

Variable Speed Wind Turbines



ECEN 2060

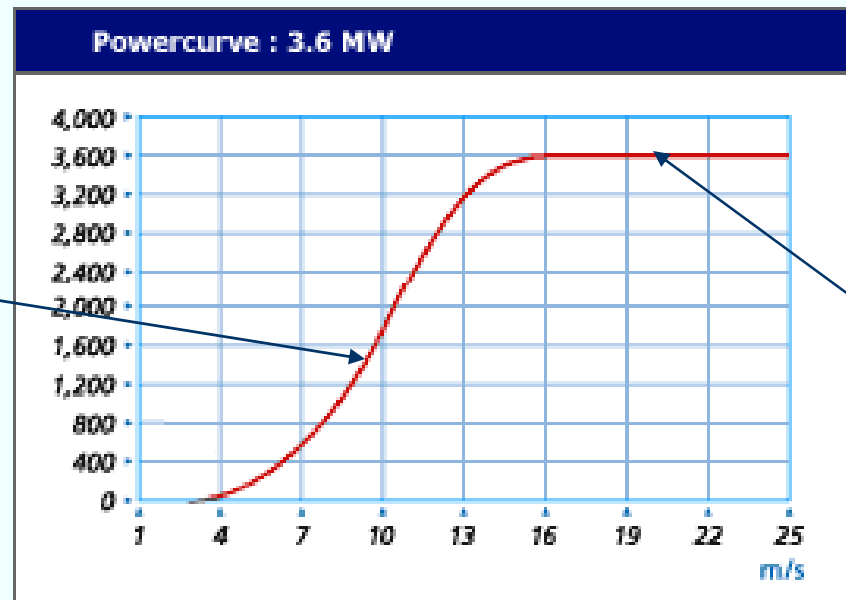
Advantages of Variable-Speed Turbines

- Improved capture efficiency

- Rotation speed follows the wind speed up to a maximum power rating of the turbine
- Turbine operates at the tip speed ratio (TSR) that results in the maximum power coefficient C_p over a wider range of wind speeds
 - Lower cut-in wind speed, determined by losses in the turbine drive train
 - Precise maximum power control up to a maximum cut-out wind speed

$$P = C_p P_w = C_p \frac{1}{2} \rho A v^3$$
$$C_p \approx C_{p_{\max}} \approx \text{const.}$$
$$TSR \approx (TSR)_{\text{opt}} \approx \text{const.}$$

MPP tracking



$P = P_{\max}$

Pitch control reduces C_p

Advantages of Variable-Speed Turbines

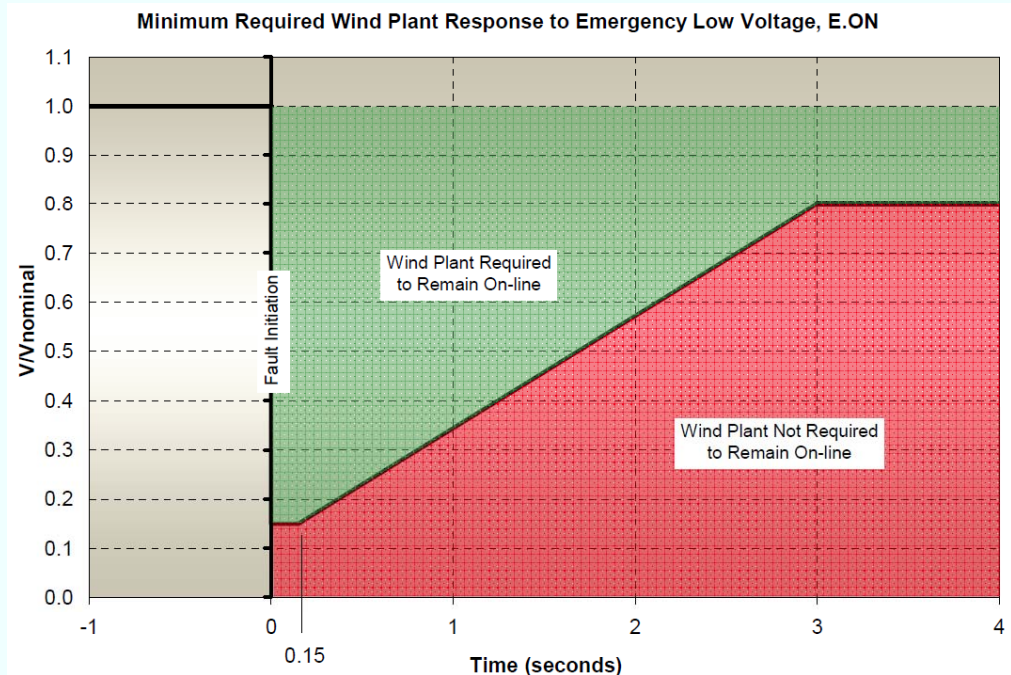
- **Reduced mechanical stress and improved reliability**
 - Stresses due to wind gusts absorbed by variable speed operation
- **Much improved grid interface**
 - Ability to actively control power delivered to the grid and the power factor, i.e. the active power and the reactive power

Active power: $\sqrt{3}V_{line}I_{phase}\cos(\theta)$

Reactive power: $\sqrt{3}V_{line}I_{phase}\sin(\theta)$

Power factor: $\cos(\theta)$

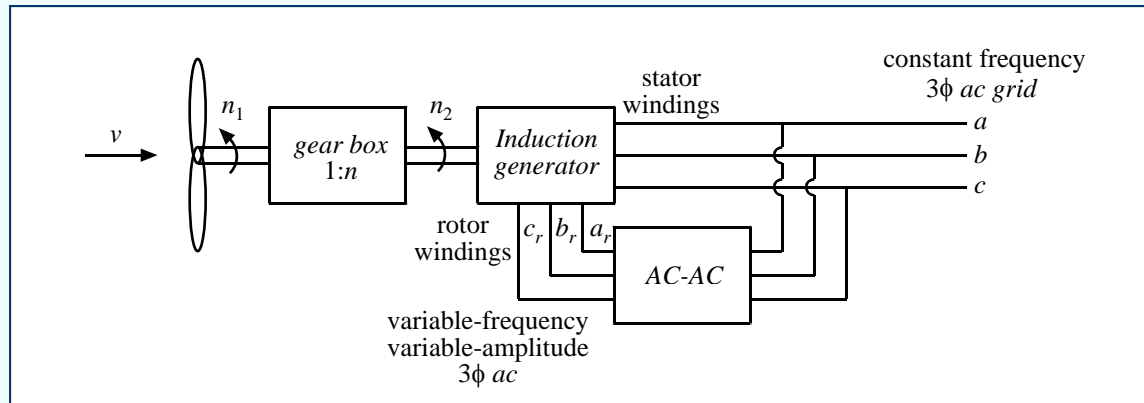
- Ride-through capability: ability to operate through grid faults (e.g. short circuit) and help restore the grid operation after the fault



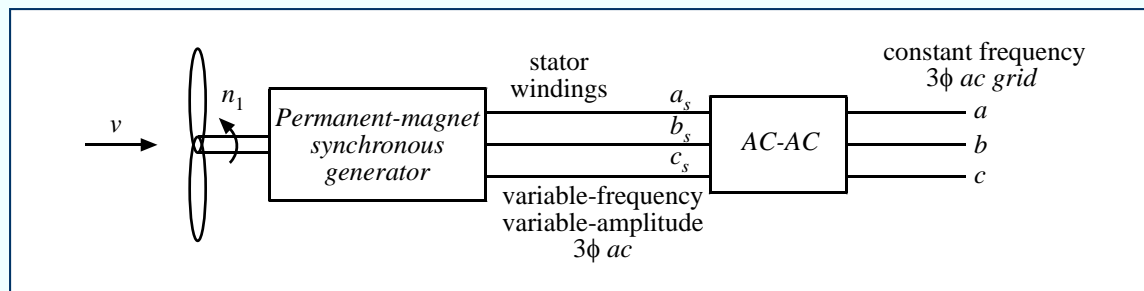
From: W. Erdman and M. Behnke, The Application of Medium-Voltage Electrical Apparatus to the Class of Variable Speed Multi-Megawatt Low Wind Speed Turbines, NREL report, 2005

Variable-Speed Turbines

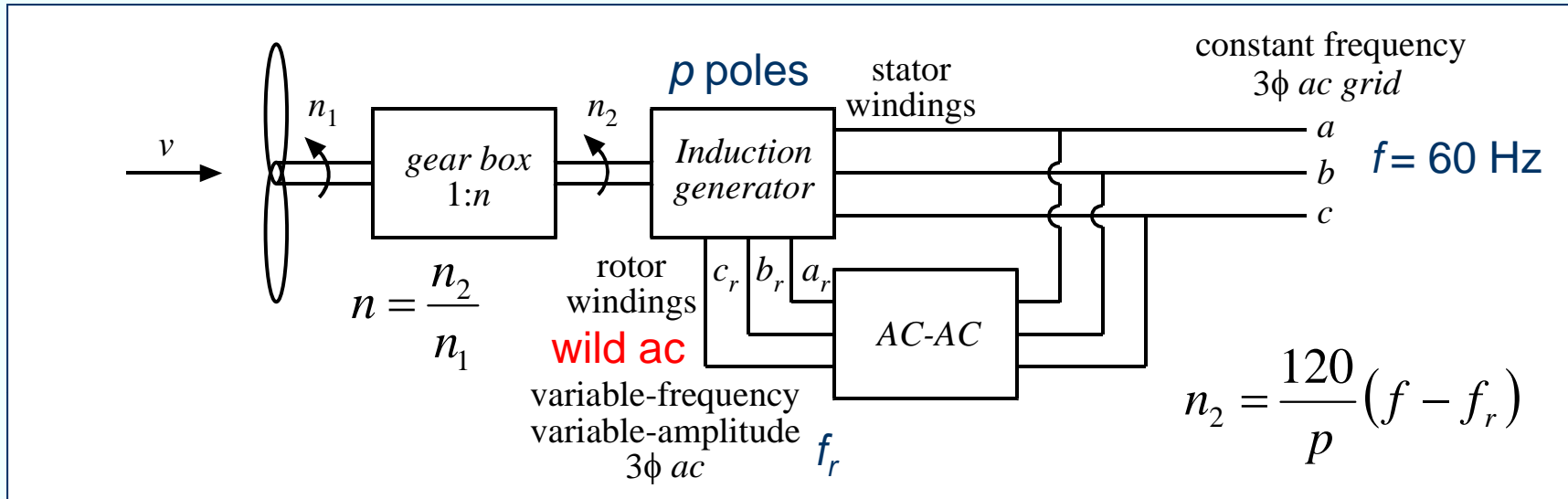
- Variable-ratio or multiple gearboxes
- Pole-changing induction generators
- Power electronics AC-AC conversion
 - Doubly-fed induction generator



- Full-power AC-AC conversion (also called “direct driven” or “series”)

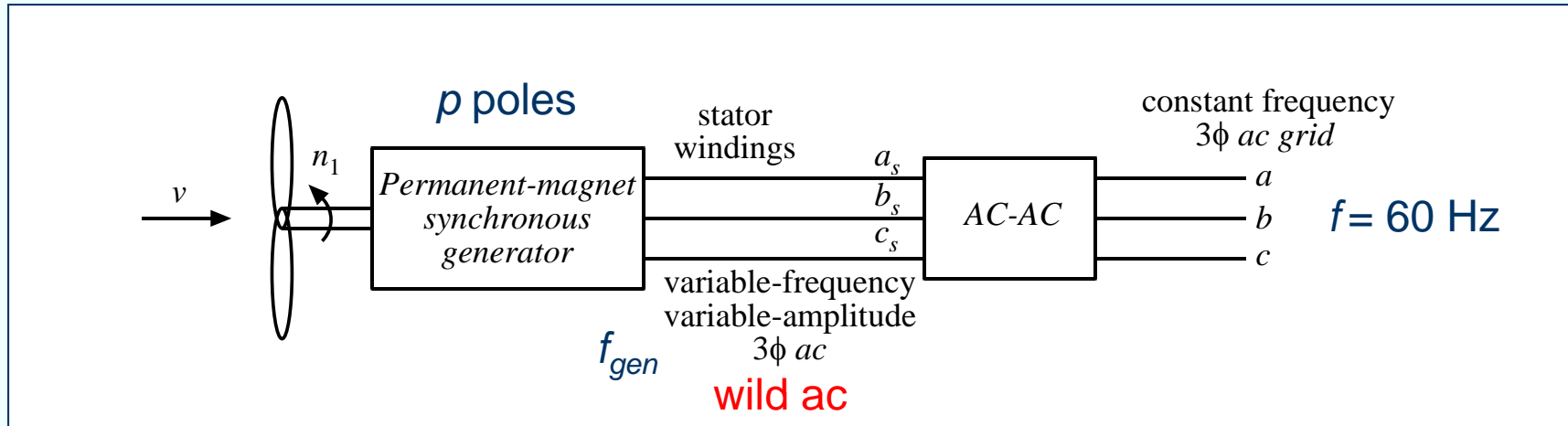


Doubly-Fed Induction Generator (DFIG)



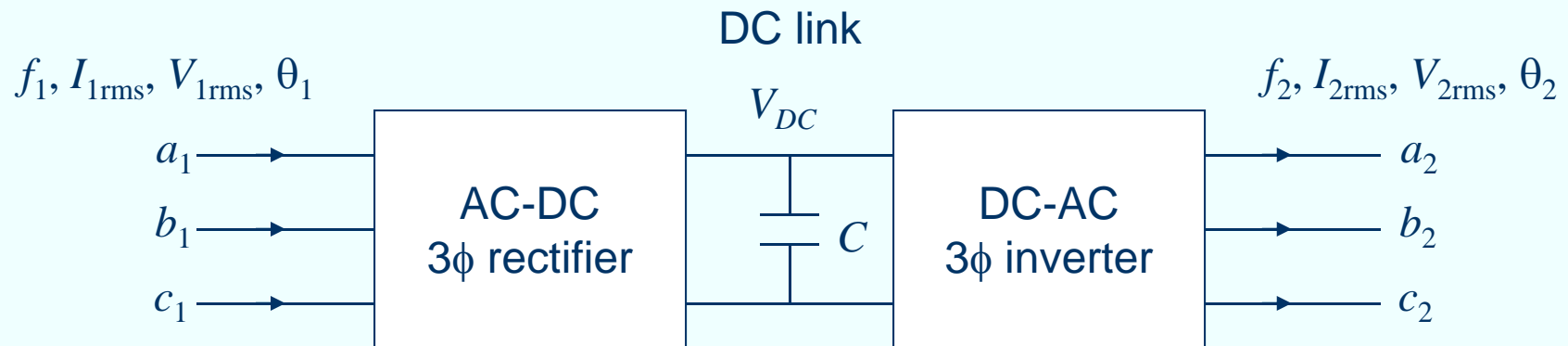
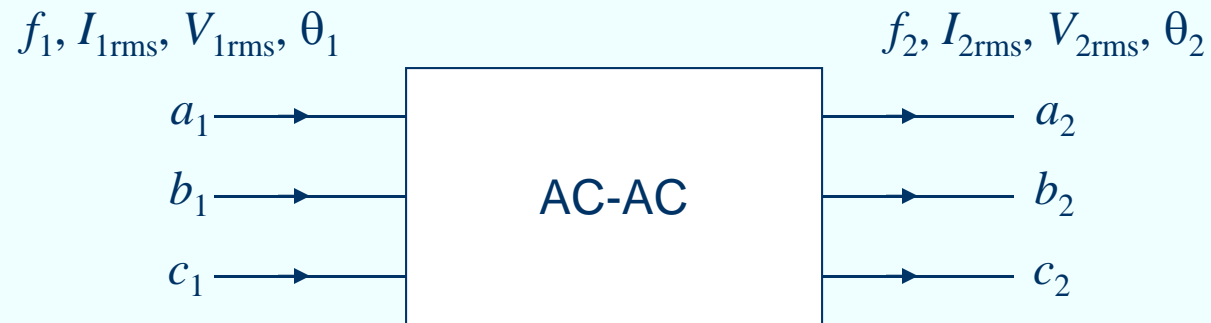
- Variable n_2 achieved by controlling frequency f_r amplitude and phase of rotor currents
- Only a portion (about 30%) of power processed by the AC-AC power converter
- +/- 30% speed range around the synchronous speed
- Requires wound-rotor induction generator, slip rings

Full-Power AC-AC Converter Drive

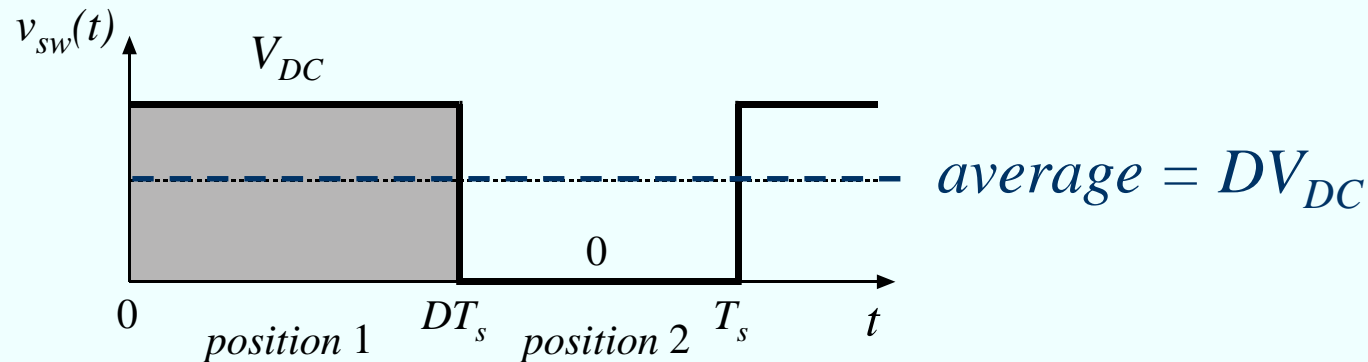
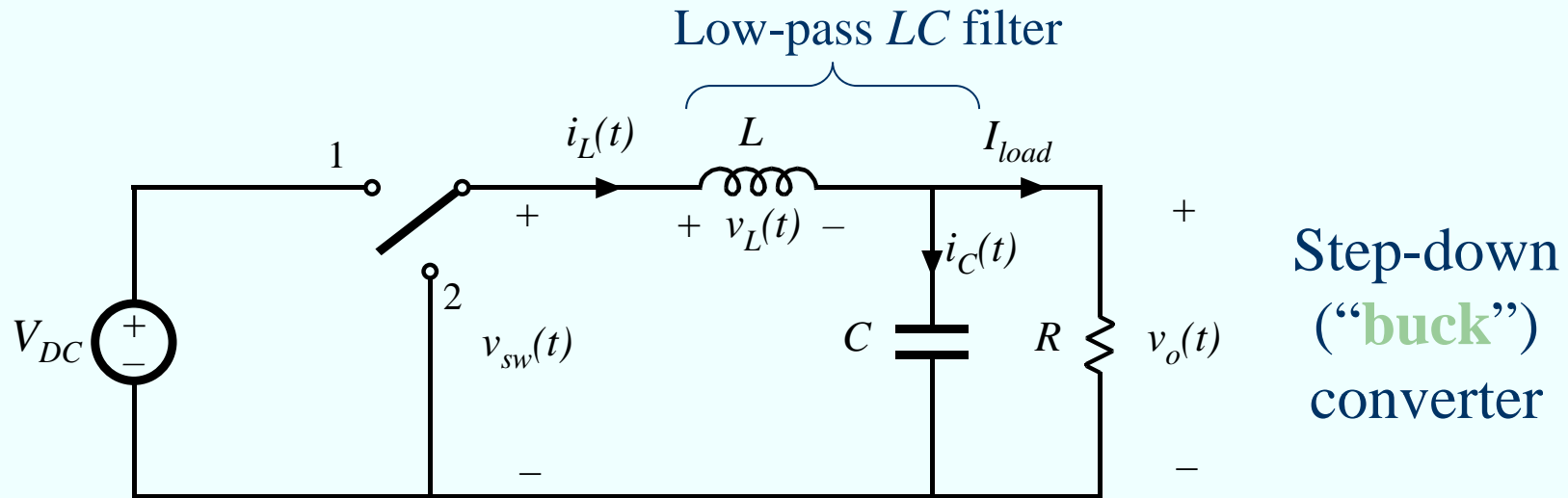


- Wide speed range
- Fast power control, excellent ride-through capabilities
- Gearbox can be eliminated
- Off-grid operation (islanding) is possible
- Frequency f_{gen} , and generator RMS voltage vary over wide ranges (both are proportional to speed)
- All power must be processed by the AC-AC converter

DC-link based AC-AC power converter

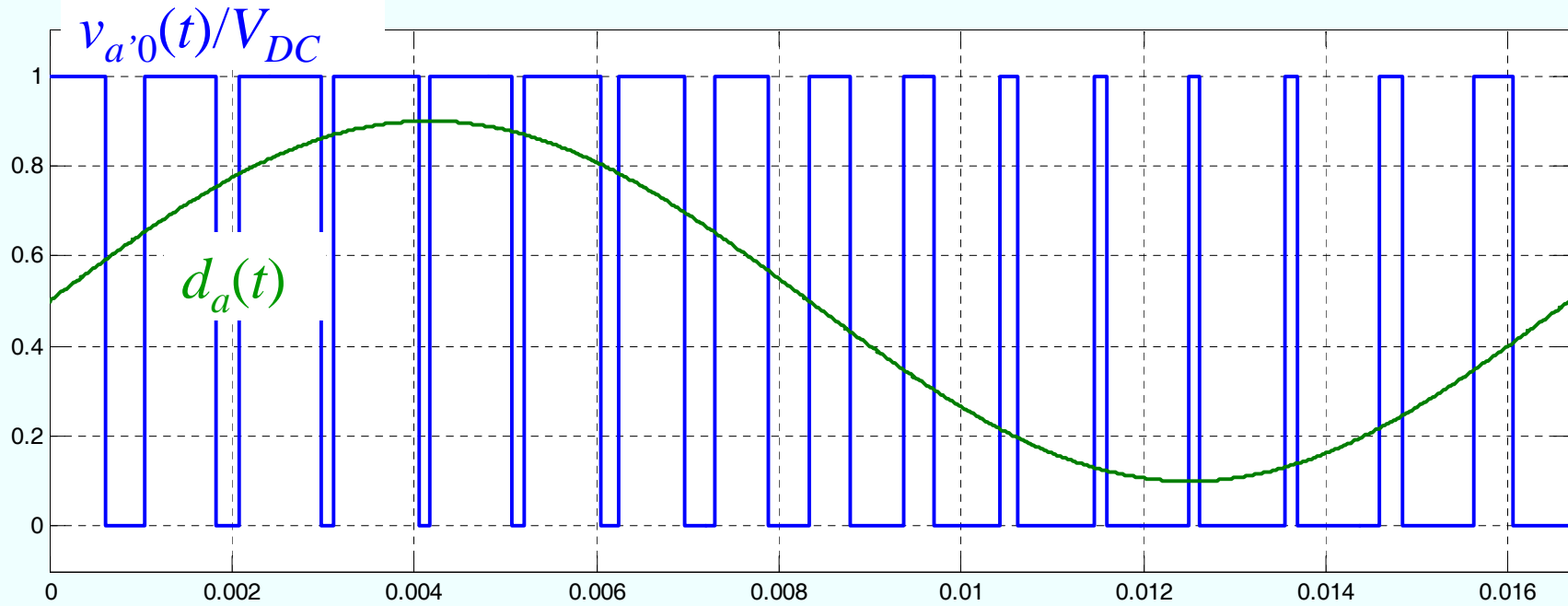
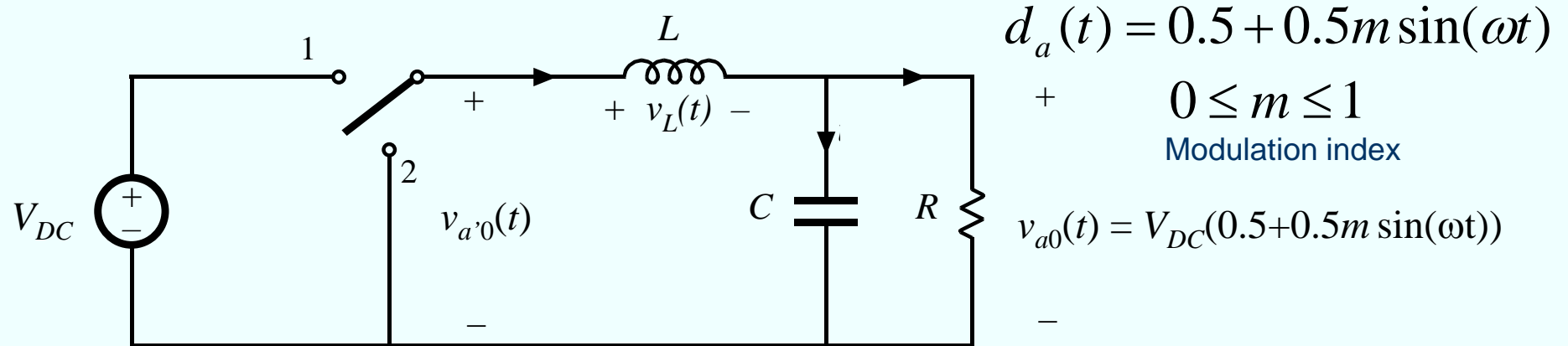


DC-AC Inverter derivation: start from Buck DC-DC

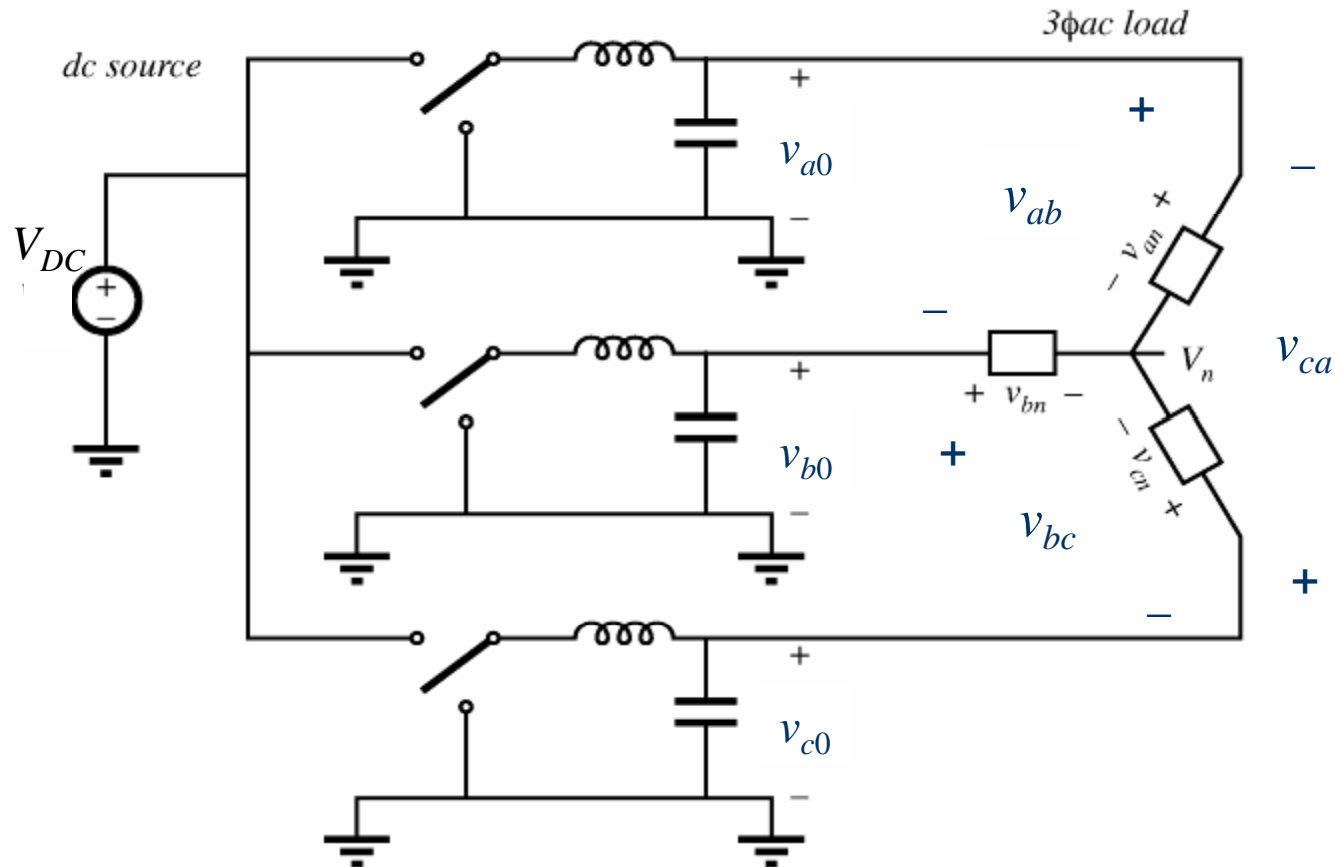


$$f_s = 1/T_s = \text{switching frequency}$$

Sinusoidal pulse-width modulation (PWM)



DC-AC Inverter derivation: 3 ϕ buck with sinusoidal PWM



Duty-cycle modulation:

$$d_a(t) = 0.5 + 0.5m \cos(\omega t)$$

$$d_b(t) = 0.5 + 0.5m \cos(\omega t - 120^\circ)$$

$$d_c(t) = 0.5 + 0.5m \cos(\omega t - 240^\circ)$$

DC-AC Inverter Outputs

$$v_{ab} = v_{a0} - v_{b0} = V_{DC}m \frac{\sqrt{3}}{2} \cos(\omega t + 30^\circ)$$

Line-to-line voltages:

$$v_{ab} = v_{a0} - v_{b0} = V_{DC}m \frac{\sqrt{3}}{2} \cos(\omega t - 90^\circ)$$

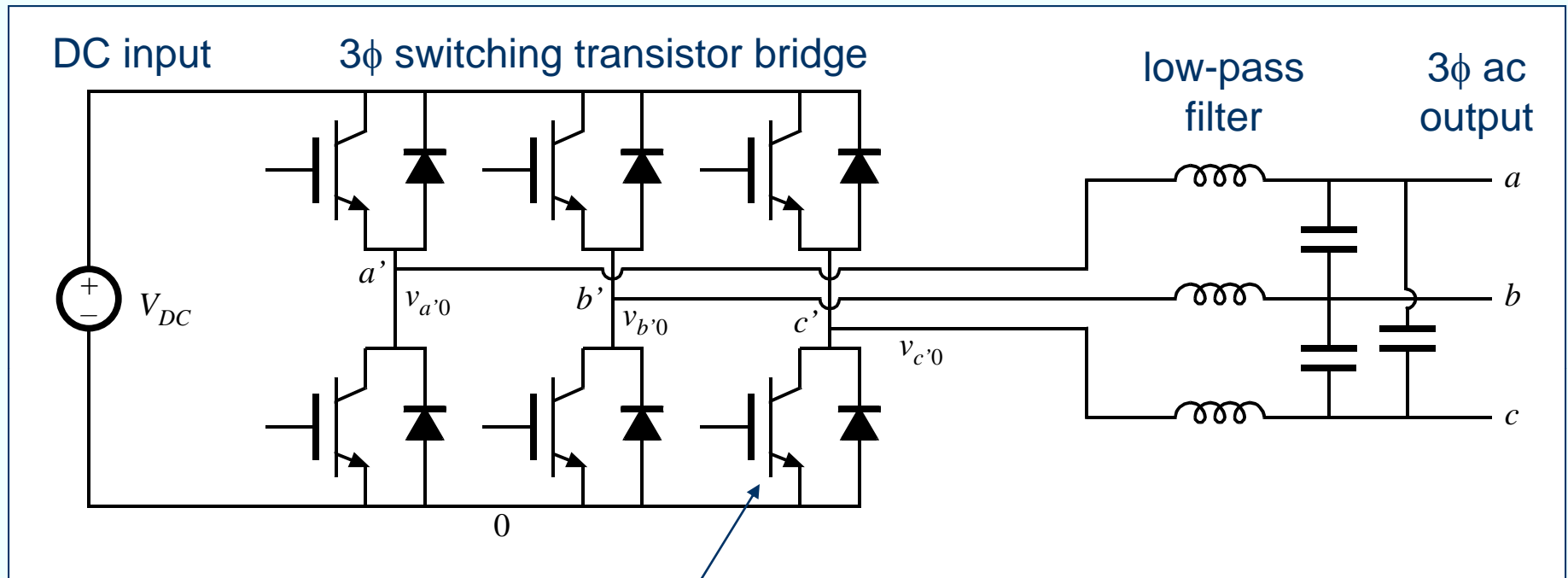
$$v_{ab} = v_{a0} - v_{b0} = V_{DC}m \frac{\sqrt{3}}{2} \cos(\omega t - 210^\circ)$$

Peak line-to-line voltage (sinusoidal PWM): $V_M = V_{dc}m \frac{\sqrt{3}}{2} = 0.87mV_{DC}$

Alternative modulation schemes can achieve $V_M = mV_{DC}$

V_{DC} must be greater than the peak line-to-line voltage

3 ϕ DC-AC inverter realization

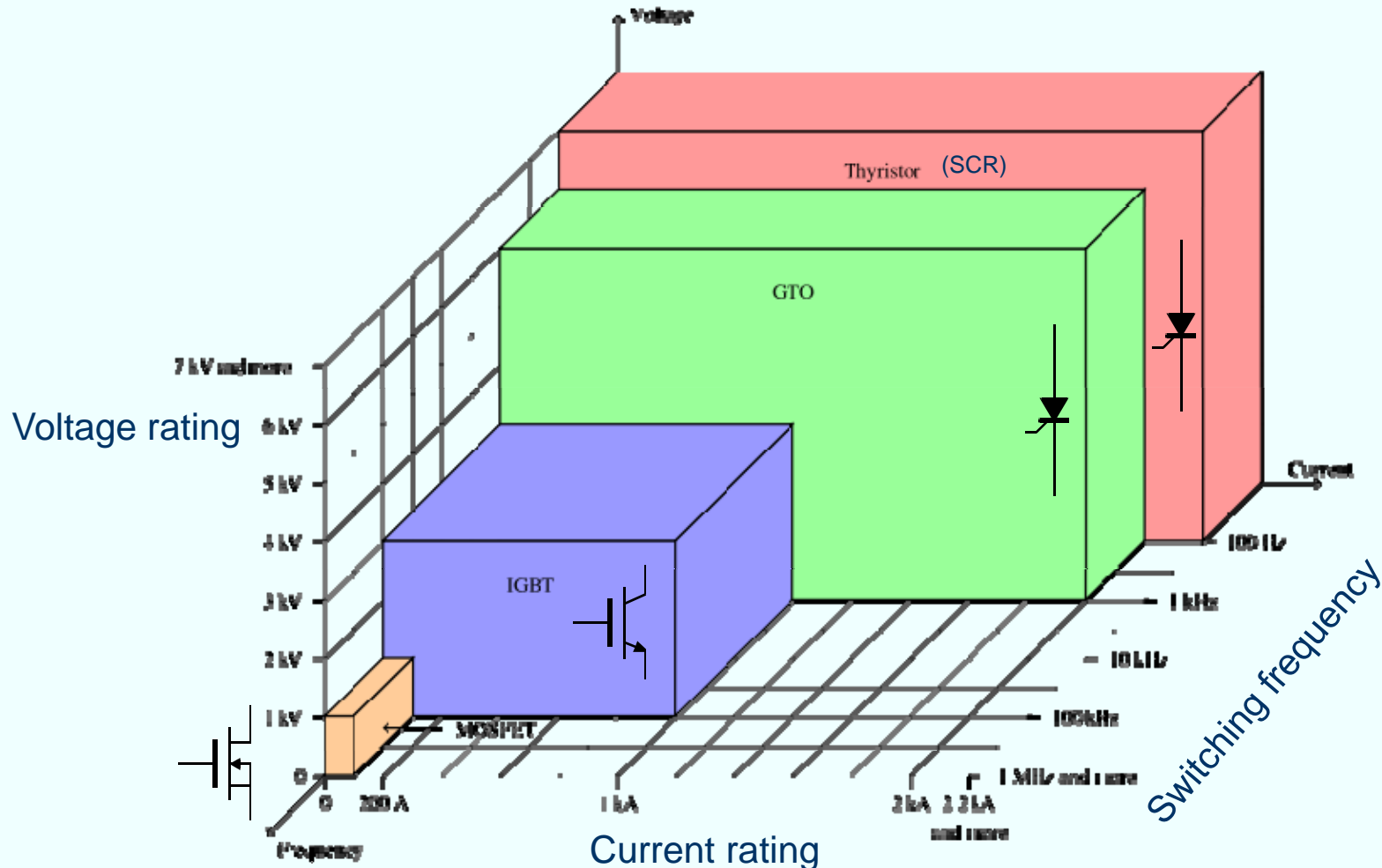


Insulated-gate bipolar transistor (IGBT) switch

IGBT switches are available that can:

- Conduct 1000's of Amps when on
- Block 1000's of Volts when off
- Switch at 10's of kHz

Voltage, current and frequency ratings of power semiconductor devices



MOSFET: Metal Oxide Semiconductor Field Effect Transistor

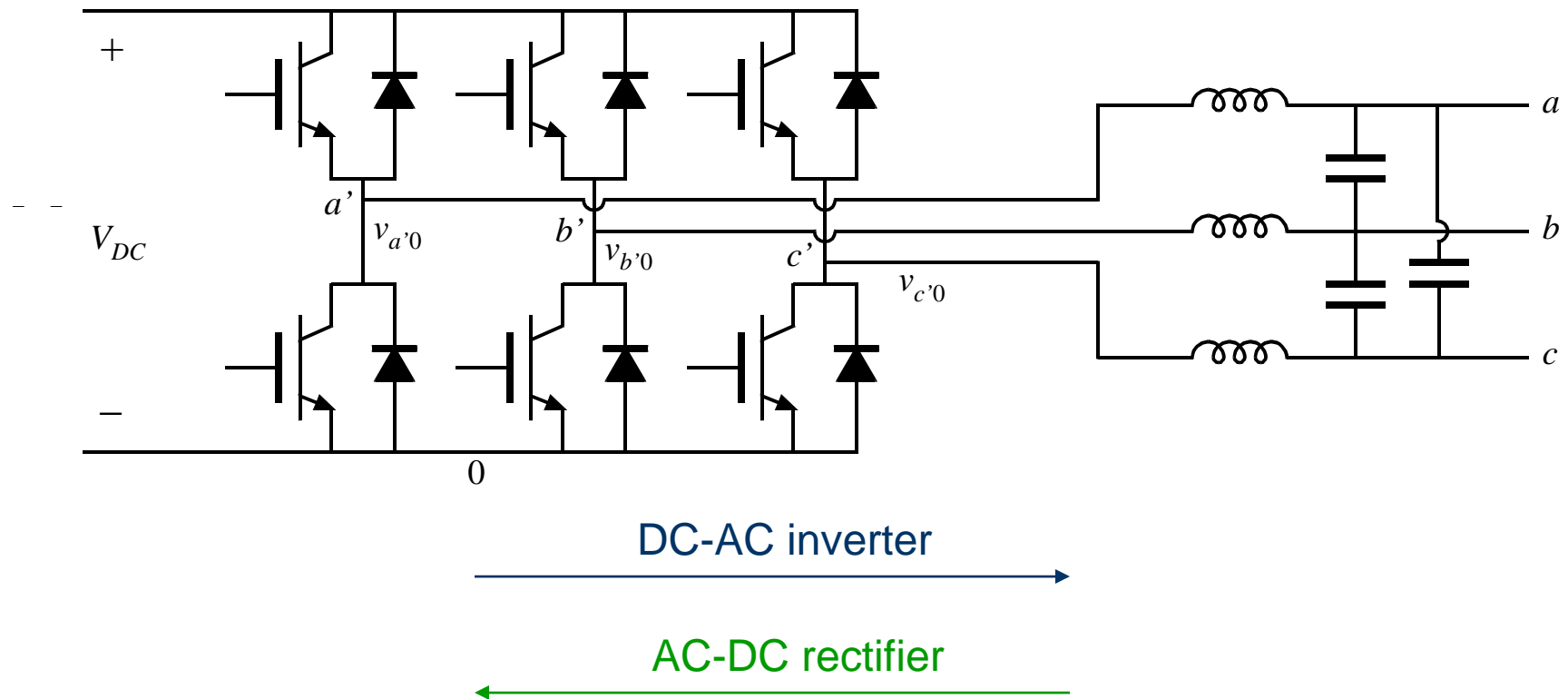
IGBT: Insulated Gate Bipolar Transistor

SCR (or Thyristor): Silicon Controlled Rectifier

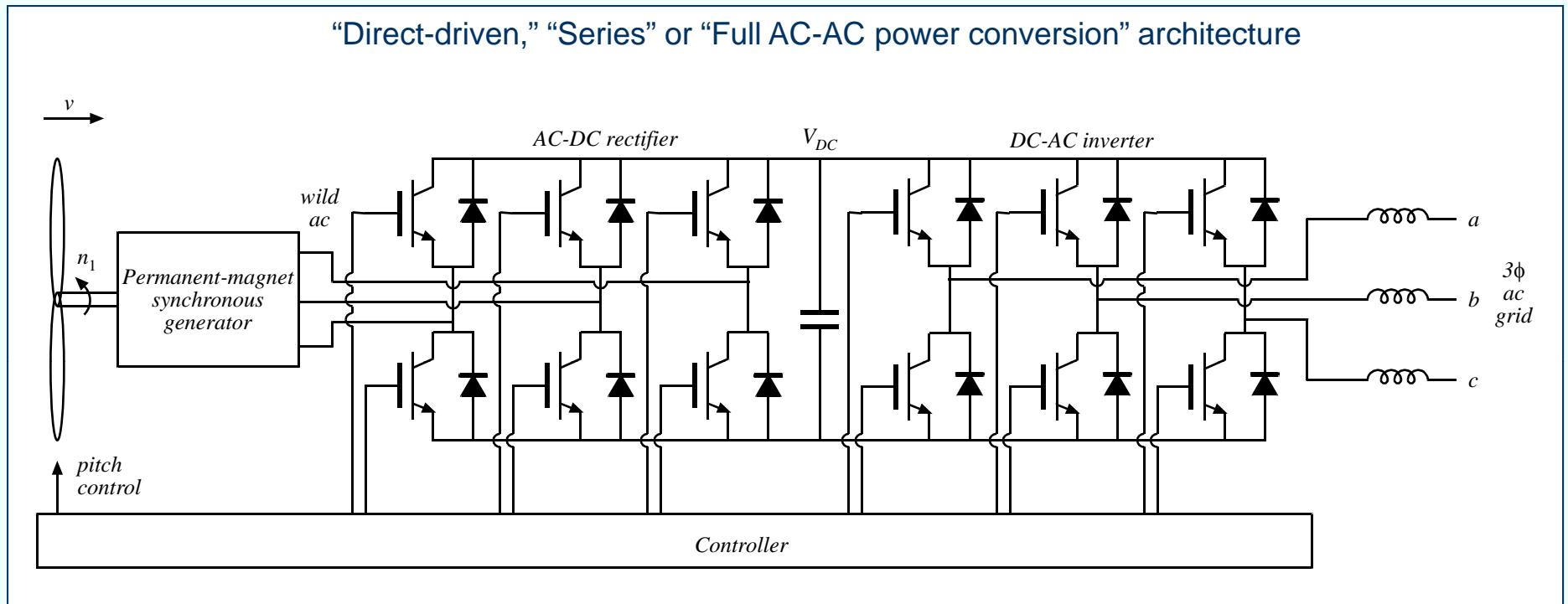
GCT: Gate Controlled Thyristor, **GTO:** Gate Turn-Off thyristor

3 ϕ inverter/rectifier

Bidirectional power flow is possible



Complete variable-speed turbine



- Wide speed range, improved efficiency of wind power capture
- Fast power control, excellent ride-through capabilities
- Gearbox can be eliminated
- Off-grid operation (islanding) is possible
- Efficient power electronics and control play key roles