

Concordia University
Department of Electrical and
Computer Engineering

ELEC-331

Lecture 13

Power electronics (from N. Mohan)

1

Outline of the lecture

- Definitions and applications
- Types/families of converters
- Main power semiconductor switches
- Ac-dc converters (rectifiers)
- Ac controllers.

2

Power electronic systems

- **Objective:** Process and control the flow of electric energy by supplying voltages and currents in a form that is optimally suited for user loads.
- Employ semiconductor devices (diodes, thyristors, MOSFETs, BJTs, IGBTs etc.) as switches.
- **Switch ON (short-circuit):** $v_{sw} = 0V$
- **Switch OFF (open-circuit):** $i_{sw} = 0A$

3

Block diagram

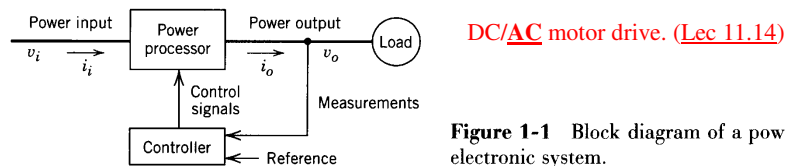


Figure 1-1 Block diagram of a power electronic system.

- **Power processor** is composed of active (switches) and passive elements (inductors and capacitors) as “filters.”
- **Controller:** linear ICs (opamps), application oriented ICs (TCA785, LM3525) or Digital Signal Processors. **They provide the appropriate gating signals (train of pulses) for the switches.**
- **Sensors** provide feedback (load) and synchronization signals (input).

4

Scope and applications

TABLE 1-1 Power Electronic Applications

<p>(a) <i>Residential</i> Refrigeration and freezers Space heating Air conditioning Cooking Lighting Electronics (personal computers, other entertainment equipment)</p>	<p>(d) <i>Transportation</i> Traction control of electric vehicles Battery chargers for electric vehicles Electric locomotives Street cars, trolley buses Subways Automotive electronics including engine controls</p>
<p>(b) <i>Commercial</i> Heating, ventilating, and air conditioning Central refrigeration Lighting Computers and office equipment Uninterruptible power supplies (UPSs) Elevators</p>	<p>(e) <i>Utility systems</i> 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</p>
<p>(c) <i>Industrial</i> Pumps Compressors Blowers and fans Machine tools (robots) Arc furnaces, induction furnaces Lighting Industrial lasers Induction heating Welding</p>	<p>(f) <i>Aerospace</i> Space shuttle power supply systems Satellite power systems Aircraft power systems</p> <p>(g) <i>Telecommunications</i> Battery chargers Power supplies (dc and UPS)</p>

5

Classification of power converters

- According to the type of input and output power:
 - Ac → dc : Rectifier
 - Ac → ac: Ac controller and frequency converter
 - Dc → dc: Chopper
 - Dc → ac: Inverter
- According to the type of commutation (switching):
 - Line frequency *naturally commutated* converters
 - Switching *forced-commutated* converters.

Note: “commutated” ~ “turned-OFF.”

6

Classification of switches

- According to the degree of controllability:
- **Uncontrolled**: ON and OFF states controlled by the “power circuit” (**Diodes**).
- **Semi-controlled**: Turned ON by a control signal but turned OFF by the “power circuit” (**Thyristors**).
- **Controllable**: Can be turned ON and OFF by a control/gating signal (**BJTs, MOSFETs, IGBTs, ...**).

7

Diodes

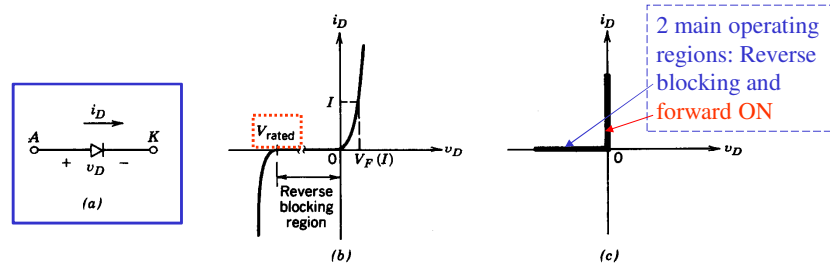


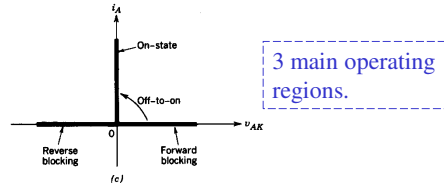
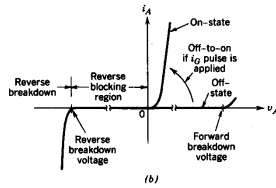
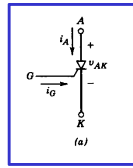
Figure 2-1 Diode: (a) symbol, (b) i - v characteristic, (c) idealized characteristic.

- 2 terminals device.
- An ideal diode **turns ON** when forward biased and **turns OFF** when its forward current goes to zero.

8

Thyristor (Silicon Controlled Rectifier - SCR)

3 terminals device.



3 main operating regions.

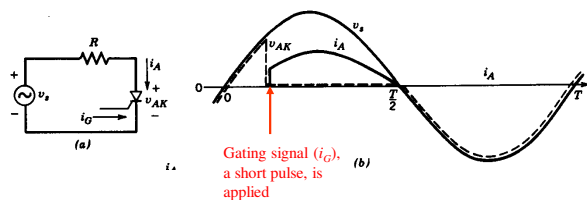
Figure 2-3 Thyristor: (a) symbol, (b) $i-v$ characteristics, (c) idealized characteristics.

- Can be “fired” by a gate current pulse when forward biased and **turns OFF** as a diode.
- Latches ON after fired. No need for continuous gate current.

9

Diodes x thyristors

- **Main advantage** of a thyristor over a diode is the capability of power flow control.
- By varying the *turn-on time*, **the moment the thyristor is turned ON**, the power supplied to the load (resistor) can be controlled.



10

Bipolar Junction Transistor (BJT)

example of a controllable switch

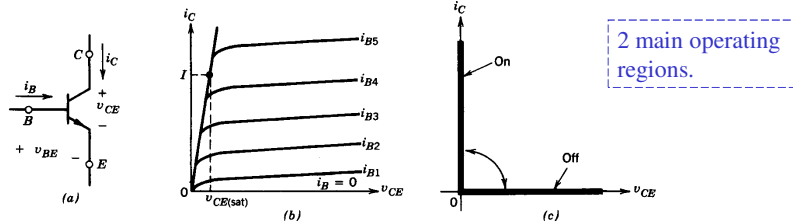
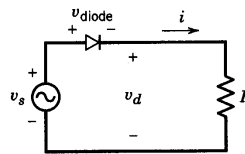


Figure 2-7 A BJT: (a) symbol, (b) $i-v$ characteristics, (c) idealized characteristics.

- State as switch (ON – OFF) depends on the base current. It is **ON** (short-circuit) when there is a base current. $I_B > \frac{I_C}{h_{fe}}$
- It is **OFF** (open-circuit) when $I_B = 0A$.
- Cannot block reverse voltages when “OFF”.
- Replaced by MOSFETs and IGBTs **more recently**.

Single-phase half-wave AC-DC converter

Diode **turns ON** at the beginning of the positive semi-cycle (due to forward bias).



Diode **turns OFF** when the current becomes zero. Should be rated to block peak grid voltage.

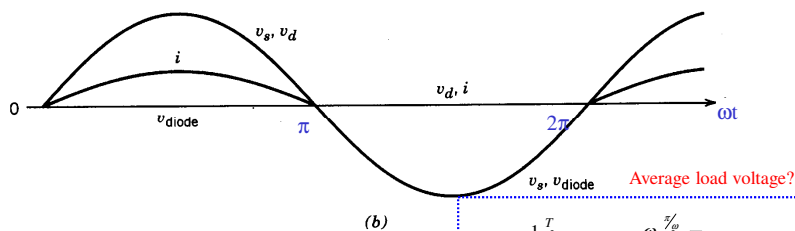
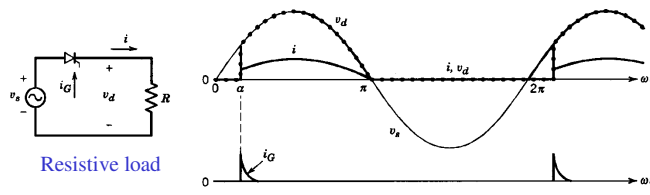


Figure 5-2 Basic rectifier with a load resistance.

$$V_d = \frac{1}{T} \int_0^T v_d(t) dt = \frac{\omega}{2\pi} \int_0^{\pi} \sqrt{2} V_S \sin \alpha dt$$

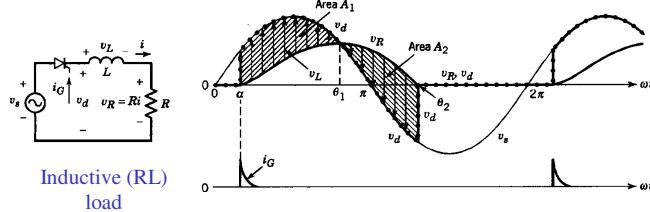
$$V_d = 0.45 V_S$$

Single-phase half-wave thyristor *rectifier*



$$V_d = \frac{1}{T} \int_0^T v_d(t) dt = \frac{\omega}{2\pi} \int_{\alpha}^{\pi} \sqrt{2} V_s \sin \alpha t dt$$

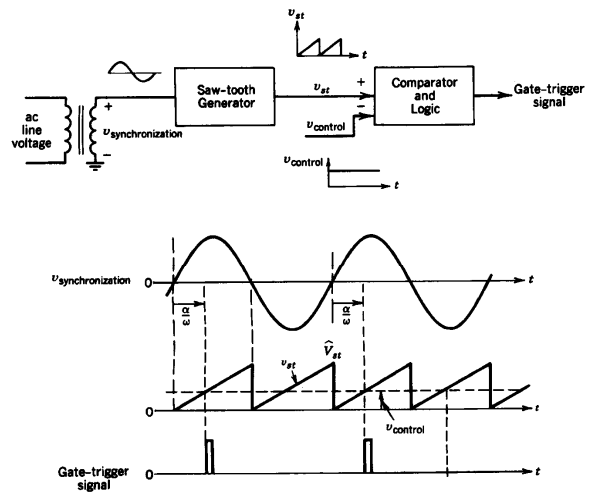
$$V_d = 0.225 V_s (1 + \cos \alpha)$$



$V_d = ?$

Thyristors (and diodes) turn OFF only when their currents fall below 0A. Until then, they are ON and $v_d = v_s$. 13

Thyristor gate signal generation: Synchronization



$$\alpha = \frac{V_{control}}{\hat{V}_{st}} 180^\circ$$

$$0 \leq V_{control} \leq \hat{V}_{st}$$

$$0^\circ \leq \alpha \leq 180^\circ$$

Figure 6-3 Gate trigger control circuit.

Single-phase diode bridge rectifier

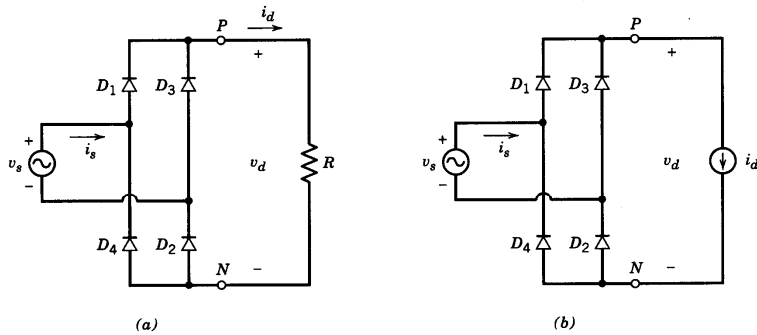


Figure 5-6 Idealized diode bridge rectifiers with $L_c = 0$.

- The “current source” in the dc side represents a highly inductive load (field winding of a synchronous or dc machine)

15

Single-phase diode bridge rectifier: Ind. load

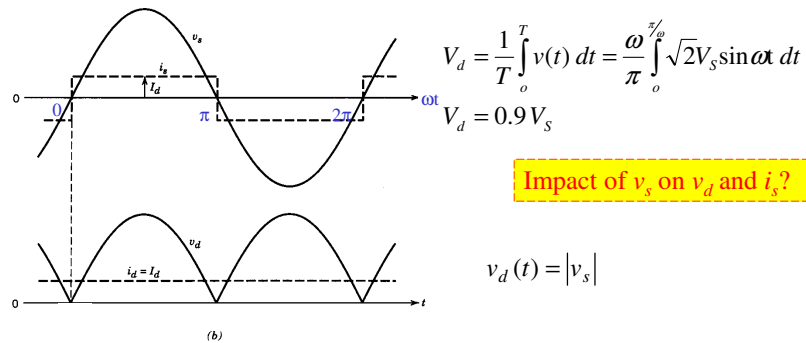
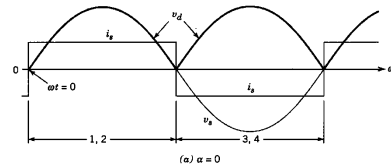
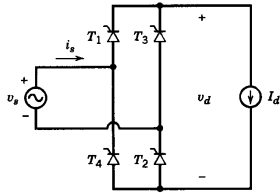


Figure 5-8 Waveforms in the rectifiers of (a) Fig. 5-6a and (b) Fig. 5-6b.

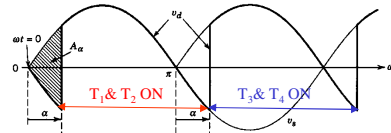
- Highly inductive (RL) load such as the field/excitation winding of a synchronous or dc machine.

16

Single-phase thyristor bridge rectifier



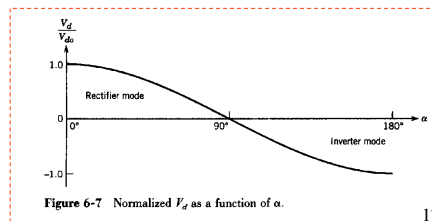
- For *continuous conduction* ($i_d > 0$) a pair of thyristors is always ON. A pair, say T_1 & T_2 , conducts until the other pair, T_3 & T_4 , is fired!



$$V_d = \frac{\omega}{\pi} \int_{\alpha/\omega}^{(\alpha+\pi)/\omega} \sqrt{2} V_s \sin \omega t \, dt$$

$$V_d = \frac{2\sqrt{2}}{\pi} V_s \cos \alpha$$

$$V_d = 0.9 V_s \cos \alpha$$

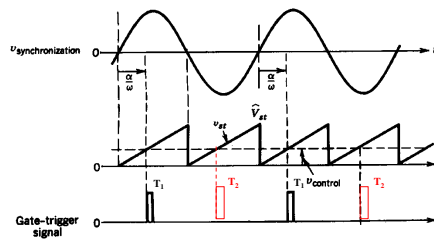
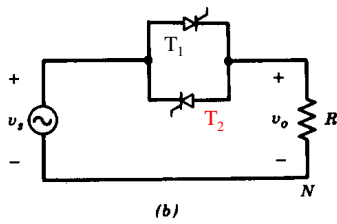


Example: Final 2009

- Consider a single-phase, half-wave thyristor rectifier with a resistive load ($10 \, \Omega$) connected to a power grid by means of a transformer. A) Derive an expression for the average voltage across the load (resistive) as a function of α and the rms value of the voltage at the secondary of the transformer (V_{TS}). Assume that the magnitude of the grid voltage can vary between $\pm 10\%$ around its rated value of 220V. B) Calculate the turns ratio of the transformer ($N_1:N_2$) so that the dc voltage across the resistor can be regulated at 100 V, as the grid voltage varies, by varying α . Assume that α is minimum (0°) for the minimum input voltage. C) What would be the range of α for regulating the load voltage at 100 V as the grid voltage varies by $\pm 10\%$?

AC controller

- *AC controller* is an ac-ac converter capable of controlling only the magnitude of the output waveform. The output *fundamental frequency* is the same as of the input waveform.
- There is a need for 2 SCRs in “anti-parallel...”
- *Operation: The firing angles of the SCRs need to be the same so as to make the average voltage at the output equal to zero.*



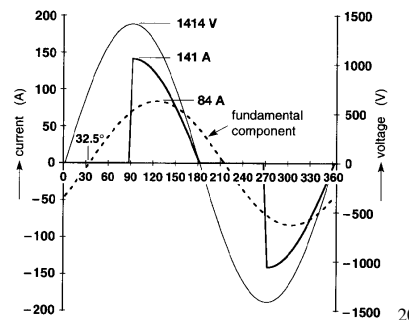
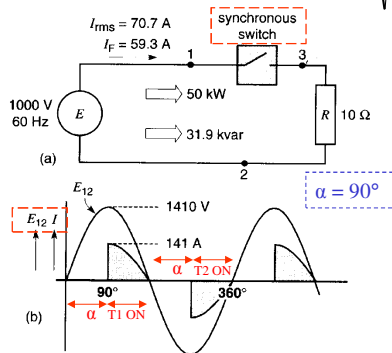
Thyristor based ac controllers

- By delaying the firing of the thyristors by an angle (α), one can control the shape of the load voltage waveform, the magnitude of its fundamental component (60 Hz) and also its total rms value.

$$V_{rms} = \sqrt{\frac{1}{T} \int_0^T (v(t))^2 dt}$$

$$V_{rms} = V_s \sqrt{\frac{1}{\pi} \left(\frac{\sin 2\alpha}{2} + \pi - \alpha \right)}$$

in rad!



Stator voltage control of an induction motor

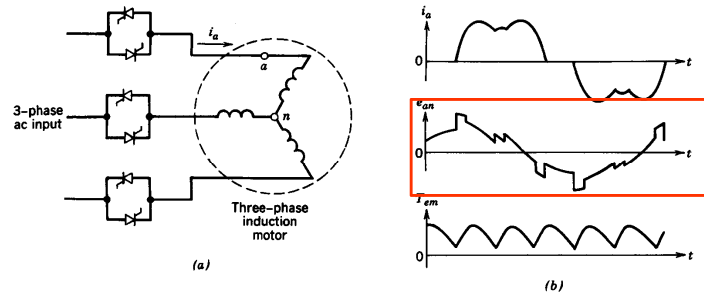


Figure 14-27 Stator voltage control: (a) circuit; (b) waveforms.

- All thyristors are fired with the same firing angle (α)
- At least 2 thyristor, one in one phase and the other in another, must be on for current to flow between the source and the motor. Stator current is NOT sinusoidal for most values of α .
- Used for “soft start” and speed control