# Load characteristics

Some aspects of loads

$$P_L = P_{L0}$$

$$Q_L = Q_{L0}$$

$P_{L0}$ and $Q_{L0}$ are the real and reactive power at nominal voltage of $V_o$ and frequency $f_o$

## Some aspects of loads

$$P_L = P_{L0} \cdot \left(1 + k_{pv}\frac{V - V_o}{V_o}\right)$$

$$Q_L = Q_{L0} \cdot \left(1 + k_{qv}\frac{V - V_o}{V_o}\right)$$

Variance with voltage

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Some aspects of loads

$$P_L = P_{L0} \cdot \left(1 + k_{pv}\frac{V - V_o}{V_o}\right) \cdot \left(1 + k_{pf}\frac{f - f_o}{f_o}\right)$$

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Variance with voltage

Variance with frequency

$P_{L0}$ and $Q_{L0}$ are the real and reactive power at nominal voltage of $V_o$ and frequency $f_o$

# Typical values for load constants

| Component | Power factor | $k_{pv}$ | $k_{qv}$ | $k_{pf}$ | $k_{qf}$ |
|---|---|---|---|---|---|
| Refrigerator | 0.8 | 0.77 | 2.5 | 0.53 | -1.5 |
| Incandescent lights | 1 | 1.55 | 0 | 0 | 0 |
| Fluorescent lights | 0.9 | 0.96 | 7.4 | 1 | -2.8 |
| Industrial motors | 0.88 | 0.07 | 0.5 | 2.5 | 1.2 |
| Fan motors | 0.87 | 0.08 | 1.6 | 2.9 | 1.7 |
| Agricultural pumps | 0.85 | 1.4 | 1.4 | 5 | 4 |
| Arc furnace | 0.7 | 2.3 | 1.6 | -1 | -1 |
| Transformer (unloaded) | 0.64 | 3.4 | 11.5 | 0 | -11.8 |

Source: Prabha Kundur, Power System Stability and Controls, TMH-1992.

# Induction motor driving a fan type of load

**Load torque for fan** as a function of speed is:

$$T_L = \text{constant}\left(\frac{\omega_r}{\omega_s}\right)^2$$

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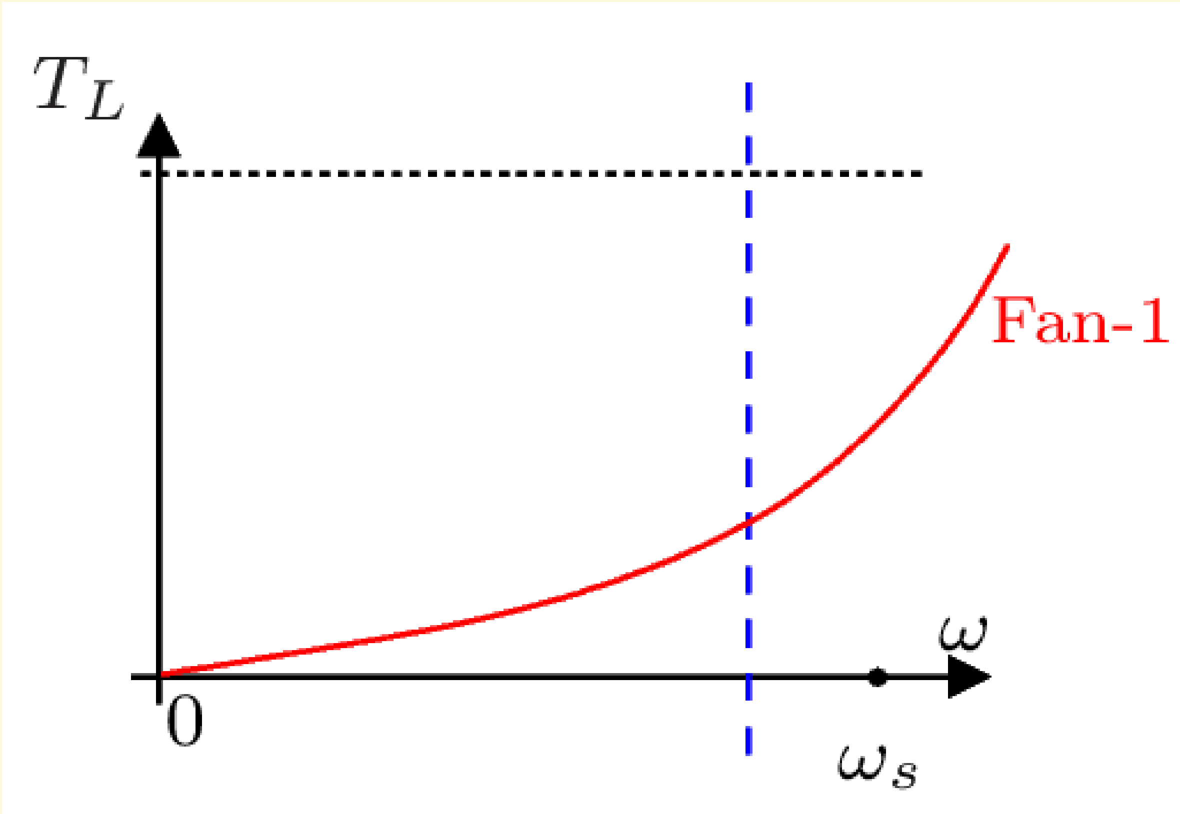

# Induction motor driving a fan type of load

**Load torque of motor** as a function of speed is

$$T_m = \frac{3V_e^2 \dfrac{R_r}{s\,\omega_s}}{\left(R_e + \dfrac{R_r}{s}\right)^2 + (X_e + X_r)^2} \quad , \quad s = \frac{\omega_s - \omega_r}{\omega_s}$$

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where,

$\omega_s$ is synchronous speed at the supply frequency

$R_r$ is rotor resistance

Thevenin impedance and a voltage source

$$V_e = \frac{jX_m}{R_s + j(X_S + X_m)} V \ , \ Z_e = R_e + jX_e = \frac{jX_m (R_s + jX_s)}{R_s + j(X_S + X_m)}$$

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$X_s$, $X_r$ and $X_m$ are the stator, rotor and magnetising reactances in at a given frequency

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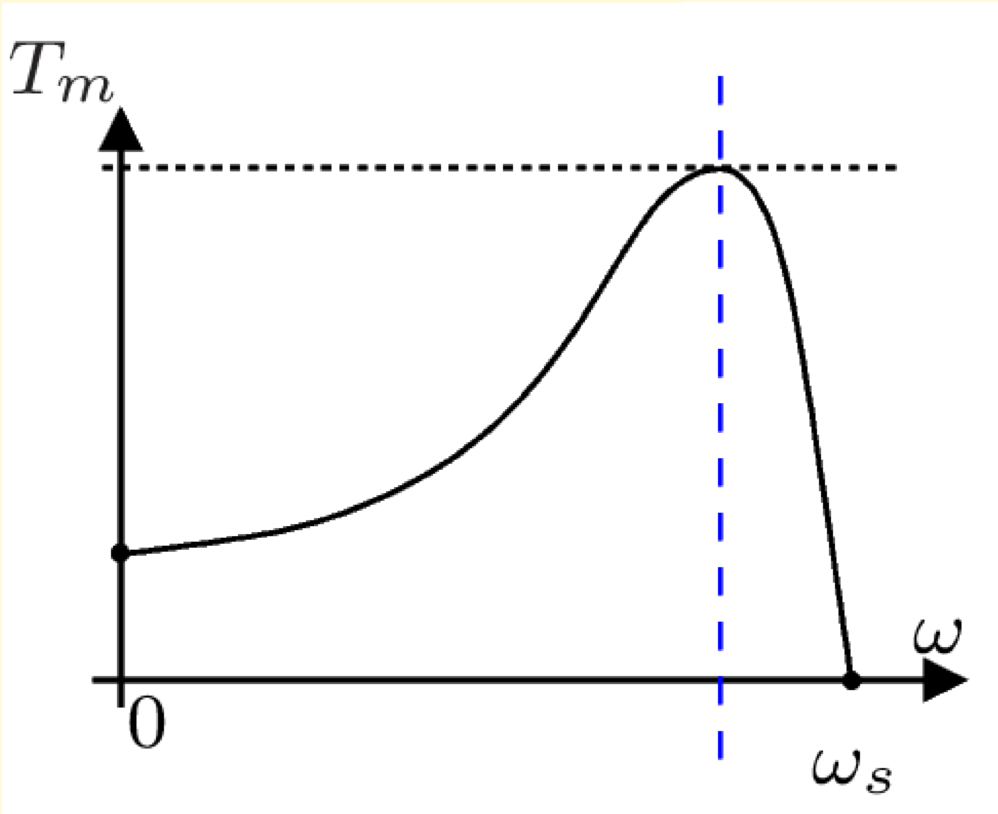

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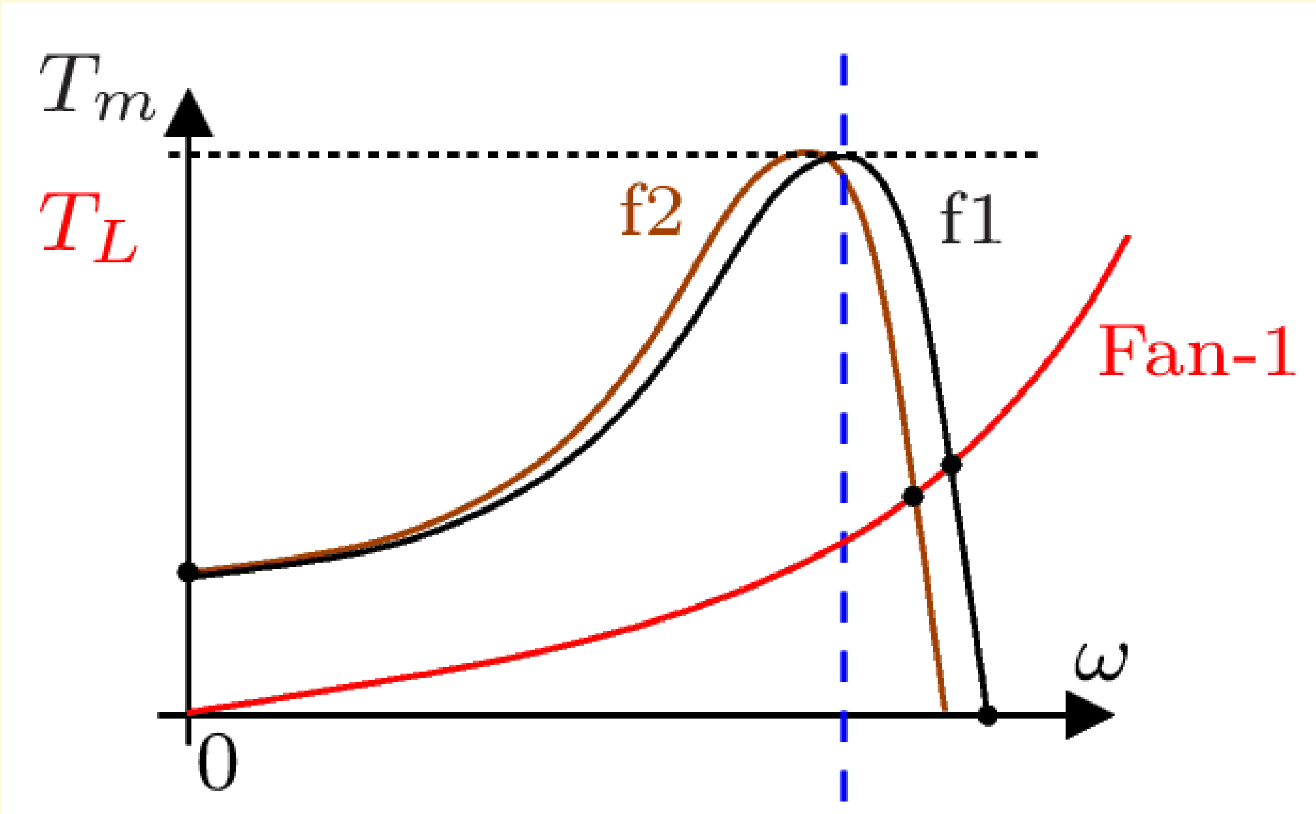

# Wind energy conversion systems (WECS)

# Some aspects of WECS

- Now a major source of energy.
- Currently more than 440 GW; expected to exceed 760 GW by 2020.
- Wind turbines with individual capacities of up to 6 to 8 MW are now available.
- Wind farms (**onshore and offshore)** having overall ratings of hundreds of megawatts are in operation.

# Some aspects of WECS

--> Wind velocity is a function of height at a given time.

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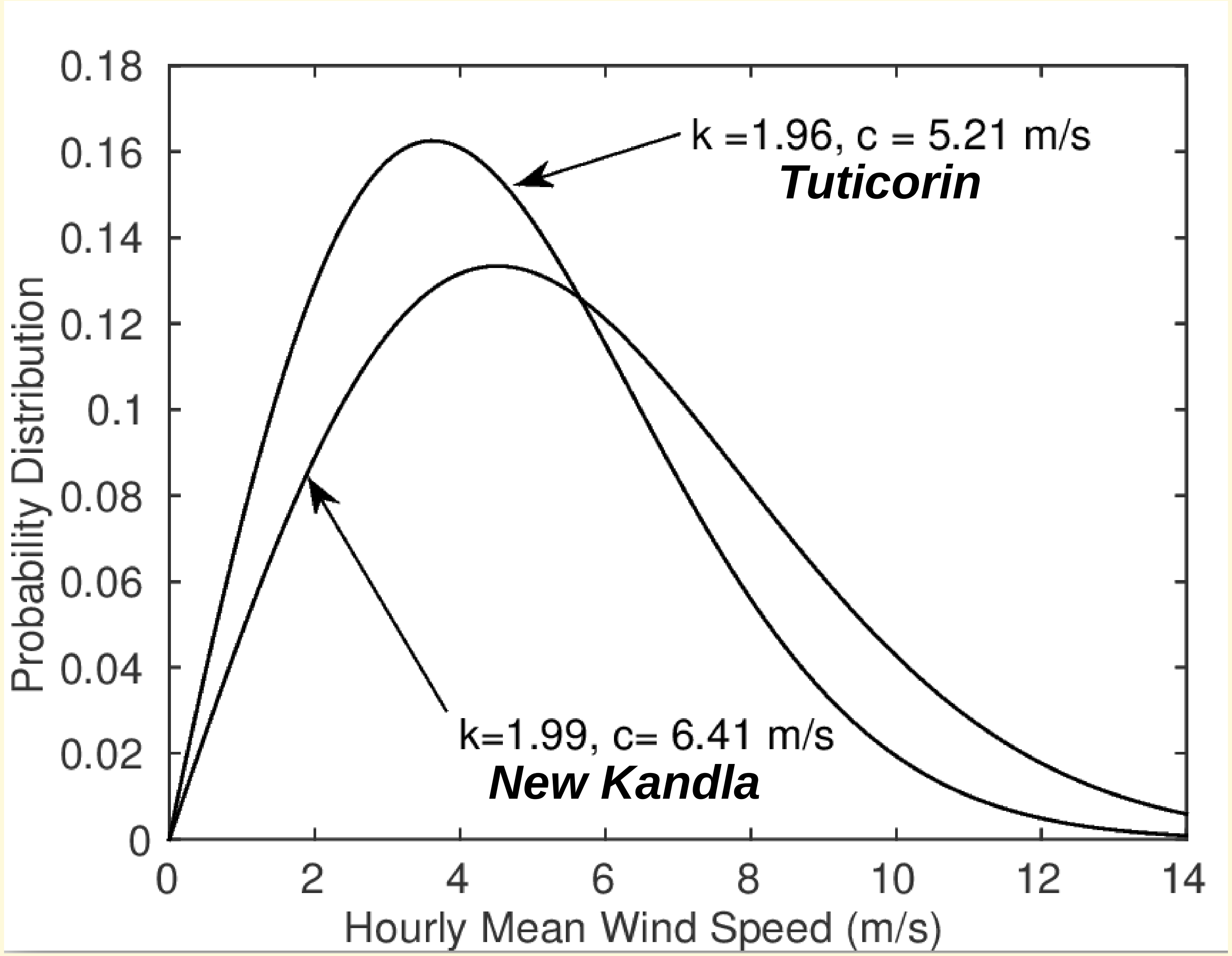
Weibull distribution:

$$p(v_w) = \frac{k}{c}\left(\frac{v_w}{c}\right)^{k-1} e^{\left[-\left(\frac{v_w}{c}\right)^{k}\right]}$$

where c is the scale factor having the unit of speed and k is a dimensionless shape factor

# Wind Characteristics

These correspond to the Weibull curves that fit the hourly mean wind speed measured at two locations in India.



# Wind Turbines: Power Extraction

--> A wind turbine can be thought of as intercepting a moving tube of wind which has a cross-sectional area ($A_w$) in $m^2$.

--> The mass of air flowing through this cross-section in *h* seconds is given by,

$$M = A_w \, \rho \, v_w \, h$$

where,
$\rho$ is the density of air in $kg/m^3$ and $\nu_w$ is the wind velocity in m/s.

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If this entire kinetic energy was to be extracted by the wind turbine, then its ***power output*** would be

$$P_o = \frac{1}{2} A_w \, \rho \, {v_w}^3$$

# Wind Turbines: Power Extraction

--> This is not feasible as the wind has to continuously flow past the turbine, and cannot be abruptly halted.

-->In practice only a fraction $C_p$ (also called the turbine power coefficient) of this energy can be extracted.

--> The theoretical maximum value of $C_p$ , which is also called the **Betz limit**, is approximately **0.59**.

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--> Thus, the power output of a wind turbine $P_m$ in W, can be expressed as follows:

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where, $C_p$ is a function of the 'tip-speed ratio' λ, and the pitch angle of the turbine blades β.

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The tip speed ratio is given as $\lambda = \dfrac{\omega'_m R}{v_w}$

$\omega'_m$ is the speed of the turbine in rad/s.

# Wind Turbines: Power Extraction

--> The following expression may be used for power system studies:

$$C_p = c_1 \left( \frac{c_2}{\lambda_i} - c_3\,\beta - c_4\,\beta^{c_5} - c_6 \right) e^{\frac{-c_7}{\lambda_i}}$$

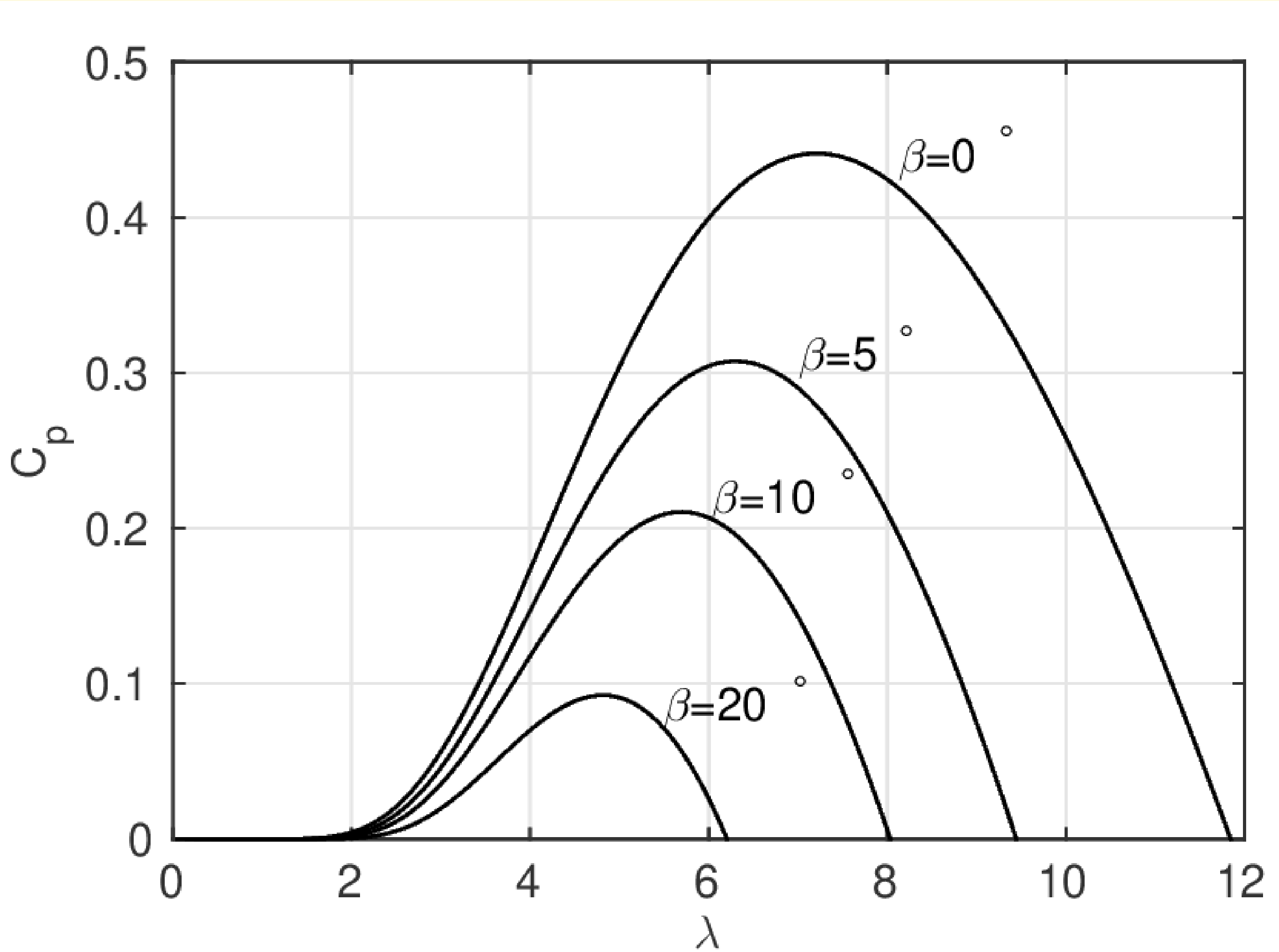
where,

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + c_8\,\beta} - \frac{c_9}{\beta^3 + 1}$$

--> The pitch angle β is expressed in degrees in these equations.

--> The coefficients $c_1$ to $c_9$ can be determined by using a numerical optimization procedure which minimizes the error between the power curve obtained from these equations and the one obtained from the manufacturer's documentation.

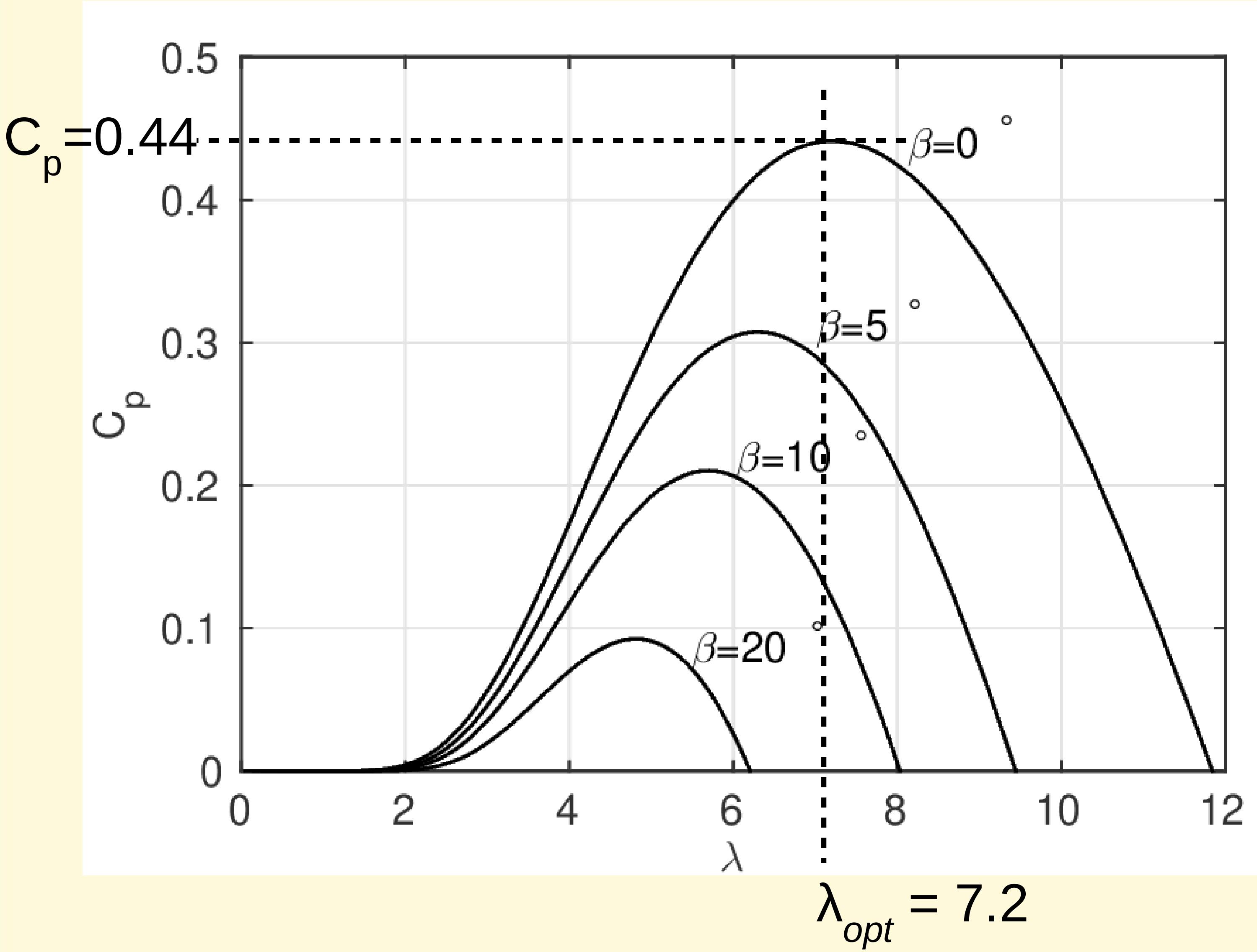
# Wind Turbines




Turbine parameters

| | |
|---|---|
| $c_1$ | 0.73 |
| $c_2$ | 151 |
| $c_3$ | 0.58 |
| $c_4$ | 0.002 |
| $c_5$ | 2.14 |
| $c_6$ | 13.2 |
| $c_7$ | 18.4 |
| $c_8$ | -0.02 |
| $c_9$ | -0.003 |

# Wind Turbines

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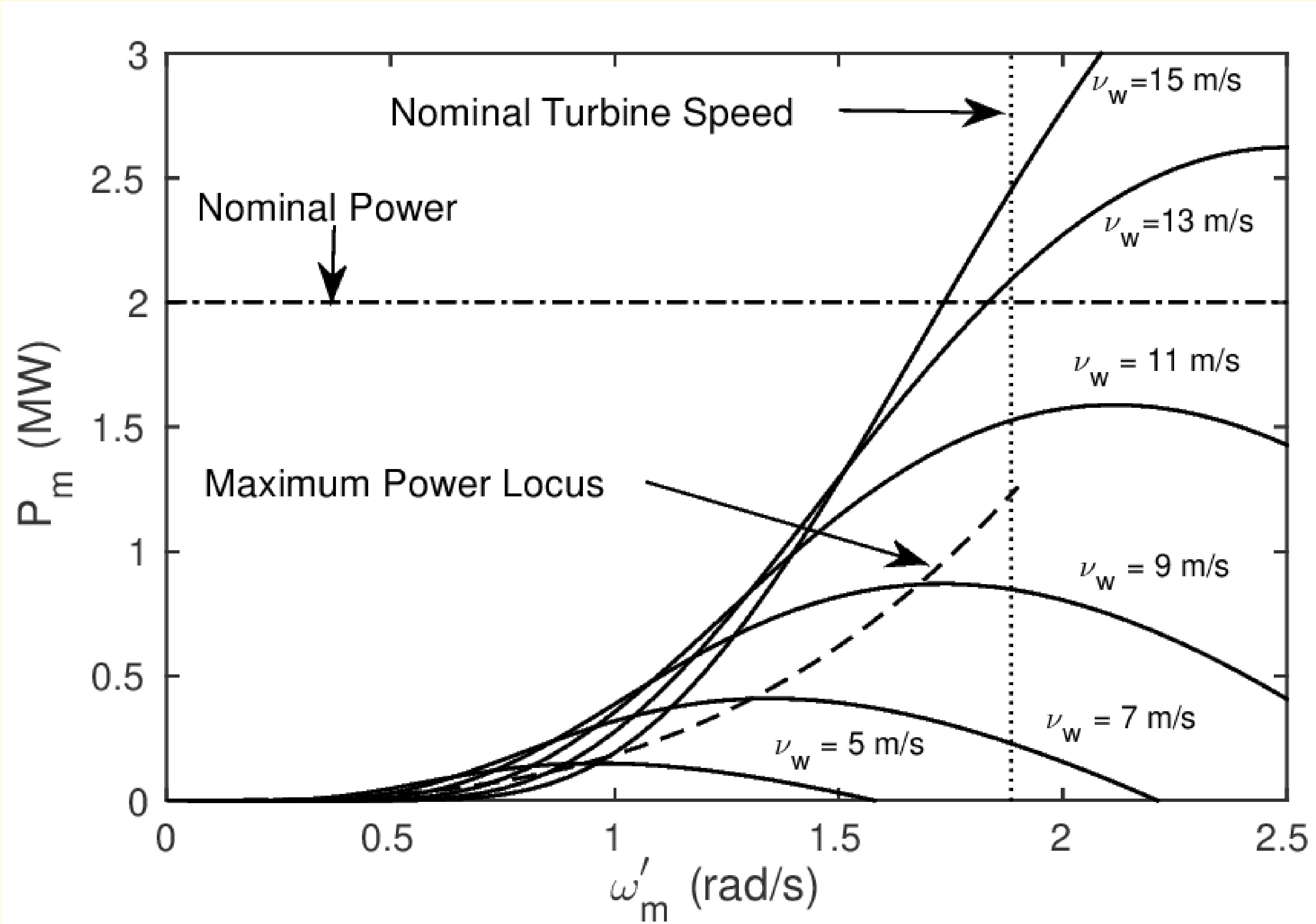
# Wind Turbines: Maximum Power Extraction (for various wind speeds)

--> For the turbine parameters given in the previous slide, for $\beta = 0^o$, the approximate optimum value of $C_p = 0.44$ which occurs when $\lambda_{opt} = 7.2$ units.

--> The maximum power that can be extracted as a function of turbine speed is given by:

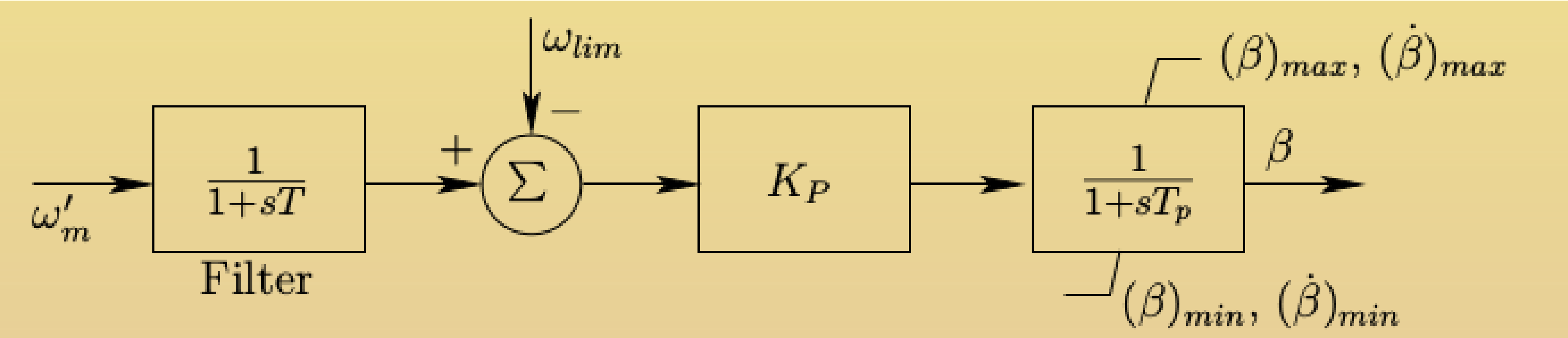
$$P_{m_{opt}} = \left[\frac{1}{2}\,\frac{\rho\, A_w\, R^3\, C_{p_{opt}}}{\lambda^3{}_{opt}}\right](\omega'_m)^3 = k_{opt}\,(\omega'_m)^3$$

# Wind Turbines: Power Extracted vs Turbine Speed (for various wind speeds)




$$\beta = 0^\circ,\ \ R = 37.5\ \mathrm{m},\ \ \rho = 1.225\ \mathrm{kg/m^3}$$

# Wind Turbines: Pitch and Stall Control

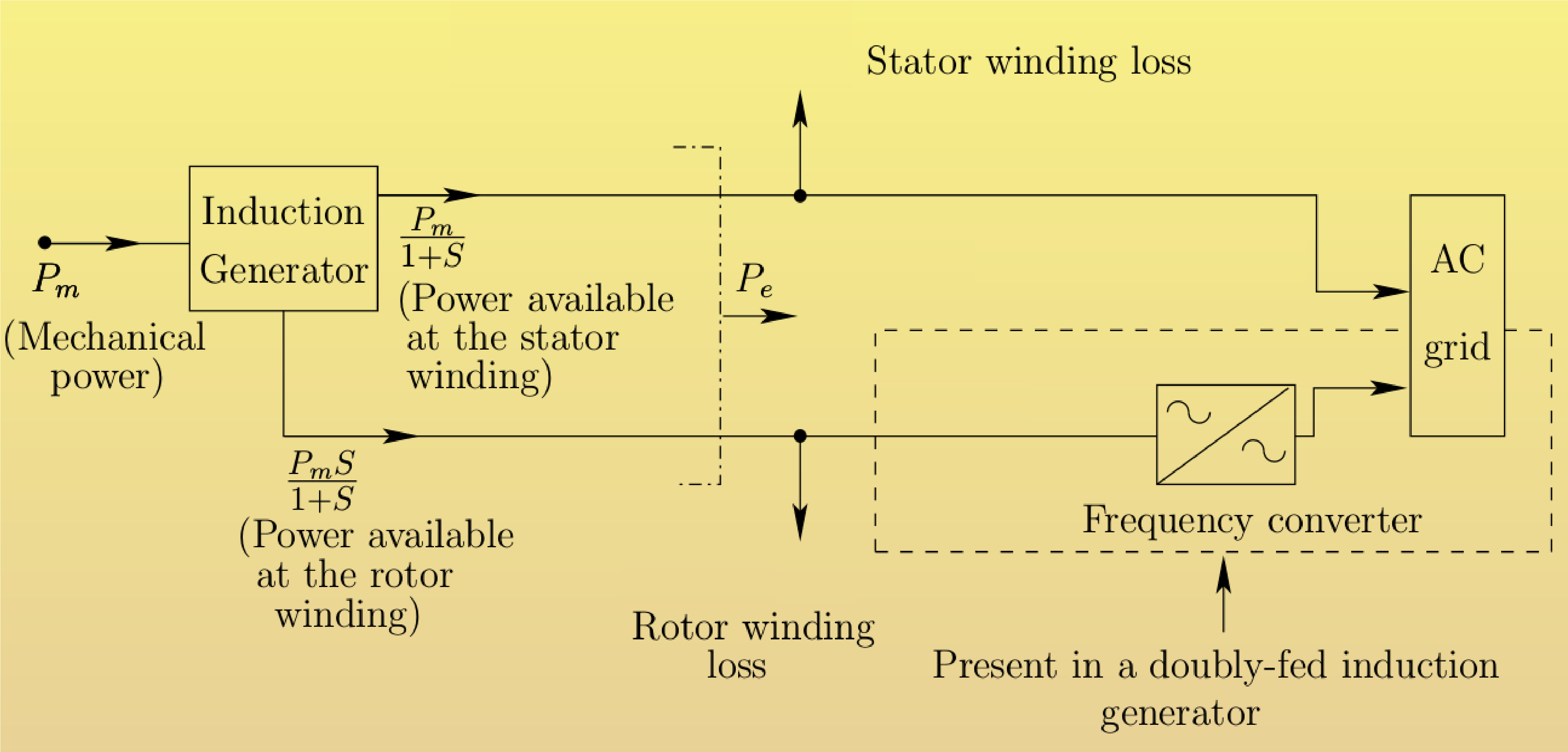



--> Pitch (β) control involves turning the blades around their longitudinal axis.

--> This reduces Cp , which is a function of β, thereby reducing the power output.

--> The rotor aerodynamics may be designed to stall (lose power) when the wind speed exceeds a certain level. This is known as stall control.

# Doubly fed induction generator (DFIG) – Power flow



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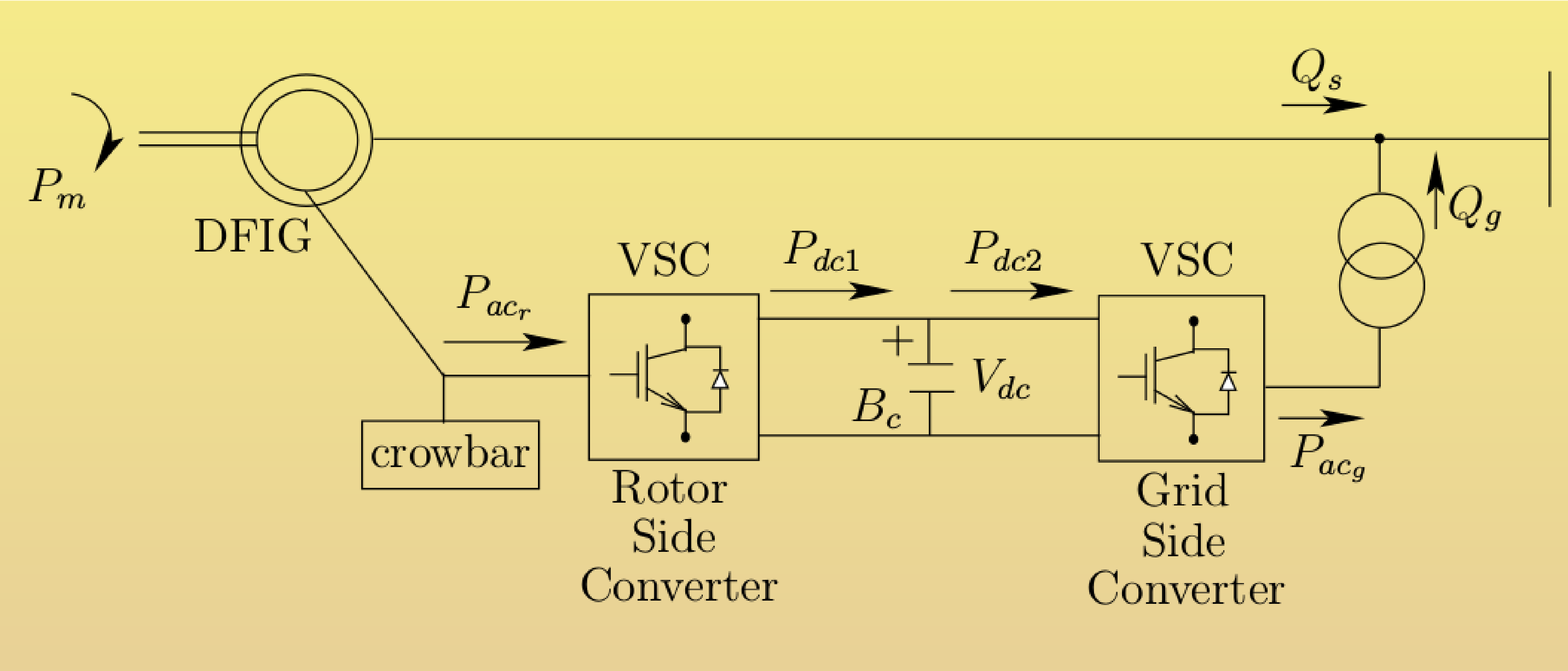
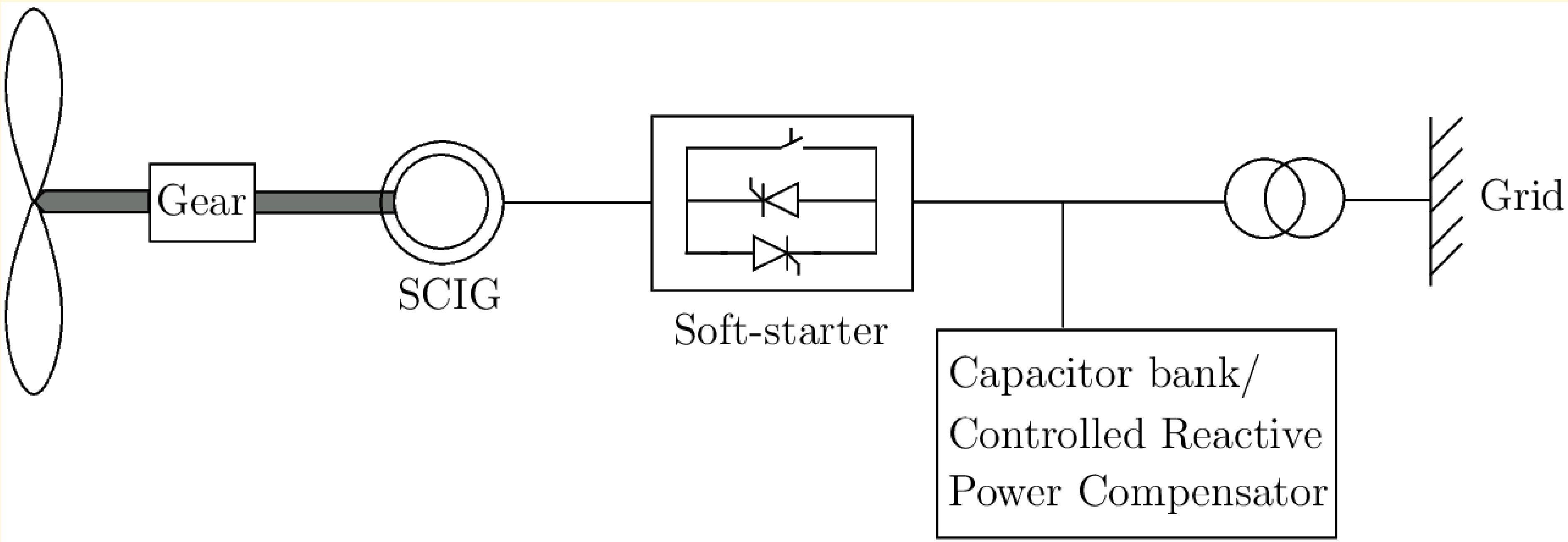
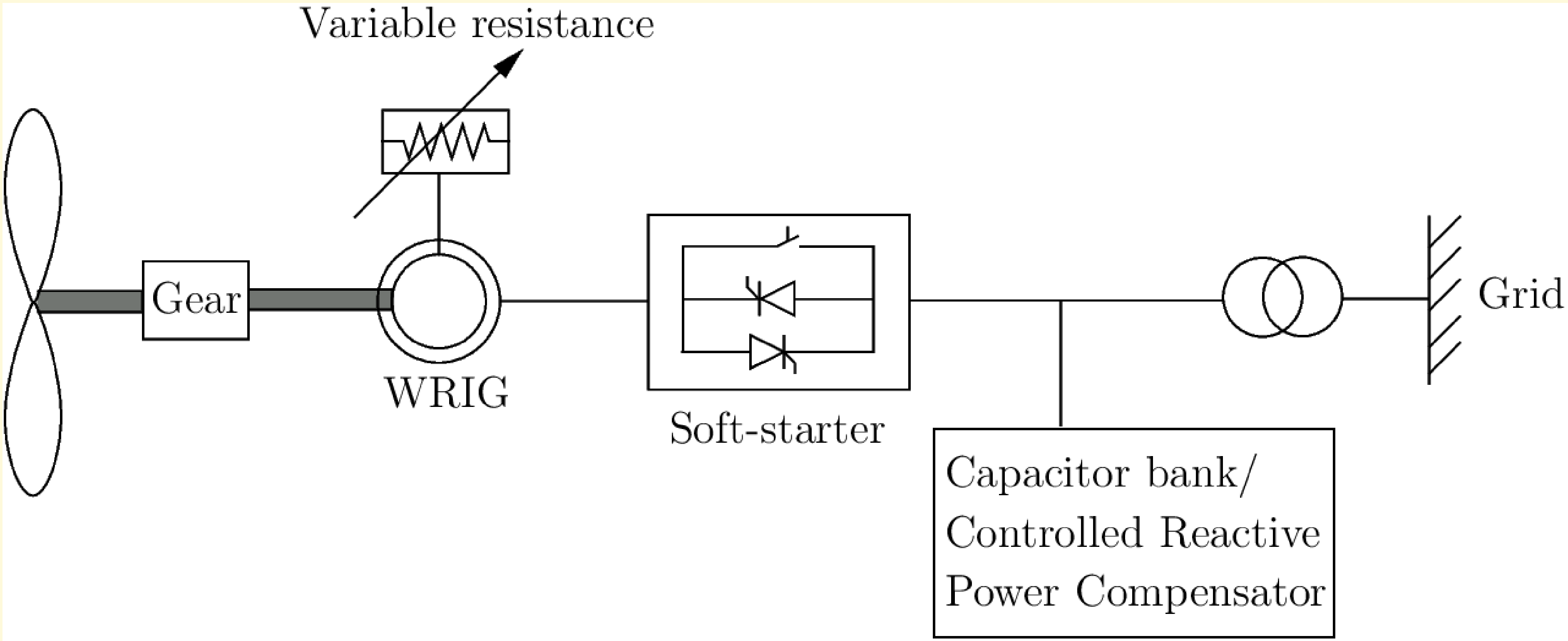


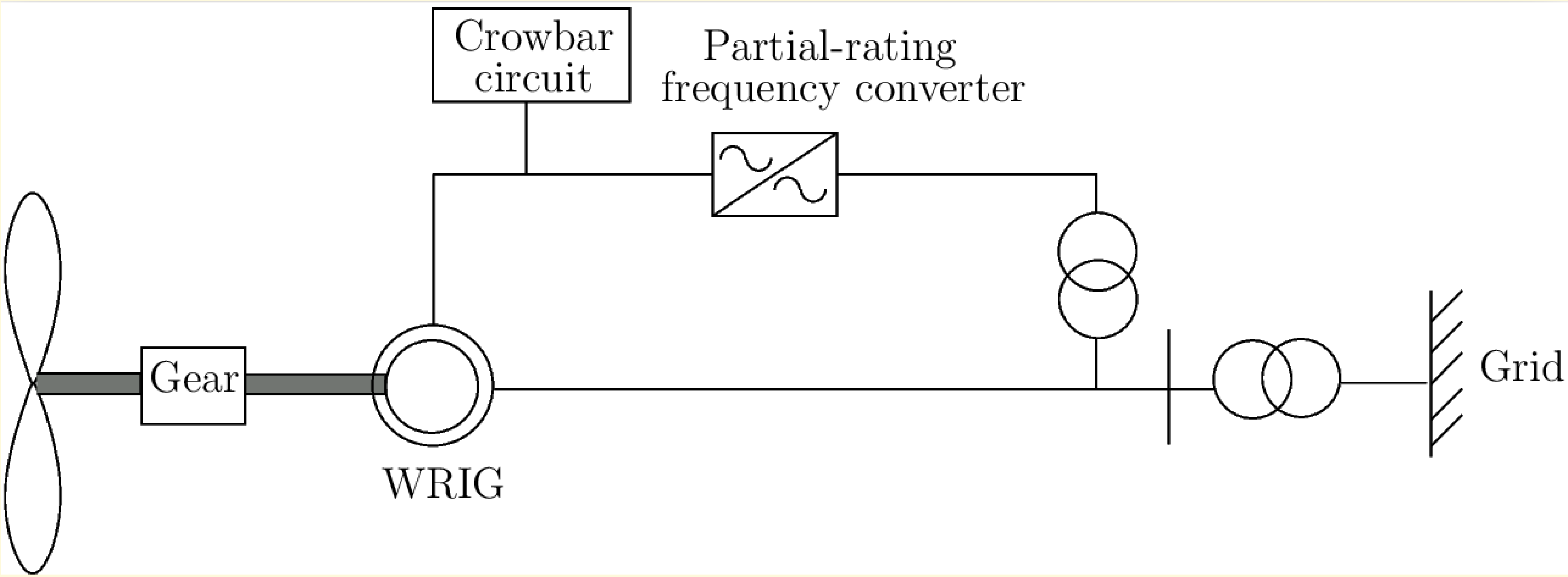
# Generator and Power Electronic Configurations - Type I



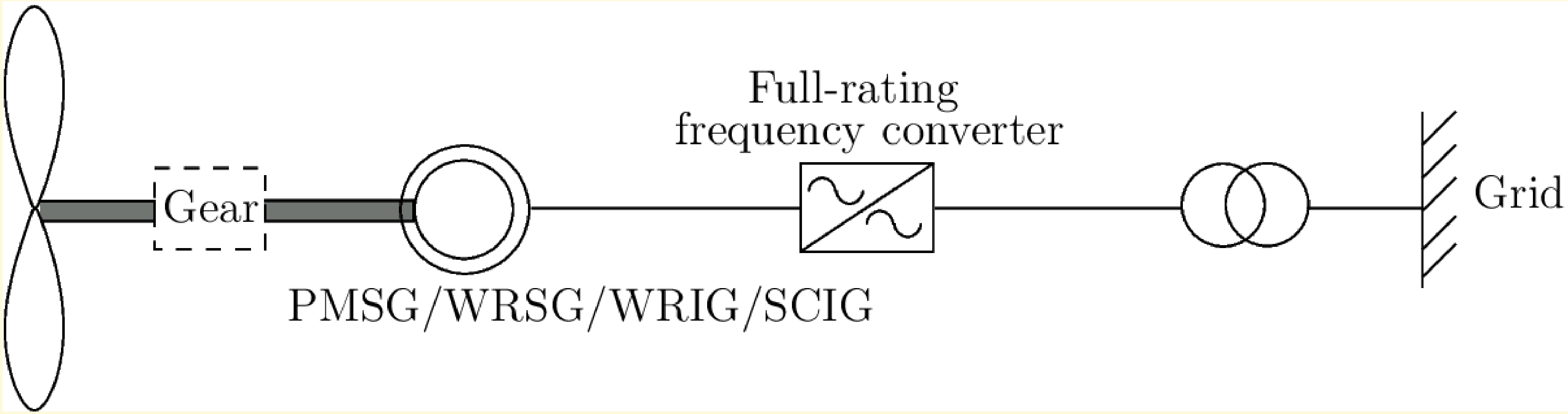
# Generator and Power Electronic Configurations - Type II



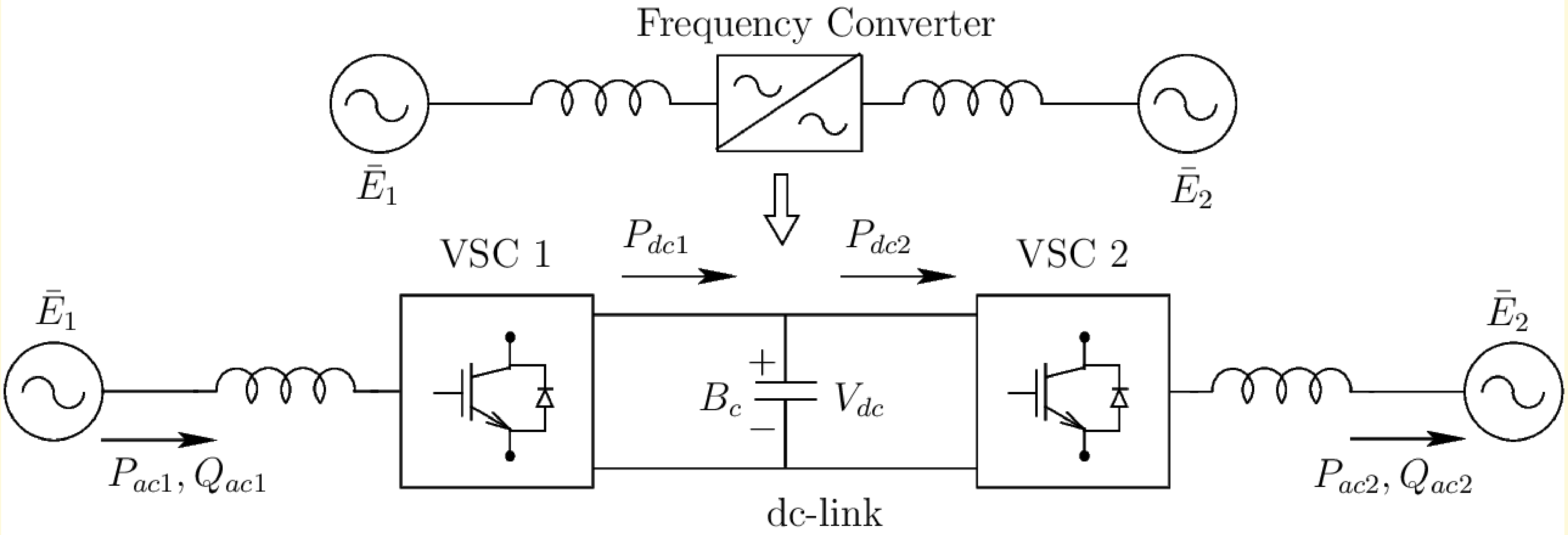
# Generator and Power Electronic Configurations - Type III



# Generator and Power Electronic Configurations - Type IV



# Generator and Power Electronic Configurations
# Frequency Conversion using VSCs




(1) $P_{ac1}$=$P_{dc1}$, $P_{ac2}$ =$P_{dc2}$ (lossless converter)
(2) $P_{dc1}$=$P_{dc2}$ in steady state
(3) $Q_{ac1}$, $Q_{ac2}$ are independently controllable

# Transmission lines and cables