Aalto University
School of Electrical
Engineering

Chapter 10
Power Electronics

ELEC-E8422 - An Introduction to Electric Energy

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Prof. Jorma Kyyrä

Content

- Examples on the use of power electronics
- Power semiconductor devices
  - Diodes, transistors (bipolar and MOSFET), thyristors, IGBT
- Power electronic circuits, converters
  - Rectifiers (AC/DC)
  - DC-DC converters (DC/DC)
  - Inverters (DC/AC)
  - Frequency converters (AC/AC)

Conversion of electric energy

- Power electronic converts the voltage or current of the supply system suitable for the load

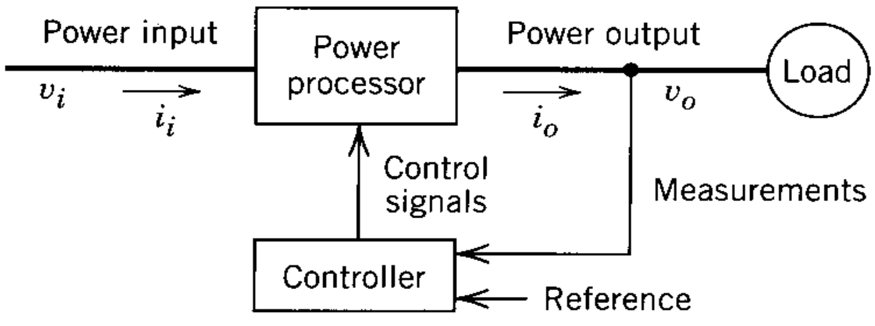


Figure 1-1 Block diagram of a power electronic system.

Requirements for power electronics

- Low losses and high efficiency
    - Savings, price of energy, cooling system
- Small size
    - High efficiency is further highlighted
        - Cooling system needs space
    - Increased integration, packaging density
- Competitive price

Power electronics vs. linear electronics

- Linear power supply
  - Controlled output voltage is obtained with base control of semiconductors, behaves like an adjustable resistor
  - Voltage drop over the device is large
  - Power loss depends on the needed voltage drop

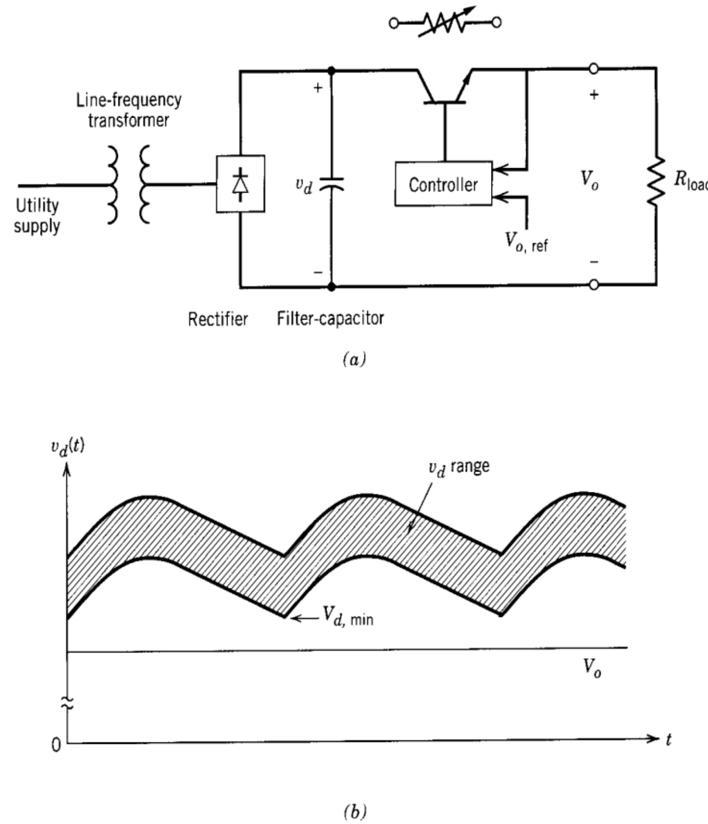


Figure 1-2 Linear dc power supply.

Switched Mode Power Supply

- Line voltage is
  - Rectified
  - Converted to a high frequency ac
  - Galvanic isolation with a high frequency transformer
  - Rectified in the secondary to a controlled output voltage
- There are no losses over an ideal switch

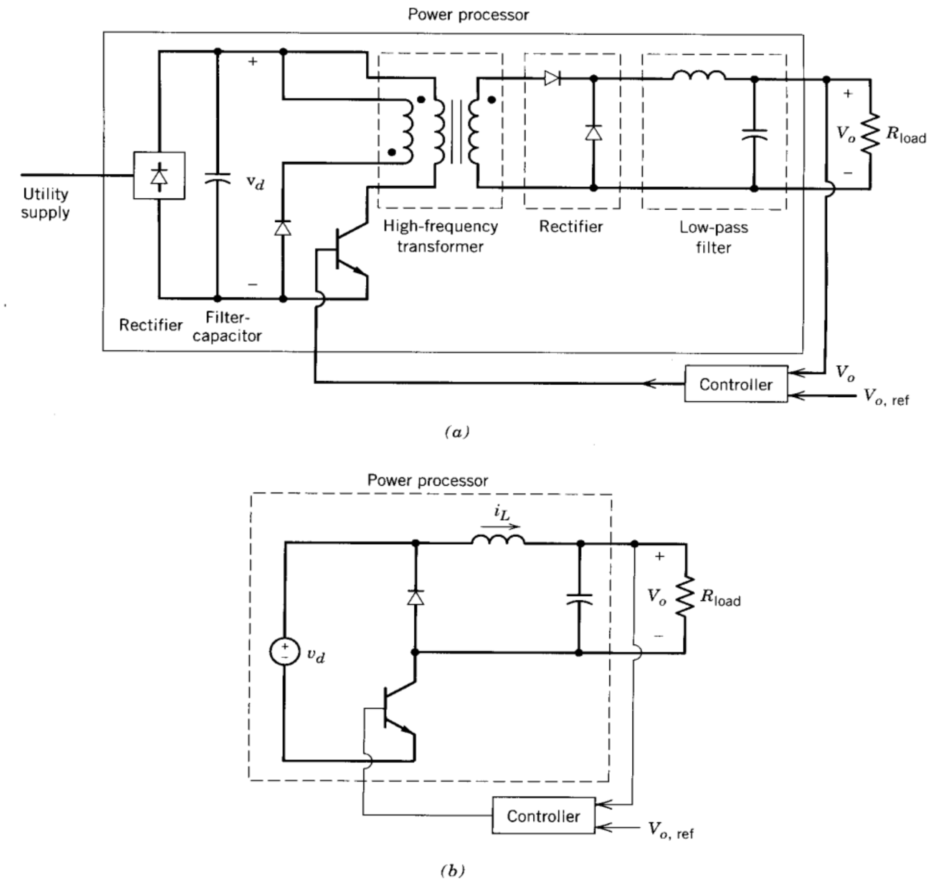


Figure 1-3 Switch-mode dc power supply.

Step down converter, Buck

- Output voltage
  - Average of the voltage depends on the relative on time of the switch, duty cycle
  - Switching frequency harmonics
  - Low pass filtering (LC)
  - The higher the switching frequency f_s is the easier filtering is
- Efficiency
  - Much higher than with linear power supplies
  - Typically 80-95 %,depends on power level

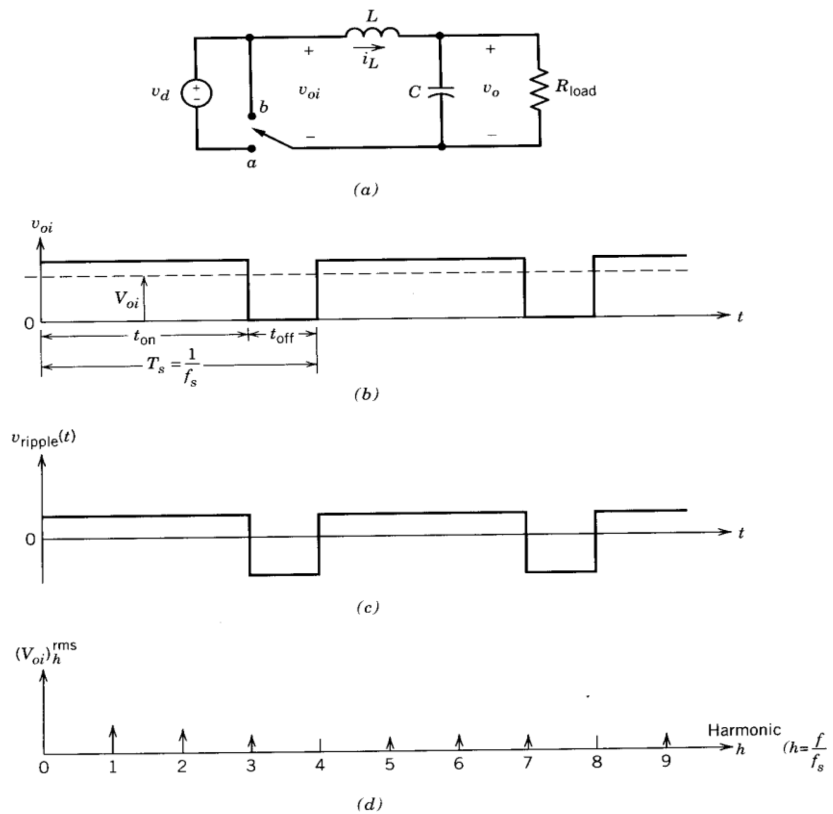


Figure 1-4 Equivalent circuit, waveforms, and frequency spectrum of the supply in Fig. 1-3.

Applications of power electronics

- Electric drives (speed controlled electric machines)
- Power supplies in ectronics, industry
- UPS systems, uninterruptible power supplies
- Ligthing
- Power systems (reactive power compensation, long distance power transmission with dc)
- Renewable energy

Electric drives

- Speed/torque controlled motor drives
  - electric motors consume approximately 50 % of electricity in industrialised countries
  - Speed control
    - Energy consumption can be reduced
    - Dynamic requirements of the load can be met
- Examples: pums, fans, paper machines, propulsion in ships, metro, trains, trams, electric vehicles, robots, electric actuators in automation…

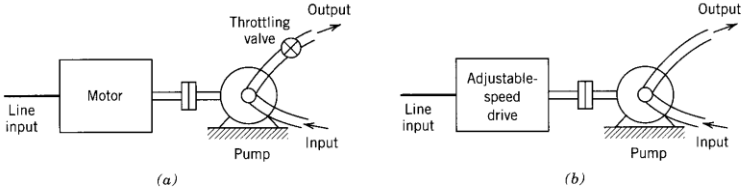


Figure 1-5 Energy conservation: (*a*) conventional drive, (*b*) adjustable-speed drive.

Power Supplies

- Power electronics
  - Operating voltages of electronic and communications equipment
  - Switch mode technique reduces size and weigth and efficiency increases

- Ligthing
  - All modern ligth sources need power electronic supply, so called electronic ballasts

Power Systems

- High Voltage DC transmission (HVDC)
  - In long distance transmission, efficiency is improved and cost reduced by using high dc voltage
  - Under sea cables
  - Connection of two not synchronous ac systems, also 50/60 Hz
- Active power filters, compensation of harmonics in the power system
- Compensation of reactive power instead of capacitors, Static VAr Compensator (SVC)
- FACTS, Flexible ac Transmission Systems, generic name on using power electronics is power systems, increasing the power transmission capacity of the existing system

Production of renewable energy

- Energy sources
  - Wind turbines
  - Solar panels
  - Fuel cells
- Grid connection
  - How to connect renewable energy in to the existing 50/60 Hz power system

10.1 Power Semiconductor Devices

- Diodes, transistors (bipolari and MOSFET), thyristors, IGBT (Insulated Gate Bipolar Transistor)
- Target is an ideal switch
  - Changes from fully on to fully blocking stage (on/off) infinitelly fast
  - No conduction losses, in on-stage, no resistance nor voltage drop over the switch
  - No leakage current when in off-stage
- In practice conduction and turn on and turn off –losses

Ideal switch

- In the following discussion we can assume the use of ideal switches, either on or off

- When it is on, there is no voltage over the switch and current is dictated by the external circuit

- When it is off, there is no current flowing through the device and voltage is dictated by the external device

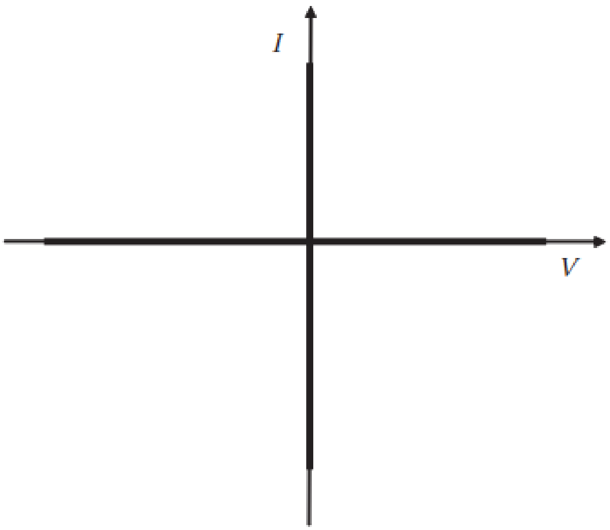


Figure 10.1 Current–voltage characteristics of a mechanical switch.

Diode

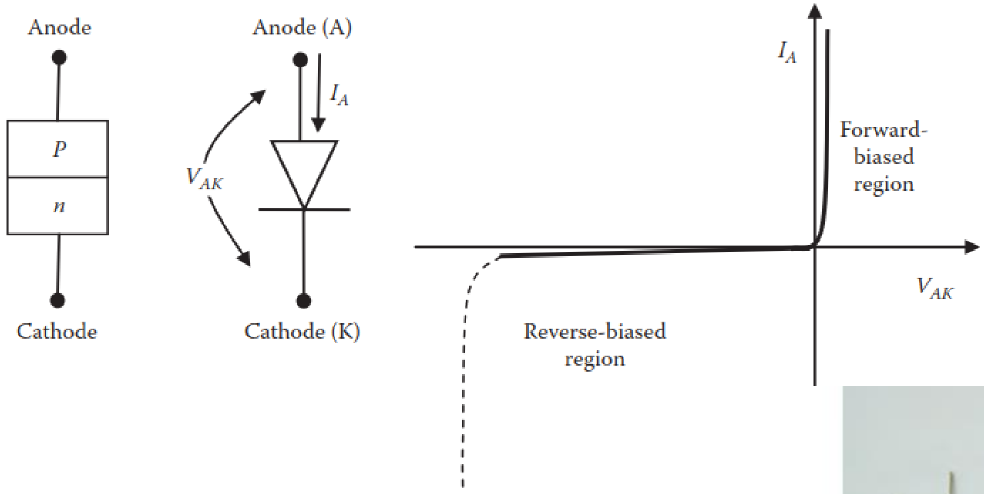


Figure 10.2 Solid-state diode.

Figure 10.3 Different rating diodes.

BJT, Bipolar junction transistor

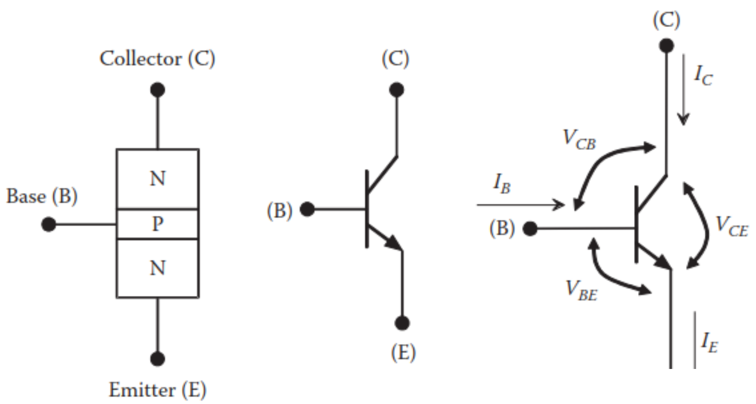


Figure 10.4 Bipolar junction transistor.

BJT is a three-layer component

Requires quite high base current when conducting => used very seldomly in power electronics

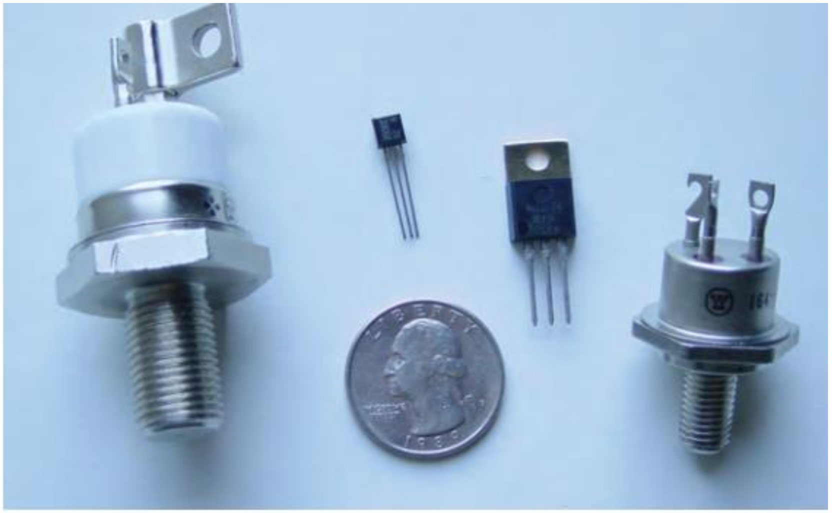


Figure 10.5 Various size transistors.

In power electronics transistor are used as switch, i.e. fully on or off (not in linear region)

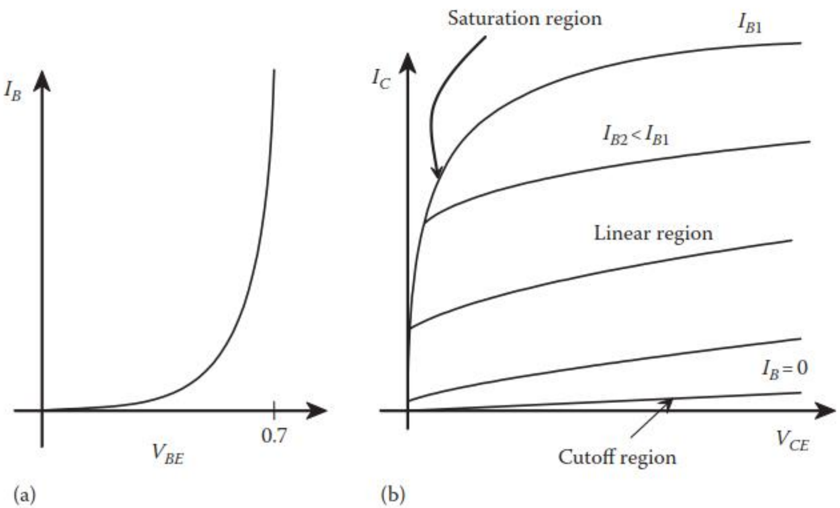


Figure 10.6 Characteristics of BJT: (a) base characteristics and (b) collector characteristics.

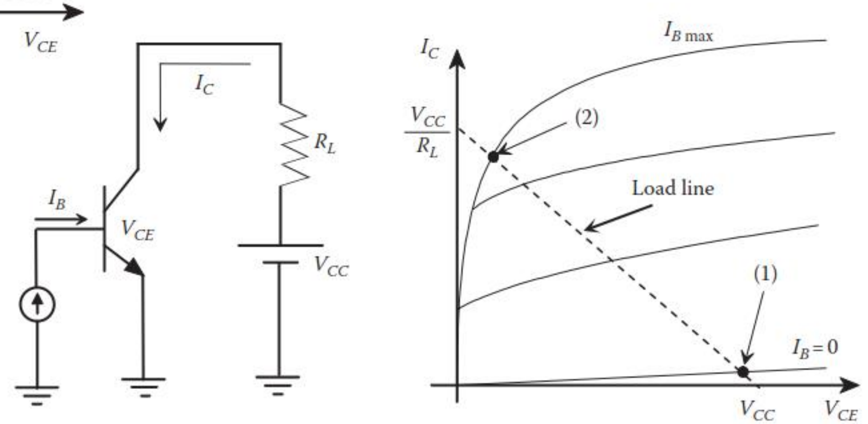


Figure 10.7 Switching of a transistor.

MOSFET is voltage controlled

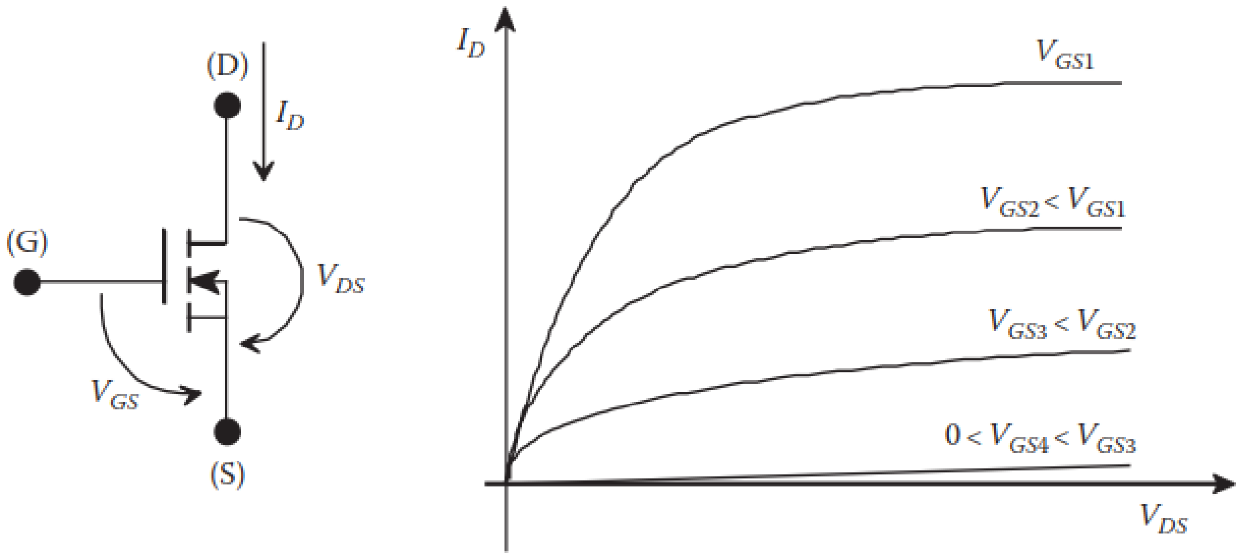


Figure 10.8 Enhanced-mode MOSFET.

- Device used often in switched-mode power supplies when maximum voltages are less than 500 V
- State (on/off) is controlled by gate voltage (not currents as in BJT)

SCR, Silicon Controlled Rectifier is Thyristor

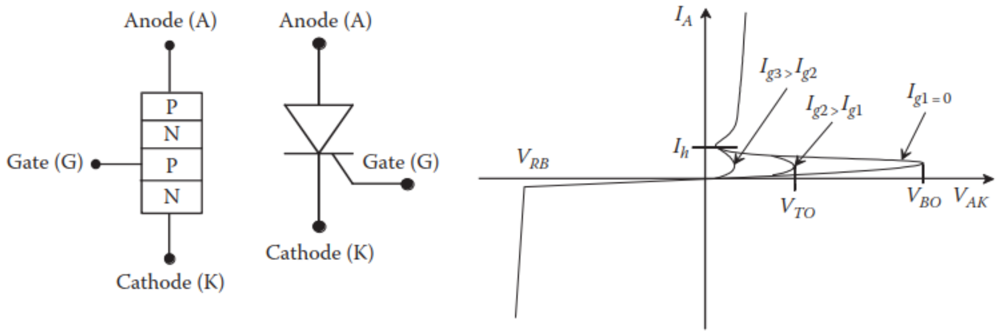


Figure 10.11 SCR structure, symbol, and characteristics.

- Four-layer component
- The turning off of thyristor can be delayed with gate control but a conducting thyristor cannot be turned off by gate

Figure 10.10 High-power SCRs.

Insulated Gate Bipolar Transistor

- IGBT is combination of a MOSFET and bipolar transistor, voltage driven
- Main component e.g. in motor drives and in inverters generally

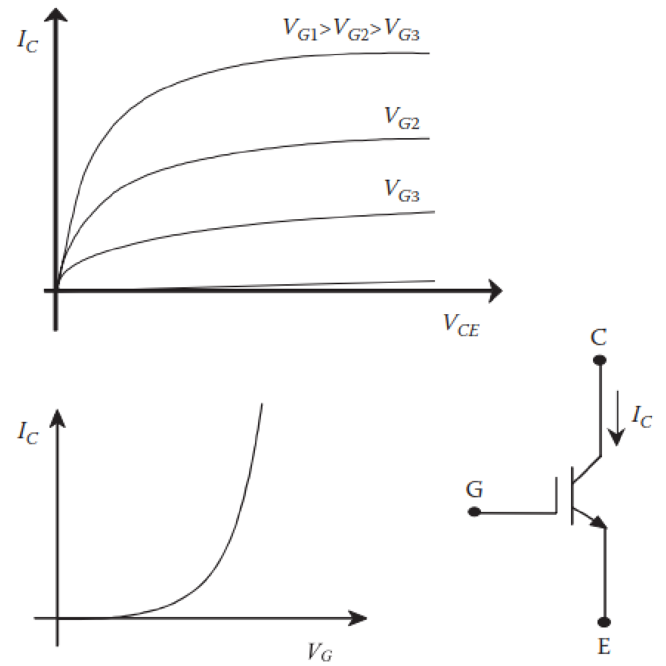


Figure 10.15 Characteristics of IGBT.

Comparison of different devices

- Figure should be modified by changing the arrow from MCT:n to IGBT (MCT is not really used and IGBT is the choice)
- GTO = Gate Turn Off Thyristor, in high power application but has practically been replaced by IGCT

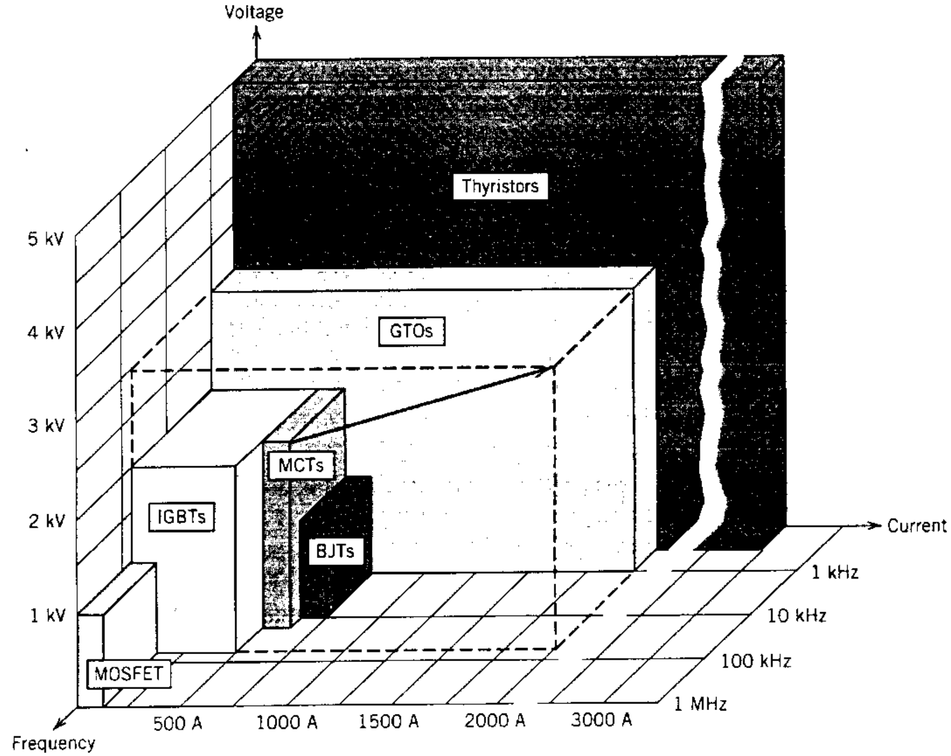


Figure 2-14 Summary of power semiconductor device capabilities. All devices except the MCT have a relatively mature technology, and only evolutionary improvements in the device capabilities are anticipated in the next few years. However, MCT technology is in a state of rapid expansion, and significant improvements in the device capabilities are possible, as indicated by the expansion arrow in the diagram.

10.2 Solid-State Switching Circuits

- Converter is general name for power electronic circuit built from power semiconductor devices
  - Tehopuolijohdekomponenteista rakennettuja kytkentöjä kutsutaan suuntaajiksi (converter)
- Basic conversions
  - Rectification, ac/dc
  - Conversion of dc, dc/dc
  - Inverter, dc/ac
  - Frequency converter, ac/ac

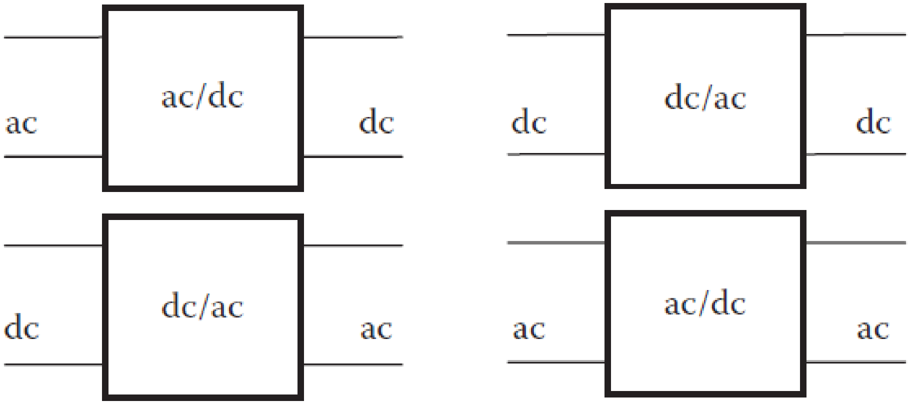


Figure 10.16 Four types of converters.

Half-wave rectifier

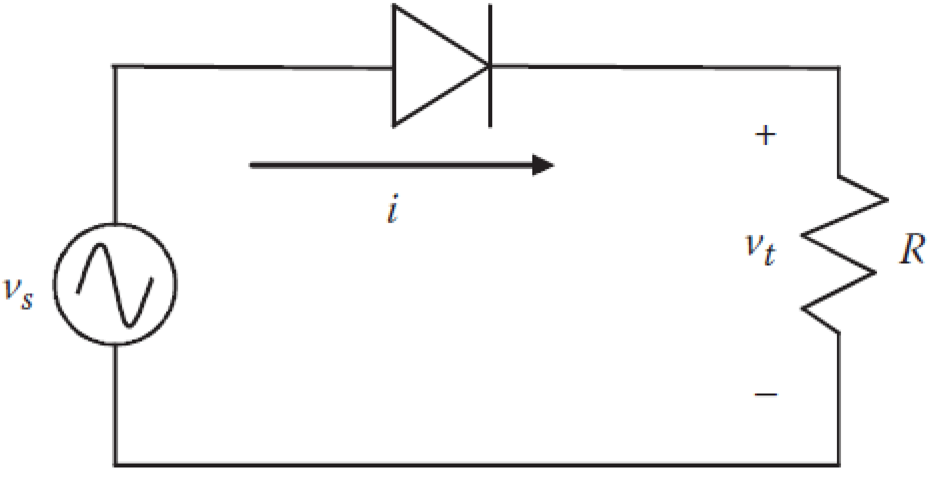


Figure 10.17 Half-wave rectifier circuit.

Voltage and current with resistive load

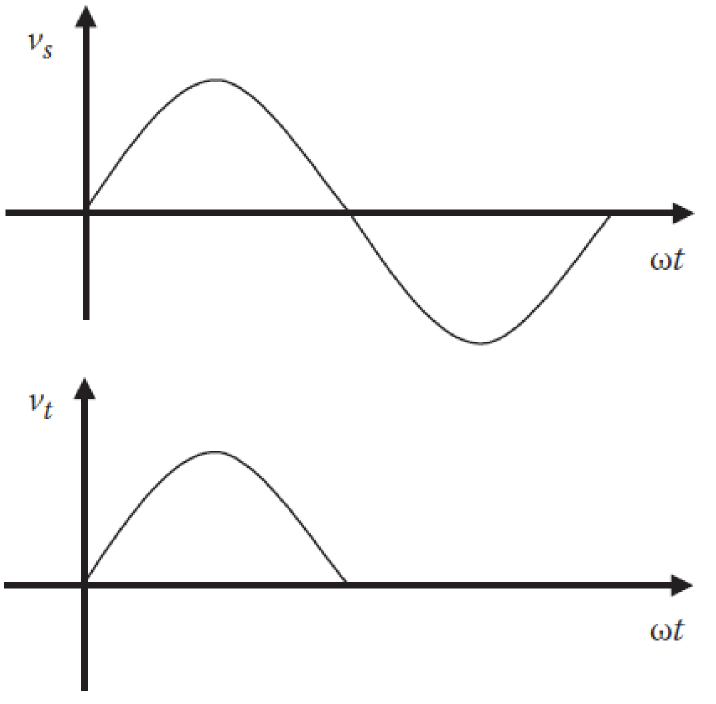


Figure 10.18 Waveforms of half-wave rectifier circuit.

Full-wave rectifier

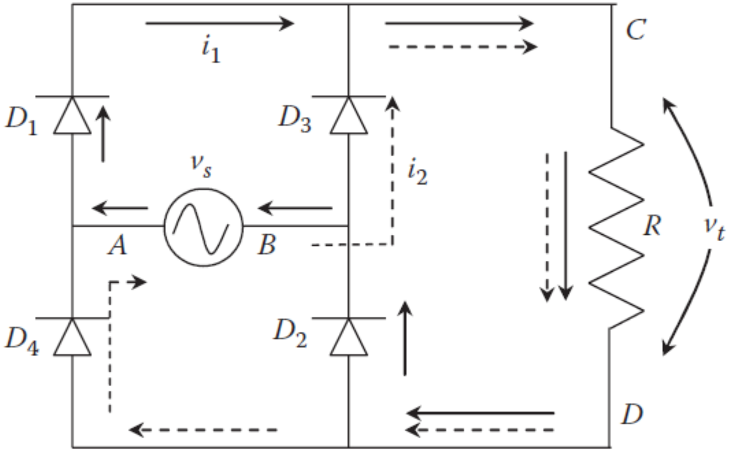


Figure 10.19 Full-wave rectifier circuit.

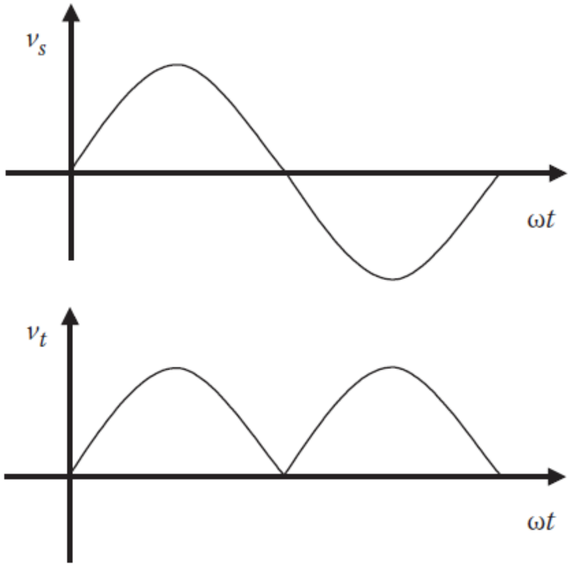


Figure 10.20 Waveforms of full-wave rectifier circuit.

- Animation of single-phase diode rectifier

Thyristor control

- SCR = Silicon Controlled Rectifier = thyristor

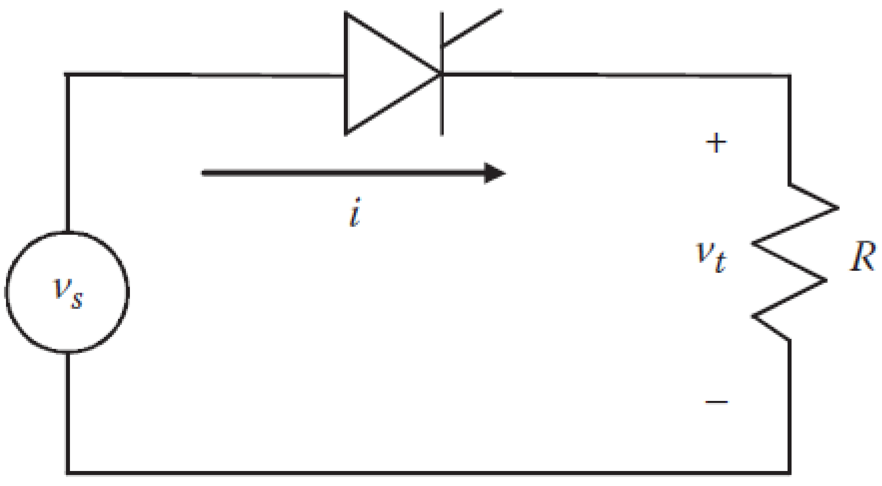


Figure 10.21 Half-wave SCR circuit.

Resistive load

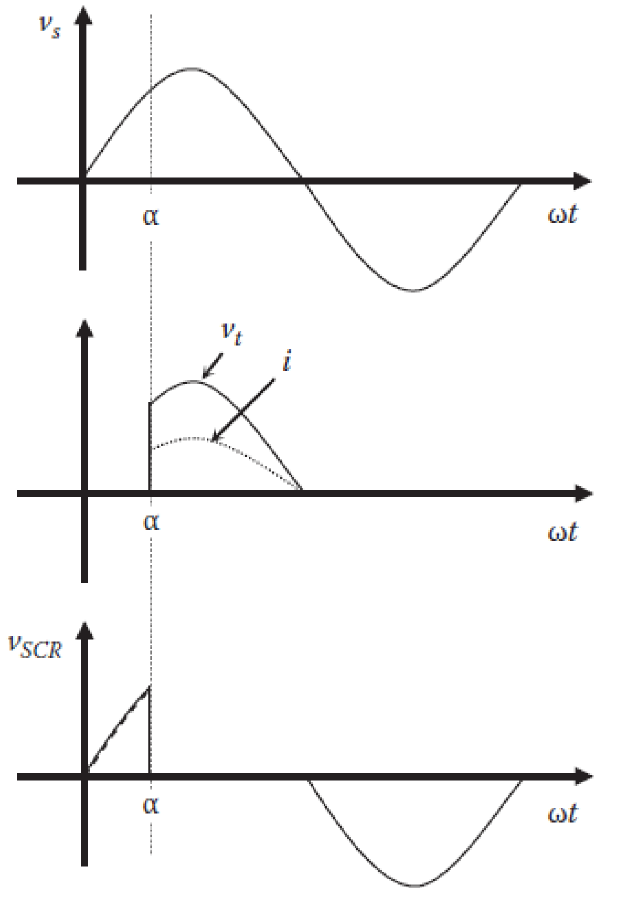


Figure 10.22 Waveforms of half-wave SCR circuit.

Thyristor bridge

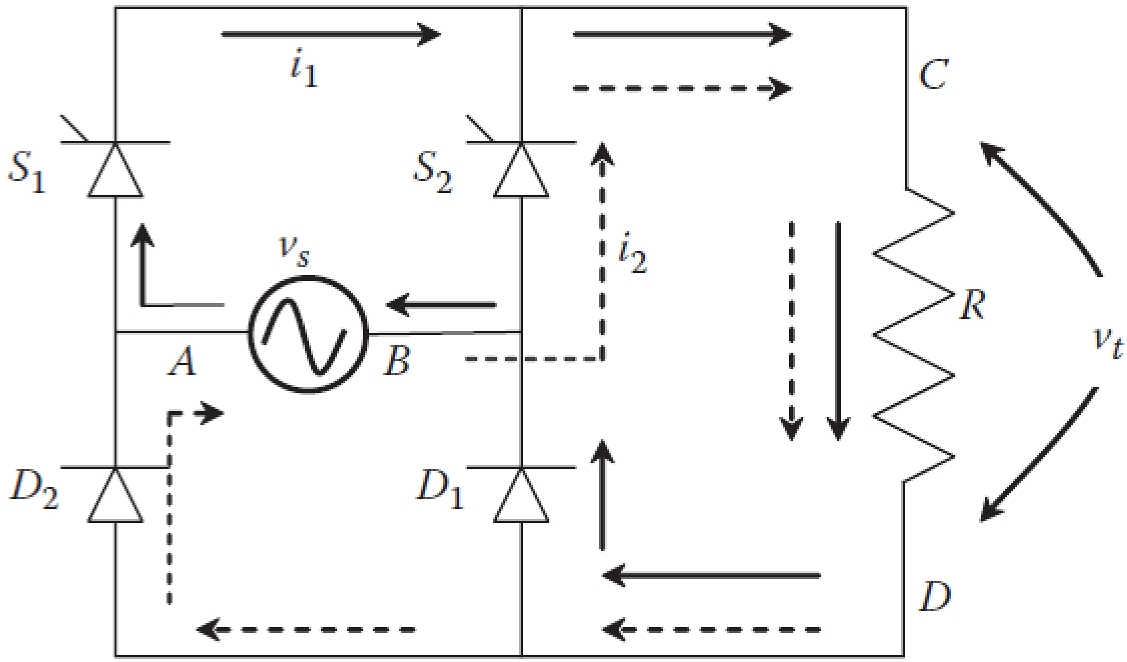


Figure 10.23 Full-wave SCR circuit.

Resistive load

- Animation in which load R/L ratio can be changed, if L = 0 waveforms are as in Fig. 10.24

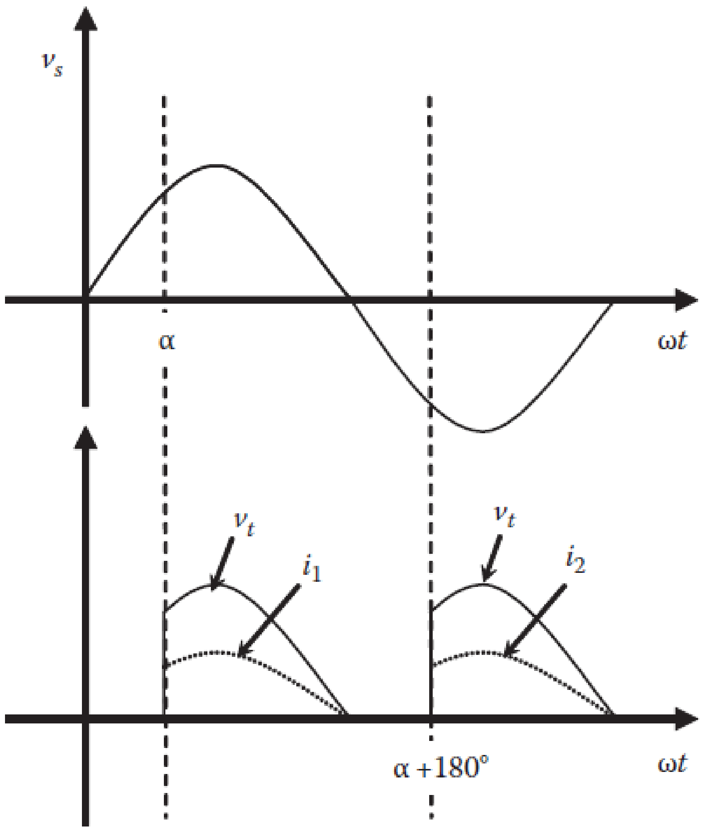


Figure 10.24 Waveforms of full-wave SCR circuit.

Average vale of the dc-voltage

- Half-wave rectifier, Figure 10.21

$$V_{ave} = \frac{1}{2\pi}\int_0^{2\pi} V_{max}\, sin(x)dx = \frac{1}{2\pi}\int_\alpha^{\pi} V_{max} \sin(x)\, dx = \frac{V_{max}}{2\pi}(1 + \cos\alpha)$$

- Full-wave rectifier, Figure 10.24

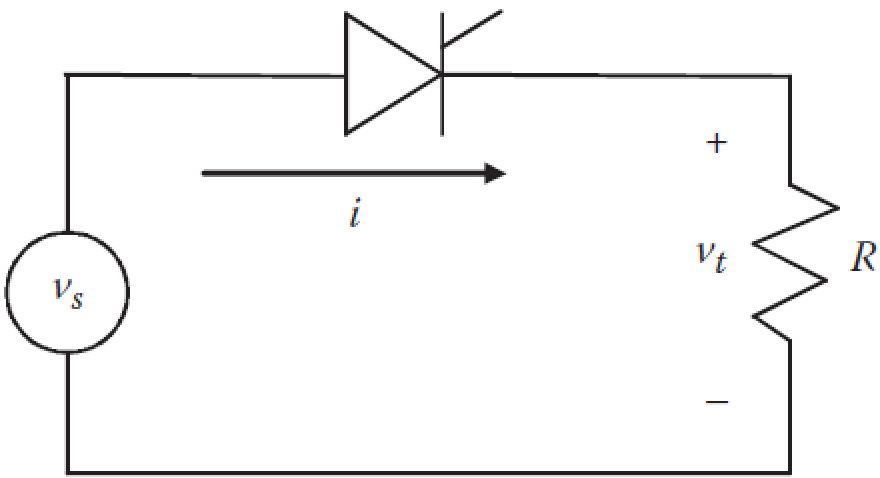
$$V_{ave} = \frac{1}{2\pi}\int_0^{2\pi} V_{max}\, sin(x)dx = \frac{1}{\pi}\int_\alpha^{\pi} V_{max} \sin(x)\, dx = \frac{V_{max}}{\pi}(1 + \cos\alpha)$$

  – i.e. it is two times higher than in half-wave rectifire

- In both cases average value is controlled with control angle α, in diode converters $\alpha = 0$

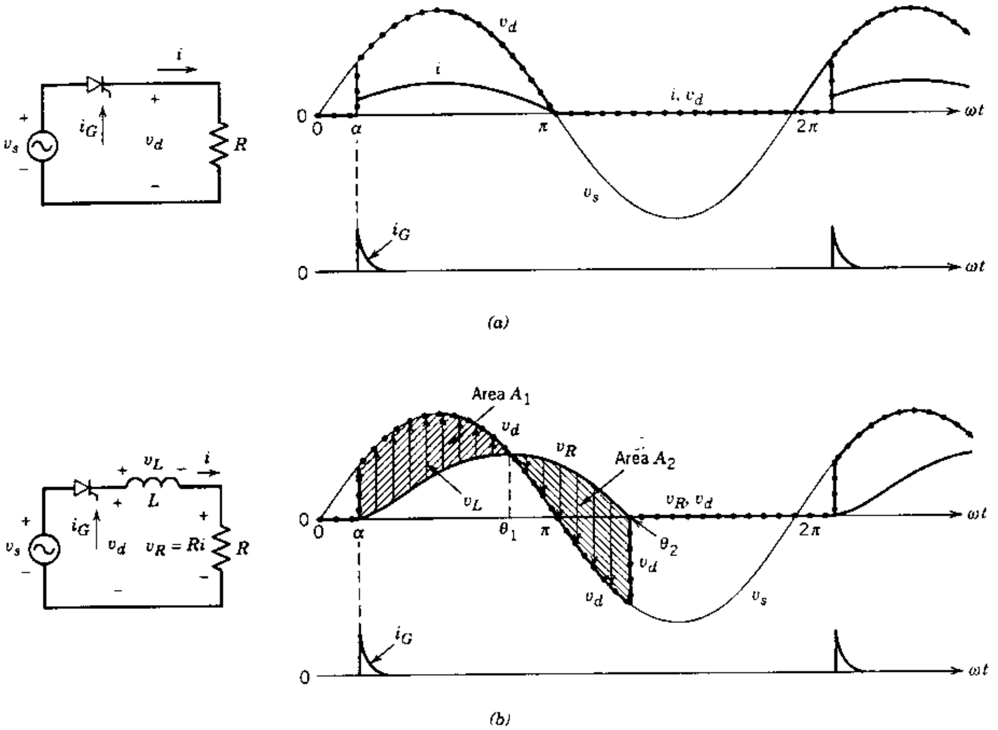
Inductive load

- What changes is load is R+L?



Inductive load

- Inductance limits the change of current
- At time π voltage is zero but inductance has still current, which continues to flow untill in becomes zero
  - Thyristor is not conducting in the reverse direction
- Animation, in which load R/L-ratio can be changed



DC-voltage source in the load, e.g. capacitor of battery

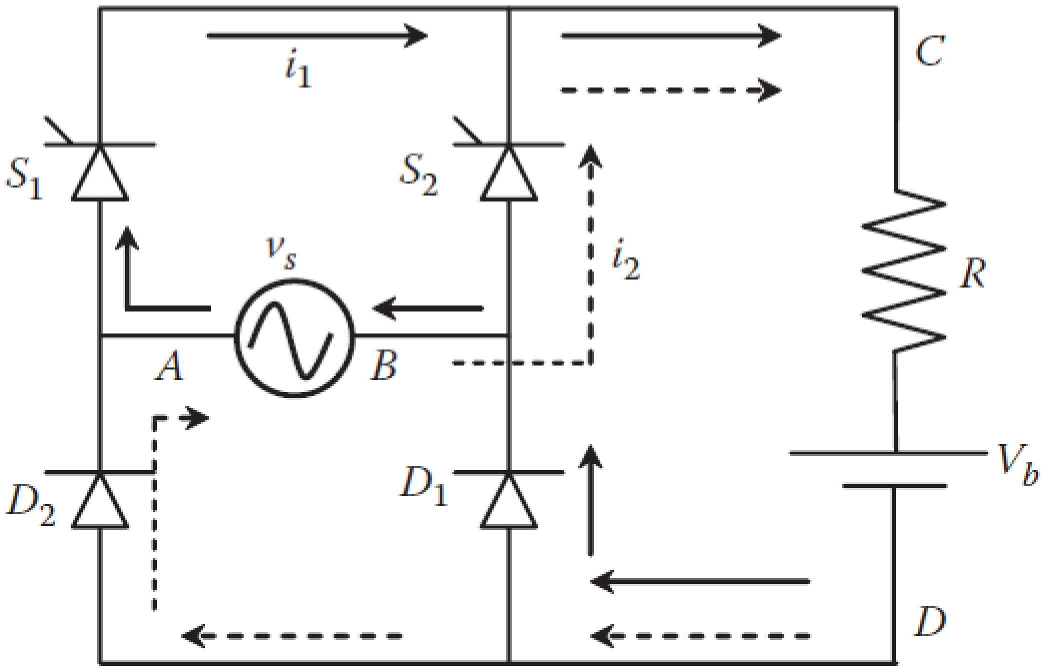


Figure 10.26 Full-wave charger circuit.

Voltage and current

- Current flows only when the input voltage is higher than the voltage of dc-load
- Current has high peaks close the peaks of the ac voltage and this stresses the power system

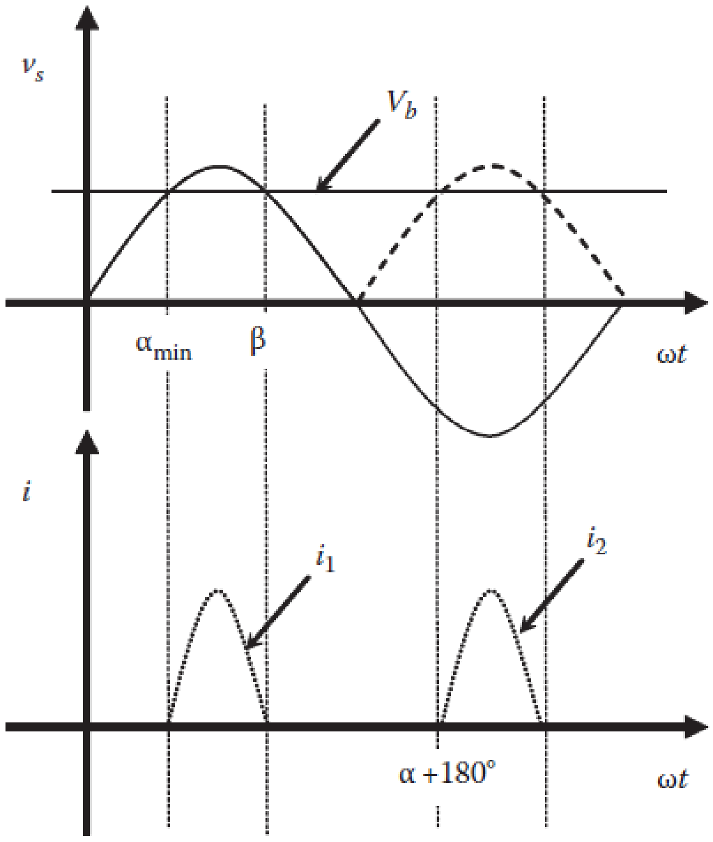


Figure 10.27 Waveforms of the full-wave charger circuit.

Some animations

- Load has a dc-voltage source and on the ac-side there is a small series inductance
- Here inductance is on the dc-side but other than that very similar situation as above
- Here the dc voltage source has been replaced by a capacitor. When the rectified ac is higher than capacitor voltage there is no current flow from the ac grid and load current reduces capacitor voltage

Three-phase midpoint connection

- Needs the midpoint of the supply system

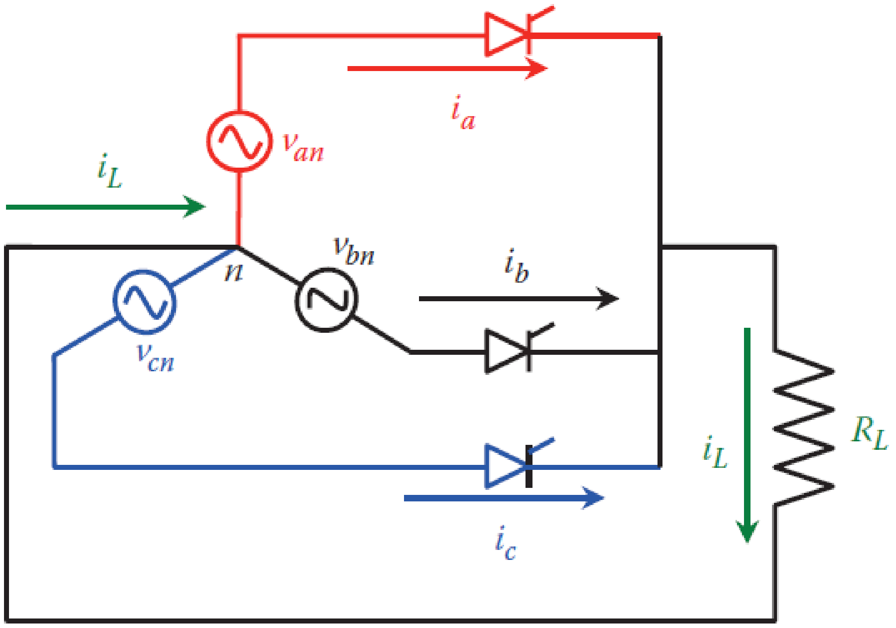


Figure 10.28 Three-phase half-wave ac/dc switching circuit.

Resistive load, diodes

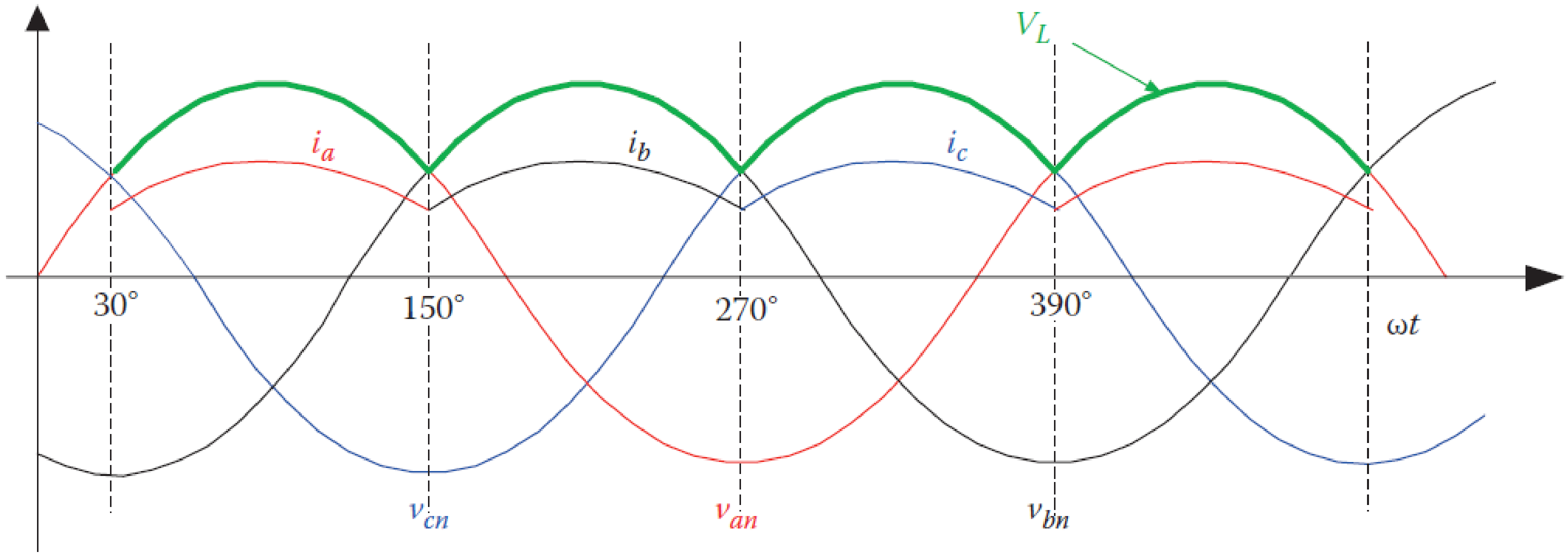


Figure 10.30 Three-phase half -wave ac/dc diode waveforms.

Resistive load, turning on is delayed by control angle α

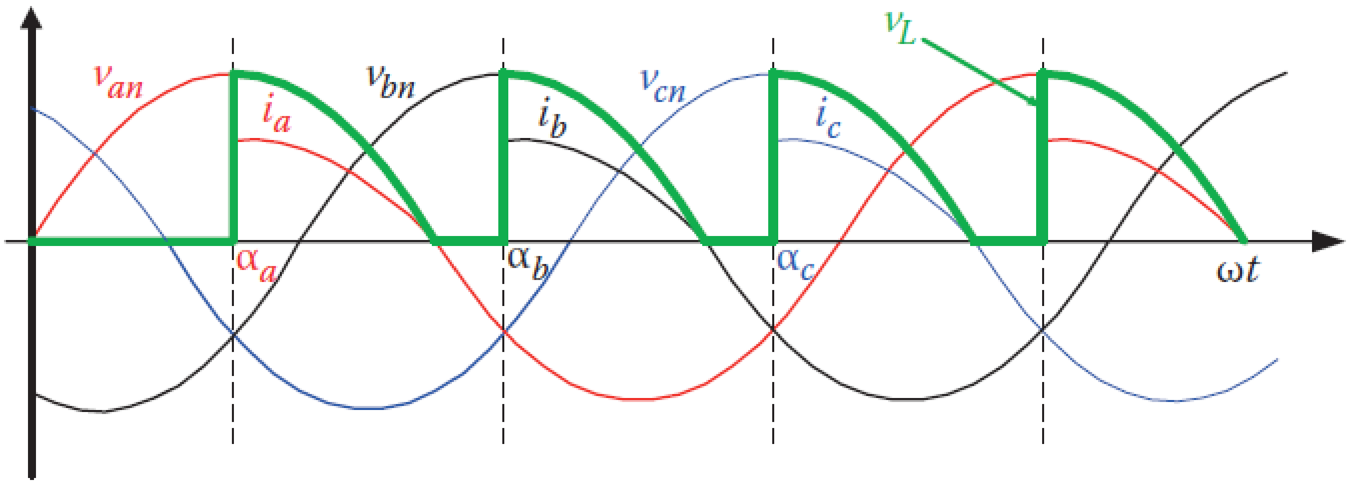


Figure 10.29 Waveforms of the circuit in Figure 10.28.

Three-phase bridge connection

- Here three thyristor have been added to the negative side of the load
- Animation where R/L-load ratio can be adjusted

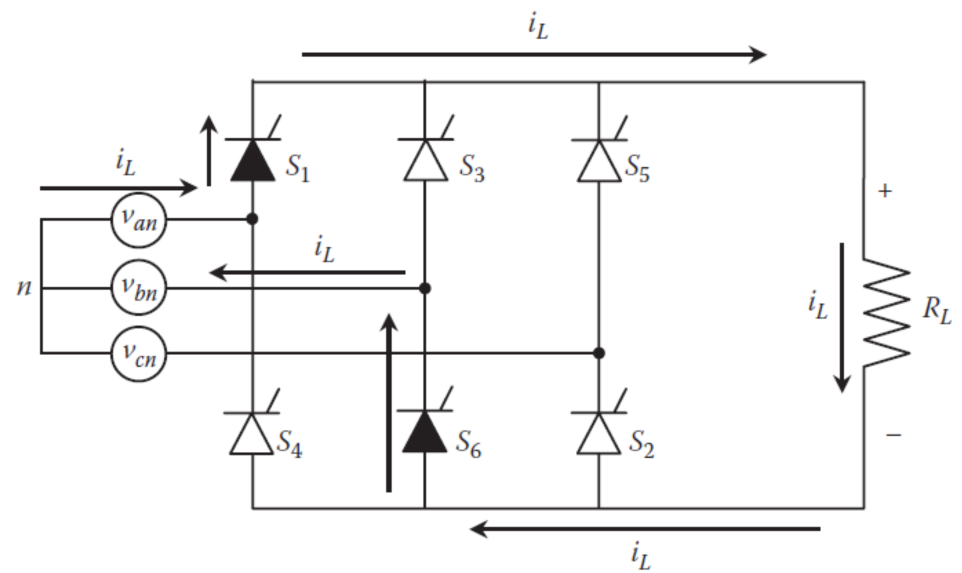


Figure 10.31 Three-phase full-wave ac/dc switching circuit operating between points 1 and 2.

Controlled output voltage

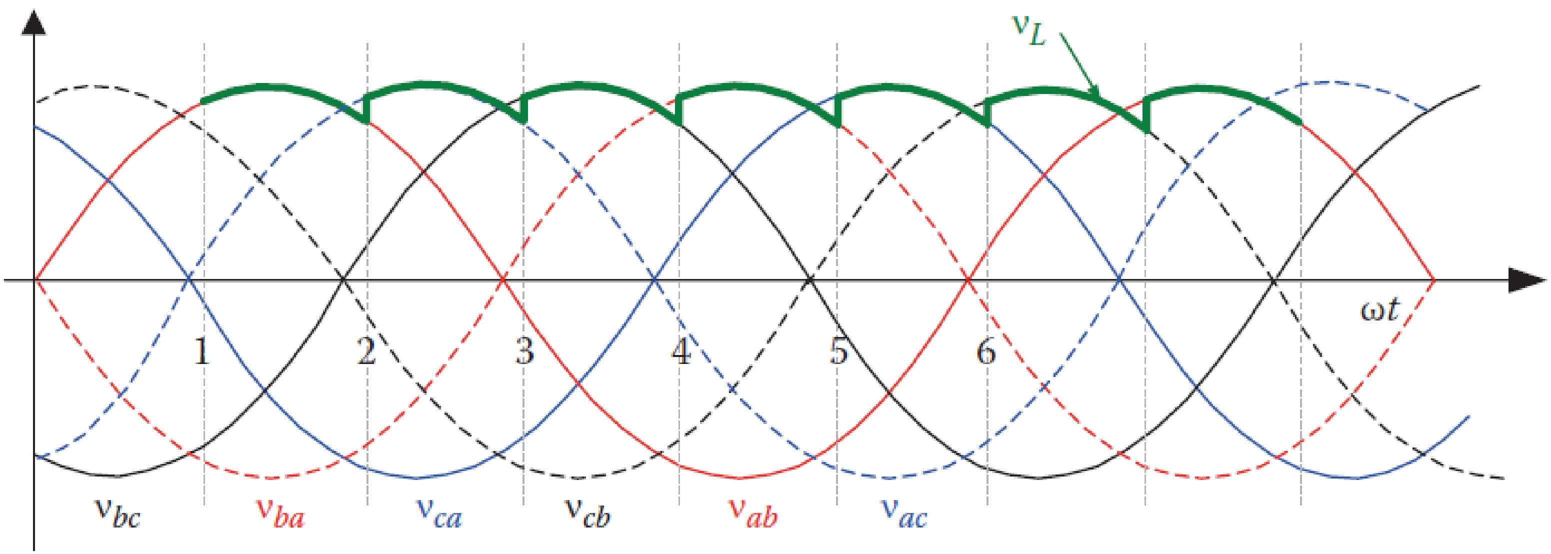


Figure 10.32 Three-phase full-wave ac/dc switching circuit waveforms.

Average of the dc-voltage

- Three-phase midpoint connection

$$V_{ave} = \frac{3}{2\pi}\int_{\alpha_a}^{\pi} V_{max}\sin(x)\,dx = \frac{3V_{max}}{2\pi}(1+\cos\alpha_a)$$

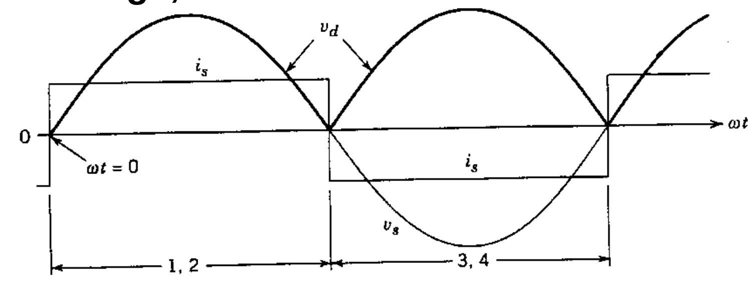
- Three-phase bridge

$$V_{ave} = \frac{6}{2\pi}\int_{\alpha_{ab}}^{\alpha_{ab}+\pi/3} \sqrt{3}V_{max}\sin(x)\,dx = \frac{3\sqrt{3}V_{max}}{\pi}\sin\left(\alpha_{ab}+\frac{\pi}{6}\right)$$

Inductive load

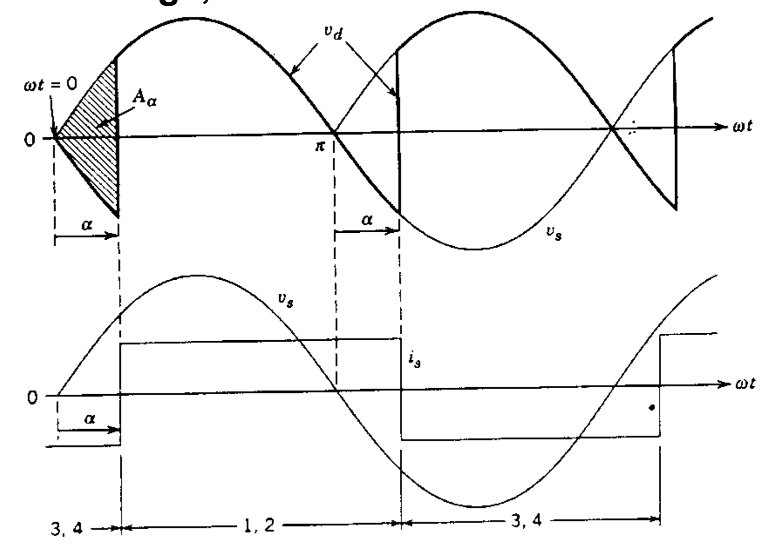
- Ideally dc-current can be assumed to be pure dc
- Current flows even if voltage becomes negative

Diode bridge, $\alpha = 0$



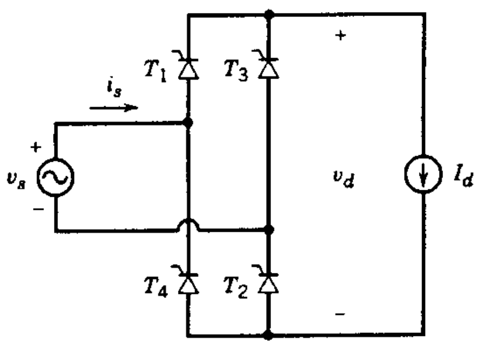
(a) $\alpha = 0$

Thyristor bridge, $0 \leq \alpha \leq \pi$



(b) α = finite

Figure 6-6 Waveforms in the converter of Fig. 6-5.



(a)

Figure 6-5 Single-phase thyristor converter

Inductive load, three-phase converter

- Dc voltage is between the most positive input voltage and most negative input voltage

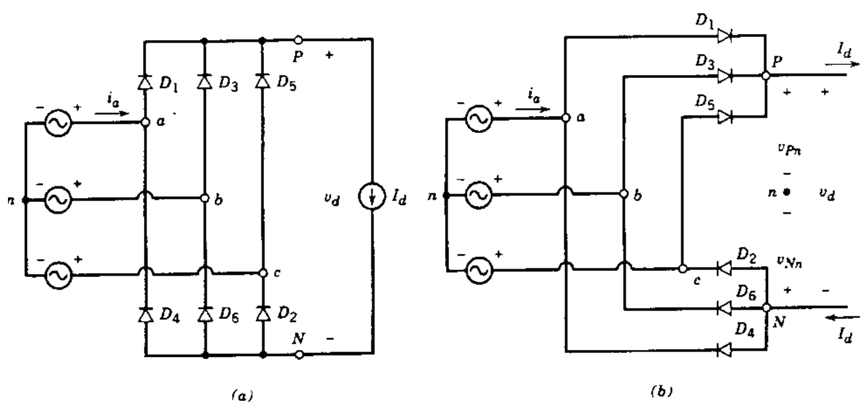


Figure 5-31 Three-phase rectifier with a constant dc current.

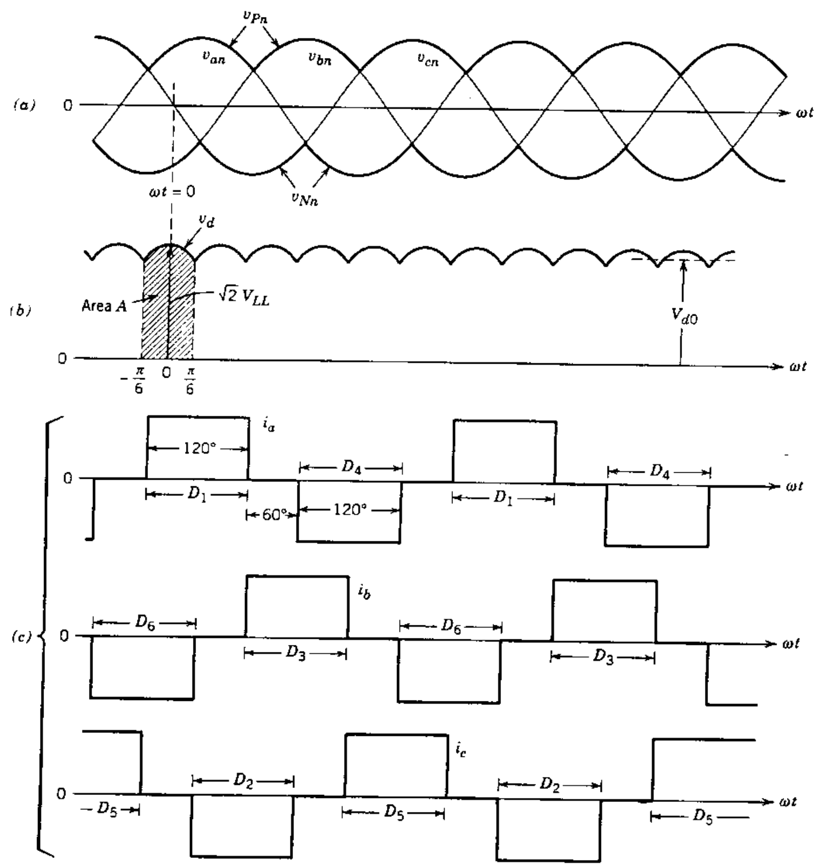
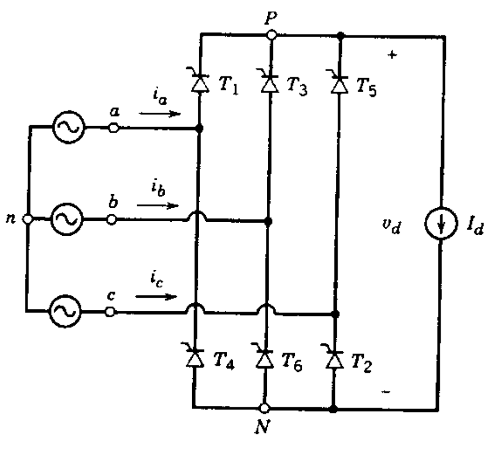


Figure 5-32 Waveforms in the circuit of Fig. 5-31.

Inductive load, three-phase thyristor converter

- Voltage value is adjusted (decreased) by increasing the delay angle



(a)

Figure 6-19 Three-phase thyristor converter with $L_s = 0$ and a constant dc current.

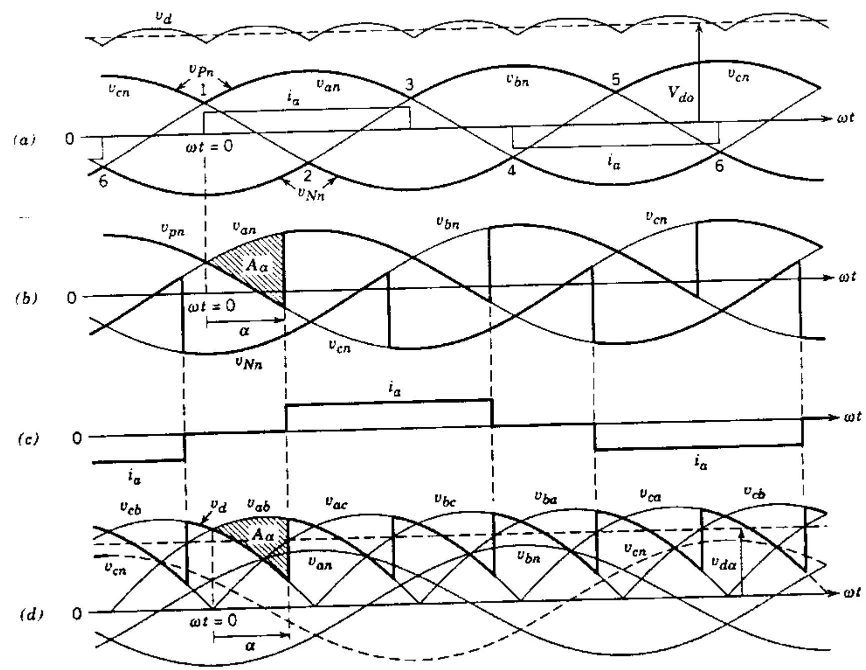


Figure 6-20 Waveforms in the converter of Fig. 6-19.

$\alpha = 0$

$\alpha > 0$

Average value of the dc-voltage when dc-side is ideal current source

- Single-phase converter

$$V_{ave} = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_{\max}\sin(x)dx = \frac{2}{\pi}V_{\max}\cos(\alpha)$$

- Three-phase bridge

$$v_d = \sqrt{3}V_{\max}\cos(x), -\pi/6+\alpha < x < \pi/6+\alpha \quad => \quad V_{ave} = \frac{6}{2\pi}\int_{-\pi/6+\alpha}^{\pi/6+\alpha} V_{\max}\cos(x)dx = \frac{3\sqrt{3}}{\pi}V_{\max}\cos(\alpha)$$

- In both case the average depends on the cosinus of the control angle
  - Control angle changes between 0 - π
  - **When α is more than $\pi/2$** average is negative and flow of power reverses from the dc-side to ac-side. Direction of the dc-current cannot change, it is always positive

10.2.2 DC-DC converters

- Step down, Buck
- Step up, Boost
- Step down and up, Buck-Boost

Buck

- ”Samples” from the higher dc-voltage
- Average of the output depends directly on the relative on time, duty cycle

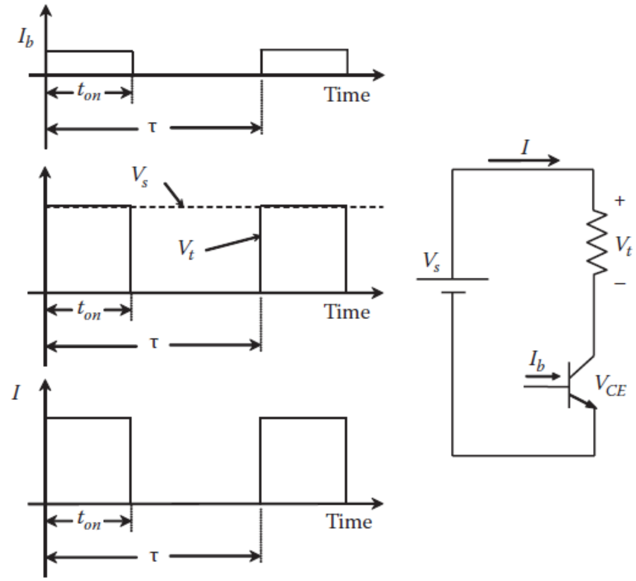


Figure 10.34 Simple chopper circuit.

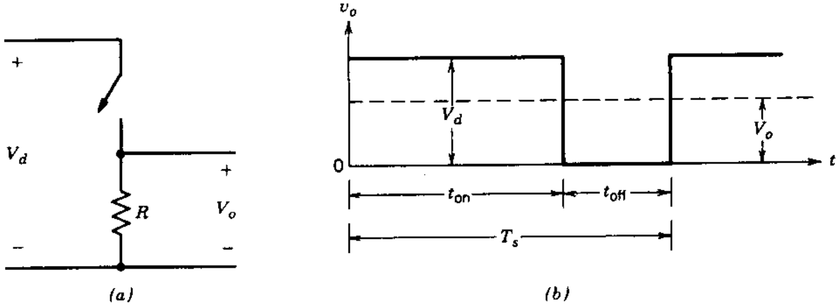


Figure 7-2 Switch-mode dc–dc conversion.

Pulse Width Modulation, PWM

- PWM (Pulse-Width Modulation)
  - High frequency carrier is compared with $v_{control}$
- Sawtooth frequency gives the switching frequency f_s of the devices
- Control voltage $v_{control}$
- is coming from the feedback
- Duty cycle

$$K = \frac{v_{control}}{\hat{V}_{st}}$$

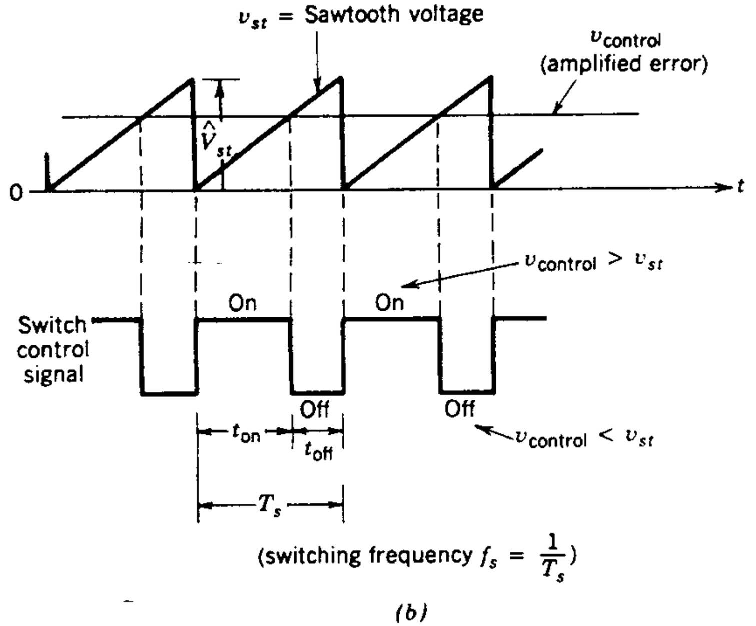
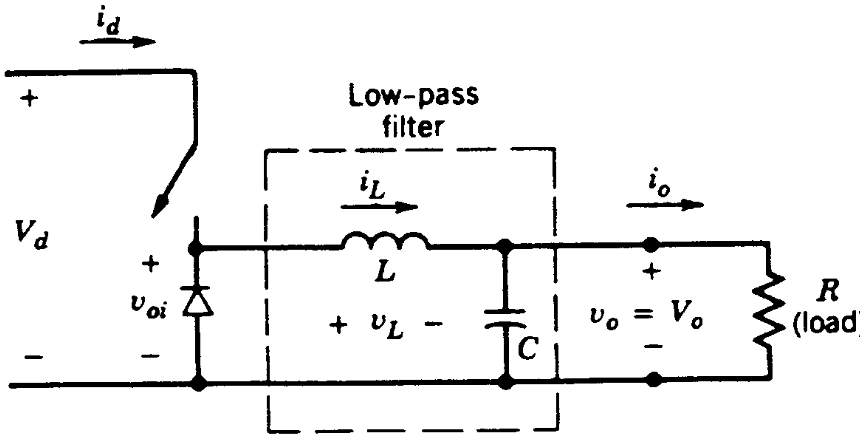


Figure 7-3 Pulse-width modulator: (a) block diagram: (b) comparator signals.

Buck, in practice

- High frequency harmonics need to be filtered with a low-pass LC-filter
- Because of the inductance L diode is needed, and it conducts when the switch is off



(a)

Buck, currents and voltages

- Output capacitor is assumed to be large enough => dc-voltage
- Voltage over the inductance
  - Switch on, difference between input and output voltages
  - Switch off, output voltage as negative
- In steady stage both areas, A and B are equal
  - Average of output voltage depends directly on duty cycle K

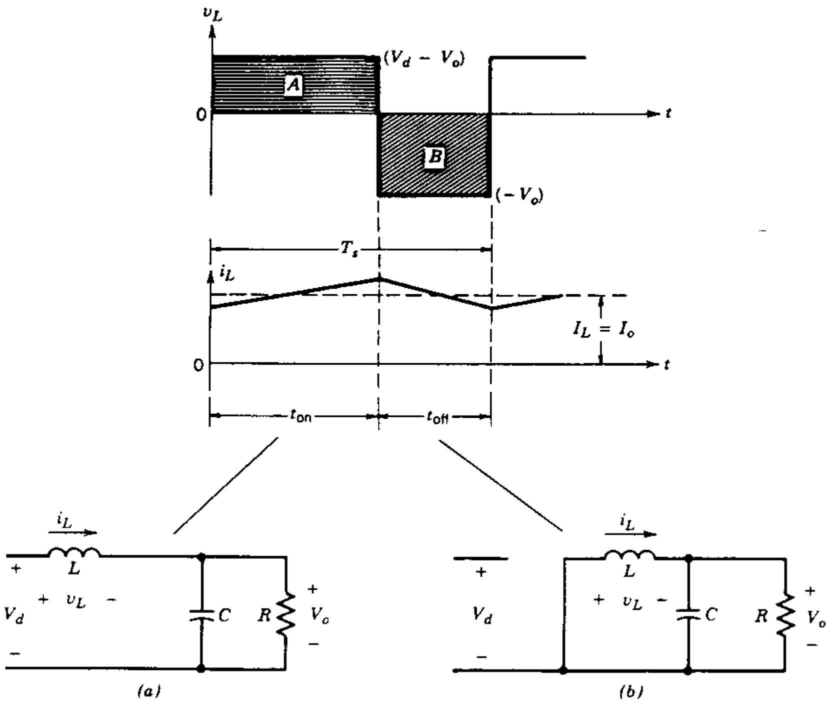


Figure 7-5 Step-down converter circuit states (assuming i_L flows continuously): (a) switch on; (b) switch off.

$$V_o = \frac{t_{on}}{T_s} V_d = K V_d$$

Boost

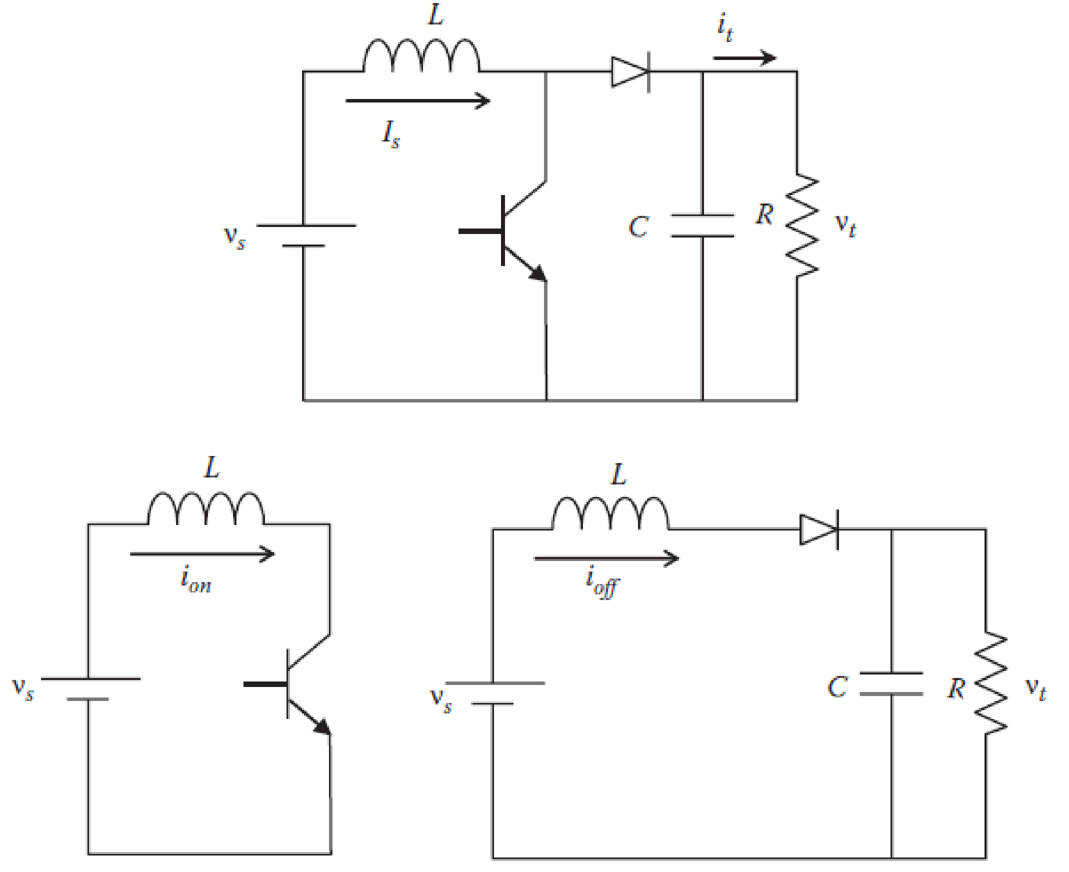


Figure 10.35 A simple boost converter.

Boost, current

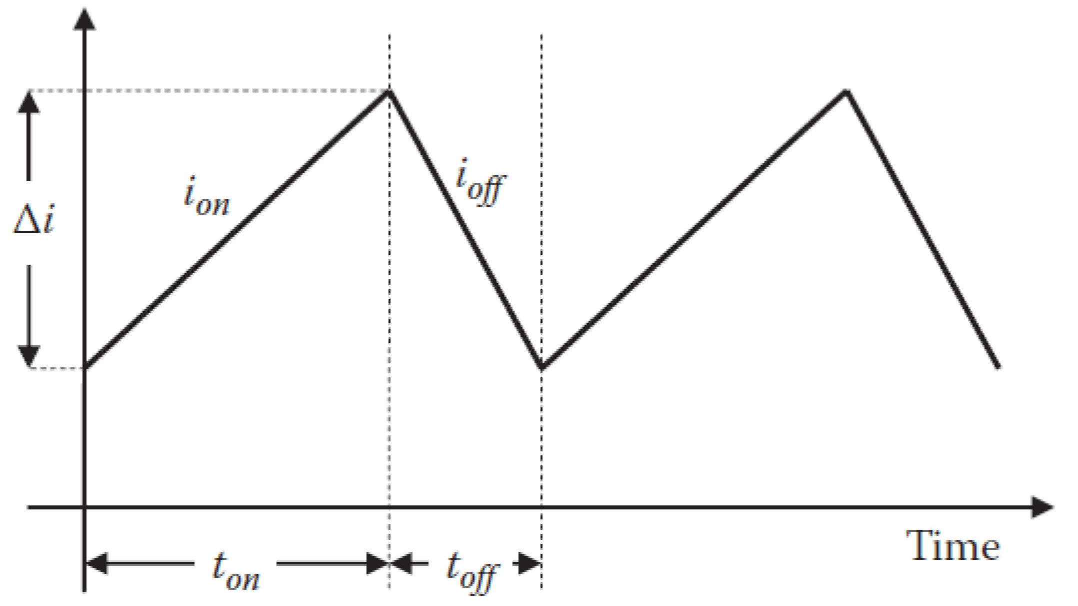


Figure 10.36 Waveform of boost converter.

Boost, currents and voltages

- The diode in the circuit conducts if output voltage would be smaller than the input voltage
- Voltage over the inductance
  - Switch on, input voltage
  - Switch off, difference betwen input and output voltages, negative
- In steady stage both current changes are equal
  - When K approaches 1 output voltage in theory is infinte, in practice resistive losses in the circuit limits this

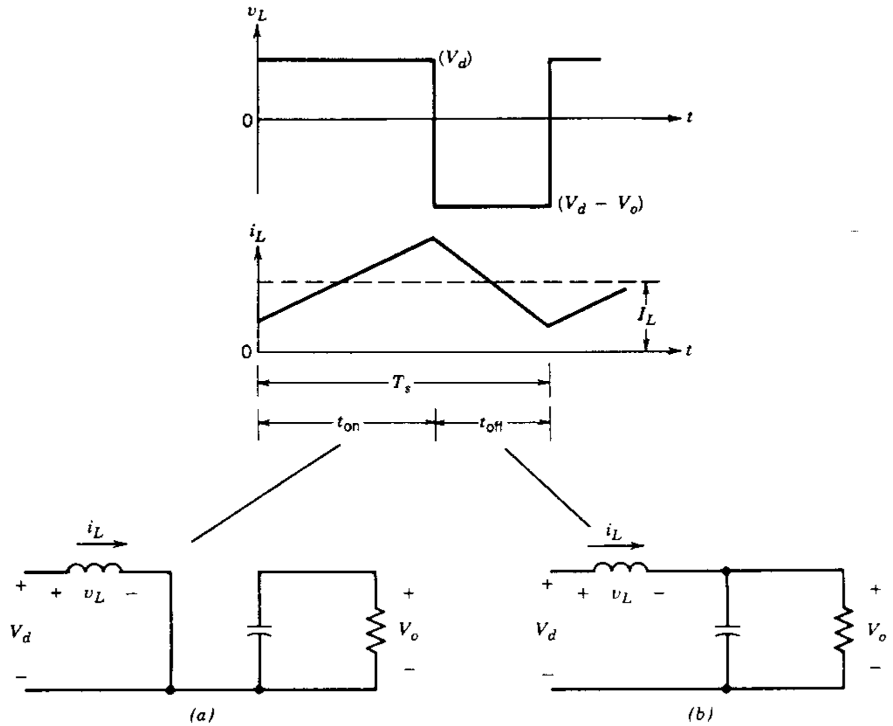


Figure 7-12 Continuous-conduction mode: (*a*) switch on: (*b*) switch off.

$$V_d t_{ON} + (V_d - V_o) t_{OFF} = 0 \Rightarrow \frac{V_o}{V_d} = \frac{T_S}{t_{OFF}} = \frac{1}{1-K}$$

Buck-Boost

- Same components as in previous circuits but have been rearranged
- Remark, output voltage direction is opposite

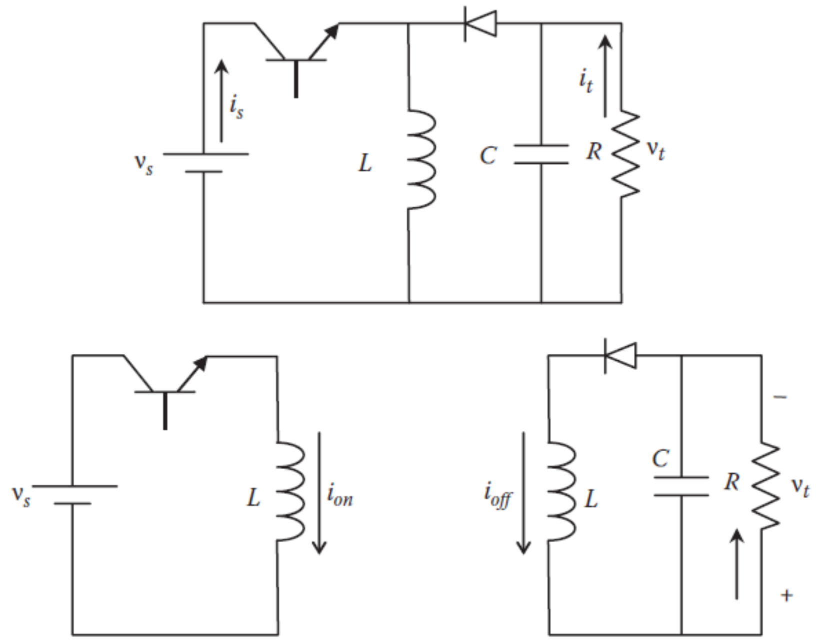
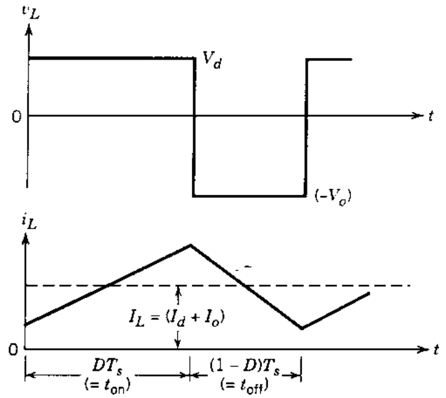
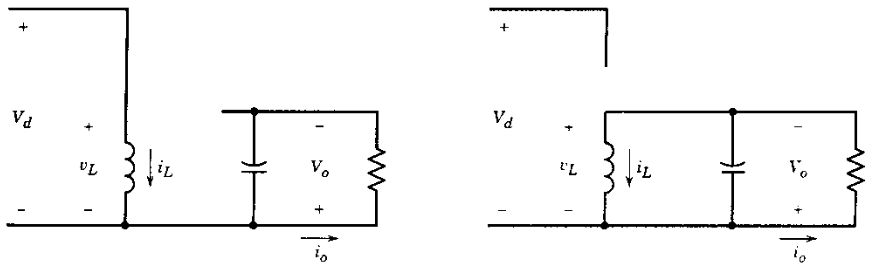


Figure 10.37 A simple buck–boost converter.

Buck-Boost, currents and voltages

- Voltage over inductance
  - Switch on, input voltage
  - Switch off, output voltage
- In steady stage both current changes are equal
  - Multiplication of buck and boost
  - When *K* = 0,5 output voltage is equal to input voltage





$$V_d t_{on} - V_o t_{off} = 0 => \frac{V_o}{V_d} = \frac{t_{on}}{t_{off}} = \frac{K}{1-K}$$

Animations on dc-dc converters

- The converters in the following animations can also work in so called discontinuous current mode.
  - Inductor current starts from zero when the switch is turned on and returns to zero when switch is not conducting
  - Current is zero part of the time
  - Figures in the textbook and in these slides are for the continuous conduction mode, inductor current is always higher than zero
- Buck, Boost, Buck-Boost

10.2.3 Inverter (DC/AC)

- Single-phase inverter
- Three-phase inverter
- Pulse-width modulation

Quadrants of operation

- Single-phase output
  - Voltage sinusoidal
  - Phase shift in current
  - Polarities of voltage and current
  - same => power dc-ac
  - different => power ac-dc
- Phase shift defines if the power flow over whole cycle is from dc to ac or vice versa

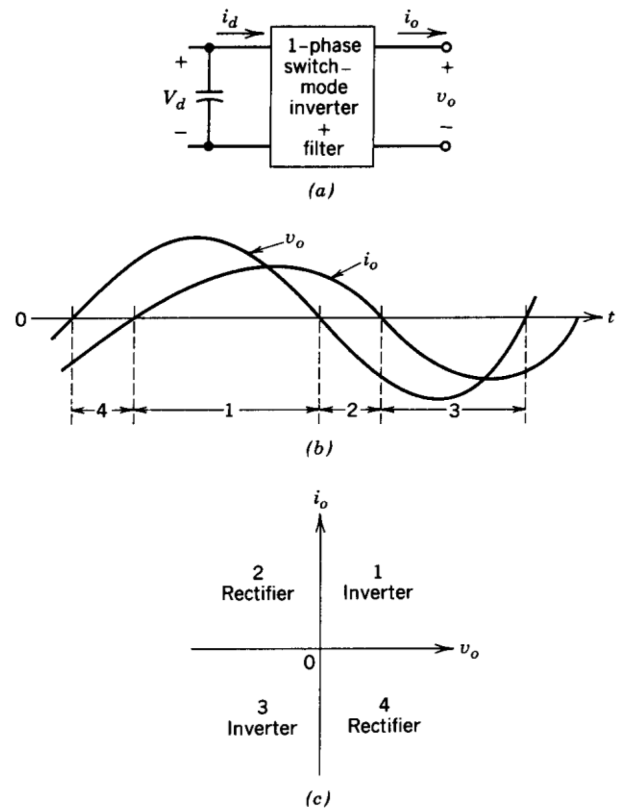


Figure 8-3 Single-phase switch-mode inverter.

Single phase inverter

- Often called as H-bridge too
  - Switches in the same leg cannot be turned on simultaneously, would cause a short circuit in the supply
- Maximum output voltage when both ends of the load are connected consecutively to plus and minus supply
- With resistive load current and voltage waveforms are the same
- There is a mistake in the figure, what?

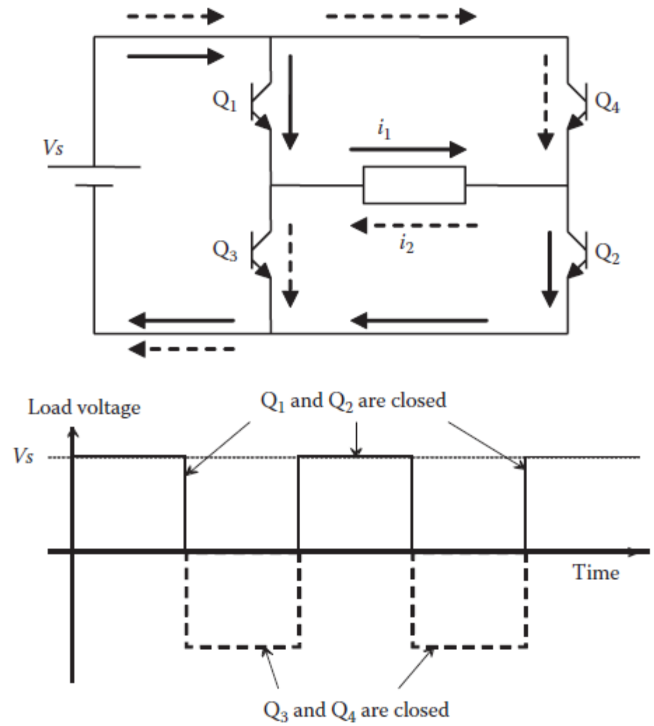


Figure 10.38 Single-phase dc/ac converter.

Single-phase inverter with freewheeling diodes

- In ac polarities of voltage and current are different if there is any phase shift
- In the figure of the previous page e.g. when Q1 is turned on, current can be negative, direction of dashed i_2
- We need antiparallel connected diodes, which are conducting depending on the phase shift of current and voltage

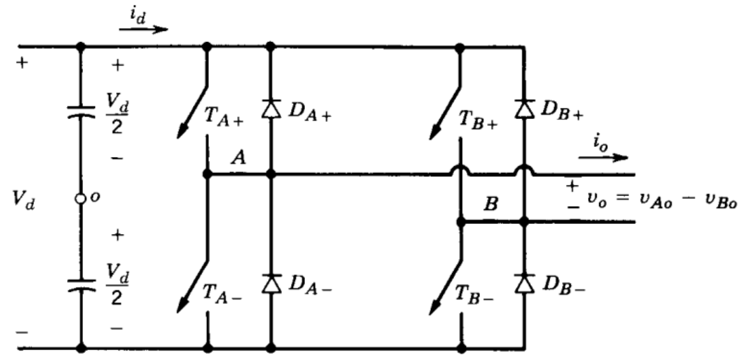


Figure 8-11 Single-phase full-bridge inverter.

Three-phase inverter

- We are adding on leg to the single-phase inverter and three phase load is connected in star or delta
- Again the figure has a mistake!

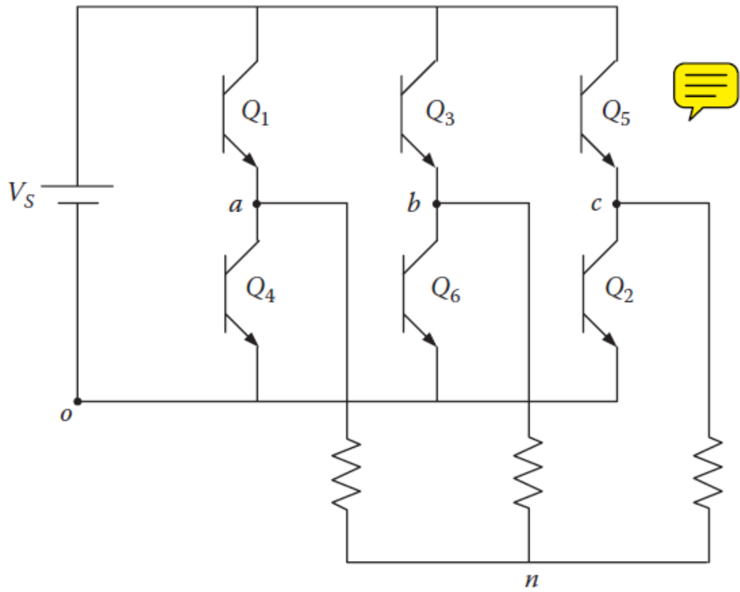


Figure 10.39 Three-phase dc/ac inverter.

Signle-phase inverter with freewheeling diodes

- We need antiparallel connected diodes, which are conducting depending on the phase shift of current and voltage

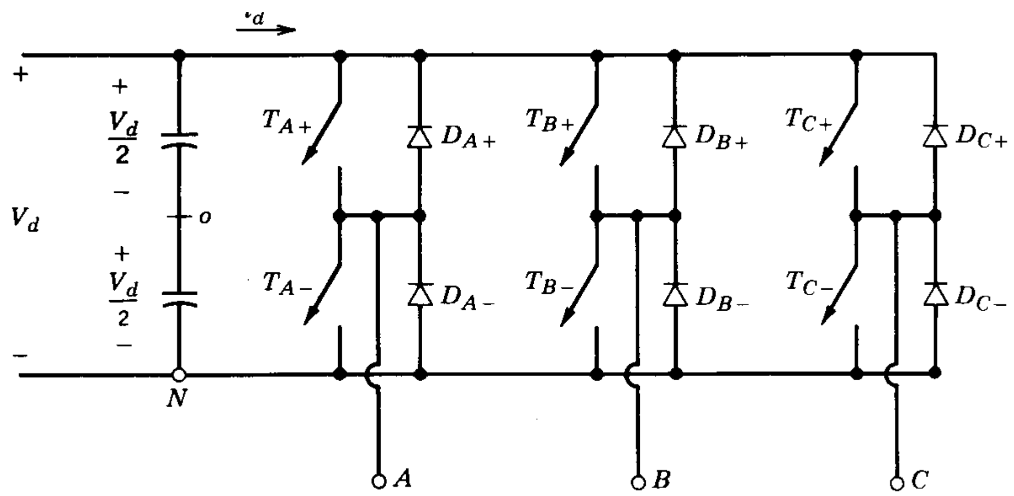


Figure 8-21 Three-phase inverter.

Operation of the inverter

- Based on the control of the switches, one phase is connected either to plus or minus
- Two different examples shown in the figure

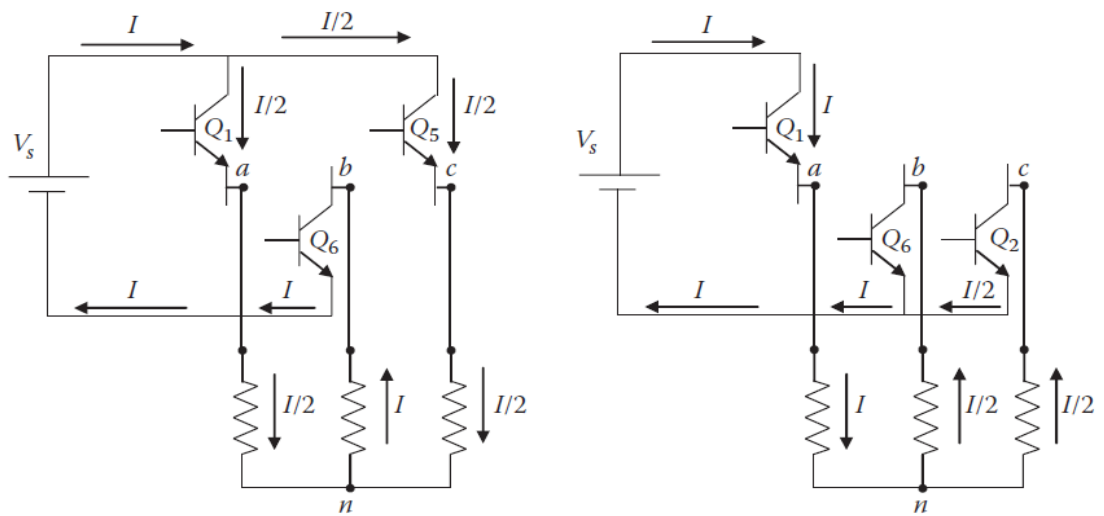


Figure 10.41 Active transistors and current flow during the first two intervals.

Resistive load

- Maximum output
  - Each leg is connect to the plus half of the time and the other half to minus, e.g. Q1/Q4
- There is a 120 degree phase-shift between the phases
- With resistive load voltage and current waveforms are similar

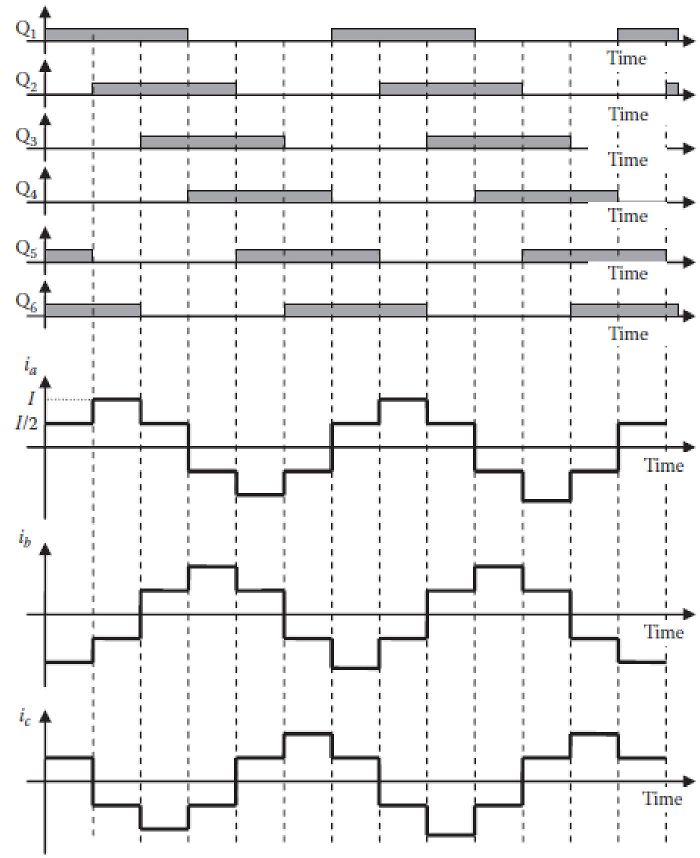


Figure 10.40 Timing of transistors and the phase currents.

Single-phase inverter, PWM

- PWM with same idea as in dc-dc converters
  - Control voltage $v_{control}$ is changed all the time (sinusoidally) => result is dc-voltage with changing amplitude which actually is ac
  - Carrier voltage needs to be negative too as ac has negative values
- Result is voltage with varying pulses, it has fundamental component, which can be adjusted with $v_{control}$

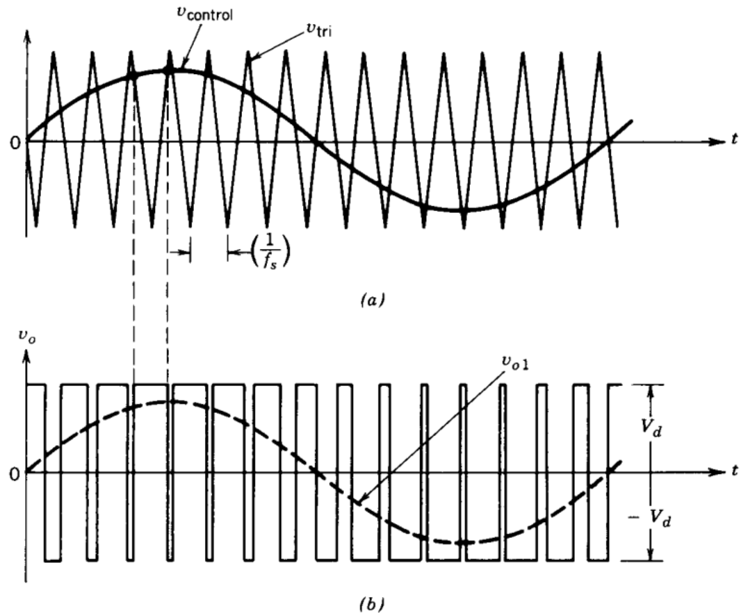


Figure 8-12 PWM with bipolar voltage switching.

Three-phase inverter, PWM

- Same principle as in single-phase but three control voltages, 120 degrees phase shift
- Line-to-line voltage is dc-bus voltage as positive or negative
- Output voltage contains harmonics depending on the switching frequency and output frequency

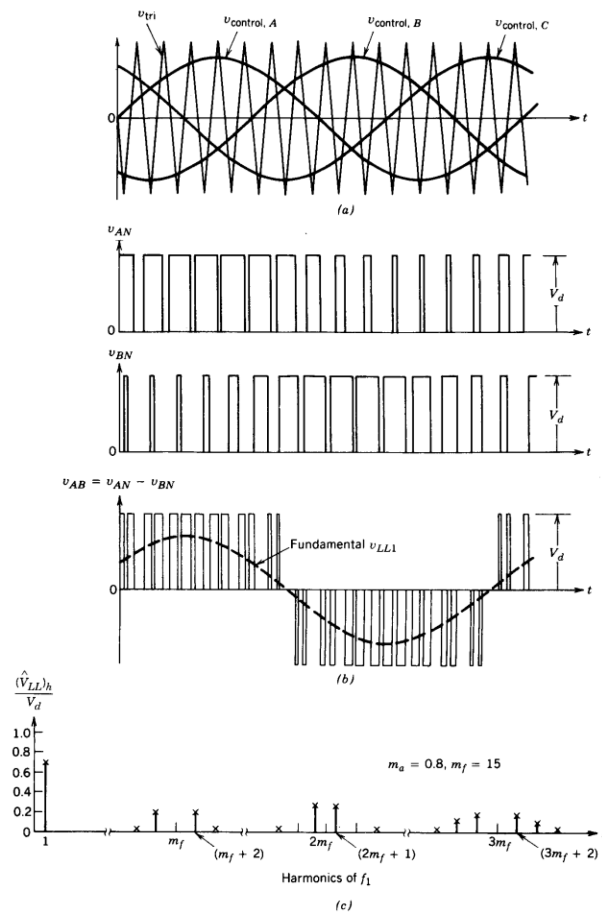


Figure 8-22 Three-phase PWM waveforms and harmonic spectrum.

Figure 10.42 in text book is wrong

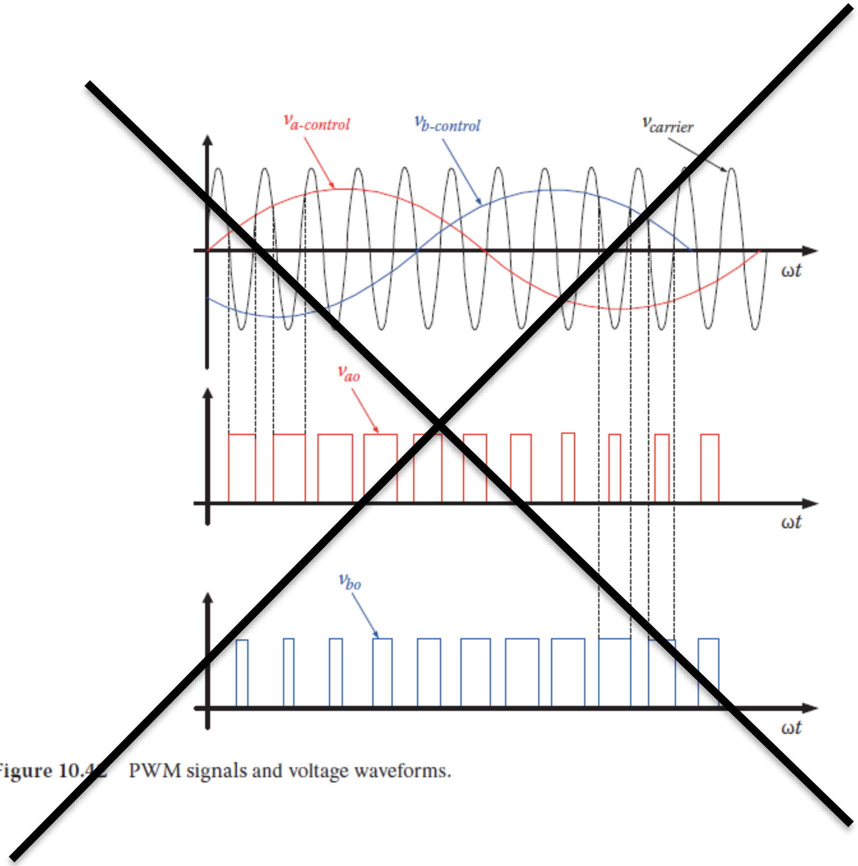


Figure 10.42 PWM signals and voltage waveforms.

Animation on single-phase inverter

- Load of the inverter is single-phase ac voltage, which has constant amplitude and frequency (i.e. could be 50 Hz, 230 V power system). In the animation the black arrows and waveforms
- You can adjust the frequency of the triangle waveform, i.e. switching frequency and the higher it is the better output current is
- The operating point of the inverter can be changed by adjusting the amplitude of the reference sine and its phase shift, you can do it also from the phasor diagram

AC-chopper

- Is not changing frequency but reduces amplitude
- Is used in soft-starters of induction machines and dimmers for incandescent lamps

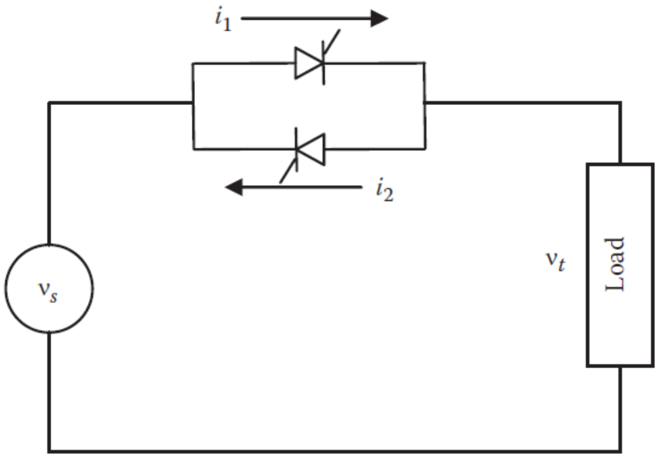


Figure 10.44 AC/AC converter.

AC-chopper, voltage and current

- Turn-on of the thyristor is delayed, load voltage is reducing
- In the figure load is assumed to be resistive

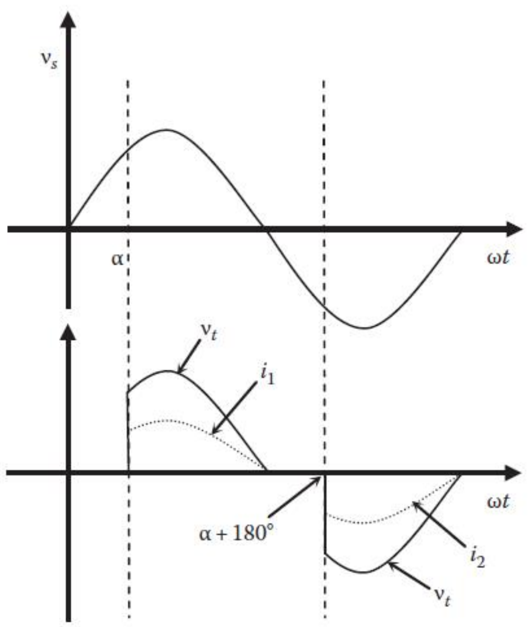


Figure 10.45 Waveform of ac/ac converter in Figure 10.44.

Frequency converter

- Frequency converters most often contain a dc-voltage bus
  - In practice it is a large dc-capacitor
- First converter operates as rectifier and second as inverter

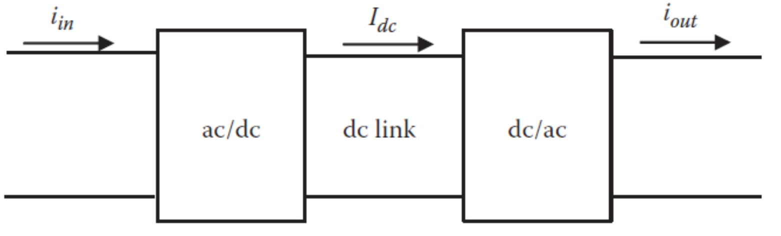


Figure 10.46 AC/AC converter with dc link.

Choices

- a) Pulse width modulated voltage sourced inverter (PWM-VSI, Voltage Source Inverter)
  - Most common, rectifier is simple diode bridge, constant dc-voltage bus
- b) Voltage source with controllable dc
  - Is used very seldom
- c) Current source inverter, CSI
  - Used in some cases with very high power synchronous machines, several megawatts

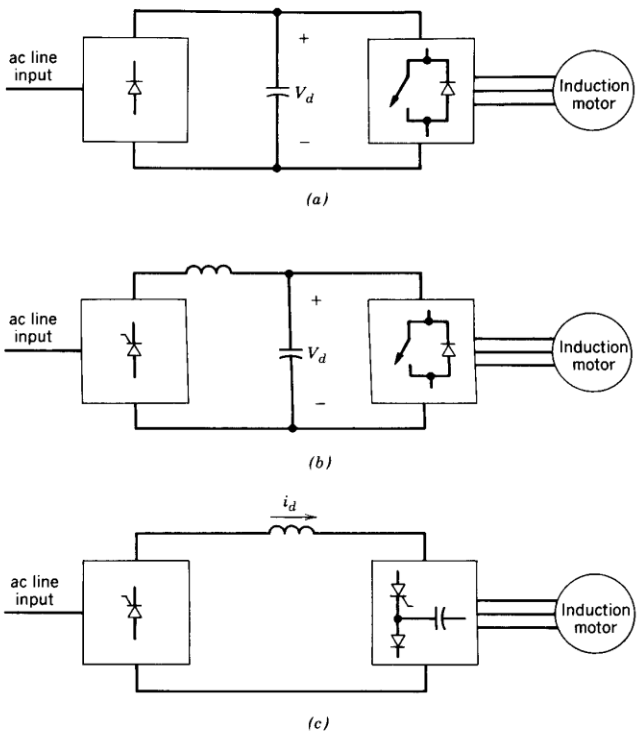


Figure 14-18 Classification of variable-frequency converters: (*a*) PWM-VSI with a diode rectifier; (*b*) square-wave VSI with a controlled rectifier; (*c*) CSI with a controlled rectifier.

Regeneration

- When motor breaks it becomes a generator and power flow reverses
- Diode bridge prevents power from flowing to the ac system
  - Voltage in the dc bus increases
  - Can be used as heat in breaking resistors
- Four-quadrant rectifier
  - Power stage is the same as in the inverter
  - More expensive, but needed e.g. in wind turbines

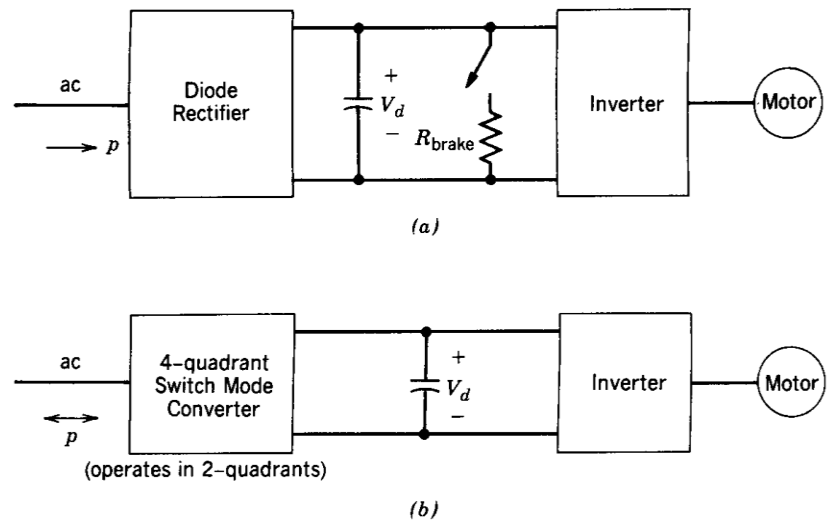


Figure 14-20 Electromagnetic braking in PWM-VSI: (*a*) dissipative braking; (*b*) regenerative braking.

References

- Most of the material is from the course textbook
- Some of the figures used are from Mohan, Undeland, Robbins: **Power Electroncis, Converters, Applications and Design**, Wiley&Sons, 2./3. edition, 1995, 2003
- Animation used during the lecture ETH, Zürich **https://www.ipes.ethz.ch/course/view.php?id=2**