ELG3336: Power Electronics Systems

Objective

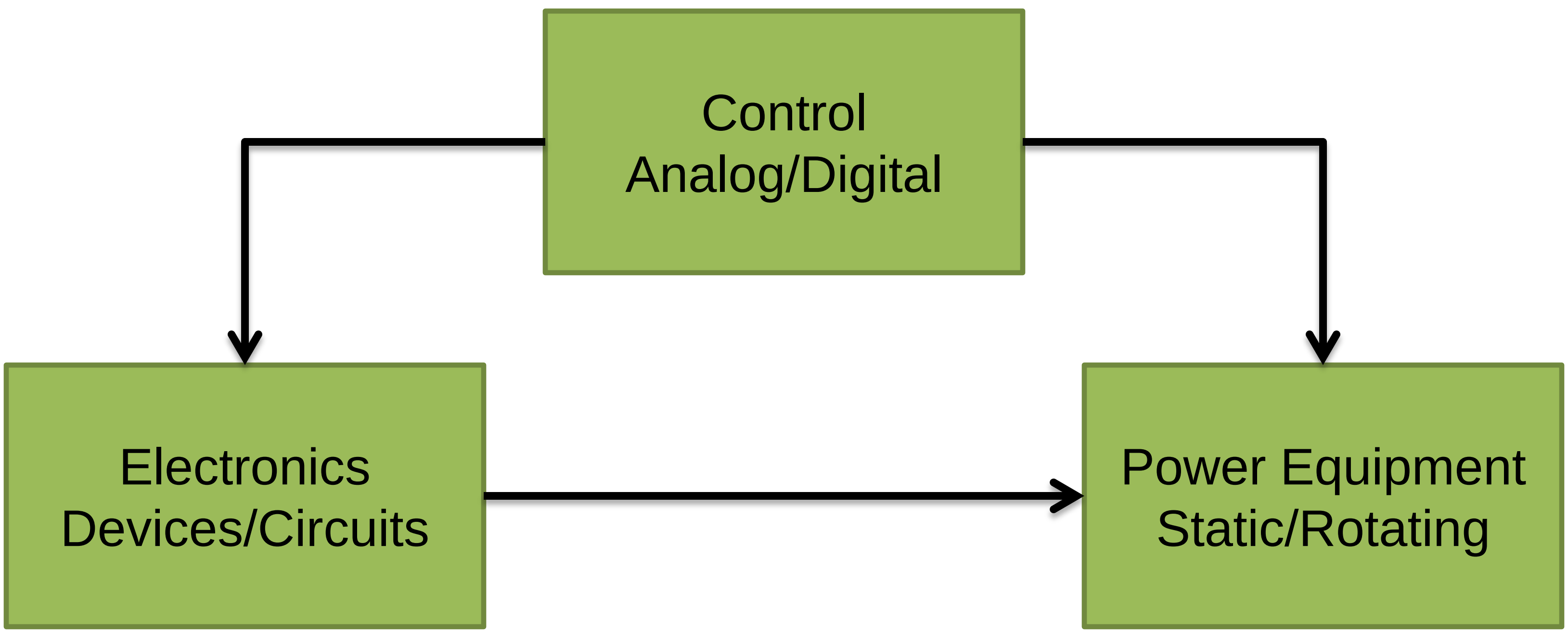
To Realize and Design Various

Power Supplies and Motor Drives!

Power electronics refers to control and conversion of electrical power by power semiconductor devices wherein these devices operate as switches. Advent of silicon-controlled rectifiers, abbreviated as SCRs, led to the development of a new field of application called the power electronics. Before SCRs, mercury-arc rectifiers were used for controlling electrical power, but such rectifier circuits were part of industrial electronics and the scope for applications of mercury-arc rectifiers was limited. The application spread to many fields such as drives, power supplies, aviation electronics, high frequency inverters and power electronics.

Why Power Electronics?

Power electronics is a growing field due to the improvement in switching technologies and the need for more and more efficient switching circuits.



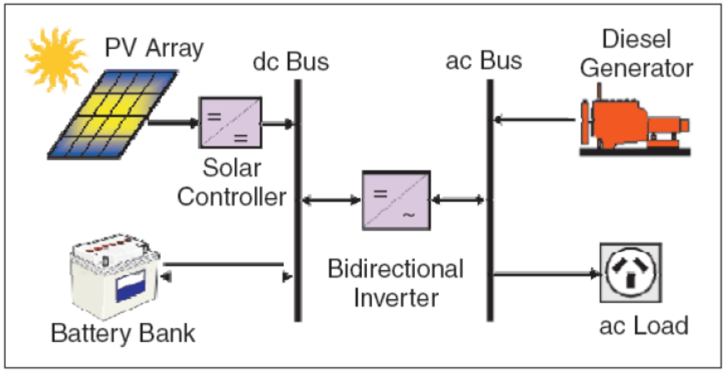
Scope of Power Electronics

Power Level (Watts)	*System*
0.1-10	• Battery-operated equipment • Flashes/strobes
10-100	• Satellite power systems • Typical offline flyback supply
100 – 1kW	• Computer power supply • Blender
1 – 10 kW	• Hot tub
10 – 100 kW	• Electric car • Eddy current braking
100 kW –1 MW	• Bus • micro-SMES
1 MW – 10 MW	• SMES
10 MW – 100 MW	• Magnetic aircraft launch • Big locomotives
100 MW – 1 GW	• Power plant
> 1 GW	• Sandy Pond substation (2.2 GW)

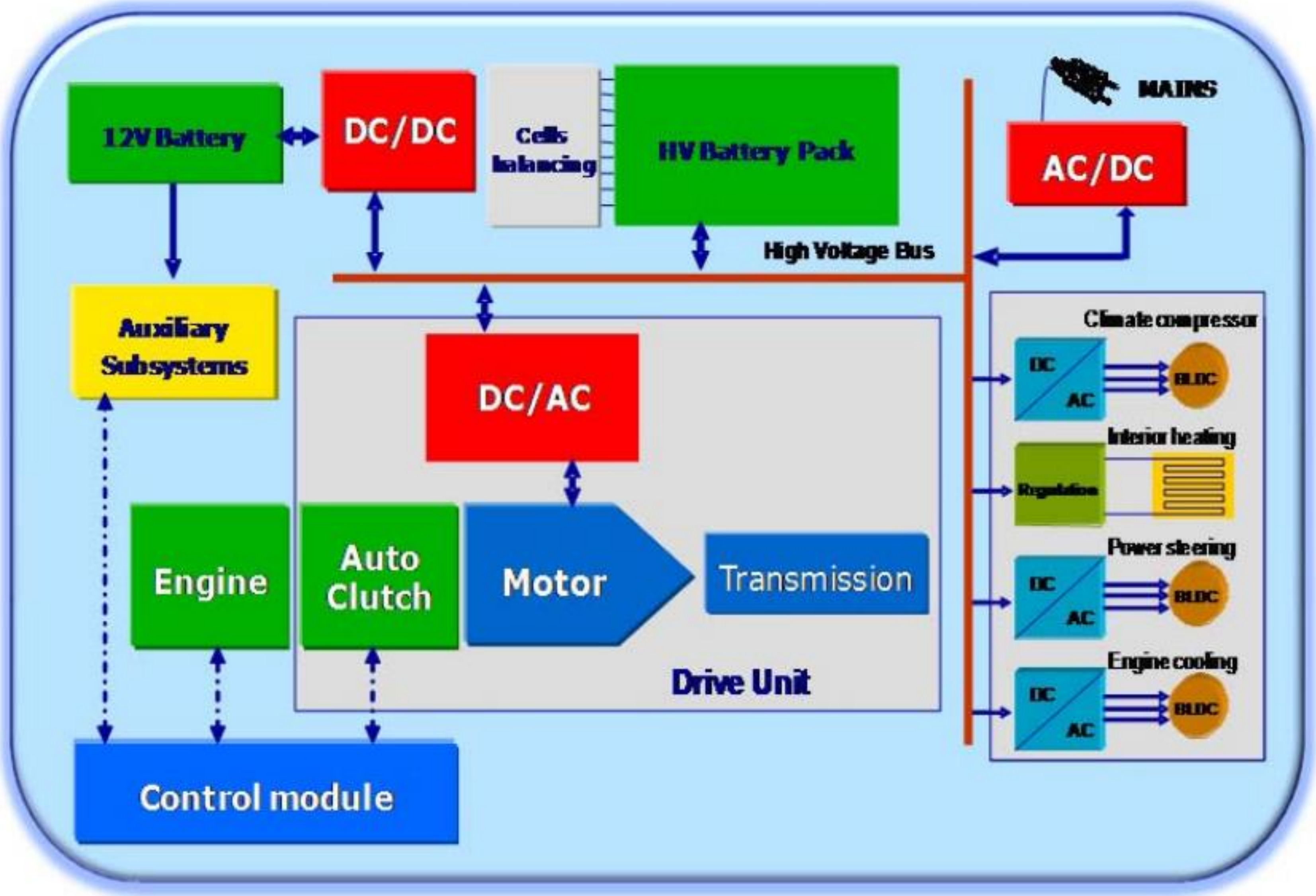
Applications

- Heating and lighting control
- Induction heating
- Uninterruptible power supplies (UPS)
- Fluorescent lamp ballasts: Passive; Active
- Electric power transmission
- Automotive electronics
- Electronic ignitions
- Motor drives
- Battery chargers
- Alternators
- Energy storage
- Electric vehicles
- Alternative power sources: Solar; Wind; Fuel Cells
- And more!

Photovoltaics



Power Train of a Hybrid Car



Some Applications of Power Electronics

- In a conventional car, power electronics applications are a major area of future expansion. Look inside the audio system, for example; the amplifiers in today's car stereos are usually capable of delivering 40 W or more. But a 12 V supply applied to an 8 Ohm speaker produces 18 W output at best. To solve this power supply problem, designers use a boost converter (DC to DC Converter) to provide higher voltage power to the amplifier circuit. This allows car amplifiers to generate the same audio output power as home stereos.
- Another universal power electronics application is the automobile's ignition system. Thousands of volts are required to ignite the fuel-air mixture inside a cylinder so that internal combustion can occur. Today's cars employ all-electronic ignition systems, which have replaced the traditional spark plugs with boost converters coupled to transformers.
- We are curious about new electric and hybrid cars, in which the primary electrical system is dominated by power electronics. Electric cars offer high performance, zero tailpipe emissions, and low costs, but are still limited in range by the need for batteries.
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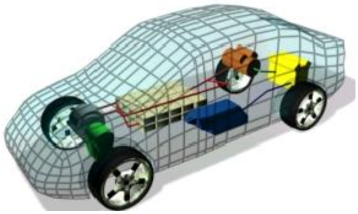
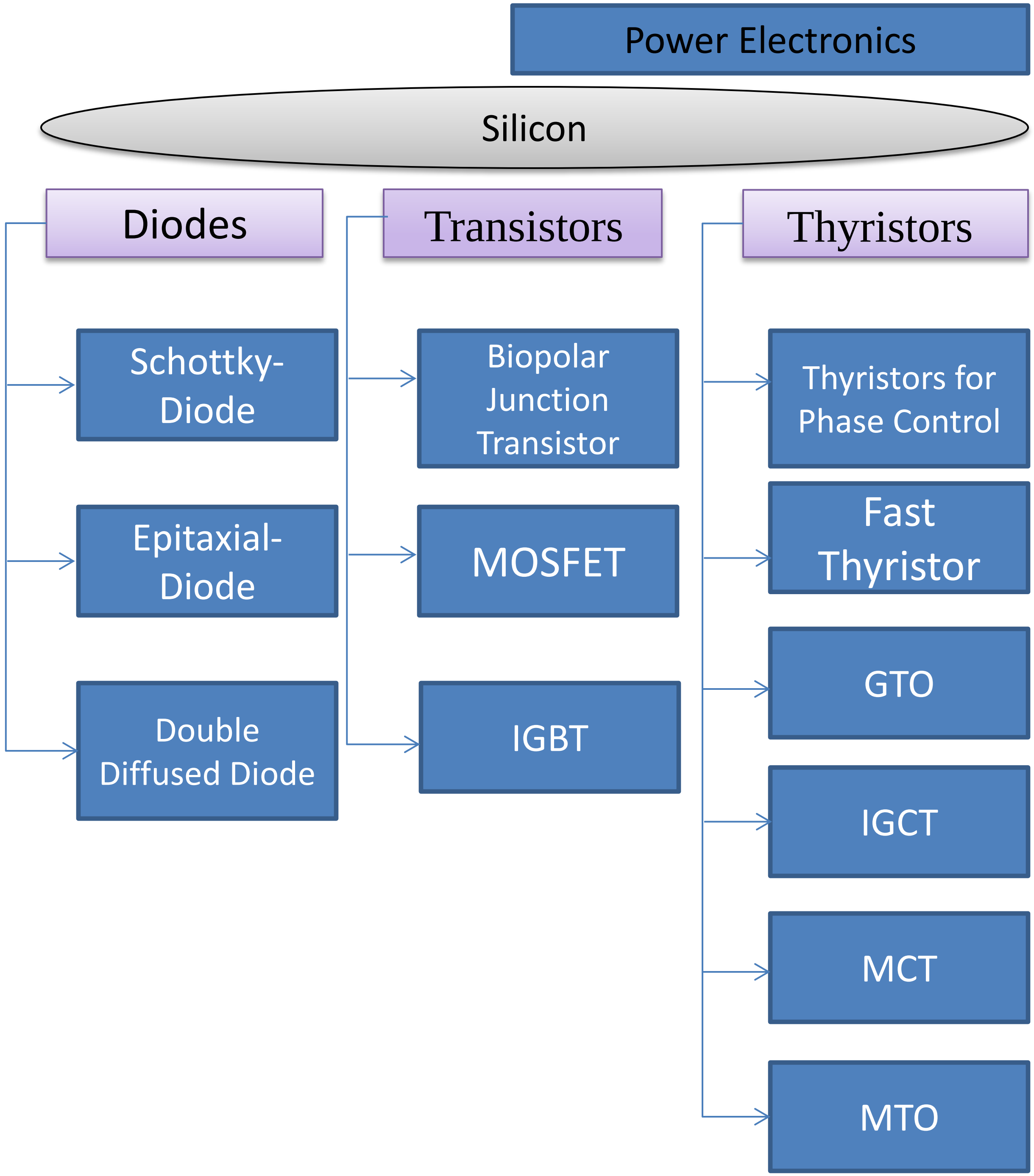


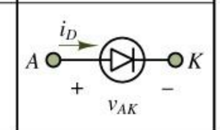
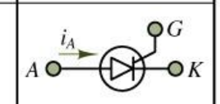
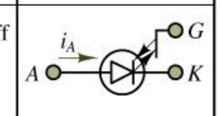
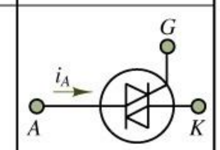
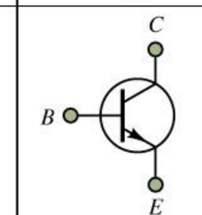
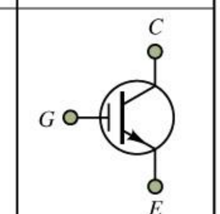
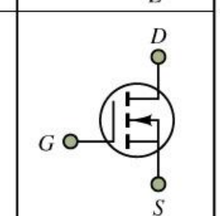
Power Electric Circuits

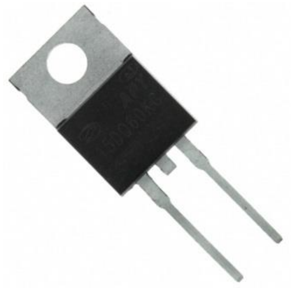
Circuit type	Essential features
Voltage regulators	Regulate a DC supply to a fixed voltage output
Power amplifiers	Large-signal amplification of voltages and currents
Switches	Electronic switches (e.g., transistor switches)
Diode rectifier	Converts fixed AC voltage (single- or multiphase) to fixed DC voltage
AC-DC converter (controlled rectifier)	Converts fixed AC voltage (single- or multiphase) to variable DC voltage
AC-AC converter (AC voltage controller)	Converts fixed AC voltage to variable AC voltage (single- or multiphase)
DC-DC converter (chopper)	Converts fixed DC voltage to variable DC voltage
DC-AC converter (inverter)	Converts fixed DC voltage to variable AC voltage (single- or multiphase)

Ideal Characteristics of a Power Semiconductor

- When on: Can carry infinite current and create no resistance(i.e. no power loss)
- When off: withstand infinite reverse voltage with infinite off state resistance (i.e. no power loss)
- Instant on-of
- Almost zero power pulse to turn on and off
- Instant reaction to input
- Ideal thermal dissipation out of the device
- Can withstand infinite fault current
- Low price!

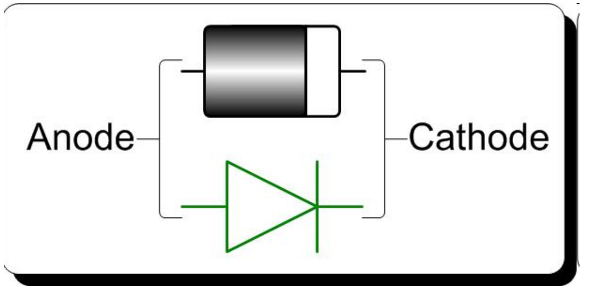


Device	Device symbol
Diode	
Thyristor	
Gate turnoff thyristor (GTO)	
Triac	
npn BJT	
IGBT	
n-channel MOSFET	

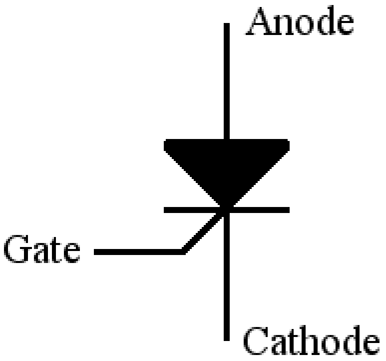


Diodes

- Characteristics:
  - Conducts one way
  - Blocks current in the opposite direction
  - Only works above an excitation voltage (ex: 3V)
- Max properties:
  - General purpose diodes: 6000V, 4500A
  - Fast recovery: 6000V, 1100A
  - Schottky(low voltage drop, fast switching, high efficiency): 100V, 300A



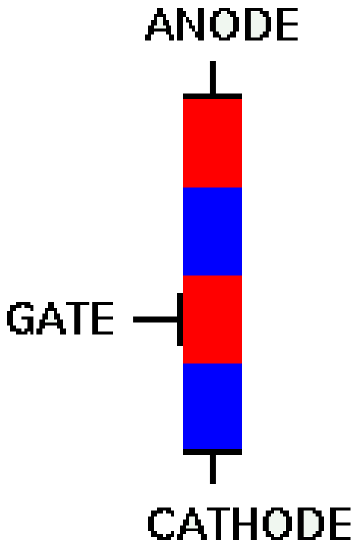
Thyristors

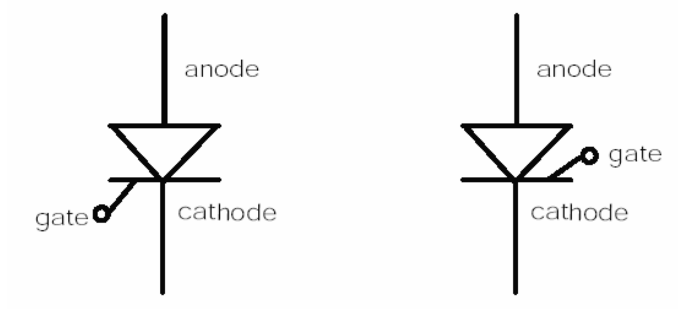


- Characteristics:
  - Only conducts when triggered by a signal at its gate
  - Some can conduct in two directions (e.g. RCTs)
- Maximum properties:
  - 6000V-4500V for line commutated thyristors
  - 10-20 nanosecond turn-off time for 3000V-3600V

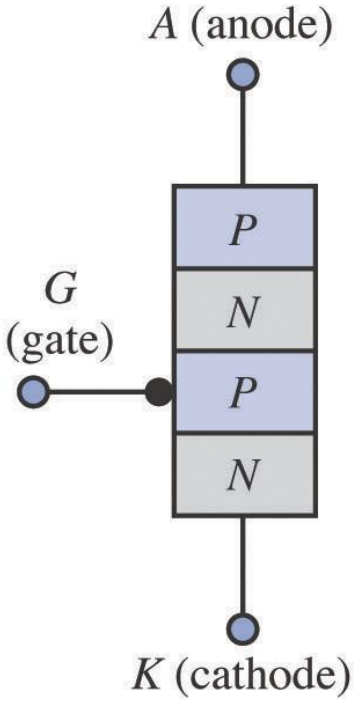
Silicon Controlled Rectifiers

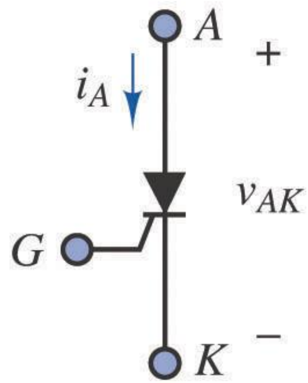
The basic purpose of the SCR is to function as a switch that can turn on or off small or large amounts of power. It performs this function with no moving parts that wear out and no points that require replacing. There can be a tremendous power gain in the SCR; in some units a very small triggering current is able to switch several hundred amperes without exceeding its rated abilities. The SCR can often replace much slower and larger mechanical switches.

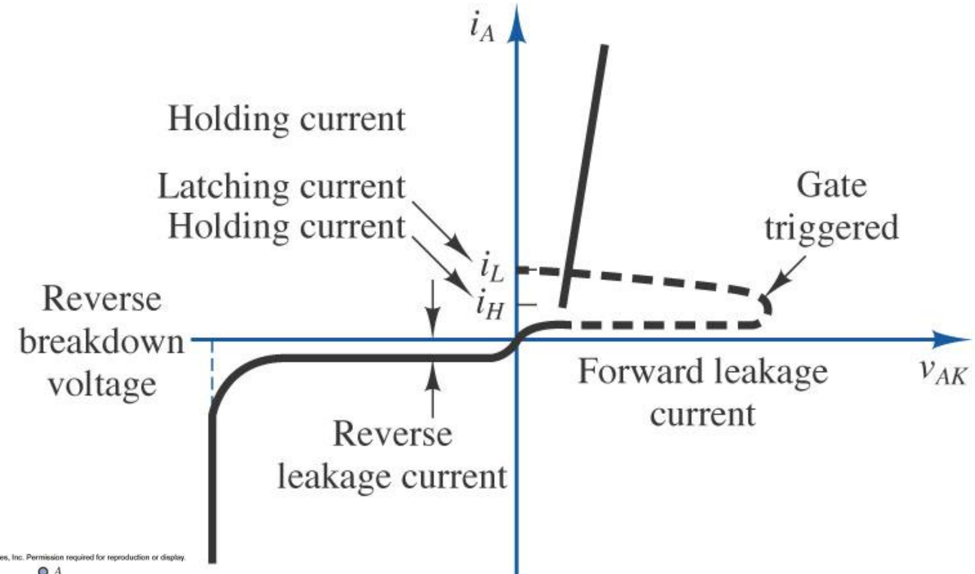


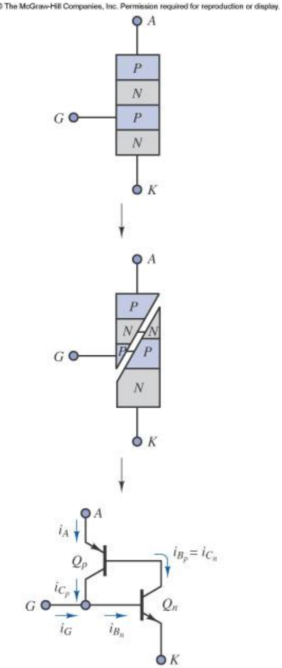


Thyristors and Controlled Rectifiers



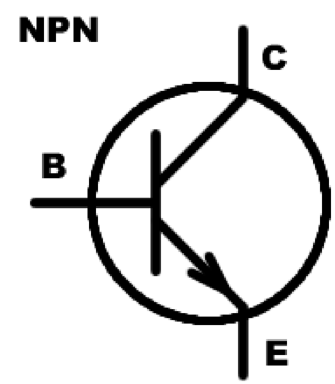






Power Transistor

- Characteristics
  - If the base current is flowing, a voltage between the collector and emitter will cause current to flow between them. (i.e. the base turns on the transistor)
  - Commonly used as a switch
- Max properties
  - 1700V,2400A for IGBTs



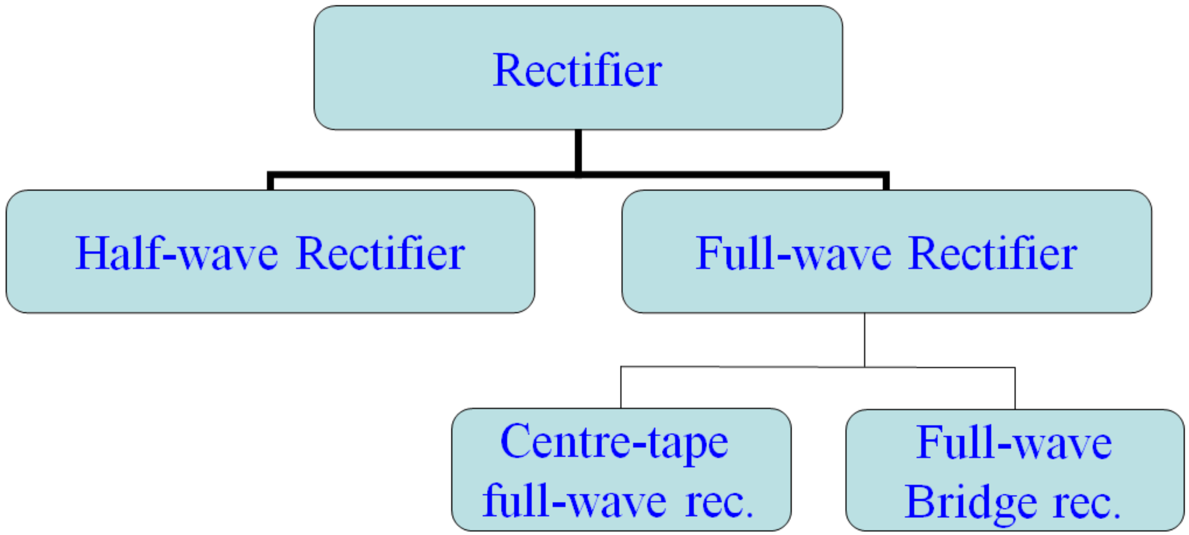
Rectifiers: AC to DC Converters

Rectifiers may be classified as uncontrolled and controlled rectifiers. Controlled rectifiers can be further divided into semi-controlled and fully-controlled rectifiers. Uncontrolled rectifier circuits are built with diodes, and fully-controlled rectifier circuits are built with SCRs. Both diodes and SCRs are used in semi-controlled rectifier circuits.

- Single-phase semi-controlled bridge rectifier
- Single-phase fully-controlled bridge rectifier
- Three-phase three-pulse, star-connected rectifier
- Double three-phase, three-pulse star-connected rectifiers with inter-phase transformer (IPT)
- Three-phase semi-controlled bridge rectifier
- Three-phase fully-controlled bridge rectifier
- Double three-phase fully-controlled bridge rectifiers with IPT.

Rectifiers and Controlled Rectifiers

AC to DC Converters

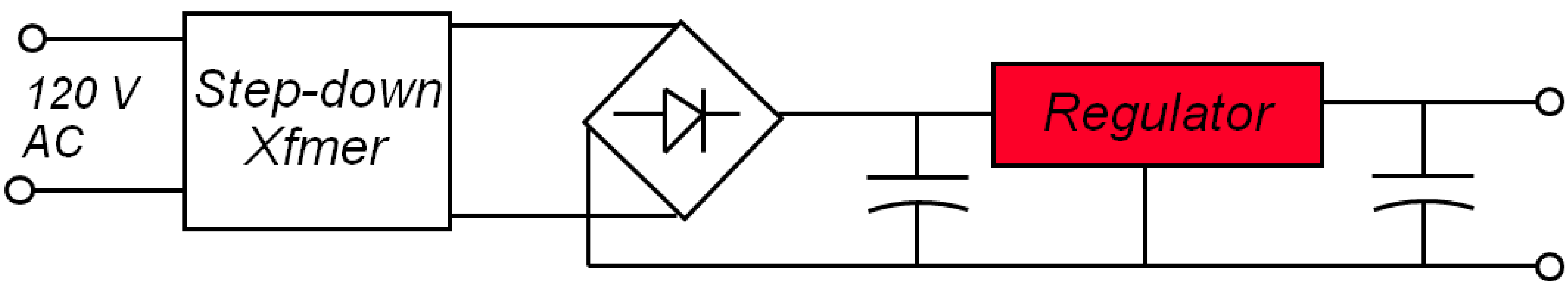


	Half-wave	Centre-tap	Bridge type
No. of diode	1	2	4
Transformer necessary	No	Yes	No
Maximum efficiency	40.6%	81.2%	81.2%

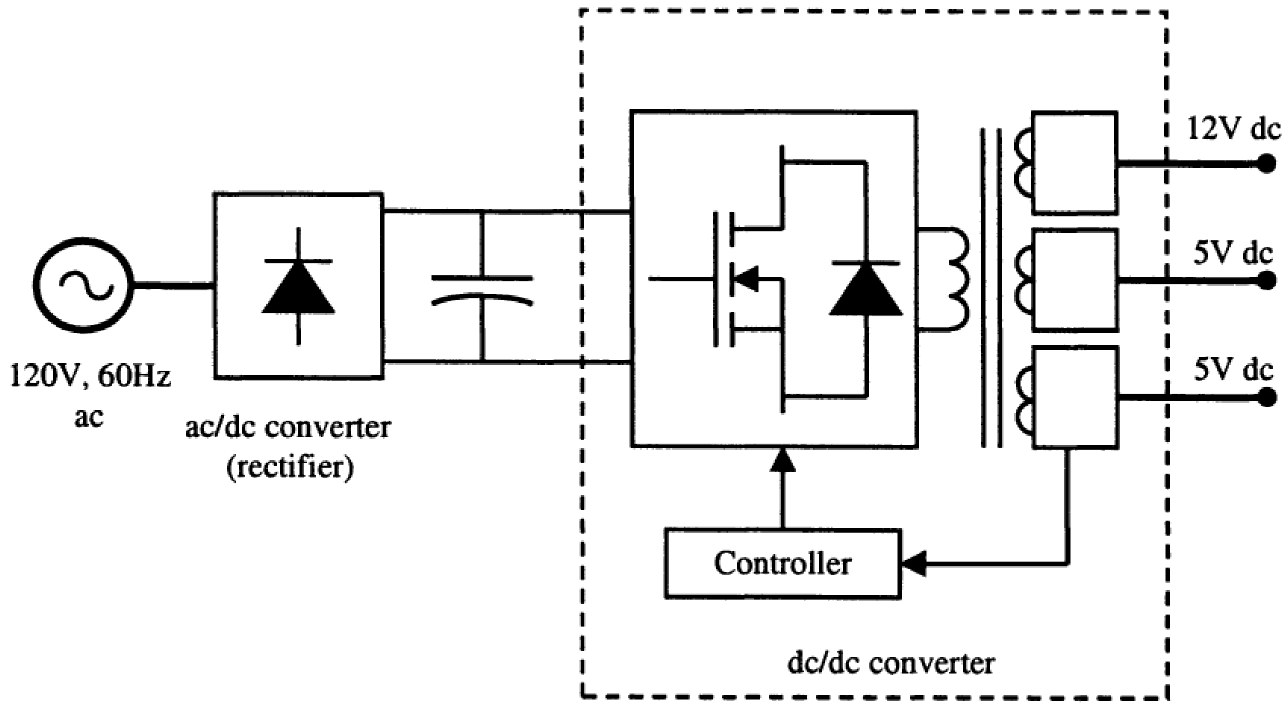
Linear Rectifier

Consist of:

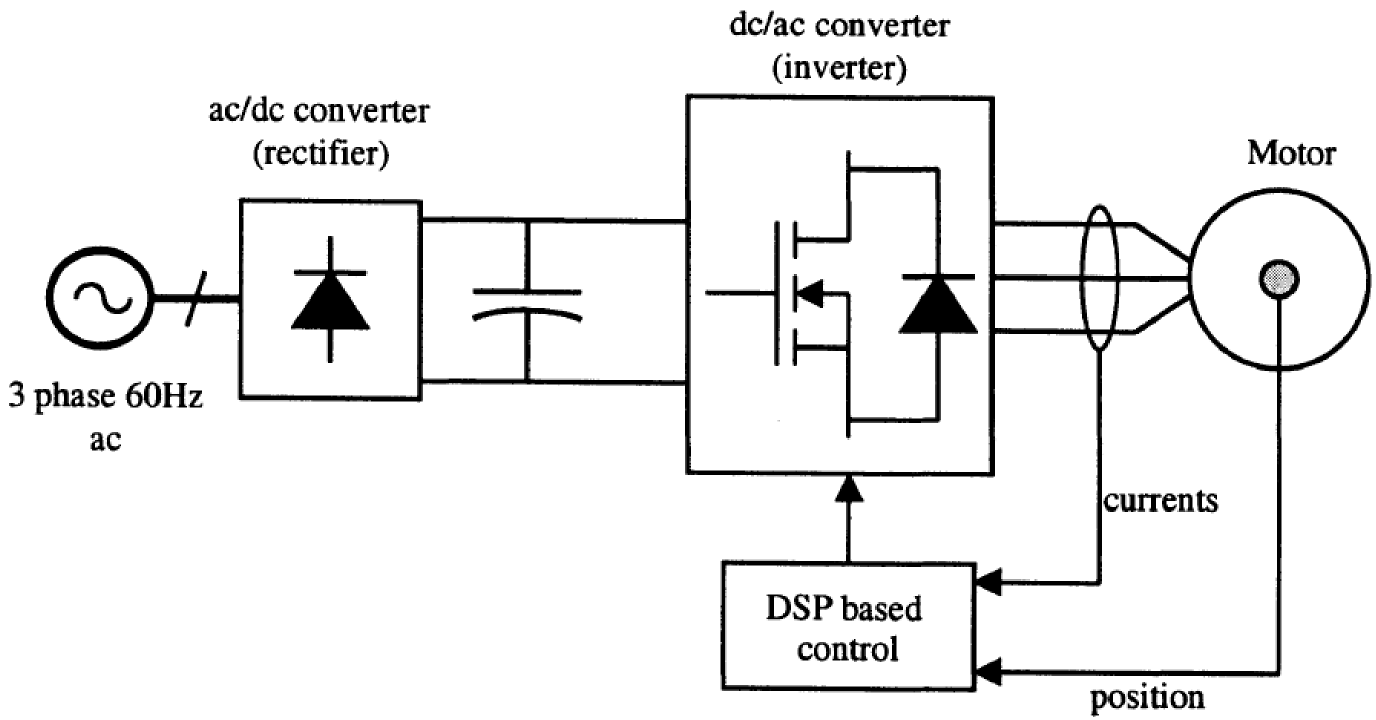
- Transformer: steps ac voltage up or down.
- Rectifier Diodes: change ac to “bumpy” dc.
- Filter Network: includes capacitors and inductors, smooths out the bumps.
- Voltage Regulator: keeps the voltage constant.
- Protection: usually a zener diode circuit.



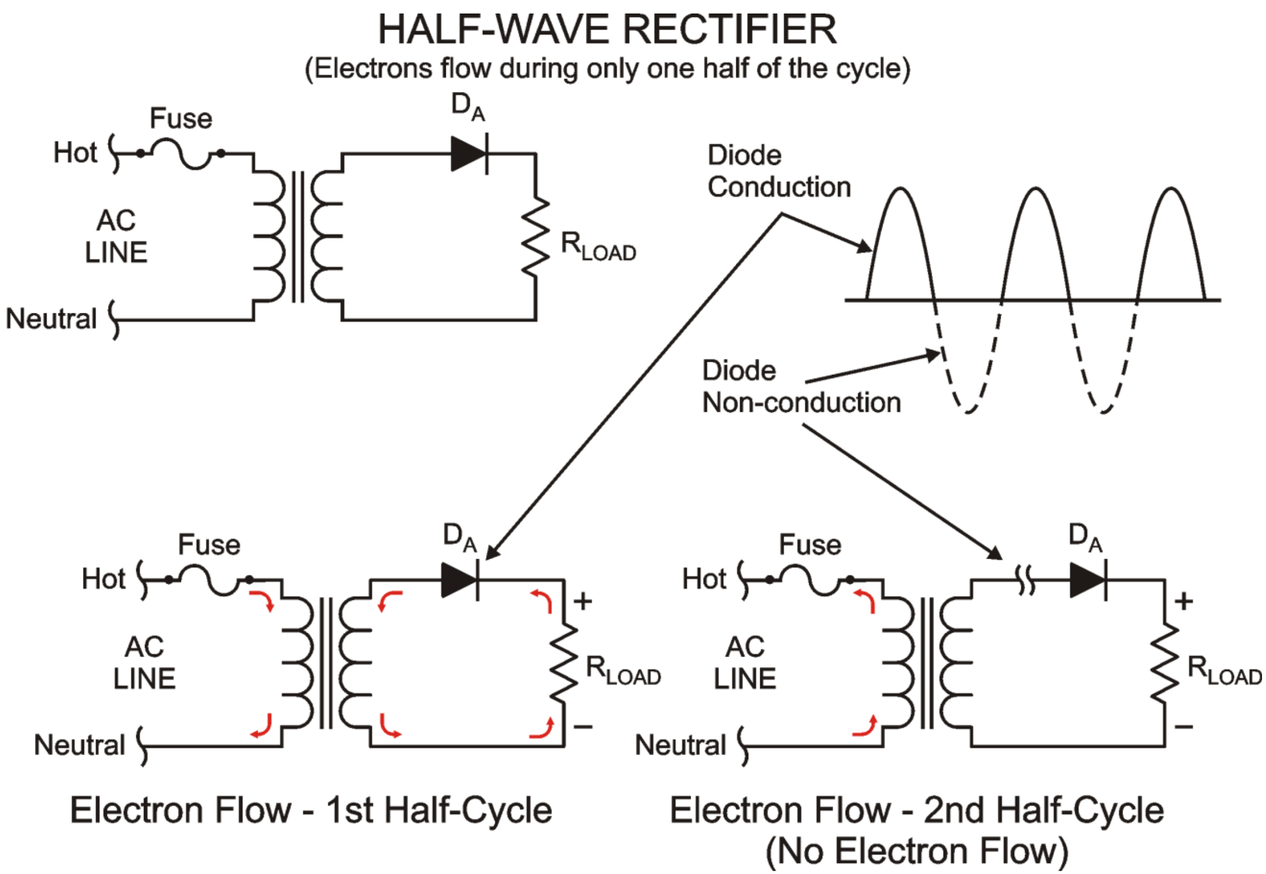
Example: Computer Power Supply



Example: Adjustable Motor Speed Drive

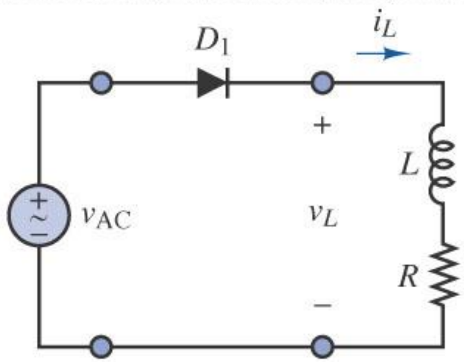


Power Supply Specifics: Half Wave Rectifier

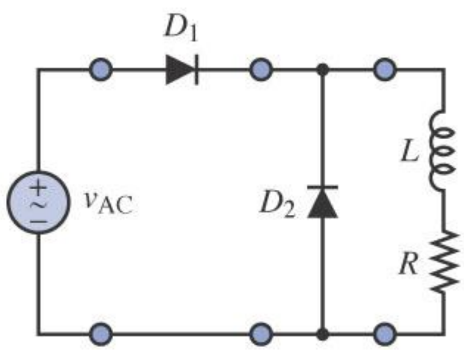


Source: ARRL

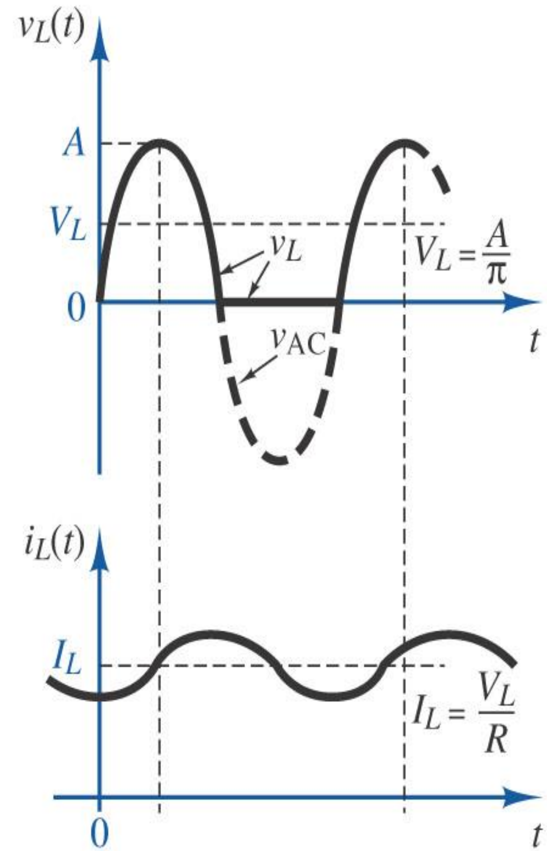
Half-Wave Rectifier



Simple half-wave rectifier



Same arrangement with freewheeling diode

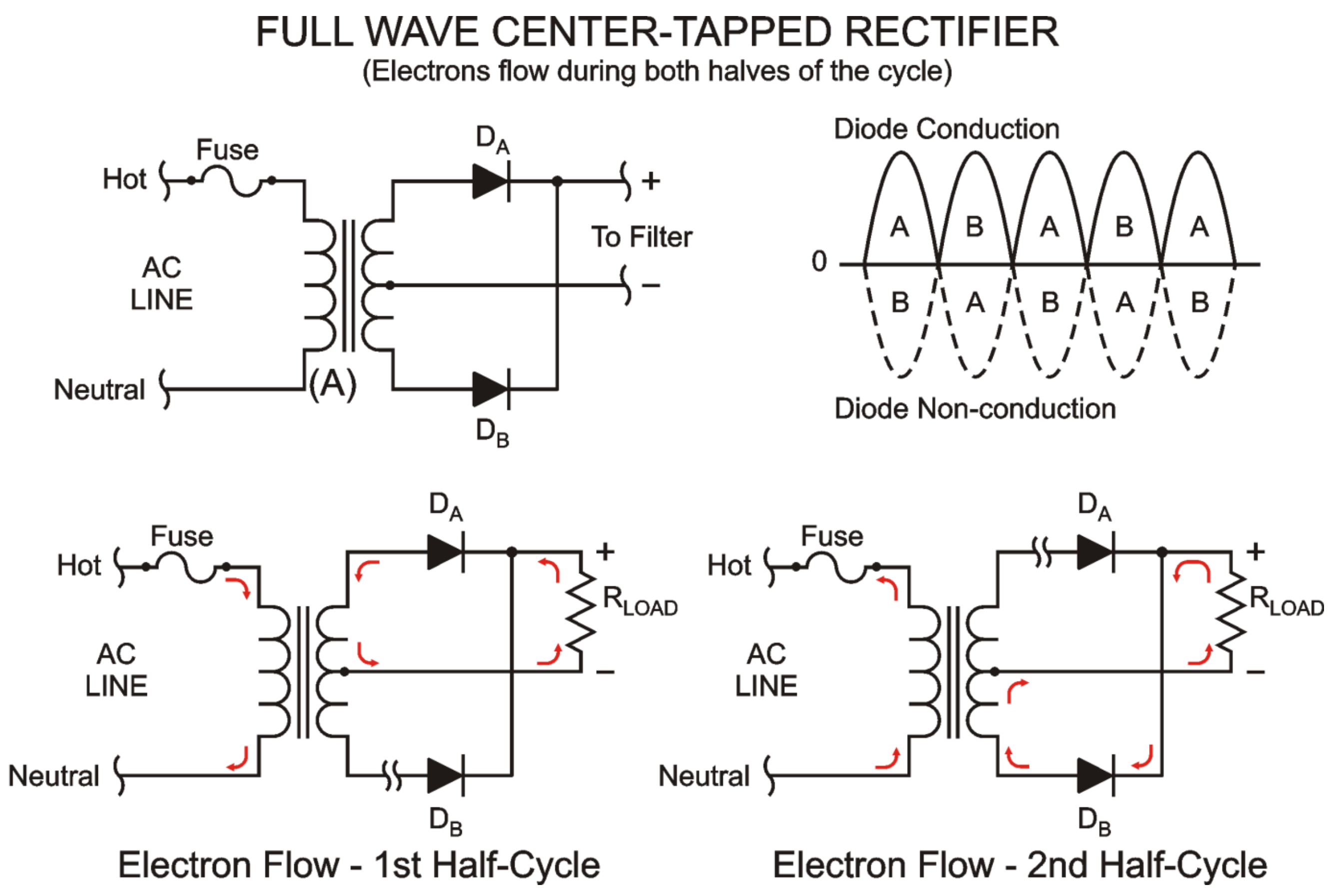


High ripple factor.

Low rectification efficiency.

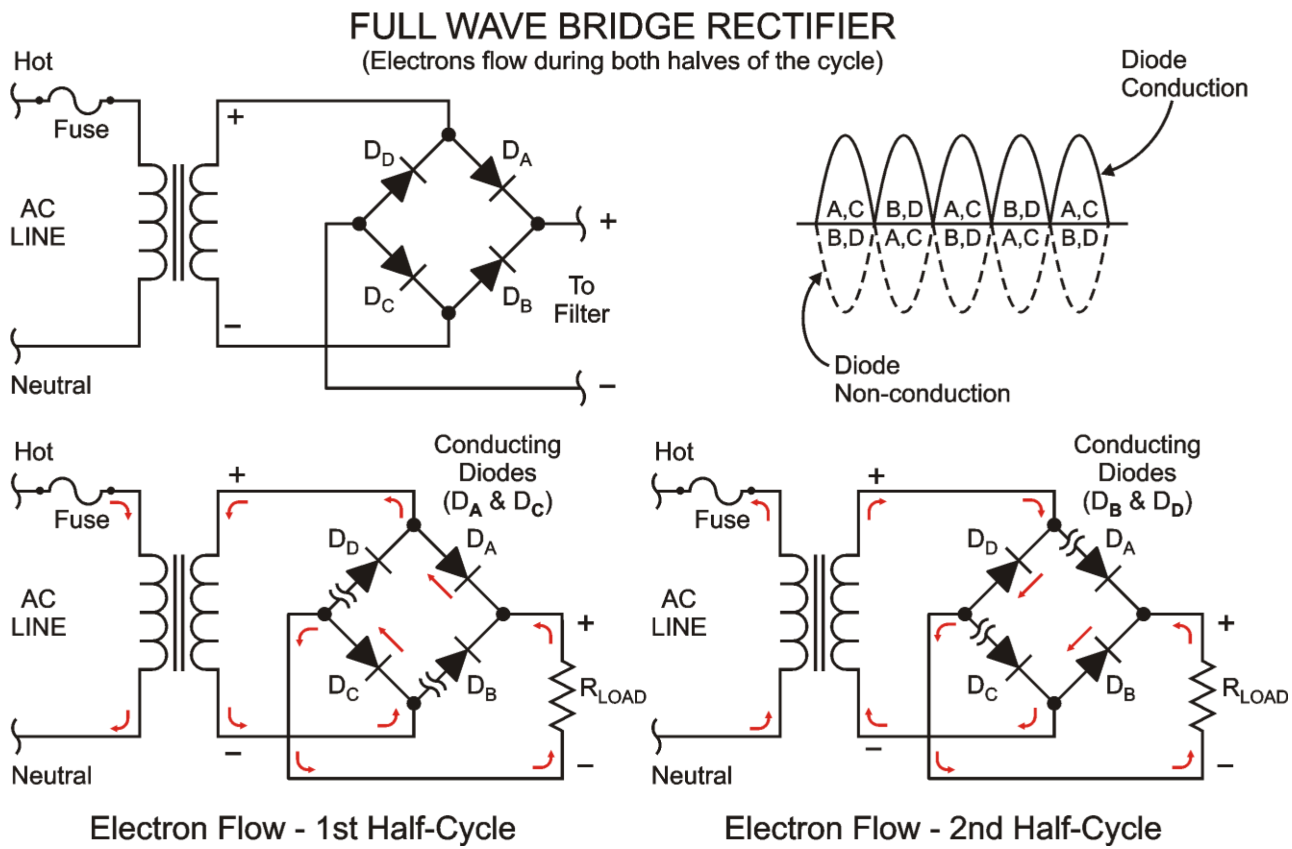
Low transformer utilization factor.

Power Supply Specifics
Full Wave Center-Tapped Rectifier



Source: ARRL

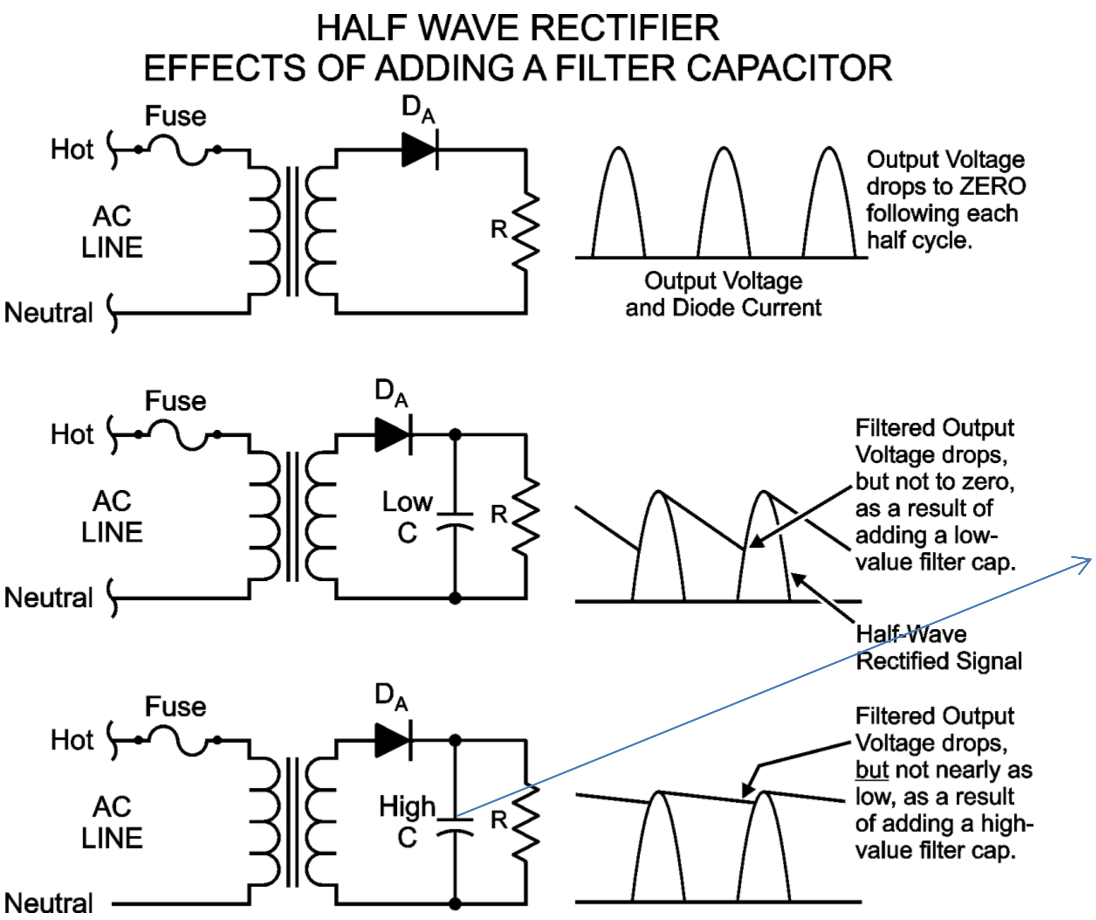
Power Supply: Full Wave Bridge Rectifier

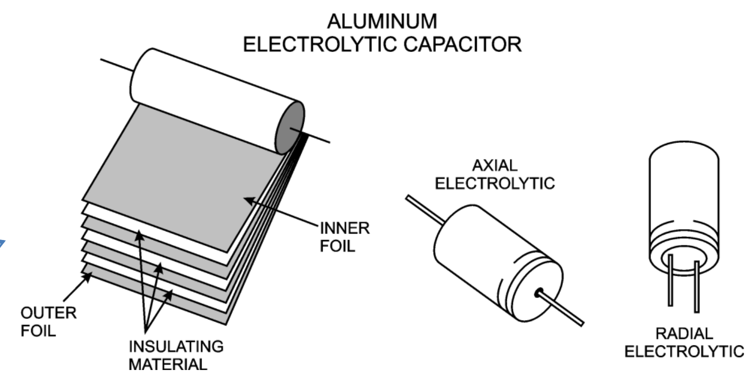


Source: ARRL

Filtering

Capacitors are used in power supply filter networks. The capacitors smooth out the rippled AC to DC.





Source: ARRL

Rectifier Performance Parameters

$\eta = P_{dc} / P_{ac}$ Rectification Efficiency

$V_{ac} = \sqrt{V_{rms}^2 - V_{dc}^2}$ $\qquad$ $P_{ac} = V_{rms} I_{rms}$

$FF = V_{rms} / V_{dc}$ $\qquad$ Form Factor

Ripple factor $\quad RF = \dfrac{V_{ac}}{V_{dc}} = \dfrac{\sqrt{V_{rms}^2 - V_{dc}^2}}{V_{dc}} = \sqrt{\dfrac{V_{rms}^2}{V_{dc}^2} - 1} = \sqrt{FF^2 - 1}$

Example 1: A half-wave rectifier has a pure resistive load of *R* Determine (a) The efficiency, (b) Form factor (c) Ripple factor.

$$V_{dc} = \frac{1}{2\pi}\int_0^{\pi} V_m \sin(\omega t)\, d\omega t = \frac{V_m}{2\pi}(-\cos\pi - \cos(0)) = \frac{V_m}{\pi} \qquad I_{dc} = \frac{V_{dc}}{R} = \frac{V_m}{\pi R}$$

$$V_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} (V_m \sin \omega t)^2} = \frac{V_m}{2} \qquad I_{rms} = \frac{V_m}{2\ R}$$

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{V_{dc} * I_{dc}}{V_{rms} * I_{rms}} = \frac{\frac{V_m}{\pi} * \frac{V_m}{\pi R}}{\frac{V_m}{2} * \frac{V_m}{2R}} = 40.53\%$$

$$FF = \frac{V_{rms}}{V_{dc}} = \frac{\frac{V_m}{2}}{\frac{V_m}{\pi}} = \frac{\pi}{2} = 1.57$$

$$RF = \frac{V_{ac}}{V_{dc}} = \sqrt{FF^2 - 1} = \sqrt{1.57^2 - 1} = 1.211$$

Example 2: A single-phase diode bridge rectifier has a purely resistive load of *R*=15 ohms and, *VS*=300 sin 314 *t* and unity transformer ratio. Determine (a) The efficiency, (b) Form factor, (c) Ripple factor, (d) and, (d) Input power factor.

$$V_{dc} = \frac{1}{\pi}\int_0^{\pi} V_m \sin\omega t \; d\omega t = \frac{2V_m}{\pi} = 190.956 \; V \qquad I_{dc} = \frac{2V_m}{\pi \; R} = 12.7324 \quad A$$

$$V_{rms} = \left[\frac{1}{\pi}\int_0^{\pi} (V_m \sin\omega t)^2 \; d\omega t \right]^{1/2} = \frac{V_m}{\sqrt{2}} = 212.132 \;\; V$$

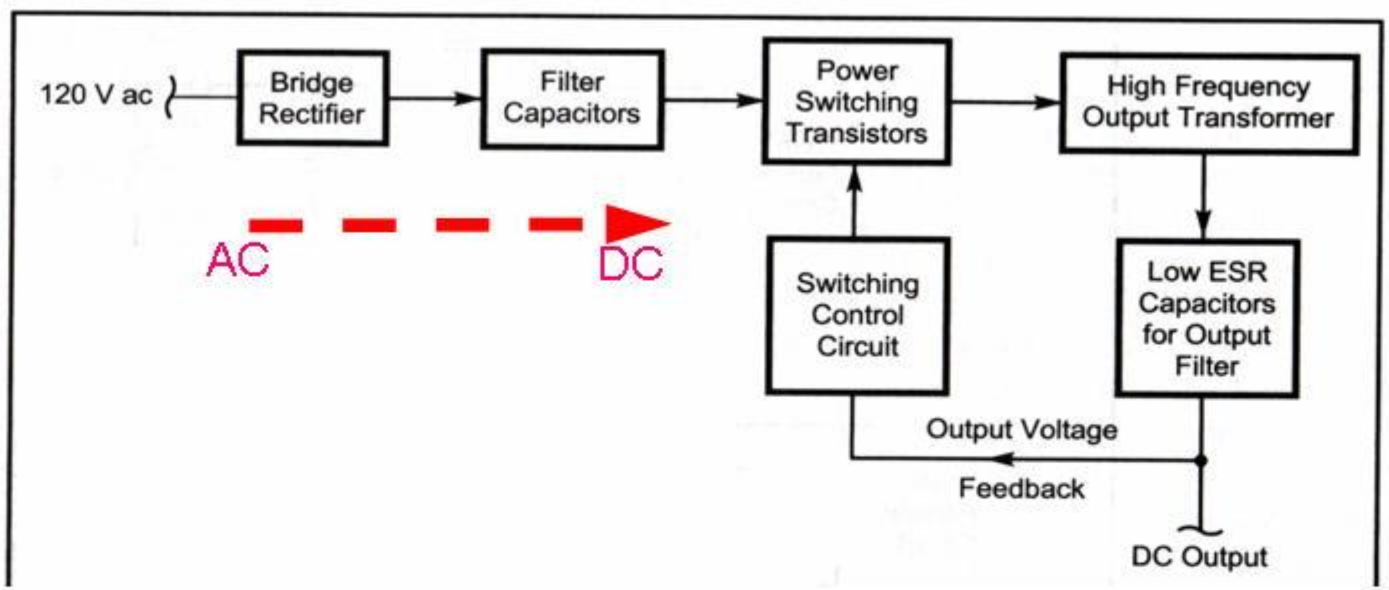
$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{V_{dc}\, I_{dc}}{V_{rms}\, I_{rms}} = 81.06 \;\; \% \qquad FF = \frac{V_{rms}}{V_{dc}} = 1.11$$

$$RF = \frac{V_{ac}}{V_{dc}} = \frac{\sqrt{V_{rms}^2 - V_{dc}^2}}{V_{dc}} = \sqrt{\frac{V_{rms}^2}{V_{dc}^2} - 1} = \sqrt{FF^2 - 1} = 0.482$$

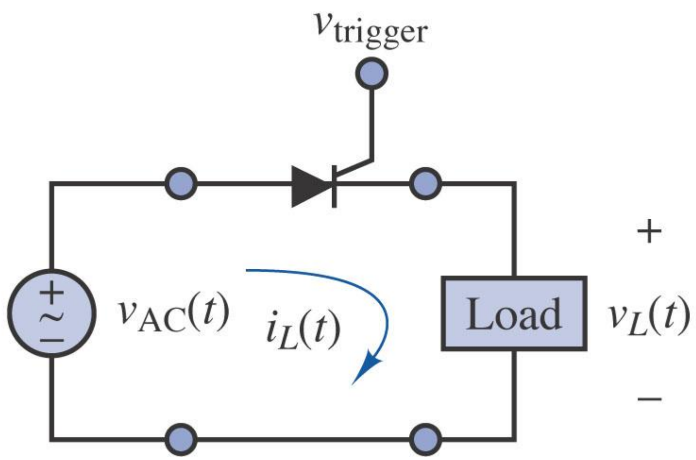
Input power factor = $$\frac{\text{Real Power}}{Apperant \;\; Power} = \frac{V_S \;\; I_S \cos\phi}{V_S \;\; I_S} = 1$$

Alternative! Controlled Switching Mode

- By using linear regulator, the AC to DC converter is not efficient and of large size and weight!
- Using Switching-Mode
- High efficiency
- Small size and light weight
- For high power (density) applications.
- **Use Power Electronics!**



Controlled Rectifier Circuit



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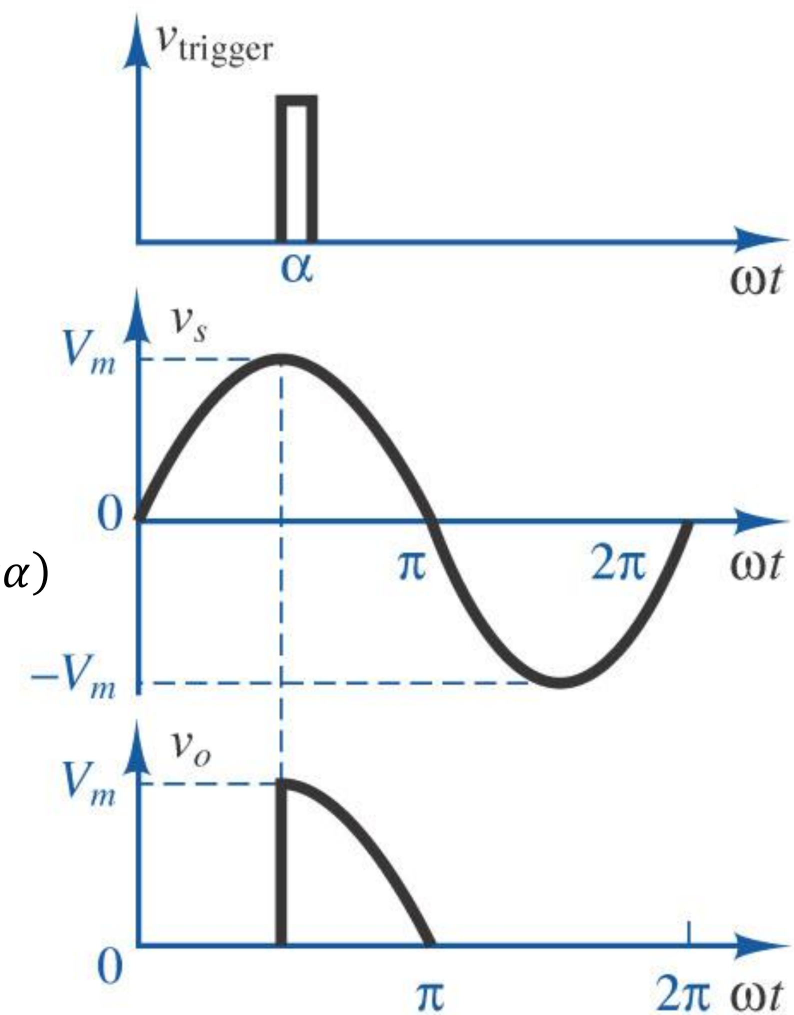
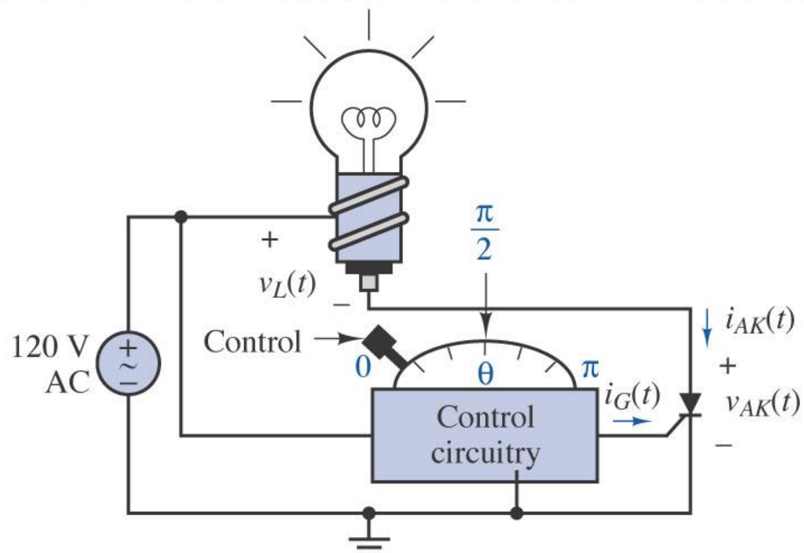


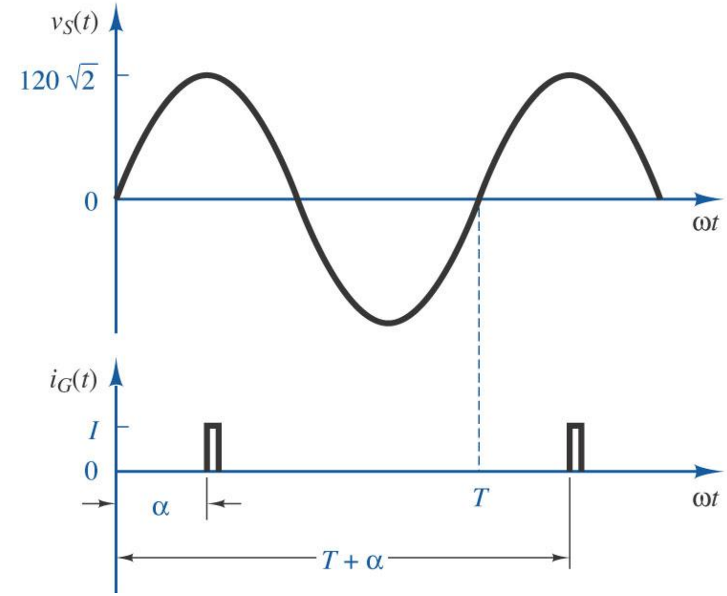
$$V_{dc} = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_p sin\omega t d\omega t = \frac{V_p}{2\pi}(1 + cos\alpha)$$

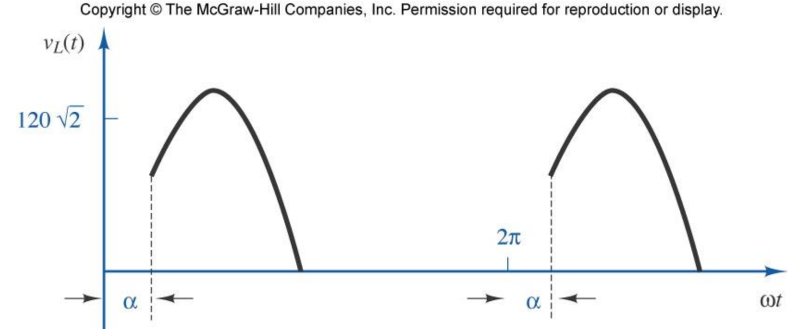
$$V_{rms} = \left[\frac{1}{2\pi}\int_{\alpha}^{\pi} \quad {V_p}^2 sin^2\omega t d\omega t\right]^{1/2}$$

$$=\frac{V_p}{2}\left[\frac{1}{\pi}\left(\pi - \alpha + \frac{sin2\alpha}{2}\right)\right]^{1/2}$$

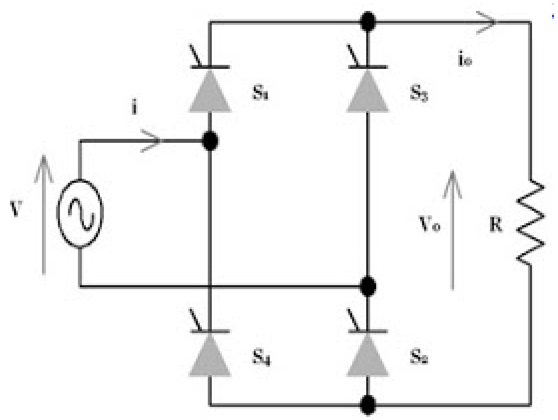
Example: Consider the following SCR-based variable voltage supply. For RL=240 Ohm, derive the RMS value of the load voltage as a function of the firing angle, and then calculate the load power when the firing angle α is 0, $\pi/2$, and π.







Full-Wave Rectifiers Using SCR



$$V_{dc} = \frac{2}{2\pi}\int_{\alpha}^{\pi+\alpha} V_p sin\omega t d\omega t = \frac{2V_p}{\pi}(cos\alpha)$$

$$V_{rms} = \left[\frac{2}{2\pi}\int_{\alpha}^{\pi+\alpha} \quad V_p{}^2 sin^2\omega t d\omega t\right]^{1/2}$$

$$= \frac{V_p}{\sqrt{2}} = V_s$$

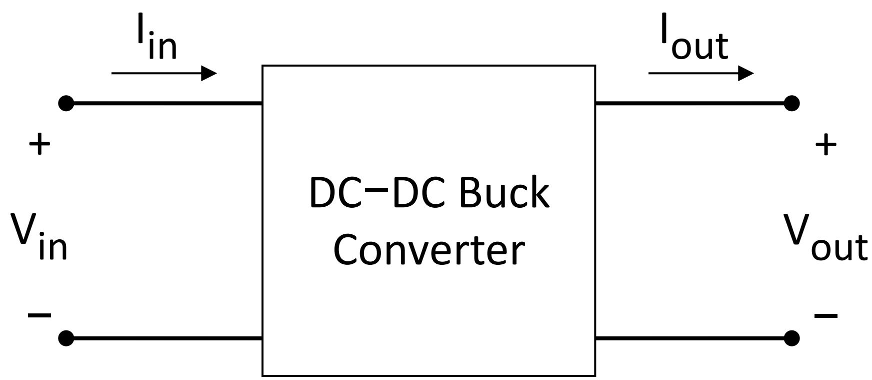
With a purely resistive load, SCRs S_1 and S_2 can conduct from α to π, and SCRs S_3 and S_4 can conduct from $\alpha+\pi$ to 2π.

DC to AC Conversion

The converter that changes a DC to AC is called an inverter. Earlier inverters were built with SCRs. Since the circuitry required to turn the SCR off tends to be complex, other power semiconductor devices such as bipolar junction transistors, power MOSFETs, insulated gate bipolar transistors (IGBT) and MOS-controlled thyristors (MCTs) are used nowadays. Currently only the inverters with a high power rating, such as 500 kW or higher.

- Emergency lighting systems
- AC variable speed drives
- Uninterrupted power supplies
- Frequency converters.

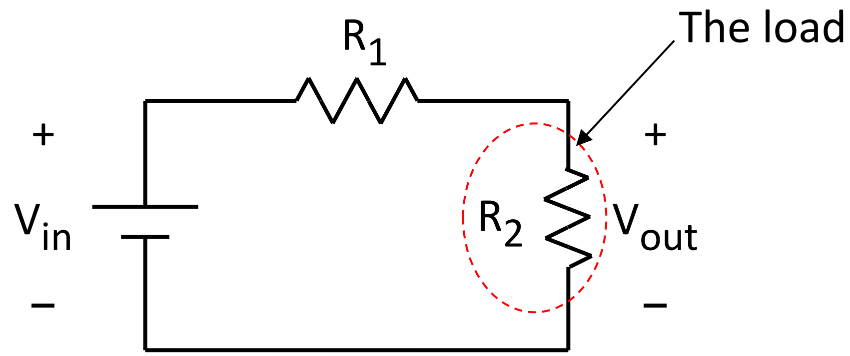
DC-DC Conversion: To efficiently Reduce DC Voltage



Lossless objective: $P_{in} = P_{out}$, which means that $V_{in}I_{in} = V_{out}I_{out}$

$$\frac{V_{out}}{V_{in}} = \frac{I_{in}}{I_{out}}$$

DC–DC Converter: Non-Efficient Way!



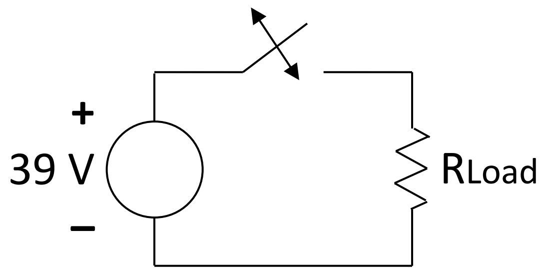
$$V_{out} = V_{in} \bullet \frac{R_2}{R_1 + R_2}$$

Voltage Divider

$$\eta = \frac{R_2}{R_1 + R_2} = \frac{V_{out}}{V_{in}}$$

If V_{in} = 39V, and V_{out} = 13V, efficiency η is only 33%!

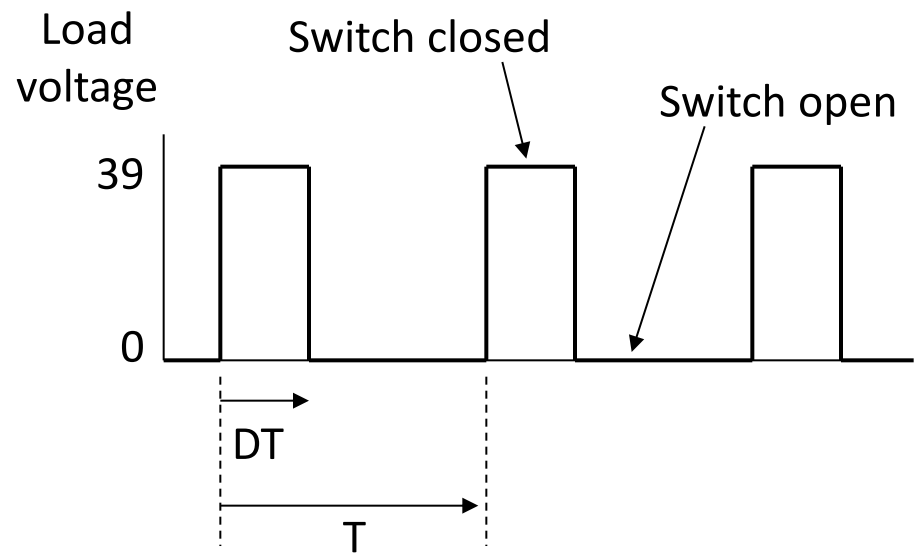
Another Technique: Lossless Conversion



Switch state, Load voltage

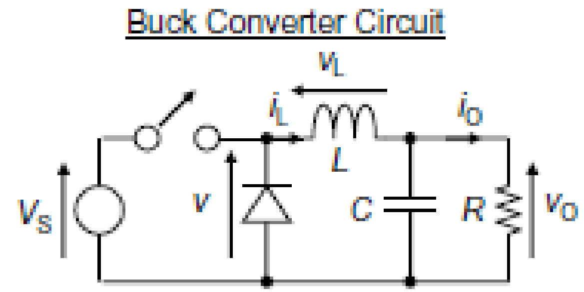
Closed, 39 V

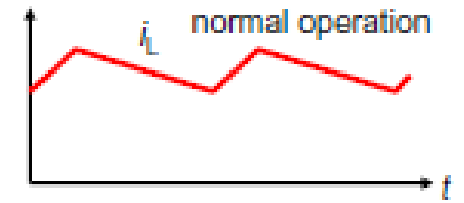
Open, 0 V

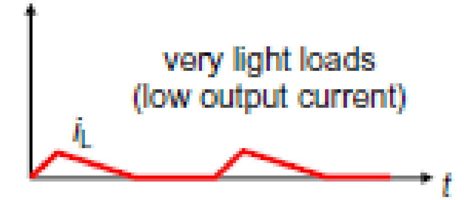


Buck (Step Down) Converter in Brief

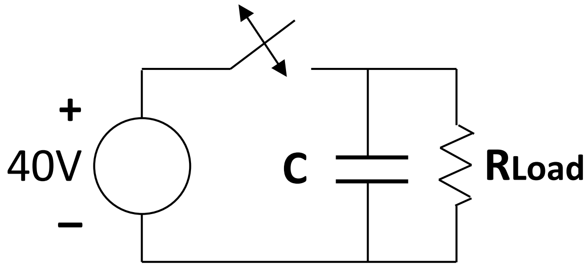
- Step down converter
- Switch
- Low-pass LC filter
- Diode
- Transition Between
  - Continuous conduction
  - Discontinuous conduction



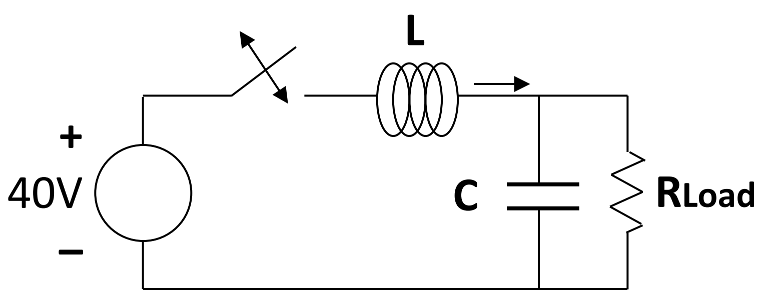




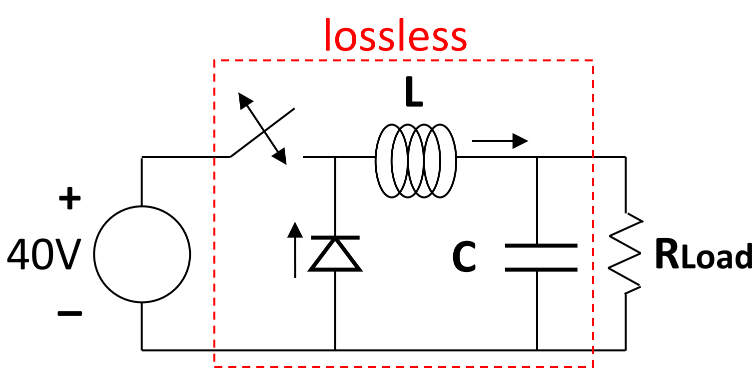
Examples of DC Conversion



Try adding a large C in parallel with the load to control ripple. But if the C has 13Vdc, then when the switch closes, the source current spikes to a huge value and burns out the switch.



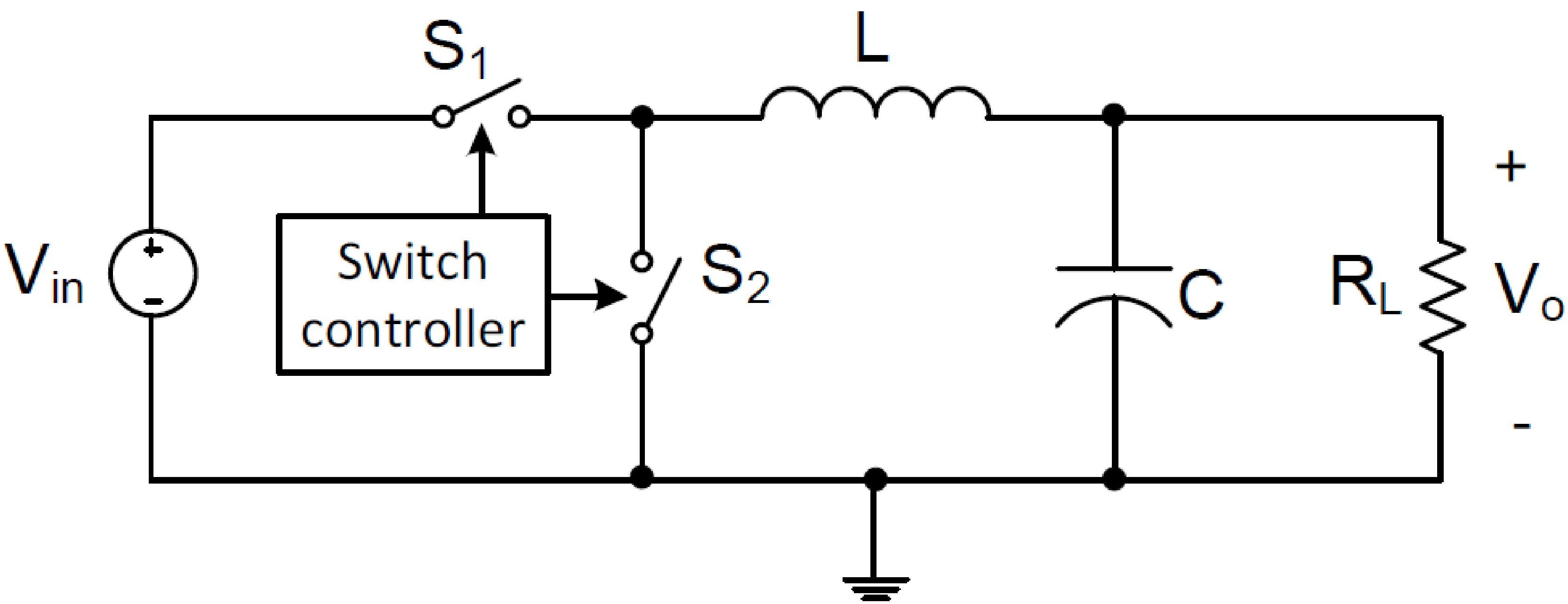
Try adding an L to prevent the huge current spike. But now, if the L has current when the switch attempts to open, the inductor's current momentum and resulting *Ldi/dt* burns out the switch.



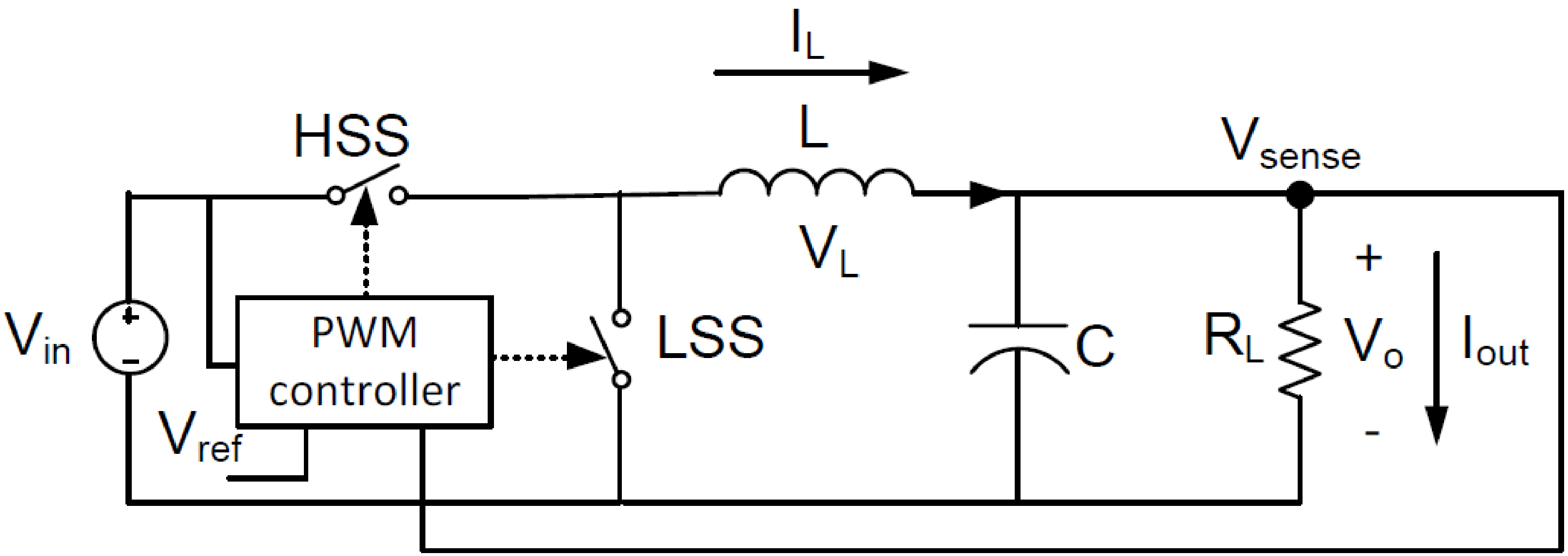
A DC-DC Buck Converter

By adding a "free wheeling" diode, the switch can open and the inductor current can continue to flow. With high-frequency switching, the load voltage ripple can be reduced to a small value.

Typical DC/DC Buck Converter Circuit

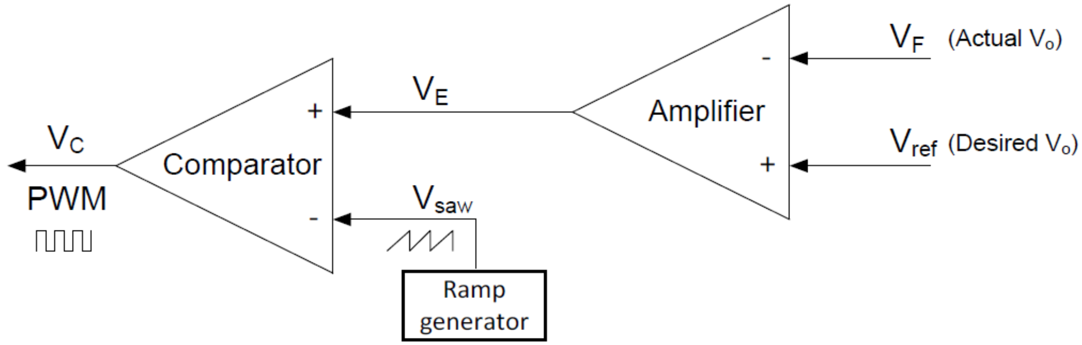


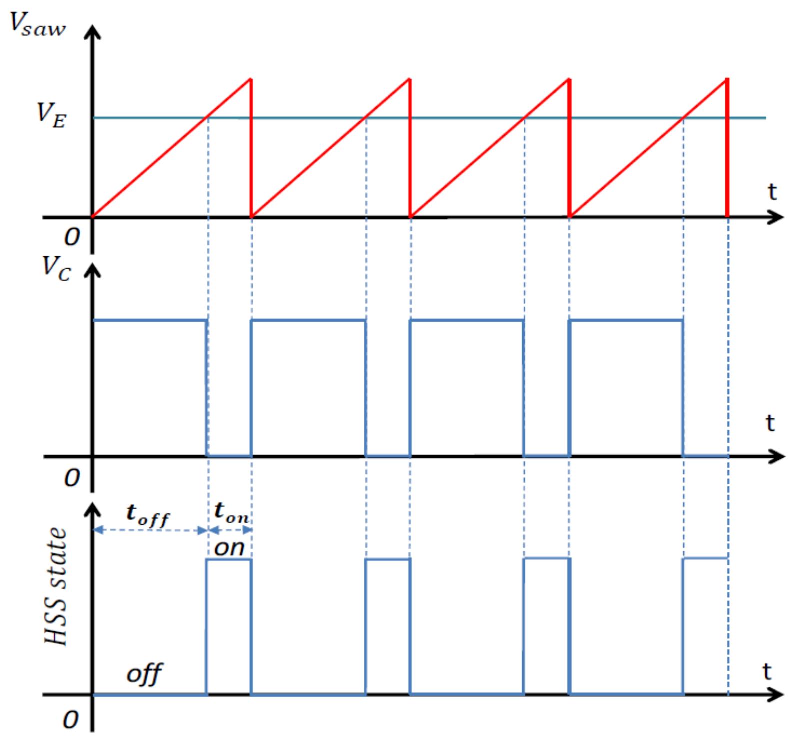
Buck Converter with Feedback Loop



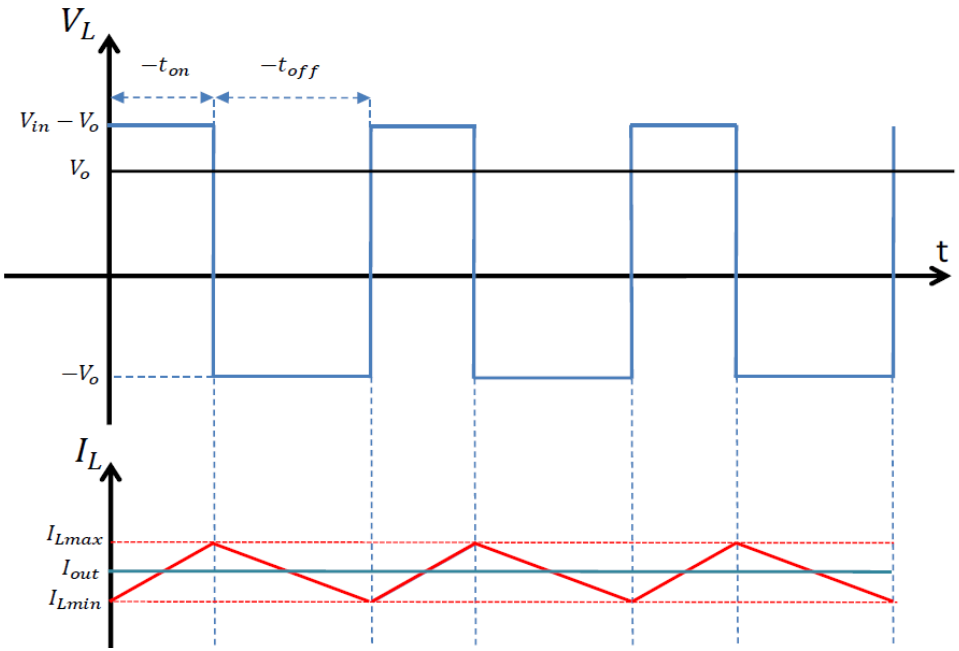
$$D = \frac{t_{on}}{T} = \frac{t_{on}}{t_{on} + t_{off}} = f_{sw}.t_{on}$$

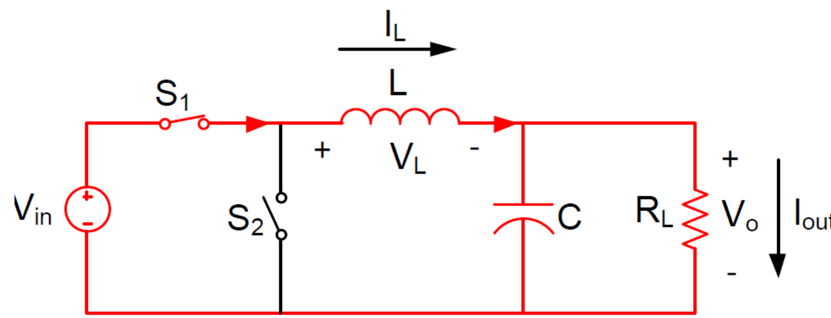
PWM Generator

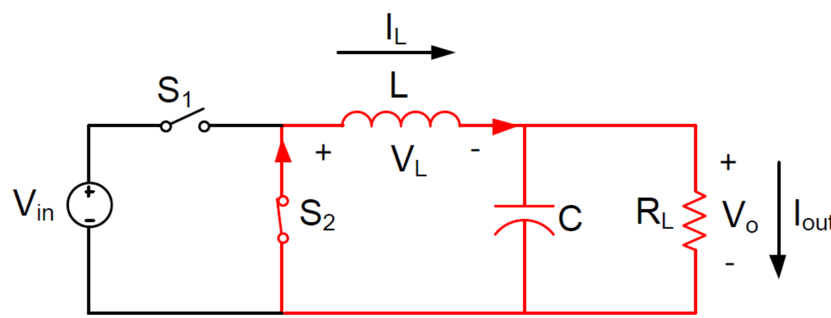




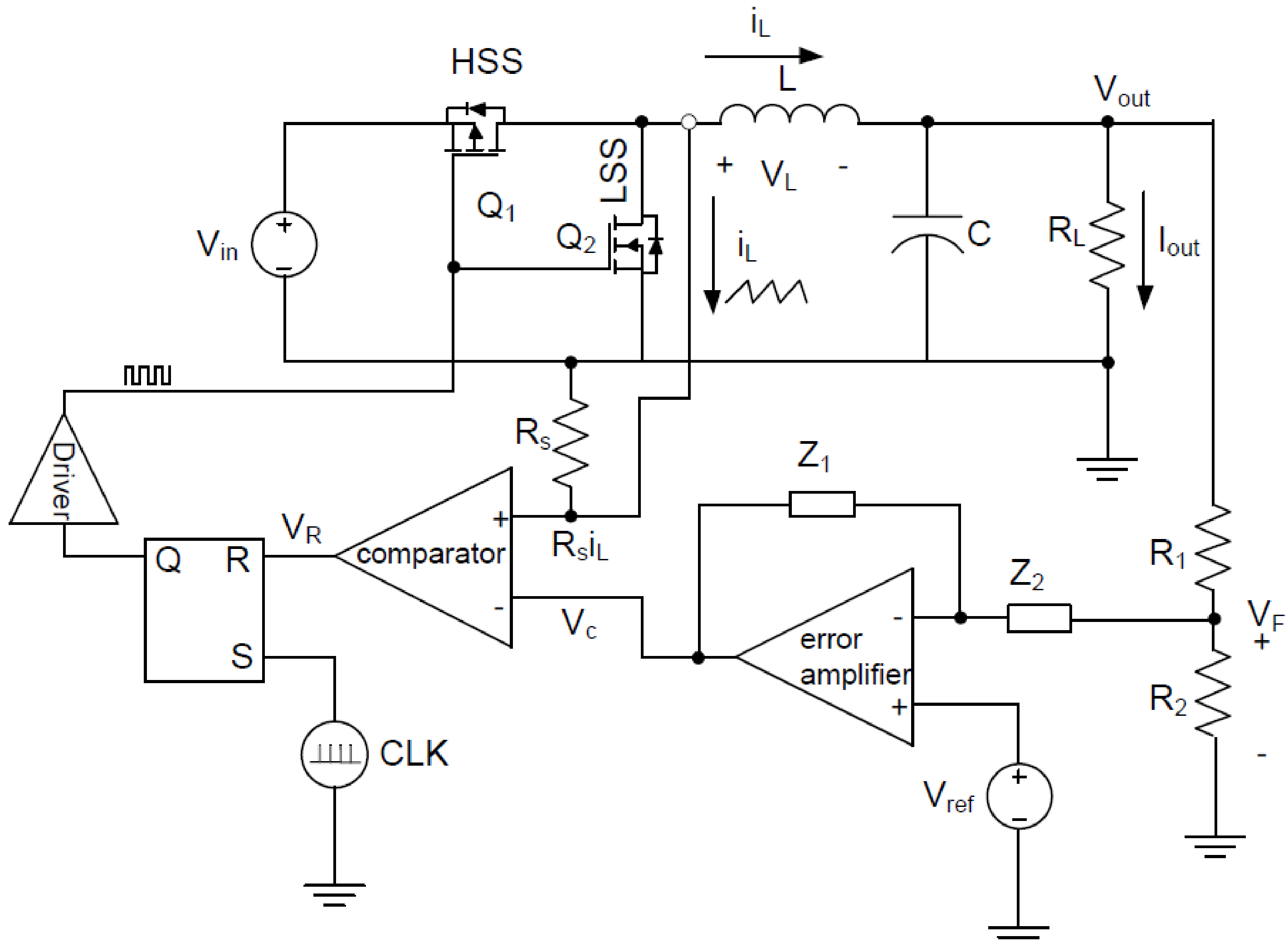
Duty Cycle Calculation for Buck Converter





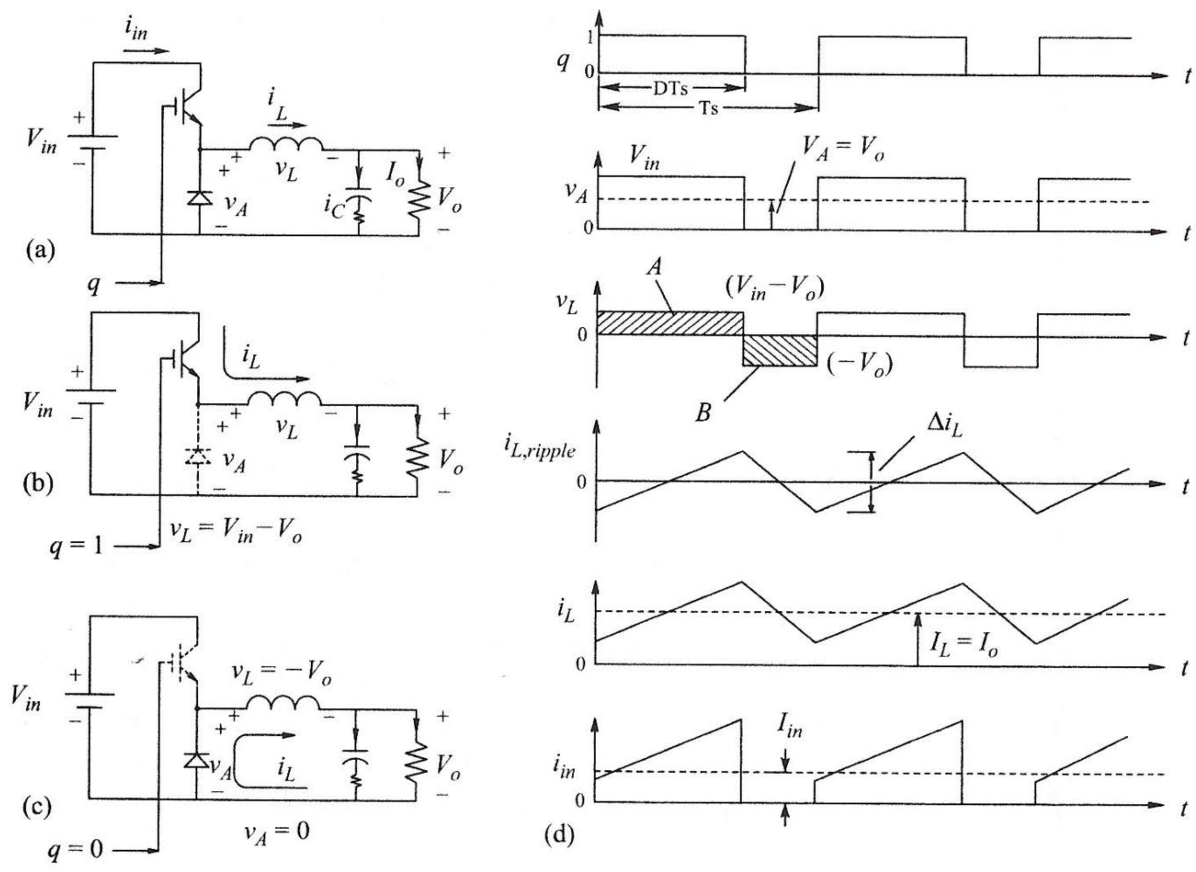


PWM Buck Converter with Current Mode Control (CMC)

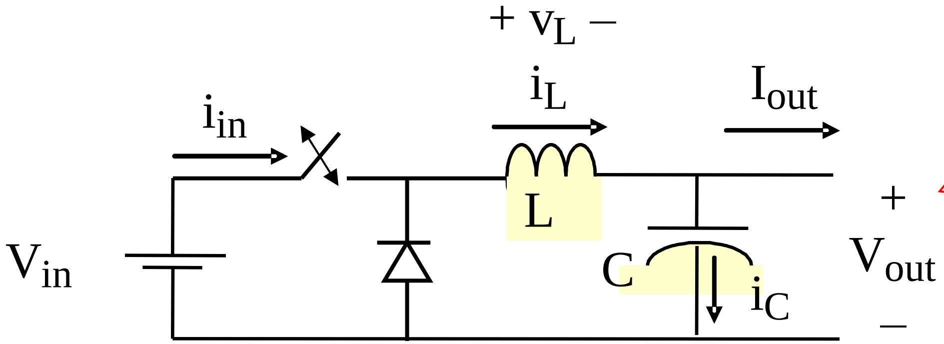


Buck Converter Analysis

- $V_o = V_A = DV_{in}$; D = switch duty ratio
- $\Delta_{iL} = \frac{1}{L}(V_{in} - V_o)DT_s = \frac{1}{L}V_o(1 - D)T_s$
- $I_L = Io = \frac{Vo}{R}$

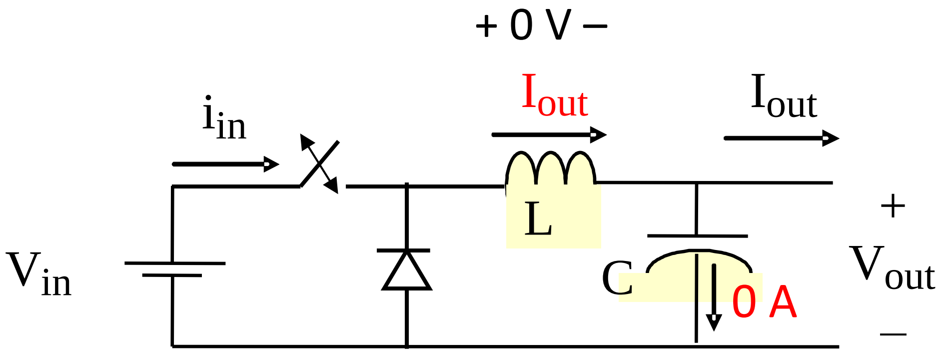


Buck (step Down) Converter



- Assume large C so that V_{out} has very low ripple
- Since V_{out} has very low ripple, then assume I_{out} has very low ripple

What do we learn from inductor voltage and capacitor current in the average sense?



Designing a Buck Converter

- Design Criteria
  - Calculate the required inductor
  - Calculate the output capacitor
  - Select the input capacitor
  - Select the diode
  - Choose the MOSFET
  - Calculate the converter Efficiency
- For a Buck DC-DC converter we first calculate the required inductor and output capacitor specifications. Then determine the input capacitor, diode, and MOSFET characteristics. With the selected components, we will calculate the system efficiency.

Designing a Buck Converter

Assume:

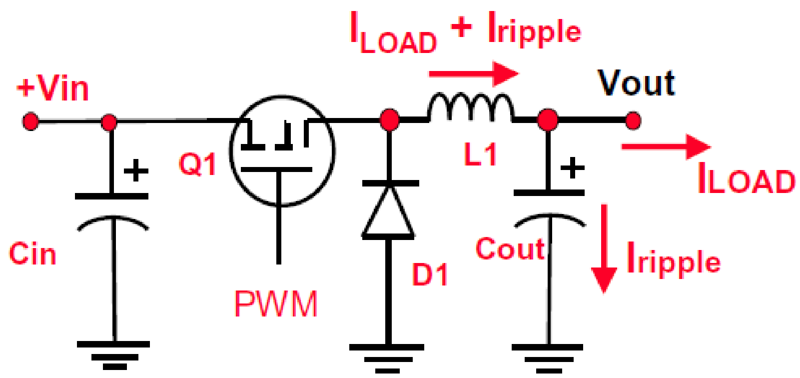
V_{in} = 12 V

V_{OUT} = 5 volts

I_{LOAD} = 2 amps

F_{sw} = 400 KHz

D = V_{in} / V_{out} = 5V /12V = 0.416



Define Ripple current:

$I_{ripple} = 0.3 \bullet I_{LOAD}$ (typically 30%)

For an Inductor: $V = L \bullet \Delta I / \Delta T$

Rearrange and substitute:

L = (Vin – Vout) • (D / Fsw) / Iripple

Calculate:

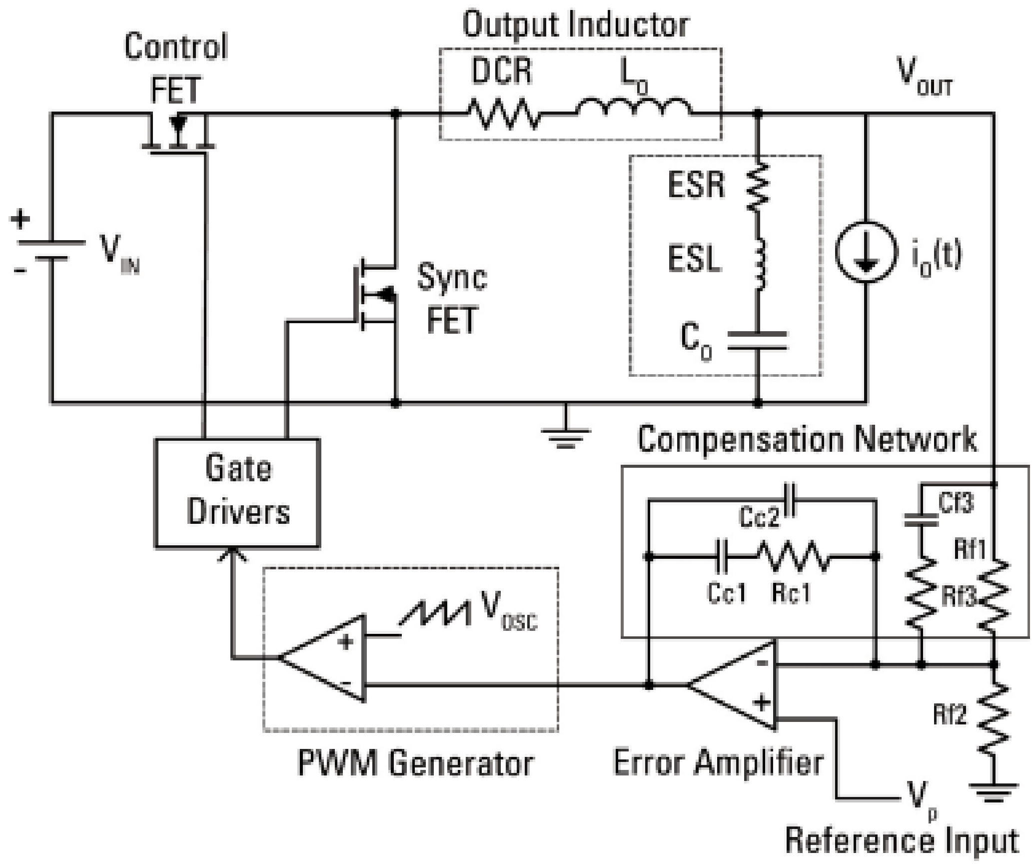
L = 7 V • (0.416 / 400 kHz) / 0.6A

L = 12.12 uh

Select C, Diode (Schottky), and the MOSFET

Calculate the Efficiency

Buck Converter with Full Control System

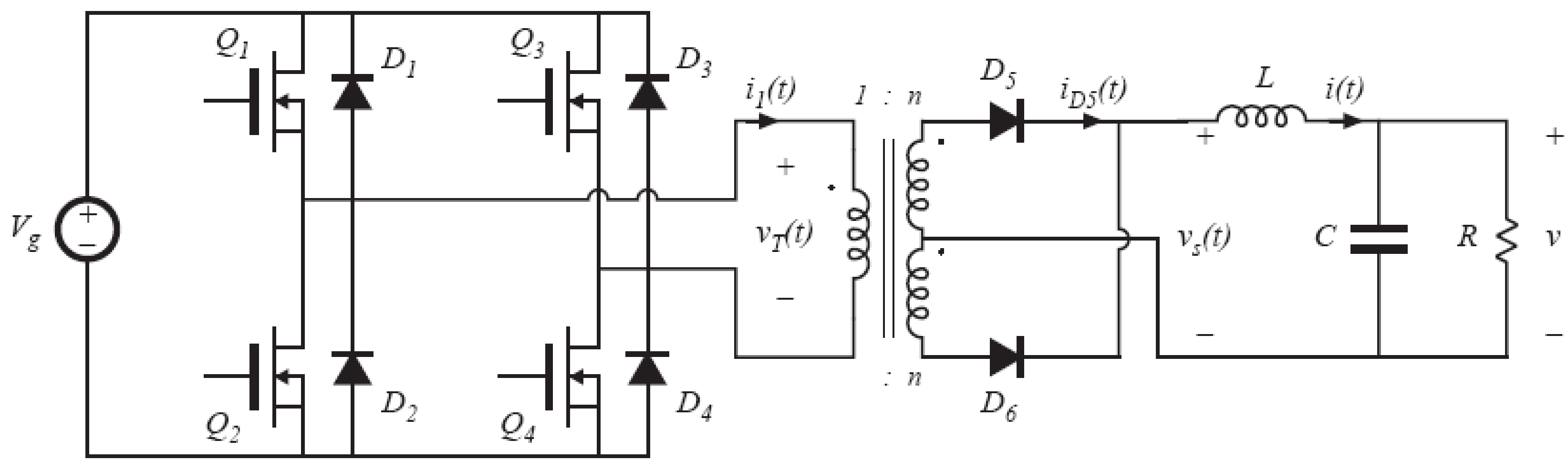


Example

- In **Buck** converter, L = 24μF (steady-state): V_{in} = 20V; D = 0.6; P_o = 14V; f_s = 200 kHz. Calculate and draw the waveform.

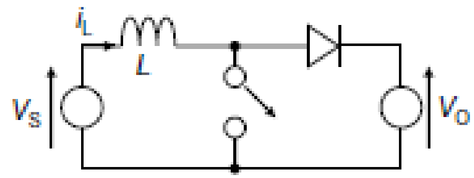
Full-Bridge and Half-Bridge Isolated Buck Converters

Full-bridge isolated buck converter

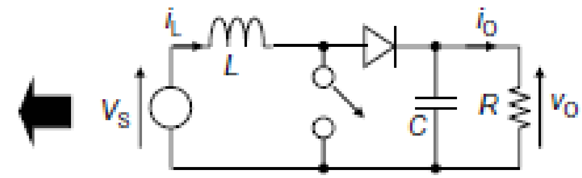


Boost (Step Up) Converter

- Step-up
- Same components
- Different topology!

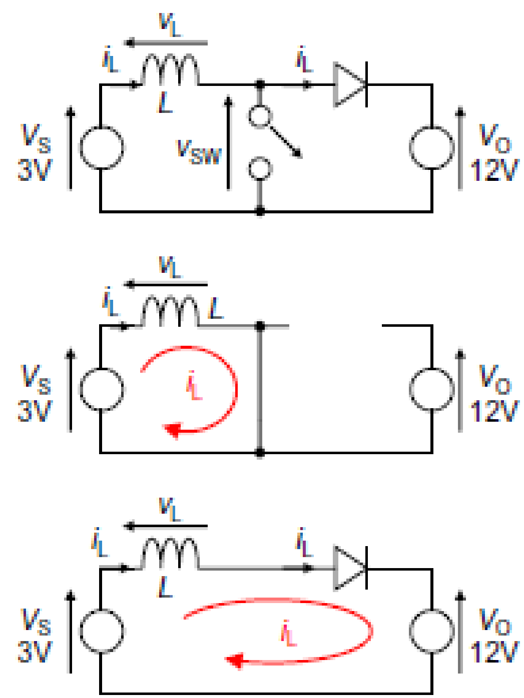


boost converter operating into a voltage source



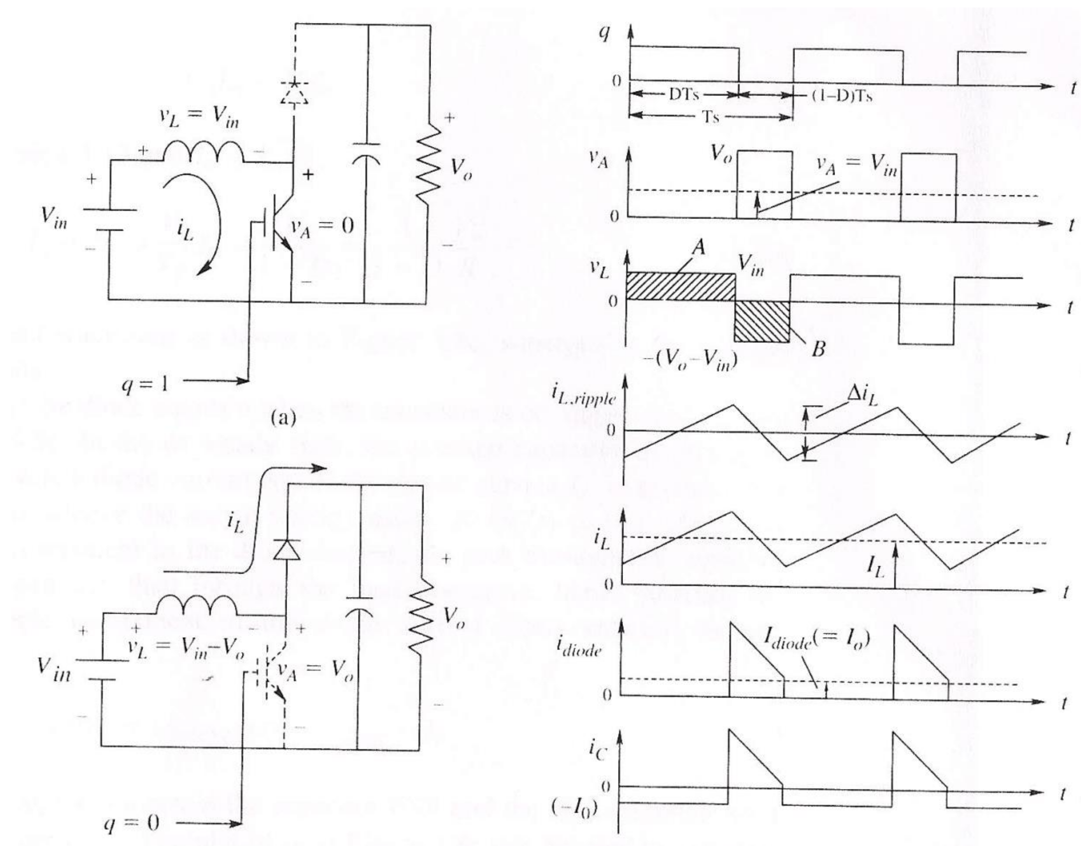
boost converter with resistive load

- See stages of operation



Boost Converter

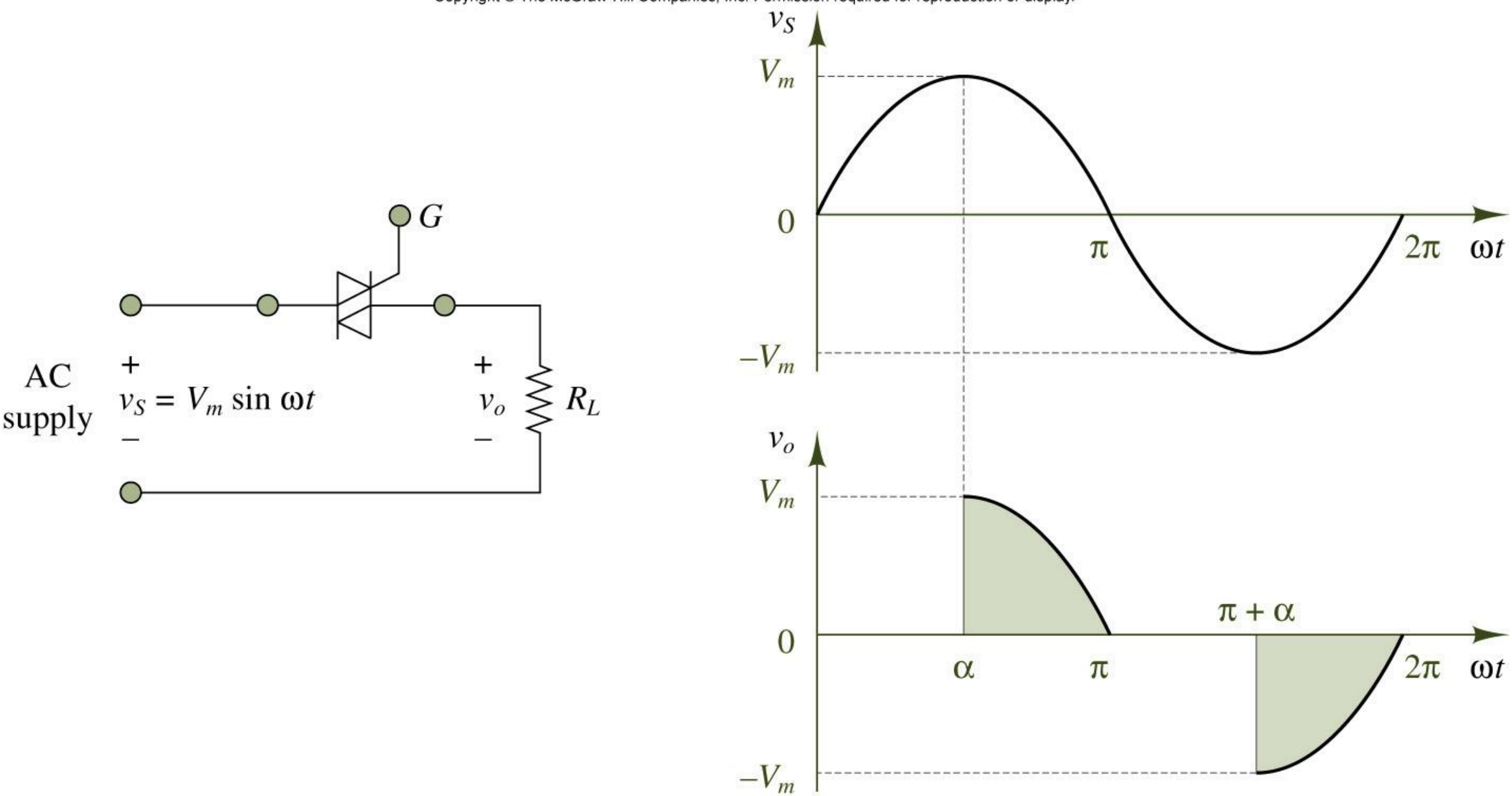
- $\Delta_{iL} = \frac{1}{L}(V_{in})DT_s = \frac{1}{L}(V_o - V_{in})(1-D)T_s$
- $\frac{V_o}{V_{in}} = \frac{1}{1-D}$



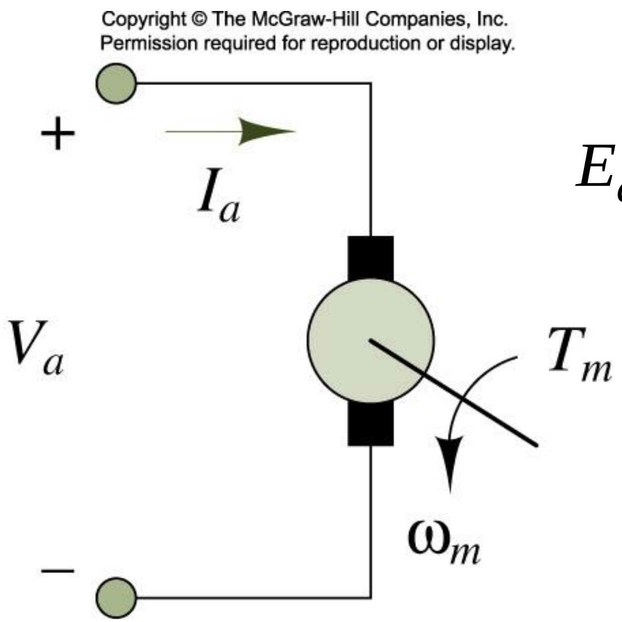
AC to AC Converter

- A cycloconverter or a cycloinverter converts an ac voltage, such as the mains supply, to another ac voltage. The amplitude and the frequency of input voltage to a cycloconverter tend to be fixed values, whereas both the amplitude and the frequency of output voltage of a cycloconverter tend to be variable.
- Tthe circuit that converts an ac voltage to another ac voltage at the same frequency is known as an AC-chopper. A typical application of a cycloconverter is to use it for controlling the speed of an AC traction motor and most of these cycloconverters have a high power output, of the order a few megawatts and SCRs are used in these circuits. In contrast, low cost, low power cycloconverters for low power ac motors are also in use and many of these circuit tend to use TRIACS in place of SCRs.
- Unlike an SCR which conducts in only one direction, a TRIACS is capable of conducting in either direction and like an SCR, it is also a three terminal device. It may be noted that the use of a cycloconverter is not as common as that of an inverter and a cycloinverter is rarely used.

AC-AC Converter Circuit and Waveform

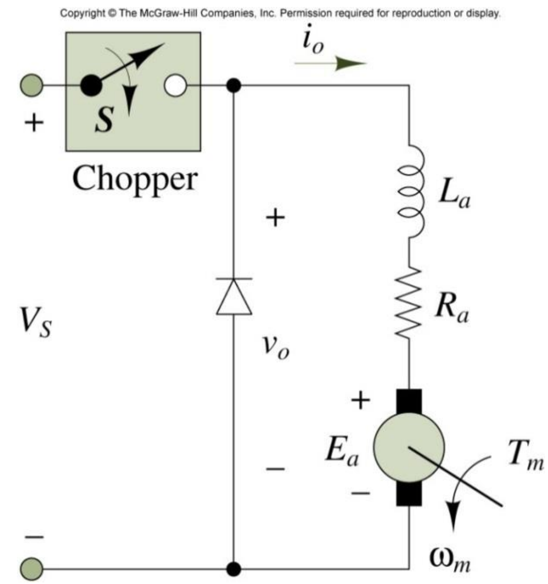


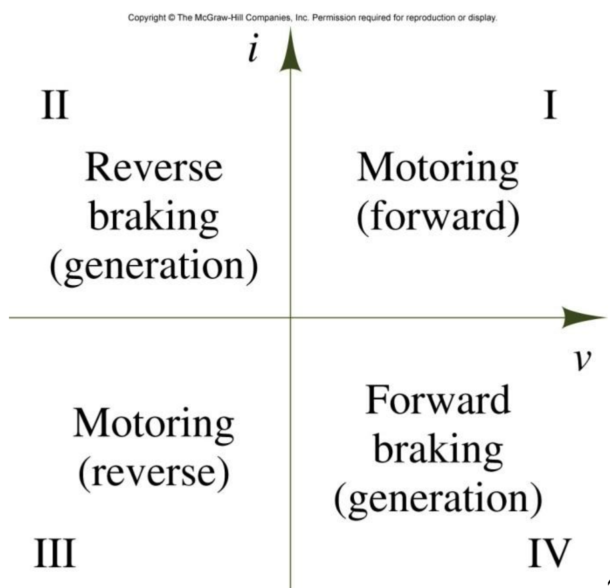
DC Motor



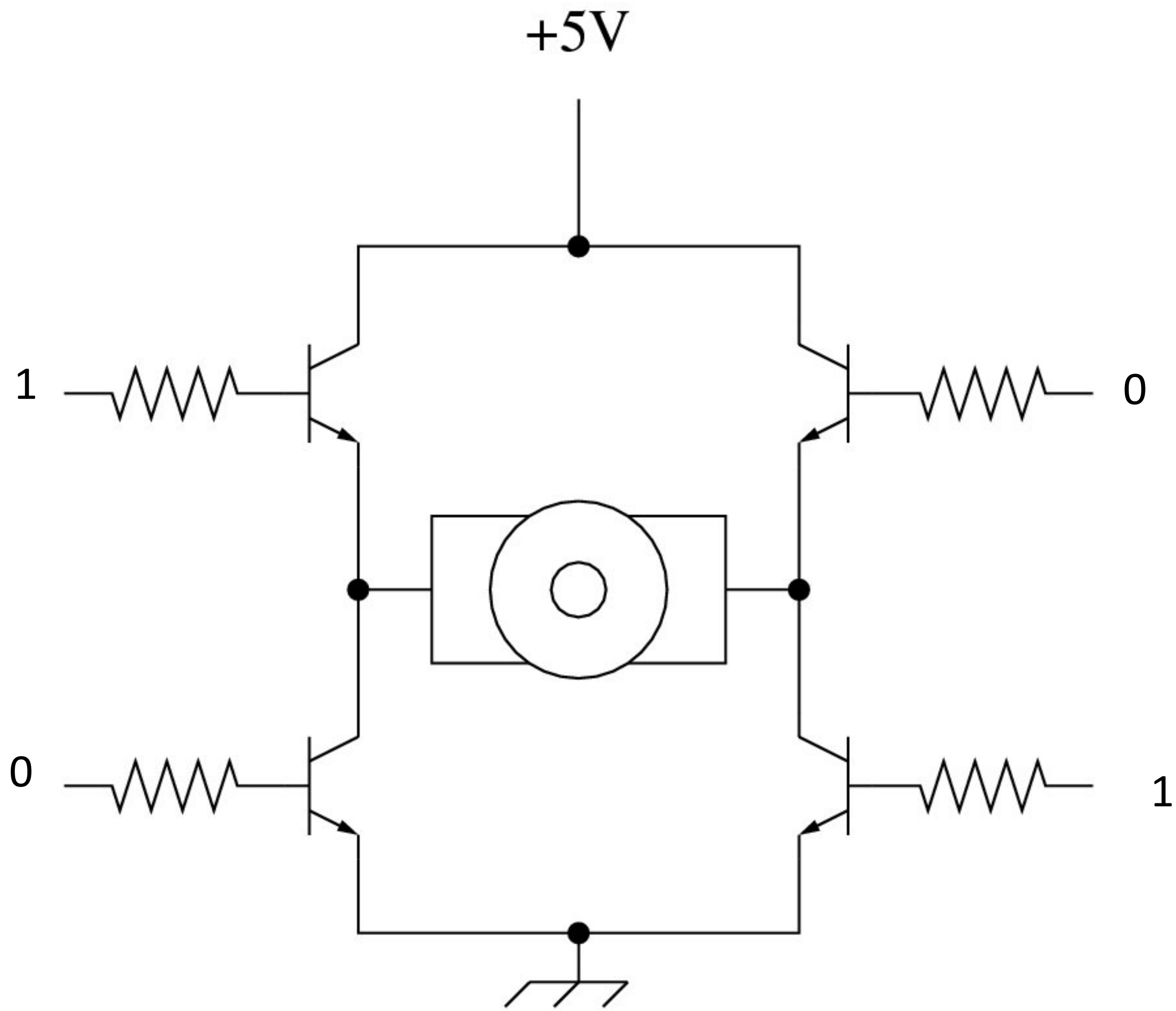
$$E_a \times I_a = T_m \times w_m$$

Step-Down Chopper (Buck Converter)





Controlling Motors using H-Bridge



Types of Electric Motors

	Permanent Magnet DC Motor	Stepper Motor	Brushless DC Motor
Advantages:	+ Low cost (high volume) + Simple operation	+ Position control (low cost control circuits)	+ High efficiency + High reliability + Low EMI + Speed control
Disadvantages:	- Medium efficiency - Poor reliability - Bad EMI	- Poor efficiency - Digital interface - High cost	- Maybe higher cost - Complex control