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EE 0113416
Wind Energy Systems

Chapter 5:
Type 2 Wind Turbine System

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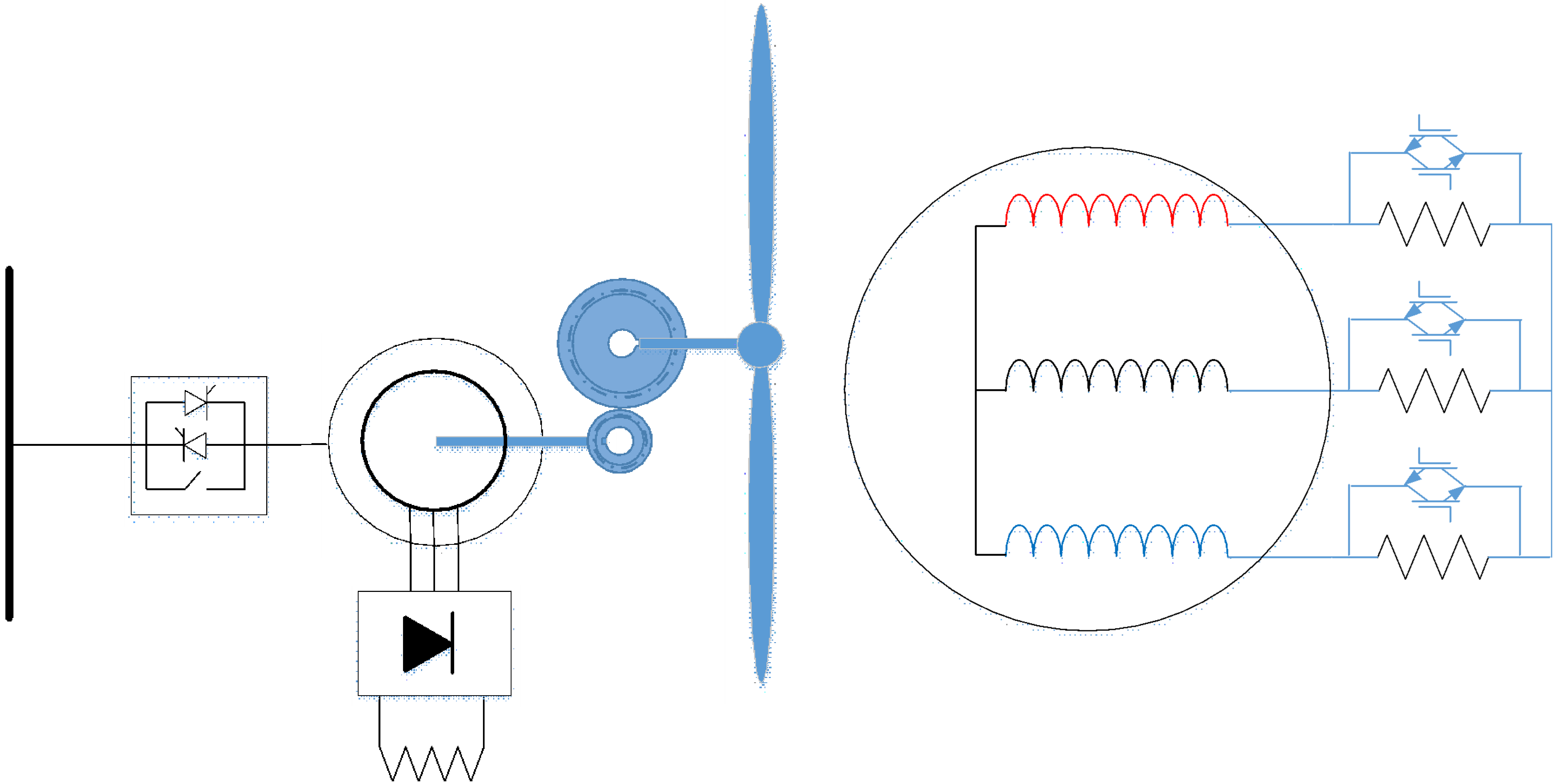
Equivalent Circuit of Type 2 Generator



Rotor Representation

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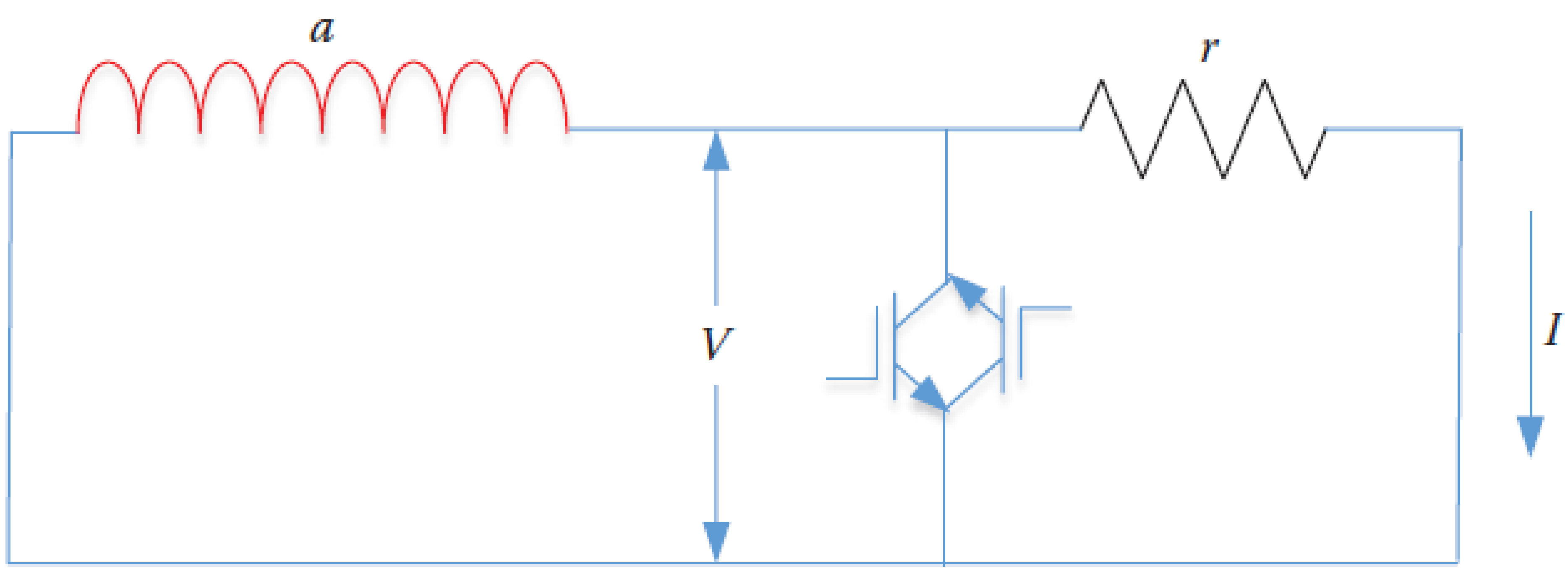
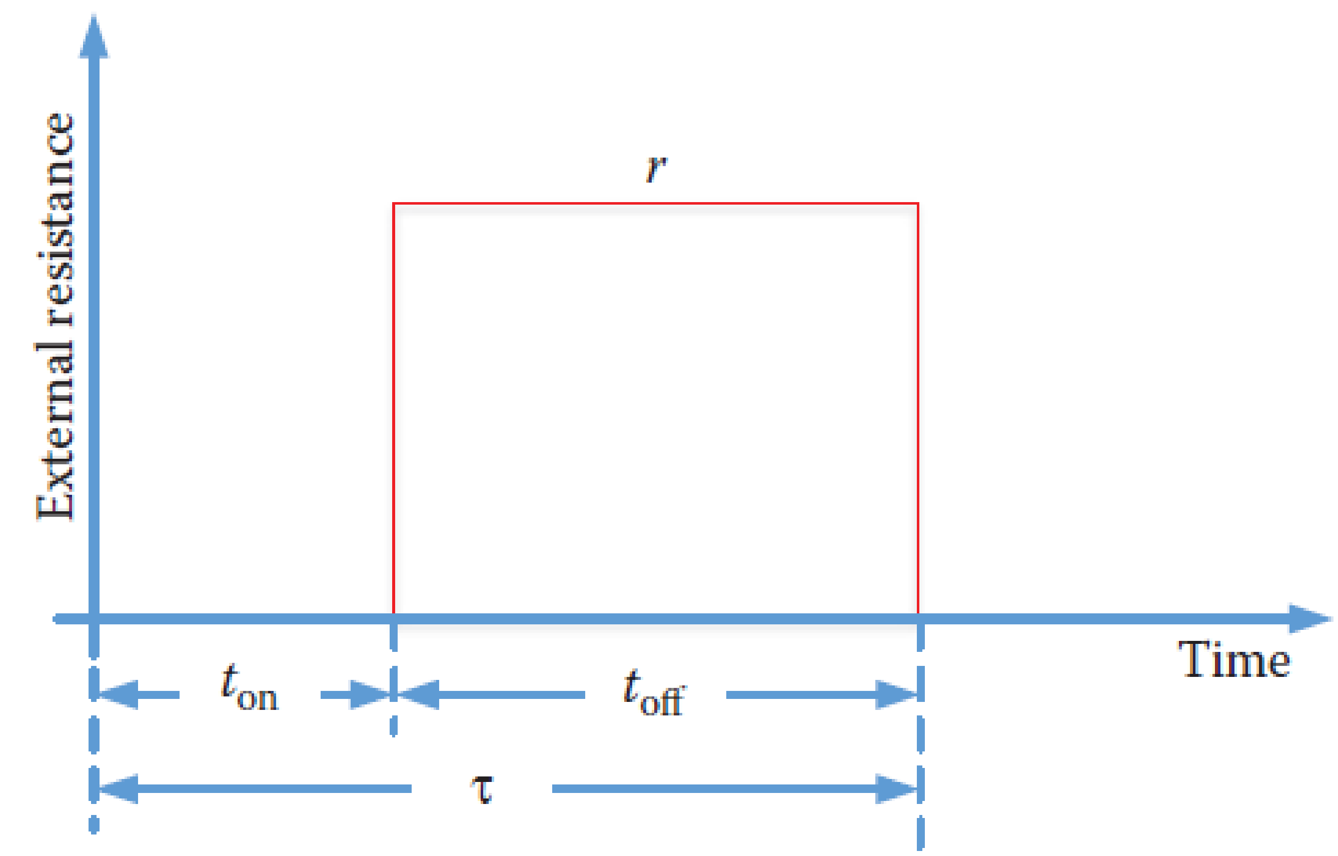


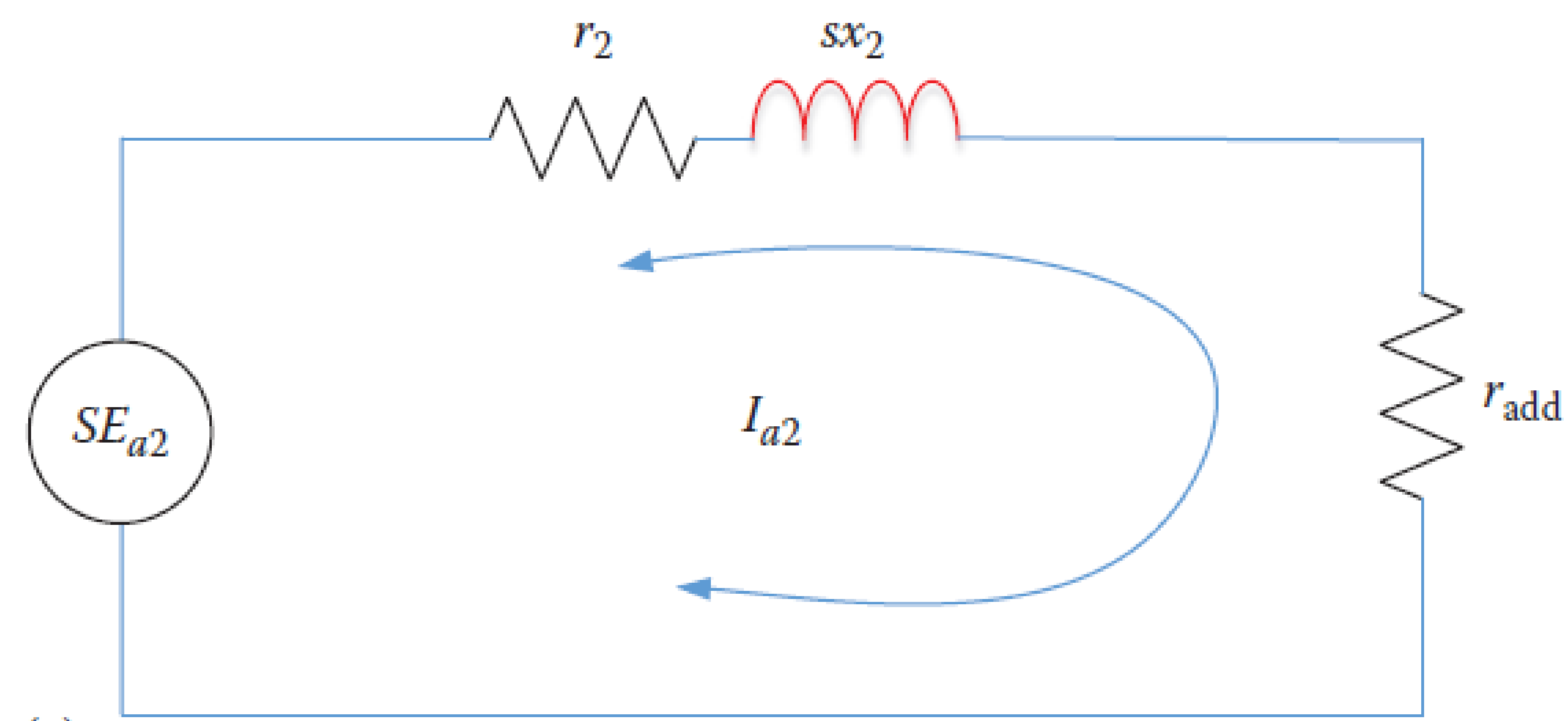
$$r_{add} = \frac{1}{\tau}\int_0^{\tau} r\,dt = r\frac{\tau - t_{on}}{\tau} = r(1-k)$$

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



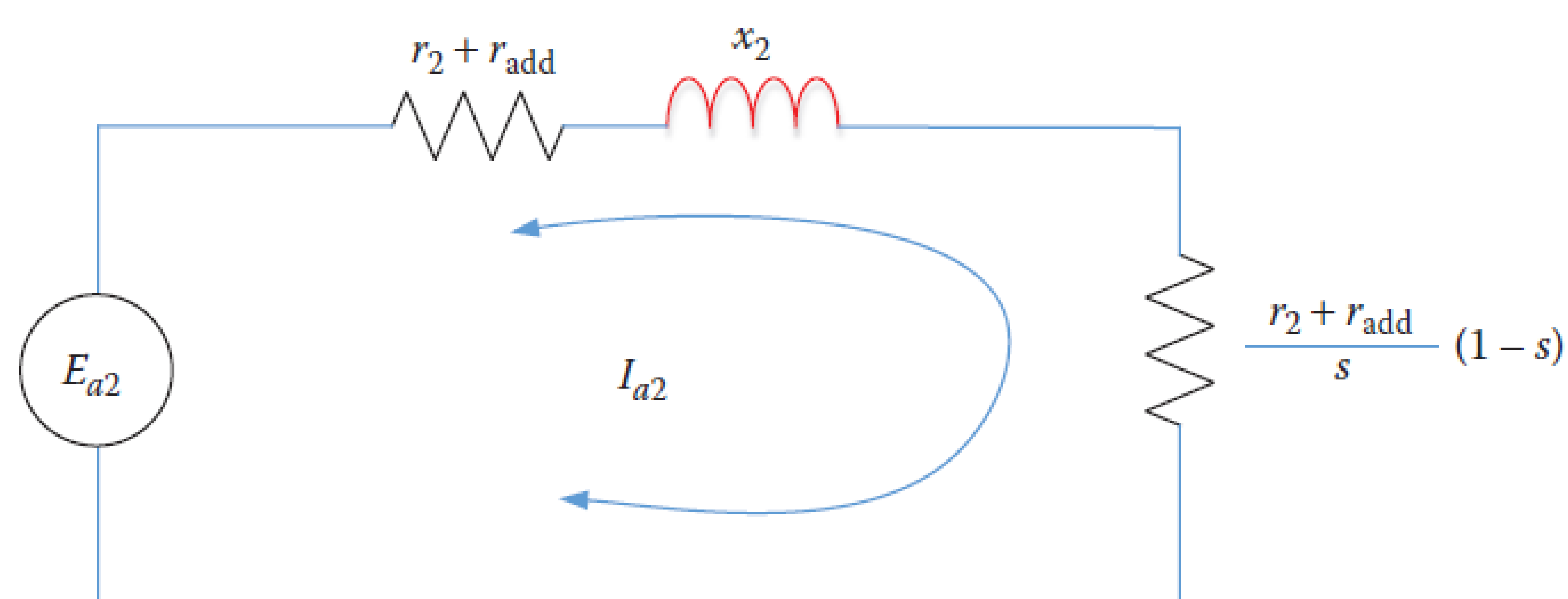
Rotor Circuit

Without added resistance



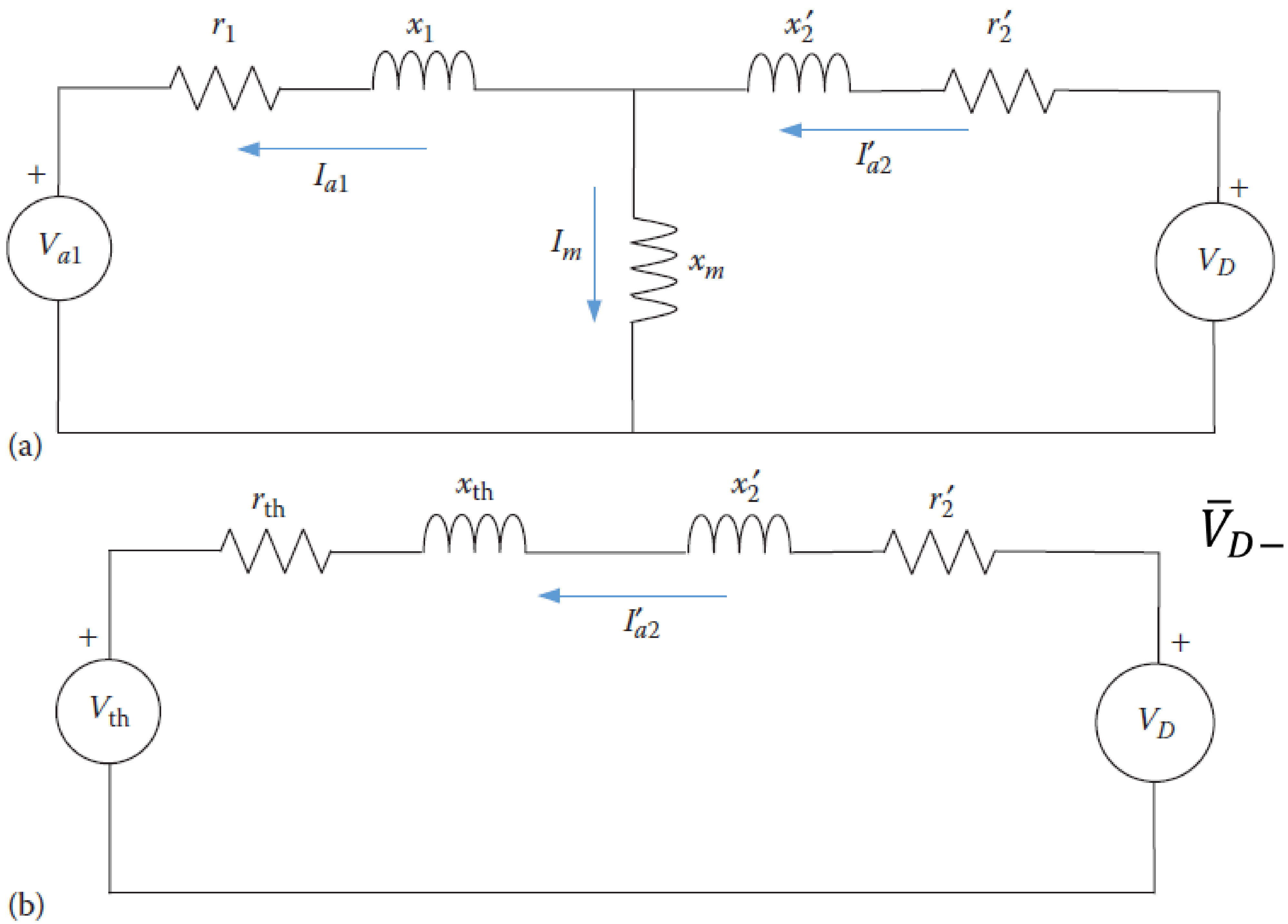
(a)

With added resistance



(b)

Machine Equivalent Circuit



$$\bar{V}_{D-add} = -\bar{I}'_{a2} \frac{r_2' + r'_{add}}{s}(1-s)$$

FIGURE 9.5
(a) Generator equivalent circuit without added resistance and (b) generator equivalent circuit with added resistance.

Real Power

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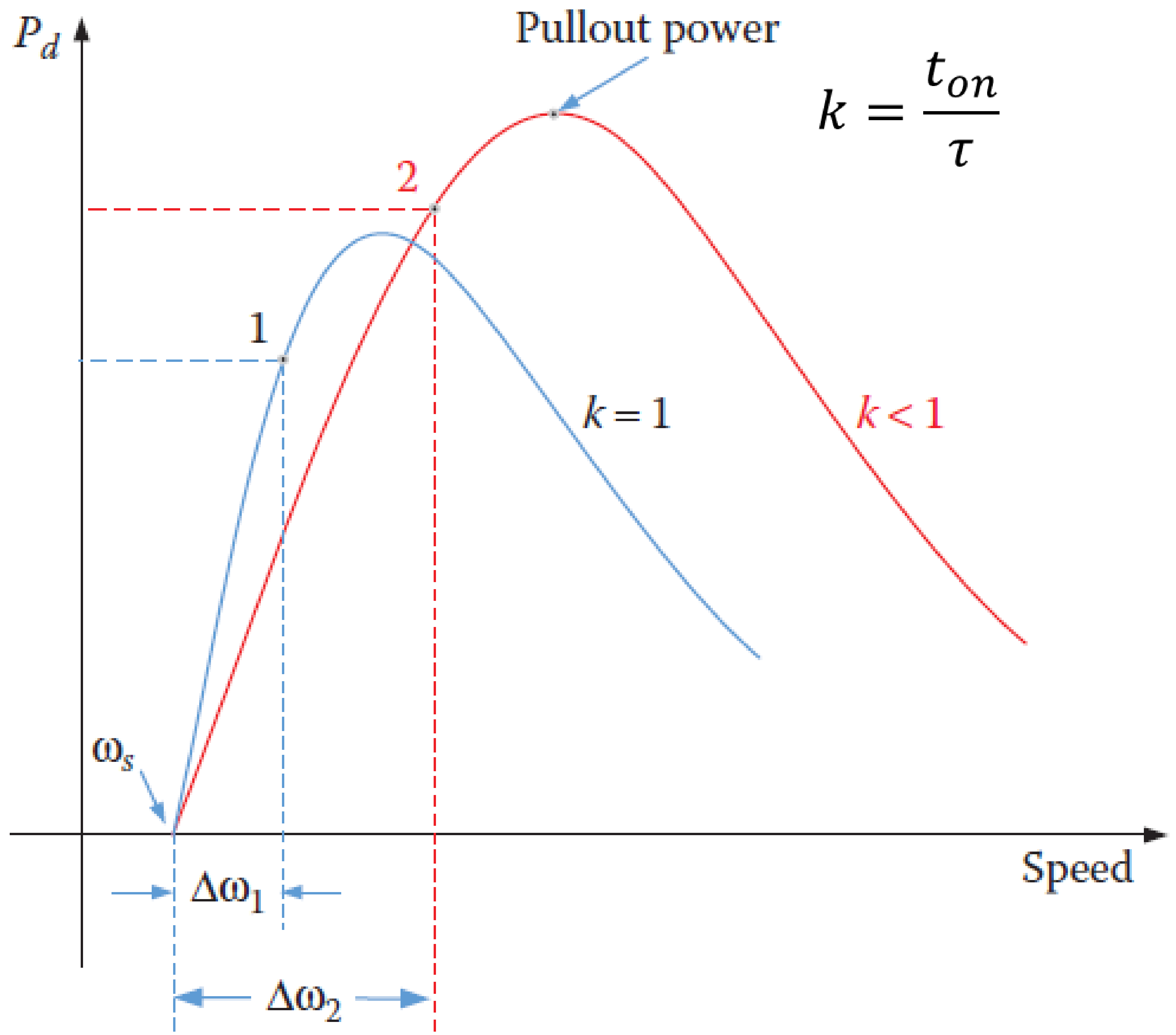
$$P_d = -3\frac{(1-s)}{s}\frac{V_{a1}^2(r_2' + r_{add}')}{\left(\frac{r_2' + r_{add}'}{s}\right)^2 + (x_2')^2}$$



Pullout Power (Maximum Power)

$$P_d = -3\frac{(1-s)}{s}\frac{V_{a1}^2(r_2' + r_{add}')}{\left(\frac{r_2' + r_{add}'}{s}\right)^2 + (x_2')^2}$$

$$\frac{dP_d}{ds} = -\frac{d}{ds}\left[3\frac{(1-s)}{s}\frac{V_{a1}^2(r_2' + r_{add}')}{\left(\frac{r_2' + r_{add}'}{s}\right)^2 + (x_2')^2}\right] = 0$$

$$s' = -m\left[m + \sqrt{m^2+1}\right] \qquad m = \frac{r_2' + r_{add}'}{x_2'}$$

$$P_d' = -3\frac{(1-s')}{s'}\frac{V_{a1}^2(r_2' + r_{add}')}{\left(\frac{r_2' + r_{add}'}{s'}\right)^2 + (x_2')^2}$$

Example

A Type 2 wind turbine has 6-pole, 60Hz three-phase, Y-connected induction generator. The terminal voltage of the generator is 690 V. The rotor parameters of the machine are:

$$r_2' = 10 \text{ m}\Omega;\ x_2' = 100 \text{ m}\Omega$$

Compute the pullout power. Repeat the solution after inserting a 0.02Ω resistance in the rotor circuit as referred to the stator. The duty ratio of its converter is 50%.

Solution

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Without the added rotor resistance, we compute the slip at pullout power

$$m = \frac{r_2'}{x_2'} = 0.1$$

$$s' = -m\left[m + \sqrt{m^2 + 1}\right] = -0.1 \times \left[0.1 + \sqrt{0.1^2 + 1}\right] = -0.1105$$

The speed at the pullout power is

$$n' = n_s(1 - s') = 1200 \times (1 + 0.1105) = 1332.6 \ \text{rpm}$$

The change in speed to pullout power is

$$\Delta n' = n_s - n' = 1200 - 1332.6 = 132.6 \ \text{rpm}$$

The pullout power (maximum power) is

$$P'_d = -3\frac{(1-s')}{s'}\,\frac{V_{a1}^2\, r'_2}{\left(\frac{r'_2}{s'}\right)^2 + (x'_2)^2} = 3\,\frac{(1+0.1105)}{0.1105}\,\frac{\frac{690^2}{3}\,0.01}{\left(\frac{0.01}{-0.1105}\right)^2 + (0.1)^2} = 2.53\ \text{MW}$$

When the resistance is added, we need to compute r_{add} based on the duty ratio

$$r_{add} = r(1-k) = 0.02 \times (1-0.5) = 0.01\ \Omega$$

Now we can compute the slip at pullout torque

$$m = \frac{r_2' + r_{add}'}{x_2'} = \frac{0.01 + 0.01}{0.1} = 0.2$$

$$s' = -m\left[m + \sqrt{m^2+1}\right] = -0.2 \times \left[0.2 + \sqrt{0.2^2+1}\right] = -0.244$$

The speed at the pullout power is

$$n' = n_s(1-s') = 1200 \times (1+0.244) = 1492.8\ \text{rpm}$$

The change in speed to pullout power is

$$\Delta n' = n_s - n' = 1200 - 1492.8 = 292.8\ \text{rpm}$$

The pullout power is

$$P'_d = -3\frac{(1-s')}{s'}\frac{V_{a1}^2(r'_2 + r'_{add})}{\left(\frac{r'_2 + r'_{add}}{s'}\right)^2 + (x'_2)^2}$$

$$= 3\frac{(1+0.244)}{0.244}\frac{\frac{690^2}{3}\,0.02}{\left(\frac{0.02}{-0.244}\right)^2 + (0.1)^2} = 2.904\ \ \text{MW}$$

Torque

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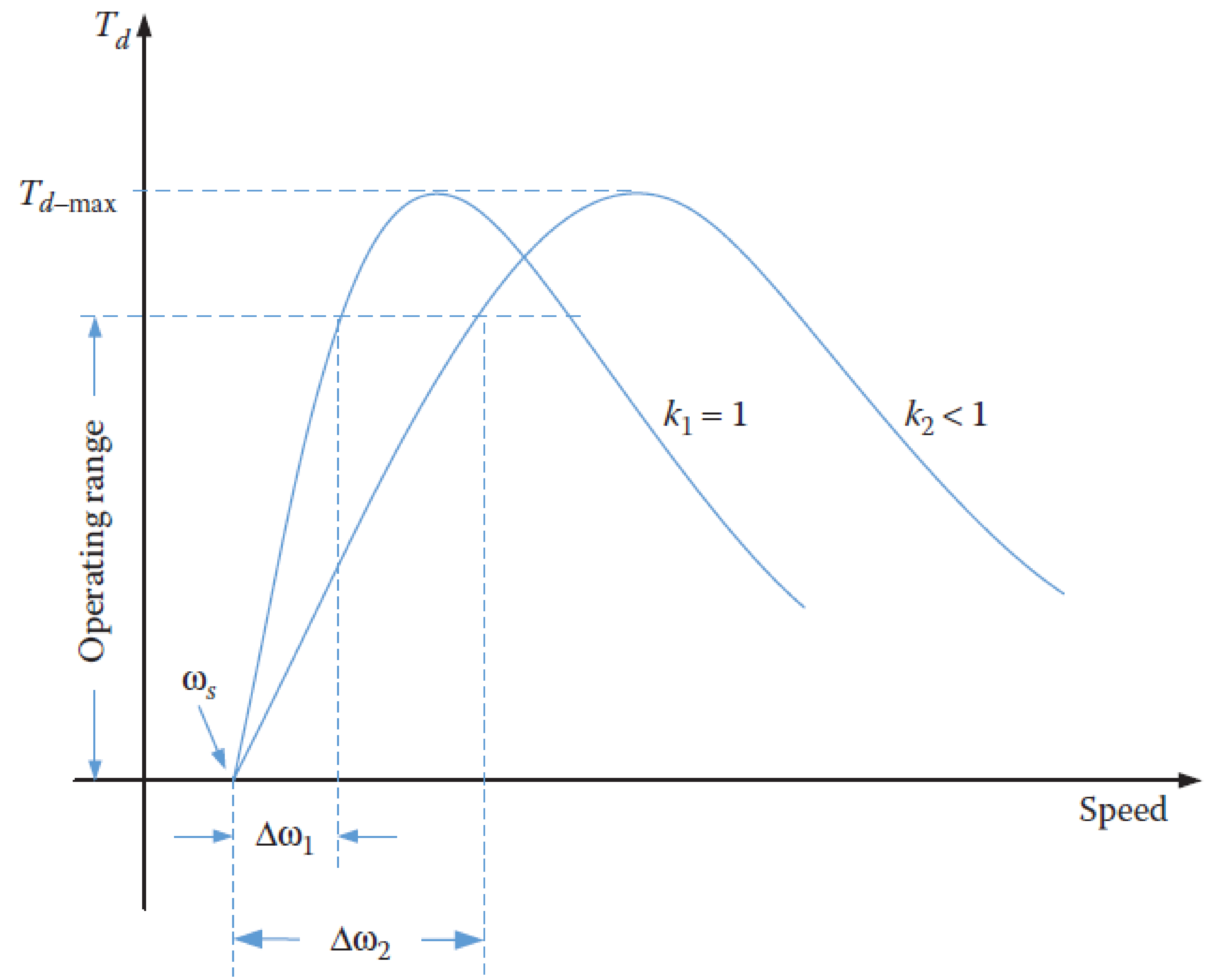
$$T_d = \frac{P_d}{\omega_2} = -3\,\frac{r_2' + r_{add}'}{s\omega_s}\,\frac{V_{a1}^2}{\left(\frac{r_2' + r_{add}'}{s}\right)^2 + (x_2')^2}$$



Maximum Torque is not a function of added resistance or speed

Maximum Torque

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$$T_d = -3 \frac{r_2' + r_{add}'}{s\omega_s} \frac{V_{a1}^2}{\left(\frac{r_2' + r_{add}'}{s}\right)^2 + (x_2')^2}$$

$$\frac{dT_d}{ds} = -\frac{d}{ds}\left[3 \frac{r_2' + r_{add}'}{s\omega_s} \frac{V_{a1}^2}{\left(\frac{r_2' + r_{add}'}{s}\right)^2 + (x_2')^2}\right] = 0$$

$$s^* = -\frac{r_2' + r_{add}'}{x_2'}$$

$$T_d^* = \frac{3}{2} \frac{V_{a1}^2}{x_2' \omega_s}$$

Example

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A Type 2 wind turbine has 6-pole, 60Hz three-phase, Y-connected induction generator. The terminal voltage of the generator is 690 V. The rotor parameters of the machine are:

$$r_2' = 10\ \text{m}\Omega;\ x_2' = 100\ \text{m}\Omega$$

Compute the maximum torque and the speed at maximum torque without and with the added resistance.

Without the added rotor resistance, we compute the slip at maximum torque

$$s^* = -\frac{r_2'}{x_2'} = \frac{0.01}{0.1} = -0.1$$

The speed at the maximum torque is

$$n^* = n_s(1 - s^*) = 1200 \times (1 + 0.1) = 1320 \ \text{rpm}$$

The maximum speed range is

$$\Delta n^* = n_s - n^* = 1200 - 1320 = 120 \ \text{rpm}$$

The maximum torque is

$$T_d^* = \frac{3}{2}\frac{V_{a1}^2}{x_2'\omega_s} = \frac{690^2}{2 \times 0.1 \times 40\pi} = 18.94 \ \text{kNm}$$

With the added resistance, the slip at maximum torque is

$$s^* = -\frac{r_2' + r_{add}'}{x_2'} = \frac{0.01 + 0.01}{0.1} = -0.2$$

The speed at the maximum torque is

$$n^* = n_s(1 - s') = 1200 \times (1 + 0.2) = 1440 \ \text{rpm}$$

The maximum speed range is

$$\Delta n^{*} = n_s - n^{*} = 1200 - 1440 = 240 \ \text{rpm}$$

The maximum torque is the same as it is not a function of the added resistance or s^*

$$T_d^{*} = \frac{3}{2}\frac{V_{a1}^2}{x_2'\omega_s} = \frac{690^2}{2 \times 0.1 \times 40\pi} = 18.94 \ \text{kNm}$$

Note that the speed at pullout power n' is not the same as the speed at maximum torque n^*

Example

Assume the generator is operating at a speed of 1230 rpm. If wind speed increases, the generator speed increases to 1260 rpm, compute the added resistance that maintains the developed power constant. Also, compute the power consumed by the added resistance.

Solution

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Without the added rotor resistance, the slip is

$$s = \frac{n_s - n}{n_s} = \frac{1200 - 1230}{1200} = -0.025$$

The developed power can be obtained

$$P_d = -3\frac{(1-s)}{s}\frac{V_{a1}^2(r_2')}{\left(\frac{r_2'}{s}\right)^2 + (x_2')^2} = 1.148 \text{ MW}$$

Compute the slip at the new speed

$$s = \frac{n_s - n}{n_s} = \frac{1200 - 1260}{1200} = -0.05$$

To compute the added resistance

$$P_d = -3\frac{(1-s)}{s}\frac{V_{a1}^2(r_2'+r_{add}')}{\left(\frac{r_2'+r_{add}'}{s}\right)^2+(x_2')^2}$$

$$1.148\times 10^6 = -\frac{(1+0.05)}{-0.05}\frac{690^2(0.01+r_{add}')}{\left(\frac{0.01+r_{add}'}{-0.05}\right)^2+(0.1)^2}$$

The solution of the above equation gives r_{add}'

$$r_{add}' = 0.0218\ \Omega$$

To compute the power dissipated in the added resistance, we need to compute the rotor current

$$\bar{I}_{a2}' \approx \frac{-\bar{V}_{a1}}{\left(\frac{r_2'+r_{\mathrm{add}}'}{s}\right)+jx_2'} = \frac{-\frac{690}{\sqrt{3}}}{\left(\frac{0.0318}{-0.05}\right)+j0.1} 618.77\angle -8.93^{\mathrm{o}} \quad \mathrm{A}$$

The dissipated power in the added resistance bank is

$$P_{add} = 3\, r_{\mathrm{add}}'\,(I_{a2}')^2 = 25.04\ \mathrm{kW}$$

Assessment of Type 2 Turbine

- Operating ranges for power and speed is higher than that for Type 1.
- Generators normally require access to the rotor through a slip ring system, which makes the machine more expensive and higher maintenance.
- However, newer systems have the resistances installed in the rotating mass of the generator whereby its converter is triggered using Optical signals from the stationary stator.
- Similar to Type 1 system, the main drawback of Type 2 turbines is their lack of reactive power control and voltage support.
- Another drawback of Type 2 system is its low efficiency.

Inrush Current Protection

- Starting sequence
  - Release the brake to allow the turbine to spin freely.
  - When the speed is near the synchronous speed, the turbine is connected to the grid.
  - Since the speed of the turbine at the initial connection to the grid cannot precisely equal to the synchronous speed, an inrush current flows through the generator.
- In Type 2 turbine, the added rotor resistance can reduce the inrush current.

Inrush Current

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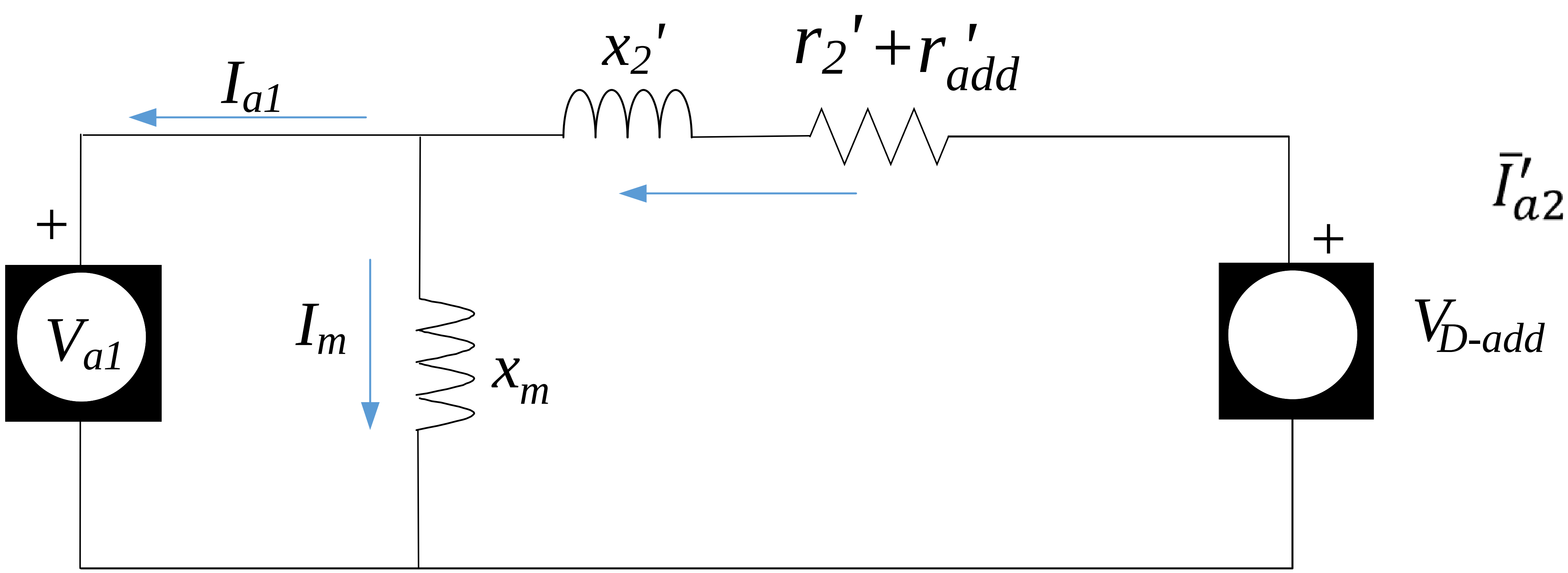

$$\bar{I}'_{a2-st} = \frac{-\bar{V}_{a1}}{\left(\frac{r'_2 + r'_{add}}{s}\right) + jx'_2}$$

$$\bar{I}_{a1-st} = \bar{I}'_{a2-st} - \bar{I}_m = \frac{-\bar{V}_{a1}}{\left(\frac{r'_2 + r'_{add}}{s}\right) + jx'_2} - \frac{\bar{V}_{a1}}{jx_m}$$

S is the slip at the connection time

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Example

- A Type 2 wind turbine has 6-pole, 60Hz three-phase, Y-connected induction generator. The terminal voltage of the generator is 690 V. The rotor parameters of the machine are:

$$r_2' = 10\ \text{m}\Omega;\ x_2' = 100\ \text{m}\Omega$$

- The turbine is connected to the grid while spinning at 1230 rpm. Compute the inrush current in the stator windings. Repeat the solution when 30mΩ resistance (referred to stator) is inserted in the rotor circuit.

Solution (without added rotor resistance)

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The slip at the grid interconnection $s = \frac{1200-1230}{1200} = -0.025$

The inrush current in the rotor without the added resistance

$$\bar{I}'_{a2-st} = \frac{-\bar{V}_{a1}}{\left(\frac{r'_2}{s}\right) + jx'_2} = \frac{-\frac{690}{\sqrt{3}}}{\left(\frac{0.01}{-0.025}\right) + j0.1} = 966.2\angle 14.04^{o} \text{ A}$$

The current in the magnetizing branch $\bar{I}_m = \frac{\bar{V}_{a1}}{jx_m} = \frac{\frac{690}{\sqrt{3}}}{j5} = j79.67 \text{ A}$

The stator inrush current $\bar{I}_{a1-st} = \bar{I}'_{a2-st} - \bar{I}_m = 950.0\angle 9.37^{o} \text{ A}$

Solution (With added rotor resistance)

The rotor inrush current is

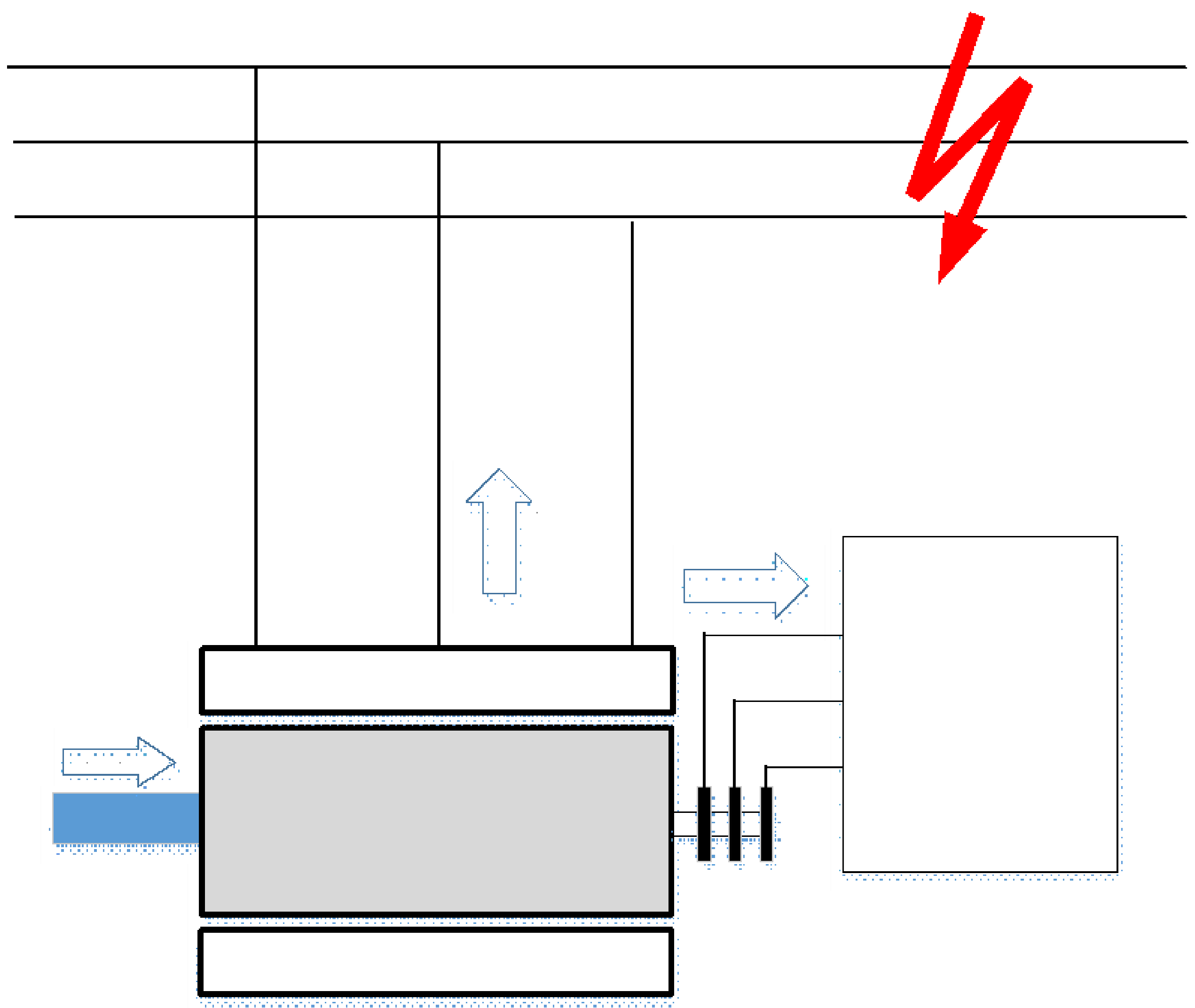
$$\bar{I}'_{a2-st} = \frac{-\bar{V}_{a1}}{\left(\dfrac{r'_2 + r'_{\text{add}}}{s}\right) + jx'_2} = \frac{-\dfrac{690}{\sqrt{3}}}{\left(\dfrac{0.01 + 0.03}{-0.025}\right) + j0.1} = 248.5\angle 3.58^{\text{o}} \ \ \text{A}$$

The stator inrush current with the added resistance is

$$\bar{I}_{a1-st} = \bar{I}'_{a2-st} - \bar{I}_m = 248.5\angle 3.58^{\text{o}} - j79.67 = 265.64\angle 21^{\text{o}} \ \ \text{A}$$

Turbine Stability

- During voltage depression, the output power of the turbine is reduced. Thus, the mechanical power from the turbine must be reduced to match the output electrical power plus all losses.
- However, the reduction of the mechanical power takes time as it involves the control of large mass.
- During this period, the extra energy acquired by the rotating mass must be dissipated to prevent the machine from damaging overspeeding.



Example

- A Type 2 wind turbine has 6-pole, 60Hz three-phase, Y-connected induction generator. The terminal voltage of the generator is 690 V. The rotor parameters of the machine are:

$$r_2' = 10\ \text{m}\Omega;\ x_2' = 100\ \text{m}\Omega$$

- When the turbine was producing 2MW at steady state speed of 1230 rpm, a nearby fault reduced the grid voltage to 80% of its steady state value.
- Compute the power consumed by 30mΩ added resistance (referred to stator) and the rotor current referred to stator. Also compute the energy consumed by the resistance if the voltage depression lasts for 50 ms.

Solution

The slip at the grid interconnection $s = \frac{1200-1230}{1200} = -0.025$

developed power without the added rotor resistance $P_{d1} = -3\frac{(1-s)}{s}\frac{V_{a1}^2 r_2'}{\left(\frac{r_2'}{s}\right)^2 + x_2'^2} = 2\text{ MW}$

The power with voltage depression and added rotor resistance

$$P_{d2} = -3\frac{(1-s)}{s}\frac{(0.8\times V_{a1})^2(r_2' + r_{add}')}{\left(\frac{r_2' + r_{add}'}{s}\right)^2 + x_2'^2}$$

$$P_{d2} = P_{d1}\frac{(0.8)^2(r_2' + r_{add}')\left(\left(\frac{r_2'}{s}\right)^2 + x_2'^2\right)}{r_2'\left(\left(\frac{r_2' + r_{add}'}{s}\right)^2 + x_2'^2\right)} = 2\frac{(0.8)^2(0.01 + 0.03)\left(\left(\frac{0.01}{-0.025}\right)^2 + 0.01^2\right)}{0.01\times\left(\left(\frac{0.01 + 0.03}{-0.025}\right)^2 + 0.01^2\right)} = 320.18\text{ kW}$$

Solution

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The power that needs to be consumed by the added resistance is

$$P_{add} = P_{d1} - P_{d2} = 2.0 - 0.32018 = 1.679 \text{ MW}$$

The rotor current

$$I'_{a2} = \sqrt{\frac{P_{add}}{r'_{add}}} = \sqrt{\frac{\frac{1.679}{3}}{0.03}} = 4.32 \text{ kA}$$

The energy consumed by the three-phase added resistance

$$E_{add} = P_{add}t = 1.679 \times 0.05 = 83.95 \text{ kJ}$$

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