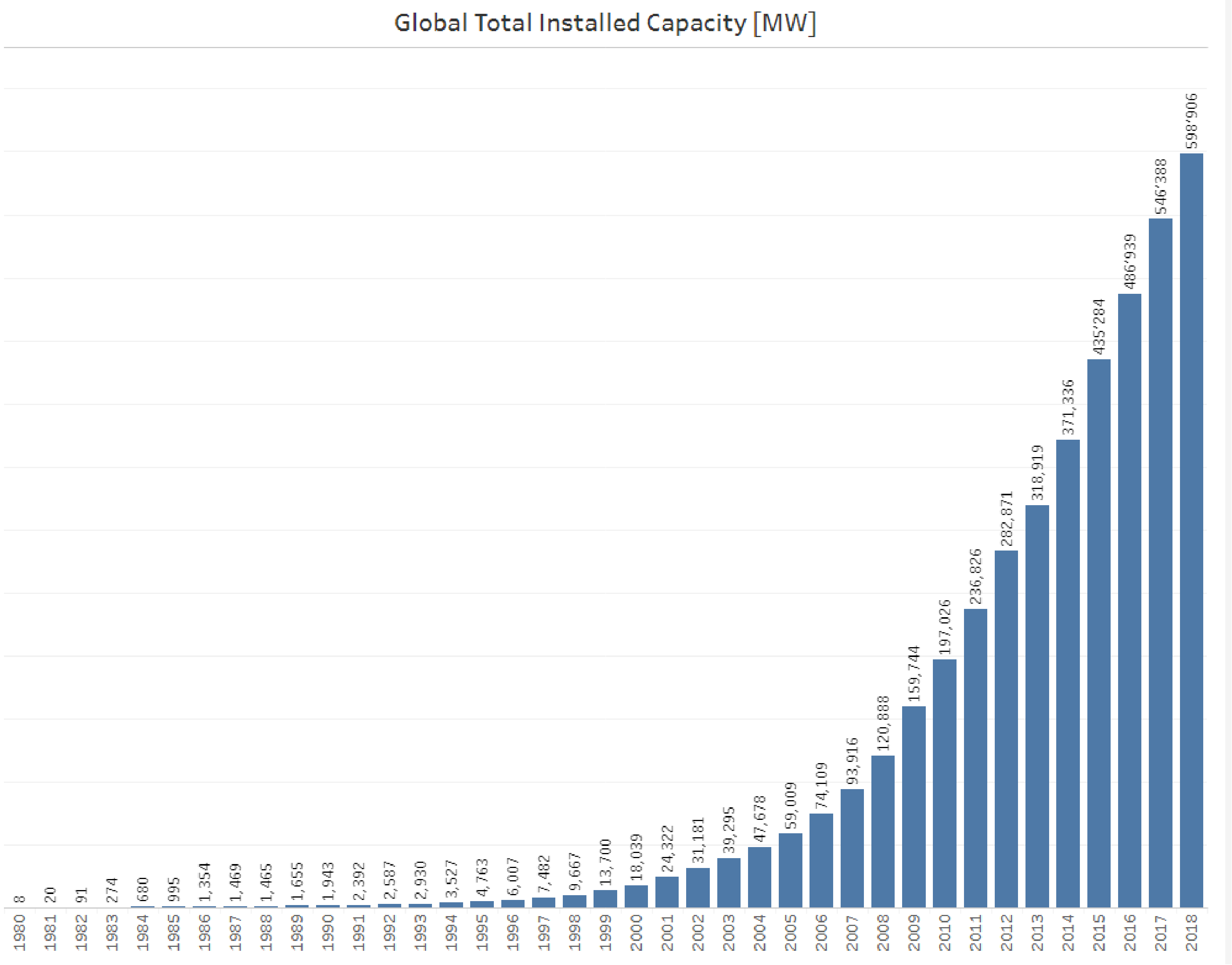
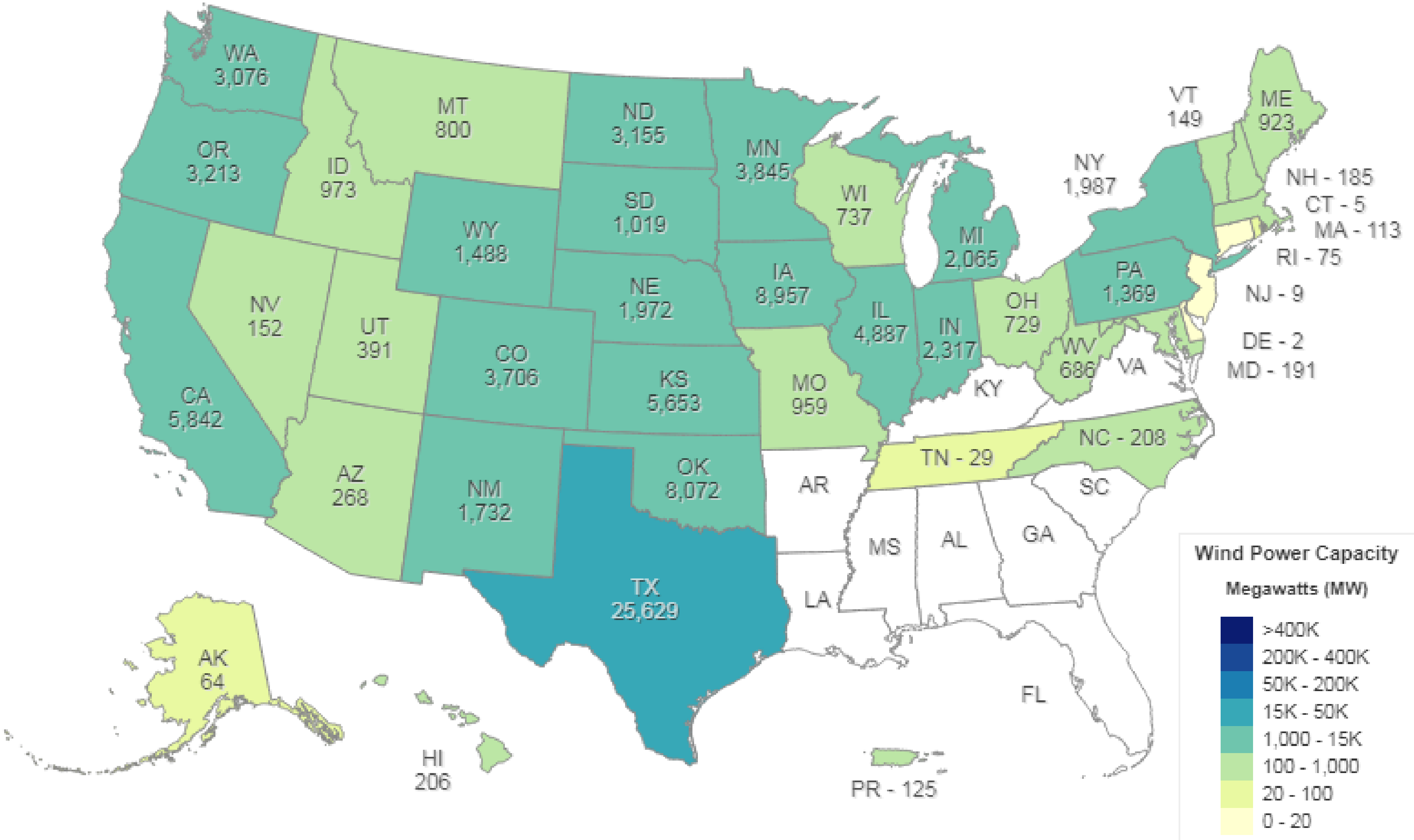
EE 742
Chap. 7: Wind Power Generation

Y. Baghzouz



https://wwindea.org/blog/2019/02/25/wind-power-capacity-worldwide-reaches-600-gw-539-gw-added-in-2018/

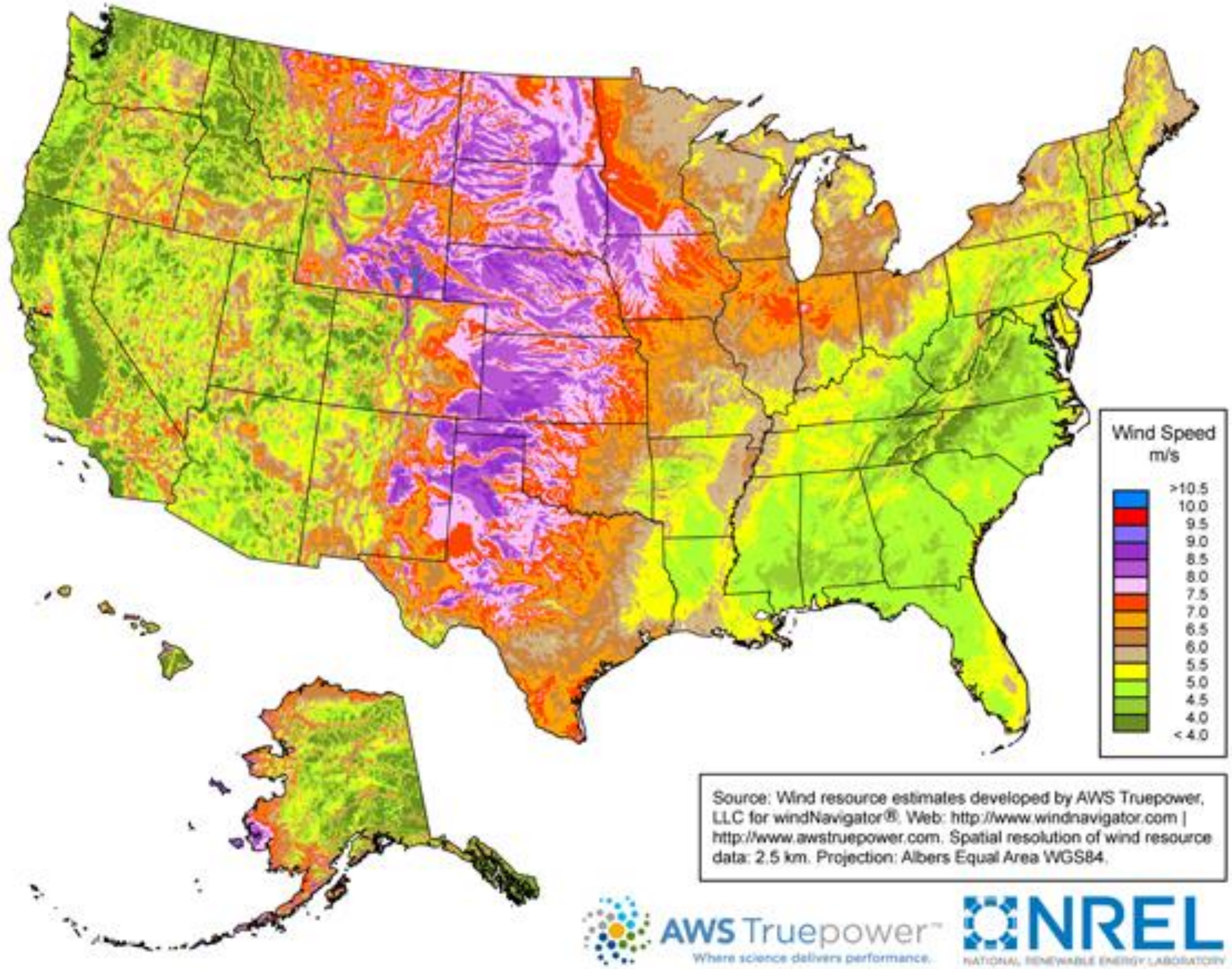
Q2 2019 Installed Wind Power Capacity (MW)



Total Installed Wind Capacity: 97,963 MW

Source: American Wind Energy Association Market Report

US Wind Resource Map

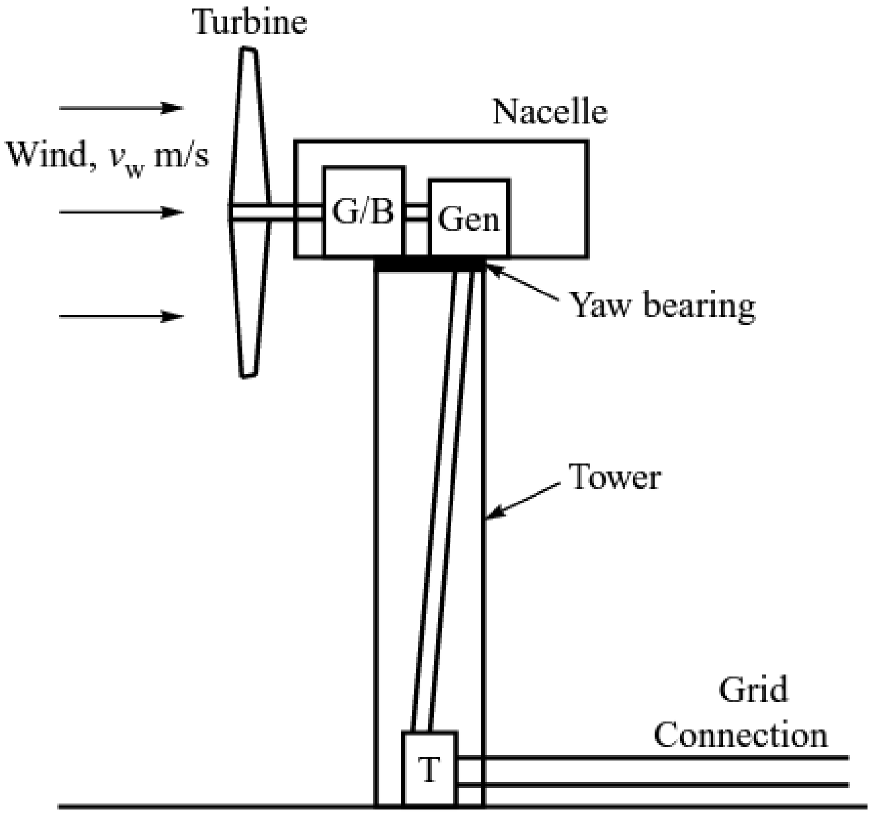


Wind turbines

- Horizontal axis wind turbines (HAWT) are the most popular - compared to vertical axis wind turbines (VAWT).
- 3 blades used to minimize power pulsations (if < 3) and aerodynamic interference (if > 3).
- The aerodynamic blades produce a lift force along the blade which produces a mechanical torque on the turbine shaft.

Typical arrangement of a wind turbine

- Typically, the low turbine speed (15-20 rpm) is stepped up to synchronous speed (e.g., 1,800 rpm) through a gear-box.
- The output shaft of the gear-box drives an induction machines.
- This generator is connected to the grid through a step-up transformer.
- A yaw system turns the turbine in the direction of the wind, and provides breaking.



Turbine power

- Wind power varies a cube of the wind speed, $P = \frac{1}{2}\rho A v^3$ W
- But the wind turbine can extracts only: $$P = \frac{1}{2}\rho A c_p v_w^3 \quad \text{W},$$

where ρ is the air density, A is the turbine sweep area, v_w is the wind speed, and c_p is the turbine performance coefficient. At 20 °C and 101.325 kPa, dry air has a density of 1.204 kg/m³.

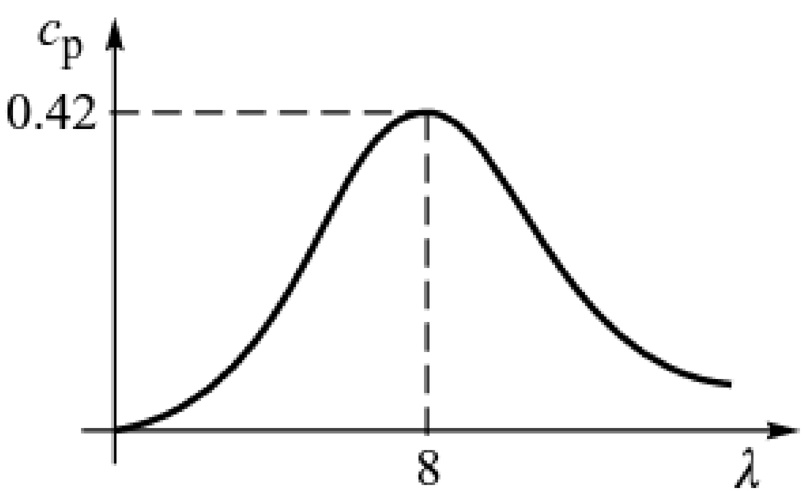
- the theoretical maximum power that can be extracted is with c_p =16/27 ≈ 60% (*Bezt limit* – conservation of mass and energy).
- In practice c_p is less than the above value and varies with the *tip speed ratio* λ (ratio of rotor tip speed over the wind speed), i.e.,

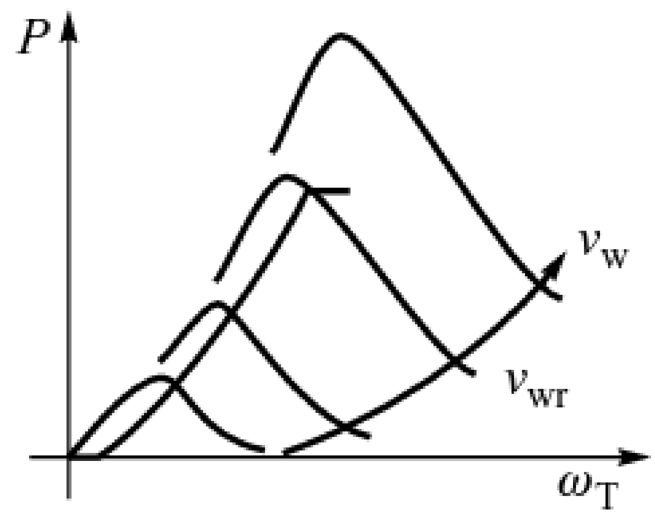
$$\lambda = \frac{\omega_T r}{v_w},$$

where r is and ω_T are the rotor radius and rotational speed.

Turbine Power

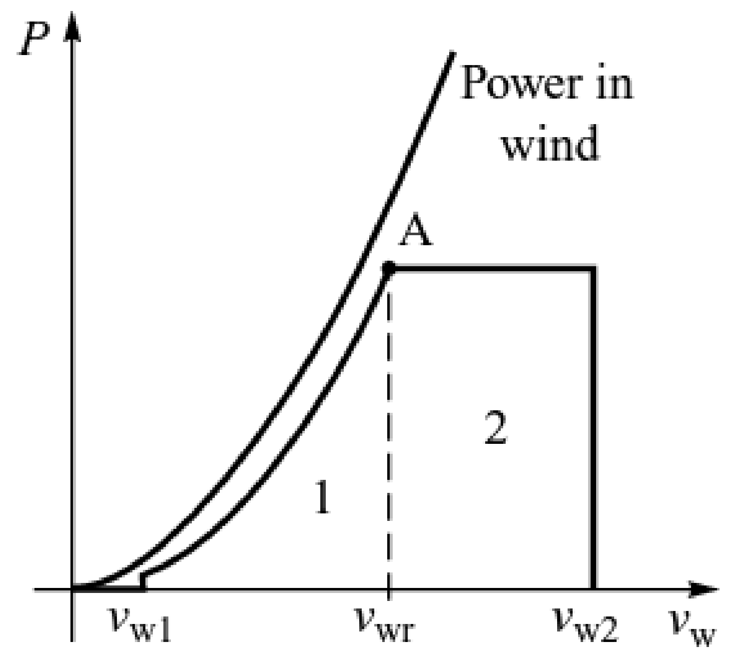
- A typical c_p - λ curve is shown below and is unique to a particular turbine design. Modern wind turbine design can reach 70-80% of the theoretical limit.
- To extract maximum power, the turbine must be operated at the peak of the curve (*peak power tracking*).
- For a given wind speed v_w and the c_p - λ characteristics, the turbine power can be calculated as a function of shaft speed.





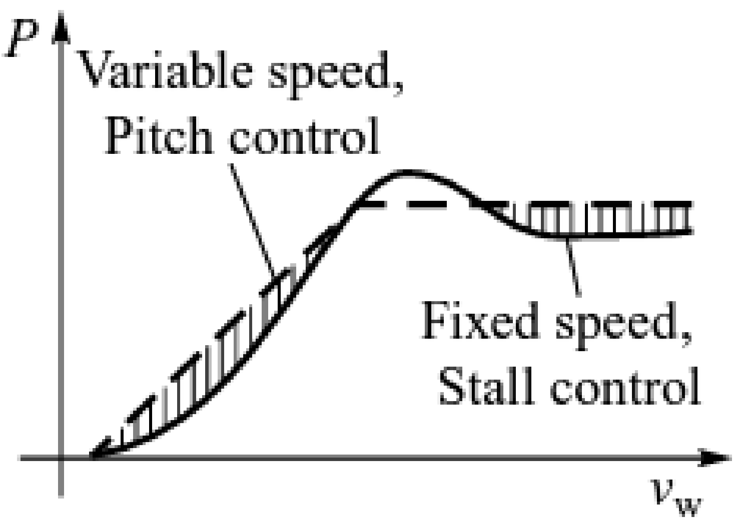
Turbine Power

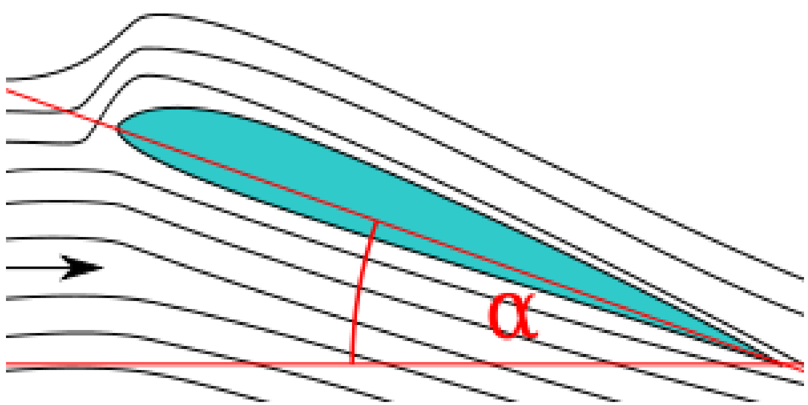
- For a given turbine c_p, the turbine power can be graphed as a function of the wind speed as shown below.
- The figure shows the cut-in speed (3-4 m/s), rated speed (12.5 m/s), and shut down speed (around 25 m/s).
- Turbines are tyically designed to withstand wind speeds of up to 50 m/s (180 km/hr)



Power Control

- Some form of power control at high wind speeds is needed so that the turbine does not exceed its rated speed. Two methods are available:
  - *Passive stall control* – normally used on fixed speed machines. In here the turbine blades are designed so that the lift force on the blades reduces and the blade progressively goes into stall with increased wind speed.
  - *Active pitch control* - in here, the pitch of the blade is changed to reduce the output power (requires feedback control signal such as rotational speed)



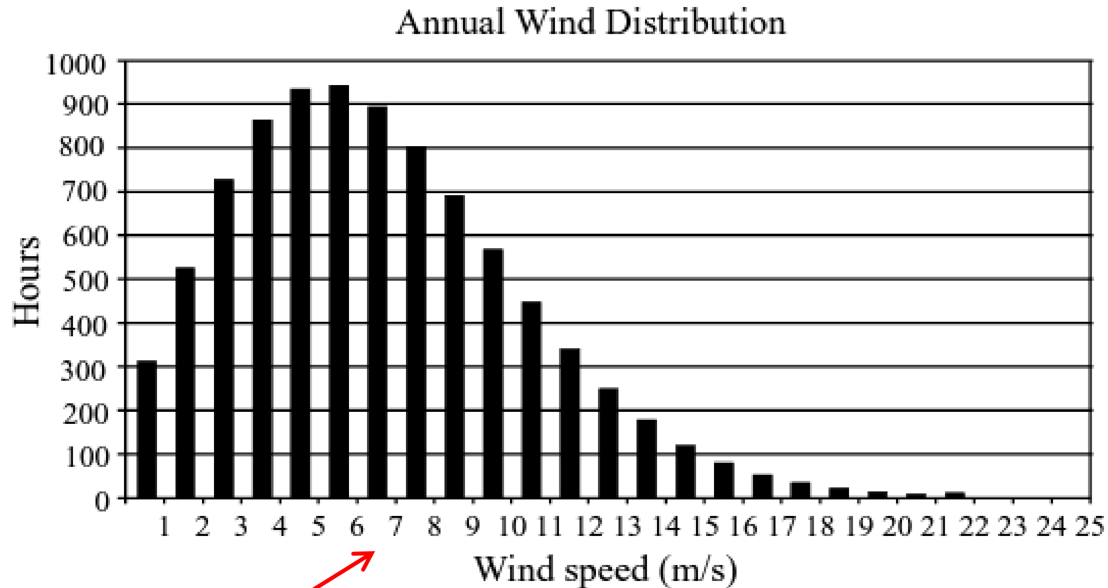


Pitch control ⟷ vary angle of attack

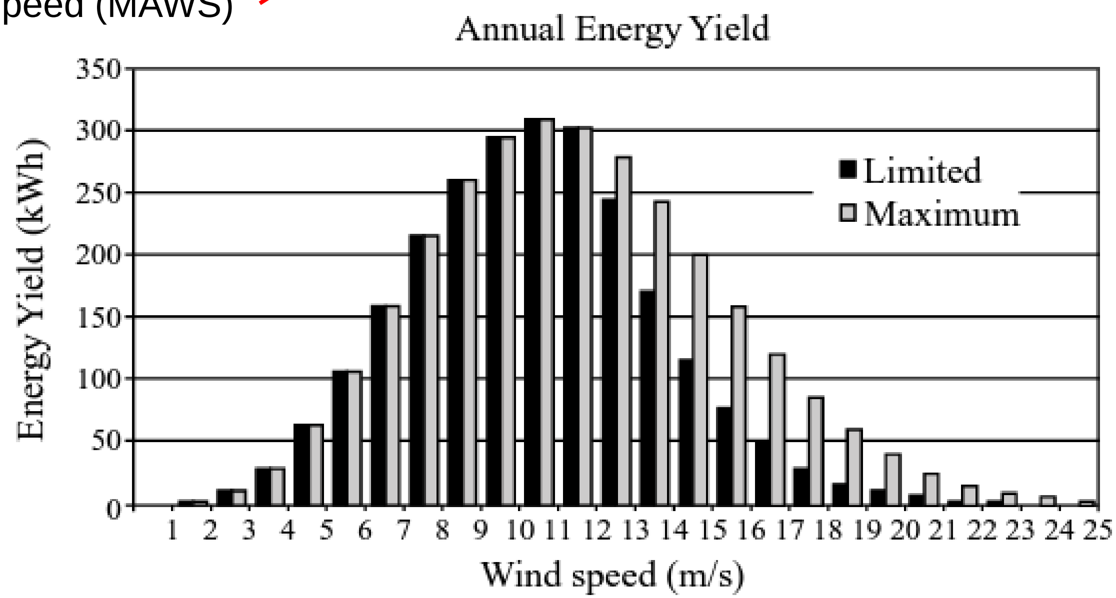
Diameter and operating speeds of various wind turbine sizes (assuming rated speed of 12.5 m/s)

Power P (kWe)	Area A (m^2)	c_p	λ	Diameter $2r$ (m)	Rotational speed ω_T (rpm)
1	2.5	0.3	4.5	1.8	629
10	24.8	0.3	4.5	5.6	199
100	247.7	0.3	5	17.8	70
500	1 238.5	0.3	6	39.7	38
1000	2 477.1	0.3	6	56.2	27
2000	4 954.2	0.3	7	79.4	22
5000	12 385.5	0.3	8	125.6	16

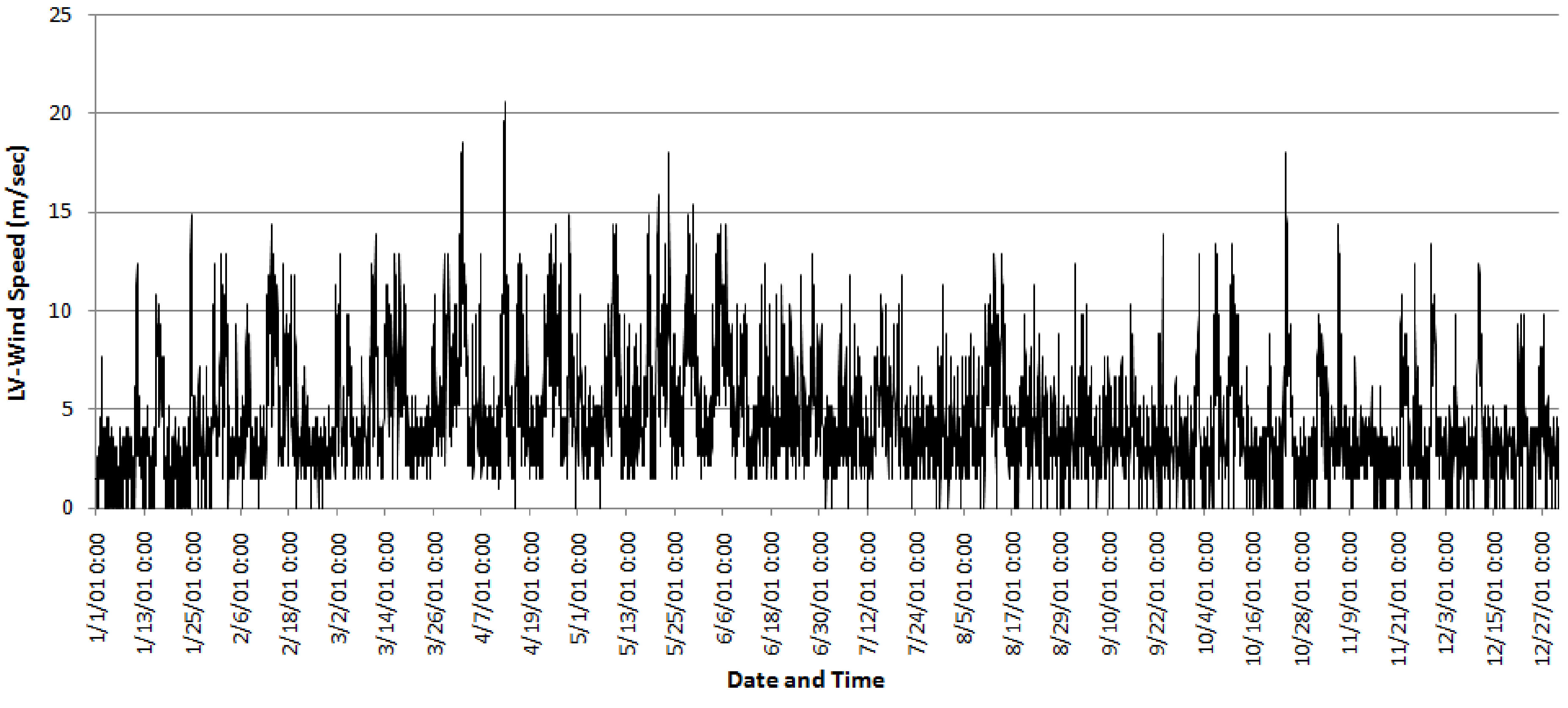
Annual wind speed distribution and energy yield by a 60 m diameter turbine (with rated speed of 12.5 m/sec)



Mean Annual Wind Speed (MAWS)



Hourly wind speed variation over 1 year is Las Vegas (MAWS: 4.9 m/s)



Capacitor Factor

- Capacity factor of a wind power generator is defined as

$$c_{\mathrm{f}} = \frac{\text{actual annual energy production}}{\text{maximum plant rating} \times 8760}.$$

for a site with a MAWS of 7 m/s, c_f is around 30%.

for a site with a MAWS of 5 m/s, c_f is about 12%.

Generator configurations

- Synchronous generator (not practical – fixed speed)

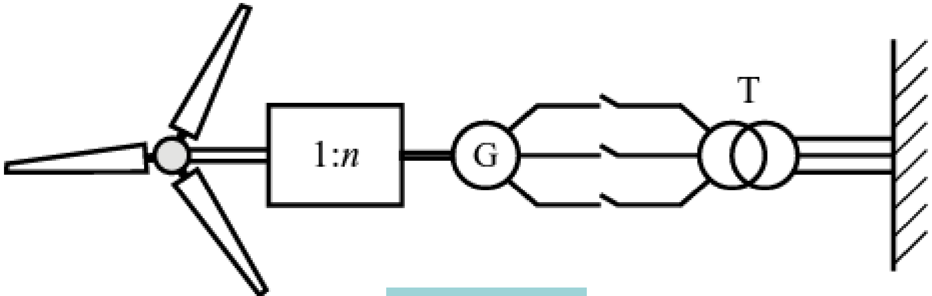


Fig. 7.5

- squirrel cage induction generator (energy capture cannot be maximized due to nearly fixed speed range)

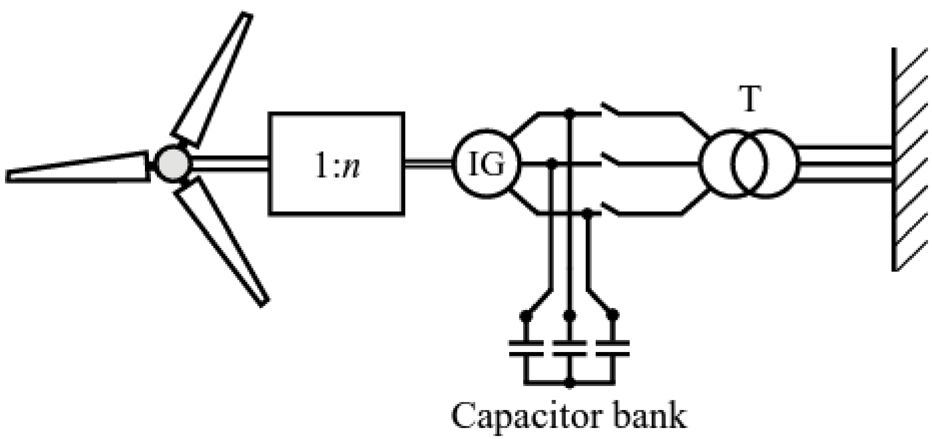


Fig. 7.6

Generator configurations

- Wound rotor induction generator (limited speed range)

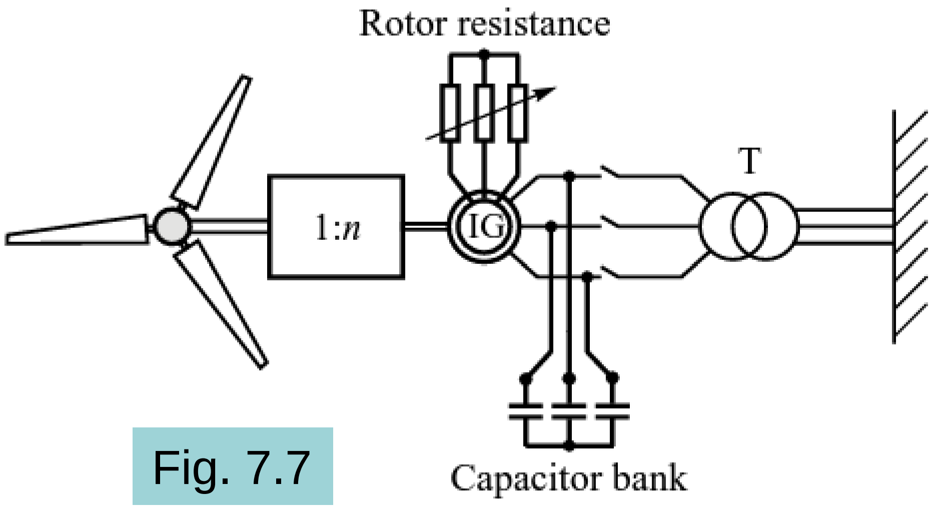


Fig. 7.7

- Squirrel cage induction generator with fully rated converter (wide range)

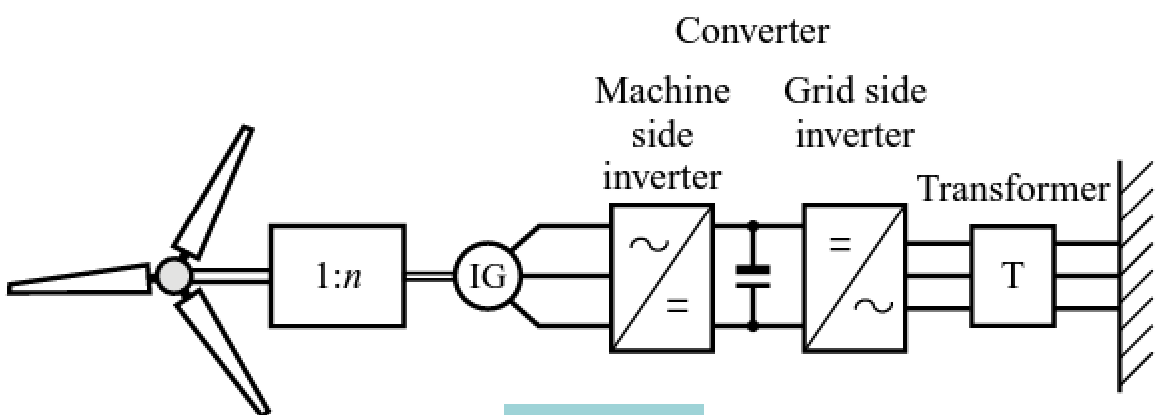


Fig. 7.8

Generator configurations

- Doubly-fed induction generator (partially rated converted) speed limit (30%)

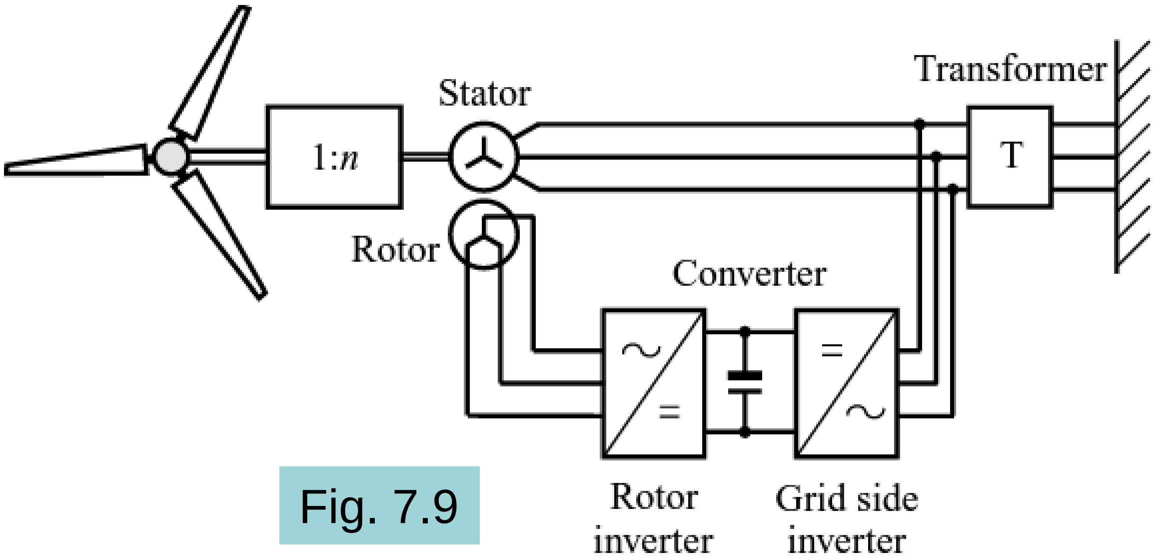


Fig. 7.9

- Permanent magnet generator with fully rated converter (wide range)

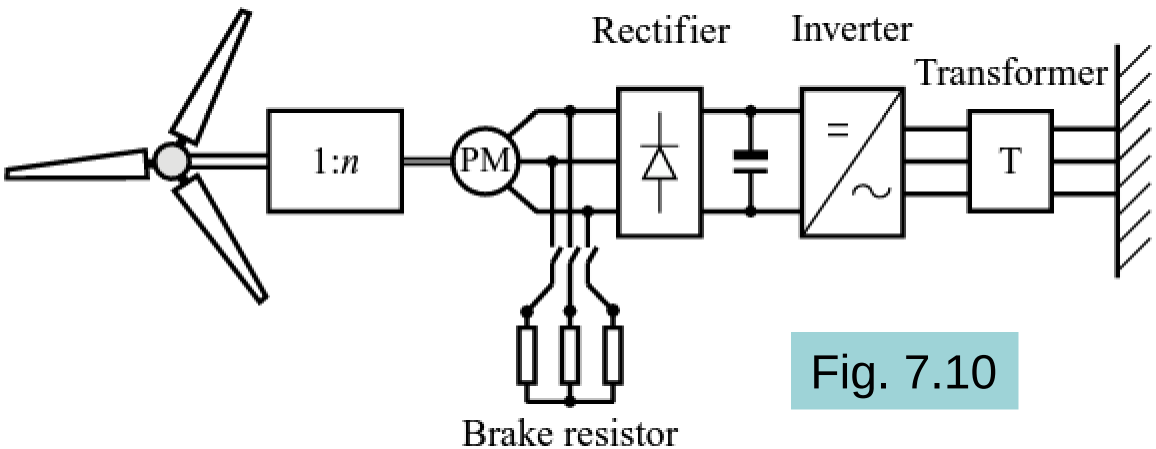


Fig. 7.10

Generator configurations

- Wound field generator with fully rated converter (wide range)

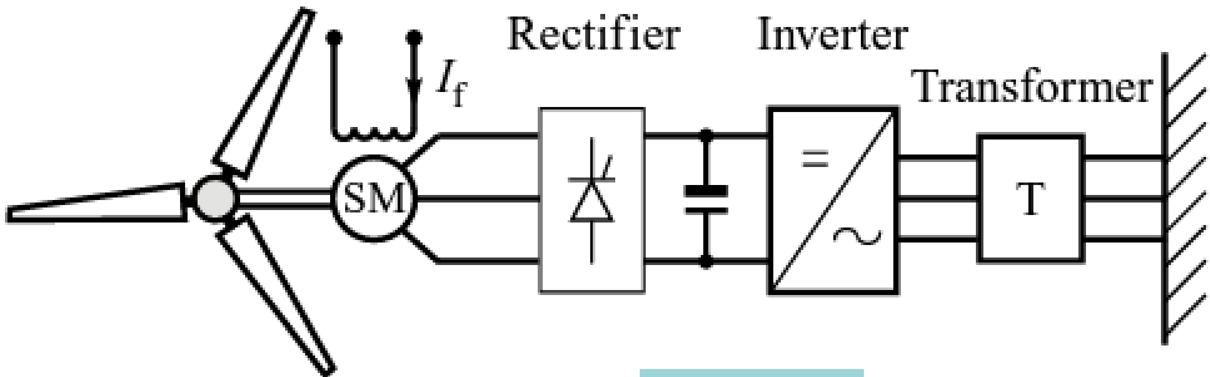
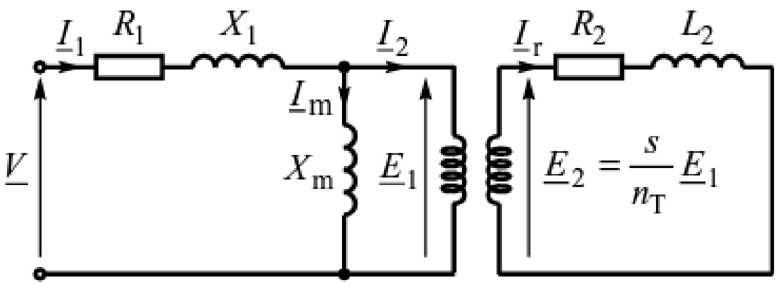


Fig. 7.11

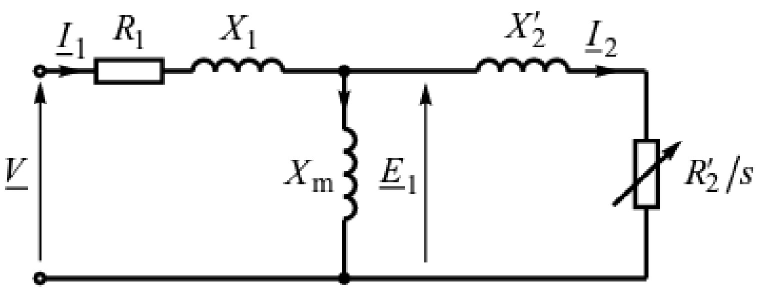
- Generator Options:

Speed range	Passive stall control	Pitch control
Fixed	Figure 7.6	Figure 7.6
Small	—	Figure 7.7
Limited (±30 %) – partially rated converter	—	Figure 7.9
Large – fully rated converter	—	Figures 7.8, 7.10 and 7.11

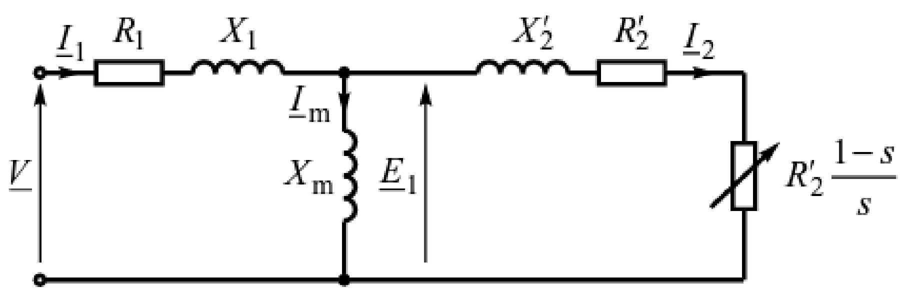
Induction motor equivalent circuit



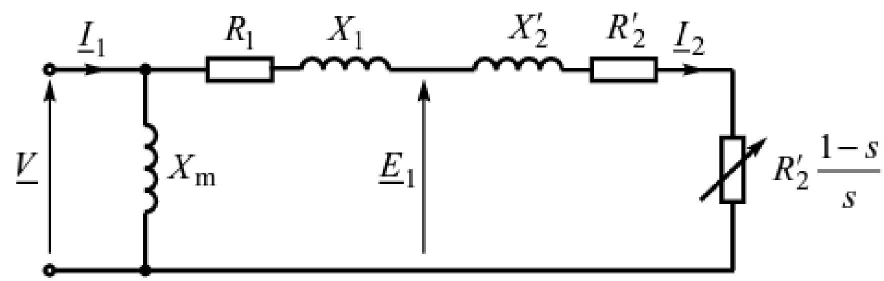
(a)



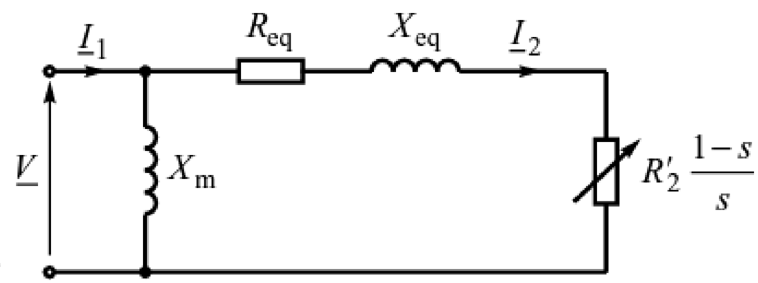
(b)



(c)



(d)



(e)

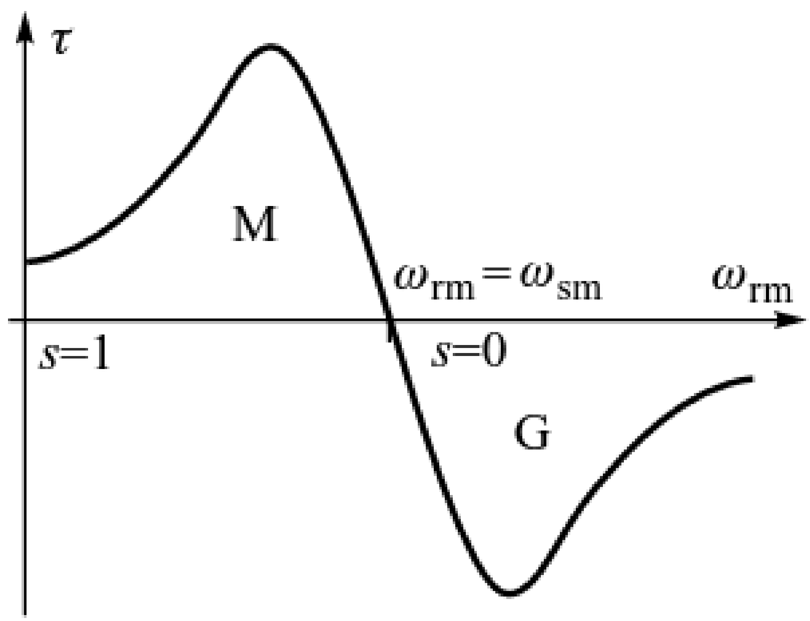
Torque-speed curve

- Mechanical power delivered to the shaft:

$$P_{\mathrm{m}} = 3 I_2^2 \frac{R_2(1-s)}{s} = P_{\mathrm{s}}(1-s) = \tau_{\mathrm{m}} \omega_{\mathrm{rm}}.$$

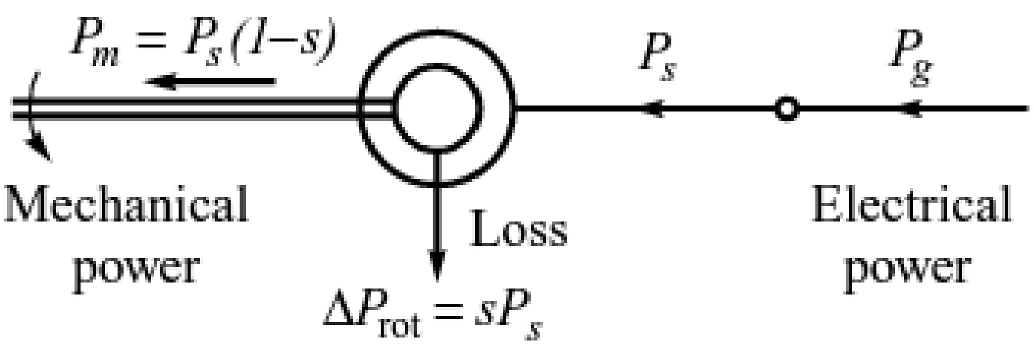
- Mechanical torque:

$$\tau_{\mathrm{m}} = \frac{P_{\mathrm{m}}}{\omega_{\mathrm{rm}}} = \frac{P_{\mathrm{m}}}{\omega_{\mathrm{sm}}(1-s)} = \frac{3}{\omega_{\mathrm{sm}}} \frac{V^2}{\left[\left(R_1 + \frac{R_2'}{s}\right)^2 + \left(X_1 + X_2'\right)^2\right]} \frac{R_2'}{s}.$$



Power flow in an induction machine

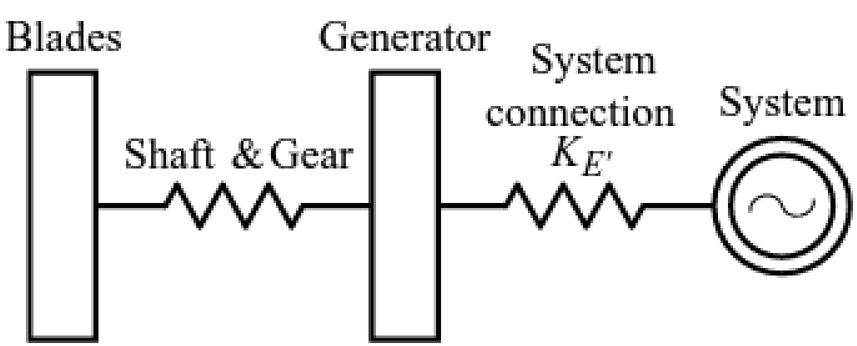
- If the losses in the stator winding resistance and iron cores are neglected, then the power supplied by the grid is the same as that supplied to the rotor.
- In the figure below, the directions are shown as positive for motor action (slip s is positive).
- for generator action (slip s is negative), P_m and P_s reverse direction, while the rotor loss remains unchanged



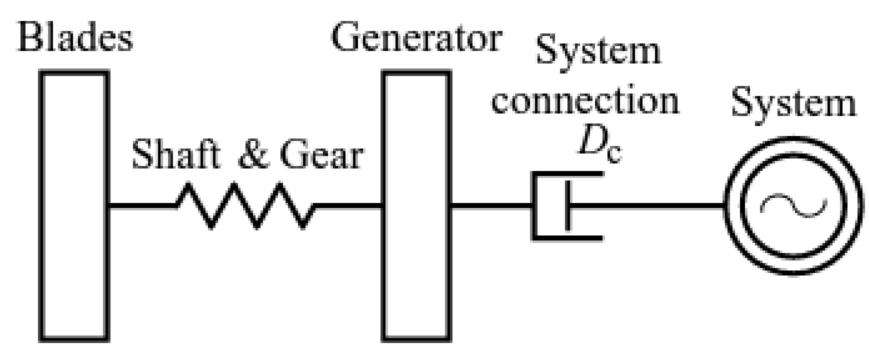
Induction generator coupled to the grid

- *Synchronous generator:* effective spring stiffness (in mass/spring/damper system) is equivalent to the synchronizing power coefficient $K_{E'}$. This creates a very stiff coupling to the network – wind turbulence can cause large stress on the drive shaft.
- *Induction generator:* “softly” coupled to the network as a it allows relative movement of the shaft speed.
  - For small slip values, the machine torque is proportional to speed deviation (this is analogous to a mechanical damper):

$$\tau_{\mathrm{m}} = \frac{3}{\omega_{\mathrm{sm}}} \frac{V^2}{\left[\left(R_1 + \frac{R_2'}{s}\right)^2 + \left(X_1 + X_2'\right)^2\right]} \frac{R_2'}{s} \approx \frac{3\,V^2}{\omega_{\mathrm{sm}}} \frac{1}{R_2'} s = D_{\mathrm{c}} \Delta\omega,$$



synchronous generator



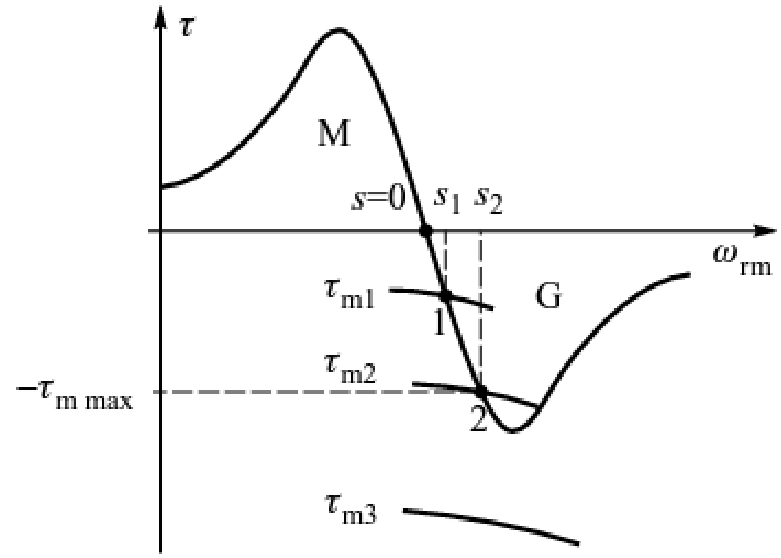
Asynchronous generator

Torque-slip curve

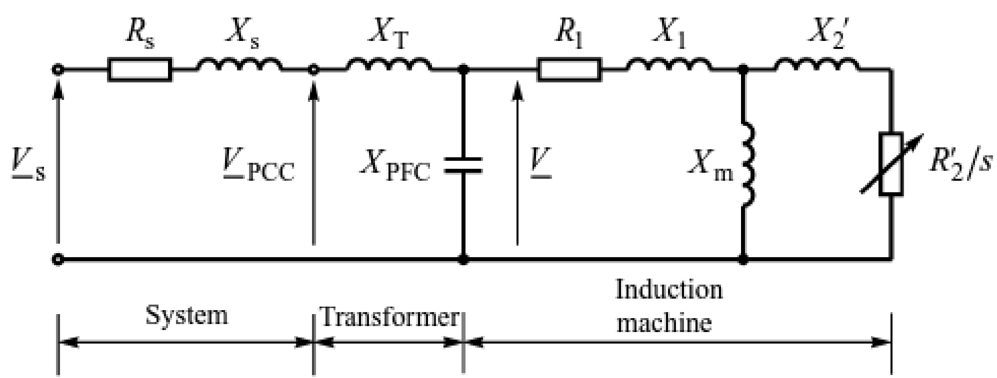
- The maximum (pull-out) torque determines the steady-state stability limit.

$$s_{\max} = \frac{R_2'}{\sqrt{R_1^2 + (X_1 + X_2')^2}} \approx \frac{R_2'}{X_1 + X_2'},$$

$$\tau_{\mathrm{mmax}} = \frac{3}{2\omega_{\mathrm{sm}}} \frac{V_{\mathrm{s}}^2}{\left[R_1 + \sqrt{R_1^2 + (X_1 + X_2')^2}\right]}.$$

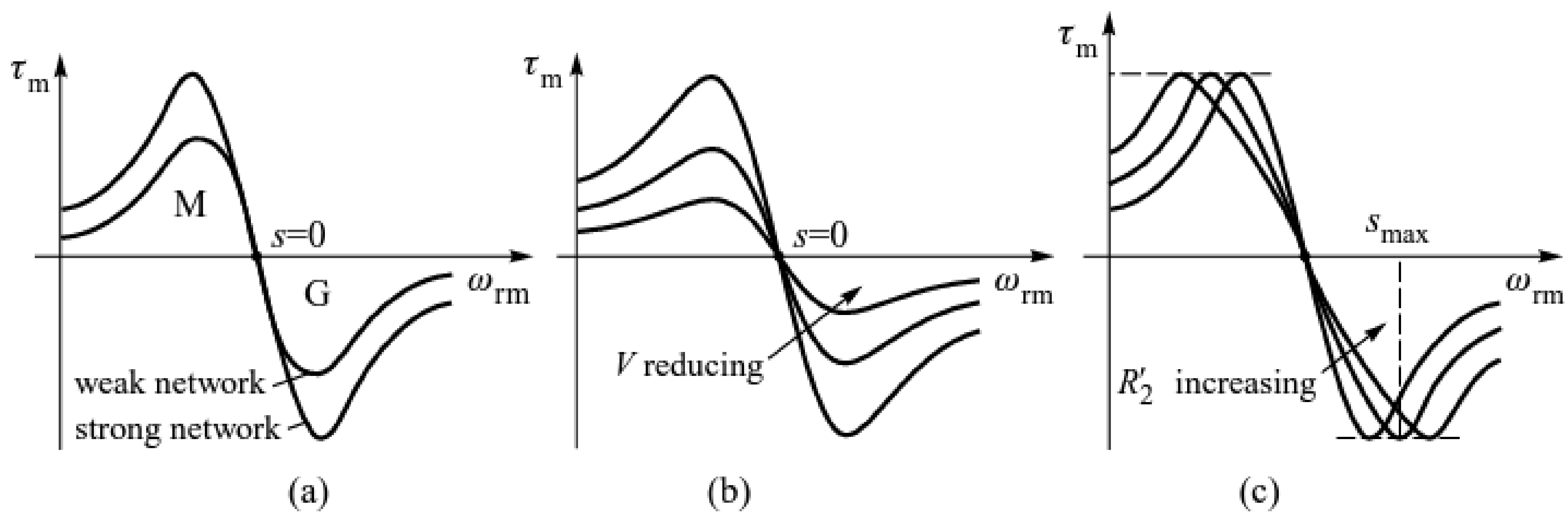


R_1 and X_1 include system impedance



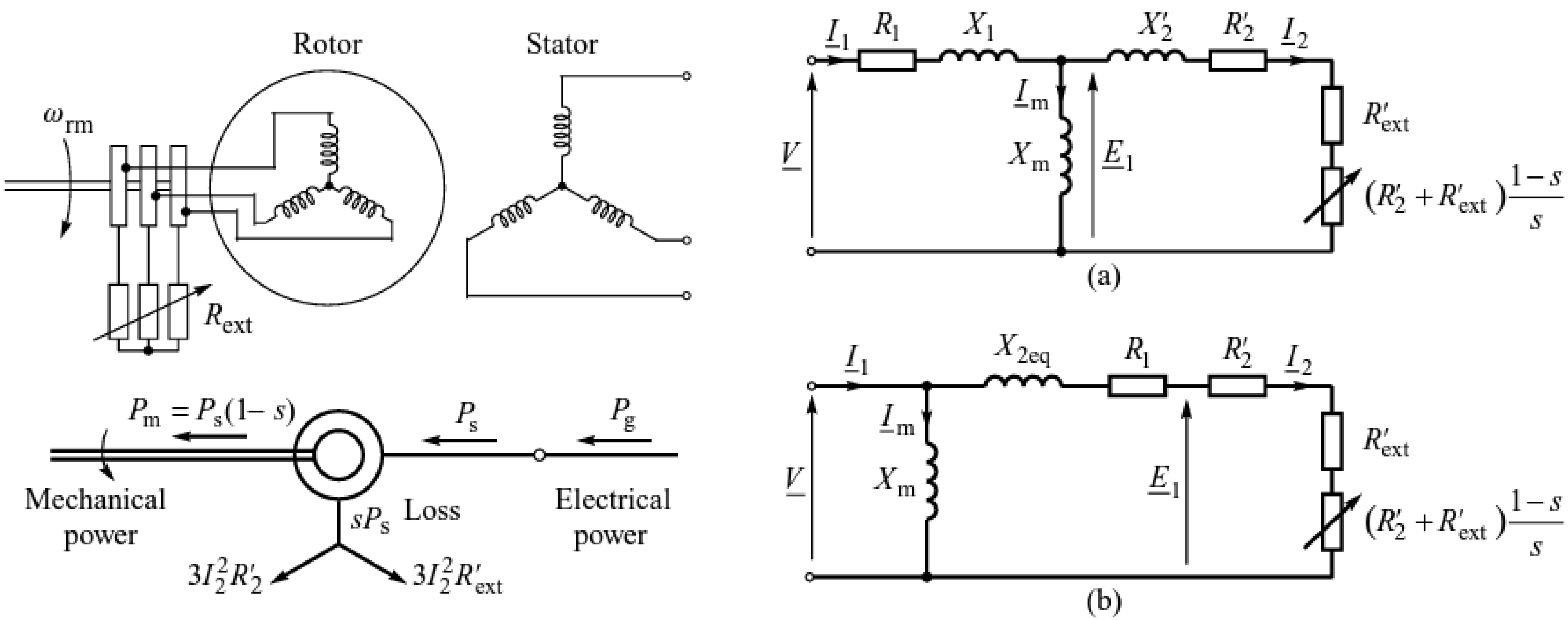
Induction generator coupled to the grid

- The maximum torque depends on X_1 (including the system reactance) and supply voltage V_s:
  - A stiff system (i.e., small X_s) results in larger max. torque
  - A weak system (i.e., large X_s) results in a smaller max. torque
  - A drop in supply voltage results in a sharp drop in max. torque
  - A larger rotor resistance does not affect the max. torque, but increases the slip at which the maximum torque occurs.



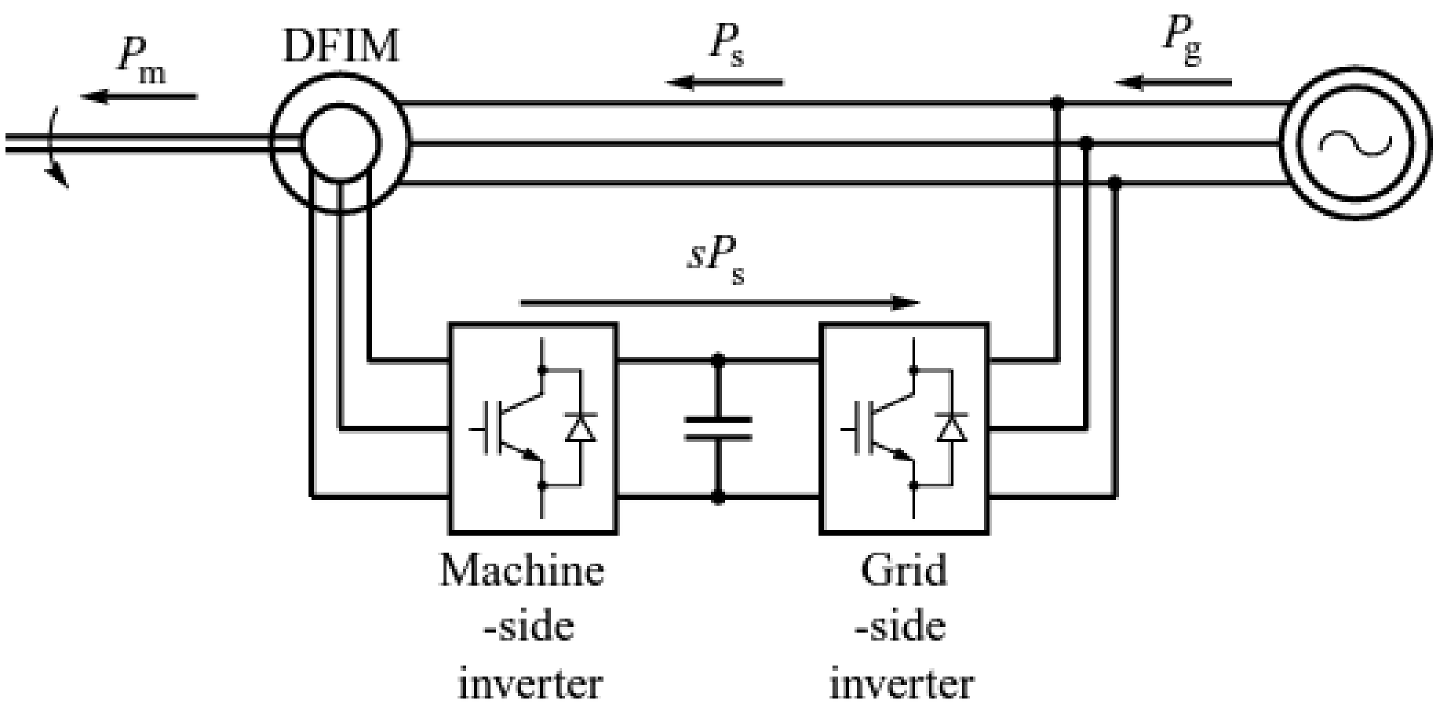
Induction generator with external rotor resistance

- This method allows and increase in speed variation..
- The gain in energy capture obtained by allowing more speed variation should be balanced against reduced efficiency.



Doubly-fed induction machine (DFIM)

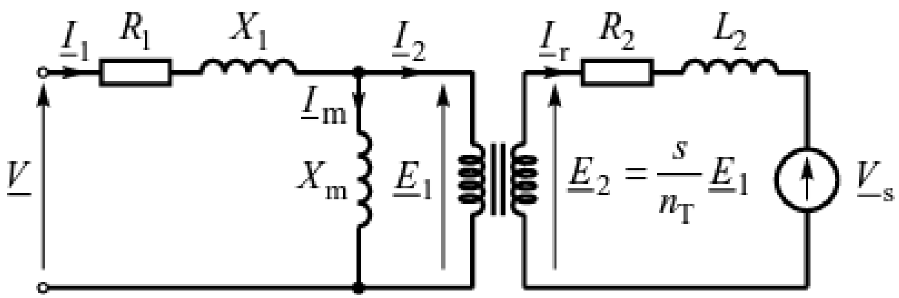
- The 4-quadrant converter can feed power to or form the rotor at any frequency or voltage.
  - The grid-side inverter is controlled to maintain constant DC link voltage
  - The rotor-side inverter injects a voltage into the rotor winding (at slip frequency) that is controlled in both magnitude and phase.



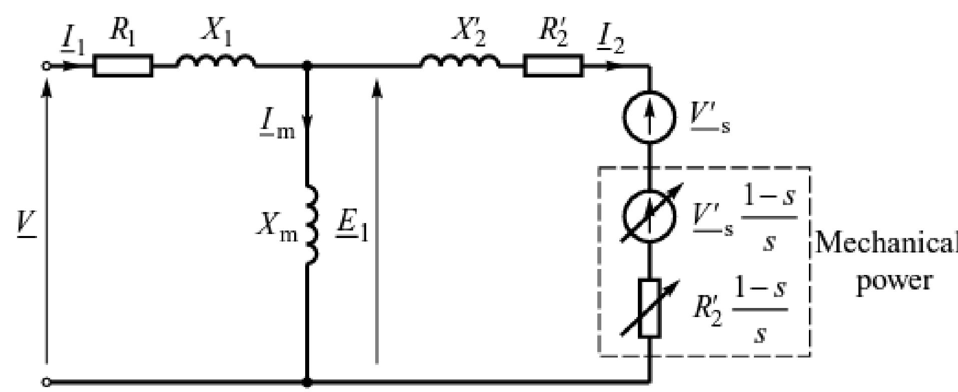
DFIM Equivalent Circuit

- V_s is the voltage injected in the rotor at slip frequency. If this voltage is in phase with the rotor current, this is equivalent to adding an external resistance.
- The rotor current and mechanical torque can be derived as before. The slip can be written in terms of the injected voltage and rotor current as

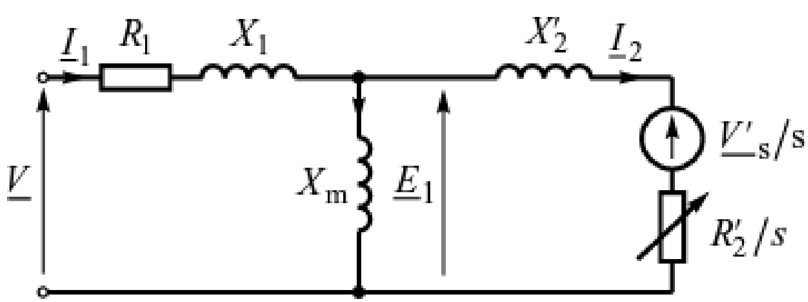
$$s = \frac{I_2 R_2' + V_s'}{\sqrt{V^2 - [I_2 X_{eq}]^2} - I_2 R_1}.$$



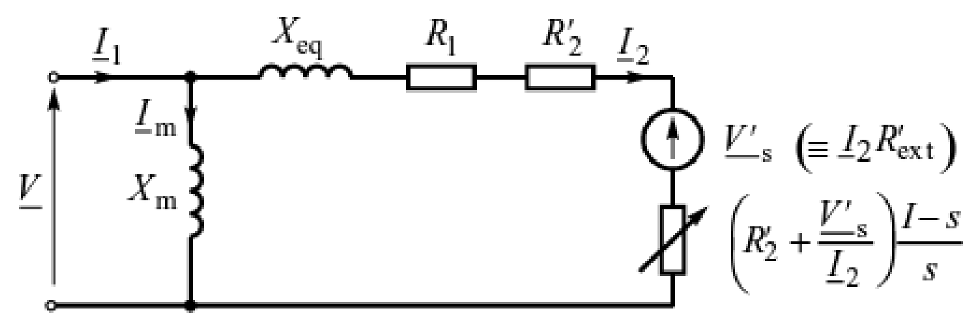
(a)



(c)



(b)



(d)

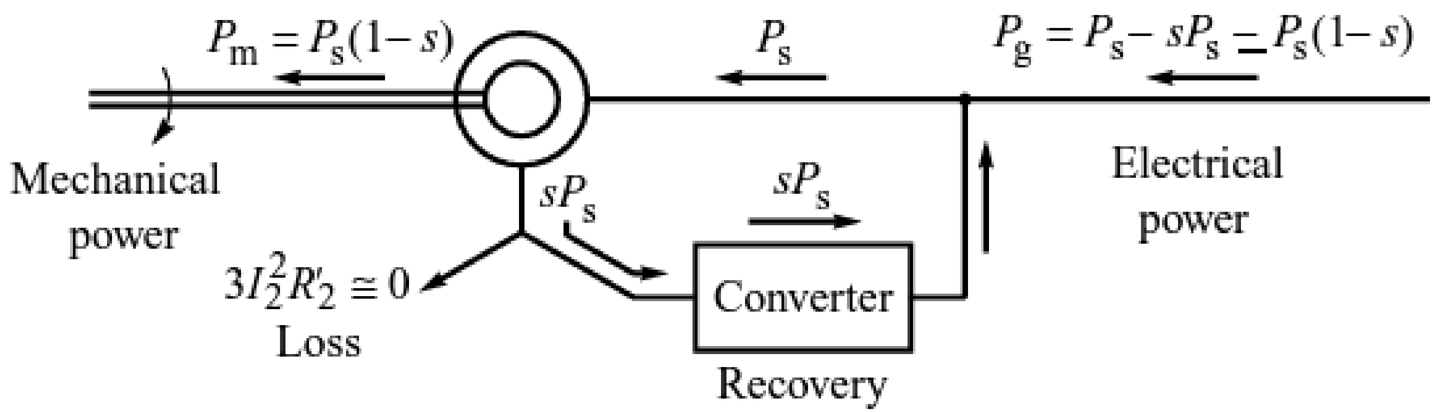
DFIM Equivalent Circuit

- If the stator winding losses are neglected, the power supplied to the machine is approximated by

$$P_s \approx P_{rot} = 3I_2^2 R_2 + 3V_s I_2 + 3I_2(V_s + I_2 R_2)\frac{(1-s)}{s} = \tau_m \omega_{sm}$$

  - The first term is the rotor copper loss, the second term is the injected power which depends on the polarity of the injected voltage (extracted from or delivered to the rotor), the third term is the mechanical power produced.

- Further, if the rotor winding resistance is neglected, then $P_g = P_m$. (i.e., 100% efficiency)

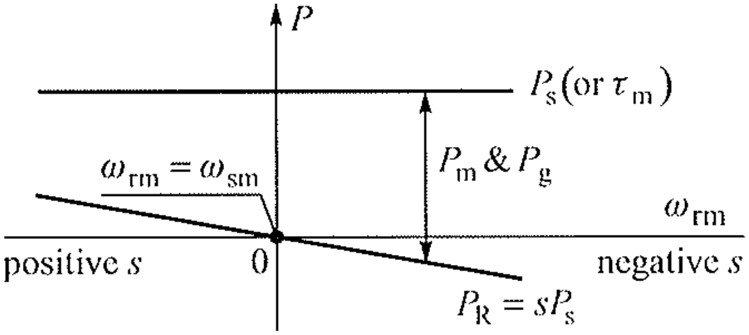


Machine operation over (+/-) 30% slip range

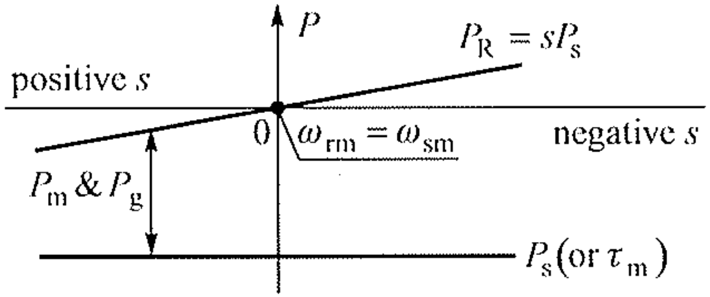
- Positive Slip:
  - Acts as a motor if power is extracted from the rotor
  - Acts as a generator if power is injected into the rotor

- Negative slip:
  - Acts as a motor if power is injected into the rotor
  - Acts as a generator if power is extracted from the rotor

- The amount of injected/extracted power determines the stator power and machine torque. Furthermore, increasing the amount of injected/extracted power increases the torque.



Motoring



Generating

DFIM as a synchronous generator

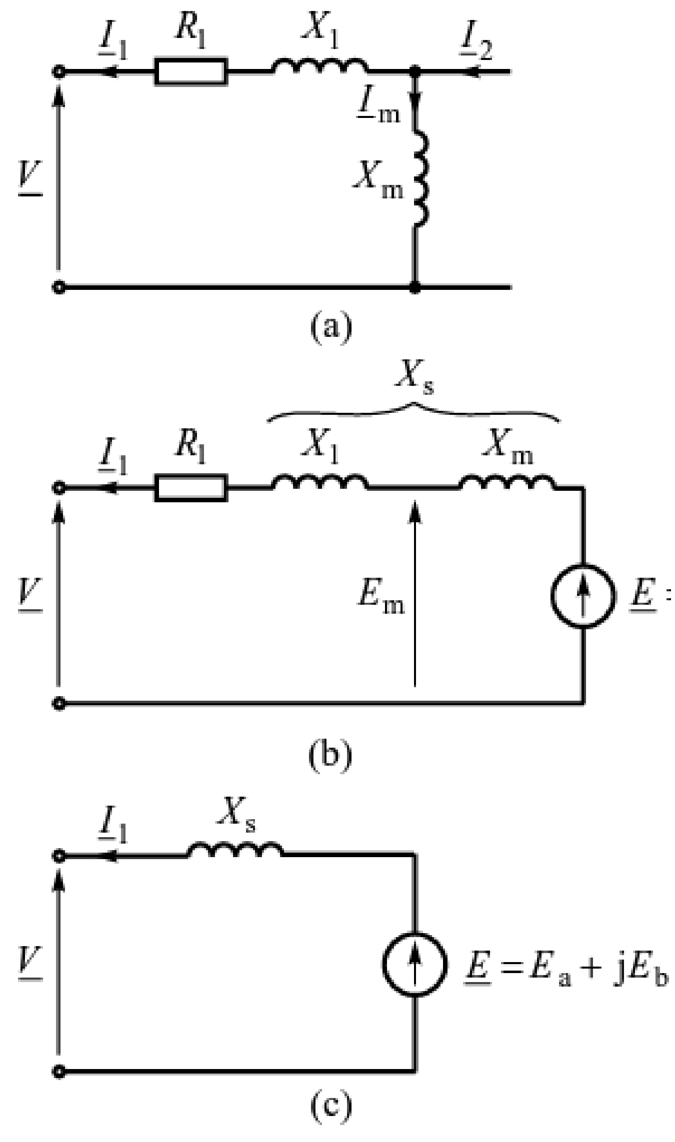
- In a SG, the DC current is fed in the rotor circuit to produce the synchronously rotating field.
- In the DFIM current is fed in the rotor circuit at slip frequency in order to produce the synchronously rotating field.
- The voltage across the magnetizing reactance can be written as

$$\underline{E}_{\mathrm{m}} = \mathrm{j}\underline{I}_{\mathrm{m}} X_{\mathrm{m}} = \mathrm{j}\underline{I}_2 X_{\mathrm{m}} - \mathrm{j}\underline{I}_1 X_{\mathrm{m}} = \underline{E} - \mathrm{j}\underline{I}_1 X_{\mathrm{m}}.$$

where

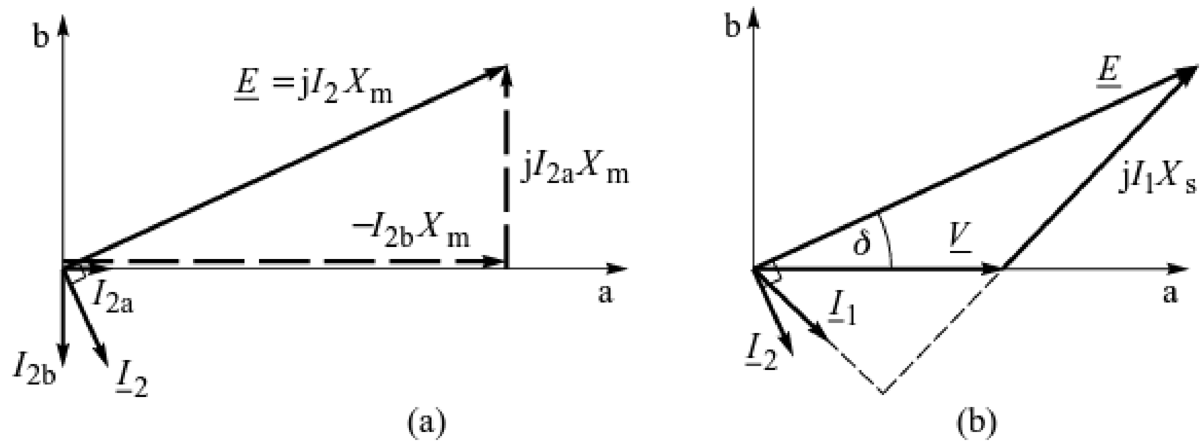
$$\underline{E} = \mathrm{j}\underline{I}_2 X_{\mathrm{m}}.$$

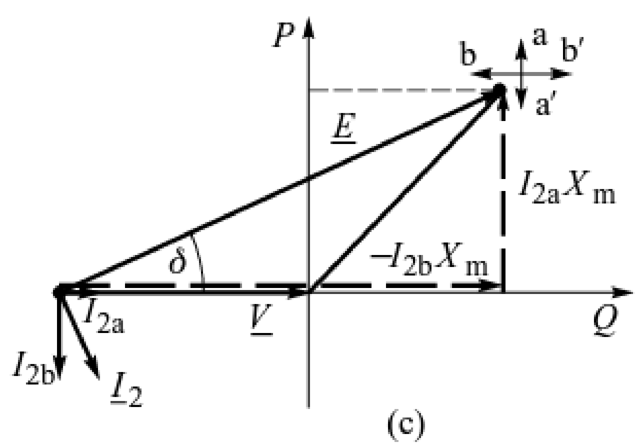
- Note that the equivalent circuit of a DFIM now resembles that of a SG. Both the magnitude and phase of I_2 (hence of E) is controlled by the injected voltage V'_s in the rotor winding.



Phasor diagram of a DFIG as a SG

- I_2 controls the magnitude and phase of E (while the field current in a SG controls only the magnitude of E).
- Machine complex power: $$S_s = \left[3\,V_a \frac{X_m}{X_s}\right] I_{2a} + j\left[\frac{3\,V_a}{X_s}\right]\left[-X_m I_{2b} - V_a\right].$$



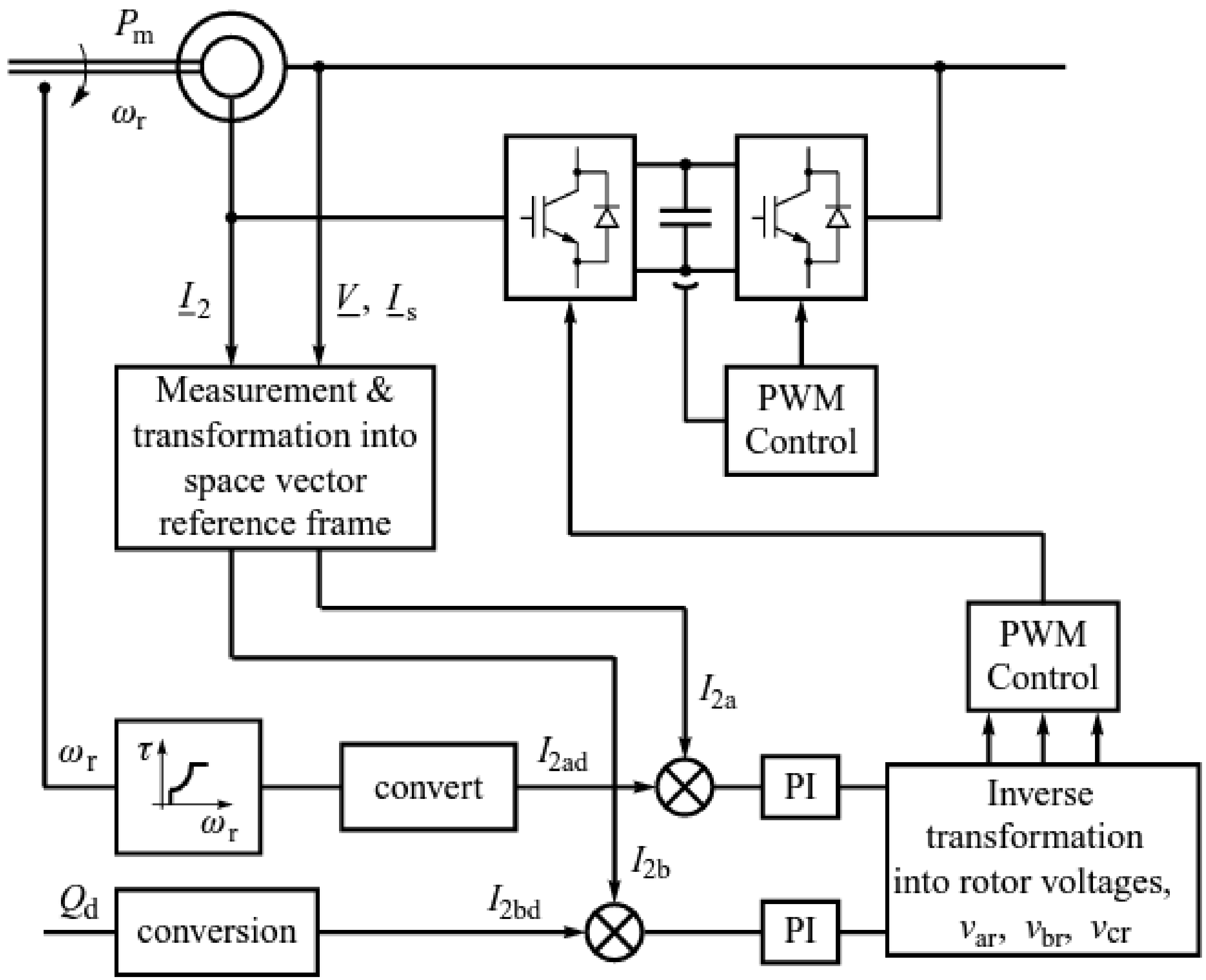


I_{2a} controls P
I_{2b} controls Q

Control strategy of DFIG

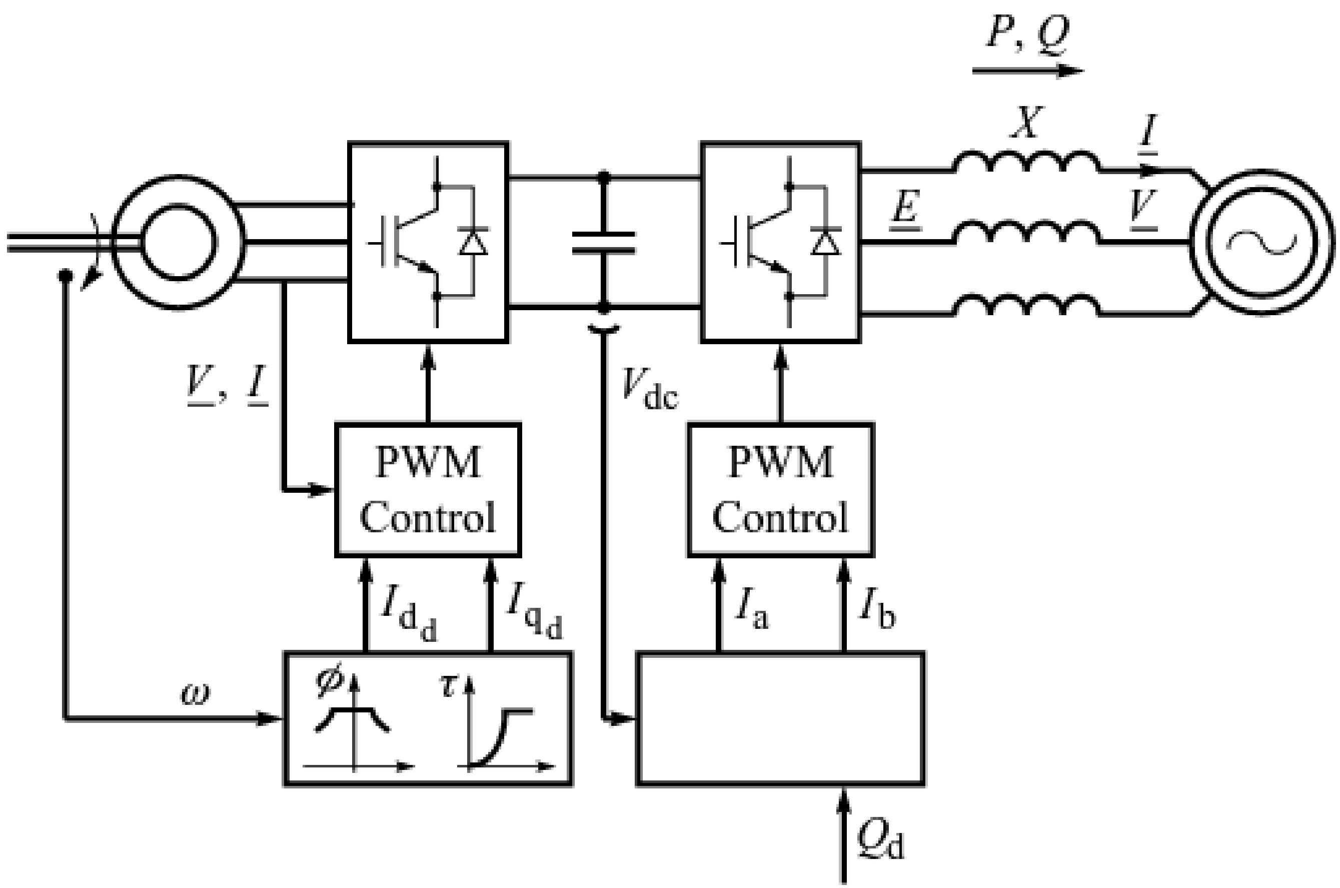
Rotor current components in terms of P and Q:

$$I_{2ad} = \frac{P_d}{3V_a}\frac{X_s}{X_m} \quad \text{and} \quad I_{2bd} = -\left[\frac{Q_d}{3V_a} + \frac{V_a}{X_s}\right]\frac{X_s}{X_m}.$$

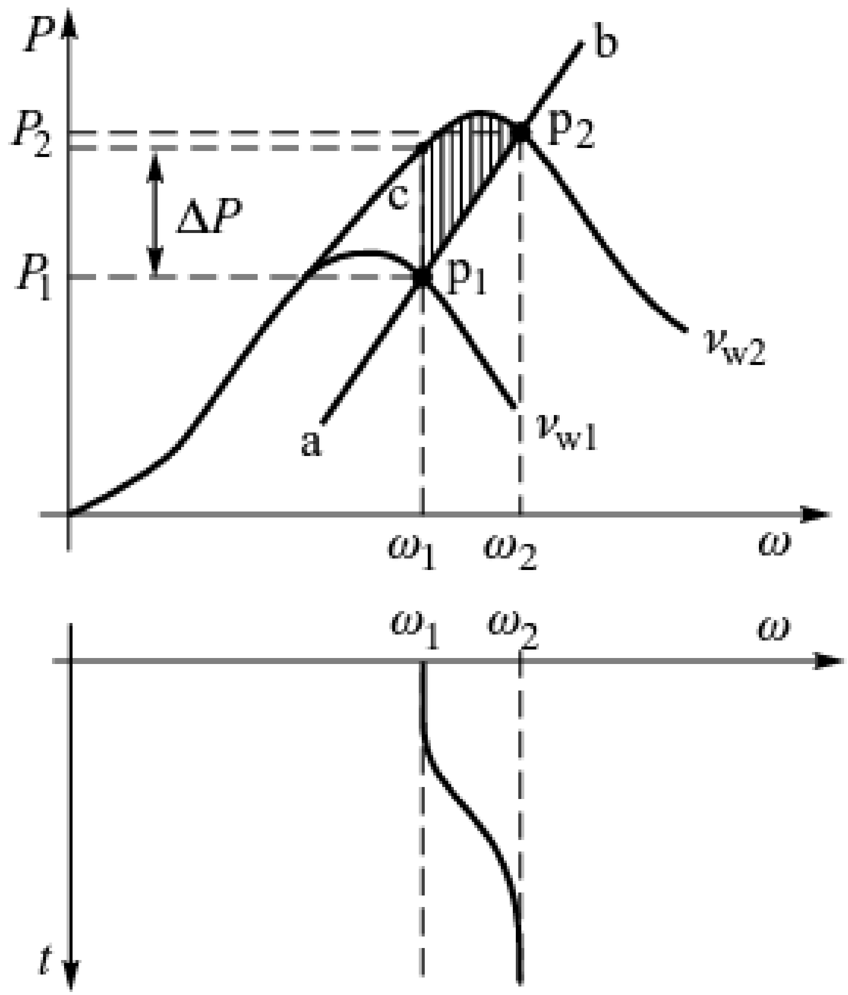


Fully rated converter systems

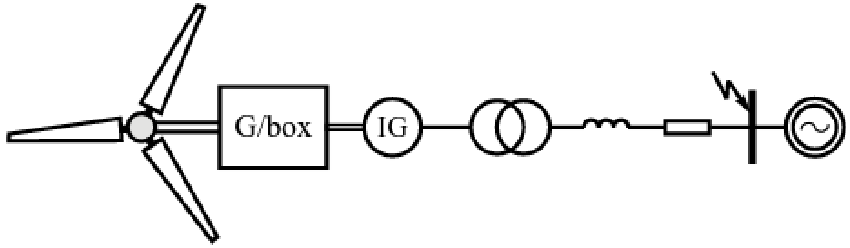
- The machine-side converter is generally operated to control the generator torque loading at a particular speed (for max power) while the grid-side inverter is operated to control reactive power and maintain constant DC bus voltage.



Peak power tracking – sudden change in wind speed



Fault behavior of induction generators



- Fixed speed induction generators consume reactive power (detrimental to voltage recovery).
  - They are disconnected from the grid as soon as a voltage drop is detected.
  - If they remain connected, then they become unstable if the fault duration is greater than t_2 (see figure to right).
- Variable speed induction generators can generate reactive power (beneficial to voltage recovery) and they can "ride through" the fault so that they can contribute to system stability (but with complex control of the power converters).