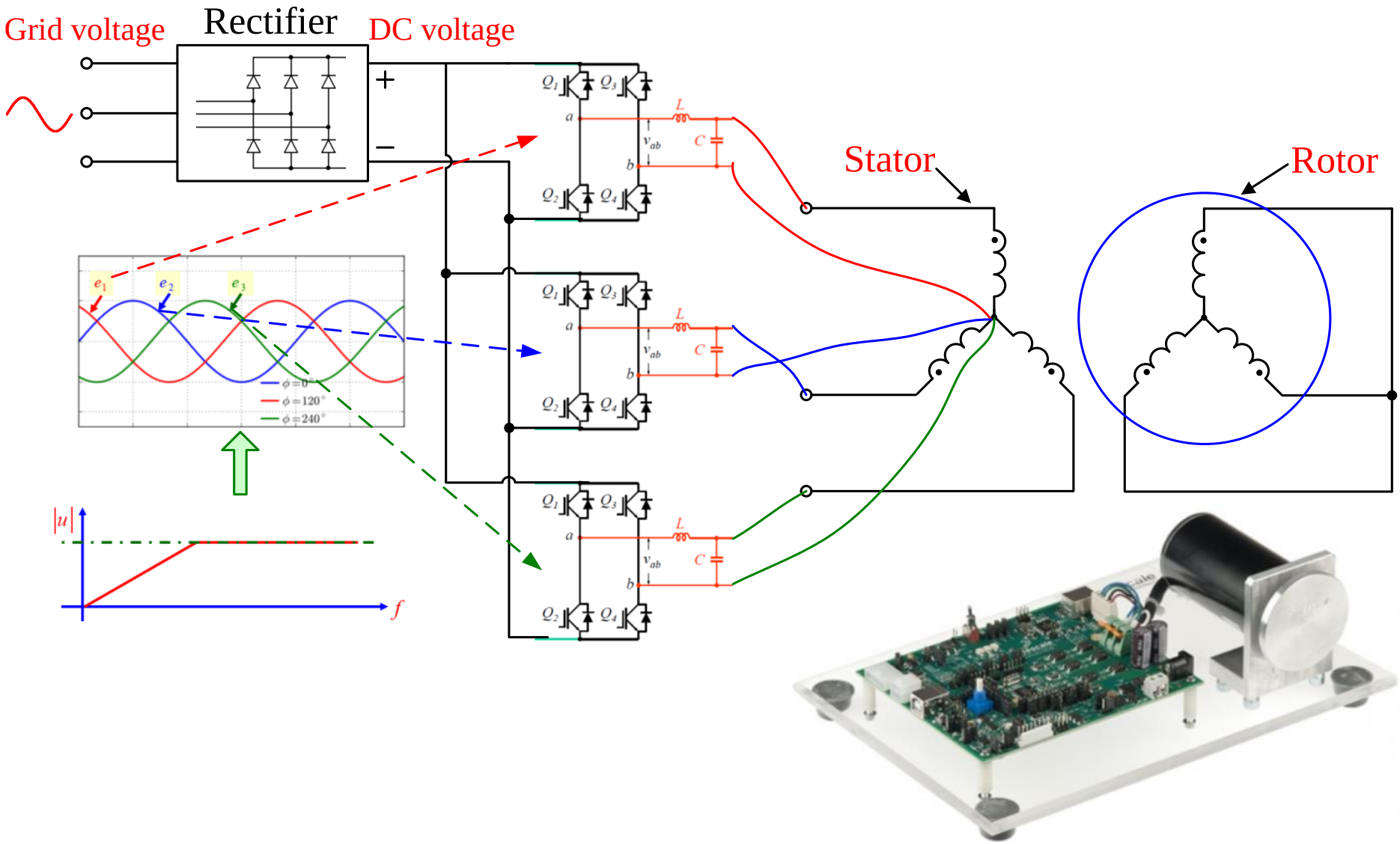




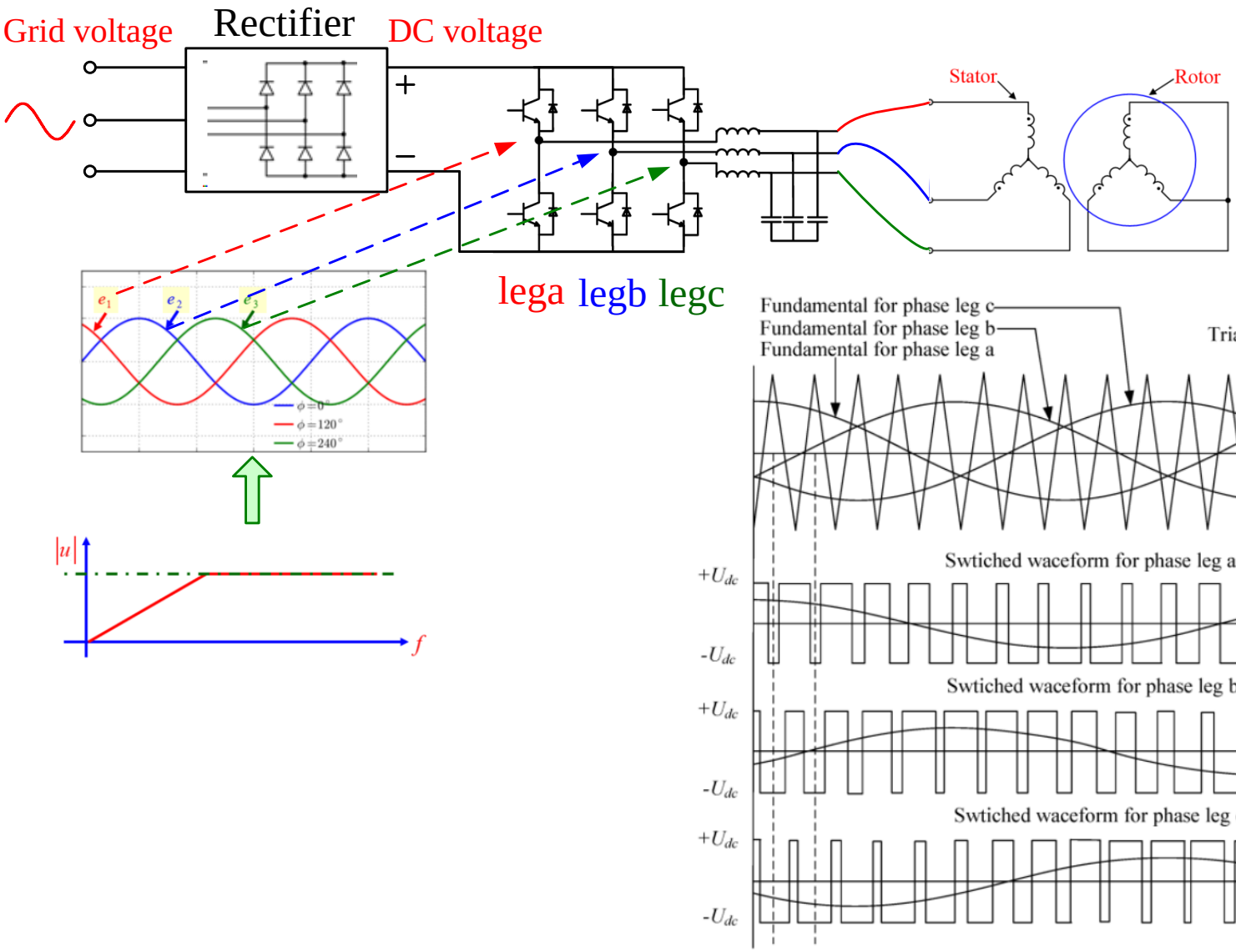
- V_{Q1}-V_{Q4} are the gating signal for Q_1-Q_4.
- Q_1-Q_2 and Q_3-Q_4 pairs are switched complementarily.

Review the operation principle of the single phase DC/AC inverter

Single phase inverter to three phase inverter



Single phase inverter to three phase inverter



Review of today's topic

- Understand the operation of DC/DC converters
- Understand the operation of power inverters

Thank you!

Jackzhang@ntu.edu.sg