

# **Introduction to Power Electronics**



Dr. Abdullah Noman

# History of Power Electronics

- In 1930, the ideas of inversion which converts DC to a variable voltage or variable frequency AC had been established.
- The first variable frequency ac drive of a synchronous machine was installed in the Logan Power Station in 1934.
- The transistor was invented in December, 1947.
- The commercial use of transistors increased in the 1950's, beginning with telephone switching equipment and military computers in 1952, hearing aids in 1953, and portable radios in 1954.



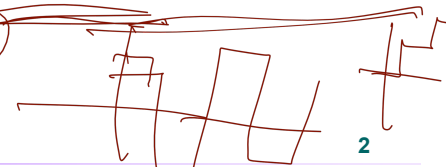
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$$f = \frac{1}{T}$$

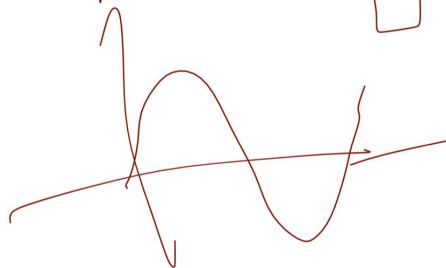
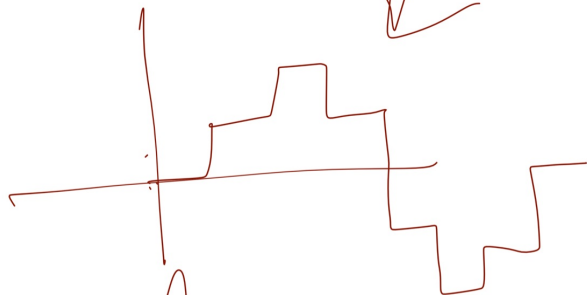
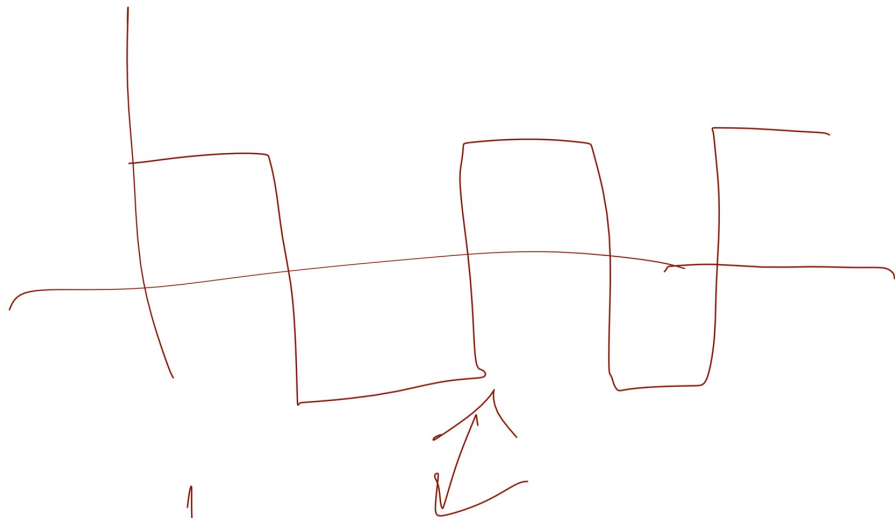
$$T = \frac{1}{f}$$

# History of Power Electronics

- In 1957, the thyristor [silicon-controlled rectifier (SCR)] was introduced.
- In 1964, principles of Inverter Circuits was published.
- The advancement in the power electronics leads to the development of Power MOSFETs is introduced in the mid of 1970's.
- The neutral-point clamped (NPC) inverter was invented in 1979.
- Three-level inverters have attracted the attention of researchers since their introduction by Nabae, in 1981.
- And So on..







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# What is power electronics?

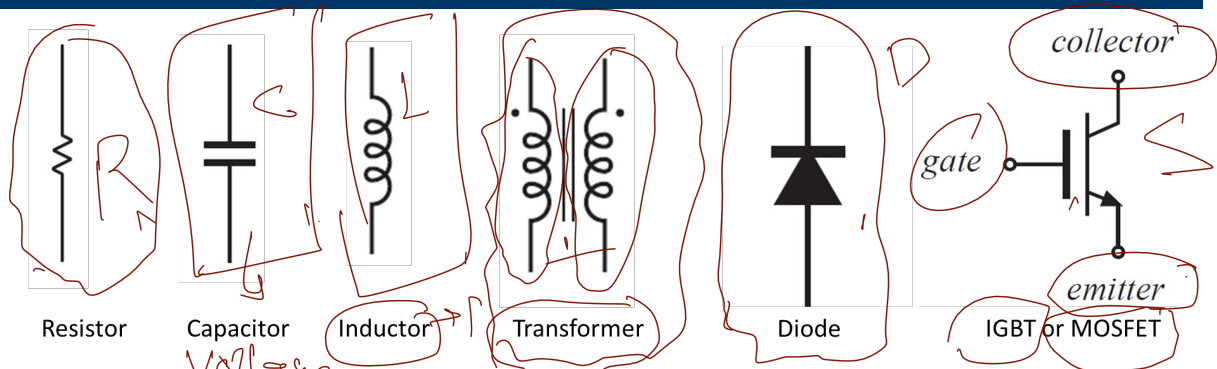
AC  
DC

- Starting in the late 1880s, Thomas Edison and Nikola Tesla were engaged in a battle now known as **the War of the Currents**.
- Edison developed the first commercial power plant (**DC**) (**Pearl Street Station**)
  - ✓ DC voltages can not be stepped up or down easily.
  - ✓ DC generator must be installed close to the load.
- Tesla believed that **AC** was the solution to this problem.
  - ✓ AC power is easier to generate.
  - ✓ AC voltages can be stepped up or down easily using transformers.
  - ✓ Power plants can be built far from cities ( the use of long distance transmission) .

# What is power electronics?

- With the recent development in power electronics, we can convert DC to higher and lower voltages.
- In broad terms, the task of power electronics is to process and control the flow of electric energy by supplying voltages and currents in the form that is optimally suited for user loads.
- Power electronics combine power, electronics and control.
- Power electronics circuits convert electric power from one form to another using electronic devices.
- Conversion is done using electronic switches, capacitors, magnetics, and control systems.

# What is power electronics?

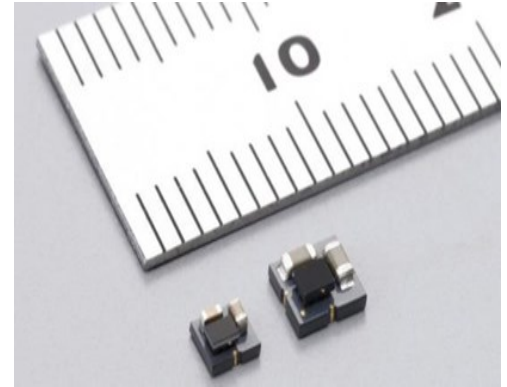


- Power electronics circuits function by using semiconductor devices as switches, thereby controlling or modifying a voltage or current.

- Applications of power electronics range from high-power conversion equipment such as dc power transmission to everyday appliances, such as cordless screwdrivers, power supplies for computers, cell phone chargers, and Electric vehicles, PV systems, etc.

# Typical applications of power electronics

- Fluorescent lamp ballast
- Motor driver
- Battery chargers.
- Electric vehicles.
- Switching power supplies.
- Electric power transmission.
- Energy storage (Flywheel, super capacitor)
- Uninterruptible power supplies (UPS).
- Active Power Filters.
- Power conditioning for alternative power sources: Solar cells, Fuel cells, Wind turbines)



AC  
AC

# Typical applications of power electronics



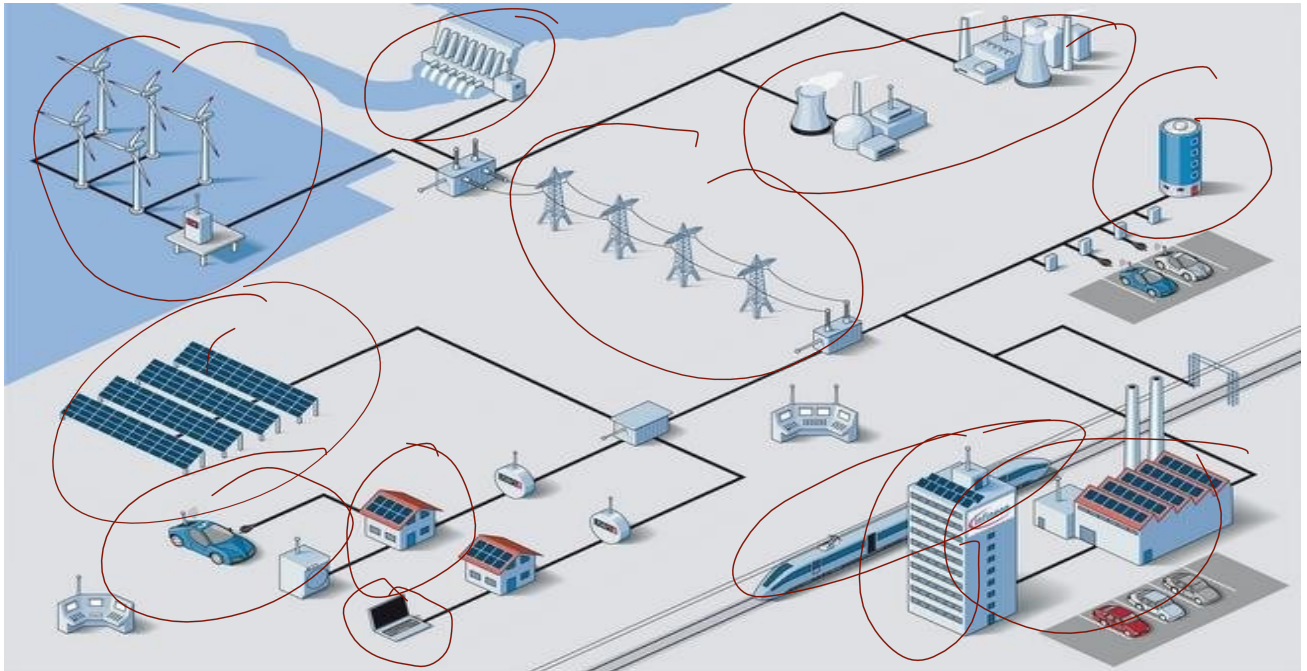
# Typical applications of power electronics





# Typical applications of power electronics

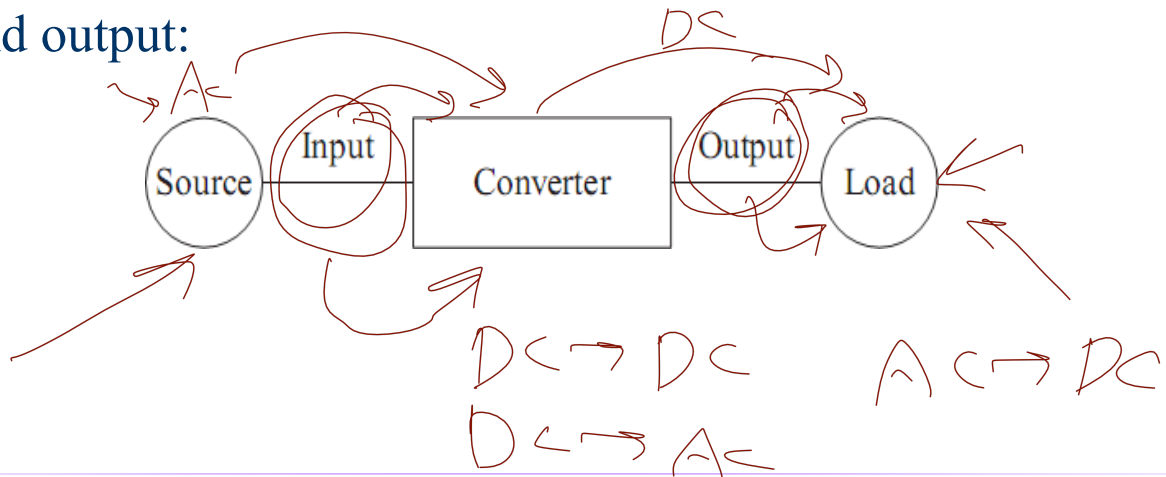
## Smart grid





# CONVERTER CLASSIFICATION

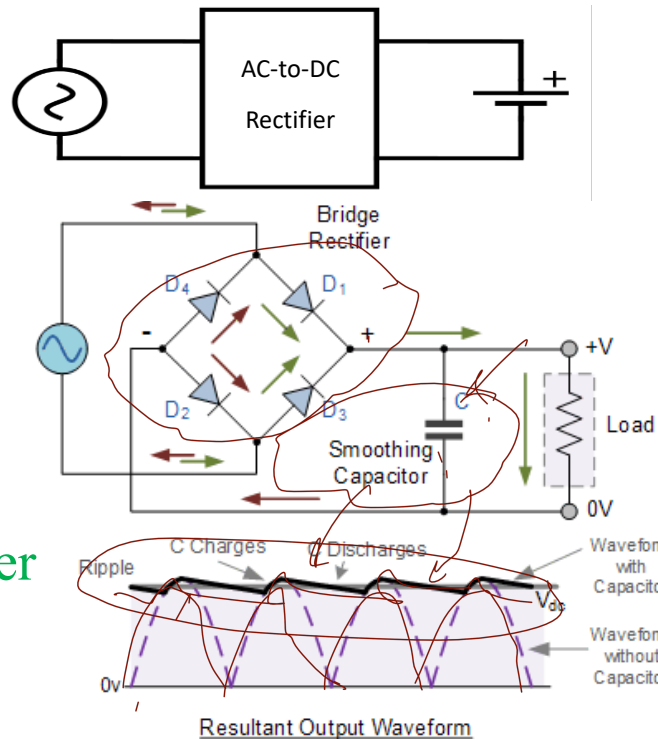
- Power electronics circuits convert one type or level of a voltage or current waveform to another and are hence called *converters*.
- Converters serve as an interface between the source and load.
- Converters are classified by the relationship between input and output:



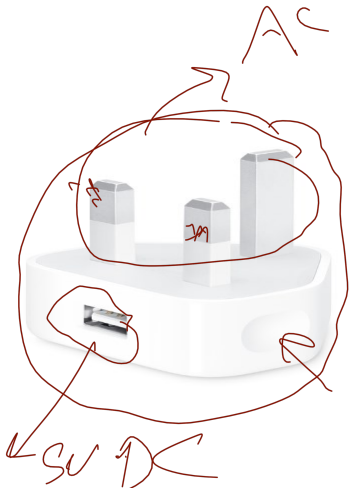
# CONVERTER CLASSIFICATION (AC/DC)

**AC input/DC output (Rectifier)** ←

Average power is transferred from an ac source to a dc load



Full wave rectifier



AC  $\rightarrow$  DC  $\rightarrow$   $\left\{ \begin{array}{l} \text{full wave} \\ \text{half wave} \end{array} \right.$

DC  $\rightarrow$  DC  $\rightarrow$   $\left\{ \begin{array}{l} \text{Buck} \\ \text{Boost} \\ \text{Buck-Boost} \end{array} \right.$

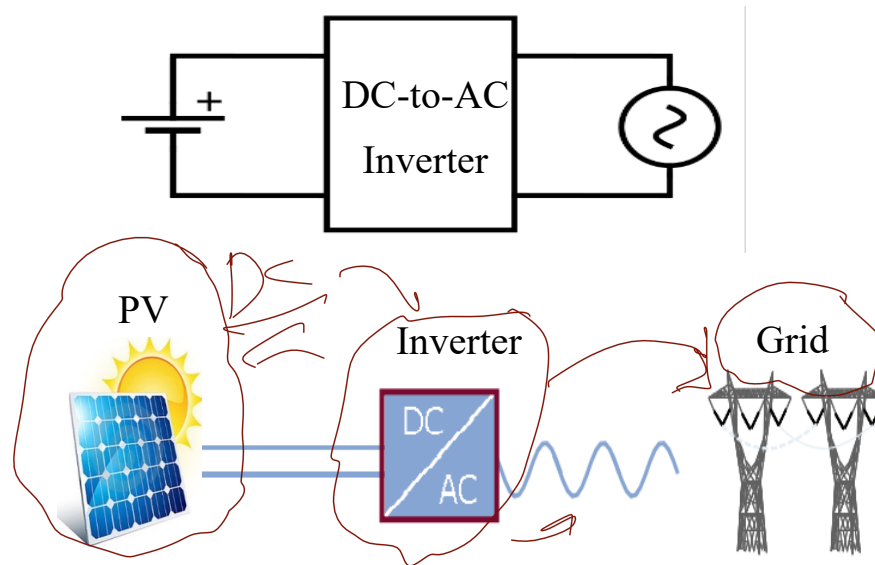
DC  $\rightarrow$  AC  $\rightarrow$  inverter

AC  $\rightarrow$  AC  $\rightarrow$  wind Energy

# CONVERTER CLASSIFICATION (DC/AC)

## DC input/AC output (Inverter)

Average power is transferred from a DC source to an AC load/Source.

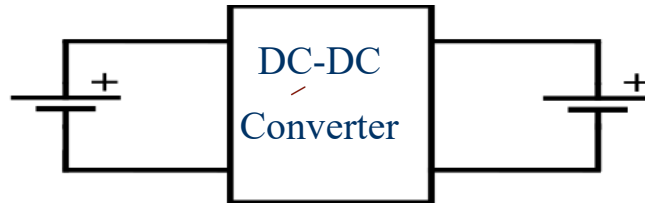


Example: 220VAC/60Hz inverter with a DC input (12 VDC or 24 VDC)

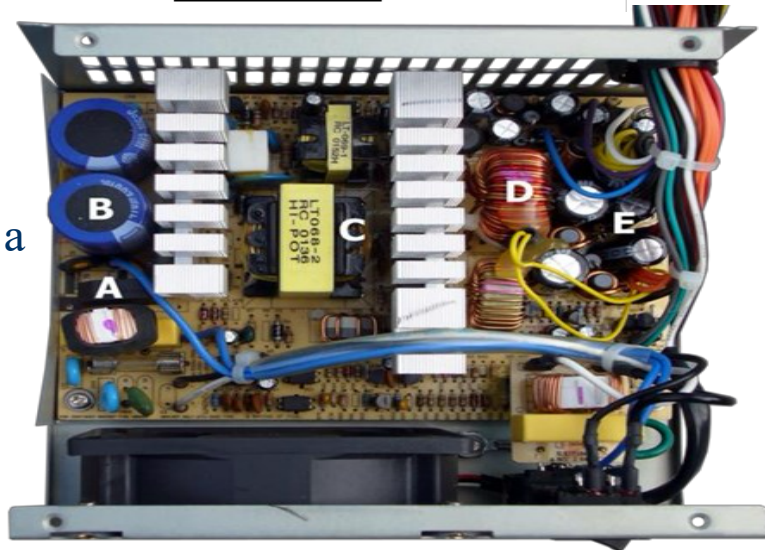
# CONVERTER CLASSIFICATION (DC/DC)

## DC input/DC output (DC-DC Converter)

Average power is transferred from DC source to a DC load/Source.



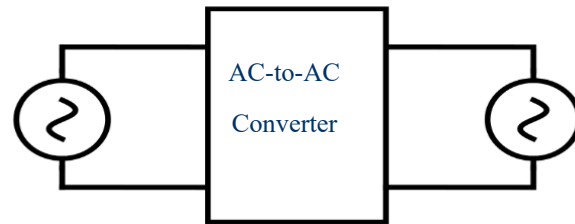
Example: 12 VDC to a  
5 VDC



# CONVERTER CLASSIFICATION (AC/AC)

## AC input/AC output (AC-AC Converter)

The ac-ac converter may be used to change the level and/or frequency of an ac signal.



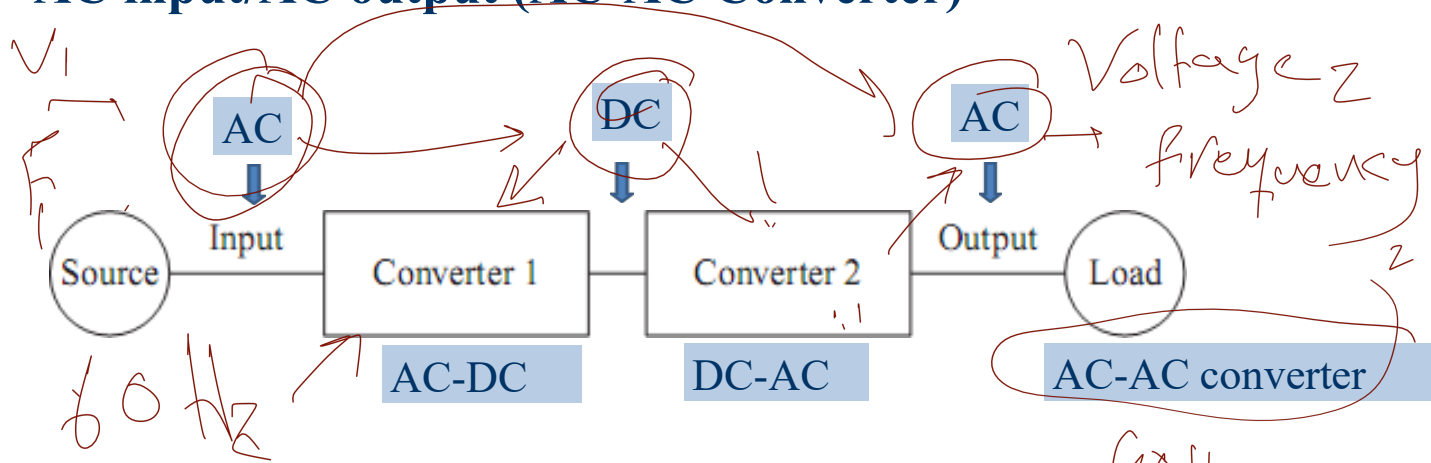
Examples:

- Light-dimmer circuit
- Speed control of an induction motor.
- All GCC countries use 50 Hz power grid except KSA uses 60 Hz.
- It is impossible to directly connect KSA power grid to other GCC countries power grid. Solution ?

$$f = 60 \text{ Hz}$$

# CONVERTER CLASSIFICATION (AC/AC)

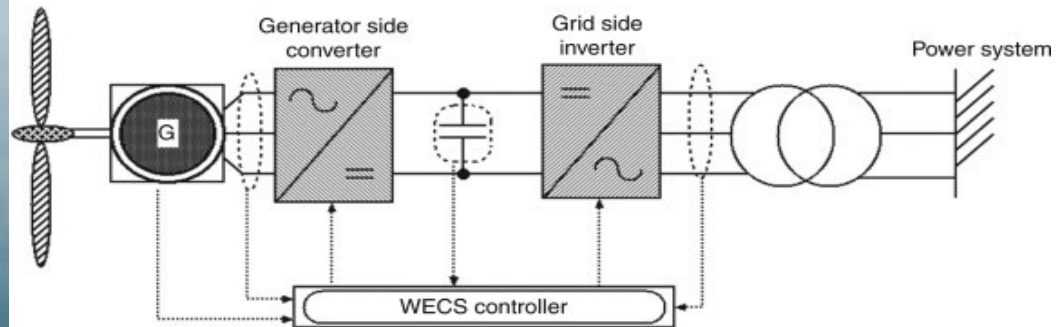
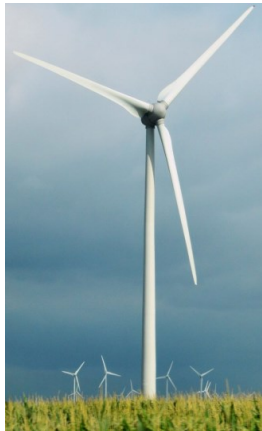
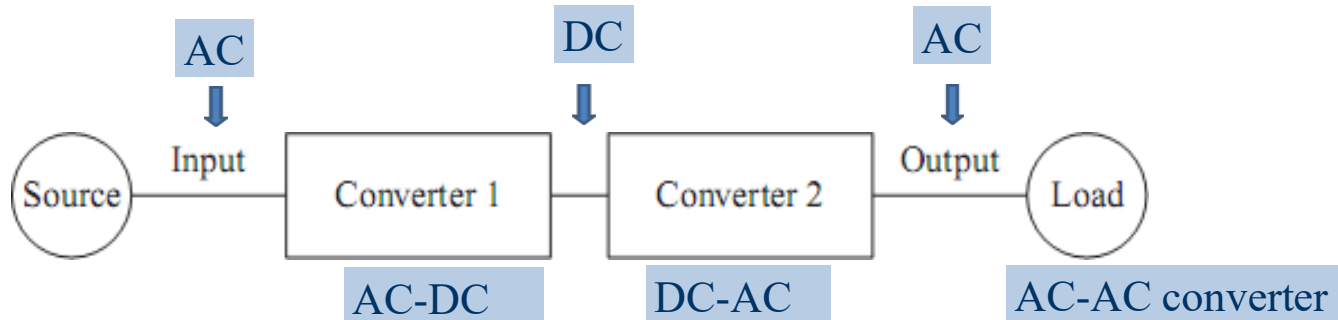
## AC input/AC output (AC-AC Converter)



an ac-dc-ac conversion can be used to modify an ac source by first converting it to direct current and then converting the dc signal to an ac signal that has an amplitude and frequency different from those of the original ac source

# CONVERTER CLASSIFICATION (AC/AC)

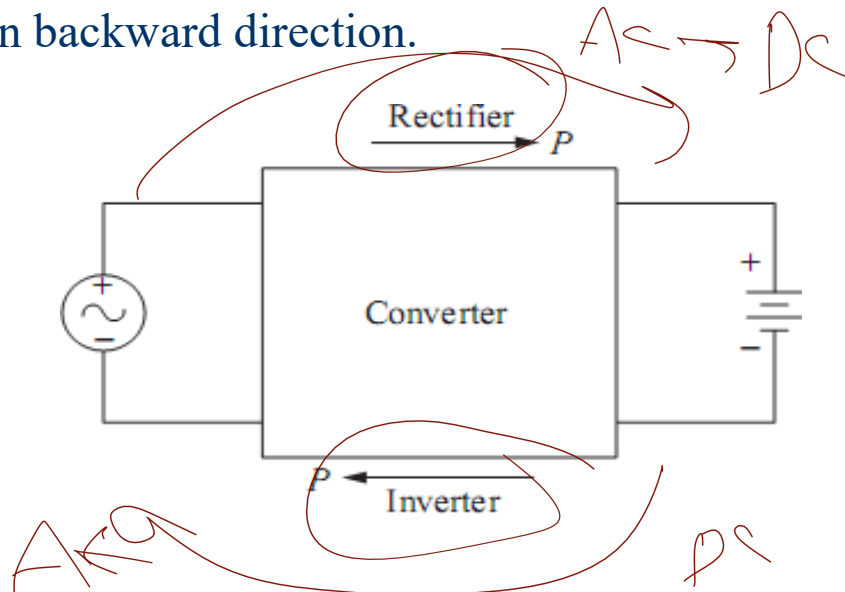
## AC input/AC output (AC-AC Converter)





# AC-DC bidirectional converter

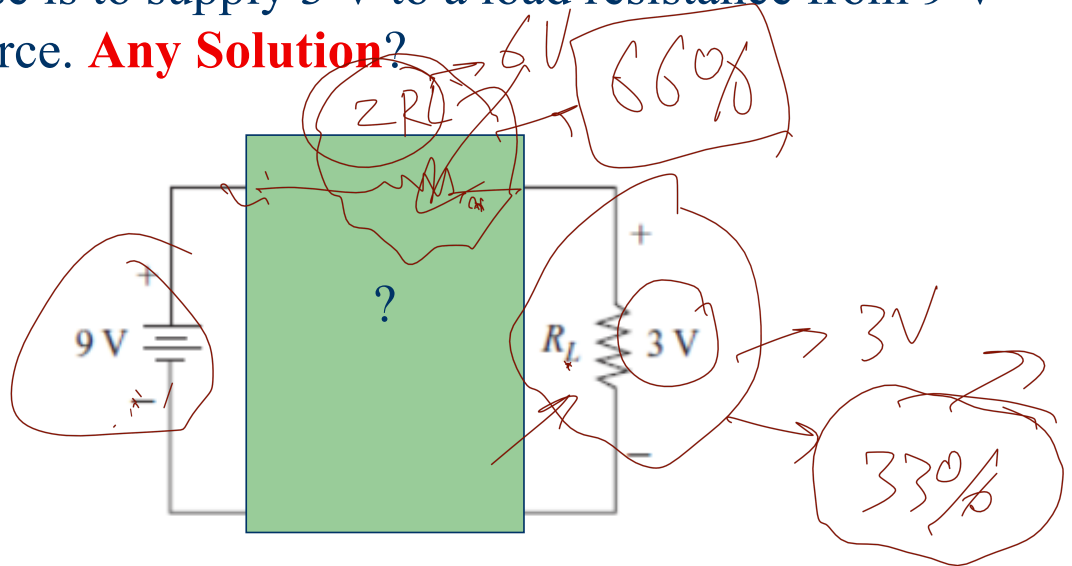
- The instantaneous power flow through the converter can be forward or backward direction at any instant of time.
- Rectifier operation: The power flows from AC source to the DC source in forward direction.
- Inverter operation: The power flows from DC source to the AC source in backward direction.



# POWER ELECTRONICS CONCEPTS

Consider the design problem of creating a 3-V dc voltage level from a 9-V battery.

The purpose is to supply 3 V to a load resistance from 9 V voltage source. **Any Solution?**

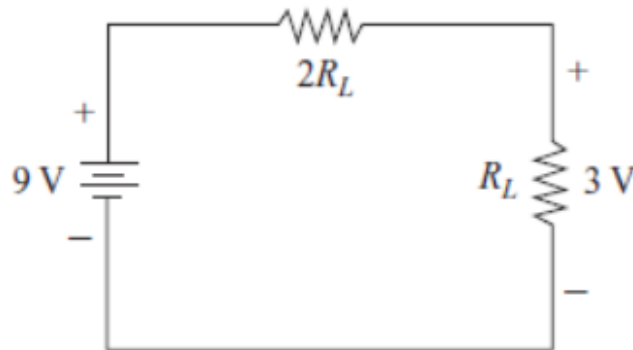


# POWER ELECTRONICS CONCEPTS

Consider the design problem of creating a 3-V dc voltage level from a 9-V battery.

The purpose is to supply 3 V to a load resistance

**Concept (1) (use a voltage divider)**



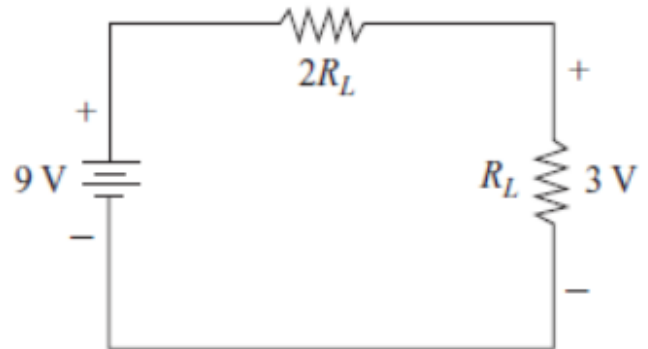
Problems:

## 1. Poor Efficiency:

The power absorbed by the  $2R_L$  resistor is twice as much as delivered to the load and is lost as heat, making the circuit only 33.3 percent efficient.

# POWER ELECTRONICS CONCEPTS

## Concept (1) (use a voltage divider)



Problems:

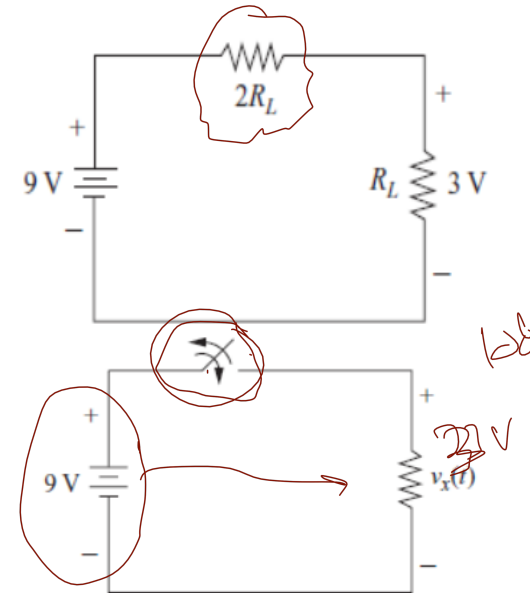
2. The output voltage regulation:

If the value of the load resistance changes, the output voltage will change unless the  $2R_L$  resistance changes proportionally.

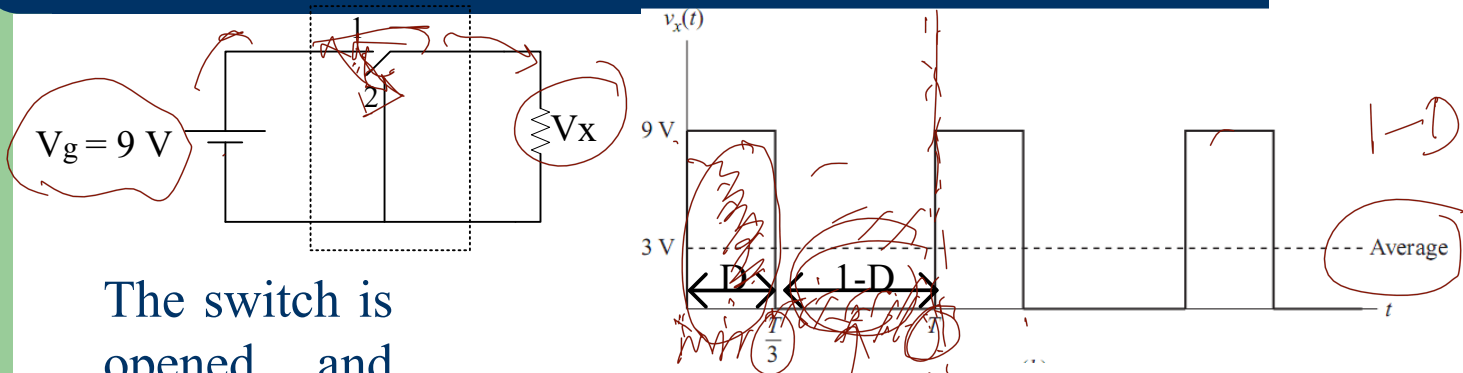
# POWER ELECTRONICS CONCEPTS

## Concept (2) (use a transistor)

- use a transistor in place of the  $2R_L$  resistance.
- The transistor would be controlled such that the voltage across it is maintained at 6 V, thus regulating the output at 3 V.
- a transistor is opened and closed periodically (control system). The switch acts as a variable resistor.
- The switch is a short circuit when it is closed and an open circuit when it is open, making the voltage across  $R_L$  equal to 9 V when the switch is closed and 0 V when the switch is open.



# POWER ELECTRONICS CONCEPTS



The switch is opened and closed periodically.

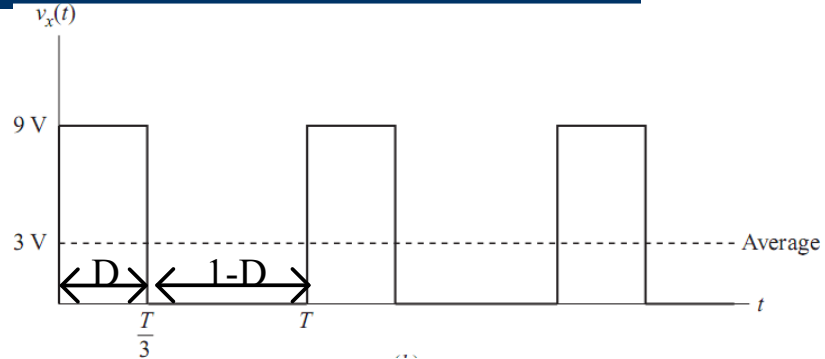
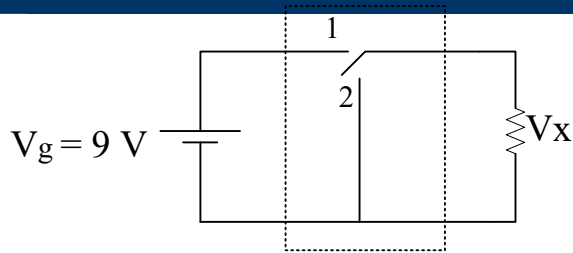
$$\text{avg}(v_x) = V_x = \frac{1}{T} \int_0^T v_x(t) dt = \frac{1}{T} \int_0^T 9 dt + \frac{1}{T} \int_{T/3}^T 0 dt = 3\text{ V}$$

$V_x = DV_g$

- Where  $T = \frac{1}{f_s}$ ,  $f_s$  is the switching frequency of the switch (frequency of the waveform of the  $V_x$ ).  $D$  is the duty cycle. Duty cycle is the fraction of time in which the switch occupies position 1. ( $0 \leq D \leq 1$ )

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

# POWER ELECTRONICS CONCEPTS



- As seen, this voltage is not a constant dc voltage,
- but if the switch is closed for one-third of the period, the average value of  $v_x$  (denoted as  $V_x$ ) is one-third of the source voltage.

# POWER ELECTRONICS CONCEPTS

## What about the efficiency?

- Instantaneous power absorbed by the switch is the product of its voltage and current.



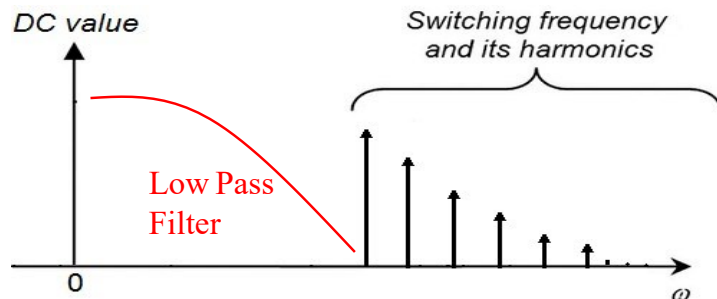
- When the switch is open, power absorbed by it is zero because the current in it is zero.
- When the switch is closed, power absorbed by it is zero because the voltage across it is zero.
- Since power absorbed by the switch is zero for both open and closed conditions, all power supplied by the 9V source is delivered to  $R_L$ , making the circuit 100% efficient.



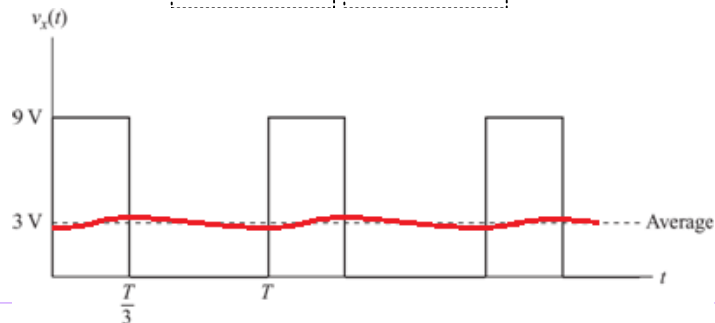
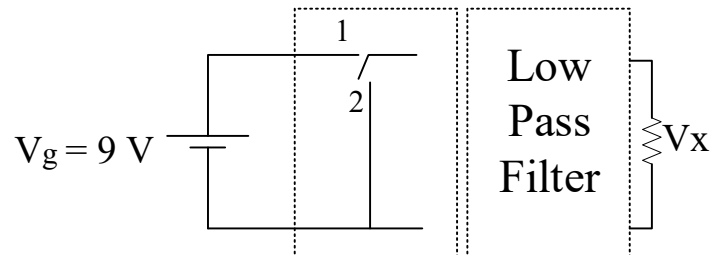
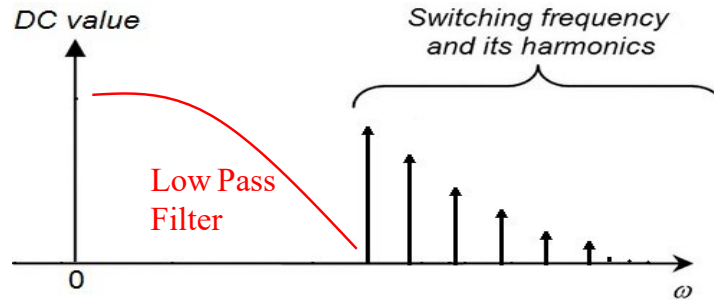
# POWER ELECTRONICS CONCEPTS

- But there is a serious problem: the output voltage waveform is not pure DC!
- The circuit so far does not accomplish the design object of creating a dc voltage of 3 V.
- However, the voltage waveform  $v_x$  can be expressed as a **Fourier series** containing a **dc term (the average value)** plus **sinusoidal terms** at frequencies that are multiples of the switching frequency.

An ideal low-pass filter allows the dc component of voltage to pass through to the output while removing the ac terms, thus creating the desired dc output.



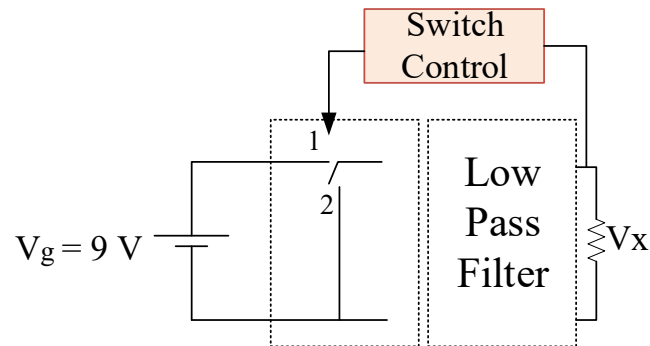
# POWER ELECTRONICS CONCEPTS



# POWER ELECTRONICS CONCEPTS

## What about the output voltage regulation?

- The power conversion process usually involves system control.
- Converter output quantities such as voltage and current are measured, and operating parameters are adjusted to maintain the desired output.
- In our example, a feedback control system would detect if the output voltage were not 3 V and adjust the closing and opening of the switch accordingly.



# POWER ELECTRONICS CONCEPTS

## In practice,

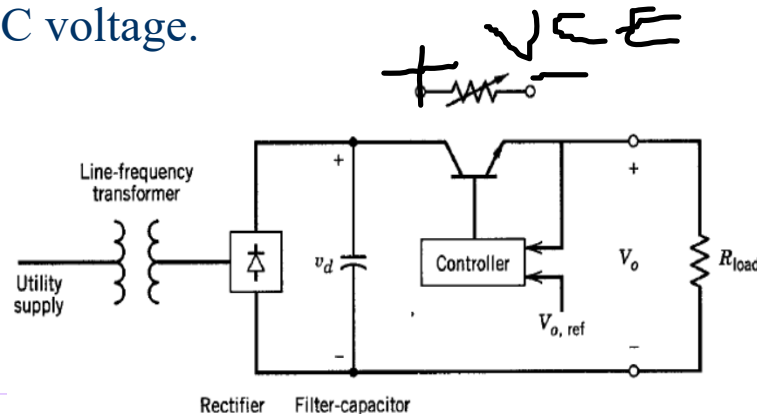
- The filter will have some losses and will absorb some power.
- Additionally, the electronic device used for the switch will not be perfect and will have losses. However, the efficiency of the converter can still be quite high (more than 90 percent).
- The required values of the filter components can be made smaller with higher switching frequencies, making large switching frequencies desirable.

# Power Electronics Versus Linear Electronics

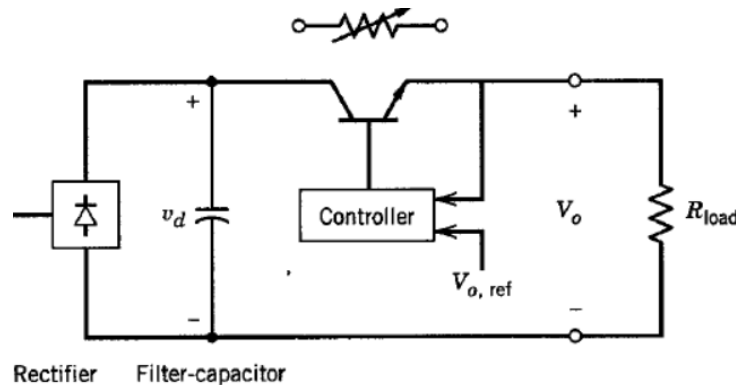
Assuming it is wanted to regulate the DC input voltage to another DC output voltage.

In linear electronics,

- The semiconductor devices are operated in their linear region (active region).
- A line frequency transformer is used for isolation purposes and to step down the line voltage.
- The rectifier converts the AC output of the transformer low voltage into a DC voltage.



# Power Electronics Versus Linear Electronics

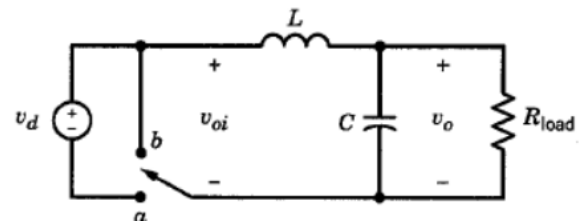
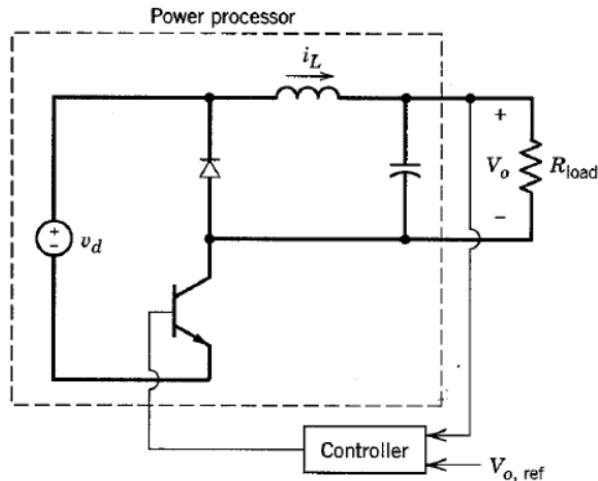


- The rectifier converts the AC output of the transformer low voltage into a DC voltage.
- The filter reduces the ripples in the DC voltage ( $v_d$ )
- The transistor is controlled to absorb the voltage difference between  $v_d$  and  $v_o$ , thus providing a regulated output.
- The transistor operates in its active region as an adjustable resistor, resulting a low energy efficiency.
- The line-frequency transformer is relatively large and heavy.

# Power Electronics Versus Linear Electronics

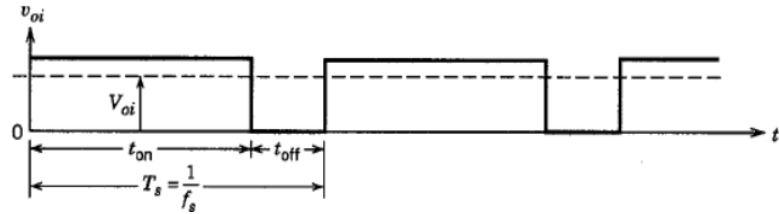
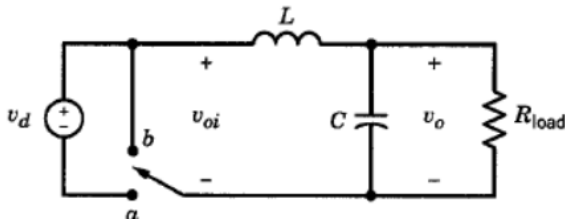
In power electronics,

- By operating the transistor as a switch (in a switch mode, either fully on or fully off) at high frequency, the DC voltage is converted into an output DC voltage.
- A transformer can be inserted to be operated at high frequency.
- The transistor-diode combination can be represented by a two-position switch.



# Power Electronics Versus Linear Electronics

In power electronics,

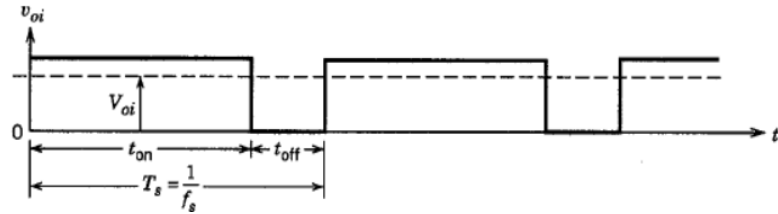
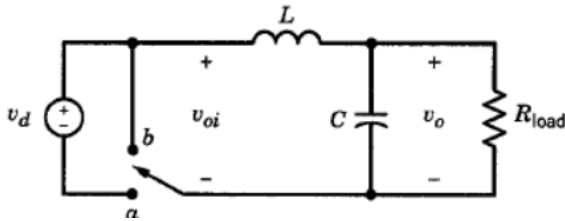


- The transistor-diode combination can be represented by a two-position switch.
- The switch is in position a:
  - ✓ during the interval  $t_{on}$  when the transistor is on
- The switch is in position b
  - ✓ when the transistor is off during  $t_{off}$ .



# AMA Power Electronics Versus Linear Electronics

In power electronics,



- The output voltage consists of an average DC voltage + ripples. The ripples can be reduced by the low-pass filter.
- The average voltage can be given as:

$$V_0 = \frac{1}{T_s} \int_0^{t_{on}} v_{oi} dt = \frac{t_{on}}{T_s} v_d$$

D

- Usually,  $T_s$  is kept constant while  $t_{on}$  is adjusted.

# Power Electronics Versus Linear Electronics

In power electronics,

- There are several worth noting:
  - ✓ Since the transistors operates fully on or fully off (switch), the power loss is minimized.
  - ✓ The power losses are linearly proportional to the switching frequency.
  - ✓ At high switching frequency, the transformer and the filter components are very small in weight and size compared to the line-frequency components. The harmonics exists at the switching frequency and its multiples. If the switching frequency is high, these harmonics can be easily eliminated by a small filter.
  - ✓ The selection of the switching frequency is dictated by the compromise between the switching losses and the size of the filters and the transformers

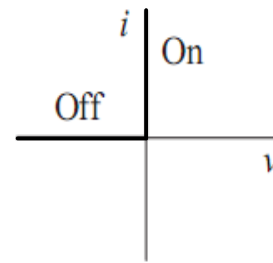
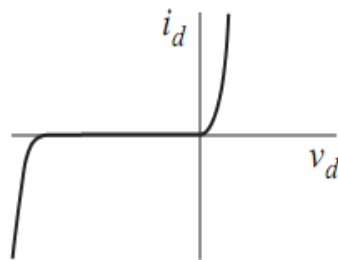
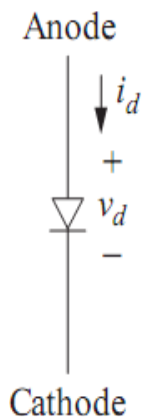
# Electronic Switches

- An electronic switch is characterized by having two states:
  - ✓ ON state: ideally short circuit,
  - ✓ OFF state: ideally open circuit
- If the **switch is ideal**, either switch current or switch voltage is zero, making the **power absorbed by it is zero**.
- However, **real devices absorb some power**:
  - ✓ when it is ON state,
  - ✓ when making transition between the ON and OFF states.

**But circuit efficiencies can still be quite high.**
- The behavior of circuit is not affected significantly by non-ideal switches, if the voltage drop across the conducting switch are small compared to other circuit voltages.
- Therefore semiconductor switches usually is modeled as ideal switch.

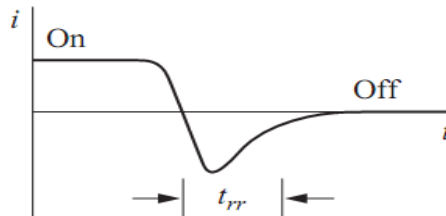
# Diode

- Simplest electronic switch
- Uncontrollable
- ON and OFF conditions are determined by voltages and currents in the circuit.
- In the ideal case, the diode is a short circuit when it is forward-biased and is an open circuit when reverse-biased.



# Diode

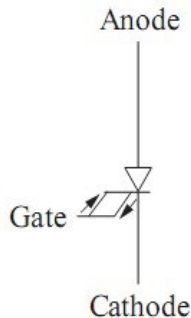
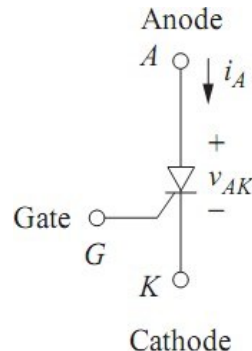
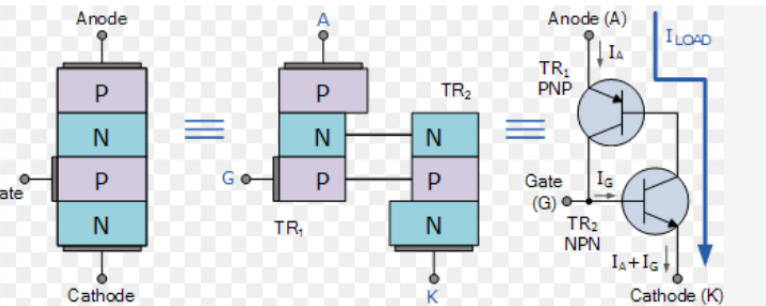
- An important dynamic characteristic of a non-ideal diode is reverse recovery current.
- When a diode turns off, the current in it decreases and momentarily becomes negative before becoming zero.
- The time  $t_{rr}$  is the reverse recovery time, which is usually less than  $1\mu\text{s}$ .
- This phenomenon may become important in high-frequency applications.
- Fast-recovery diodes are designed to have a smaller  $t_{rr}$  than diodes designed for line-frequency applications.
- Silicon carbide (SiC) and schottky diodes have very little reverse recovery.



RURG3020C

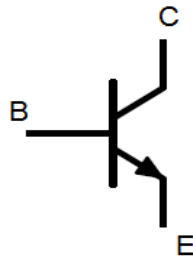
# Thyristor (SCR) and GTO

- SCR (Silicon Controlled Rectifier).
- It is a controllable diode with three terminal (Anode, Cathode, Gate).
- Thyristors are capable of large currents and large blocking voltages for use in high-power applications.
- For the SCR to begin to conduct, it must have a gate current applied while it has a positive anode-to-cathode voltage. After conduction is established, the gate signal is no longer required to maintain anode current. The SCR will continue to conduct as long as the anode current remains positive.
- GTO (Gate turn off thyristor)

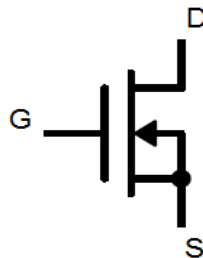


# Transistors

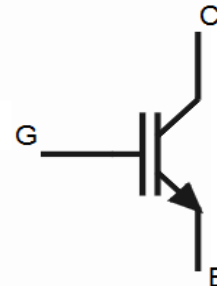
- Three terminal device
- Unlike the diode, turn-on and turnoff of a transistor are controllable.
- Types:
- MOSFET (Metal Oxide Semiconductor Field Effect Transistor)
- BJT (Bipolar Junction Transistor)
- IGBT (Isolated Gated Bipolar Transistor)



BJT



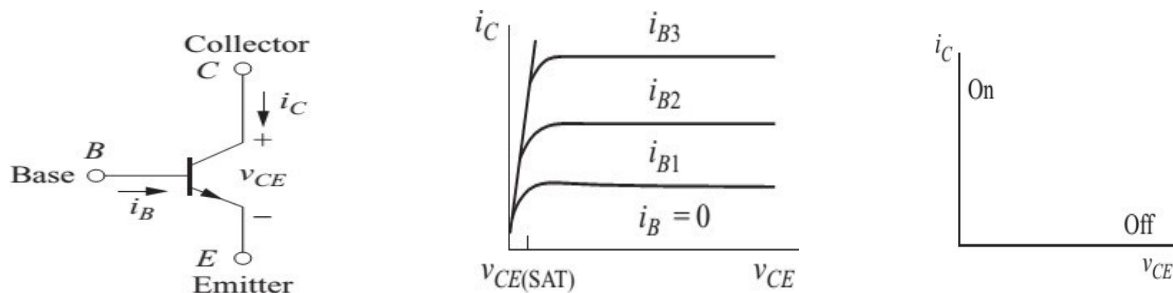
MOSFET



IGBT

# BJT

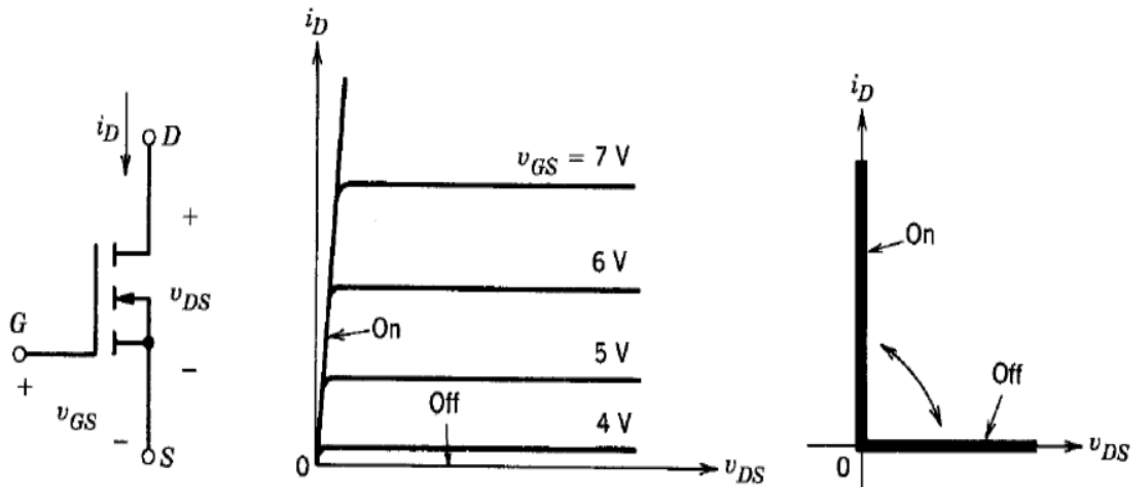
- The on state for a power BJT is achieved by providing sufficient current to the Base.
- The on-state voltage ( $V_{CE(SAT)}$ ) is small (in the range 1-2 V), so that the conduction power loss are small.
- It needs flowing a continuous base current to keep the transistor in the on stated.
- Zero base current causes to turn off the transistor.





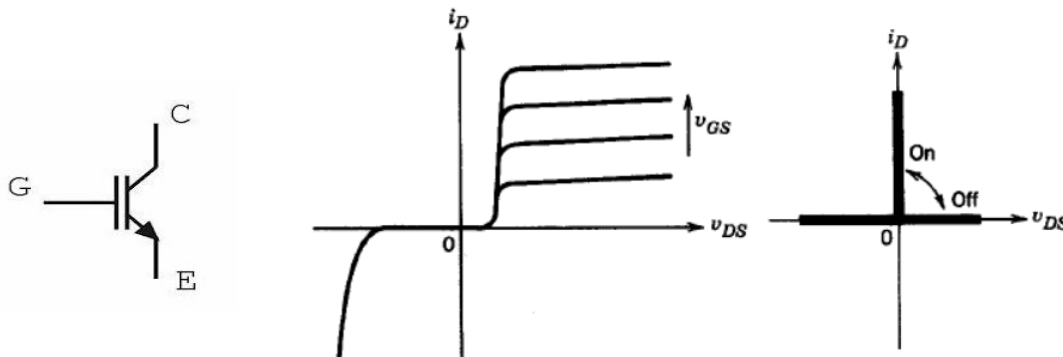
# MOSFET

- The MOSFET is a voltage-controlled device. A sufficiently large gate-to-source voltage will turn the device on, resulting in a small drain-to-source on-state voltage.
- MOSFET require a continuous application of the gate-source voltage in order to be in the on state.
- The switching time (on to off and vice versa) of the MOSFETS are very short.

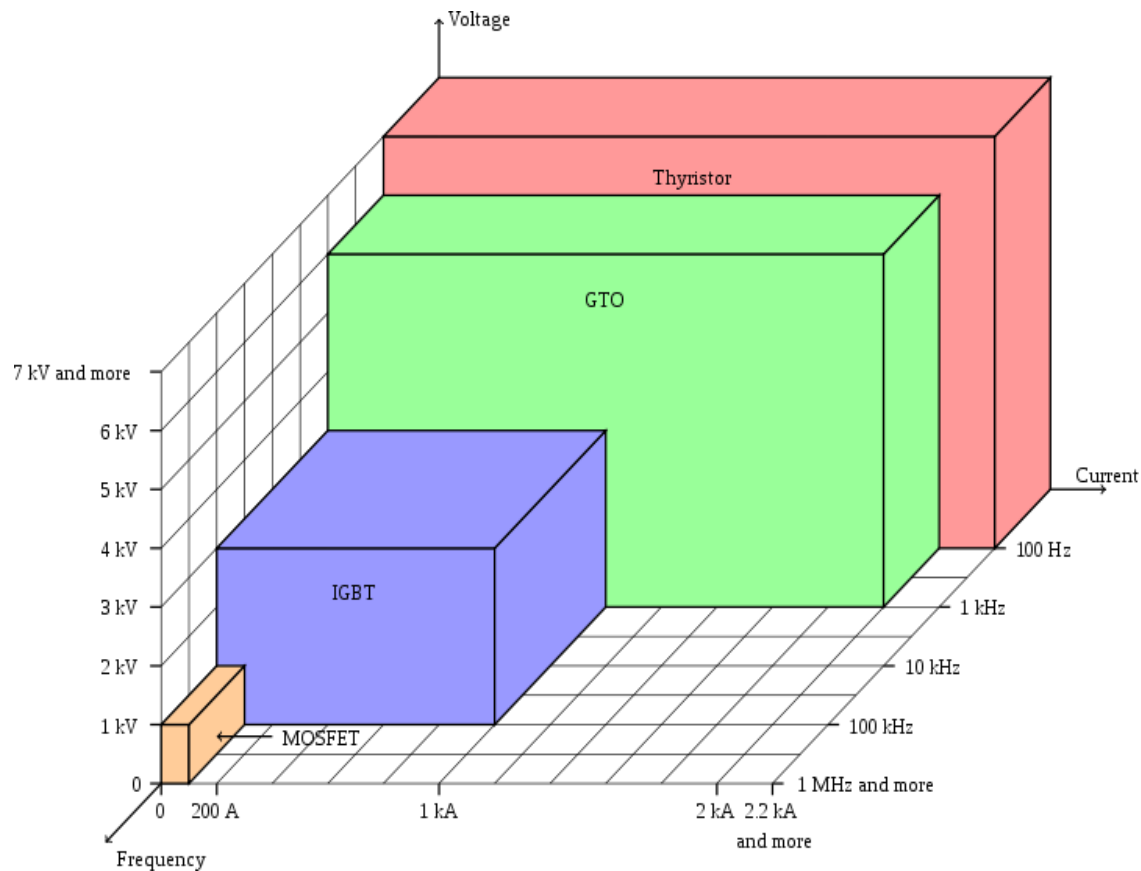


# IGBT

- IGBT is an integrated connection of a MOSFET and a BJT.
- IGBTs have some advantages of the MOSFET, BJT, and GTO.
- Similar to MOSFET, IGBT has a high impedance gate, which requires only a small amount of energy to switch the device.
- Like BJT, IGBT has a small on-state voltage even in devices with large blocking devices ( e.g. 2-3 V in 1000 V devices).
- Similar to GTO, IGBT is designed to block negative voltage.
- IGBTs have replaced BJTs in many applications.



# Power semiconductors

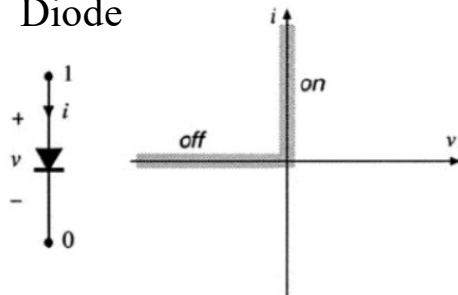


# Switch selection

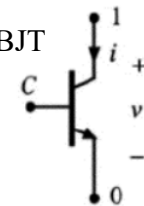
- The selection of a power device for a particular application depends not only on the required voltage and current levels but also on its switching characteristics.
  - Transistors and GTOs provide control of both **turn-on** and **turnoff**
  - SCRs of **turn-on** but not **turnoff**
  - and diodes of neither.
- Switching speeds and the associated power losses are very important in power electronics circuits.

# Switch selection

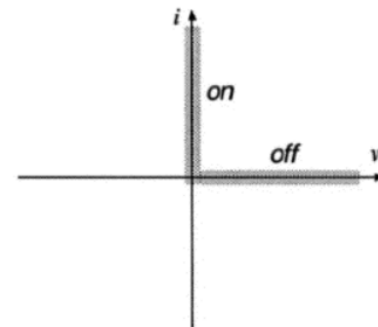
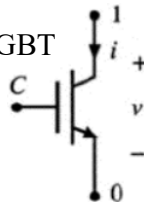
## Diode



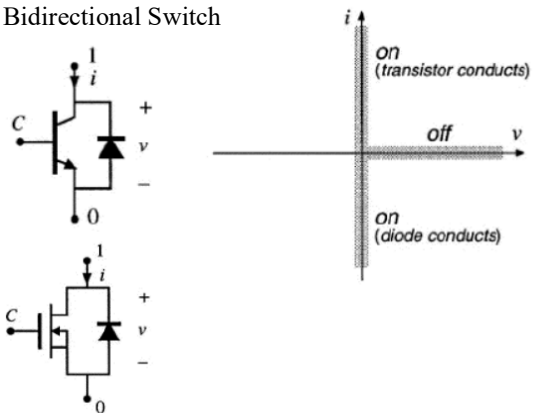
## BJT



## IGBT



## Bidirectional Switch

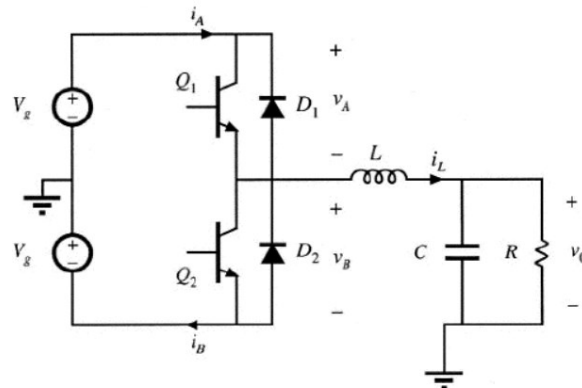


Bidirectional Switch is used in the inverters and in the bidirectional DC-DC converters.

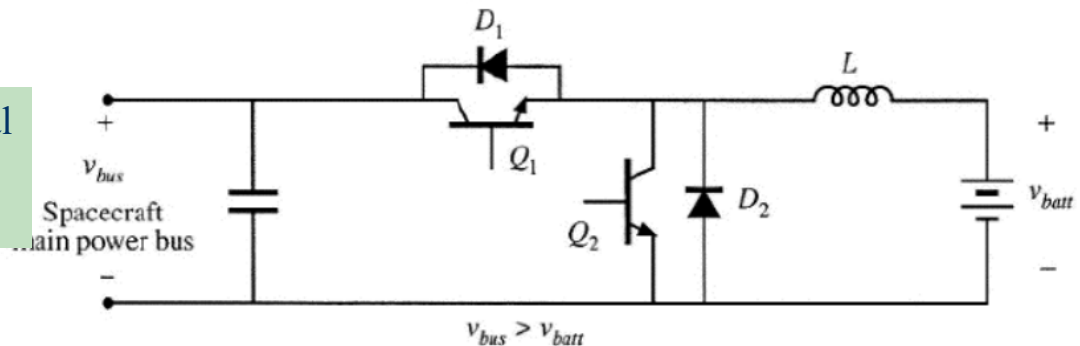
# Switch selection

Bidirectional Switch is used in the inverters and in the bidirectional DC-DC converters.

inverter

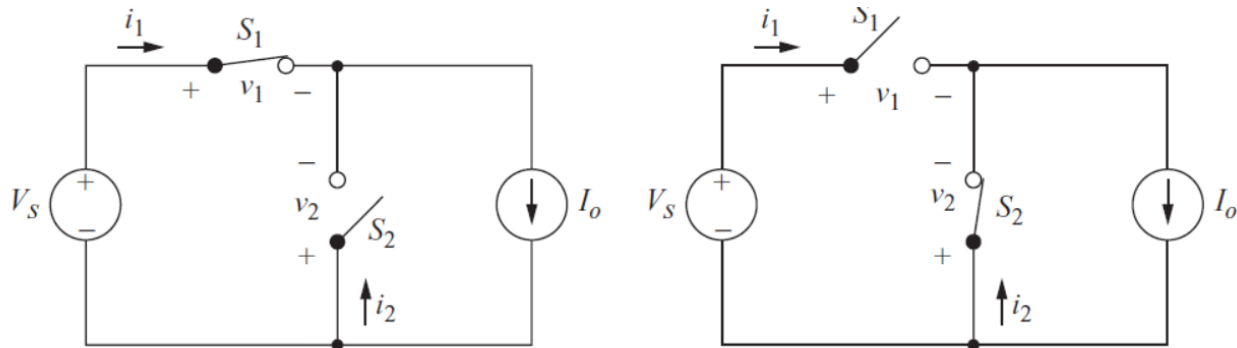


bidirectional  
DC-DC  
converters



# Switch selection

- The switch  $S_1$  connects the voltage source ( $V_s=24V$ ) to the current source ( $I_o=2A$ ). Switching frequency is 200 kHz.
- When  $S_1$  is opened,  $S_2$  must be close in order to provide current path.
- Similarly, when  $S_2$  is opened,  $S_1$  is closed.
- **Select the switching devices for  $S_1$  and  $S_2$ .**



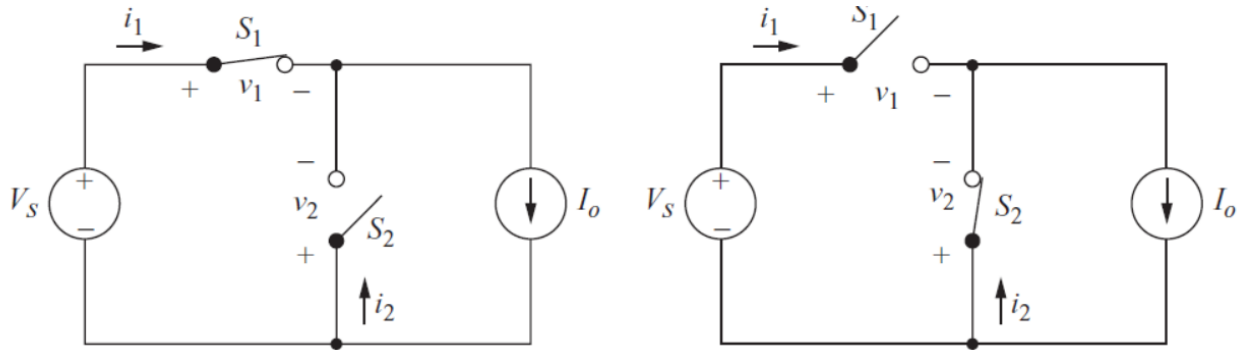
**Solution is on the board**

# Computer Simulation

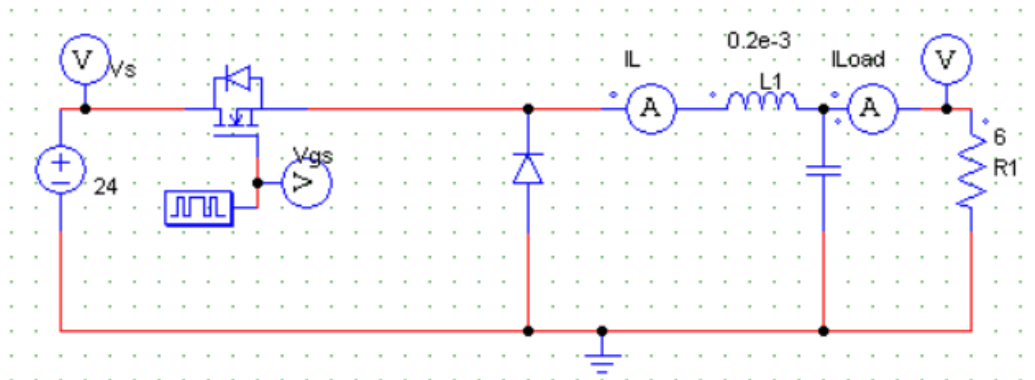
- Computer simulation is a valuable analysis and design tool for power electronics.
- **PSIM – Powersim**
- **Pspice**
- **SIMULINK**



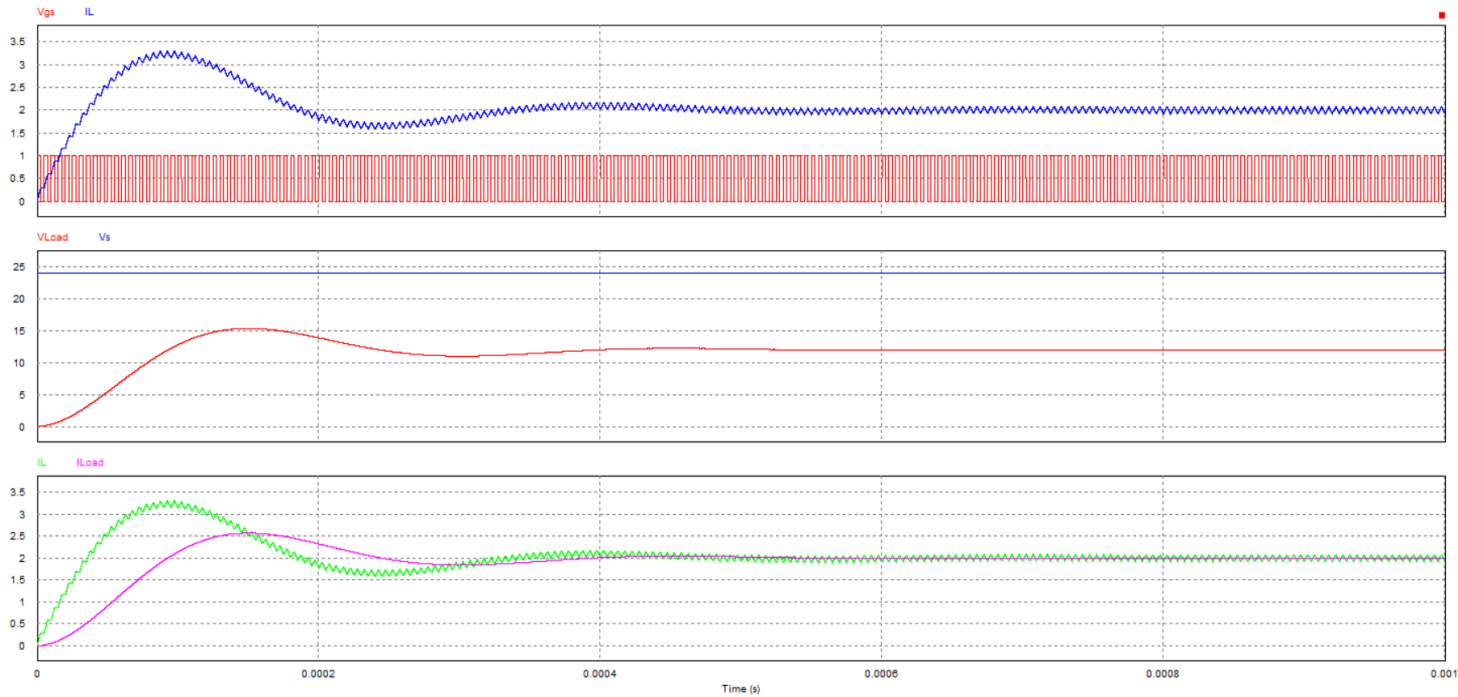
# Computer Simulation Exercise



This circuit can be modeled using PSIM software as seen bellow



# Computer Simulation



# Computer Simulation

