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Tafila Technical University

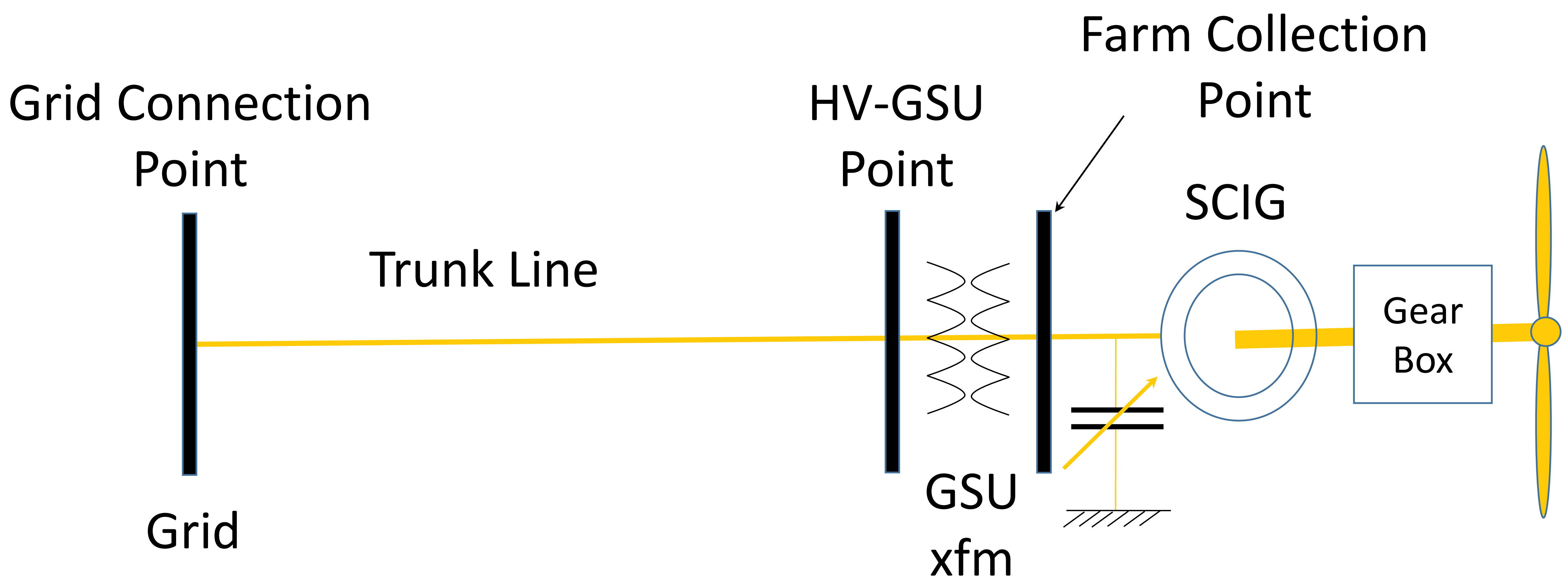
EE 0113416
Wind Energy Systems

Chapter 4:
Type 1 Wind Turbine System (SCIG)

Dr. Abdullah Awad

Email:
abdullah.awad@ttu.edu.jo

Type1: Squirrel Cage Induction Generator (SCIG)



generator step-up (GSU) transformers,

Type 1 System

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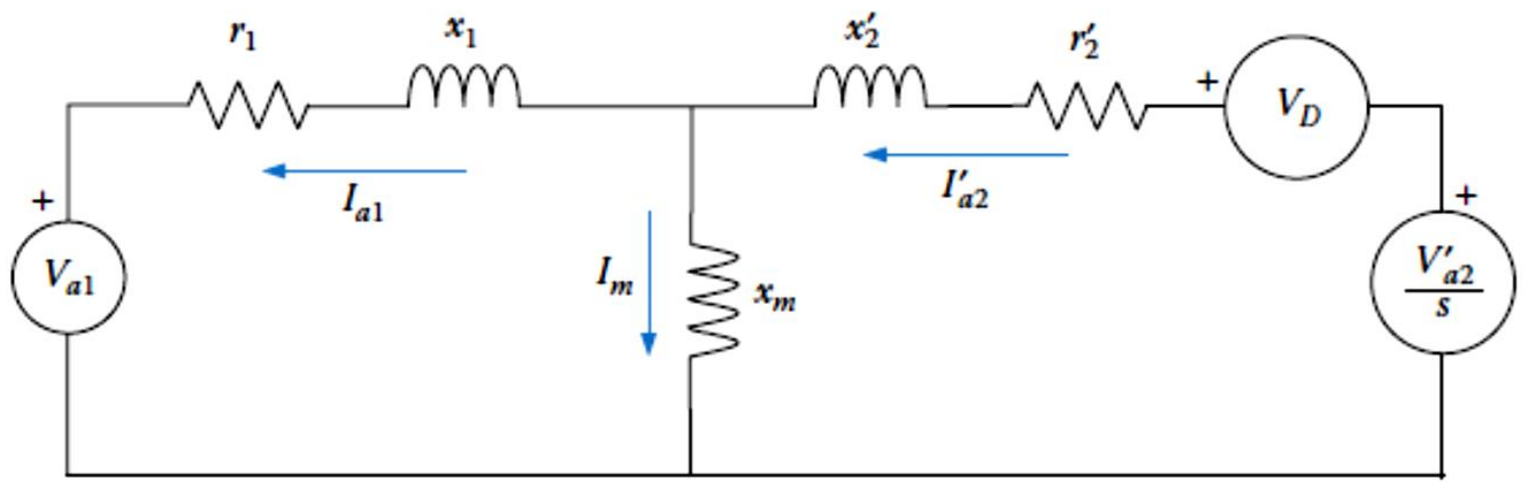
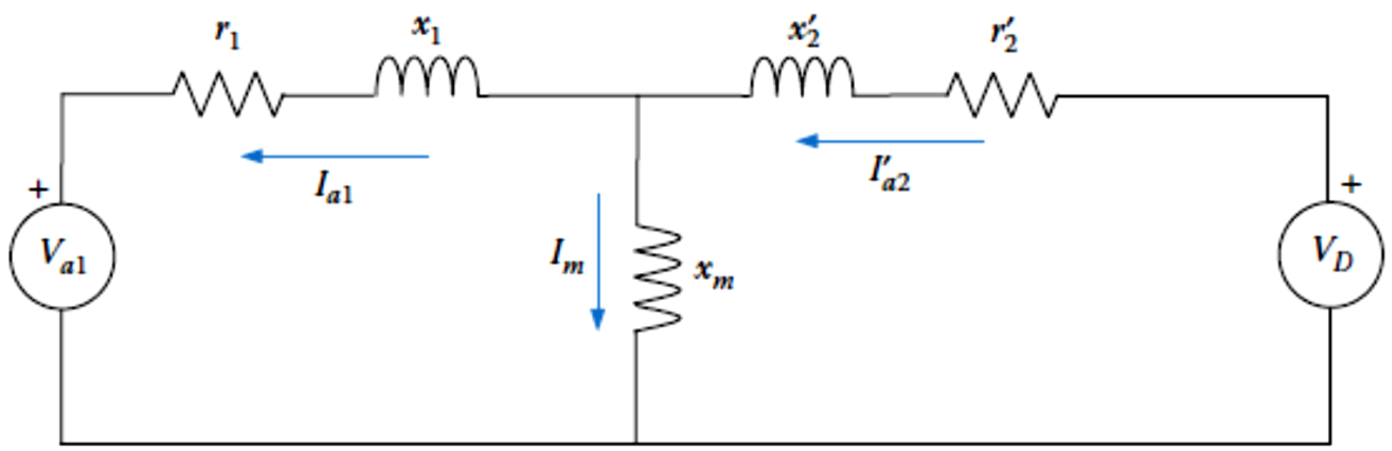
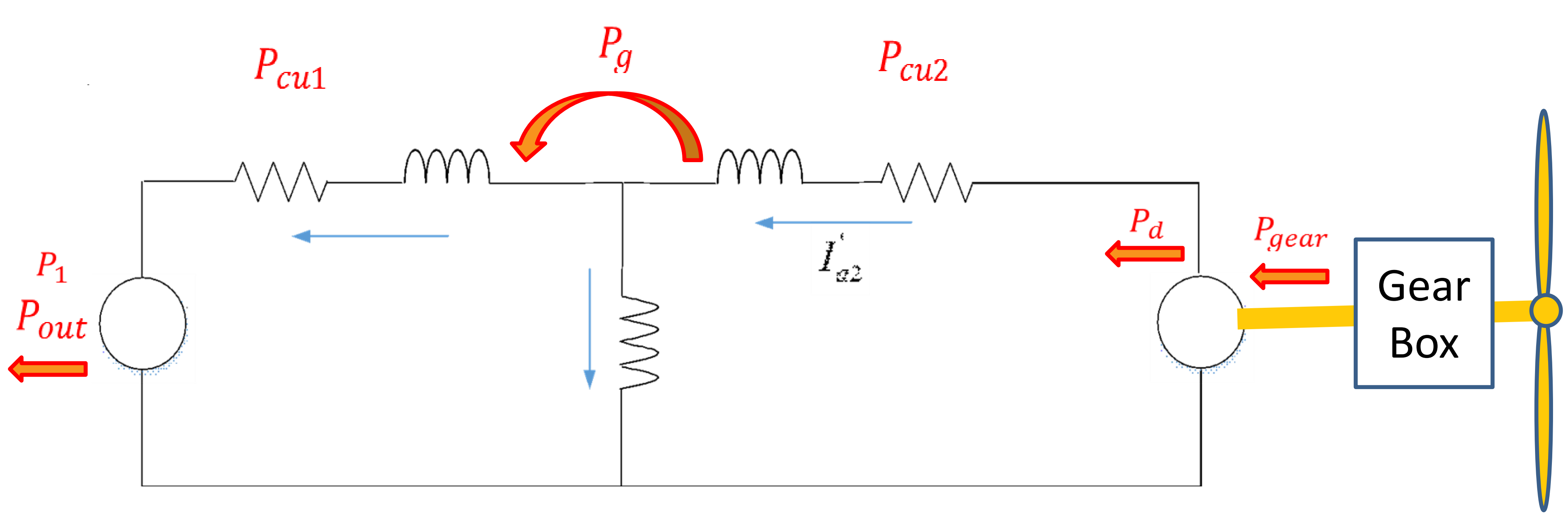
$$V_D = -r_d I'_{a2} = -\frac{r'_2}{s}(1-s)I'_{a2}$$

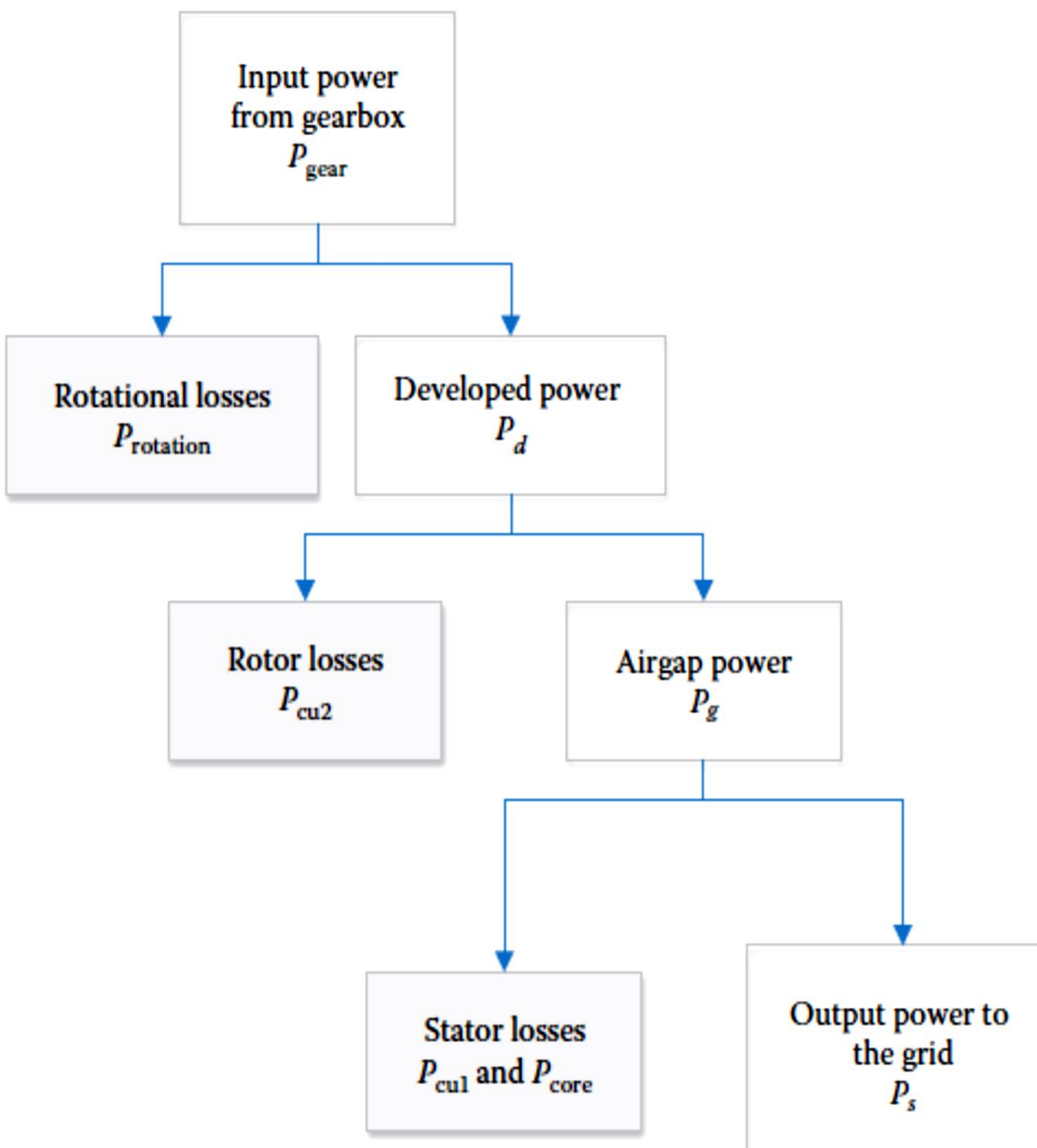




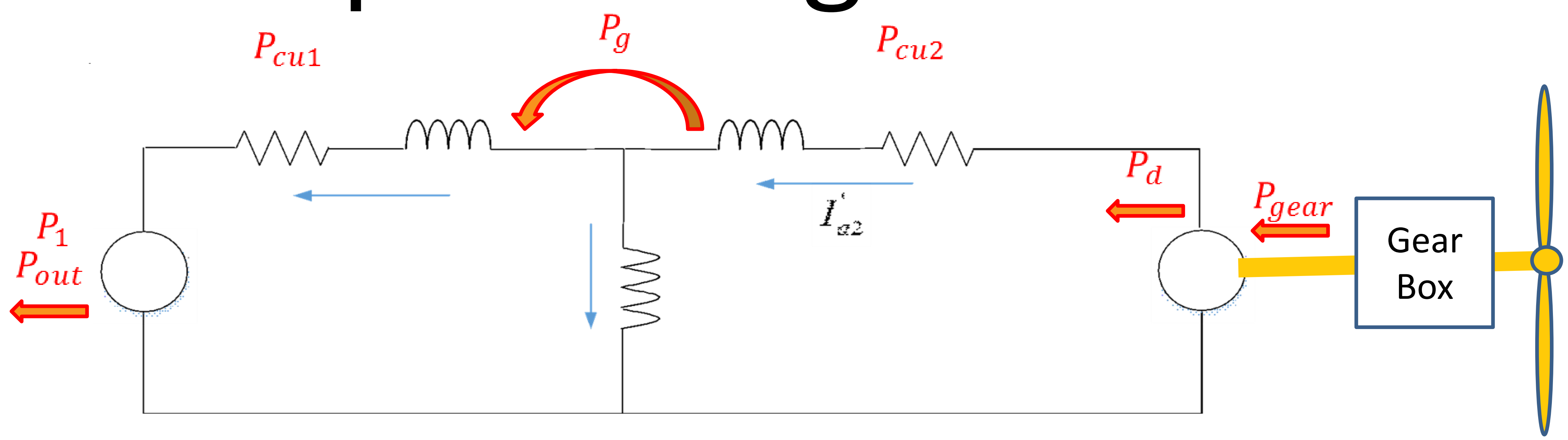
When the generator is *not* subjected to external injection, $v'_{a2} = 0$

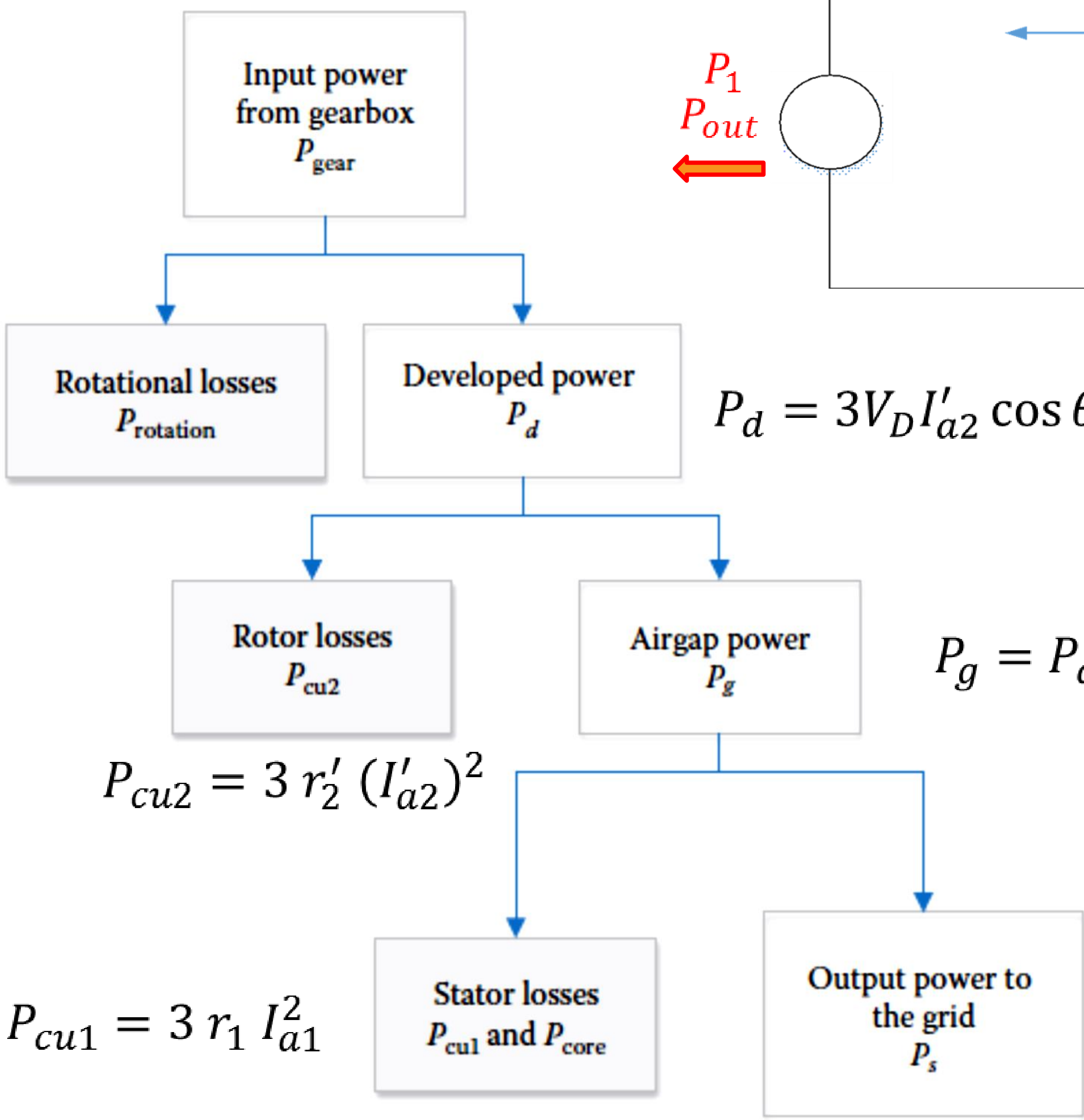
Power Flow: Squirrel Cage Generator





Power Flow: Squirrel Cage Generator





$$P_d = 3V_D I'_{a2} \cos\theta = -3r_d (I'_{a2})^2 = -3\frac{r'_2}{s}(1-s)(I'_{a2})^2 = T_d \omega_2$$

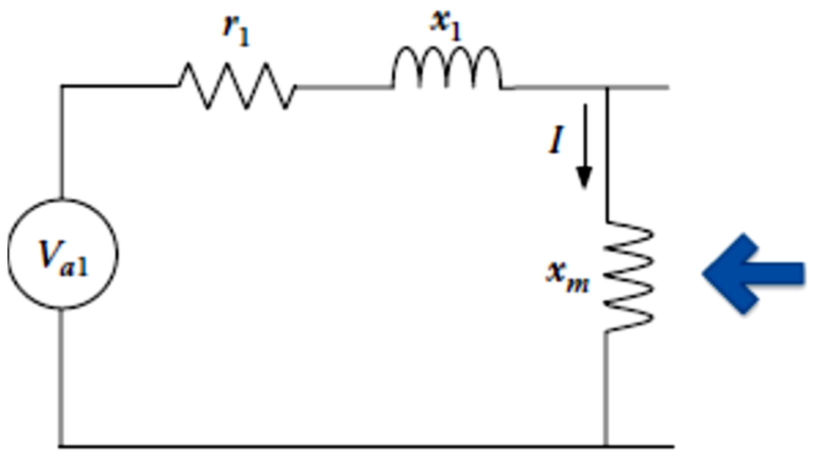
$$P_g = P_d - P_{cu2} = -3\frac{r'_2}{s}(I'_{a2})^2 = T_d\ \omega_s \Rightarrow P_g = \frac{P_d}{(1-s)}$$

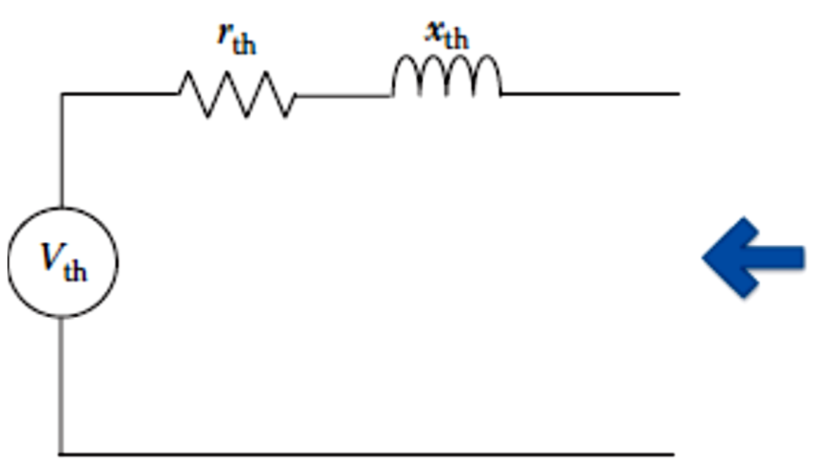
$$P_{cu2} = 3\ r'_2\ (I'_{a2})^2$$

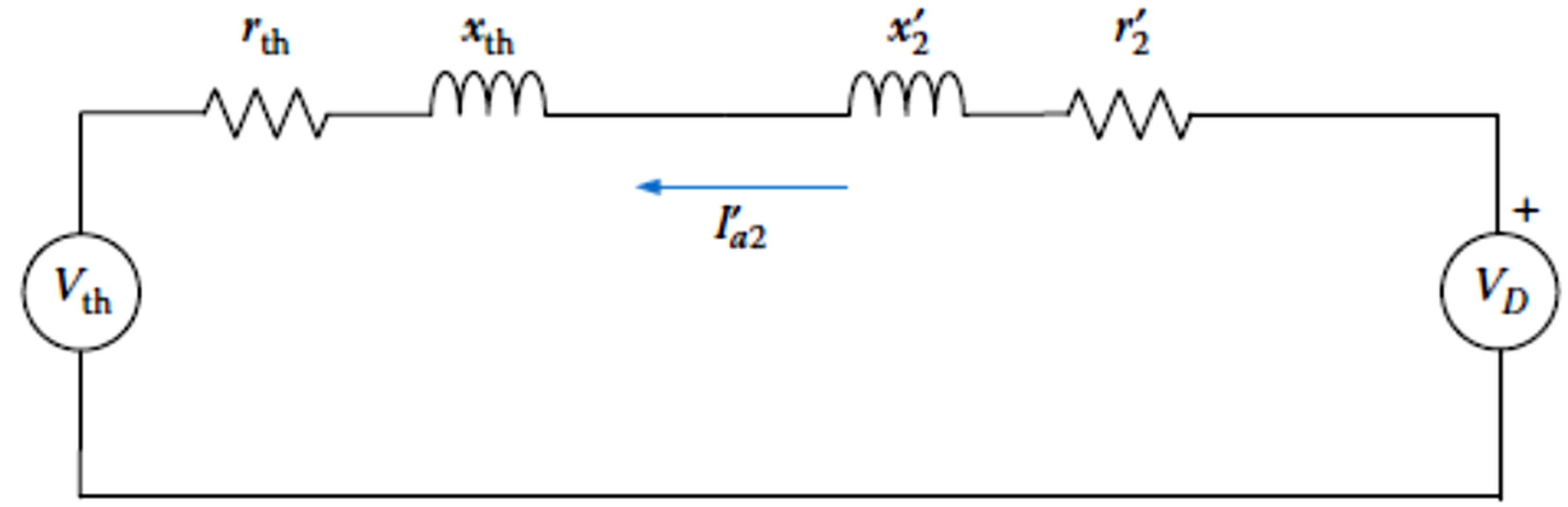
$$P_{cu1} = 3\ r_1\ I_{a1}^2$$

$$P_1 = P_g - P_{cu1} = -3\frac{r'_2}{s}(I'_{a2})^2 - 3\ r_1\ I_1^2 = 3V_{a1} I_{a1} \cos\theta_1$$

Reduced Model for Stator



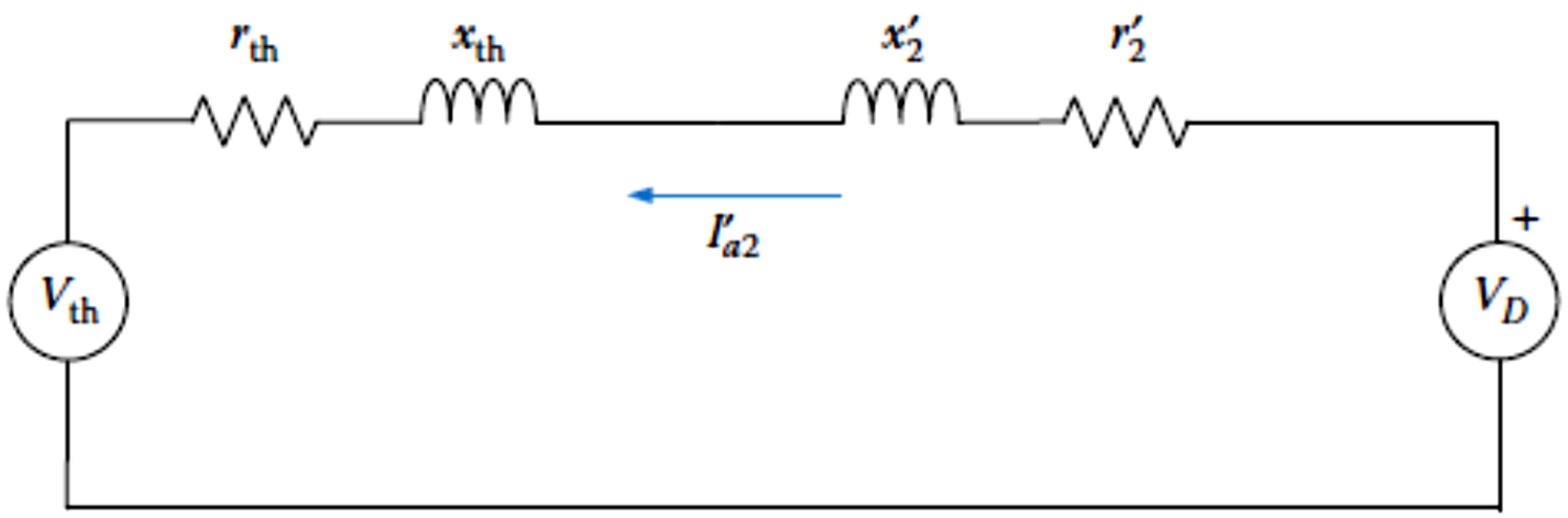




$$\bar{Z}_{th} = \frac{jx_m(r_1 + jx_1)}{r_1 + j(x_1 + x_m)} = r_{th} + x_{th}$$

$$\bar{V}_{th} = jx_m\bar{I} = jx_m\frac{\bar{V}_{a1}}{r_1 + j(x_1 + x_m)}$$

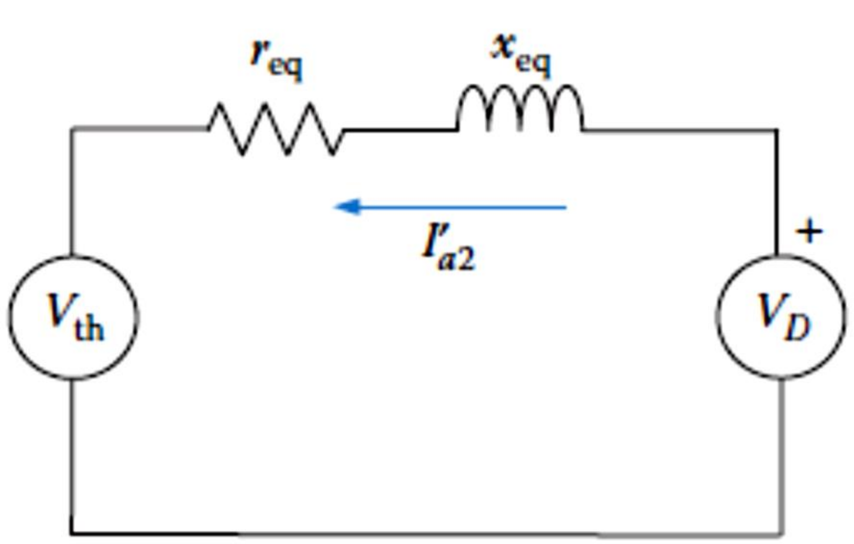
Equivalent Circuit



$$\bar{I'}_{a2} = \frac{\bar{V}_D - \bar{V}_{th}}{r_{eq} + jx_{eq}}$$

$$\bar{V}_D = -r_d \bar{I}'_{a2} = -\frac{r'_2}{s}(1-s)\bar{I}'_{a2}$$

$$\bar{I}'_{a2} = \frac{-\bar{V}_{th}}{\left(r_{th} + \frac{r'_2}{s}\right) + jx_{eq}}$$



$$r_{eq} = r_{th} + r'_2$$
$$x_{eq} = x_{th} + x'_2$$

$$I'_{a2} = \frac{V_{th}}{\sqrt{\left(r_{th} + \frac{r'_2}{s}\right)^2 + x_{eq}^2}}$$

Speed Torque Characteristics

$$P_d = -3\frac{r_2'}{s}(1-s)(I_{a2}')^2 = T_d\omega_2$$

$$T_d = -3\frac{r_2'}{s\omega_2}(1-s)(I_{a2}')^2 = -3\frac{r_2'}{s\omega_s}(I_{a2}')^2$$

$$I'_{a2} = \frac{V_{th}}{\sqrt{\left(r_{th}+\frac{r_2'}{s}\right)^2 + x_{eq}^2}}$$

$$T_d = -3\frac{r_2'}{s\omega_s}\frac{V_{th}^2}{\left(r_{th}+\frac{r_2'}{s}\right)^2 + x_{eq}^2}$$

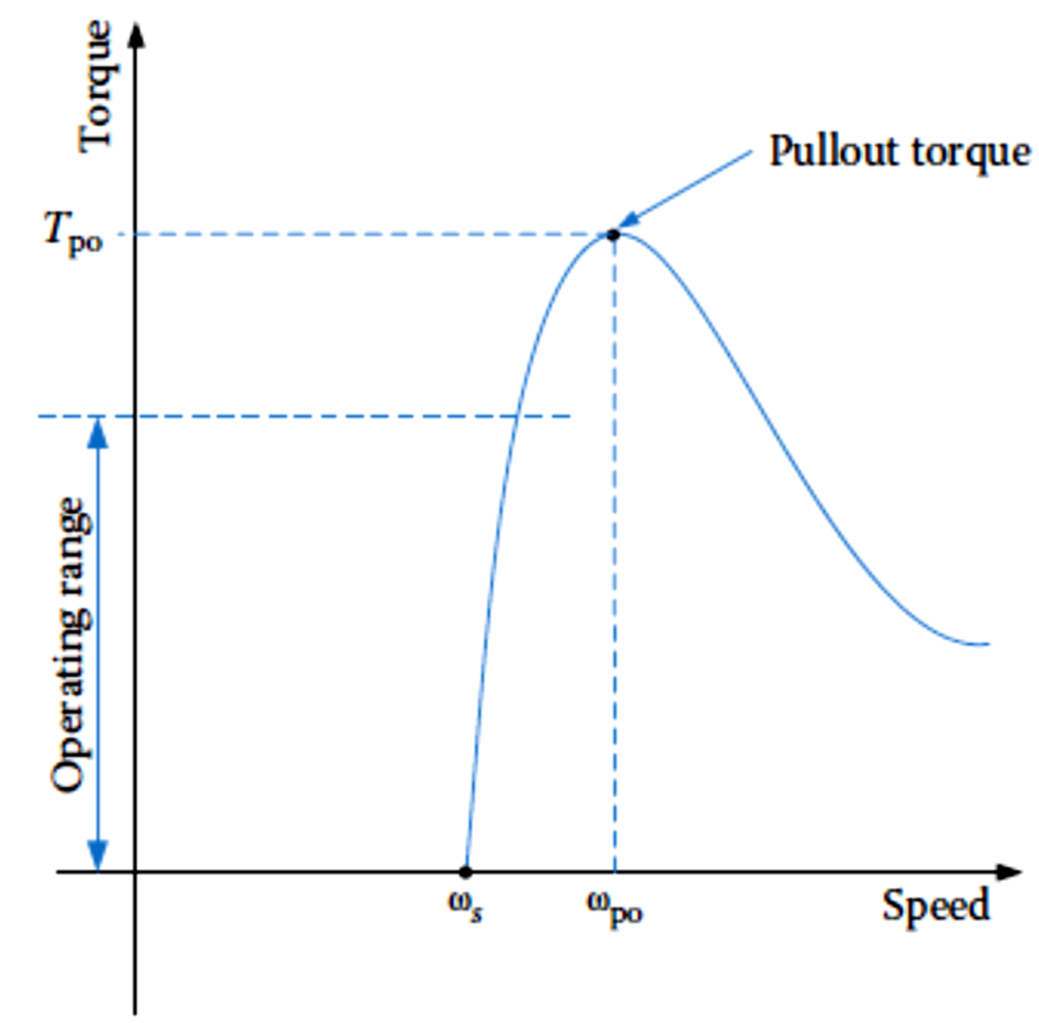


FIGURE 8.8
Torque–speed characteristic of a squirrel-cage induction generator.

Example

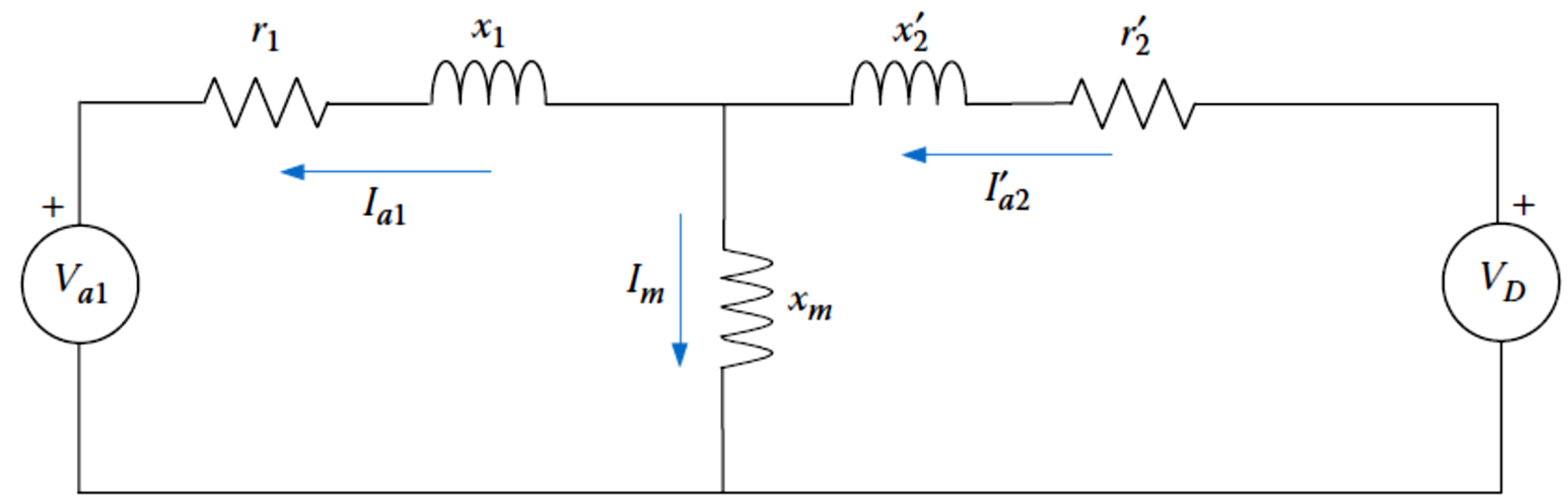
A Type 1 wind turbine with 6-pole, 60Hz three-phase, Y-connected induction generator is spinning the generator at 1250 r/min. The terminal voltage of the generator is 690 V. The parameters of the machine are:

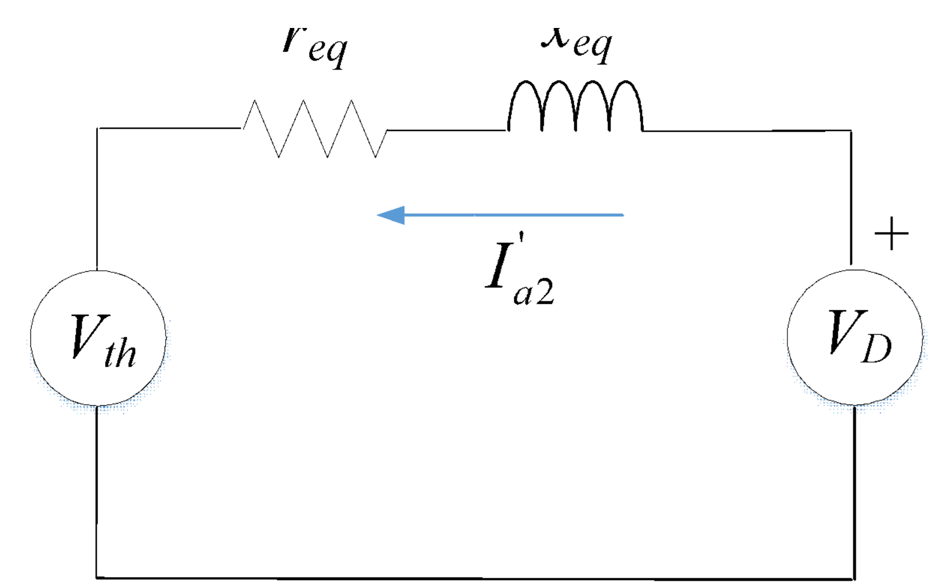
$$r_1 = r_2' = 10 \text{ m}\Omega;\ x_1 = x_2' = 100 \text{ m}\Omega;\ x_m = 2\ \Omega$$

Ignore the core losses and the rotational losses of the generator. Compute the following

a. Current in the rotor circuit referred to stator
b. Developed power
c. Airgap power
d. Power delivered to the grid

Solution: Part a





$$\bar{V}_{th} = jx_m \frac{\bar{V}_{a1}}{r_1 + j(x_1 + x_m)} = j2 \frac{\frac{690}{\sqrt{3}} \angle 0^o}{0.01 + j2.1} = 379.39\angle 0.27^o \text{ V}$$

$$\bar{Z}_{th} = \frac{jx_m(r_1 + jx_1)}{r_1 + j(x_1 + x_m)} = \frac{j2 \times (0.01 + j0.1)}{0.01 + j2.1} = 0.00907 + j0.09528 \ \Omega$$

$$n_s = 120\frac{f}{p} = 120\frac{60}{6} = 1200 \ \text{ r/min} \qquad s = \frac{n_s - n}{n_s} = \frac{1200 - 1250}{1200} = -0.0417$$

$$\bar{I}_{a2}' = \frac{-\bar{V}_{th}}{\left(r_{th} + \frac{r_2'}{s}\right) + j(x_{th} + x_2')} = -\frac{379.39\angle 0.27^o}{\left(0.00907 + \frac{0.01}{-0.0417}\right) + j0.19528} = 1.255\angle 40.23^o \ \text{ kA}$$

Solution: Parts b and c

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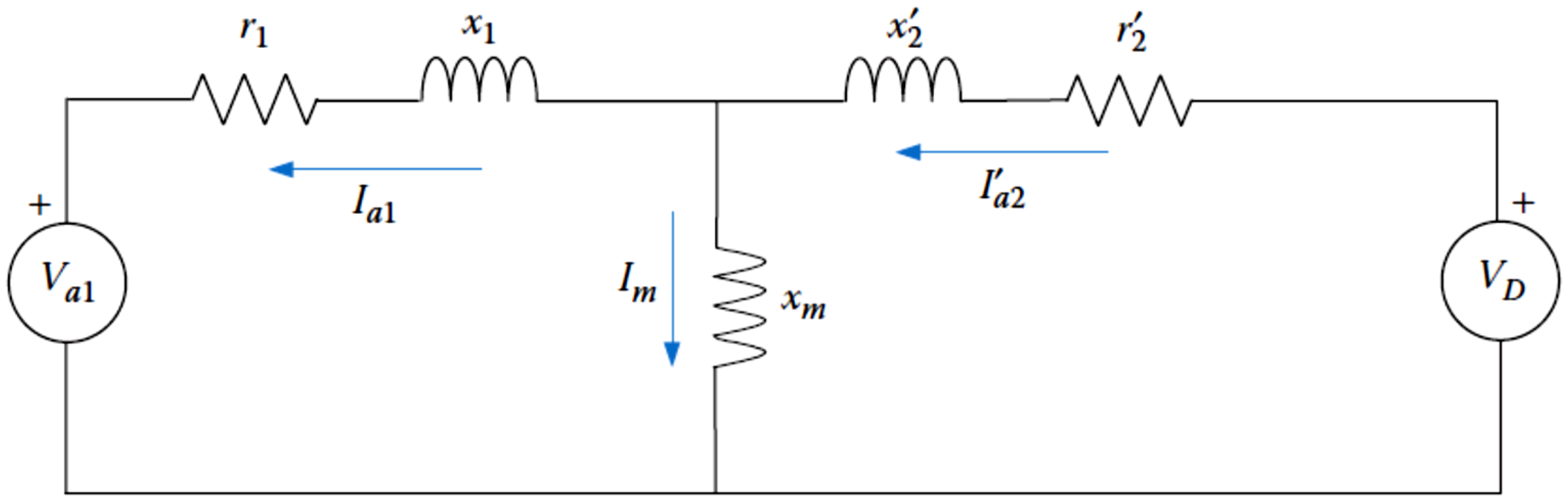

$$P_d = -3\frac{r_2'}{s}(1-s)(I_{a2}')^2 = -3\frac{0.01}{-0.0417}(1+0.0417)(1255)^2 = 1.18 \text{ MW}$$

$$P_g = P_d - P_{cu2} = P_d - 3r_2'(I_{a2}')^2 = 1.828 - 3\times 0.01(1255)^2\times 10^{-6} = 1.132 \text{ MW}$$

Solution: Part d

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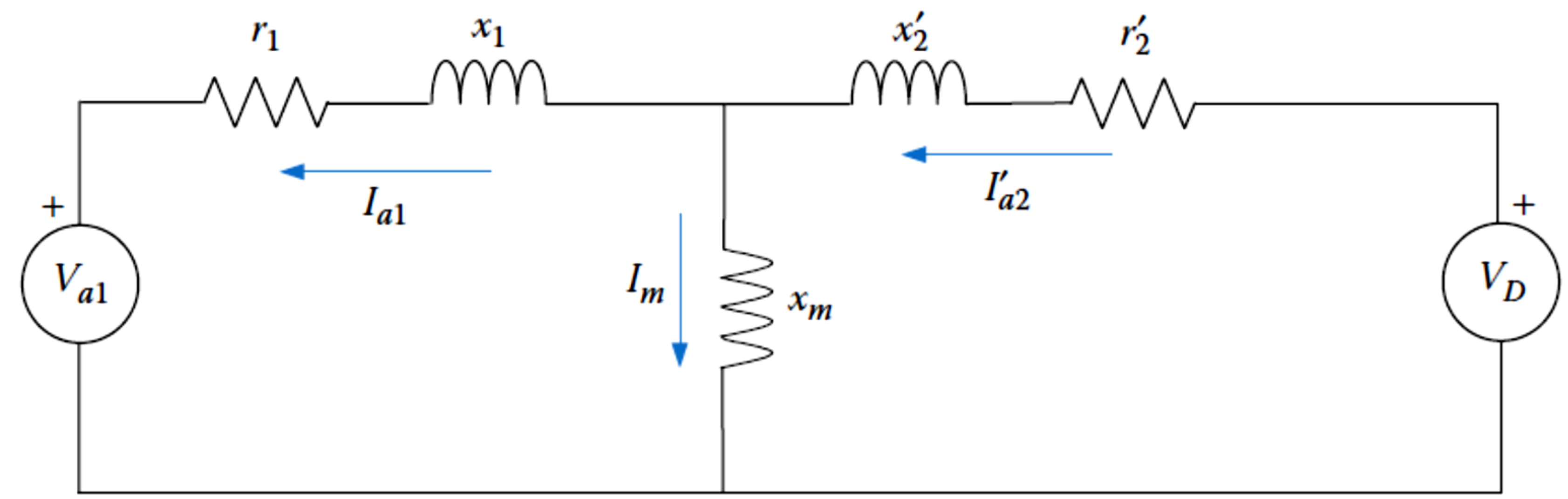

$$V_D = -\frac{'2}{s}(1-s)I'_{a2}$$

$$\bar{V}_m + \bar{I}'_{a2}\left(\frac{r'_2}{s} + jx'_2\right) = 0$$

$$\bar{V}_m = -\bar{I}'_{a2}\left(\frac{r'_2}{s} + jx'_2\right) = -1.255\angle 40.23^o \times \left(\frac{0.01}{-0.0417} + j0.1\right) = 326.08\angle 17.59^o \text{ V}$$

$$\bar{I}_{a1} = \frac{\bar{V}_m - \bar{V}_{a1}}{r_1 + jx_1} = \frac{326.08\angle 17.59^o - \frac{690}{\sqrt{3}}}{0.01 + j0.1} = 1.312\angle 47.31^o \text{ kA}$$

$$P_1 = P_g - 3r_1(I'_{a1})^2 = 1.75 - 3 \times 0.01 \times (1255)^2 \times 10^{-6} = 1.085 \text{ MW}$$

Limitations of Type 1

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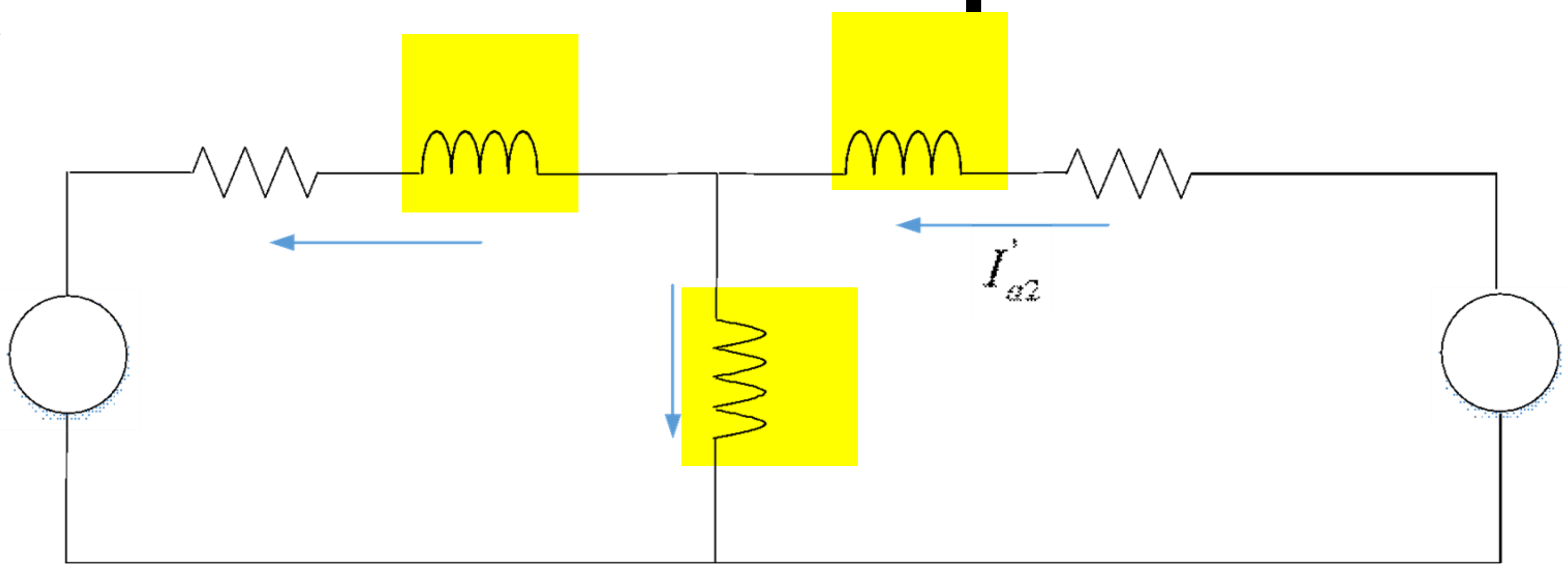
Type 1 system employs squirrel cage induction generator. Although inexpensive and rugged, the squirrel cage generator has some drawbacks, among them are:

- Without the rotating flux in the airgap, the generator cannot produce any power. The flux is produced by the grid voltage, and the generator must therefore be connected to the grid. Hence, Type 1 turbine cannot operate as a stand-alone system.
- The induction generator consumed reactive power from the grid as it cannot generate its own. Thus, Type 1 system cannot provide voltage support to the grid.
- The generator draws high current at starting. This can cause a dip in voltage and may cause the machine to trip due to excessive over currents.

Reactive power of Type 1 System



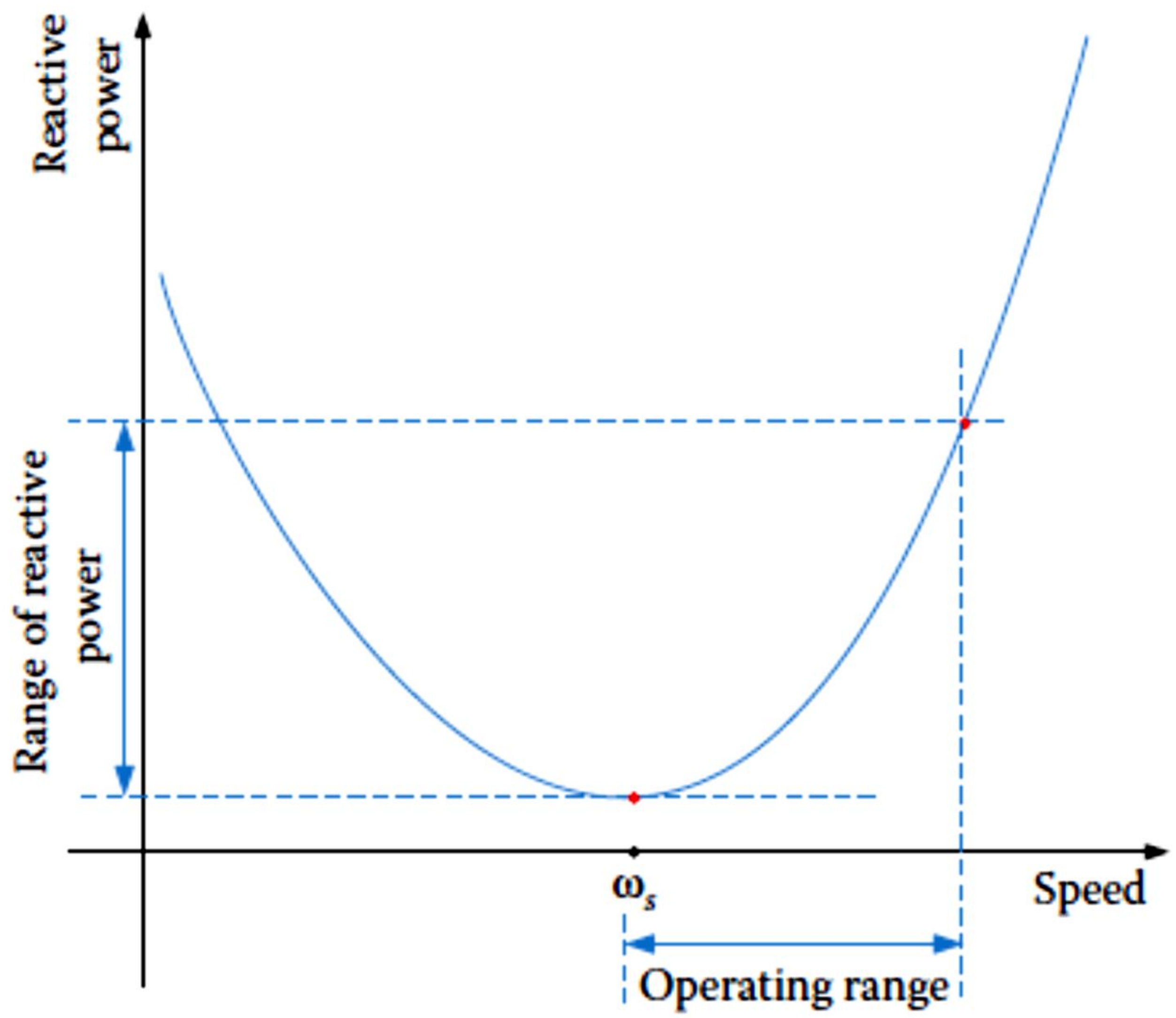
$$Q_1 = 3\, x_1 I_{a1}^2$$

$$Q_2 = 3\, x_2' (I_{a2}')^2$$

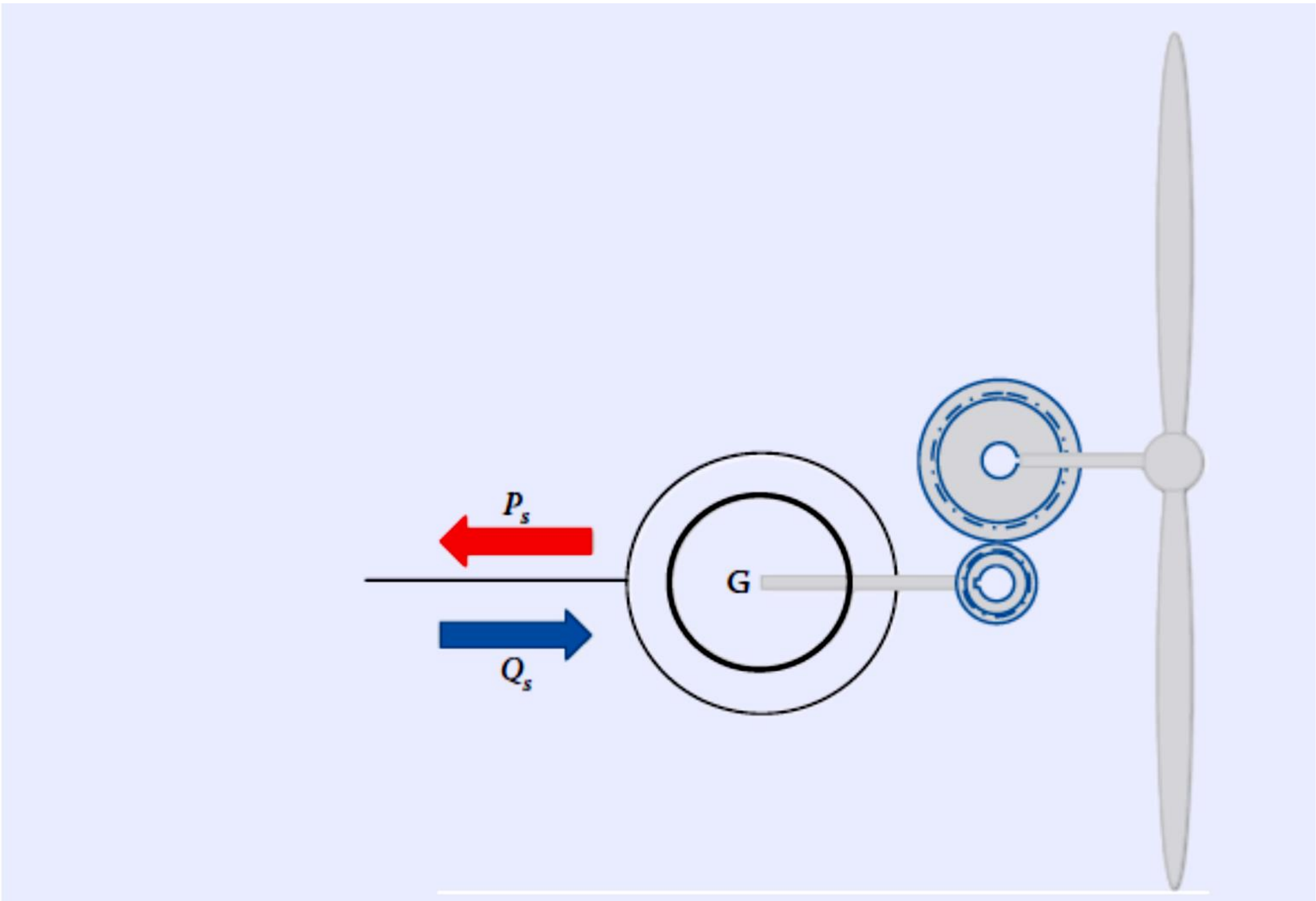
$$Q_m = 3\, x_m I_m^2$$

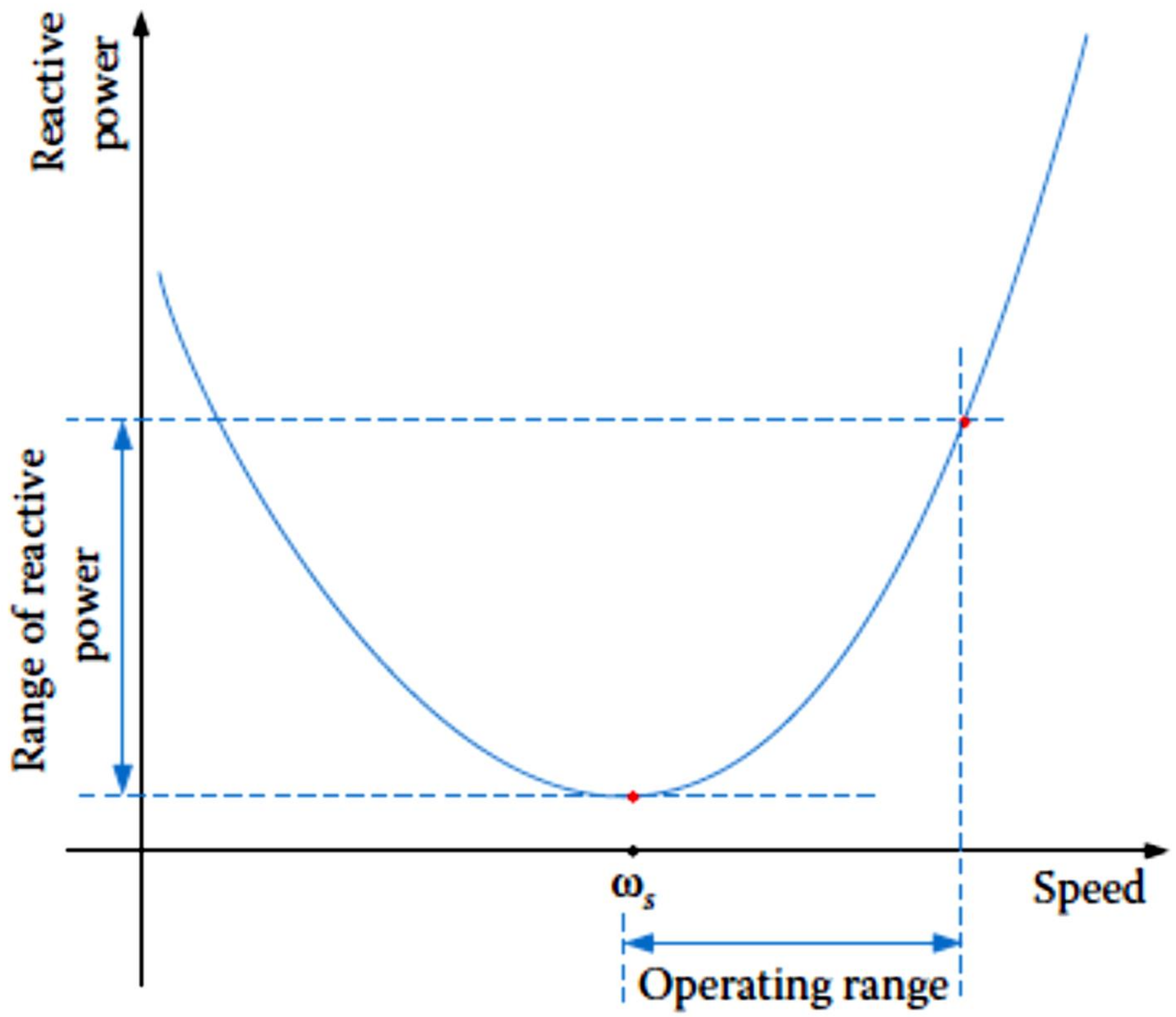
$$\bar{I}_{a2}' = \frac{-\bar{V}_{th}}{\left(r_{th} + \frac{r_2'}{s}\right) + j x_{eq}}$$

$$Q = Q_1 + Q_m + Q_2$$



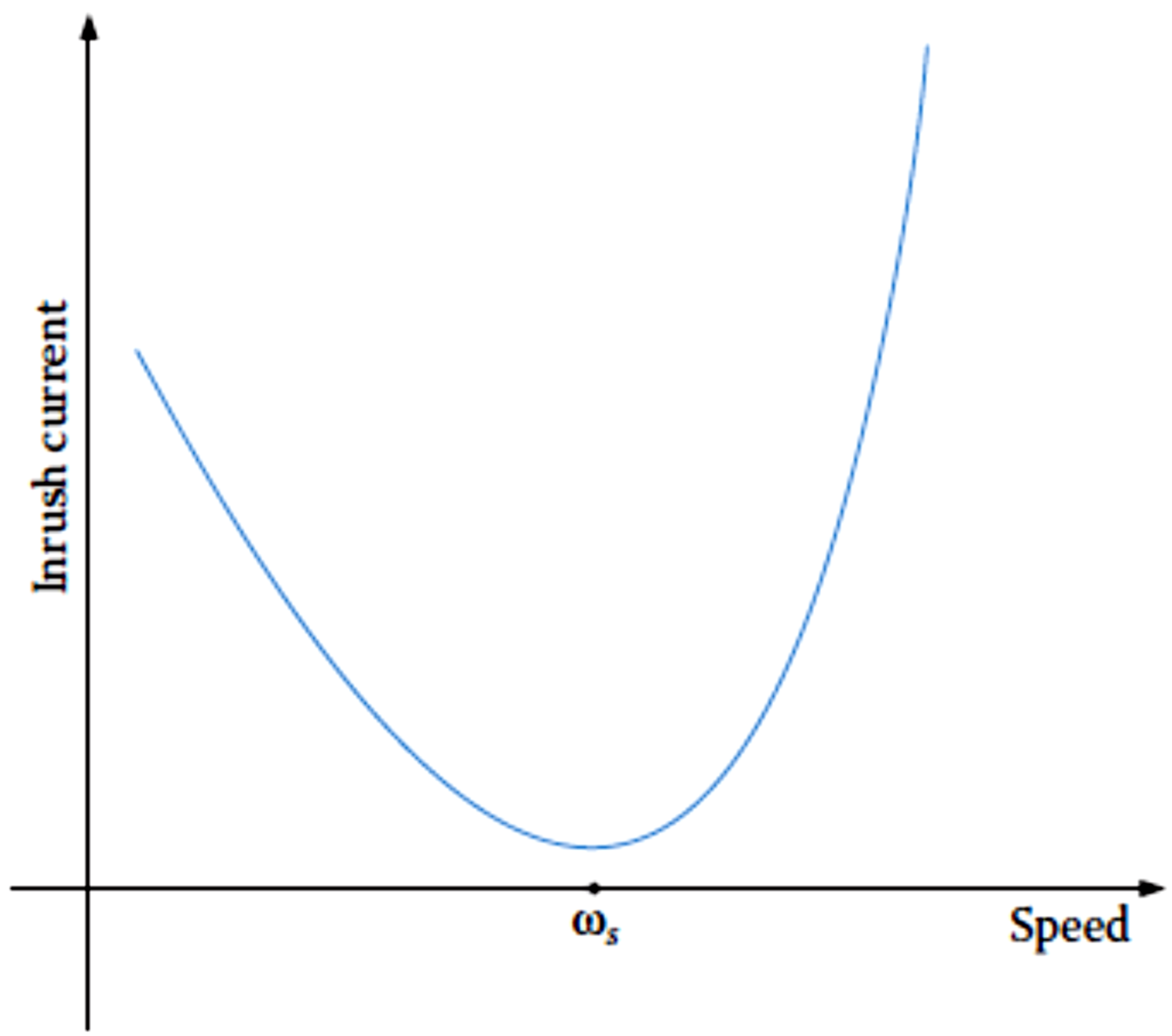
Reactive power of Type 1 System





Inrush Current

- At the moment when the generator is connected to the grid, its rotor speed could be different from the synchronous speed.
- Even for a small speed deviation, the current at the connection time could be excessive.
- This current is called inrush current.



Example

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A Type 1, 6-pole, 60Hz three-phase, Y-connected induction generator. The terminal voltage of the generator is 690 V. The parameters of the machine are:

$$r_1 = r_2' = 10 \text{ m}\Omega;\ x_1 = x_2' = 100 \text{ m}\Omega;\ x_m = 2\ \Omega$$

compute the rotor inrush current at starting. Assume the turbine is spinning the generator at 1350 r/min when the connecting switch is closed

Solution

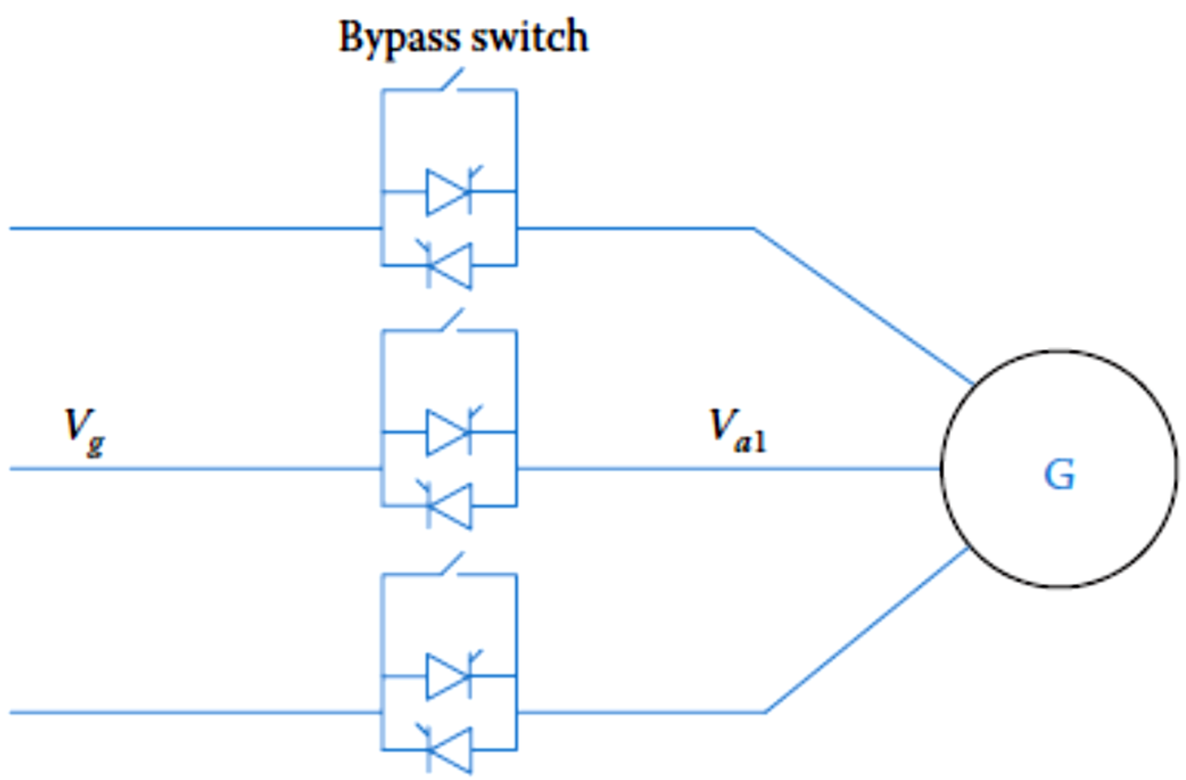
From previous example, $I'_{a2} = 1.562$ kA in normal operation

$$s = \frac{n_s - n}{n_s} = \frac{1200 - 1350}{1200} = -0.125$$

$$I'_{a2} = \frac{V_{th}}{\sqrt{\left(r_{th} + \frac{r'_2}{s}\right)^2 + x_{eq}^2}} = \frac{379.39}{\sqrt{\left(0.0952 + \frac{0.01}{-0.125}\right)^2 + 0.109^2}} = 3.447 \text{ kA}$$

$$\frac{3.447}{1.562} \times 100 = 221\%$$

Reduction of Inrush Current



$$V_{a1-st} = V_g \sqrt{\left(1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}\right)}$$

Stability

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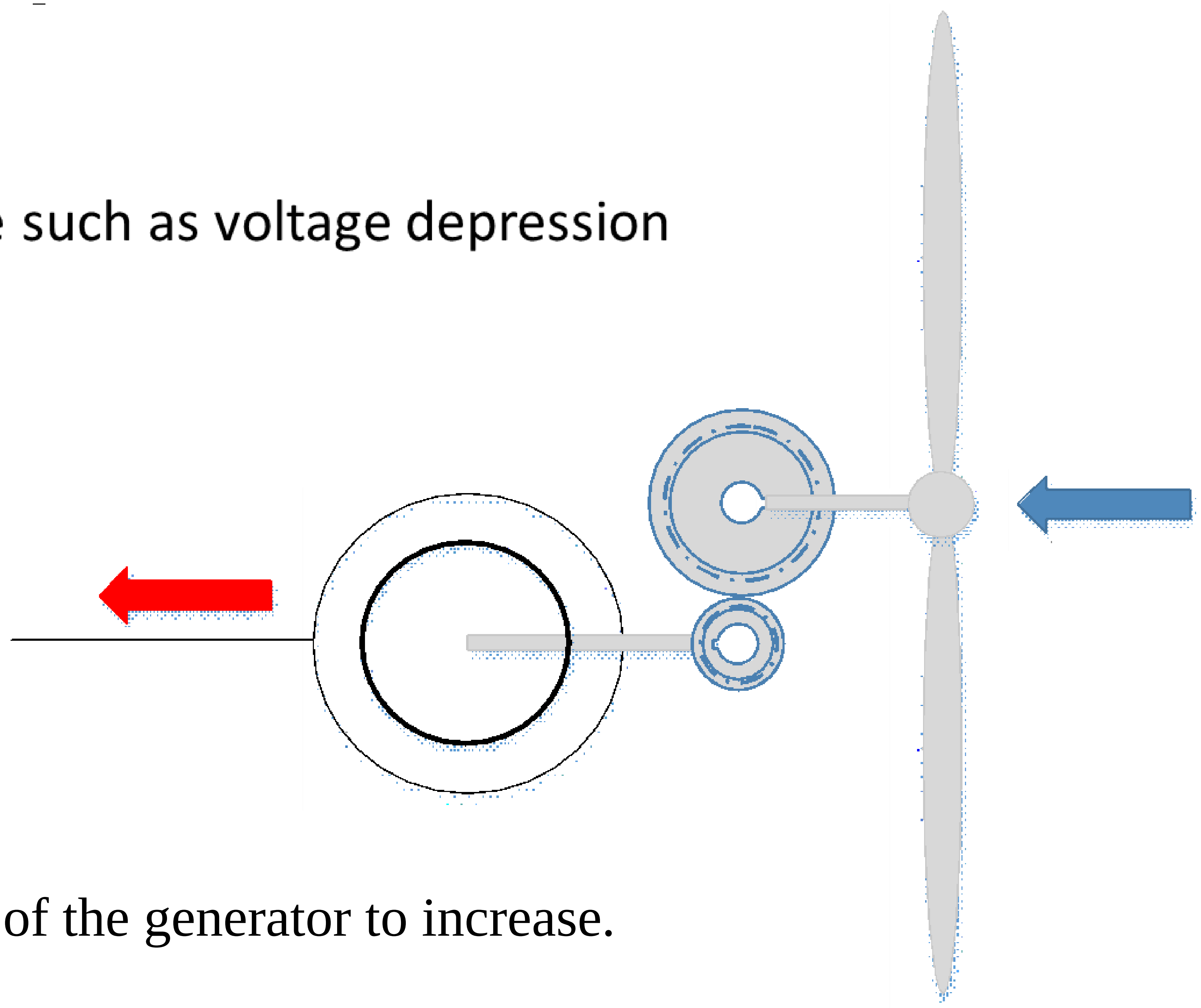
Ignore losses

What if $P_m > P_{out}$? Due to disturbance such as voltage depression

$$P_m t > P_{out} t \qquad E_m > E_{out}$$

$$\Delta KE = E_m - E_{out} = \frac{1}{2} J \frac{d\omega_2}{dt}$$



During fault $\Delta KE>0$ causing the speed of the generator to increase.

This could result in the blades speeding up to a level that could damage the turbine.

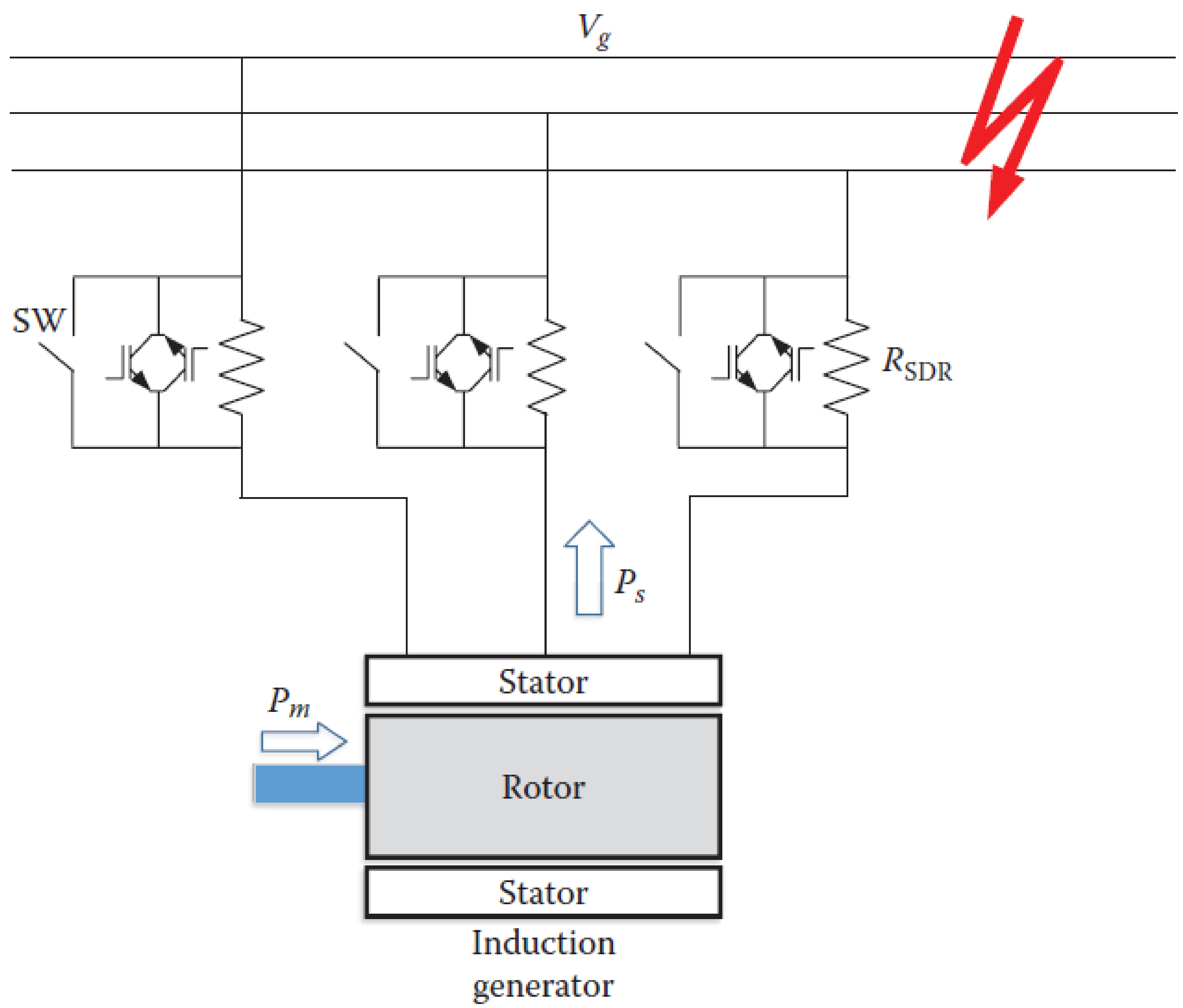
Options to Restore the Balance of Energy

- ***Option 1:*** Reduce the mechanical power quickly.
  - However, the mechanical power cannot be changed fast enough for the cases of severe faults.
  - Pitching the blades takes some time as it involves rapid motion of large masses (blades, gearbox, generator, etc.).
  - In addition, rapid actuation may cause the blades to wobble and could hit the tower.
- ***Option 2:*** Increase the electrical power output.
- ***Option 3:*** A combination of Option 1 and Option 2

Increase the Electrical Power Output During Faults

- Option 2 can be implemented by two methods:
  - Store the extra energy ΔKE somewhere outside the rotating mass.
  - Dissipate the extra energy in external circuits.

Stator dynamic Resistance (SDR)



Stator dynamic Resistance (SDR)

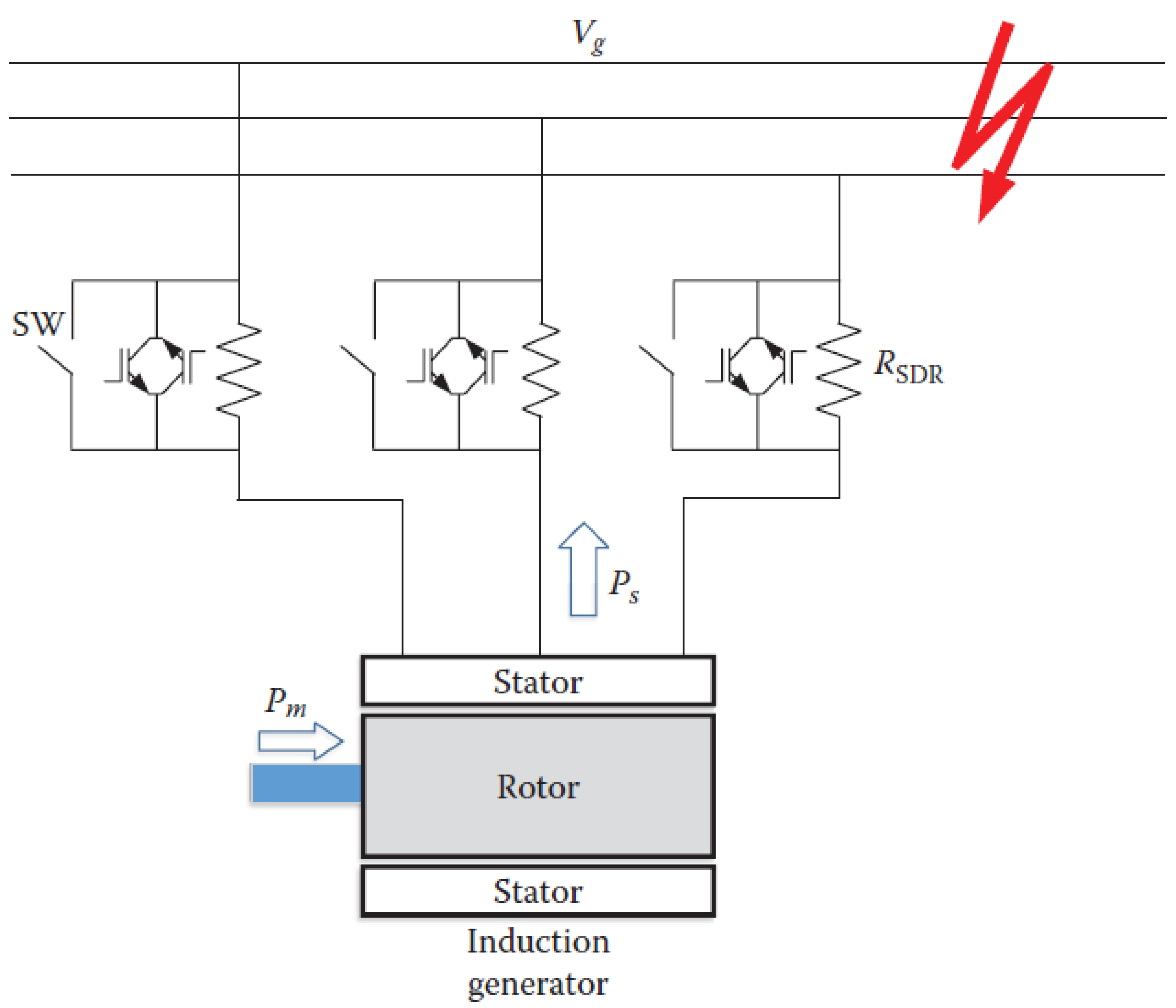
$$p_{SDR} = 3\, i^2\, R_{SDR}$$

$$i = I_{max} \sin \omega t$$

$$P_{SDR} = \frac{3}{\pi}\left[\int_0^{\alpha} i^2 R_{SDR}\ d\omega t + \int_{\beta}^{\pi} i^2 R_{SDR}\ d\omega t\right]$$

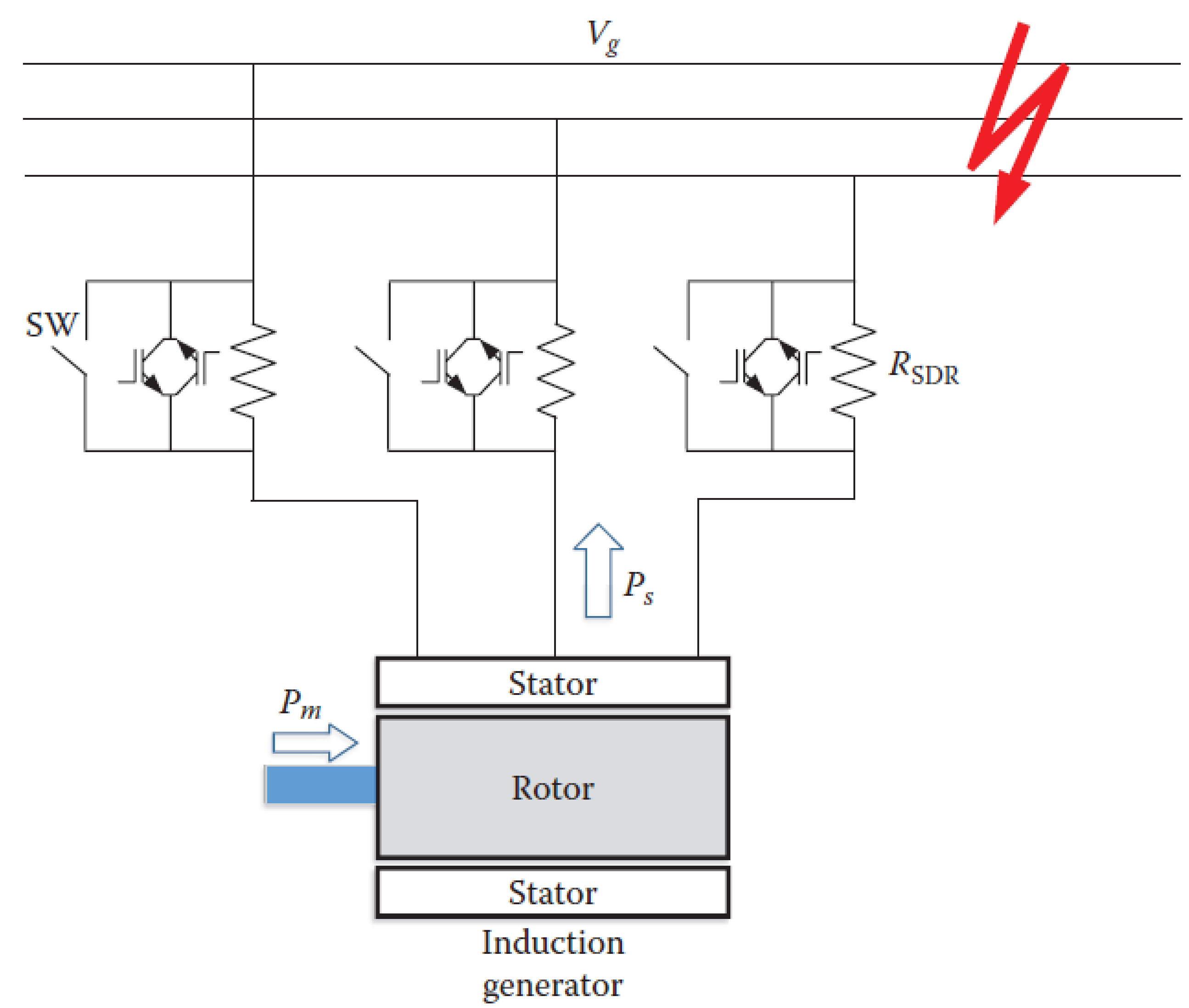
$$P_{SDR} = \frac{3\, I_{a1}^2\, R_{SDR}}{\pi}\left(\pi - \gamma - \frac{\sin 2\alpha}{2} + \frac{\sin 2\beta}{2}\right)$$

$$\gamma = \beta - \alpha$$



Stator dynamic Resistance (SDR)

$$P_{SDR} = \frac{3\, I_{a1}^2\, R_{SDR}}{\pi}\left(\pi - \gamma - \frac{\sin 2\alpha}{2} + \frac{\sin 2\beta}{2}\right)$$



Effective resistance

$$R_e = \frac{R_{SDR}}{\pi}\left(\pi + \gamma - \frac{\sin 2\alpha}{2} + \frac{\sin 2\beta}{2}\right)$$

$$P_{SDR} = 3\, I_{a1}^2 R_e$$

Set the current equal to the steady state fault current

$$I_{a1} = I_{f-ss}$$

Example

- A fault occurs near Type 1 wind turbine causing the voltage at the grid side to substantially reduce. The fault lasts for 100ms, and its steady state value is 1000A. During fault, the average deficit in energy is 300kJ. Compute the value of the effective resistance to be inserted between the generator and the grid during fault.

If the SDR resistance is 5Ω, compute the triggering and commutation angles

Solution

$$P_{SDR} = \frac{E_{SDR}}{t} = \frac{300}{0.1} = 3.0 \ \text{MW}$$

$$R_e = \frac{P_{SDR}}{3\, I_{f-ss}^2} = \frac{3 \times 10^6}{3 \times 10^6} = 1.0$$

$$\frac{R_e}{R_{SDR}} = \frac{1}{5} = \frac{1}{\pi}\left(\pi - \gamma - \frac{\sin 2\alpha}{2} + \frac{\sin 2\beta}{2}\right)$$

$$\text{set } \alpha = 30^o$$

$$-2.603 = -\beta + \frac{\sin 2\beta}{2}$$

$$\beta = 123^o$$

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