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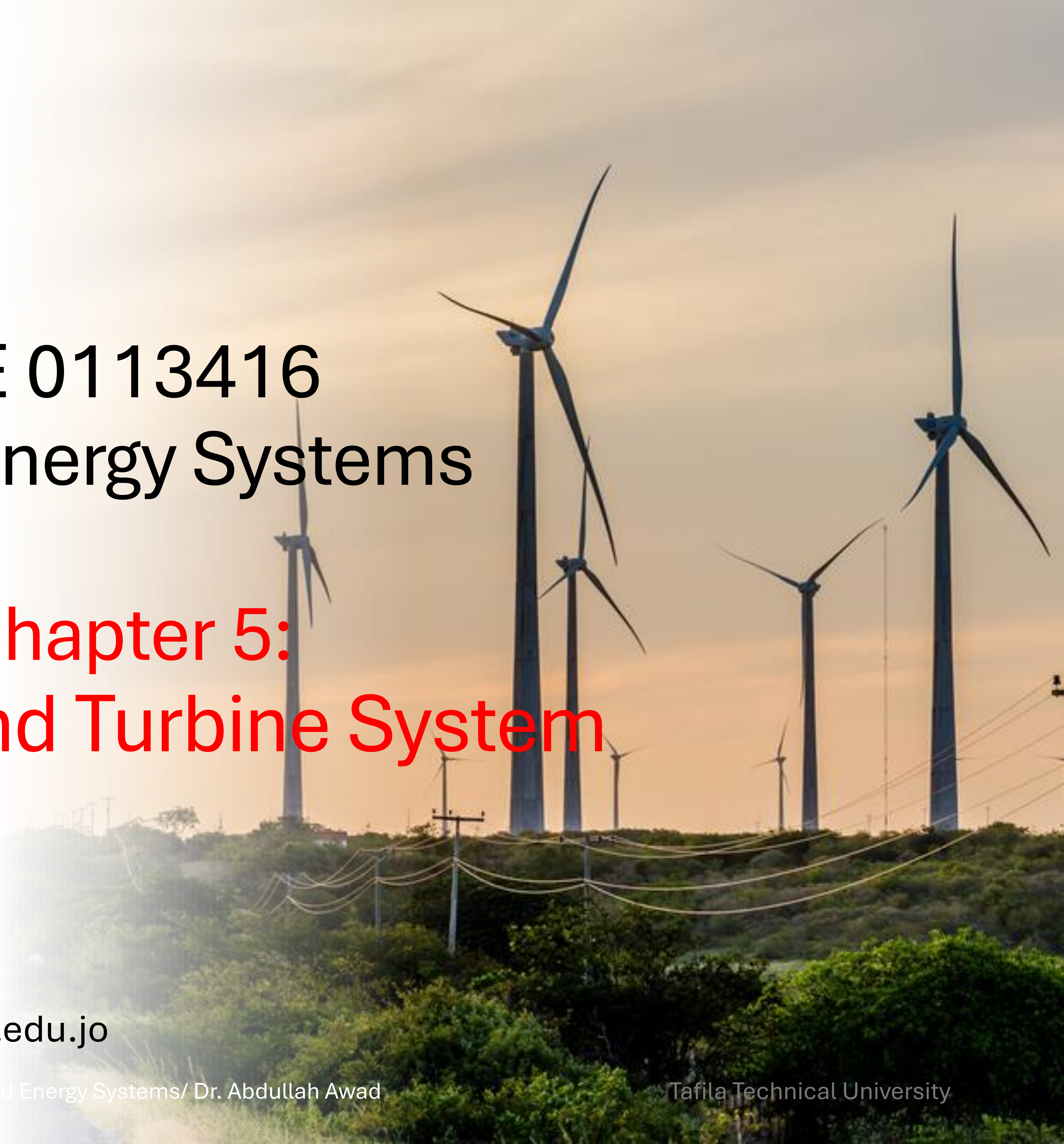
Wind Energy Systems



Chapter 5:
Type 4 Wind Turbine System

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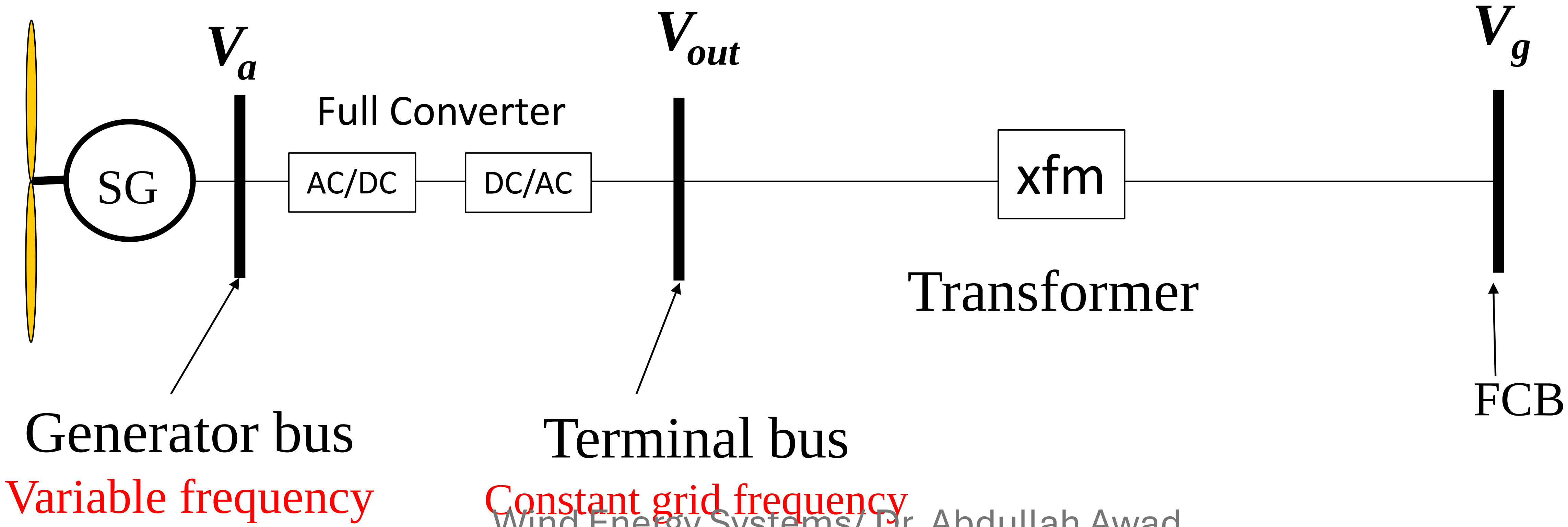
Type 4 Direct Drive Wind Turbine System

Most type 4 turbines are direct drive systems without gearboxes; the generator is directly coupled to the hub of the blades. Most of the generators for type 4 systems are synchronous machines with electric or permanent magnet excitation. In most designs, the magnet is mounted on the rotor, which is coupled to the hub, and the armature (where the electric power is extracted) is mounted on the stator. The magnet in this case is spinning with the blades and the armature is stationary. In newer designs, the arrangement is reversed; the magnet is mounted on the stator and is coupled to the hub (thus spinning), whereas the armature is mounted on the rotor, which is stationary.



Number of Poles

- To maximize the efficiency of the generator and to reduce the complexities of the converters, the generator is designed to have its output frequency near the grid frequency.
- Since the speed of the blades is typically low (ranging from 6-60 rpm), the number of poles of the generator is large.
  - $$f = \frac{n}{120} p$$
- Type 4 synchronous generator has typically more than 100 poles, and its cross section is very wide to fit all these magnetic poles.

- Most Type 4 turbines are direct drive system without gearboxes
- Most of the generators for Type 4 system are synchronous machines
    - Electric magnet
    - Permanent magnets.
- In most designs, the magnet is mounted on the rotor which is coupled to the hub, and the armature (where the electric power is extracted) is mounted on the stator.
- In newer designs, the arrangement is reversed; the magnet is mounted on the stator and is coupled to the hub (thus spinning) while the armature is mounted on the rotor which is stationary.

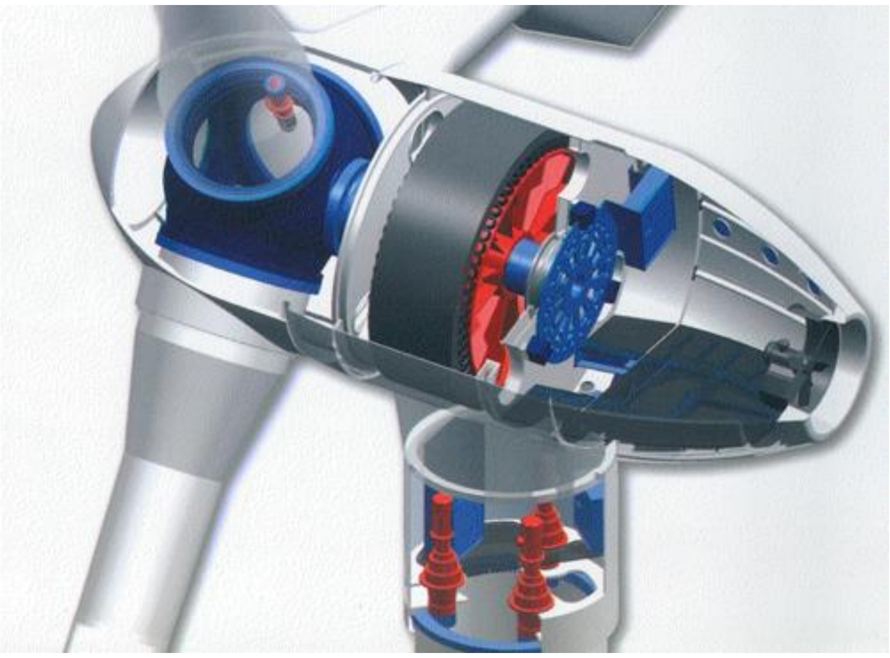
Turbine with Gear

Gearless Turbine


DIRECT WIND


E-126

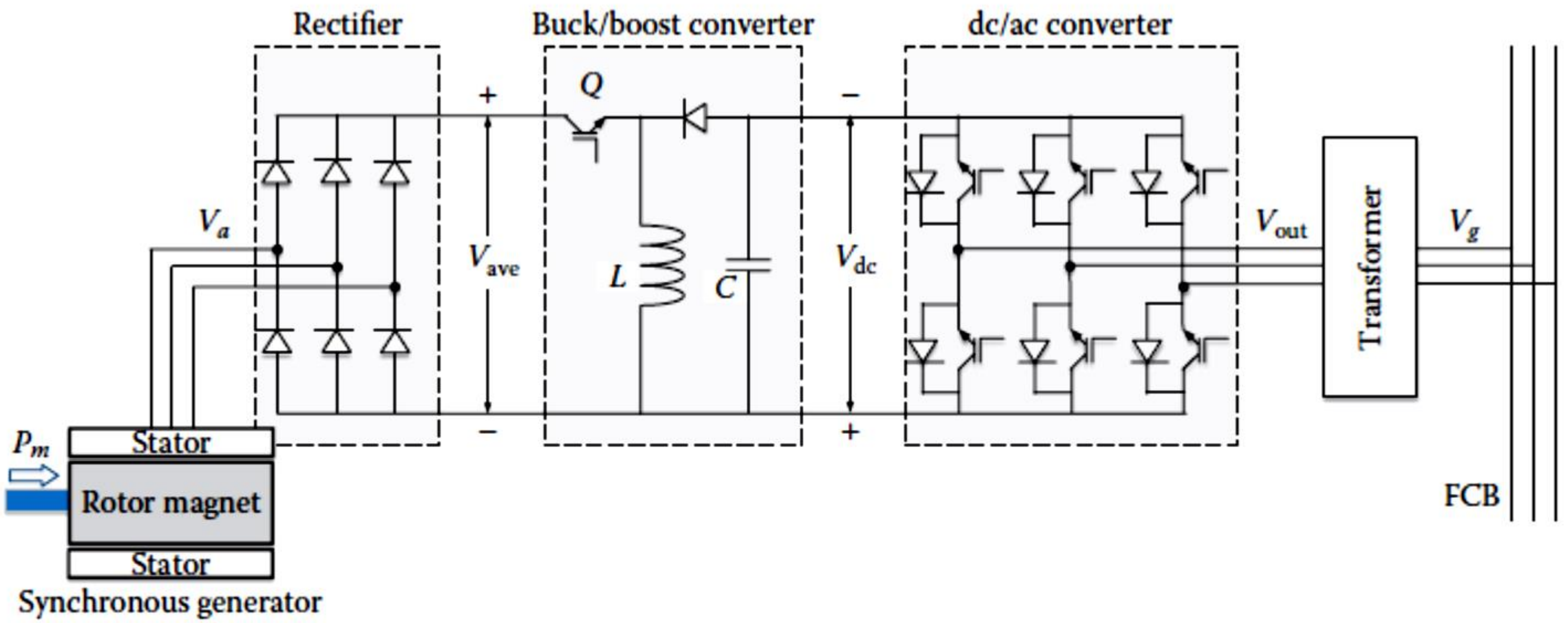

ALSTOM



Direct Drive Generator

Gear vs Gearless Systems

- Turbines with Gear
  - Allows the use of generators with small number of poles (4-6 poles)
  - Size of generator is relatively small
  - Requires gear to step up the speed of the wind to drive the generator at its high speed (1200-1800rpm)
- Direct Drive Turbine (Gearless)
  - The generator has a large number of poles (~200 poles)
  - The speed of the generator is low (32-36 rpm)
  - There is no need for a gear
  - The machine has a large diameter and heavy



dc/ac Converter with PWM, $v_{out} = k\, V_{dc} \sin(2\pi f_s t)$

$$k = \frac{V_r}{V_{car}}$$

V_r is the value of the reference signal of the PWM (max or rms).

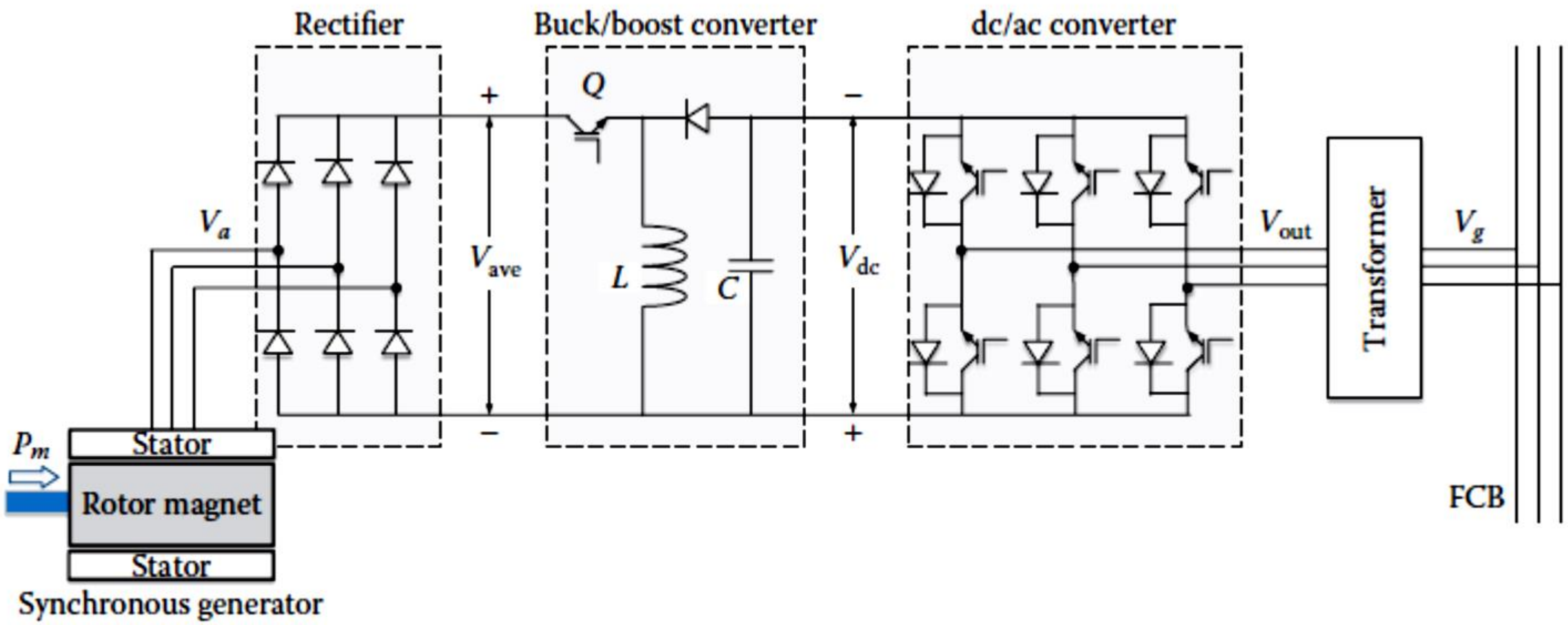
Rectifier Equation, $V_{ave} = \frac{3\sqrt{3}}{2\pi}\sqrt{2}\, V_a = 1.17\, V_a$

V_{car} is the value of the carrier signal (max or rms).

Buck/Boost Converter, $V_{dc} = -V_{ave}\, \frac{t_{on}}{t_{off}}$

f_s is the frequency of the refernce signal, which is set equal to the frequency of the grid

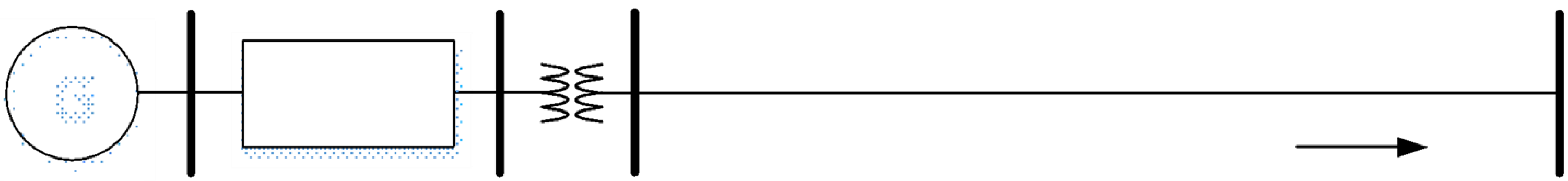
k is the gain ratio



$$v_{out} = -1.17\, V_a \frac{V_r}{V_{car}} \frac{t_{on}}{t_{off}} \sin(2\pi f_s t)$$

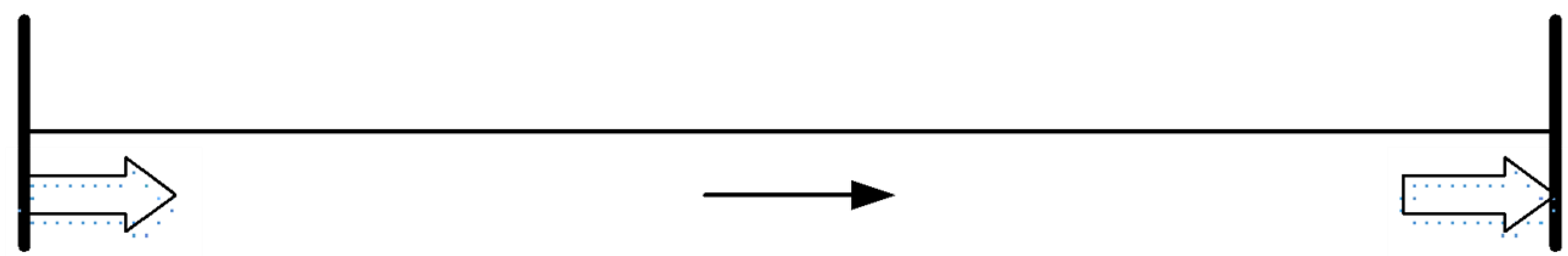
In rms, $V_{out} = -0.827\, V_a \frac{V_r}{V_{car}} \frac{t_{on}}{t_{off}}$

Power Flow



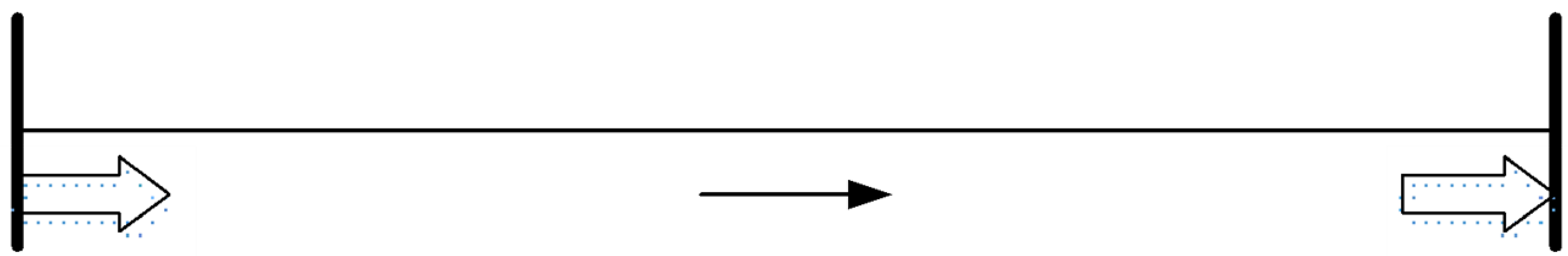
$$V'_{out} = V_{out}\frac{N_1}{N_2}$$

$$x = x_{line} + x_{xfm}$$



$$\bar{S}_g = \bar{V}_g\,\bar{I}^* = P_g + jQ_g$$

Power Flow



$$\bar{I} = \frac{\bar{V}'_{out} - \bar{V}_g}{jx}$$

$$\bar{I} = \frac{V'_{out}(\cos\delta + j\sin\delta) - V_g}{jx}$$

$$\bar{S}_g = \bar{V}_g\,\bar{I}^* = P_g + jQ_g$$

$$\bar{S}_g^* = V_g^*\,\bar{I} = P_g - jQ_g$$

$$\bar{S}_g^* = V_g\,\frac{V'_{out}(\cos\delta + j\sin\delta) - V_g}{jx} = \frac{V'_{out}V_g}{x}\sin\delta - j\frac{V_g}{x}\left(V'_{out}\cos\delta - V_g\right)$$

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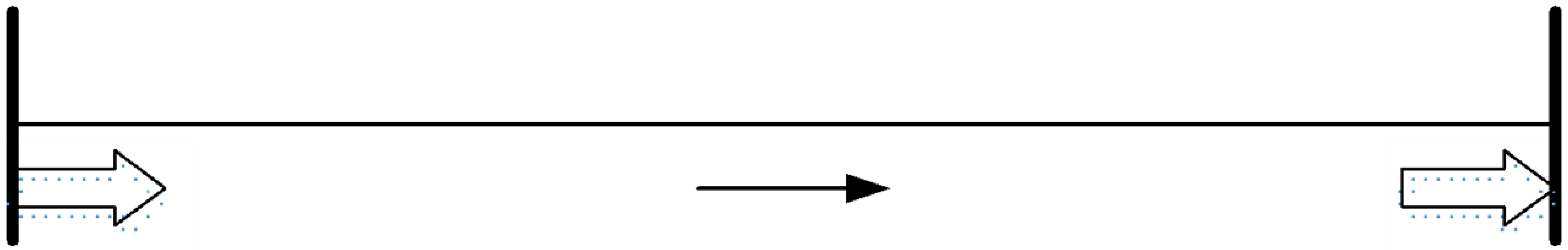
Power Flow

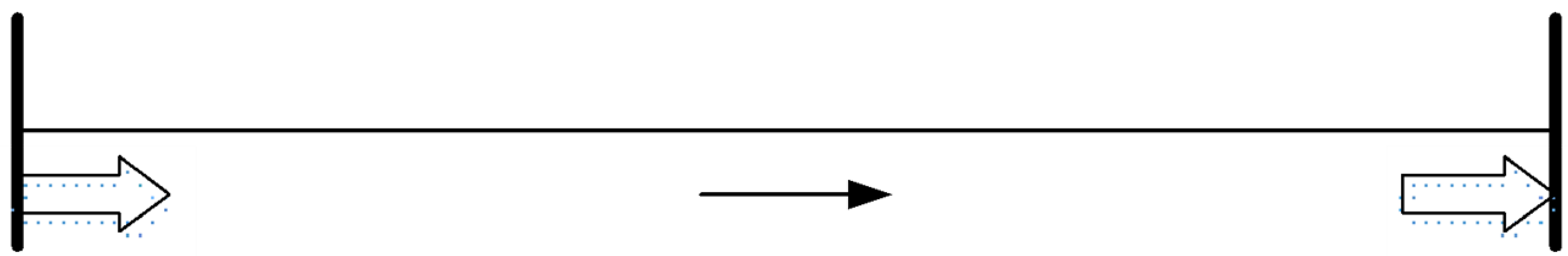


$$\bar{S}_g^* = V_g \frac{V'_{out}(\cos\delta + j\sin\delta) - V_g}{jx} = \frac{V'_{out}V_g}{x}\sin\delta - j\frac{V_g}{x}\left(V'_{out}\cos\delta - V_g\right)$$

$$P_g = \frac{V'_{out}V_g}{x}\sin\delta = P_{max}\sin\delta$$

$$Q_g = \frac{V_g}{x}\left(V'_{out}\cos\delta - V_g\right)$$

Approximation for small δ



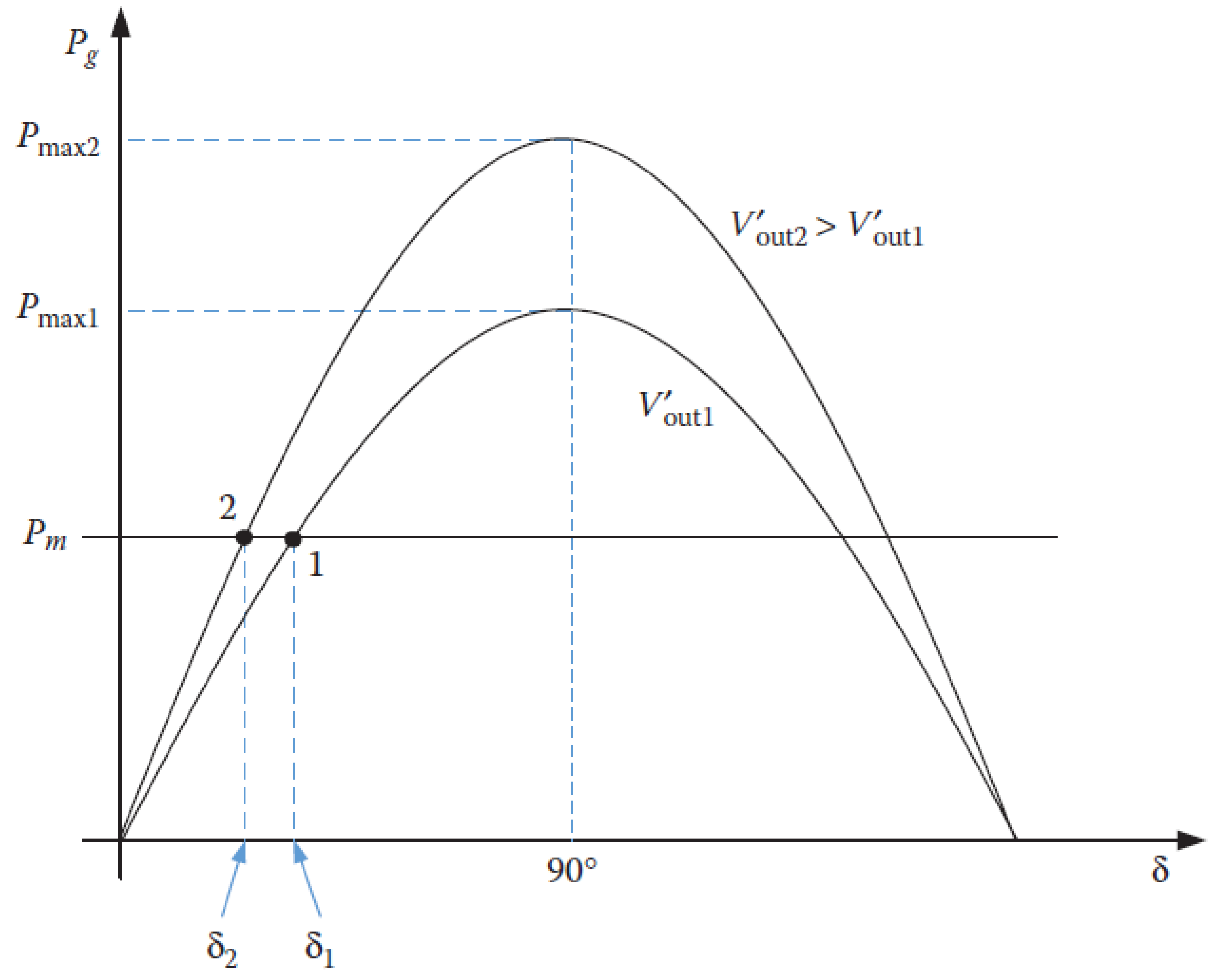
$$\sin\delta \approx \delta$$

$$P_g = P_{max}\sin\delta \approx P_{max}\,\delta$$

$$Q_g = \frac{V_g}{x}\left(V'_{out}\cos\delta - V_g\right) \approx \frac{V_g}{x}\left(V'_{out} - V_g\right)$$

Real Power Control

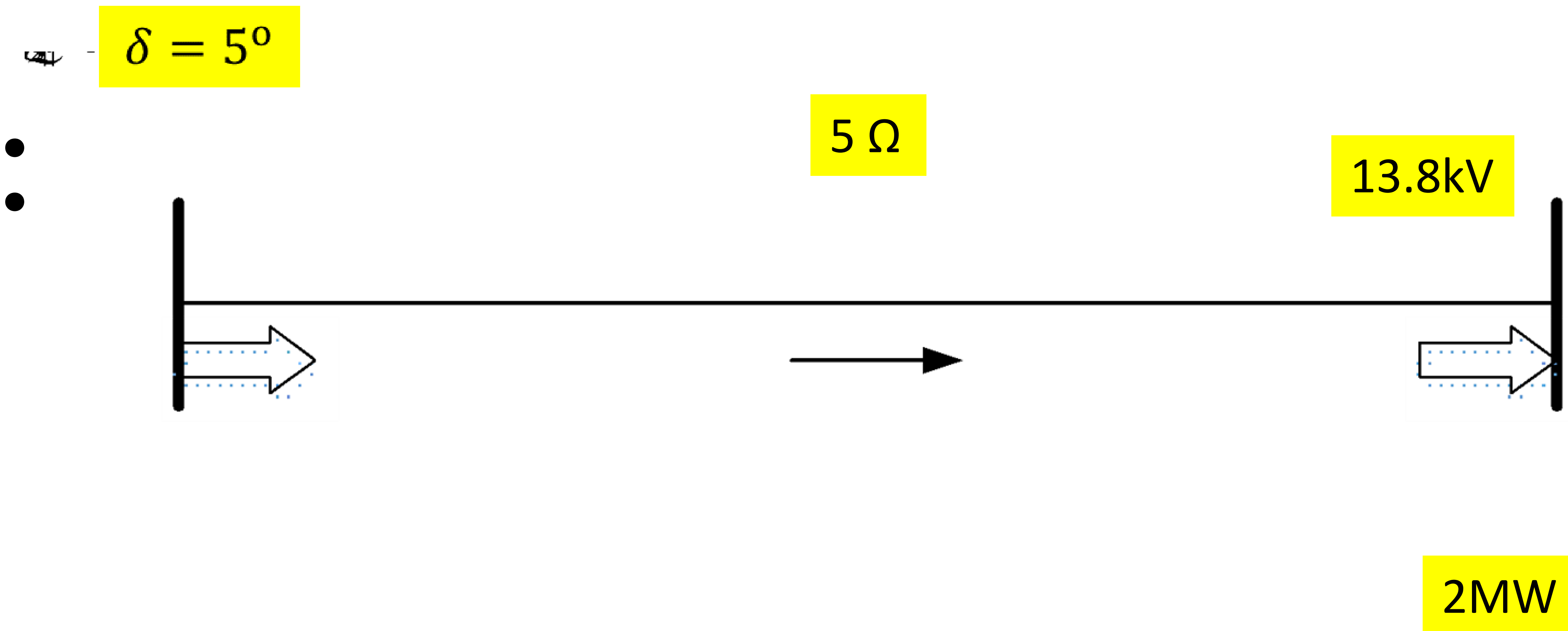
- Real power output cannot change unless the power from the turbine changes
- Changing V_{out} changes the power angle δ



Example

- A Type 4 wind turbine is acquiring 2MW from wind. The synchronous reactance of the generator is 2 Ω and that for the transmission line is 5 Ω. The voltage at the grid bus is 13.8kV. Compute the output voltage of the full converter that operates the system at $\delta = 5^{\circ}$. Also, compute the pullout power.

Solution:

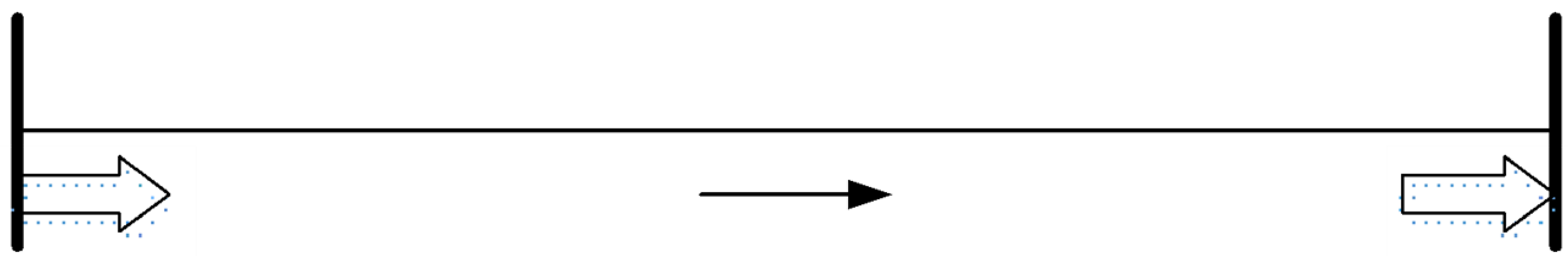


$$P_g = \frac{V_g\, V'_{out}}{x} \sin\delta$$

$$V'_{out} = \frac{xP_g}{V_g \sin\delta} = \frac{(2+5)\times 2\times 10^6}{13.8\times 10^3 \times \sin(5^o)} = 11.64\ \text{kV}$$

$$P_{max} = \frac{V'_{out}V_g}{x} = \frac{11.64\times 13.8}{7} = 22.95\ \text{MW}$$

Reactive Power Control



$$Q_g = \frac{V_g}{x}\left(V'_{out}\cos\delta - V_g\right)$$

If $V'_{out}\cos\delta > V_g$; Q_o *is positive and Current is lagging* V_g

If $V'_{out}\cos\delta < V_g$; Q_o *is negative and Current is leading* V_g

If $V'_{out}\cos\delta = V_g$; Q_o *is zero and Current is in phase with* V_g

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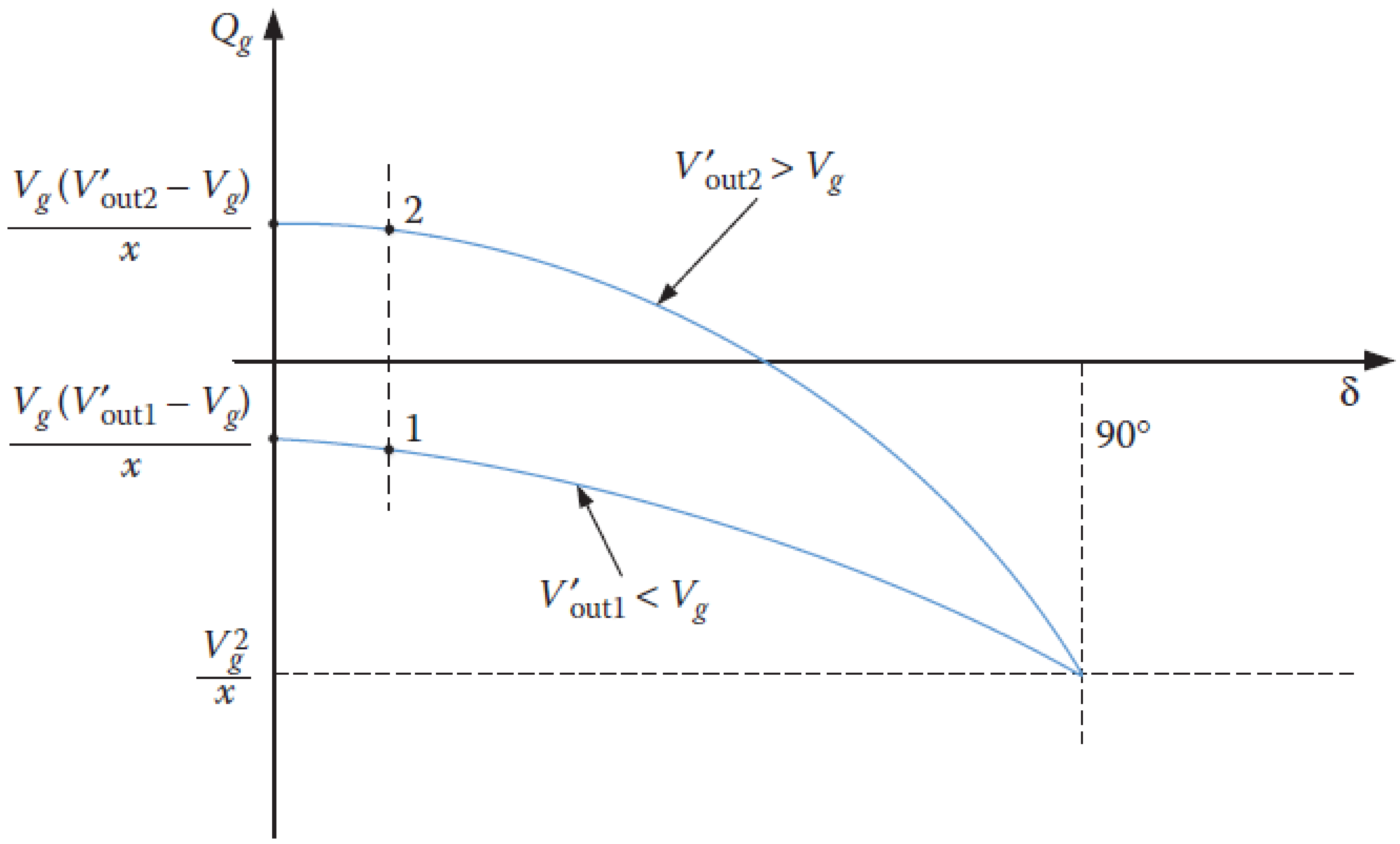
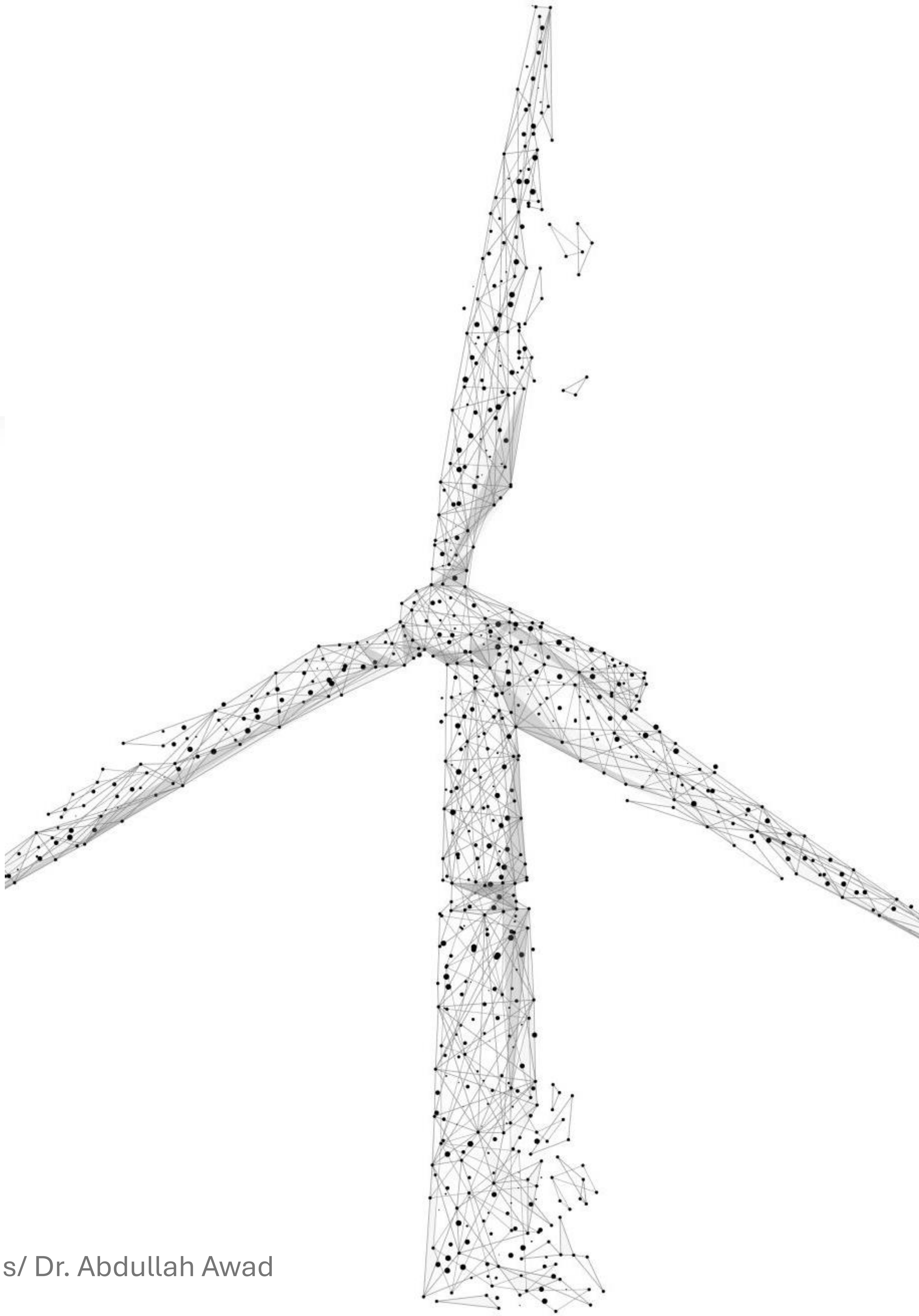
Reactive Power Control

$$Q_g = \frac{V_g}{x}\left(V'_{out}\cos\delta - V_g\right)$$



Example:

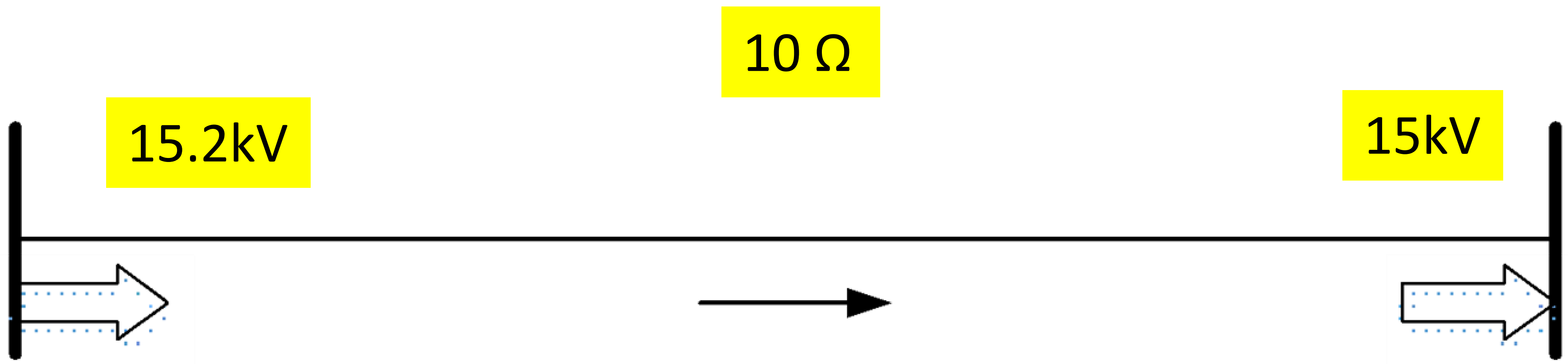
- The power captured by the blades of Type 4 turbine is 1.3MW. The efficiency of the turbine system is 77%. The output voltage of the converter at the high voltage side of the transformer is 15.2kV. The Inductive reactance of the transmission line connecting the turbine to the grid and the transformer is 10Ω. The grid voltage is 15 kV. Compute the real and reactive power delivered to the grid.



Solution:

P_{blade}=1.3MW

η= 77%.



$$P_{out} = P_{blade}\,\eta = 1.3 \times 0.77 = 1 \text{ MW}$$

$$P_g = P_{out} = 1 \text{ MW}$$

$$P_g = \frac{V_g\, V'_{out}}{x} \sin\delta$$

$$1.0 = \frac{15 \times 15.2}{10} \sin\delta$$

$$\delta = 2.5^{o}$$

$$Q_g = \frac{V_g}{x}\left(V'_{out}\ \cos\delta - V_g\right) = \frac{15}{10}\left(15.2\ \cos(2.5^{o}) - 15\right) = 278.3 \text{ kVAr}$$

Protection of Type 4 Turbines

- Chopper
- Dynamic Resistance

Chopper

Chopper System

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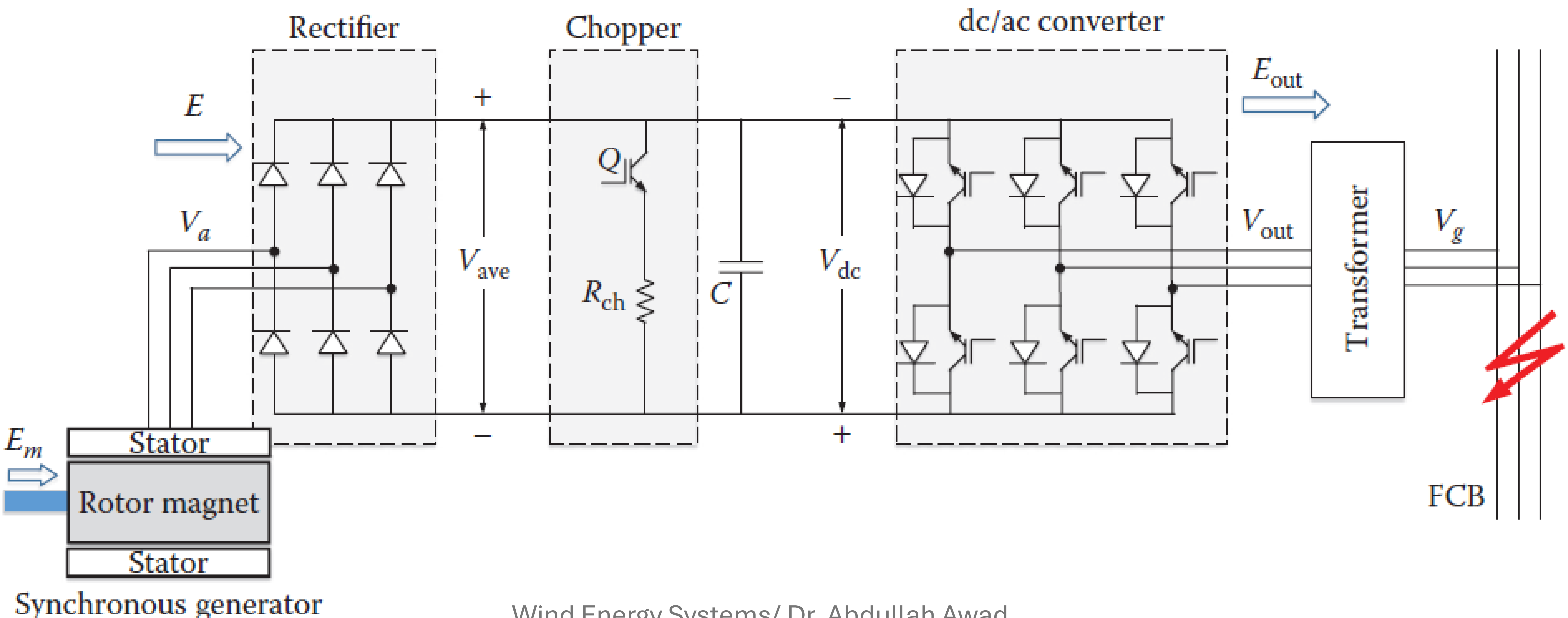
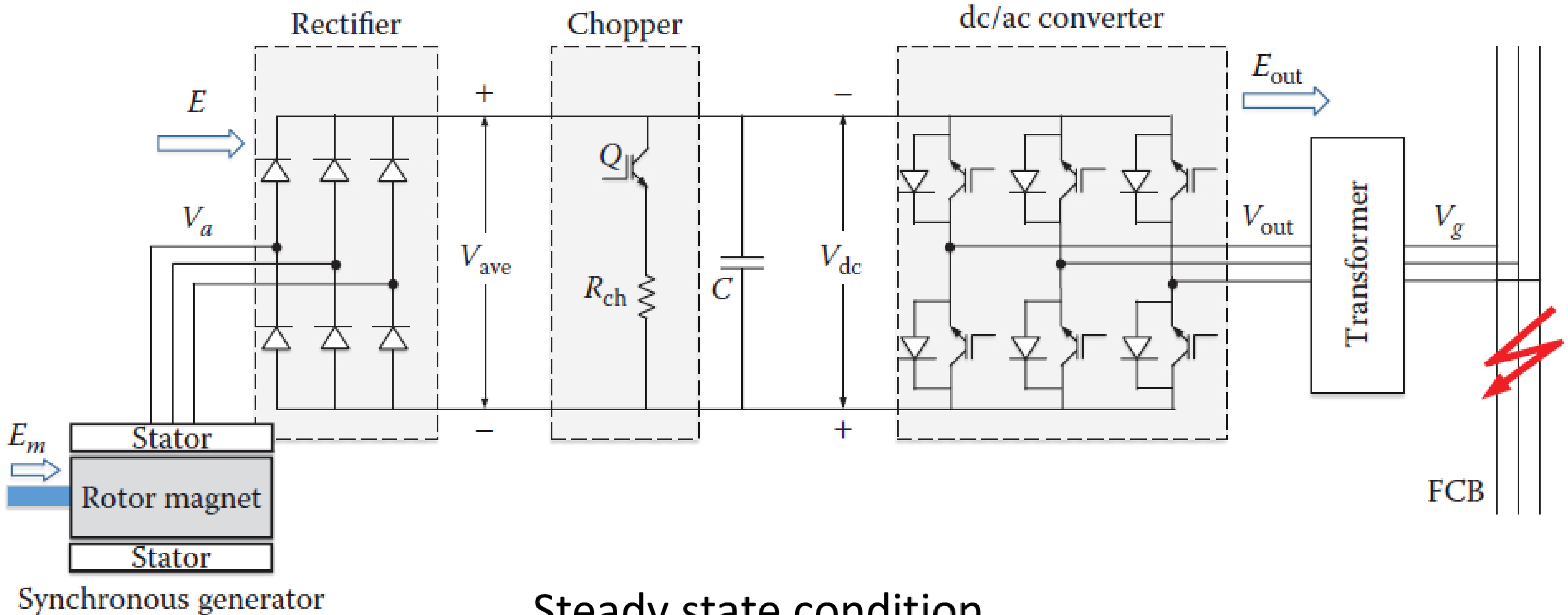
- The switching of the chopper resistance (R_{ch}) is designed dissipate the extra energy and thus prevent over-voltage in the dc link.





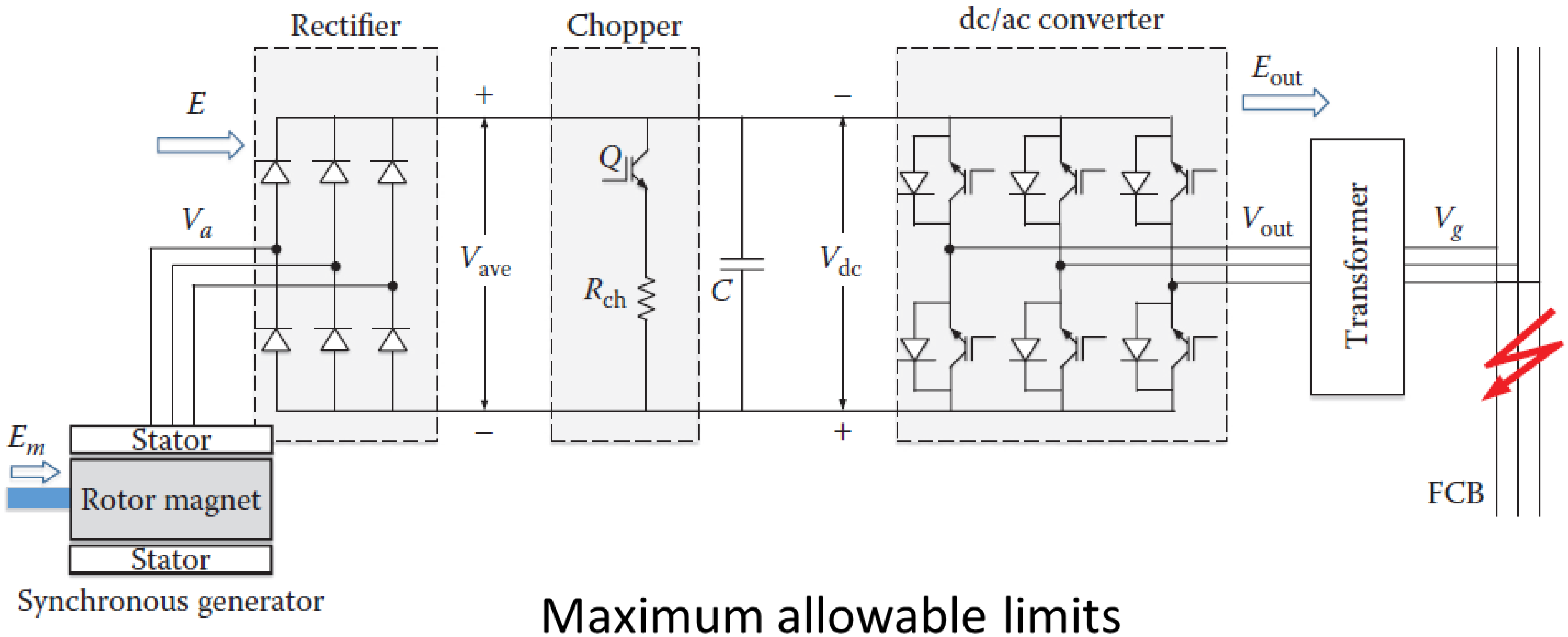
Steady state condition

$$E_{co} = \frac{1}{2} C \, V_{dco}^2$$

E_{co} is the stored energy in the capacitor during steady state operation

V_{dco} is the steady state voltage of the dc link

C is the capacitance of the capacitor



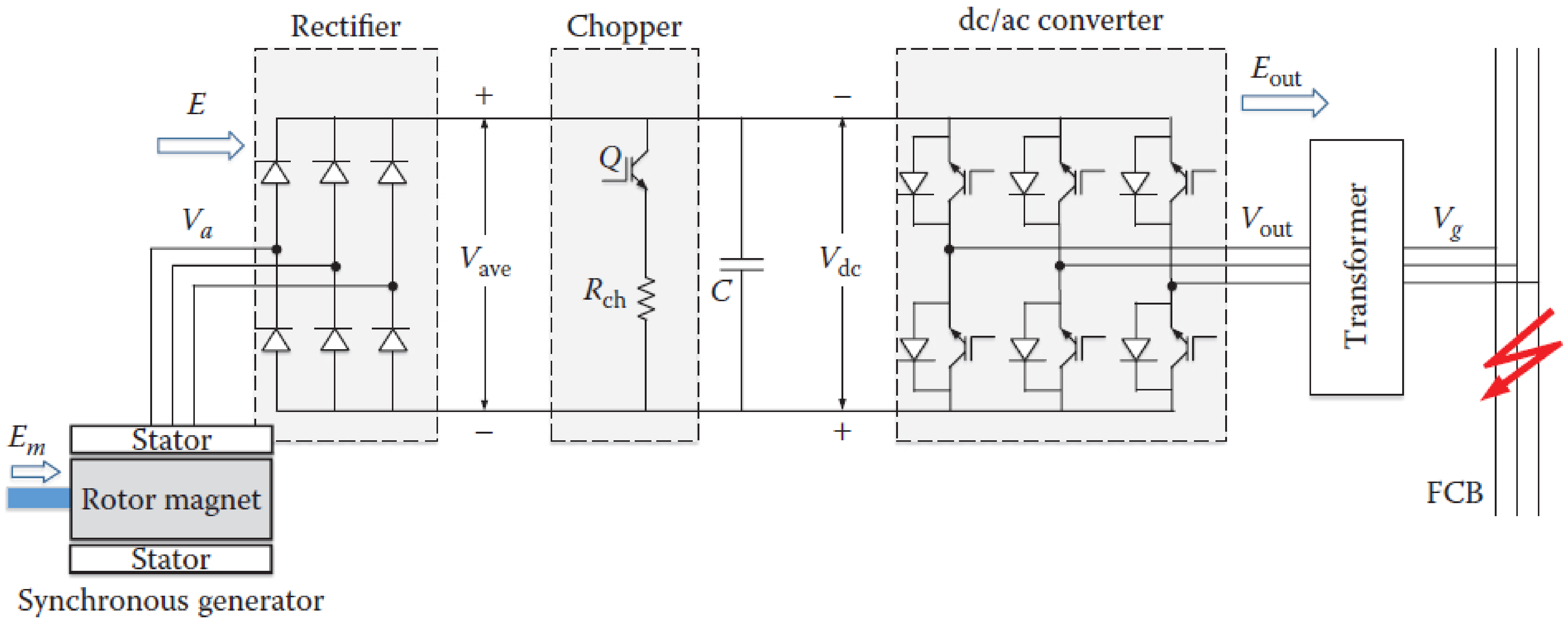
Maximum allowable limits

$$E_{c-max} = \frac{1}{2} C\, V_{dc-max}^2$$

energy consumed by the chopper resistance

$$E_R = \Delta E_{c-max} = E_{c-max} - E_{co} = \frac{1}{2} C \left(V_{dc-max}^2 - V_{dco}^2\right)$$

$$E_R = P_R t = \frac{V_R^2}{R_{ch}} t$$



$$E_R = \frac{V_R^2}{R_{ch}} t$$

With switching of Chopper transistor

$$V_R = kV_{dc-max}$$

$$k = \frac{t_{on}}{\tau}$$

$$E_R = \frac{V_{dc-max}^2}{R_{ch}} k^2 t = \frac{1}{2} C \left(V_{dc-max}^2 - V_{dco}^2\right)$$

$$k = \sqrt{\frac{C\,R_{ch}}{2t}\left(1 - \left(\frac{V_{dco}}{V_{dc-max}}\right)^2\right)}$$

Example

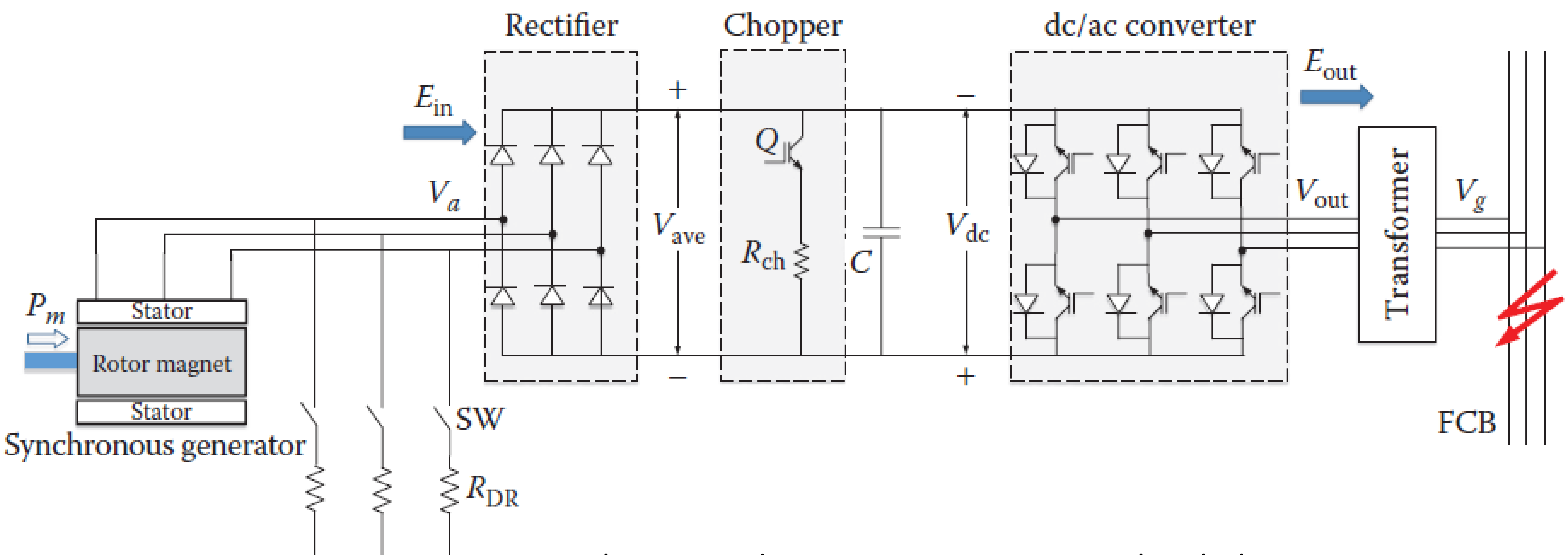
- The rated voltage of the dc bus of Type 4 turbine is 1000V. The dc bus capacitor is 100 μF and the chopper resistance is 2Ω. The maximum allowed increase in dc bus voltage is 10%. Compute the duty ratio that dissipate the extra energy in 1.0 ms.

Solution:

$$k = \sqrt{\frac{C\,R_{ch}}{2\,t}\left(1-\left(\frac{V_{dco}}{V_{dc-max}}\right)^2\right)} = \sqrt{\frac{10^{-4}\ \times 2}{10^{-3}}\left(1-\left(\frac{1000}{1100}\right)^2\right)} = 0.186$$

Dynamic Resistance

Dynamic Resistance



Chopper and Dynamic Resistance can absorb the extra energy

Example

- A grid fault occurs while Type 4 turbine is capturing 1MW from wind. The dc/ac converter is disabled during fault and the extra kinetic energy is dissipated in a dynamic resistance bank. The excitation system is adjusted to keep the terminal voltage of the generator at 1.0kV. Compute the value of the dynamic resistance.

<u>Solution:</u>

$$R_{DR} = \frac{V_a^2}{P_{DR}} = \frac{10^6}{10^6} = 1\,\Omega$$

Website

Use the course website:

- To check for announcements
- To get copies of the lecture slides and other material
- To get the homework and project assignments

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