Power Electronics

Short notes for B.Tech EE · EEE · ECE · GATE EE

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I. Introduction and Power Devices

- **Power electronics** = control and conversion of electric power using semiconductor **switches**.
- Devices work as switches (fully ON or fully OFF) to keep losses low.

➤ Types of converters

Converter	Conversion	Example
Rectifier	AC → DC	Battery charger, DC drive
Chopper	DC → DC	Buck, boost, SMPS
Inverter	DC → AC	UPS, solar inverter, VFD
AC voltage controller	AC → AC (same f)	Fan regulator, light dimmer
Cycloconverter	AC → AC (different f)	Low-speed large drives

➤ Device comparison

Device	Control	Turn-off by gate?	Switching speed	Typical use
Power diode	Uncontrolled	-	-	Rectifiers
SCR	Gate pulse (current)	No	Low	High power, line converters
TRIAC	Gate pulse	No	Low	AC control (bidirectional)
GTO	Gate current	Yes (large negative pulse)	Low–medium	High power inverters
Power BJT	Base current	Yes	Medium	Older designs
Power MOSFET	Gate voltage	Yes	Very high	SMPS, low-voltage converters
IGBT	Gate voltage	Yes	Medium–high	Inverters, drives, EVs

- **IGBT** = MOSFET-like input (voltage control, high input impedance) + BJT-like output (low conduction loss).
- MOSFET has a positive temperature coefficient of on-resistance, so it is easy to parallel.
- **Power diode reverse recovery time** trr: time for reverse current to die out at turn-off. Fast-recovery and Schottky diodes have small trr.

2. Thyristor (SCR)

- 4-layer PNPN device, 3 terminals: anode, cathode, gate. Three junctions J1, J2, J3.
- Modes: reverse blocking, forward blocking, forward conduction.

➤ Important currents

- **Latching current (IL)**: minimum anode current needed to keep the SCR ON just after the gate pulse is removed.
- **Holding current (IH)**: minimum anode current below which the SCR turns OFF.
- IL > IH (latching is usually 2–3 times holding).

➤ Turn-on methods

1. Gate triggering (normal, most used)
2. Forward voltage above break-over voltage
3. High dv/dt (unwanted)
4. Temperature rise (unwanted)
5. Light (LASCR)

➤ Turn-off (commutation)

- Reduce anode current below IH and apply reverse voltage for at least the **turn-off time tq**.
- **Natural (line) commutation**: AC supply reverses by itself (rectifiers, AC controllers).
- **Forced commutation**: extra L-C circuit forces current to zero (in DC circuits like choppers). Classes A to F.
- Circuit turn-off time tc must be greater than device turn-off time tq.

➤ Protection

- **dv/dt protection**: RC **snubber** across the SCR.

- **di/dt protection**: small inductor in series.
- Overcurrent: fast-acting fuse (I^2 t rating). Overvoltage: MOV, snubber.
- **Gate triggering circuits**: R, RC, UJT relaxation oscillator, pulse transformer for isolation.

EXAM POINT Series connection of SCRs needs static (resistor) and dynamic (RC) equalising networks. Parallel connection needs current sharing (series reactors).

3. Phase-Controlled Rectifiers

- **Firing angle α**: delay from the natural start of conduction to the gate pulse.
- With a free-wheeling diode, negative output voltage is cut off.

FORMULA 1-phase half-wave, R load: $V_o = (V_m / 2\pi)(1 + \cos \alpha)$.

FORMULA 1-phase full converter (continuous current, highly inductive load): $V_o = (2V_m/\pi) \cos \alpha$. With R load: $V_o = (V_m/\pi)(1 + \cos \alpha)$.

FORMULA 1-phase semi converter: $V_o = (V_m/\pi)(1 + \cos \alpha)$.

FORMULA 3-phase full converter: $V_o = (3\ V_{mL} / \pi) \cos \alpha = 1.35\ V_L \cos \alpha$ (V_L = RMS line voltage).

FORMULA 3-phase half-wave converter: $V_o = (3\sqrt{3}\ V_{mp} / 2\pi) \cos \alpha$ (V_{mp} = peak phase voltage).

Converter	Quadrants	Inversion possible?
Semi converter	One (V+, I+)	No
Full converter	Two (V+ and V-, I+)	Yes, when $\alpha > 90°$
Dual converter	Four	Yes ($\alpha 1 + \alpha 2 = 180°$)

- **Inverter mode** of a full converter: $\alpha > 90°$, V_o is negative, power flows from DC side (e.g. motor during braking) to AC supply.
- Input power factor of a 1-phase full converter with ripple-free current = $0.9 \cos \alpha$. For 3-phase full converter = $0.955 \cos \alpha$.
- **Source inductance** causes **overlap** (commutation angle μ): both SCRs conduct together, output voltage drops by $(3\omega L_s/\pi)\ I_d$ in a 3-phase converter.

EXAMPLE 1-phase full converter, 230 V, 50 Hz, $\alpha = 30°$, highly inductive load R = 10 Ω. $V_m = 230\sqrt{2} = 325.3$ V. $V_o = (2 \times 325.3 / \pi) \times \cos 30° = 207.1 \times 0.866 = 179.3$ V. $I_o = 179.3/10 = 17.9$ A.

EXAMPLE 3-phase full converter, 415 V line, $\alpha = 60°$. $V_o = 1.35 \times 415 \times 0.5 = 280$ V.

4. DC-DC Converters (Choppers)

- Duty cycle $D = T_{on} / T = T_{on} \times f$.
- Control: **constant frequency** (PWM, vary T_{on}) or **variable frequency** (vary T).

Converter	Output voltage (CCM)	Output polarity	Note
Buck (step-down)	$V_o = D V_s$	Same	$V_o < V_s$
Boost (step-up)	$V_o = V_s / (1 - D)$	Same	$V_o > V_s$
Buck-boost	$V_o = -D V_s / (1 - D)$	Inverted	Up or down
Cuk	$V_o = -D V_s / (1 - D)$	Inverted	Continuous input and output currents

FORMULA Buck inductor ripple $\Delta I_L = V_s D (1 - D) / (f L)$. Maximum at $D = 0.5$. Capacitor ripple $\Delta V_c = \Delta I_L / (8 f C)$.

EXAMPLE Buck: $V_s = 48$ V, $D = 0.25$, $f = 20$ kHz, $L = 500$ µH. $V_o = 12$ V. $\Delta I_L = 48 \times 0.25 \times 0.75 / (20000 \times 500 \times 10^{-6}) = 9 / 10 = 0.9$ A.

EXAMPLE Boost: $V_s = 12$ V, $D = 0.6$. $V_o = 12 / 0.4 = 30$ V.

- **CCM** = inductor current never reaches zero. **DCM** = it falls to zero for part of the cycle; the output formula changes.
- Chopper classes by quadrant: Class A (1st quadrant), B (2nd, regenerative), C (two-quadrant, I reverses), D (two-quadrant, V reverses), E (four-quadrant).

TIP In GATE, boost converter questions often use volt-second balance: $V_s D = (V_o - V_s)(1 - D)$. Use it instead of memorising.

5. Inverters

- **VSI** (voltage source inverter): stiff DC voltage, needs anti-parallel (feedback) diodes. **CSI**: stiff DC current, large series inductor.
- **Half bridge**: output swings ±Vdc/2. **Full bridge**: output swings ±Vdc.

FORMULA Full bridge square wave: Vo(rms) = Vdc. Fundamental RMS = 4Vdc / (π√2) = 0.9 Vdc. nth harmonic peak = 4Vdc / (nπ), only odd n.

FORMULA 3-phase VSI, 180° mode: line voltage RMS = 0.816 Vdc, phase voltage RMS = 0.471 Vdc. In 120° mode each switch conducts for 120°.

- 180° mode: 3 switches ON at any time. 120° mode: 2 switches ON at any time.
- **Dead time** between upper and lower switch of a leg prevents **shoot-through** (DC short).

➤ PWM

- **Sinusoidal PWM (SPWM)**: compare sine reference with triangular carrier.
- Modulation index ma = Vref(peak) / Vcarrier(peak). Linear range: ma ≤ 1. ma > 1 is **overmodulation** (more low-order harmonics).
- Frequency modulation ratio mf = fcarrier / fref. Harmonics appear around mf and its multiples, so filtering is easy.
- Other methods: single pulse, multiple pulse, space vector PWM (better DC bus use).
- Harmonic elimination: in single-pulse PWM with pulse width 2d, the nth harmonic is removed when nd = 180°, e.g. width 120° removes the 3rd harmonic.

Point	VSI	CSI
DC source	Voltage (large capacitor)	Current (large inductor)
Output	Fixed voltage waveform	Fixed current waveform
Diodes	Feedback diodes needed	Series diodes, no feedback diodes
Short-circuit risk	Shoot-through is dangerous	Inherently protected

6. AC Voltage Controllers and Cycloconverters

- Two SCRs in anti-parallel (or a TRIAC) in series with the load.

- **Phase control**: vary α in every half cycle. **Integral cycle (on-off) control**: pass n full cycles, block m cycles (for heaters, high thermal time constant).

FORMULA 1-phase AC controller, R load: Vo(rms) = Vs sqrt[(1/π)(π - α + sin 2α / 2)].

FORMULA Integral cycle control: Vo(rms) = Vs sqrt(n / (n + m)). Power factor = sqrt(n / (n + m)).

- For R-L load with load angle ϕ: control is possible only for α > ϕ. For α < ϕ the output is full sine wave.
- **Cycloconverter**: direct AC to AC frequency conversion without a DC link. Step-down type is common (output frequency up to about 1/3 of input). Used in large low-speed drives (cement mills, ship propulsion).

7. Applications

- **SMPS**: high-frequency switching → small transformer, high efficiency. Topologies: flyback (low power, isolated), forward, push-pull, half and full bridge.
- **Linear supply vs SMPS**: linear is simple and low-noise but bulky and less efficient.
- **UPS**: offline (standby), line-interactive, online (double conversion, no transfer time).
- **HVDC** converters, **FACTS** devices (SVC, STATCOM, TCSC), solar MPPT converters, EV chargers, induction heating.
- **Harmonics**: converters draw non-sinusoidal current. THD = sqrt(I2^2 + I3^2 + ...) / I1. Reduce with filters, multi-pulse converters (12-pulse), PWM rectifiers.

FORMULA Power factor = distortion factor x displacement factor = (I1 / Irms) x cos ϕ1.

REMEMBER A p-pulse converter has harmonics on AC side of order kp ± 1 and on DC side of order kp. For 6-pulse: AC 5, 7, 11, 13...; DC 6, 12...

8. Most Asked Questions (practice)

1. Draw and explain the V-I characteristics of an SCR. Define latching and holding current.
2. Explain the two-transistor model of an SCR and its turn-on methods.
3. What is a snubber circuit? Explain dv/dt and di/dt protection.
4. Derive output voltage of a 1-phase full converter with RL load. Explain inverter mode.
5. Compare semi converter and full converter. What is a dual converter?
6. Derive the output voltage of buck and boost converters. Find inductor ripple.
7. Explain 3-phase VSI in 180° mode with waveforms.
8. Explain sinusoidal PWM. Define modulation index.
9. Explain 1-phase AC voltage controller with R load and integral cycle control.
10. Compare IGBT, MOSFET and GTO. Where is each used?

TIP GATE EE power electronics: rectifier average/RMS voltage and input pf, buck/boost with ripple, inverter harmonics and SCR basics. Draw the waveform first, then integrate; it avoids formula confusion.