Power Electronics Introduction

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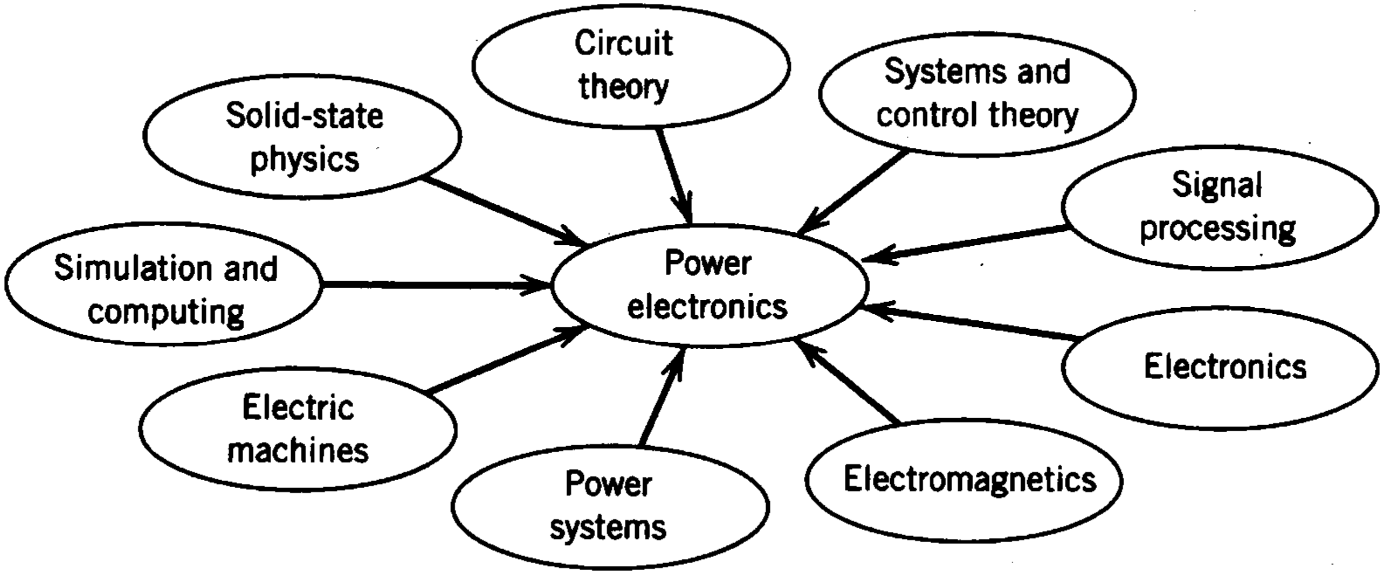
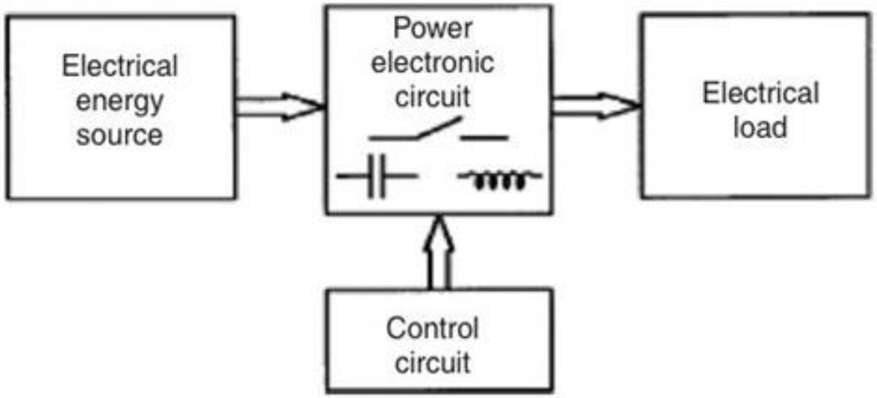
EE 442-642

Power Electronics: an Overview



Power electronics is an interdisciplinary subject within electrical engineering.

Power Electronic System



A power electronic system consists of power electronic <u>switching devices</u>, linear circuit elements, digital circuits, microprocessors, electromagnetic devices, DSPs, filters, controllers, sensors, etc.…

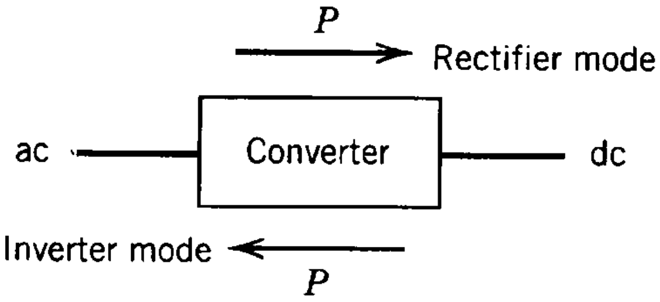
Ideal switch: controls energy flow with no loss.

a) when on, it has zero voltage drop and will carry any current,
b) wen off, it blocks the flow of current regardless of the voltage.

Desired Features:

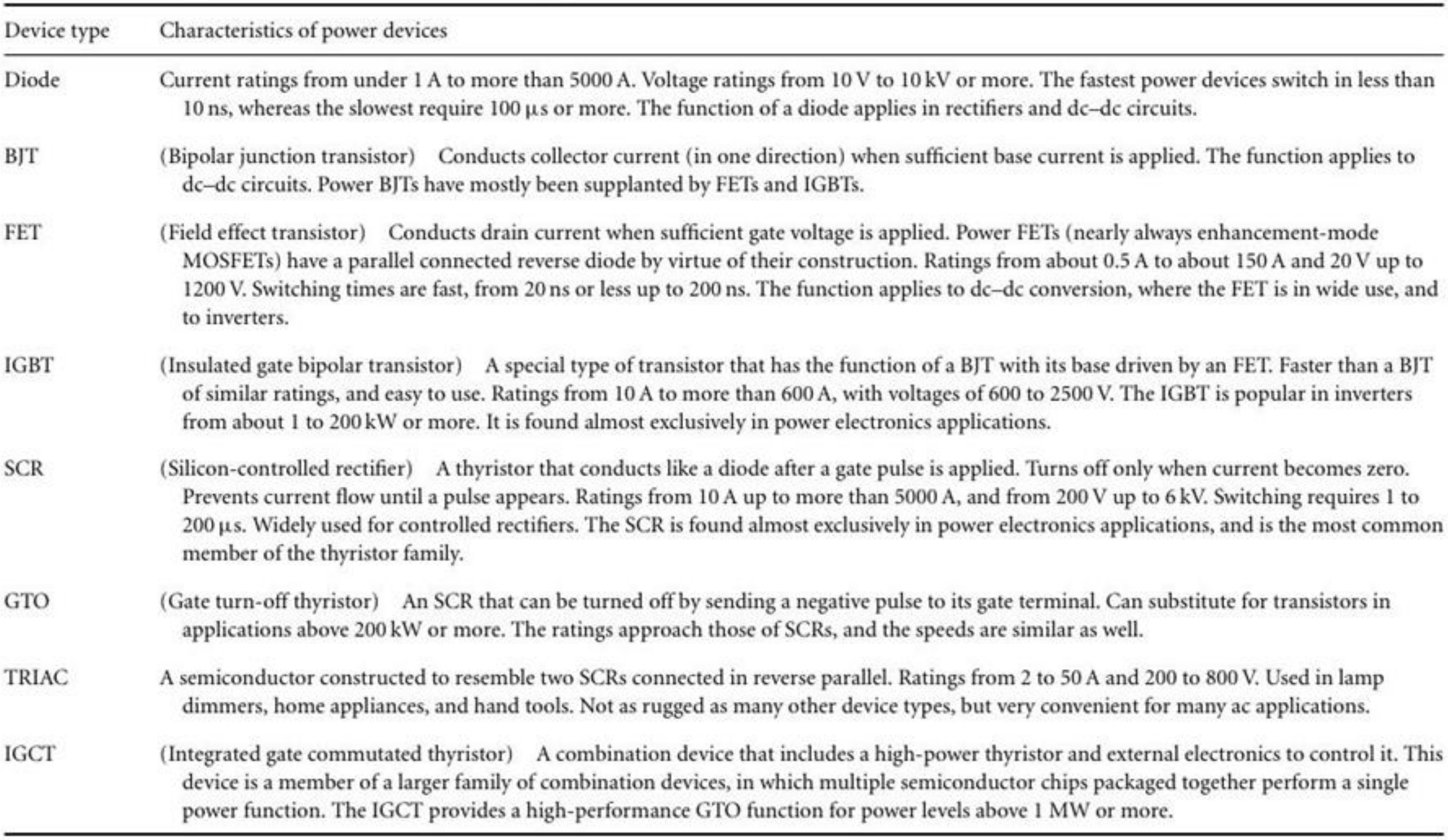
a) 100% efficiency
b) 100% reliability

Power Converter



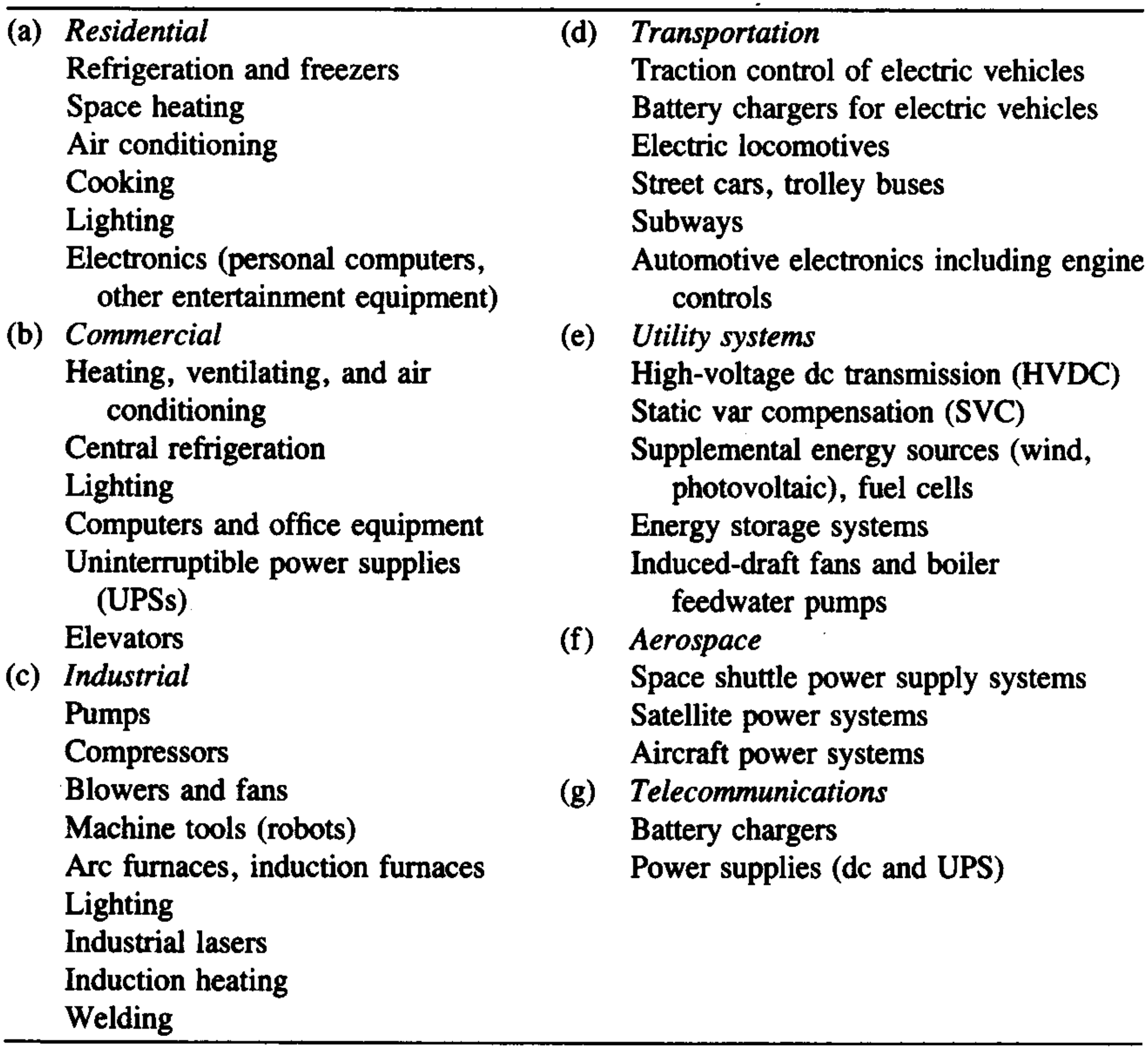
- “Converter” is a general term - an AC/DC converter is shown above.
  - Rectifier Mode of operation when power from AC to DC
  - Inverter Mode of operation when power from DC to AC
- Power converters can also convert
  - DC-to-DC
  - AC-to-AC
- Practical switching devices are selected based on their power handling rating – the product of their voltage and current ratings – rather than their power dissipation ratings.

Types of Semiconductor Switches



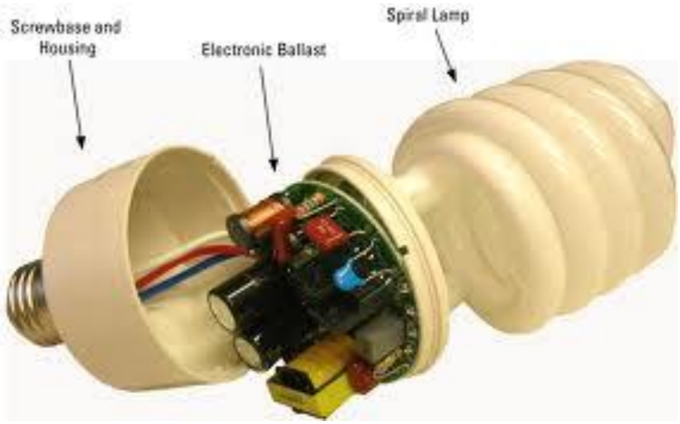
Device type	Characteristics of power devices
Diode	Current ratings from under 1 A to more than 5000 A. Voltage ratings from 10 V to 10 kV or more. The fastest power devices switch in less than 10 ns, whereas the slowest require 100 μs or more. The function of a diode applies in rectifiers and dc–dc circuits.
BJT	(Bipolar junction transistor) Conducts collector current (in one direction) when sufficient base current is applied. The function applies to dc–dc circuits. Power BJTs have mostly been supplanted by FETs and IGBTs.
FET	(Field effect transistor) Conducts drain current when sufficient gate voltage is applied. Power FETs (nearly always enhancement-mode MOSFETs) have a parallel connected reverse diode by virtue of their construction. Ratings from about 0.5 A to about 150 A and 20 V up to 1200 V. Switching times are fast, from 20 ns or less up to 200 ns. The function applies to dc–dc conversion, where the FET is in wide use, and to inverters.
IGBT	(Insulated gate bipolar transistor) A special type of transistor that has the function of a BJT with its base driven by an FET. Faster than a BJT of similar ratings, and easy to use. Ratings from 10 A to more than 600 A, with voltages of 600 to 2500 V. The IGBT is popular in inverters from about 1 to 200 kW or more. It is found almost exclusively in power electronics applications.
SCR	(Silicon-controlled rectifier) A thyristor that conducts like a diode after a gate pulse is applied. Turns off only when current becomes zero. Prevents current flow until a pulse appears. Ratings from 10 A up to more than 5000 A, and from 200 V up to 6 kV. Switching requires 1 to 200 μs. Widely used for controlled rectifiers. The SCR is found almost exclusively in power electronics applications, and is the most common member of the thyristor family.
GTO	(Gate turn-off thyristor) An SCR that can be turned off by sending a negative pulse to its gate terminal. Can substitute for transistors in applications above 200 kW or more. The ratings approach those of SCRs, and the speeds are similar as well.
TRIAC	A semiconductor constructed to resemble two SCRs connected in reverse parallel. Ratings from 2 to 50 A and 200 to 800 V. Used in lamp dimmers, home appliances, and hand tools. Not as rugged as many other device types, but very convenient for many ac applications.
IGCT	(Integrated gate commutated thyristor) A combination device that includes a high-power thyristor and external electronics to control it. This device is a member of a larger family of combination devices, in which multiple semiconductor chips packaged together perform a single power function. The IGCT provides a high-performance GTO function for power levels above 1 MW or more.

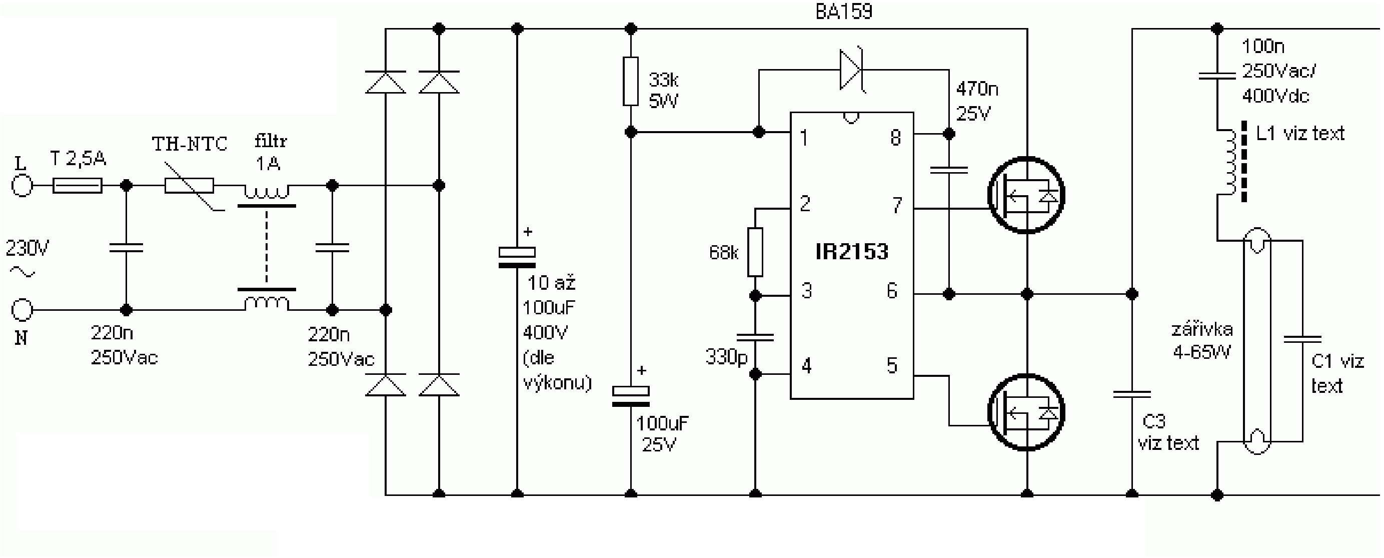
Power Electronic Applications



- (a) *Residential*
  - Refrigeration and freezers
  - Space heating
  - Air conditioning
  - Cooking
  - Lighting
  - Electronics (personal computers, other entertainment equipment)
- (b) *Commercial*
  - Heating, ventilating, and air conditioning
  - Central refrigeration
  - Lighting
  - Computers and office equipment
  - Uninterruptible power supplies (UPSs)
  - Elevators
- (c) *Industrial*
  - Pumps
  - Compressors
  - Blowers and fans
  - Machine tools (robots)
  - Arc furnaces, induction furnaces
  - Lighting
  - Industrial lasers
  - Induction heating
  - Welding
- (d) *Transportation*
  - Traction control of electric vehicles
  - Battery chargers for electric vehicles
  - Electric locomotives
  - Street cars, trolley buses
  - Subways
  - Automotive electronics including engine controls
- (e) *Utility systems*
  - High-voltage dc transmission (HVDC)
  - Static var compensation (SVC)
  - Supplemental energy sources (wind, photovoltaic), fuel cells
  - Energy storage systems
  - Induced-draft fans and boiler feedwater pumps
- (f) *Aerospace*
  - Space shuttle power supply systems
  - Satellite power systems
  - Aircraft power systems
- (g) *Telecommunications*
  - Battery chargers
  - Power supplies (dc and UPS)

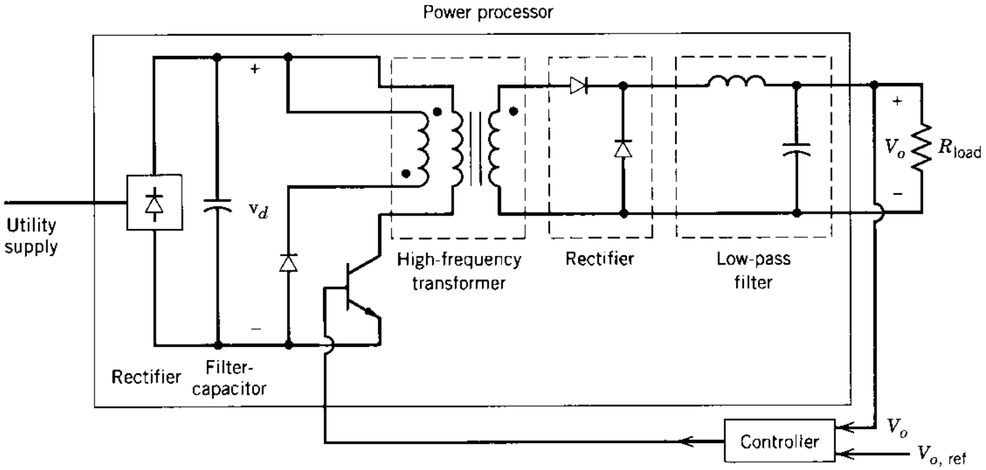
Example: Fluorescent Lighting





The line-frequency AC is converted to DC, then to high-frequency AC.

Example: Switch-Mode Power Supply



- Transistor is operated in switch mode (either fully ON or fully OFF) at high switching frequency.
- Electrical isolation achieved by high-frequency transformer (smaller, lighter and more efficient)
- Result: compact and efficient power supply

Example: Adjustable Speed Drives

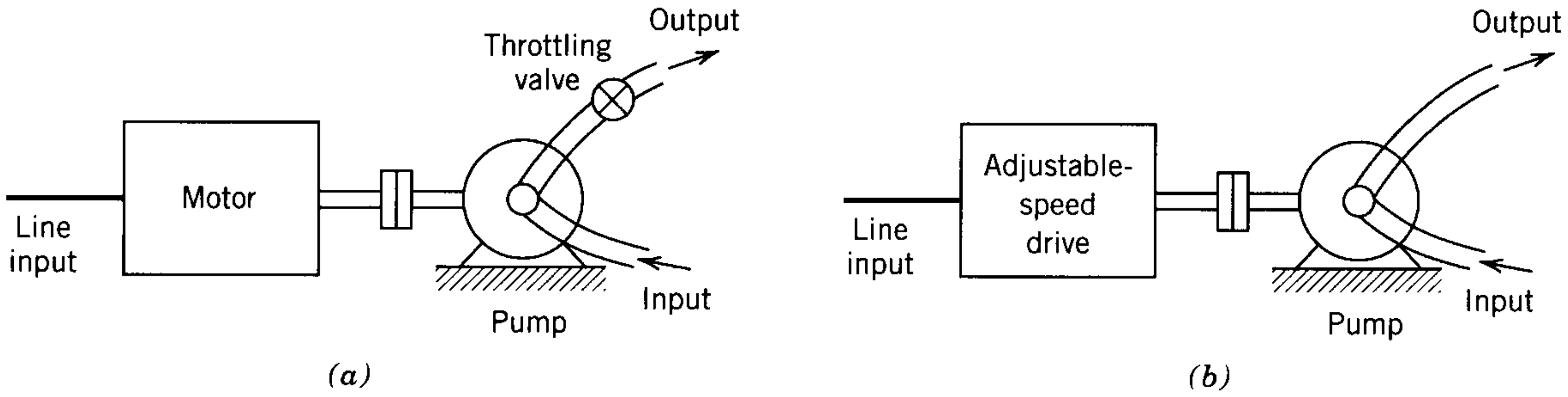


Figure 1-5 Energy conservation: (*a*) conventional drive, (*b*) adjustable-speed drive.

- Conventional drive wastes energy across the throttling valve to adjust flow rate.
- Using power electronics, motor-pump speed is adjusted efficiently to deliver the required flow rate.

AC Motor Drive

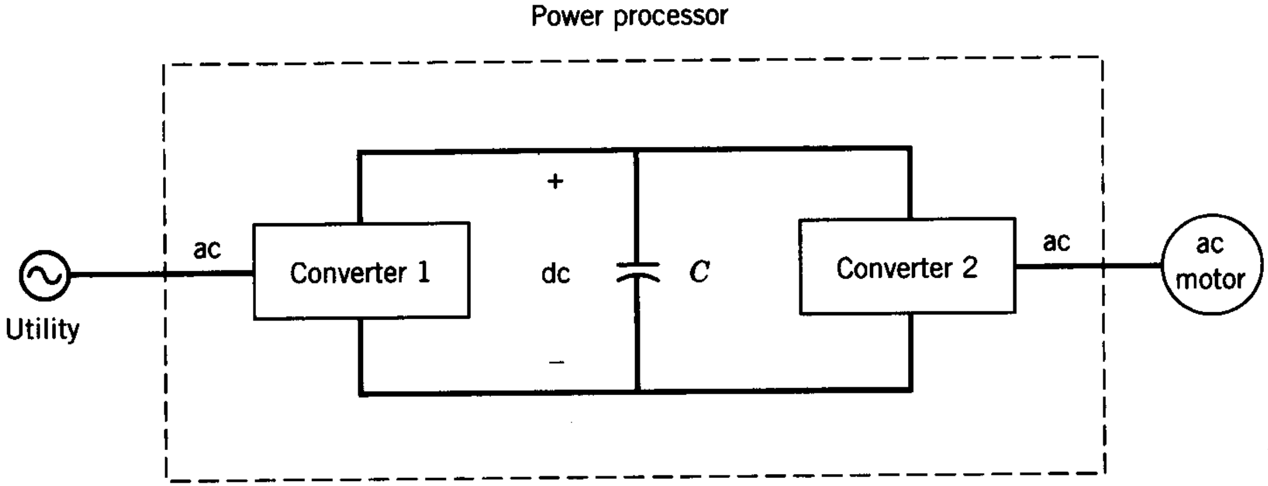
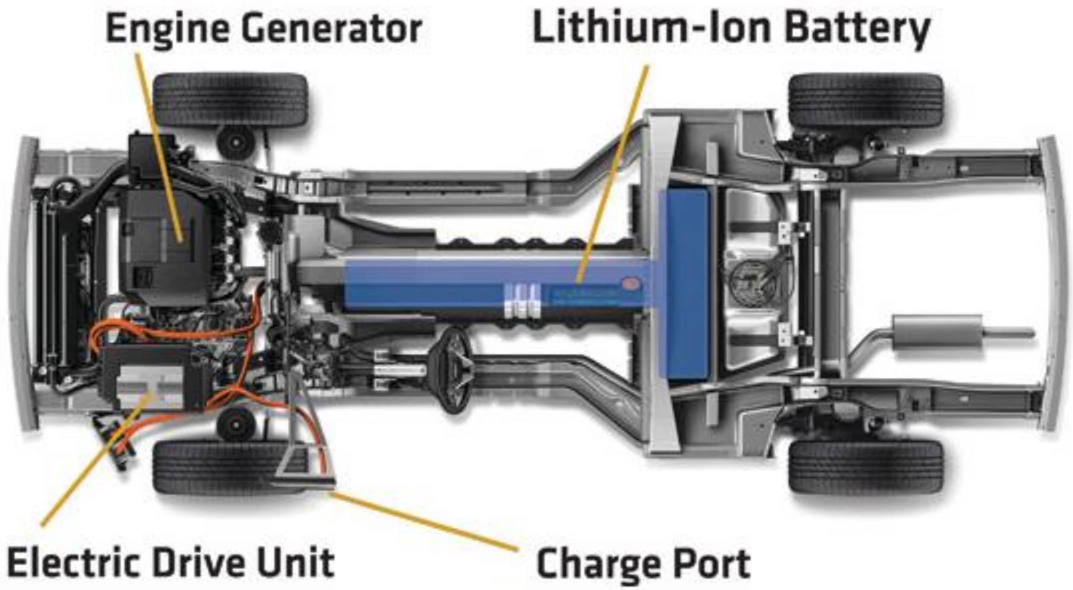


Figure 1-8 Block diagram of an ac motor drive.

- Converter 1 rectifies line-frequency AC into DC
- Capacitor acts as a filter; stores energy and decouples the two converters.
- Converter 2 inverts dc to variable frequency AC – as needed by the motor.

Pure Electric and Plug-In Hybrid Vehicles



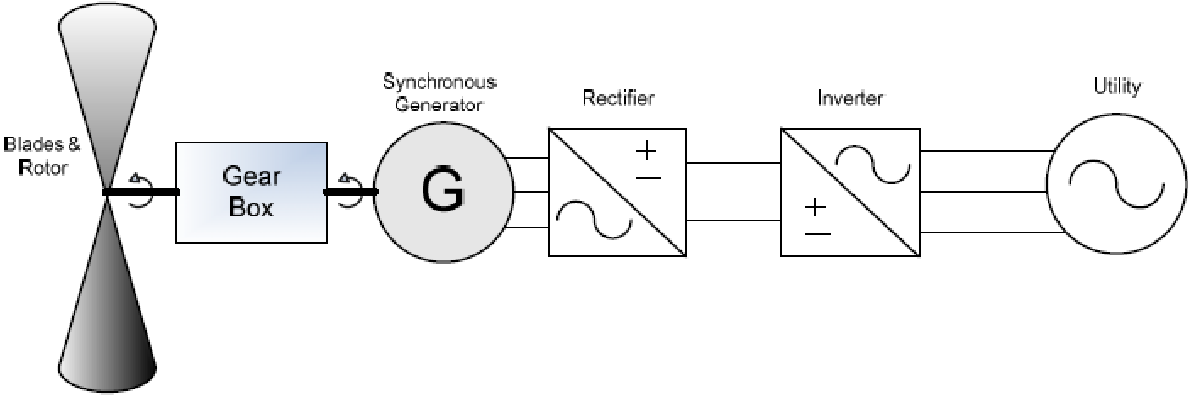
Electric Drive System: DC-AC Converter

Battery Charger: AC-DC converter

Example: Renewable Power Generation (PV)

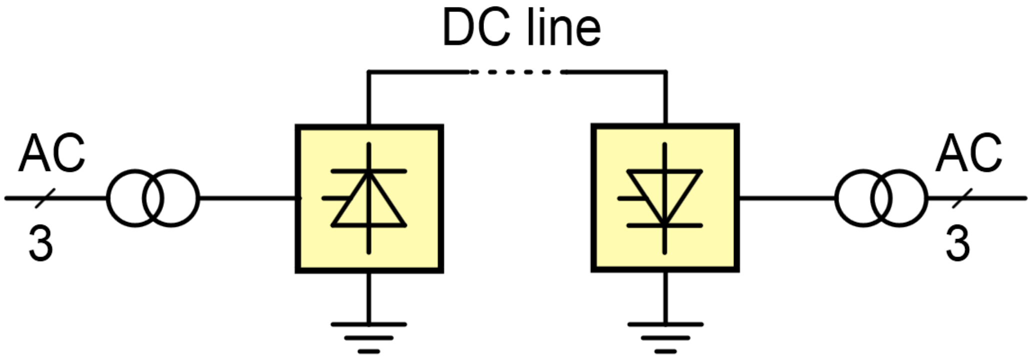
PV Inverter: DC-AC Converter

Example: Renewable Power Generation (Wind)



The rectifier-inverter converts variable-frequency AC to fixed line-frequency AC.

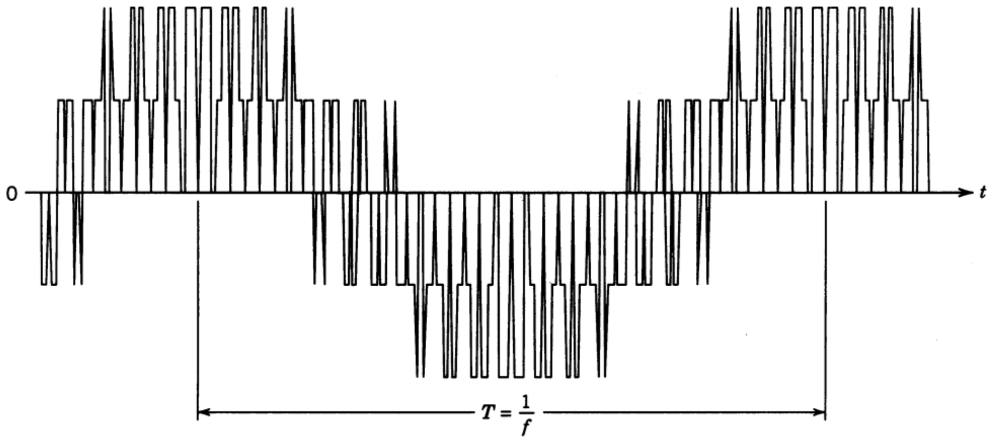
Example: HVDC Transmission



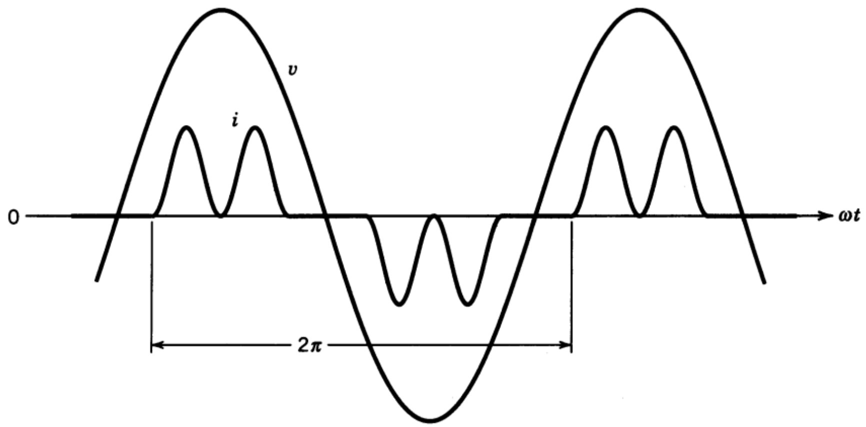
- Because of the large fixed cost necessary to convert ac to dc and then back to ac, dc transmission is only practical in specialized applications
  - long distance overhead power transfer (> 400 miles)
  - long underwater cable power transfer (> 25 miles)
  - providing an asynchronous means of joining different power systems.

Power electronic circuits are non-linear.

- Periodic waveforms but often not sinusoidal → analytical expressions in terms of Fourier components

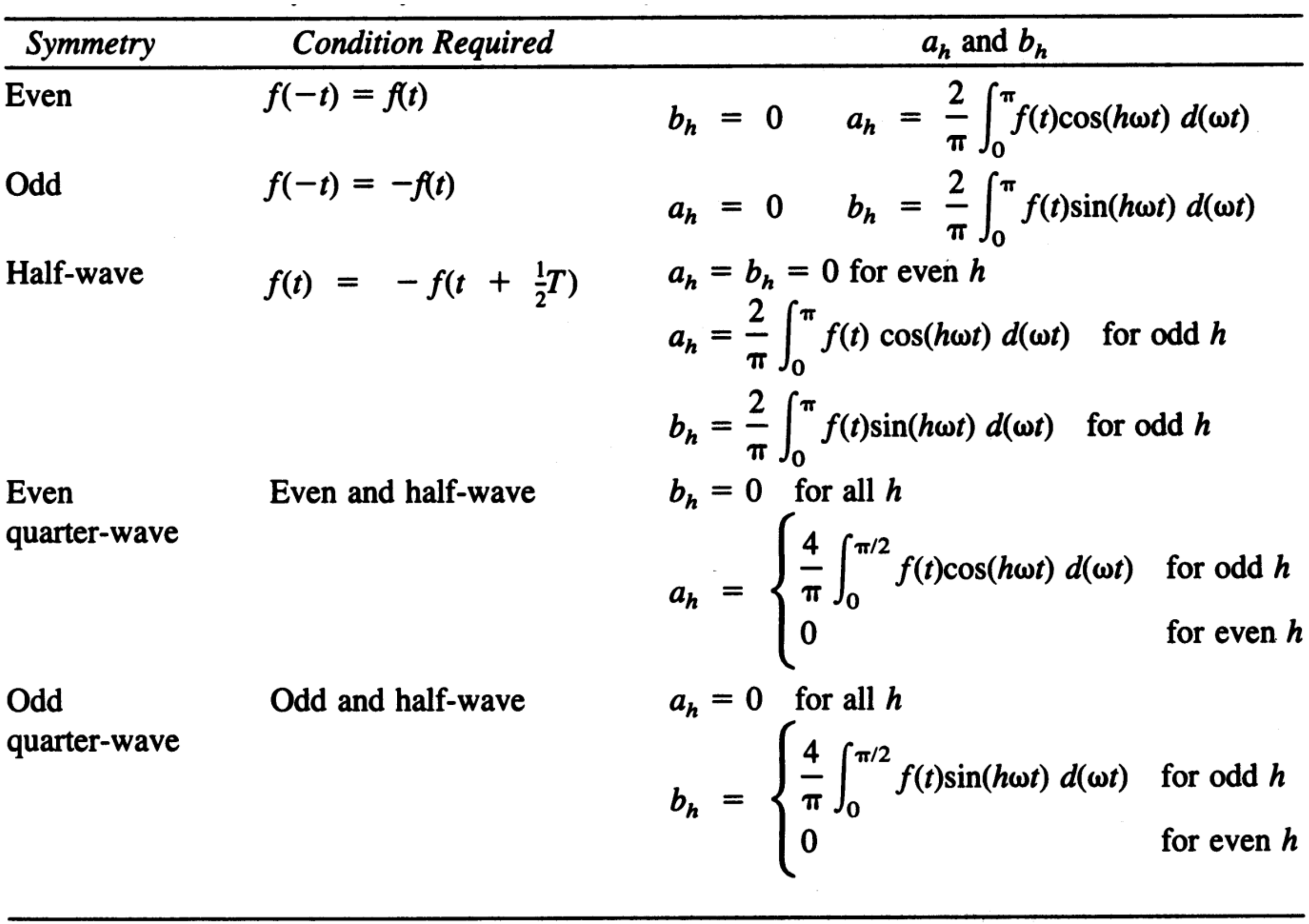


(a)



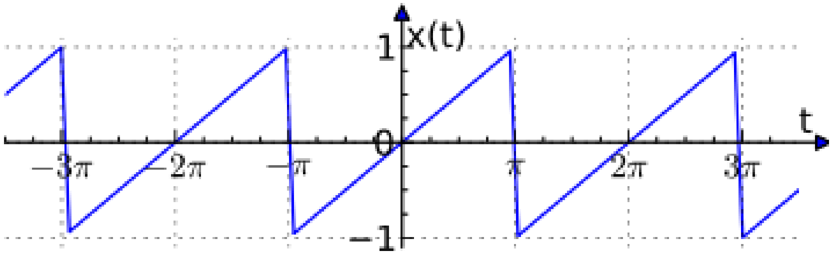
(b)

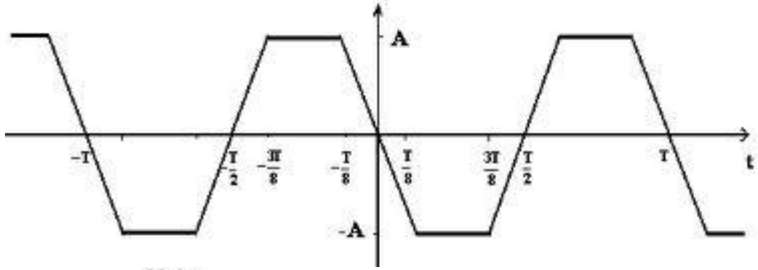
Fourier Analysis

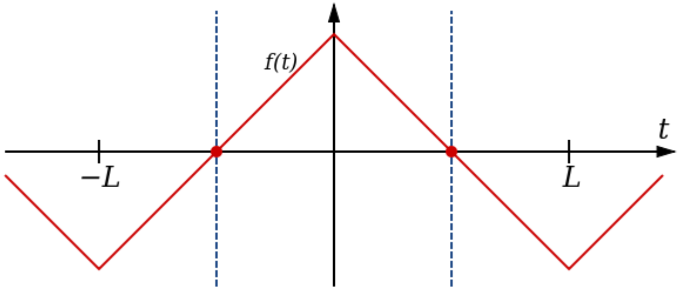


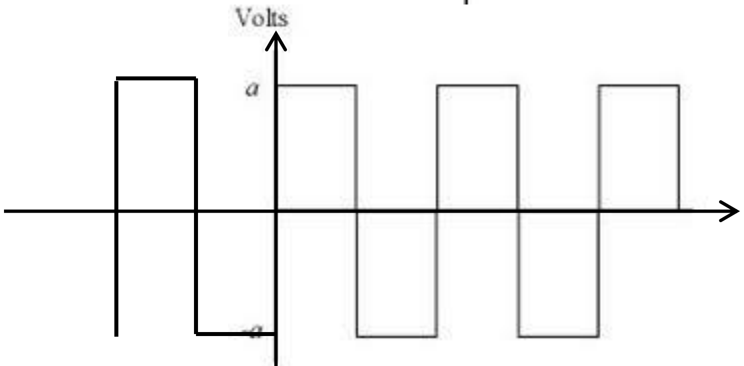
Symmetry	*Condition Required*	a_h and b_h
Even	$f(-t) = f(t)$	$b_h = 0 \qquad a_h = \frac{2}{\pi}\int_0^{\pi} f(t)\cos(h\omega t)\, d(\omega t)$
Odd	$f(-t) = -f(t)$	$a_h = 0 \qquad b_h = \frac{2}{\pi}\int_0^{\pi} f(t)\sin(h\omega t)\, d(\omega t)$
Half-wave	$f(t) = -f(t + \frac{1}{2}T)$	$a_h = b_h = 0$ for even h $a_h = \frac{2}{\pi}\int_0^{\pi} f(t)\cos(h\omega t)\, d(\omega t)$ for odd h $b_h = \frac{2}{\pi}\int_0^{\pi} f(t)\sin(h\omega t)\, d(\omega t)$ for odd h
Even quarter-wave	Even and half-wave	$b_h = 0$ for all h $a_h = \begin{cases} \frac{4}{\pi}\int_0^{\pi/2} f(t)\cos(h\omega t)\, d(\omega t) & \text{for odd } h \\ 0 & \text{for even } h \end{cases}$
Odd quarter-wave	Odd and half-wave	$a_h = 0$ for all h $b_h = \begin{cases} \frac{4}{\pi}\int_0^{\pi/2} f(t)\sin(h\omega t)\, d(\omega t) & \text{for odd } h \\ 0 & \text{for even } h \end{cases}$

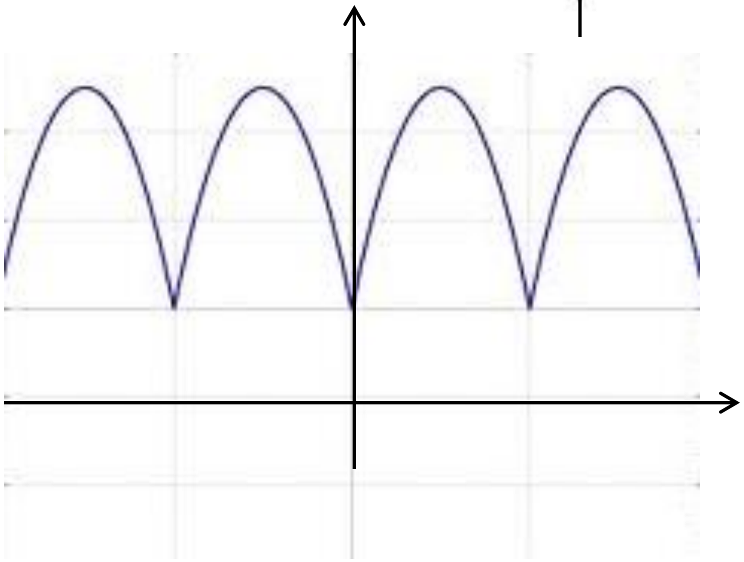
Example of simple non-sinusoidal periodic signals











Current Decomposition

- Current decomposition of into fundamental (i_{s1}) and distortion current (i_{dis}):

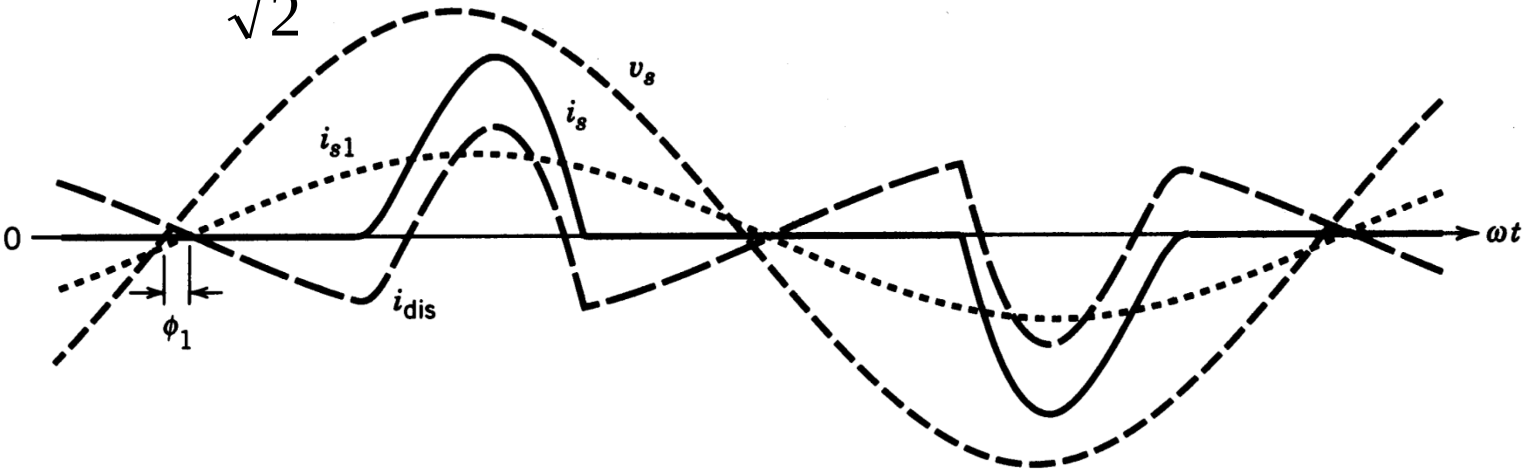
$$i_s(t) = i_{s1}(t) + \sum_{h \neq 1} i_{sh}(t) = i_{s1}(t) + i_{dis}(t)$$

where

$$i_{sh}(t) = a_h \cos(h\omega_1 t) + b_h \sin(h\omega_1 t) = \sqrt{2} I_{sh} \cos(h\omega_1 t - \theta_h)$$

Herein,

$$I_{sh} = \frac{\sqrt{a_h^2 + b_h^2}}{\sqrt{2}}, \qquad \theta_h = \arctan(b_h / a_h)$$



RMS Value and Total Harmonic Distortion

- The rms value of a distorted waveform is equal to the square-root of the sum of the square of the rms value of each harmonic component (including the fundamental).

$$I_s = \sqrt{I_{s1}^2 + \sum_{h \neq 1} I_{sh}^2} = \sqrt{I_{s1}^2 + I_{dis}^2}$$

- Total Harmonic Distortion

$$THD(\%) = 100 \frac{I_{dis}}{I_{s1}} = 100 \frac{\sqrt{I_s^2 - I_{s1}^2}}{I_{s1}}$$

Power and Power Factor

- Average (real) power: $P = \sum_{h=0,1,\ldots} V_h I_{sh} \cos(\phi_h)$
- Apparent Power: $S = V_s I_s$
- Power factor: $PF = \dfrac{P}{S}$
- Case of sinusoidal voltage and non-sinusoidal current:

$$P = V_{s1} I_{s1} \cos(\phi_1)$$

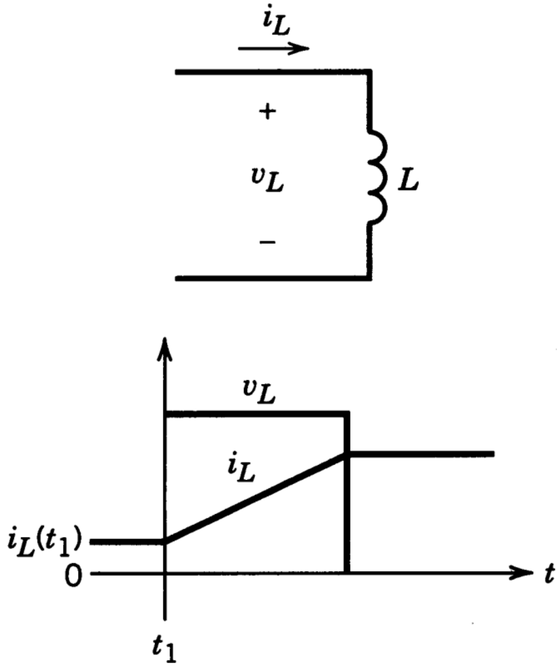
$$PF = \frac{V_{s1} I_{s1} \cos(\phi_1)}{V_{s1} I_s} = \frac{I_{s1}}{I_s} \cos(\phi_1) = \frac{I_{s1}}{I_s} DPF = \frac{1}{\sqrt{1 + (THD)^2}} DPF$$

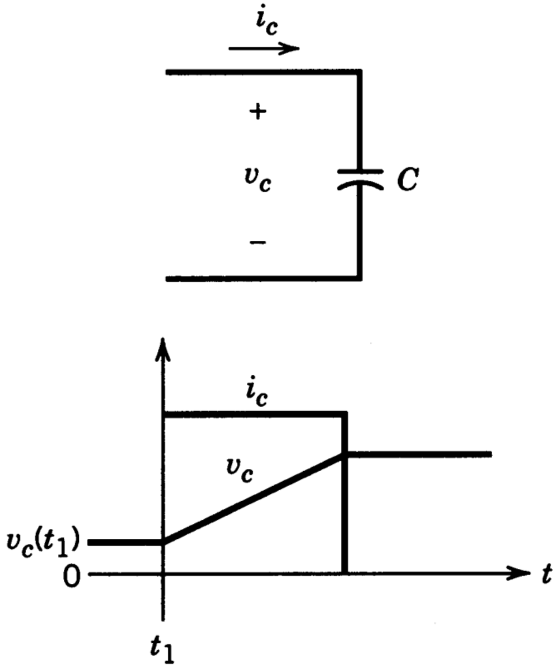
- Displacement Power Factor: $DPF = \cos(\phi_1)$

Current-voltage in an inductor and capacitor

- In an inductor, the voltage is proportional to the rate of change of current. → An inductor cannot sustain a constant voltage for a long time.
- In a capacitor, the current is proportional to the rate of change of voltage. → A capacitor cannot sustain a constant current for a long time.

$$v = L\,\frac{d\,i}{d\,t} \qquad i = \frac{1}{L}\int_{t_0}^{t} v(t)\,d\,t + i(t_0) \qquad i = C\,\frac{d\,v}{d\,t} \qquad v = \frac{1}{C}\int_{t_0}^{t} i\,d\,t + v(t_0)$$

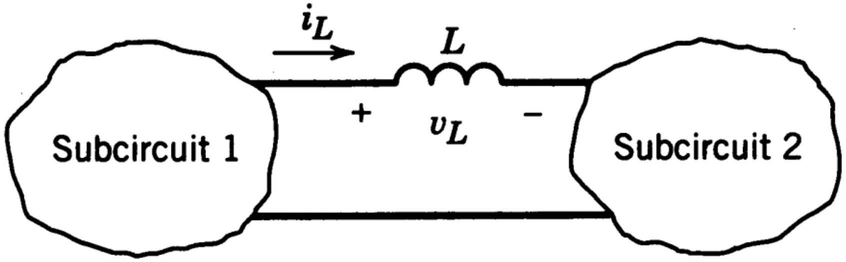




Inductor response in steady-state

- At steady-state, $i(t+T) = i(t) \rightarrow \int_{t_0}^{t_o+T} v\, d\, t = 0$

- Volt-seconds over T = 0 → Area “A” = Area “B”



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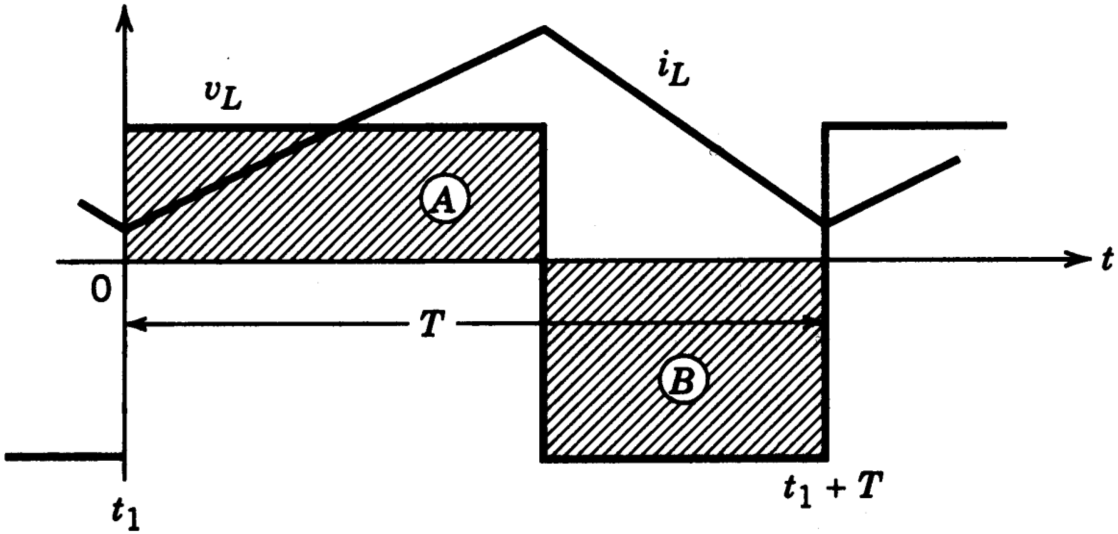
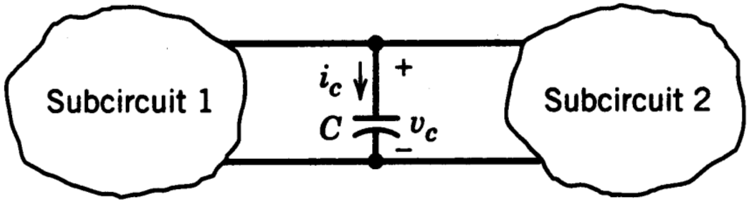


(b)

Capacitor response in steady-state

- At steady-state, $v(t+T) = v(t) \quad \rightarrow \quad \int_{t_0}^{t_o+T} i\, d\, t = 0$
- Amp-seconds over T = 0 → Area "A" = Area "B"



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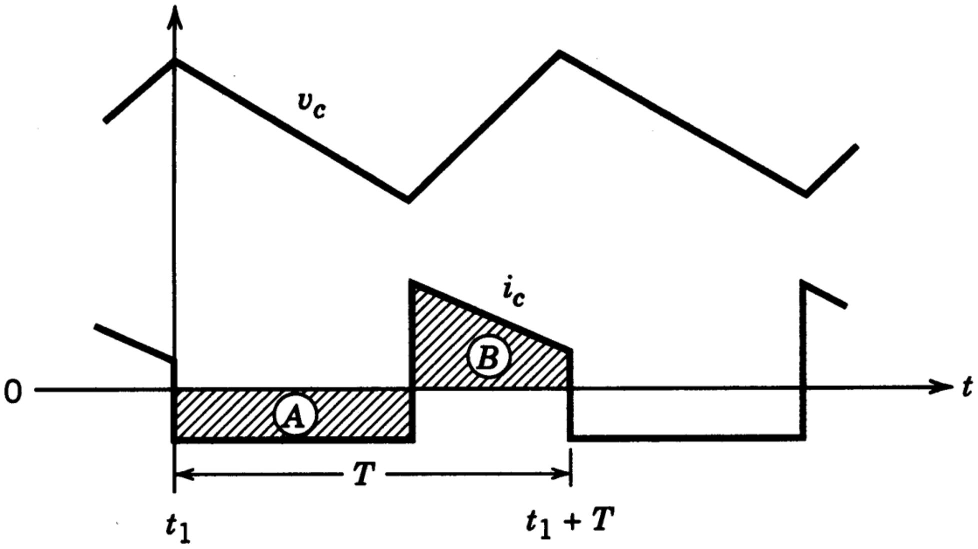
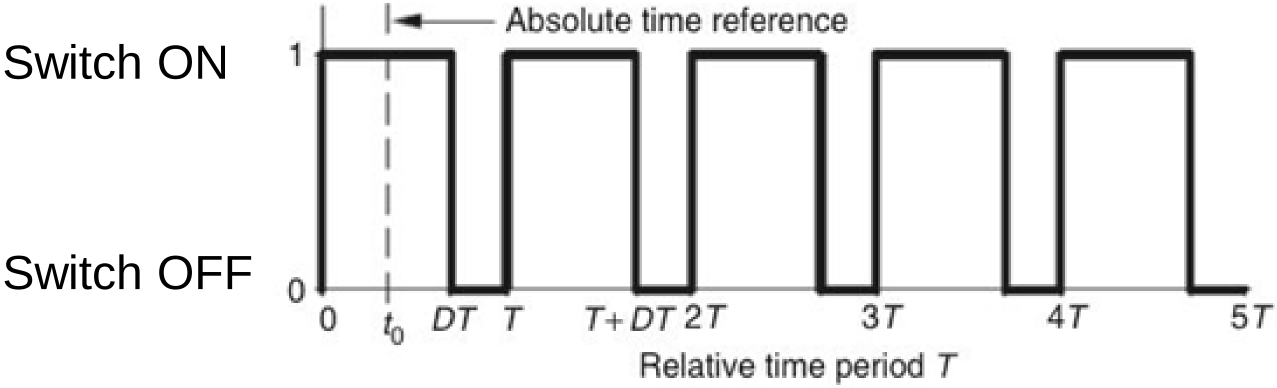
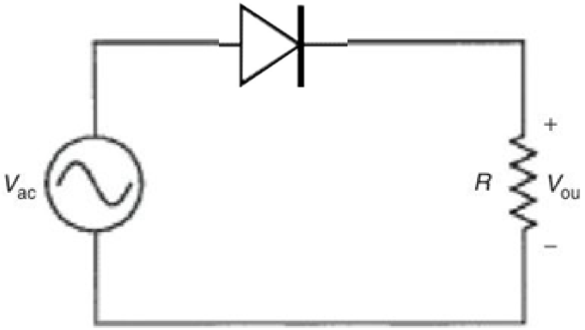


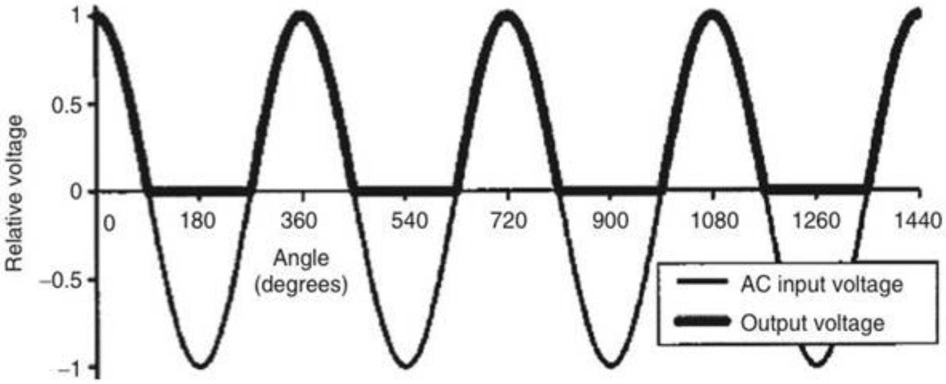
Switching Function (switch control)



- T: period
- t_o : time delay (used in rectifiers)
- f = 1/T : switching frequency
- D: duty ratio - fraction of time during which the switch is ON

Example 1: Simple Power Converter





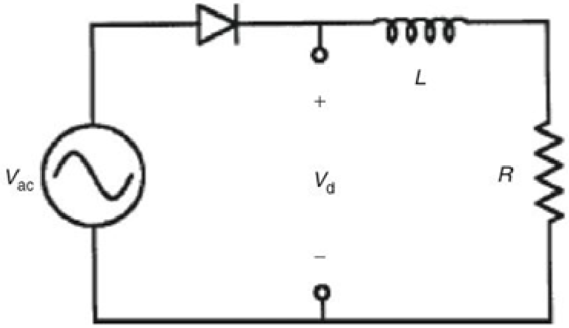
Assume the diode is ideal, and let Vac = 170 sin (377t) , and R = 120 Ω

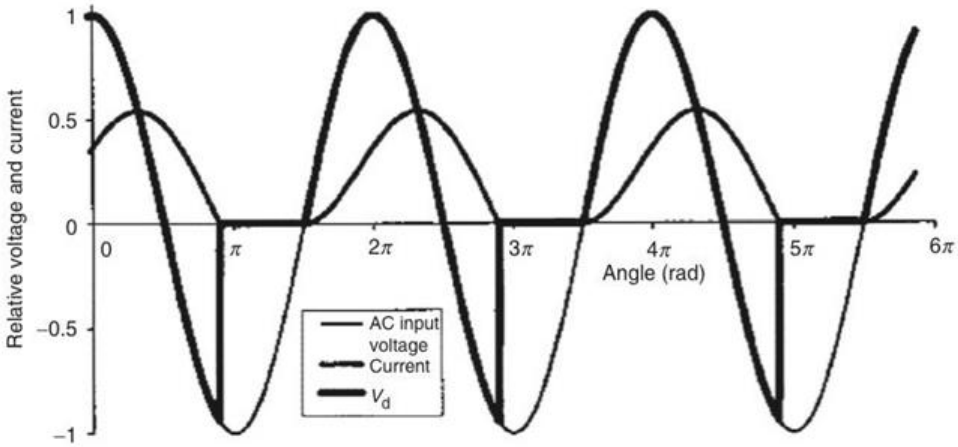
1. Average value of output voltage Vout = 54.11 V
2. Average (DC) current Io = 0.45 A
3. Average (active) power supplied by source P = 60 W
4. RMS value of current = 0.707 A
5. RMS value of fundamental current = 0.5 A
6. Phase angle of fundamental current = 0 deg
7. RMS Value of distortion current = 0.5 A
8. Apparent power S = 84.85 VA
9. Non-active power = 60 (?)

$$\int \sin x \cos x dx = -\frac{1}{4}\cos 2x + C$$

$$\int \sin^2 x dx = \frac{x}{2} - \frac{1}{4}\sin 2x + C$$

Assignment 1: Diode wit RL Load

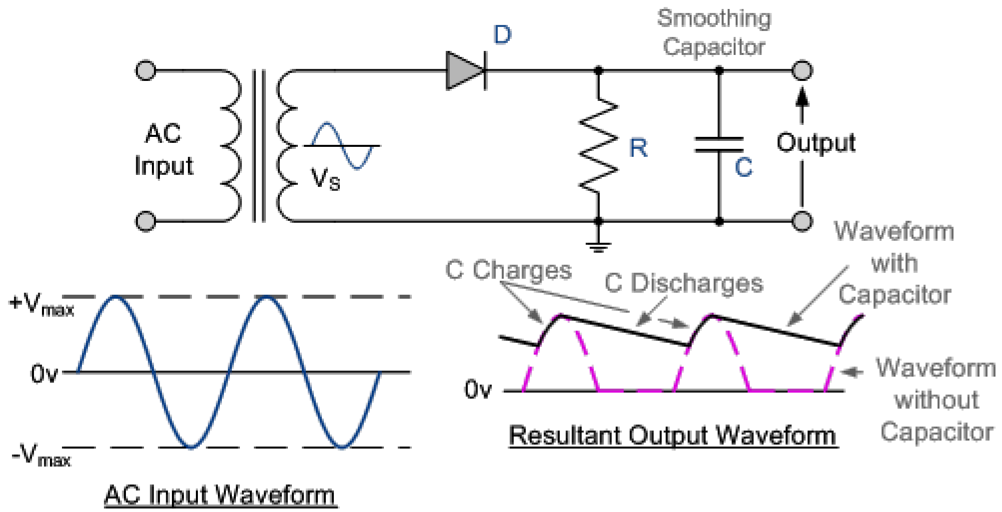




Repeat the previous example after placing and inductor L = 200 mH (use any manual our computer tool). Verify the values below:

1. Average value of output voltage Vout = 50 V
2. Average (DC) current Io = 0.417 A
3. Average (active) power supplied by source P = 47.18 W
4. RMS value of current = 0. 627 A
5. RMS value of fundamental current = 0. 441 A
6. Phase angle of fundamental current = -27.1 deg
7. RMS Value of distortion current = 0.446 A
8. Apparent power S = 75.24 VA
9. Non-active power = 58.61 (?)

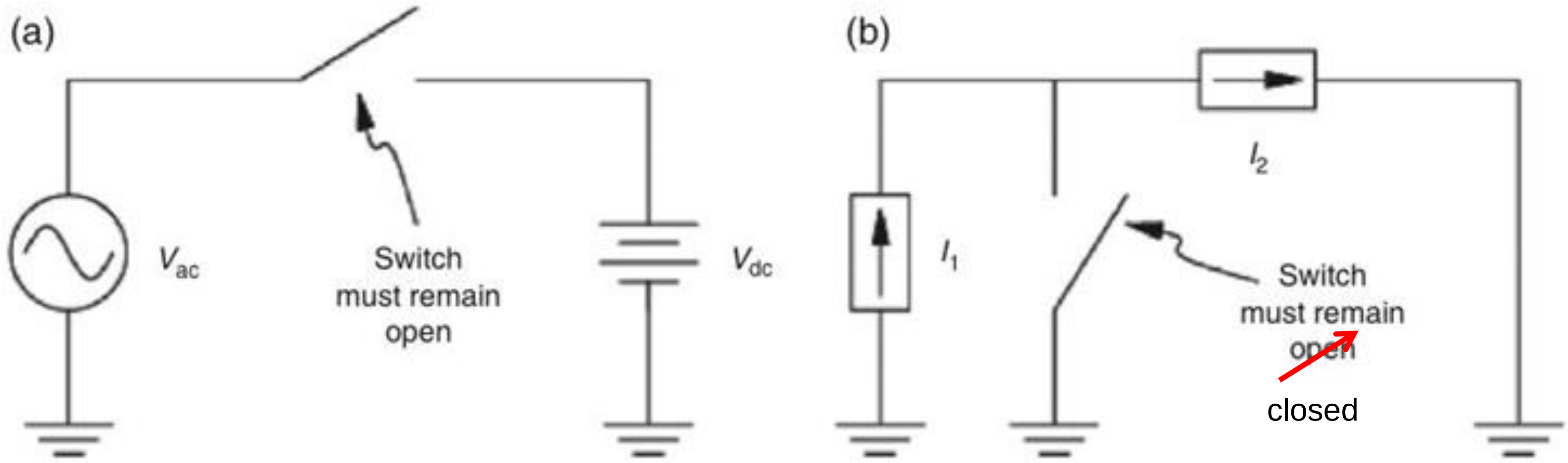
Assignment 2: Diode with RC Load



Repeat the previous example after placing and capacitor C = 150 uF in parallel with the 120 Ohm resistive load (use any manual our computer tool).

1. Average value of output voltage Vout = ……………. V
2. Peak value of capacitor current = ……….. A
3. Average (active) power supplied by source P = ……….W
4. RMS value of source current = ……….A
5. RMS value of fundamental current (source) = ………. A
6. Phase angle of fundamental current (source) = ………….. deg
7. RMS Value of distortion current (source) = ……………..A
8. Apparent power S = ……….VA
9. Non-active power = …………… (?)

Obey KCL and KVL



- KVL and KCL place necessary constraints on the operation of switches.
  - In the case of voltage sources, switches must not act to create short-circuit paths among unlike sources.
  - In the case of KCL, switches must not attempt to interconnect unequal current sources.

High-frequency vs. Low-frequency Transformers

- Nickel-steel is used (instead of silicon-iron) to reduce core losses at high frequency.
- Fewer copper winding turns are needed to produce the same flux density.
  - An increase in frequency permits a large increase in power capacity.
  - For the same power capacity, a high frequency transformer is much smaller, cheaper, more efficient and lighter than a 60 Hz transformer.

<u>Example</u>:

- 60 Hz, 120/24 V, 36 VA, B = 1.5 T, core loss = 1 W, N1/N2 = 600/120, weight = 500 g.
- 6 kHz, 120/24, 480 VA, B = 0.2 T, core loss = 1 W, N1/N2 = 45/9, weight = 100 g.