Control of Wind Turbine Generators

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EE 566, Fall Semester 2014
Colorado State University

Review from Day 1

Review

- Last time, we started with basic concepts from physics such as magnetic fields, flux, and inductance to define terms and derive magnetic equivalent circuits (MECs) for different devices.
- We examined some basic stationary devices and introduced a rotating member—giving rise to the concept of inductance that is *position dependent*.
- We then looked at cylindrical devices and introduced the concept of *sinusoidal winding distributions*.
- We showed how balanced three phase currents in sinusoidal windings give rise to a *rotating mmf*.

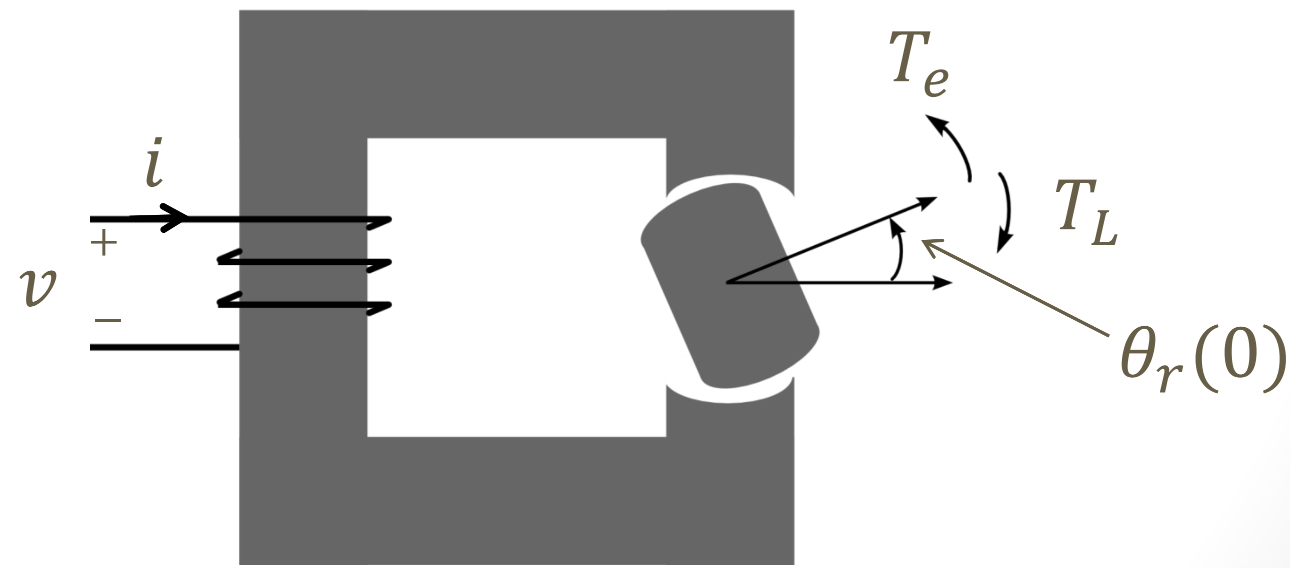
Review (continued)

- We saw how rotating *mmfs* give rise to torque in electrical machines:
  - In the induction machine, the rotating *mmf* on the stator *induces* an *mmf* on the rotor. The rotor seeks to align with the stator *mmf* which causes a torque.
  - In the permanent magnet machine, there are magnetic poles already on the rotor—these poles seek to align with the stator *mmf* giving rise to torque.

Why is EM Torque Produced?

Consider the device shown below, where the rotor position is initially fixed at a position $\theta_r(0)$ and $i = 0$.

What happens when the winding is energized? Can we *prove* what will happen?



Mathematical Derivation

Torque and Co-Energy

We can derive the following equation from fundamental energy relations :

$$\boxed{T_e(i,\theta_r) = \frac{\partial W_c(i,\theta_r)}{\partial \theta_r}}$$

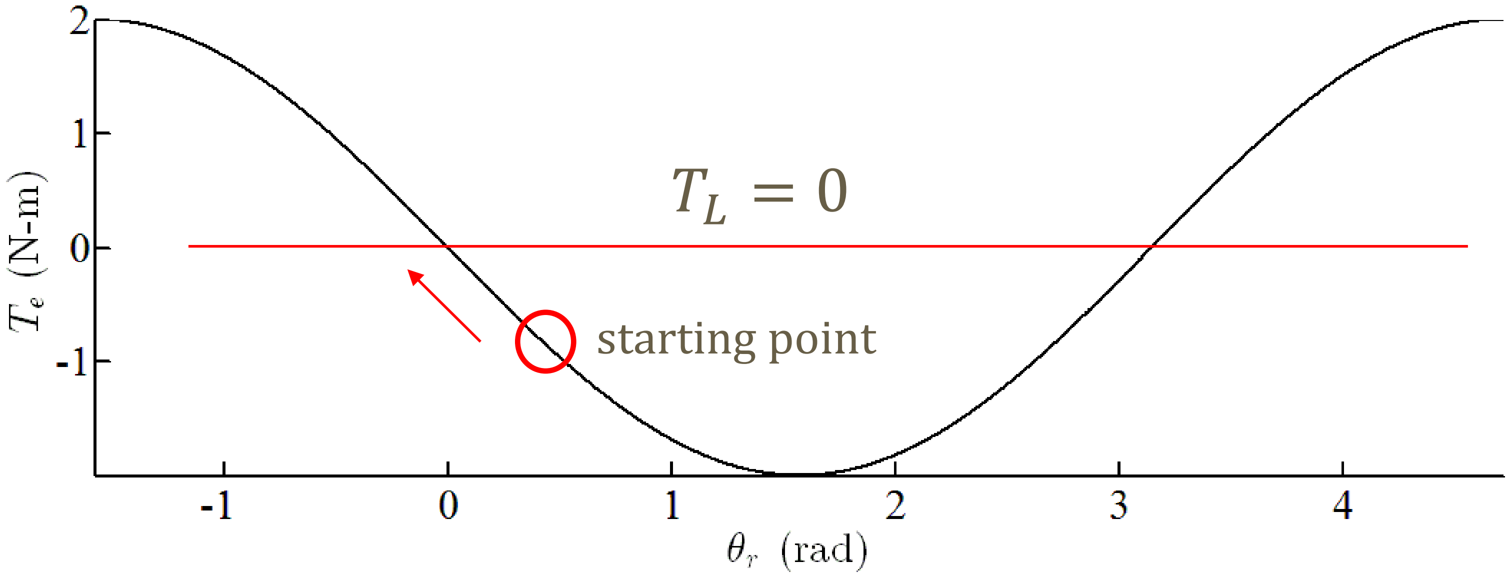
For this simple machine,

$$L(\theta_r) = L_1 + L_2 \cos\theta_r$$

$$W_c = \frac{1}{2} L(\theta_r) i^2$$

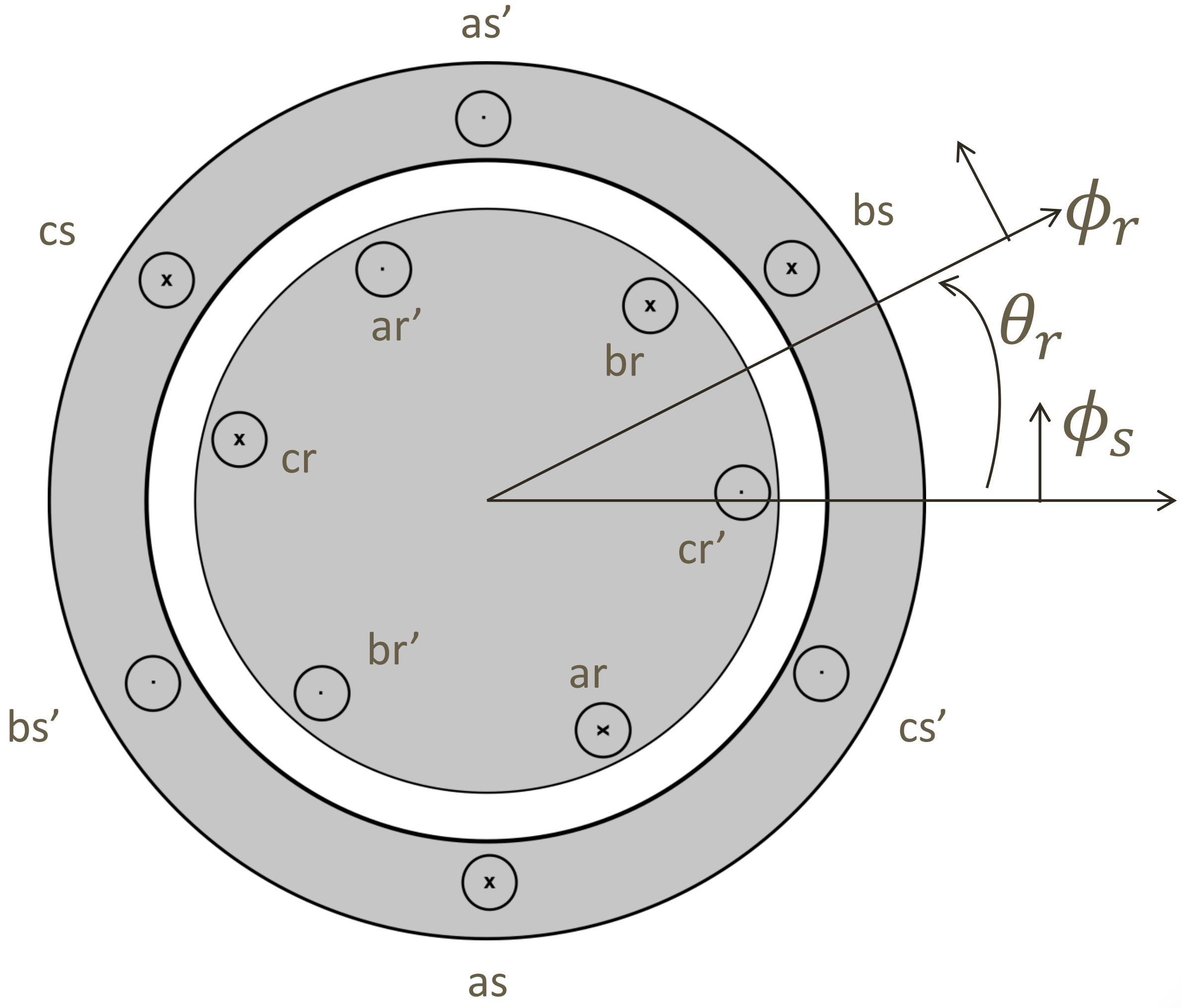
$$\Rightarrow T_e = -\frac{1}{2} L_2 i^2 \sin\theta_r$$

Torque vs. Position



We can see that with the torque relation that was derived, there will be an electromagnetic torque that pulls the rotor in the negative θ_r direction until $T_e = T_L = 0$ at $\theta_r = 0$.

Induction Machines (Review)



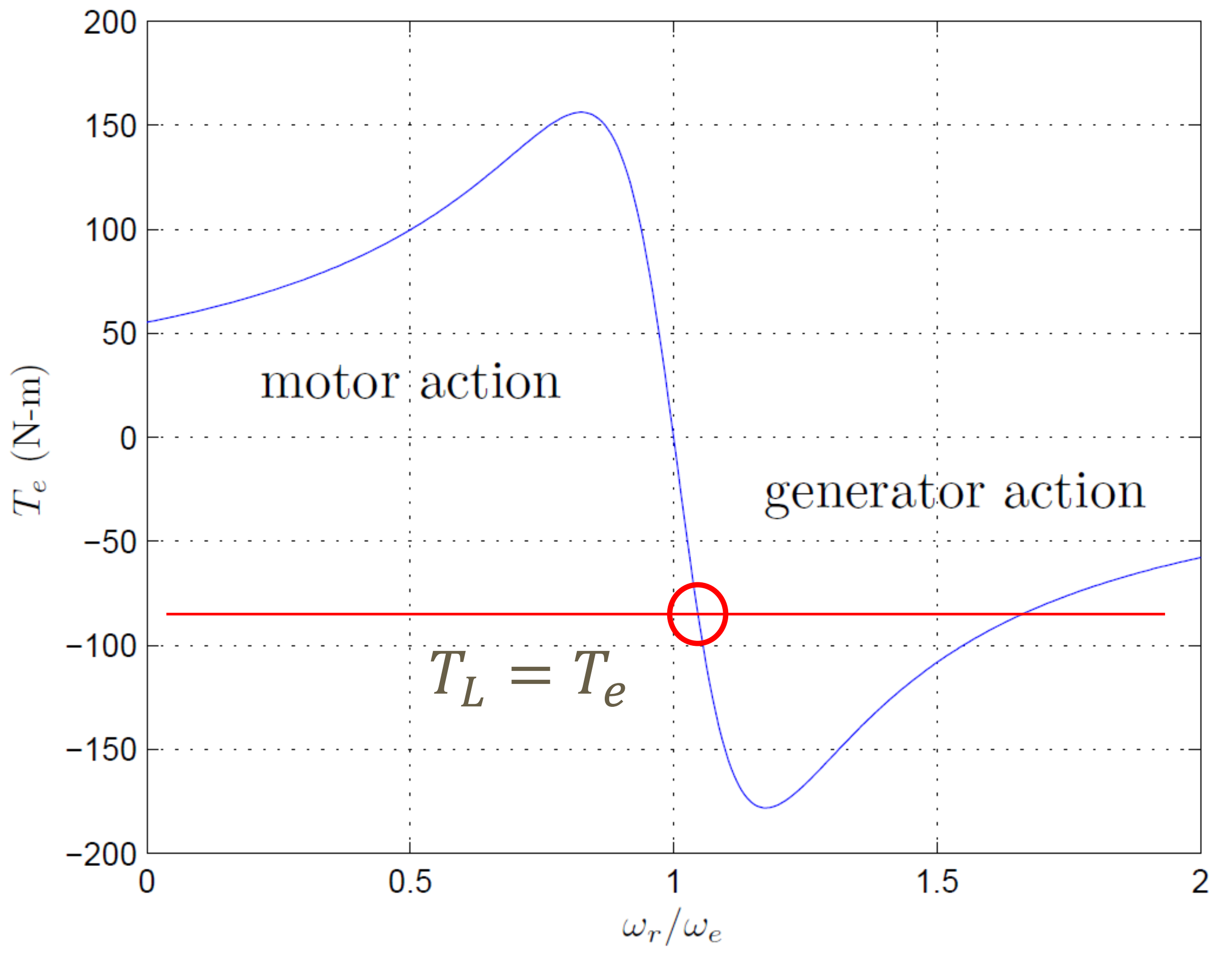
Review of Induction Machines

Summary Notes:

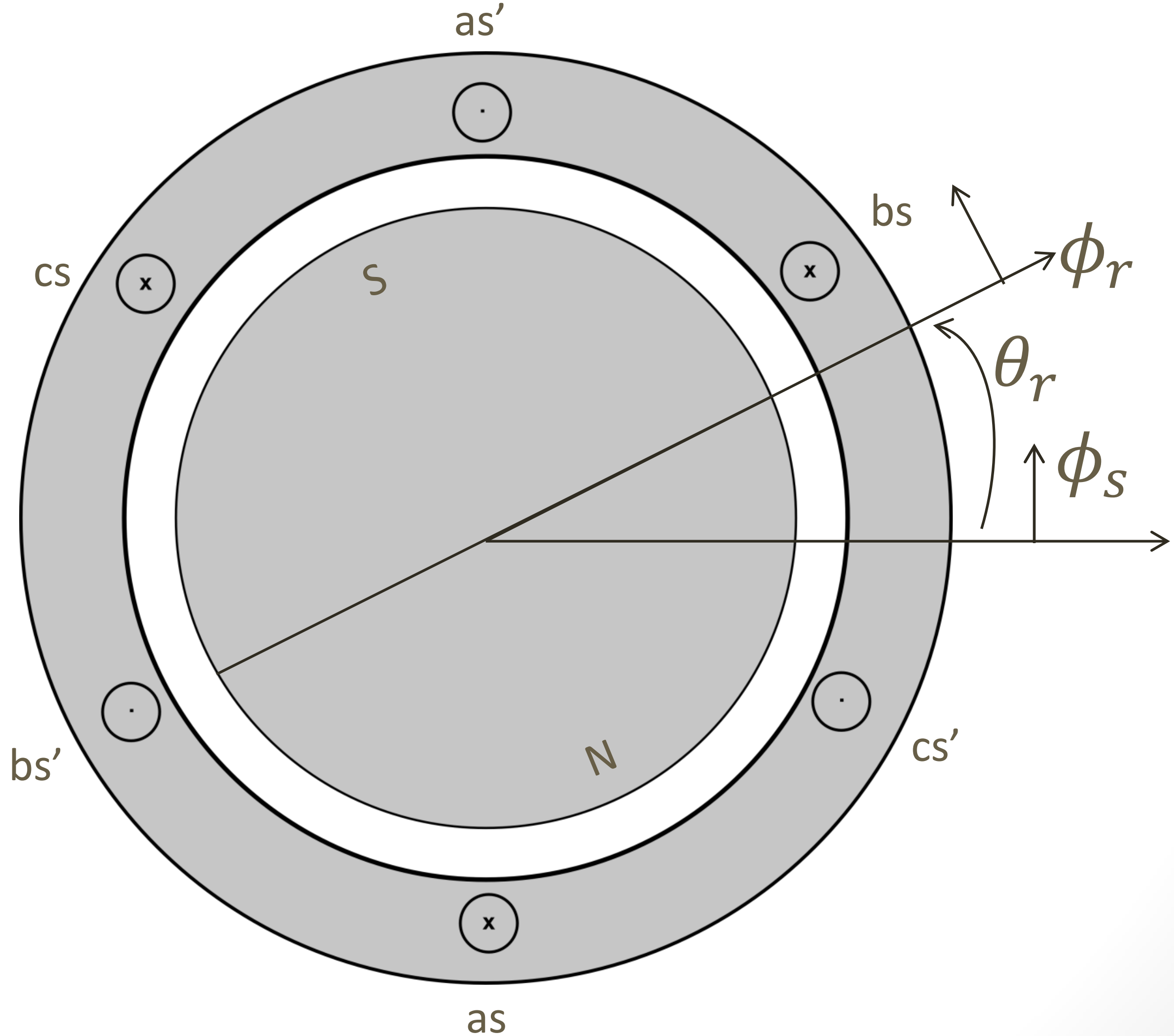
- Operates (produces torque) at speeds <u>other</u> than synchronous speed.
- Since torque-speed curve has large slope near s = 0, once machine is in steady-state, rotor speed will not vary much. It is like a "constant" speed machine.
- For steady-state analysis, use the equivalent T circuit; for transient analysis, must use full time domain equations, typically in *qd0* variables.

Induction Machines (Review)

Torque-Speed Curve



Permanent Magnet Synchronous Generators (Review)



PMSG Machine Review

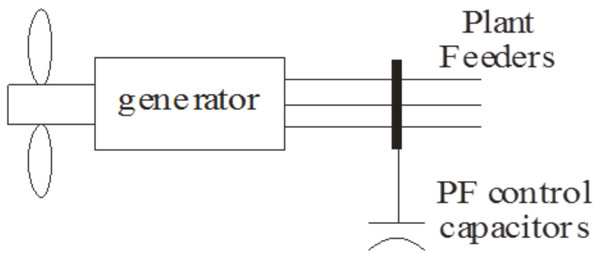
Summary Notes:

- In the PMSG, the frequency of the rotor currents is the same as the frequency of the stator currents (not true in IM machine) – hence the word "synchronous" in the title.
- Another view – by controlling the frequency of the stator currents (e.g., through power electronics) we can control the rotor speed.
- We'll see that by control of the voltage phase angle, can generate unique torque-speed curves.

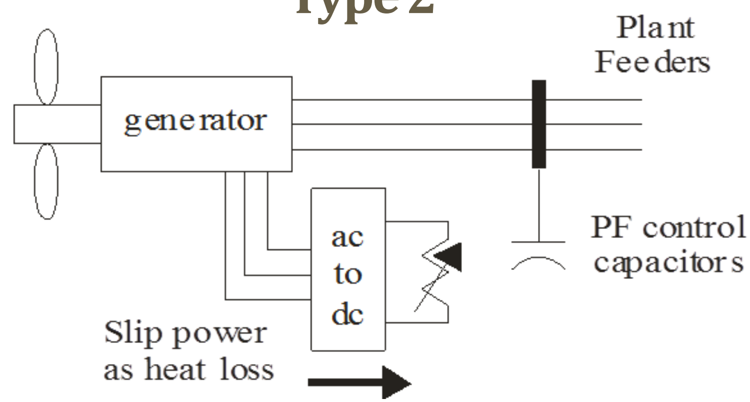
Wind Turbine Controls

Four Types of Wind Turbine Generators

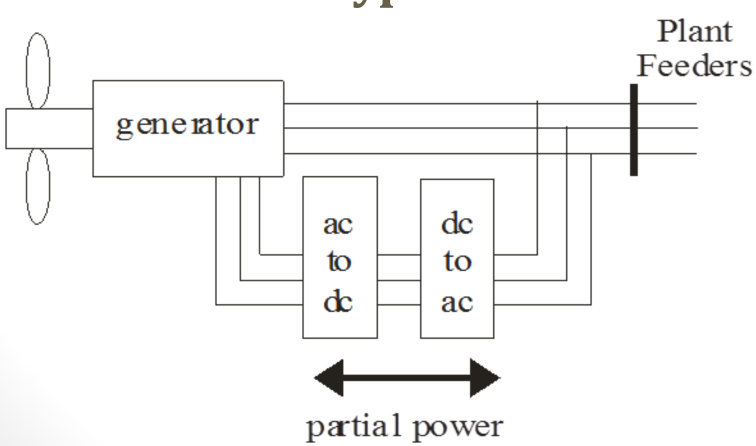
Type 1



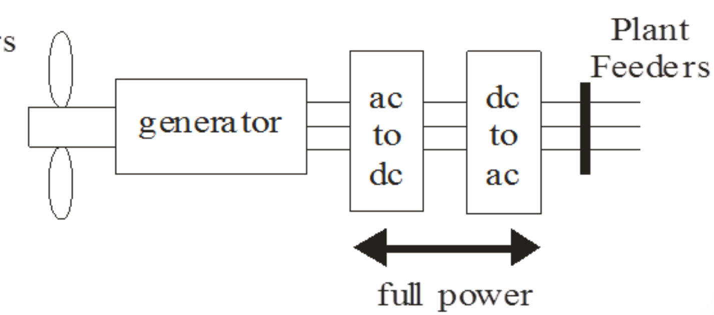
Type 2



Type 3

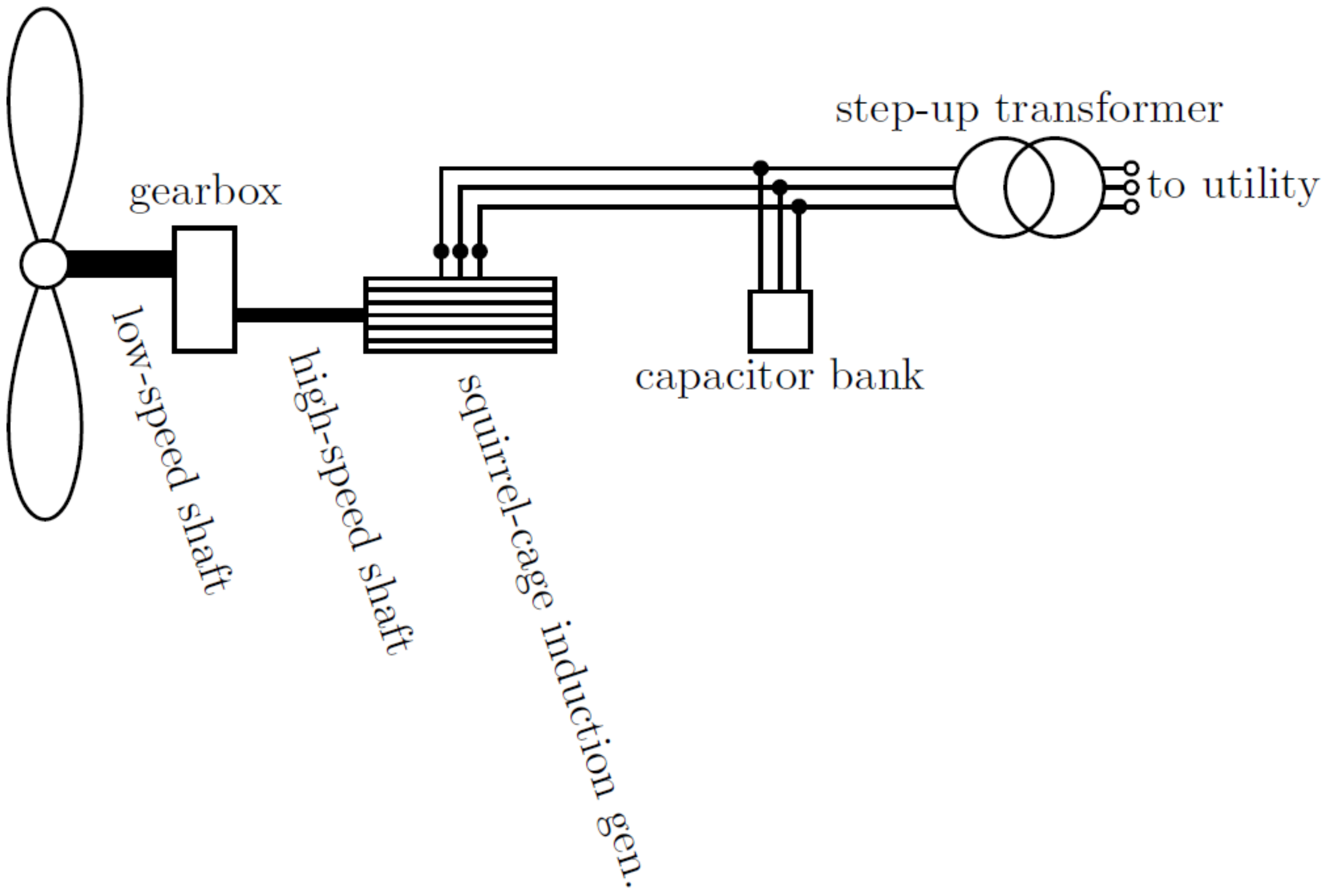


Type 4

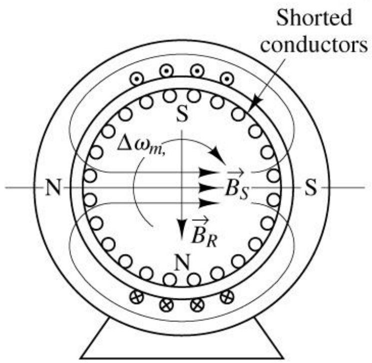


Type 1 Topology

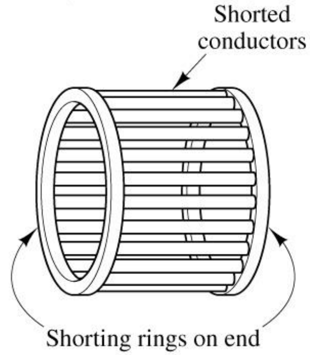
Squirrel-cage induction machine



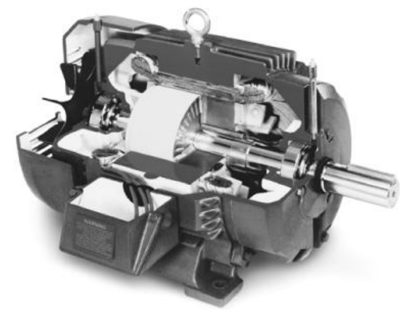
Squirrel Cage Induction Machine



(a)



(b)



(c)

(d)

(a) Squirrel cage induction motor; (b) conductors in rotor; (c) photograph of squirrel cage induction motor; (d) views of Smokin' Buckey motor: rotor, stator, and cross section of stator (*Courtesy: David H. Koether Photography*)

Type 1 Topology

Advantages:

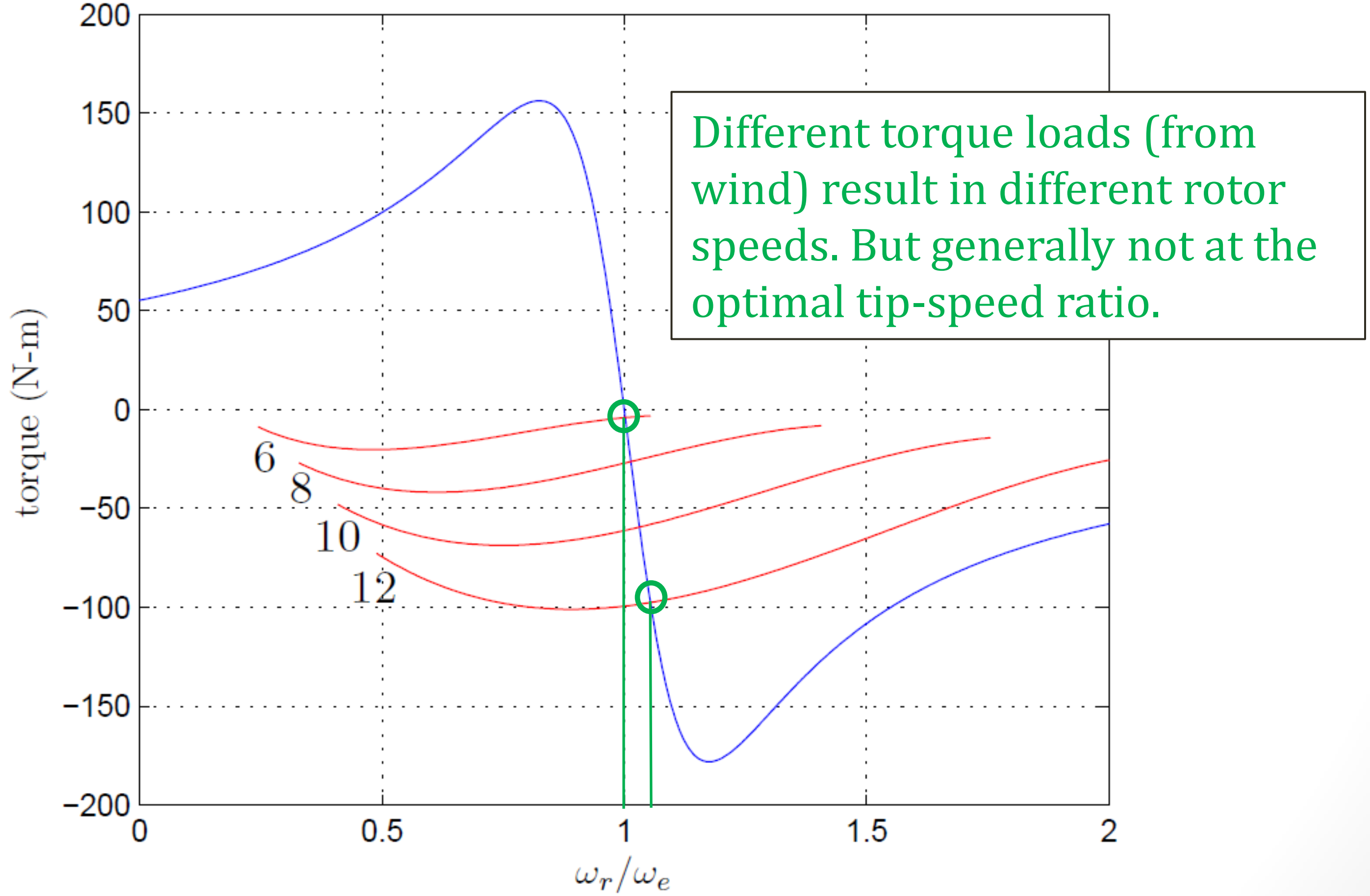
- Rugged electrical machine and simple (inexpensive) design—no power electronics.

Disadvantages:

- Can't control rotor speed—single torque-speed relation determines speed.
- Lack of rotor speed control means we are (generally) not at the optimal tip-speed ratio.
- Variations in rotor speed from wind can couple directly onto electrical grid.
- Requires cap bank for improved power quality.

Induction Machines

Torque-Speed Curve with Wind Torque Load Curves



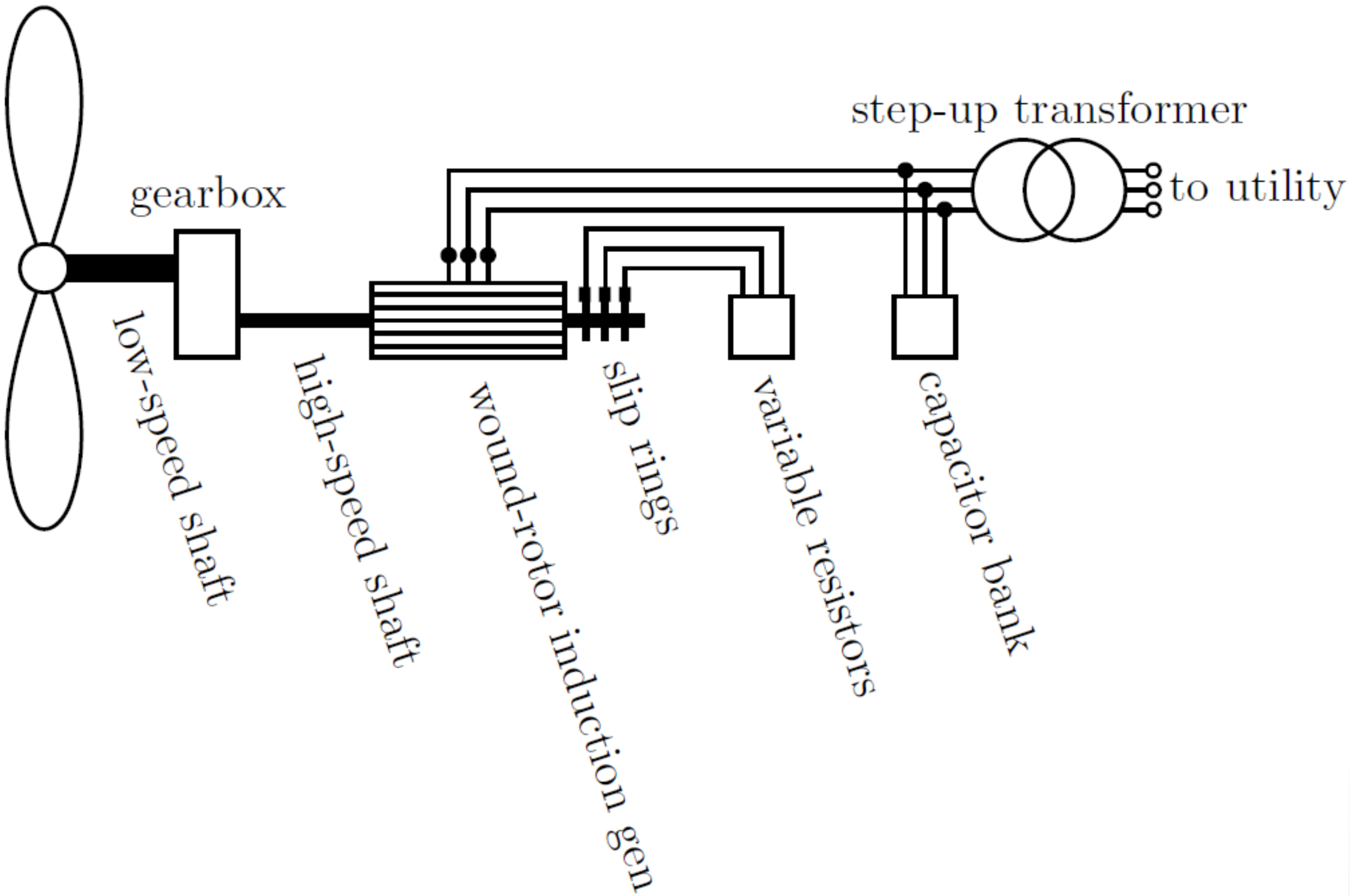
Type 1 Topology

Other Notes:

- First generation of wind turbine designs—many turbine manufacturers still use this design.
- Rotor speed varies with slip (0-2%), most rated at 1%, with max slip at 2%.
- Connected to the turbine shaft via a gear box.
- It always absorbs reactive power—in generator and motoring mode (thus requiring VAR compensation).
- Minimum absolute value of torque is reached at $s = 0$ (i.e., synchronous speed).

Type 2 Topology

Wound-rotor induction machine



Type 2 Topology

Advantages:

- Allows for some degree of rotor speed control through the use of variable rotor resistance.

Disadvantages:

- Speed control limited by range of acceptable slip values—typically 0-10%. Not optimal for wind turbine design.
- Efficiency poor at high values of slip, since more power is being lost in the rotor resistance. From (3.1) of Aliprantis' notes:

$$P_{ag} = (1 - s)P_m$$

Type 2 Topology

Disadvantages (continued):

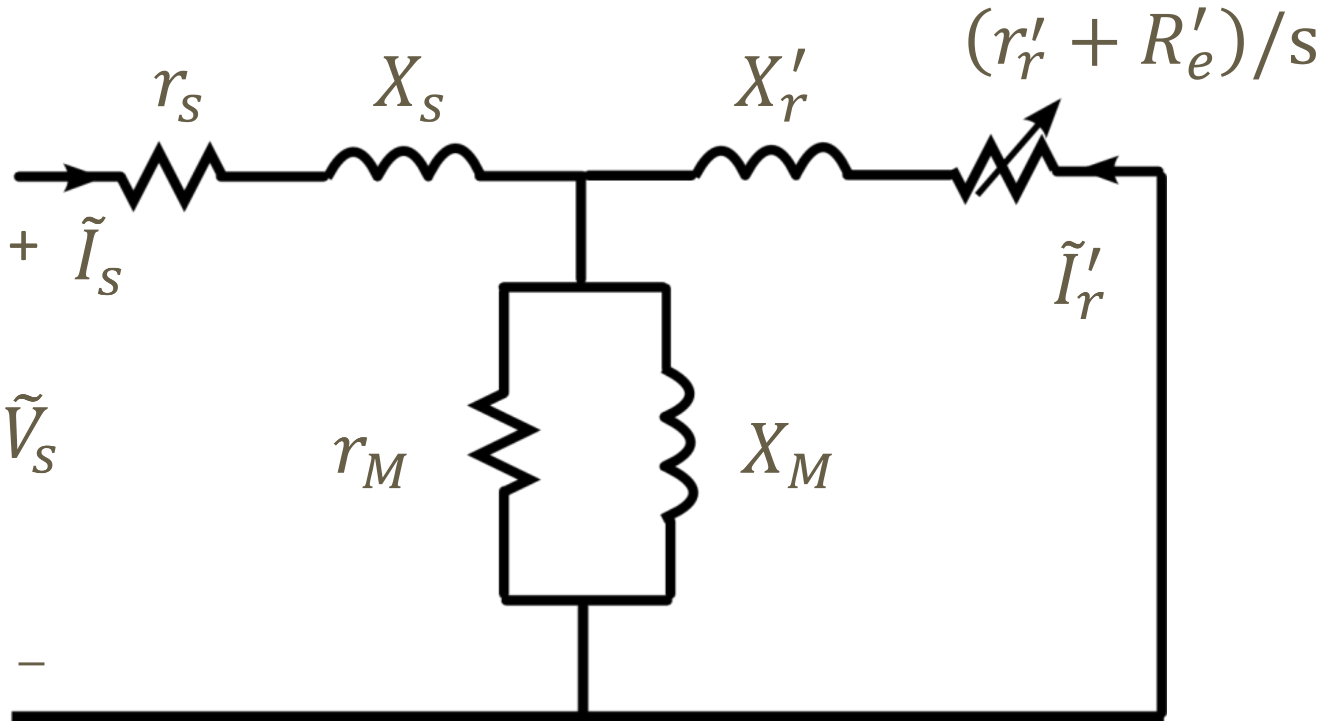
- Brushes are mechanical—require maintenance.
- Lack of refined rotor speed control means we still may not be at the optimal tip-speed ratio.
- Wind variability still coupled to grid.
- Still have power factor correcting cap bank.

Other Notes:

- Connected to the turbine shaft via a gear box.
- It always absorbs reactive power—in generator and motoring mode (thus requiring VAR compensation).

Wound-Rotor Induction Machines

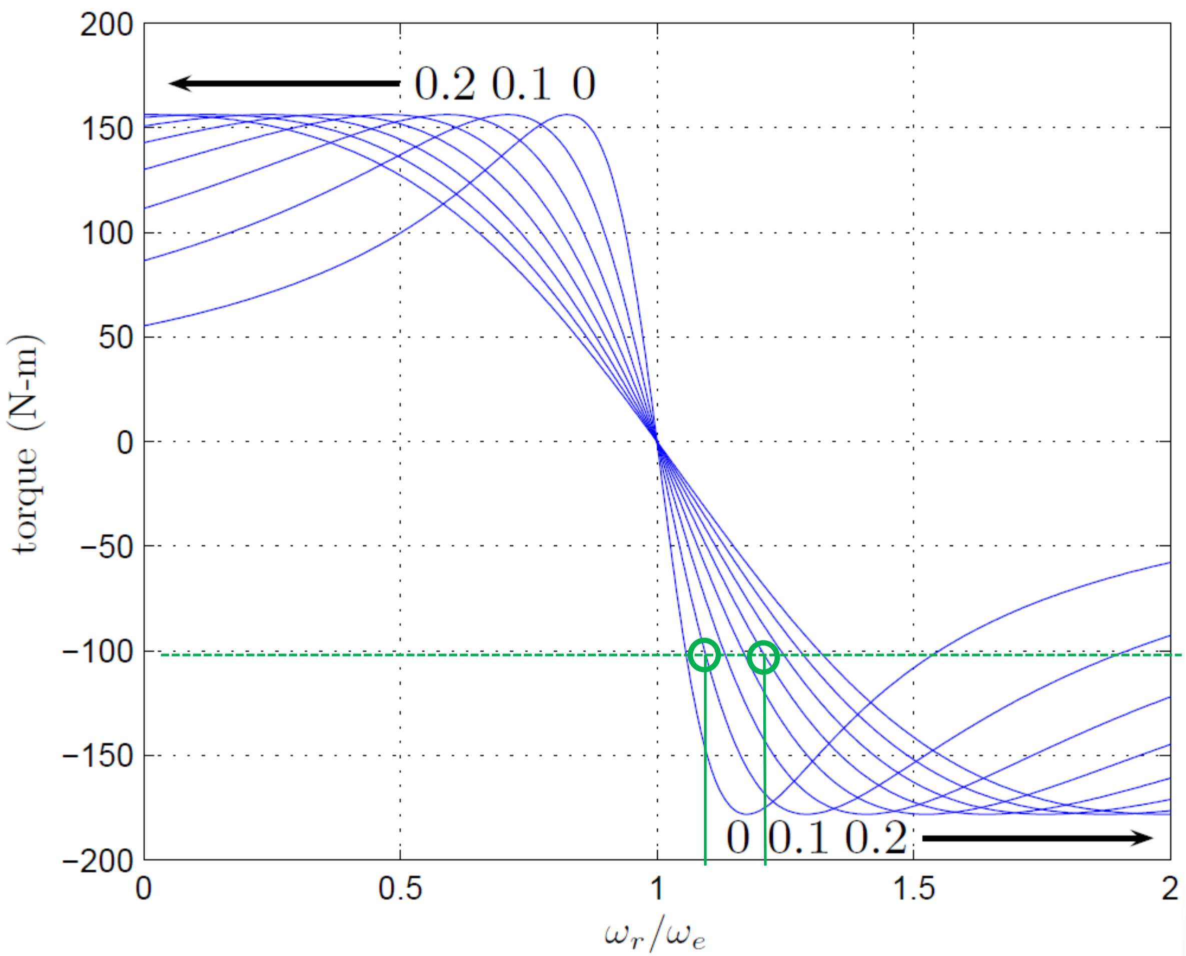
Steady-State Equivalent T Circuit – Wound Rotor



$$s = \frac{\omega_e - \omega_r}{\omega_e} = 1 - \frac{\omega_r}{\omega_e}$$

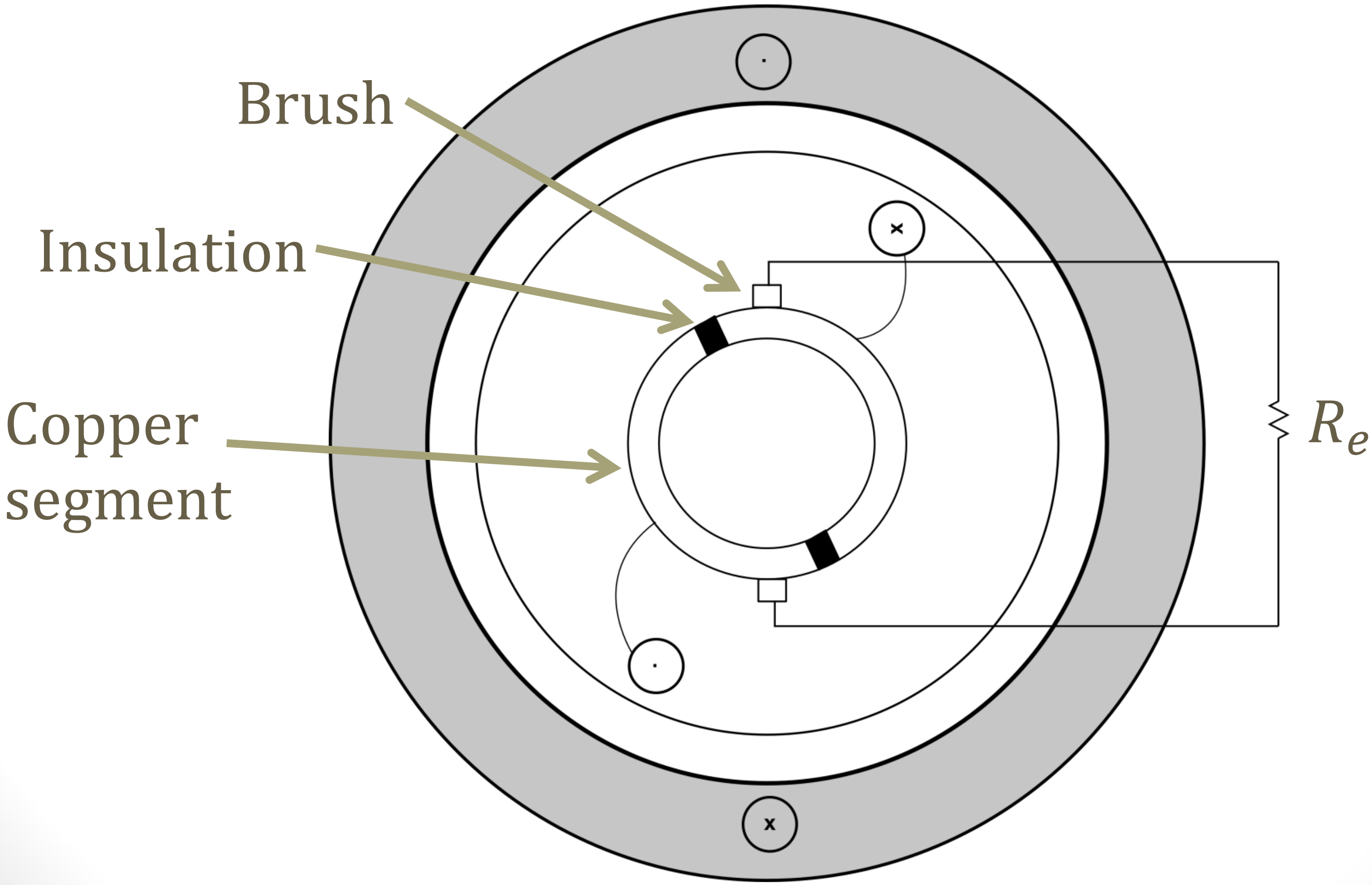
Induction Machines

Using rotor resistance to change torque-speed curve—to help achieve optimal *tip-speed ratio*.



What are Brushes?

Recall that brushes are used in some electrical machines (e.g., wound-rotor induction machines) to access the rotor winding.

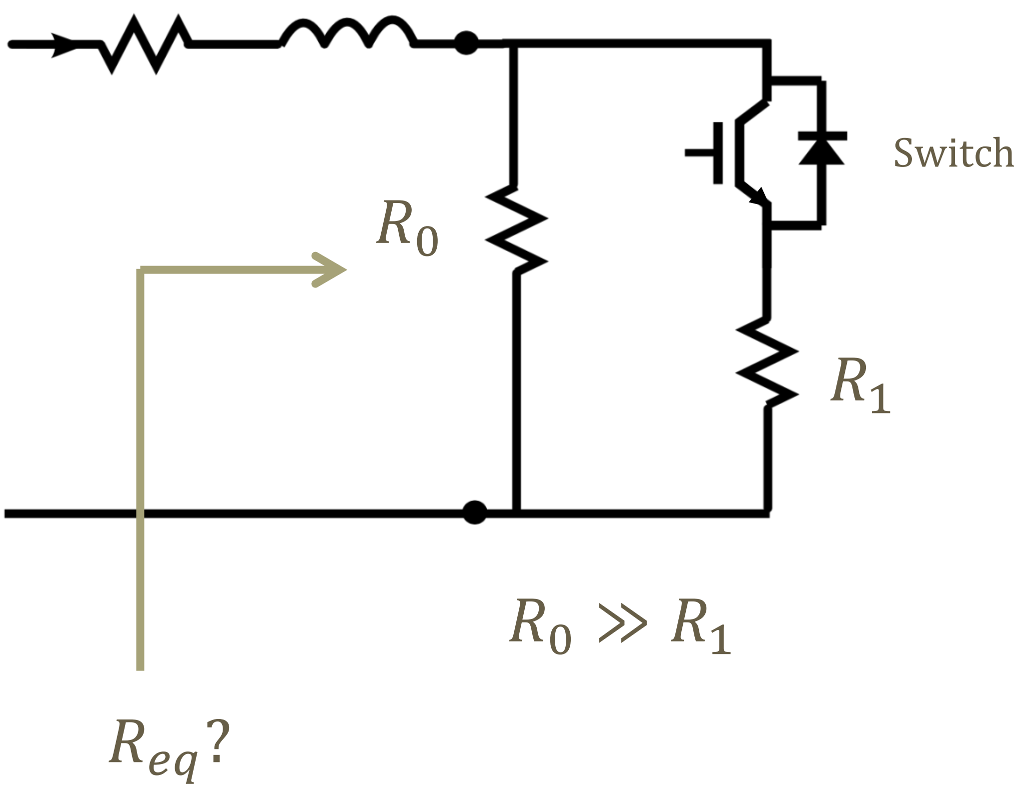


Varying Resistance using PE

To generate a family of toque speed curves, you could connect a bank of power resistors to the rotor through brushes. You could then obtain a discrete number of resistor values by series or parallel combinations of the resistors, using power electronic switches.

Another idea: could you use power electronics to get a linearly varying rotor resistance?

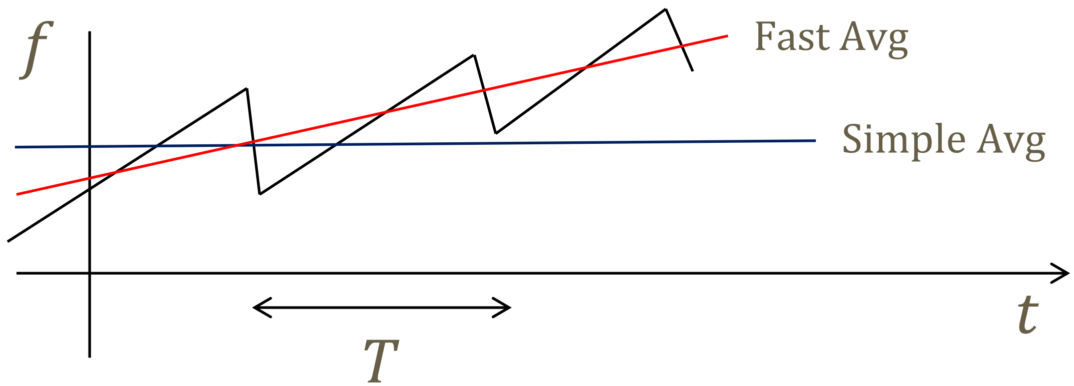
Varying Resistance using PE



When switch off: $R_{eq} = R_0$

When switch on: $R_{eq} \cong R_1$

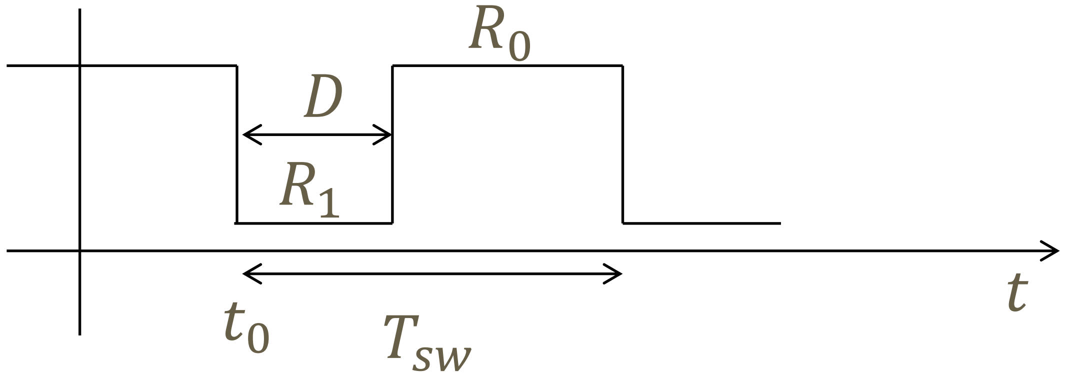
Defining the "Fast-Average"



$$\tilde{f}_{avg}(t) = \frac{1}{T}\int_{t-T/2}^{t+T/2} f(\tau)d\tau$$

The fast ("moving") average generally tracks the waveform more closely than the simple average.

Varying Resistance using PE



$$\tilde{R}_{eq} = \frac{1}{T_{sw}} \int_{t_0}^{t_0+T_{sw}} R_{eq}(\tau) d\tau$$

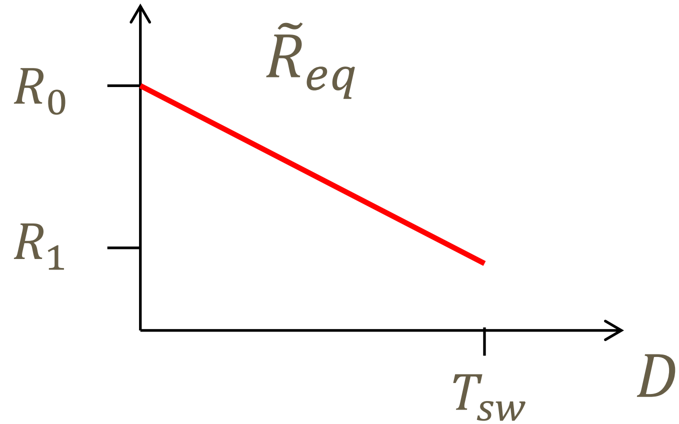
$$= \frac{DR_1 + (T_{sw} - D)R_0}{T_{sw}}$$

$$= \left(\frac{D}{T_{sw}}\right)(R_1 - R_0) + R_0$$

Varying Resistance using PE

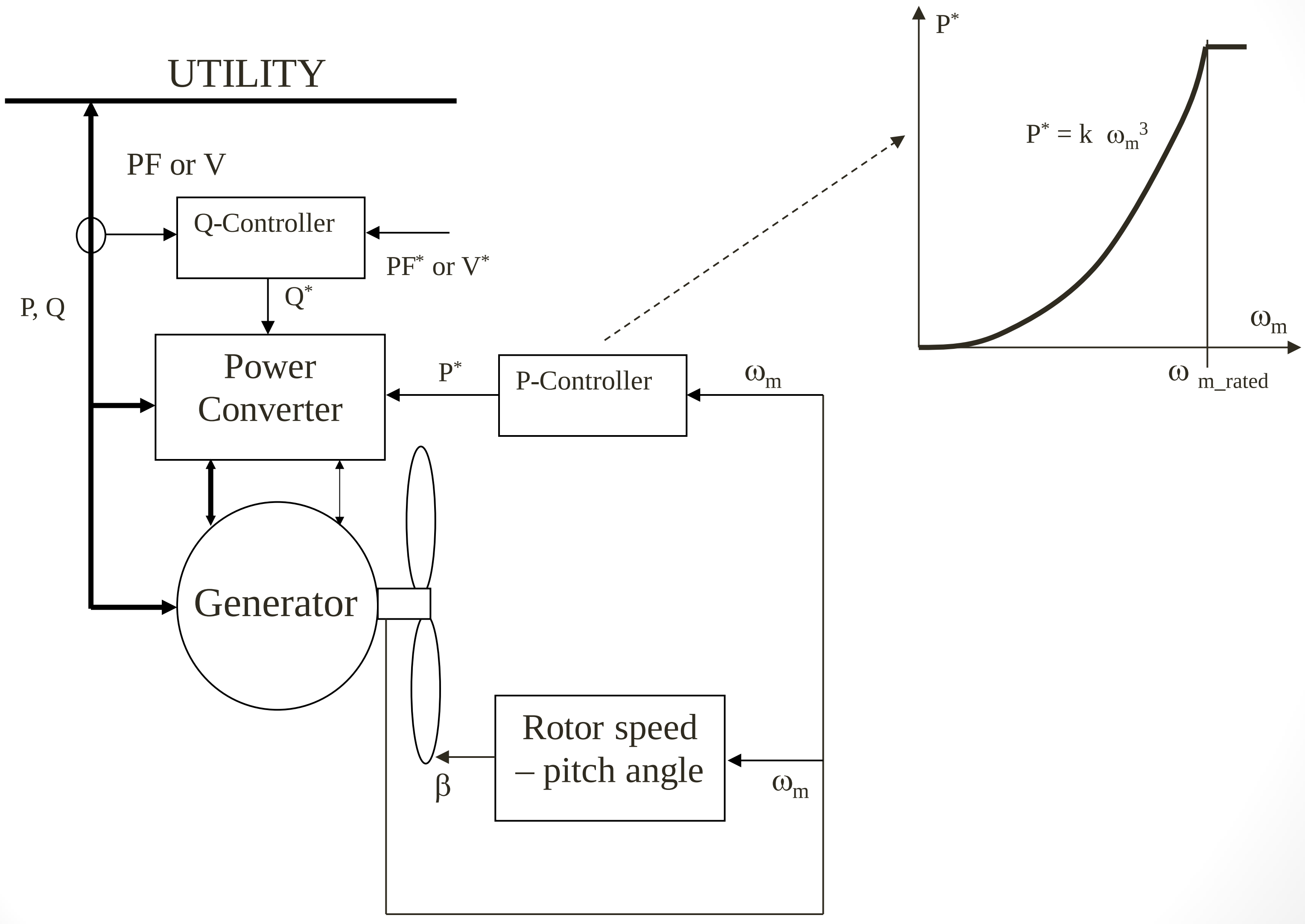
$$\tilde{R}_{eq} = \left(\frac{D}{T_{sw}}\right)(R_1 - R_0) + R_0$$

When $D = 0$, $\tilde{R}_{eq} = R_0$
When $D = T_{sw}$, $\tilde{R}_{eq} = R_1$



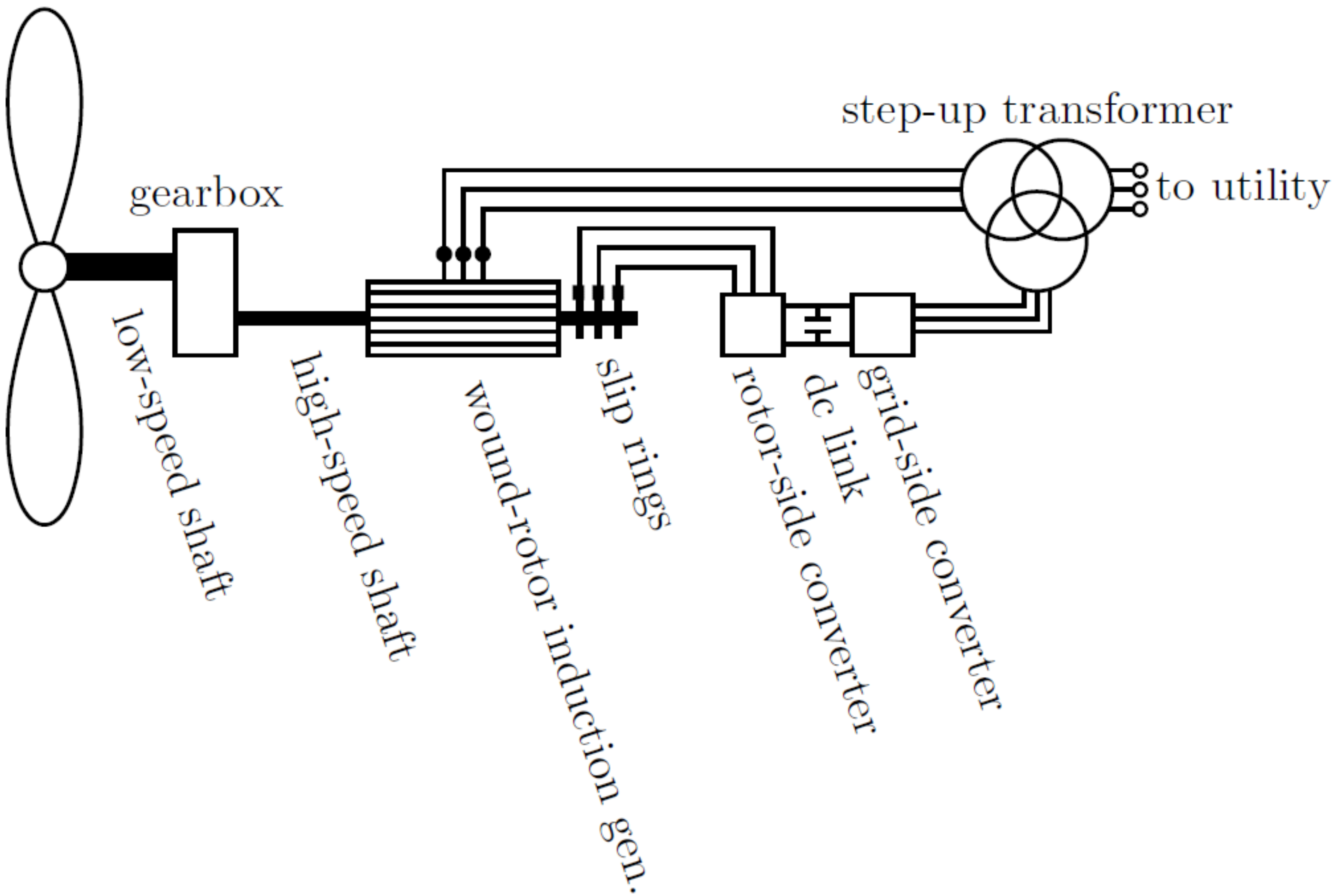
How is this useful? (a) Gives a wide variation in effective rotor resistance with two resistors, (b) Can obtain a desired torque-speed relation through closed-loop control of *D* – this corrects for temperature effects on resistance and/or brush corrosion.

Variable Speed Wind Turbines



Type 3 Topology

Wound-rotor, doubly-fed induction generator (DFIG)



Type 3 Topology

- Uses a wound-rotor induction machine, but now the rotor is connected to the grid through an *ac-dc-ac* power electronic link.
- The power electronic link is composed of two bi-directional converters, connected through a dc link (capacitor).
- These converters are referred to as the rotor-side converter (connects the rotor circuits to the dc link) and the grid-side converter (connects the dc link to the grid).

Rotor-Side Converter

- Controls the frequency of the rotor currents to maintain synchronism between the rotor and stator rotating *mmfs*.
- Controls the magnitude and phase of the rotor currents—which controls the real and reactive power delivered to the grid.

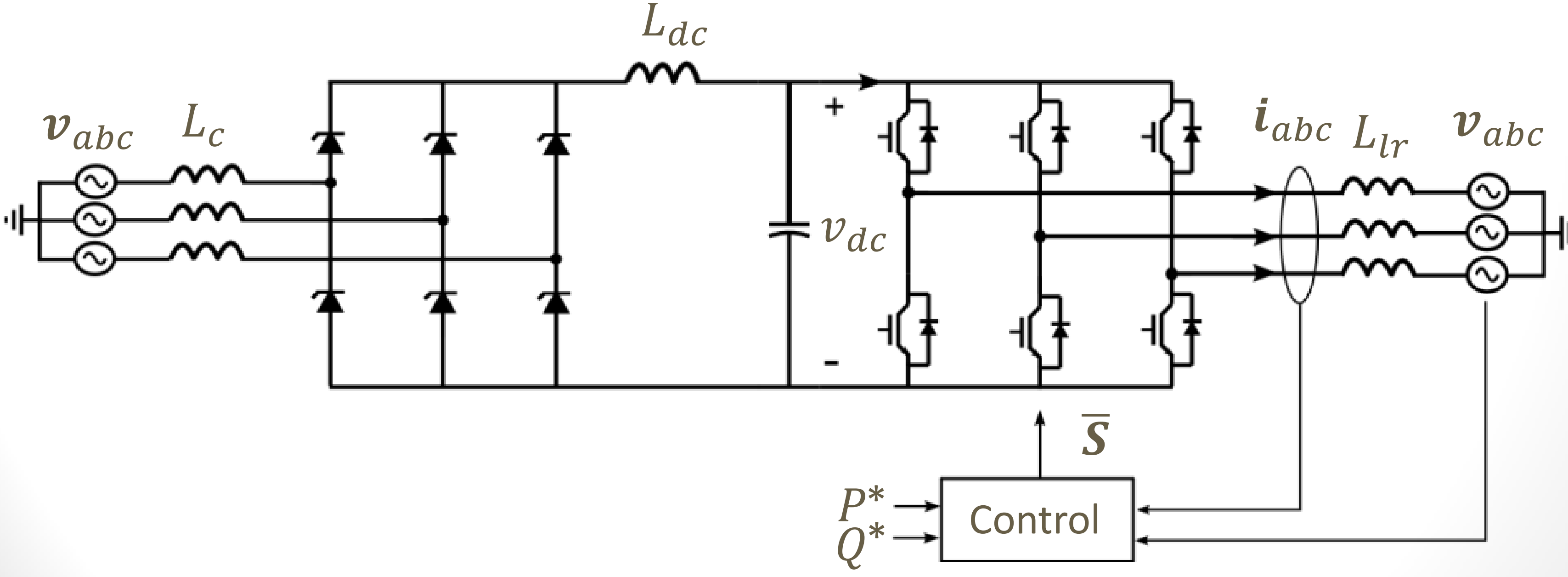
Grid-Side Converter

- Maintains the dc link voltage, which provides the dc voltage for the rotor-side converter.

AC-DC-AC Power Electronic Link

How can we use power electronics to generate arbitrary currents, with phase angle referenced from utility voltage?

Example AC-DC-AC Converter



AC-DC-AC Power Electronic Link

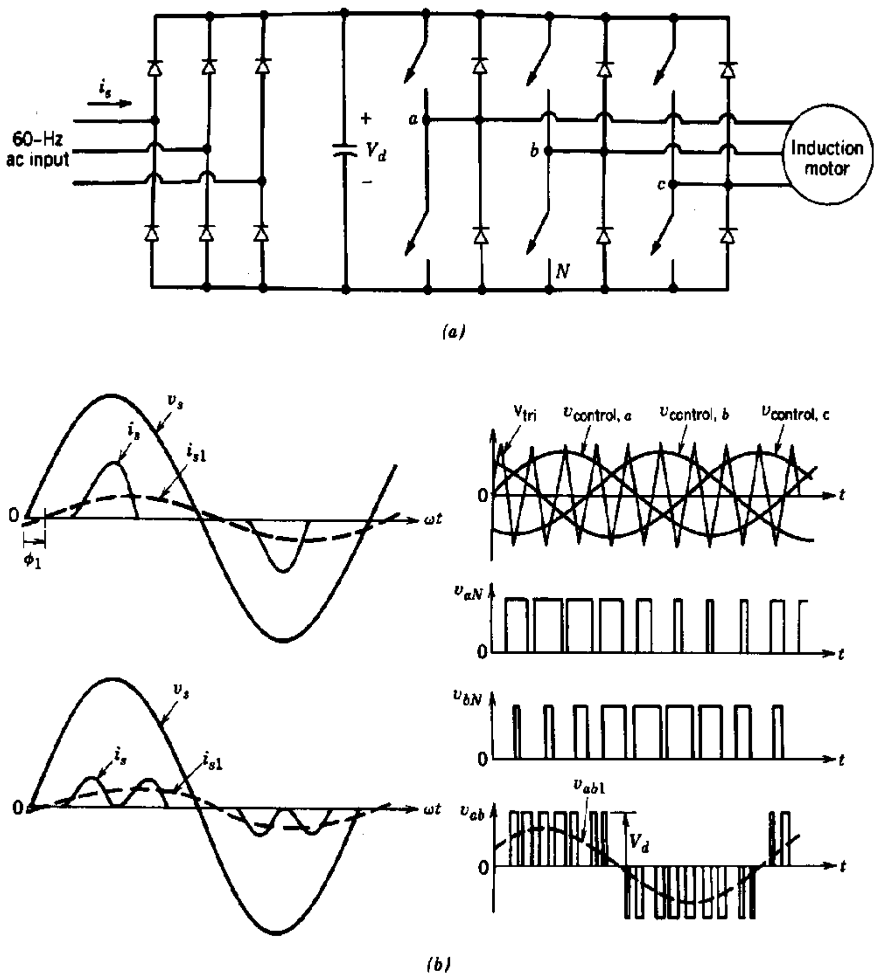


Figure 14-19 PWM-VSI: (*a*) schematic; (*b*) waveforms.

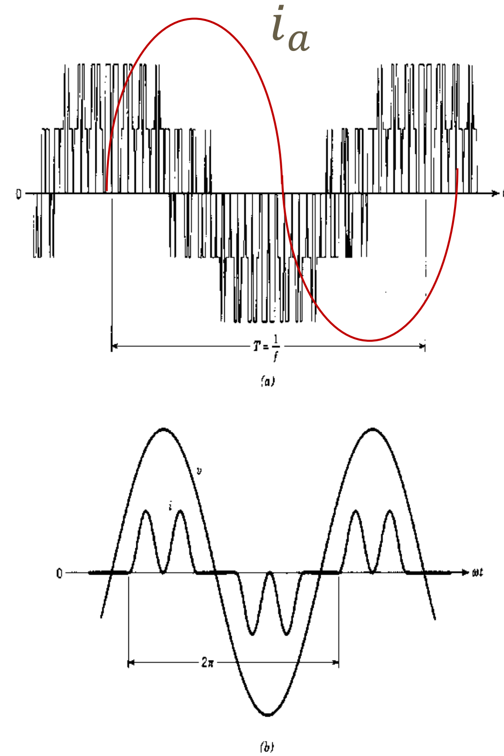
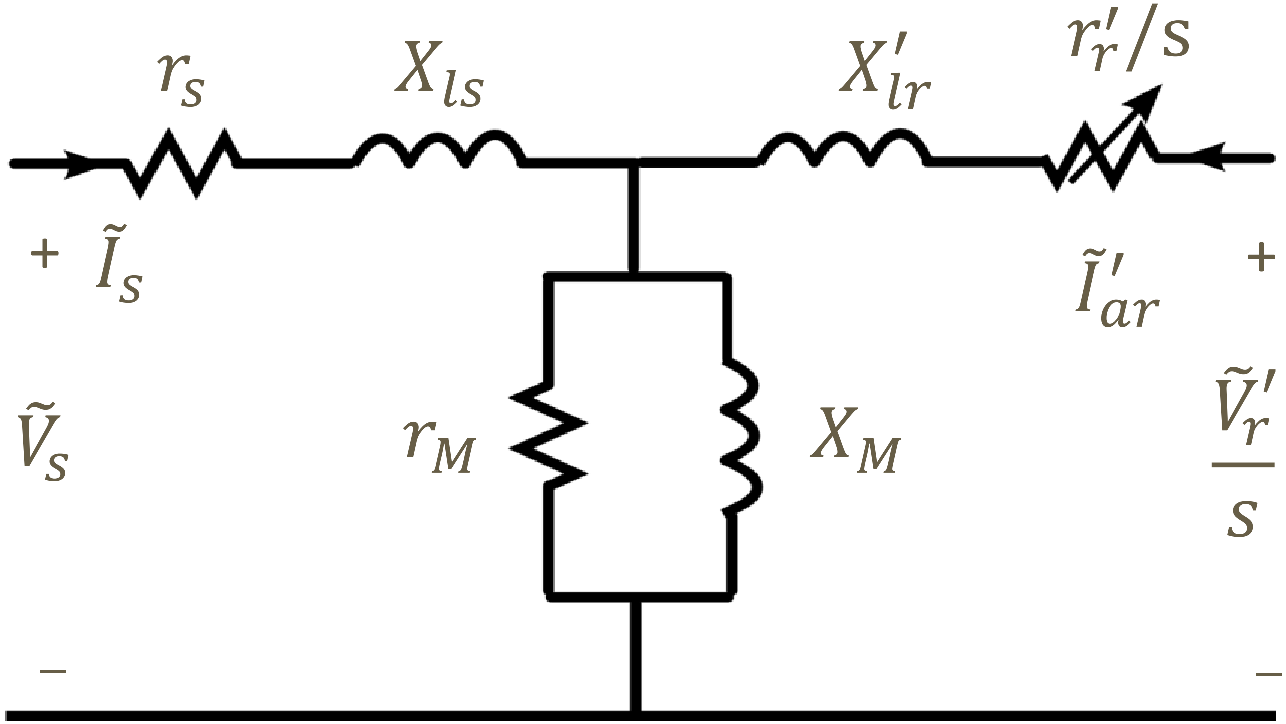


Figure 3-4 Nonsinusoidal waveforms in steady state.

Power Electronics; Converters, Applications and Design, 3rd Edition, by N. Mohan, T.M. Undeland and W.P. Robins; John Wiley & Sons

Induction Machines-Doubly Fed

Induction Machine Equivalent T Circuit



$$s = \frac{\omega_e - \omega_r}{\omega_e} = 1 - \frac{\omega_r}{\omega_e}$$

Rotor-Side Converter

From the voltage equations derived from the steady-state equivalent circuit, you can derive (see Aliprantis' notes, page 30):

$$P_r \approx -sP_s$$

$$P_{ag} = \frac{P_m}{(1-s)}$$

- For $s > 0$ ("sub-synchronous operation"), the rotor side power has opposite sign of stator side power. For generator action $P_s < 0$, the rotor is absorbing power.
- For $s < 0$, ("super-synchronous operation"), the rotor side power has the same sign as stator side power. For generator action $P_s < 0$, the rotor is generating power.

Note on Terminology

From the definition of slip:

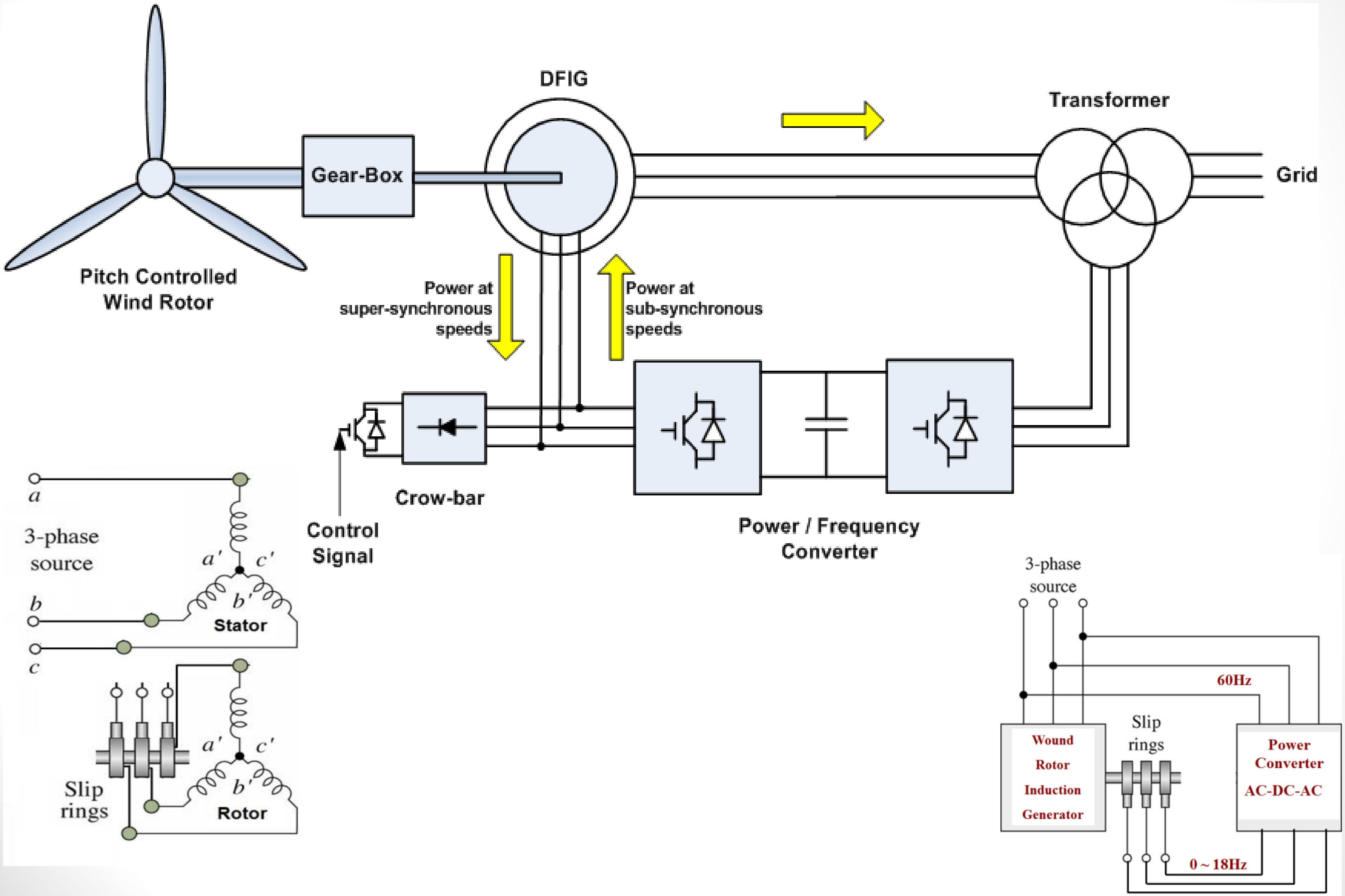
$$s = \frac{\omega_e - \omega_r}{\omega_r} > 0$$

$$\Rightarrow \omega_e - \omega_r > 0$$

$$\Rightarrow \omega_r < \omega_e$$

So in this case, the rotor speed is less than the synchronous speed, hence the term "sub-synchronous." The opposite is true in the super-synchronous case.

Type 3 Wind Turbine Generator



Rotor-Side Converter

Other Notes:

- Power that was *lost* in the resistor of the Type 2 turbine can be recovered using power electronics. Can operate efficiently at large slips ($\pm$30% is typical).
- Since

$$|P_s| \approx \left|\frac{P_r}{s}\right|$$

for low values of slip, the stator carries the bulk of the power. So rotor side power electronics are rated for lower power levels (which means they're less expensive!).

Control of *P* and *Q*

From the equivalent T circuit

$$\tilde{V}_s = (R_1 + jX_s)\tilde{I}_s + jX_0\tilde{I}_r'$$

where we've defined $X_s = X_0 + X_1$. Now if $R_1 \ll X_s$,

$$\tilde{I}_s \approx \frac{\tilde{V}_s - jX_0\tilde{I}_r'}{jX_s}$$

Using these expressions to compute complex power $S_s = 3\tilde{V}_s\tilde{I}_s$

$$P_s \approx -3\frac{X_0}{X_s}V_s I_{ra}'$$

$$Q_s \approx 3V_s\frac{V_s + X_0 I_{rb}'}{X_s}$$

where $\tilde{I}_r' = I_r' \angle \theta_{ir} = I_{ra}' + jI_{rb}'$

A Simple PLL

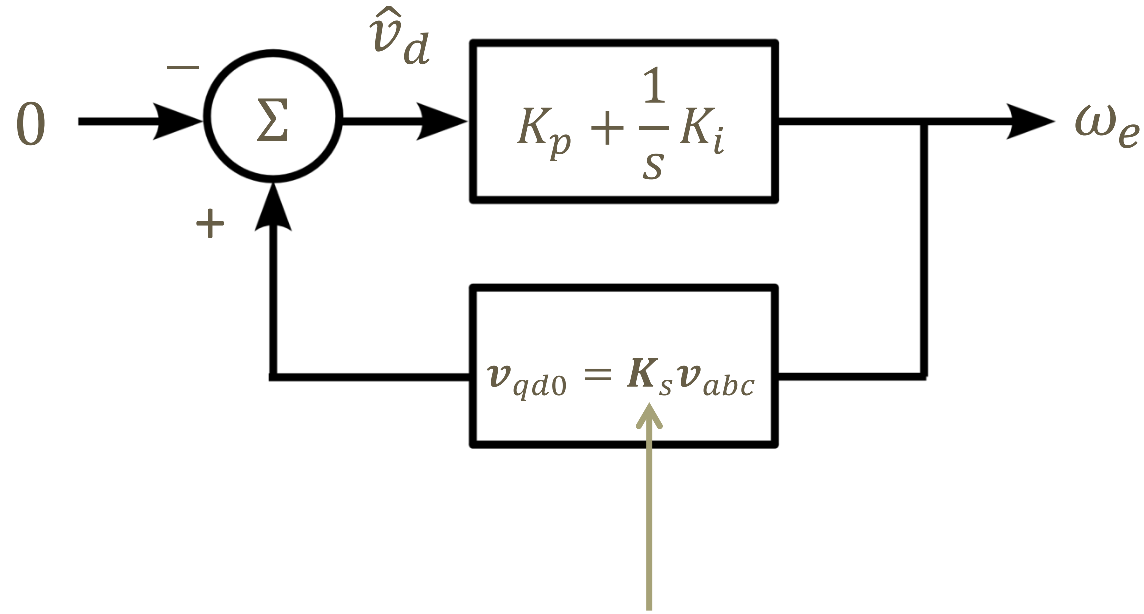
First note that for

$$\boldsymbol{v}_{abc} = \sqrt{2}V_s \begin{bmatrix} \cos(\theta) \\ \cos\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \qquad \boldsymbol{K}_s = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin(\theta) & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

$$\Rightarrow \boldsymbol{v}_{qd0} = \boldsymbol{K}_s \, \boldsymbol{v}_{abc} = \begin{bmatrix} \sqrt{2}V_s \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix}$$

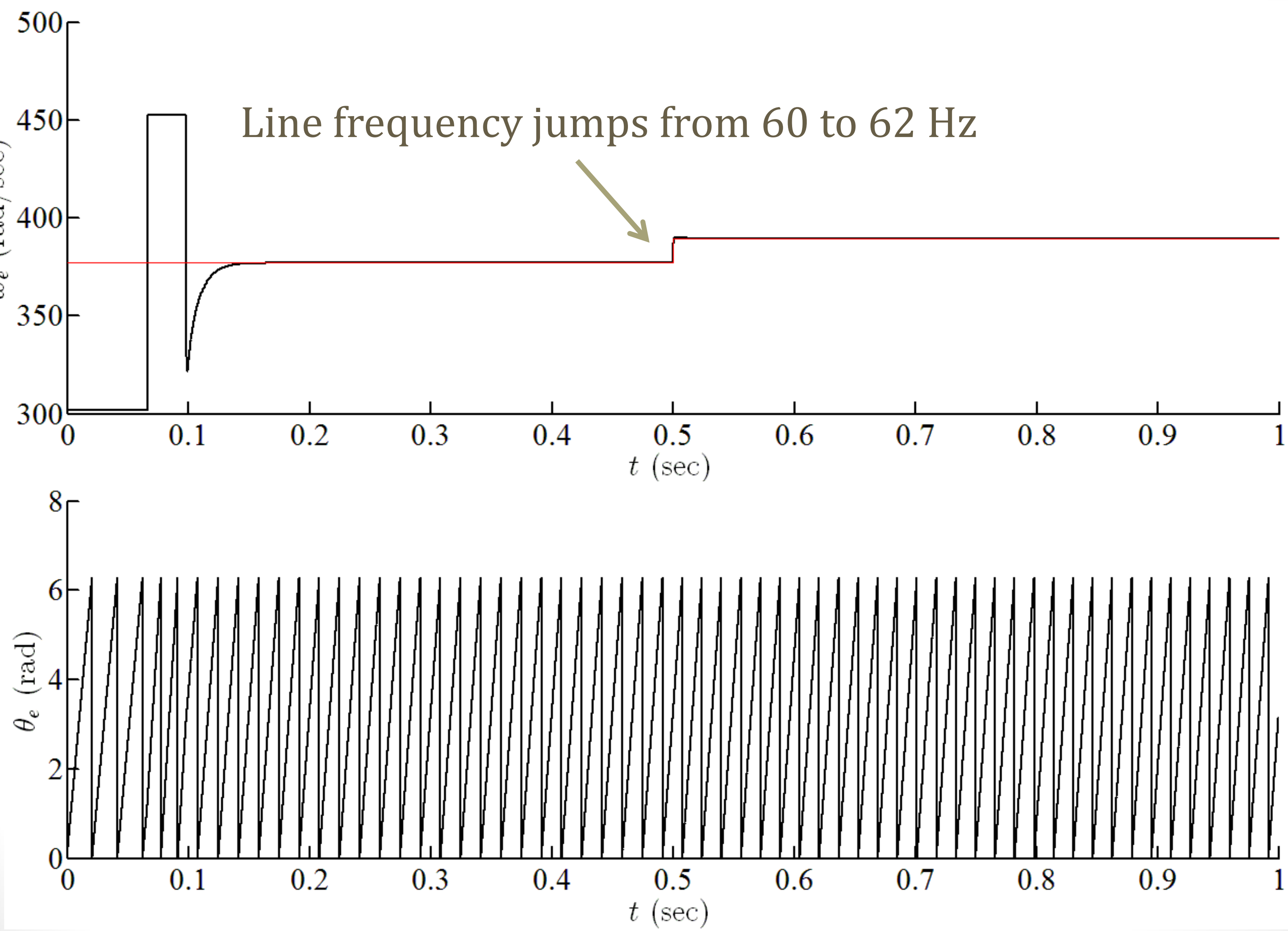
Key points: (a) we transform to the $qd0$ reference frame so that sinusoidally varying quantities become <u>dc quantities</u>, (b) note that in this case, v_d should be zero.

A Simple PLL



$$\theta_e = \int_0^t \omega_e(\tau) d\tau + \theta_e(0)$$

A Simple PLL



Line frequency jumps from 60 to 62 Hz
500
450
400
350
300
w_e (rad/sec)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
t (sec)
8
6
4
2
0
θ_e (rad)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
t (sec)

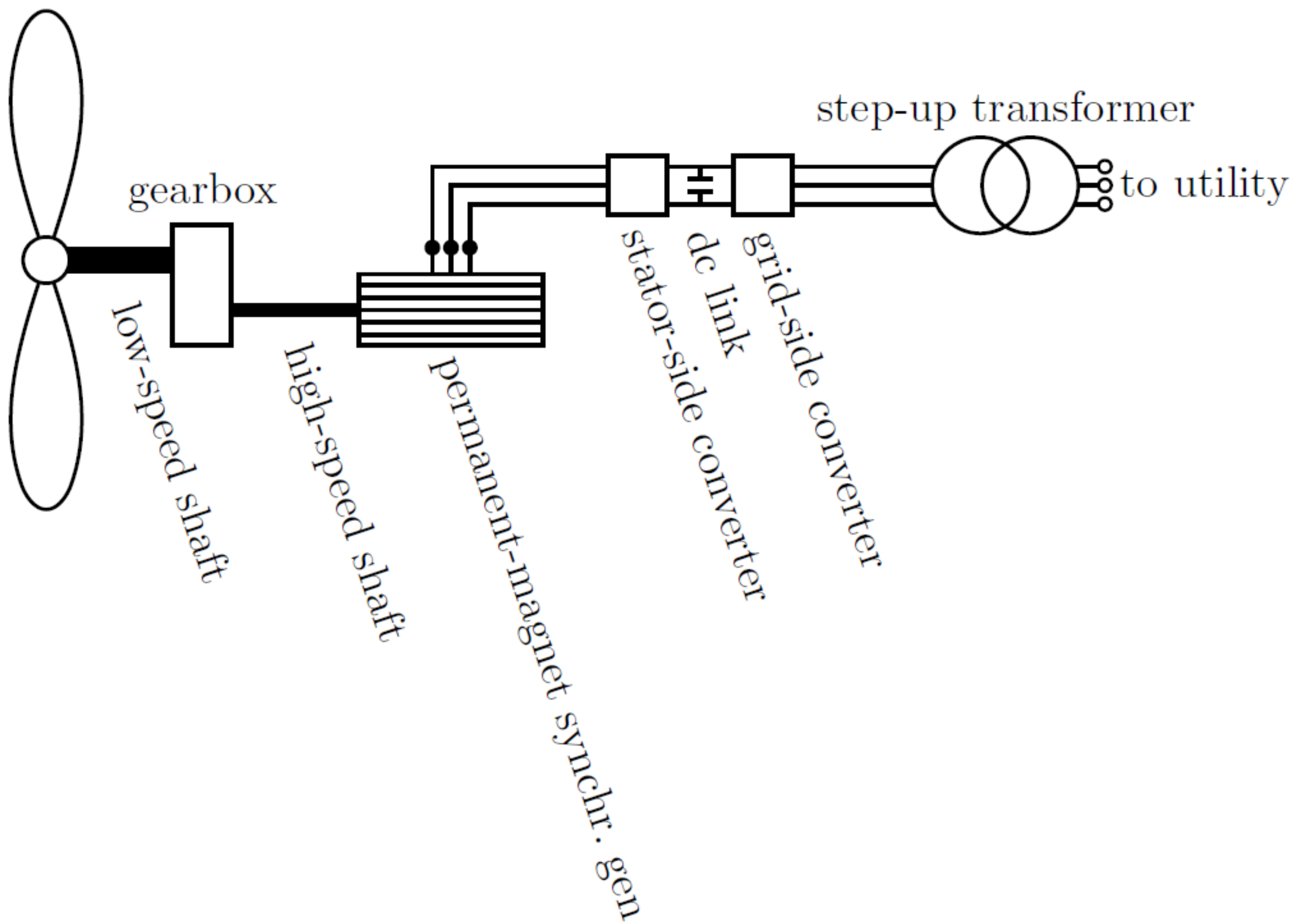
Type 3 Topology

Summary Notes:

- Variable speed (±30 slip, or 70%<speed<130%)
- Variable frequency 3-phase, current regulated PWM inverter is fed to the rotor winding.
- Can control real and reactive power by control of the rotor magnitude and phase.
- Low power absorbed/generated by rotor results in less expense rotor converter.
- Induction generator always absorbs reactive power (still need reactive power compensation)
- Currently dominates the global market.

Type 4 Topology

Permanent Magnetic Synchronous Generator (PMSG)



Type 4 Topology

- Uses a permanent magnetic synchronous machine with stator connected to the grid through an *ac-dc-ac* power electronic link.
- The power electronic link is composed of two bi-directional converters, connected through a dc link (capacitor).
- These converters are referred to as the stator-side converter (connects the stator circuits to the dc link) and the grid-side converter (connects the dc link to the grid).

Type 4 Topology

- Variable Speed – variable frequency at generator side and fixed frequency (60Hz) at the utility side
- Latest generation of wind turbines.
- Rotor speed varies in a very large range—so connected to the turbine shaft via gear box or direct drive (no gear box).
- Absorbs/supplies reactive power (± 95% power factor) so no cap bank needed.
- Always use power converter to convert generator power and to return the power to the utility supply (ac-dc-ac)
- Power converter sized to carry rated power.

Type 4 Topology

- Output power (real power, active power) – adjustable at any speed (within design limit).
- Reactive power (non-revenue related) – adjustable at any speed (within design limit).
- Real and reactive power are controllable independently.
- Output electrical power is controllable independent of input mechanical power and speed, however, it is normally controlled to follow:
  - Real power as a cube function of rotor rpm to optimize the aerodynamic energy capture - real power = $K_w \, w_m^{\ 3}$
  - Reactive power is controlled to control constant voltage at the output of the generator or power factor.

Type 4 Topology

Stator Side Converter

- Current magnitude is adjustable by controlling the power converter
- Starting current and starting torque is adjustable
- Max Const. Pitch Operation: Real power = $K_w\, w_m^3$

Grid Side Converter

- Output power factor adjustable (normally between 0.95 pf-lagging to 0.95 pf-leading.
- Real power is adjusted to keep the DC bus voltage constant

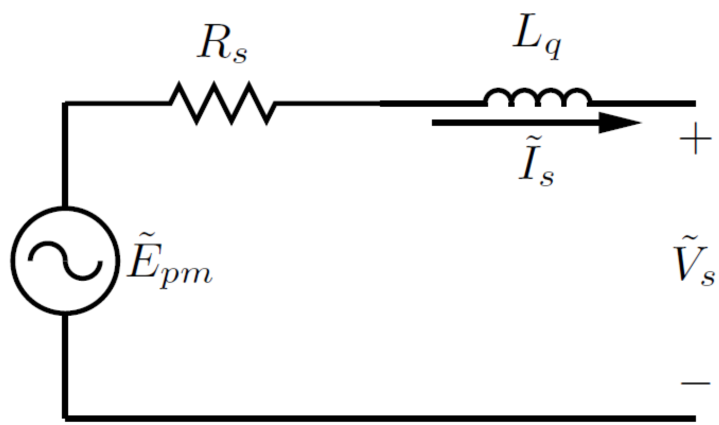
Having capability to adjust the power factor means that the generator output terminal voltage can be adjusted by controlling the output reactive power.

Stator-Side Converter

- Controls the frequency of the stator currents to maintain synchronism between the rotor and stator rotating *mmfs*.
- Controls the magnitude and phase of the stator currents to control electromagnetic torque—in order to obtain the optimal tip-speed ratio.

Determining P and Q

From the equivalent steady-state circuit:



$$S_s \approx 3\left(\tilde{E}_{pm} - j\omega_r L_q \tilde{I}_s\right)\tilde{I}_s^*$$

$$\approx \frac{3}{2}\omega_r\left[\lambda_{pm} - \left(L_d - L_q\right)I_{ds}\right]I_{qs} +$$

Real power

$$\mathrm{j}\frac{3}{2}\omega_r\left[\lambda_{pm}I_{ds} - L_d I_{ds}^2 - L_q I_{qs}^2\right]$$

Reactive power

Torque

Energy, torque, and power are related by:

$$E = \int P_s dt = \int T_e d\theta$$

$$\Rightarrow P_s = T_e \frac{d\theta}{dt} = T_e \omega_{rm}$$

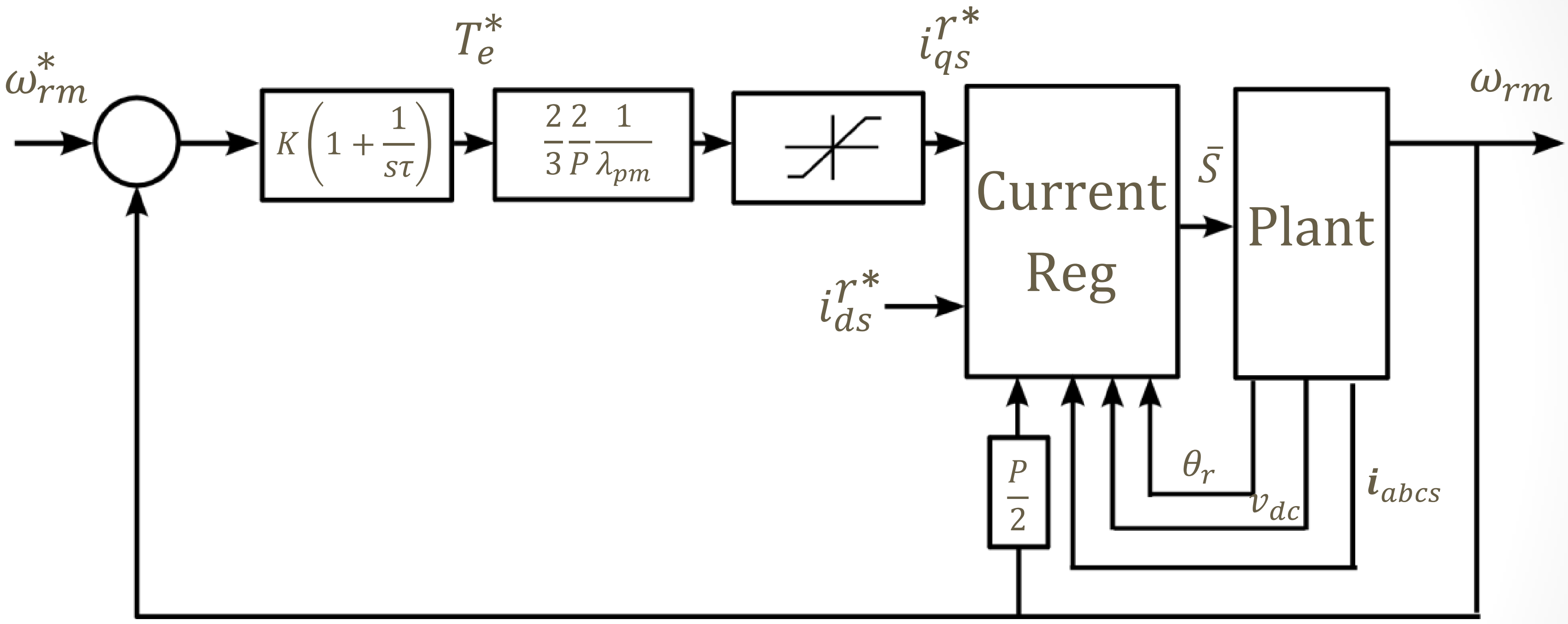
where $\omega_{rm} = \frac{2}{P}\omega_r$ (here P is the number of machine poles, not power!)

$$T_e = \frac{3}{2}\frac{P}{2}\left[\lambda_{pm} - \left(L_d - L_q\right)I_{ds}\right]I_{qs}$$

For a non-salient machine, $L_d = L_q$, in which case

$$T_e = \frac{3}{2}\frac{P}{2}\lambda_{pm} I_{qs}$$

Current Regulated Speed Control



Maximum Torque Per Amp

$$\text{maximize}_{I_{qs},I_{ds}} \ \frac{3}{2}\frac{P}{2}\left[\lambda_{pm} - (L_d - L_q)I_{ds}\right] I_{qs}$$
$$\text{subject to} \ \ I_{qs}^2 + I_{ds}^2 = I_s^2$$