ECE 404-TD / 504-TD

ST: T&D APPLICATIONS OF VOLTAGE SOURCE CONVERTERS

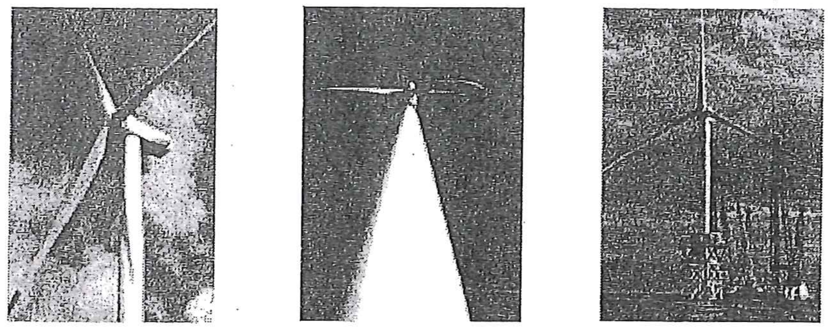
SESSION no. 23

University of Idaho

$$R_{ps} = 0.40 \frac{^{\circ}C}{W}$$

Table 1-10. Examples of commercial DFIG WECS

Parameter	Model		
	Nordex N100	Vestas V90	Repower 5M
Power rating	2.5 MW	3 MW	5 MW
Turbine diameter	100 m	9 0m	126 m
Turbine speed	9.6 ~ 14.9 rpm	8.6 ~ 18.4 rpm	7.7 ~ 12.1 rpm
Wind speed (cut-in/rated/cut-out)	3/13/20 m/s	3.5/15/25 m/s	3.5/14/25 m/s
Generator	6-pole WRIG	4-pole WRIG	6-pole WRIG
Gearbox	Planetary/spur stages	Planetary/helical stages	Planetary/spur stages
Pitch/stall mechanism	Pitch	Pitch	Pitch



Photos courtesy (from left to right) Nordex, Vestas Wind Systems A/S, and REpower Systems AG.

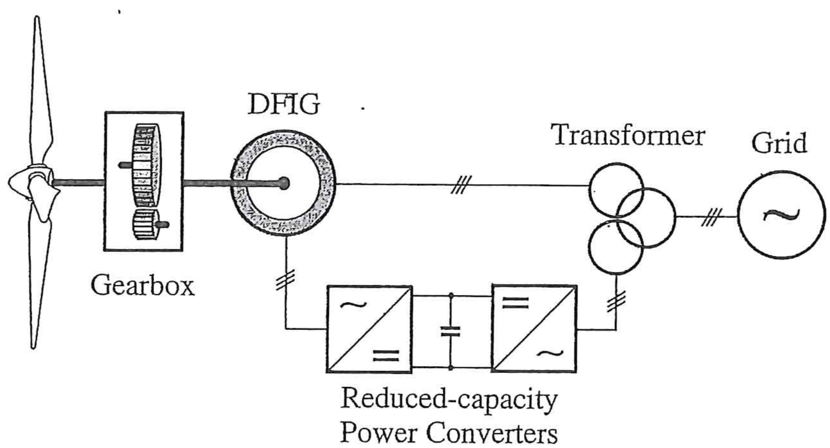


Figure 1-13. Variable-speed configuration with reduced-capacity converters.

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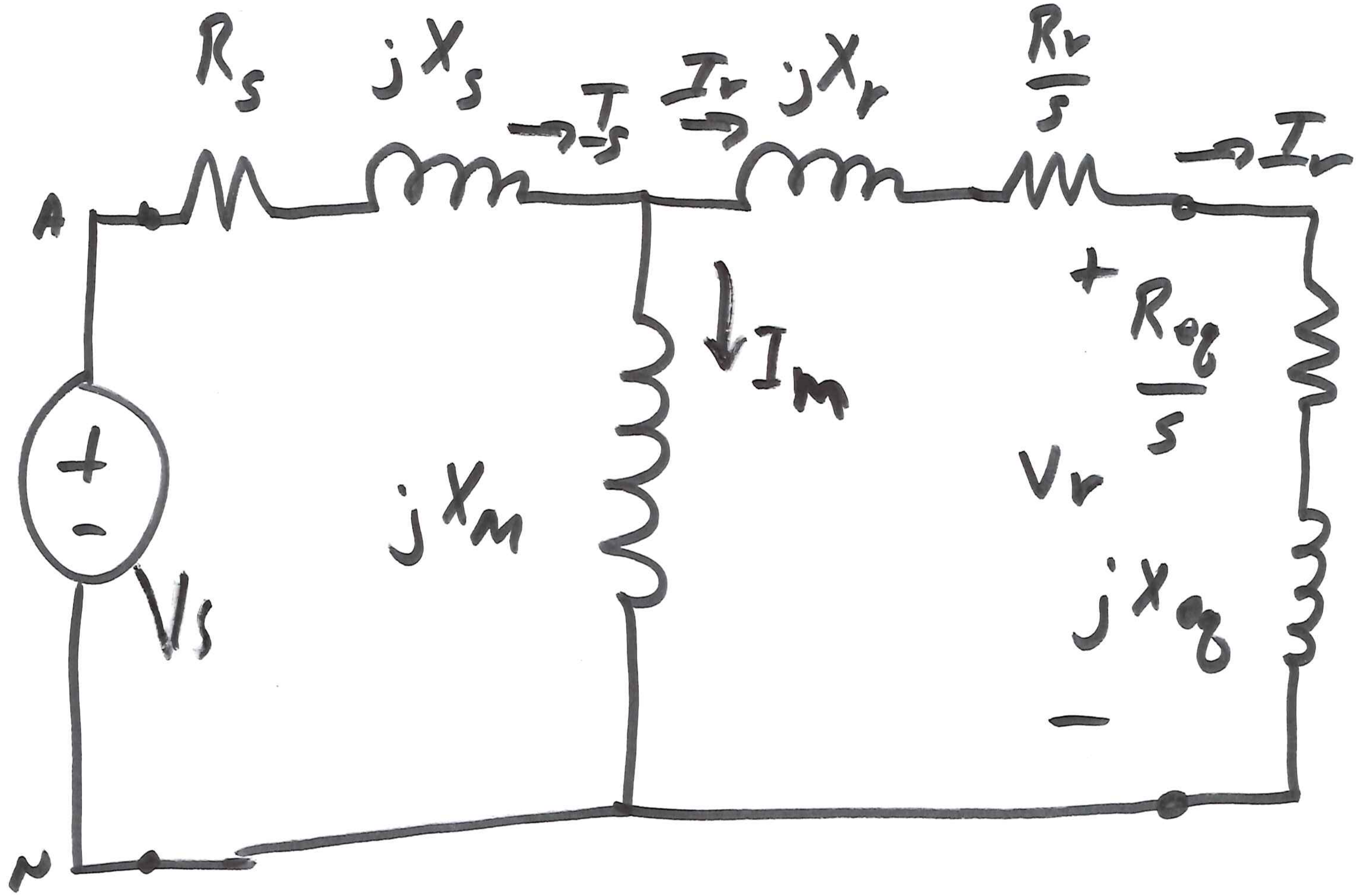

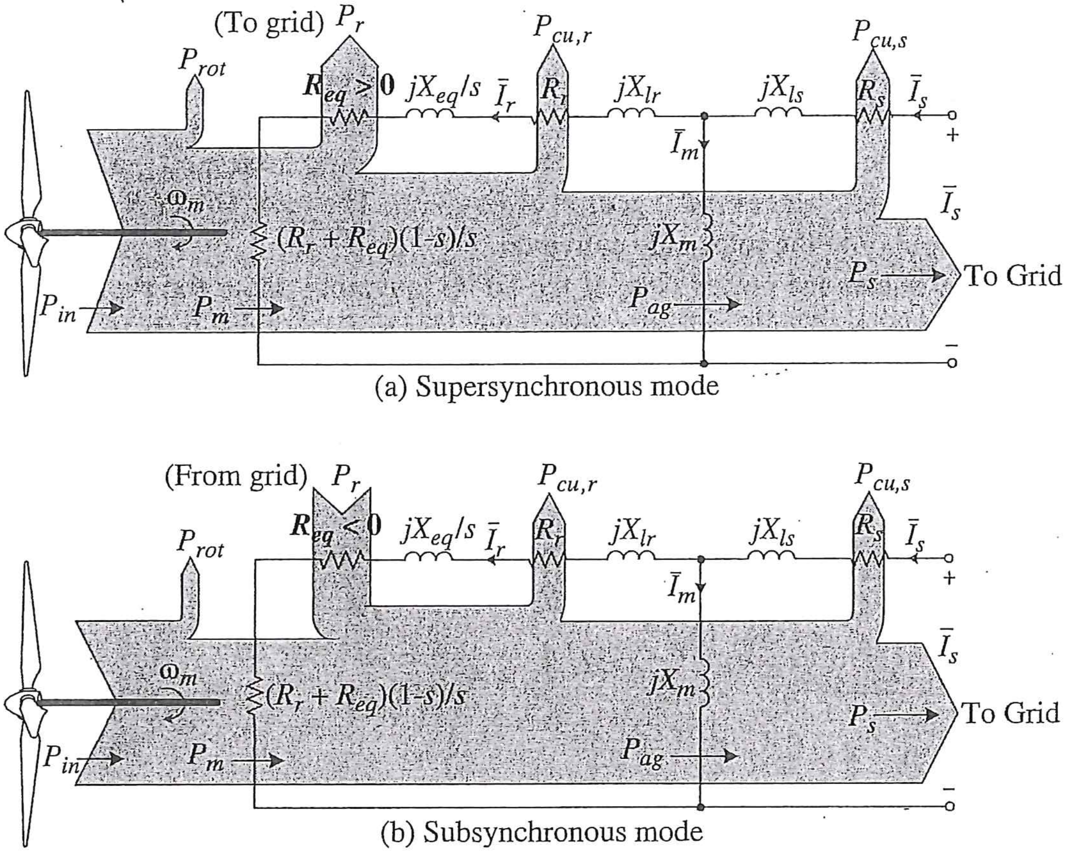

Figure 8-9. Power flow of DFIG with rotor-side converter represented by R_{eq} and X_{eq}.

$$S = \frac{W_s - W_m}{W_s}$$

$$s\omega_s = \omega_s - \omega_m$$

slip freq (rotor freq) — synch — mech

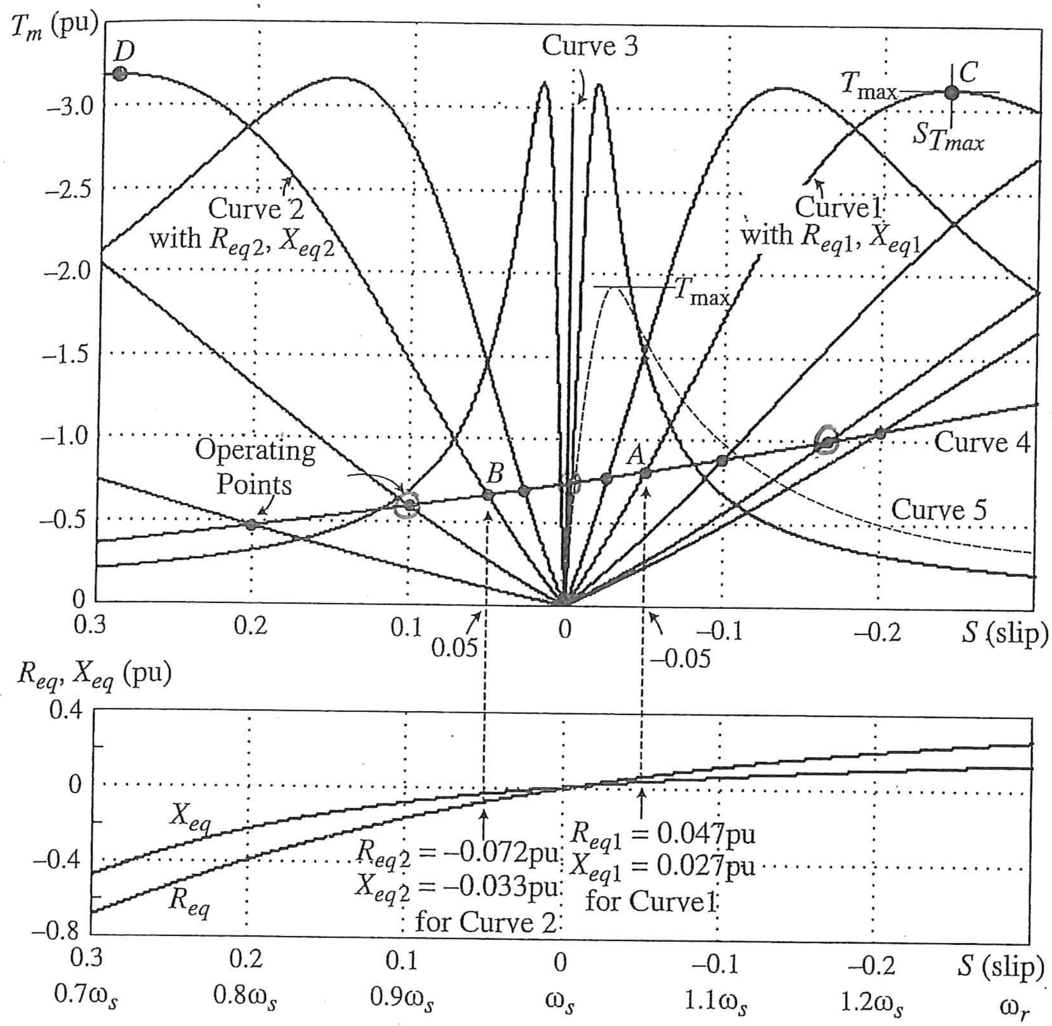

Figure 8-6. Torque-slip characteristics of DFIG wind energy system ($PF_s = 1$).

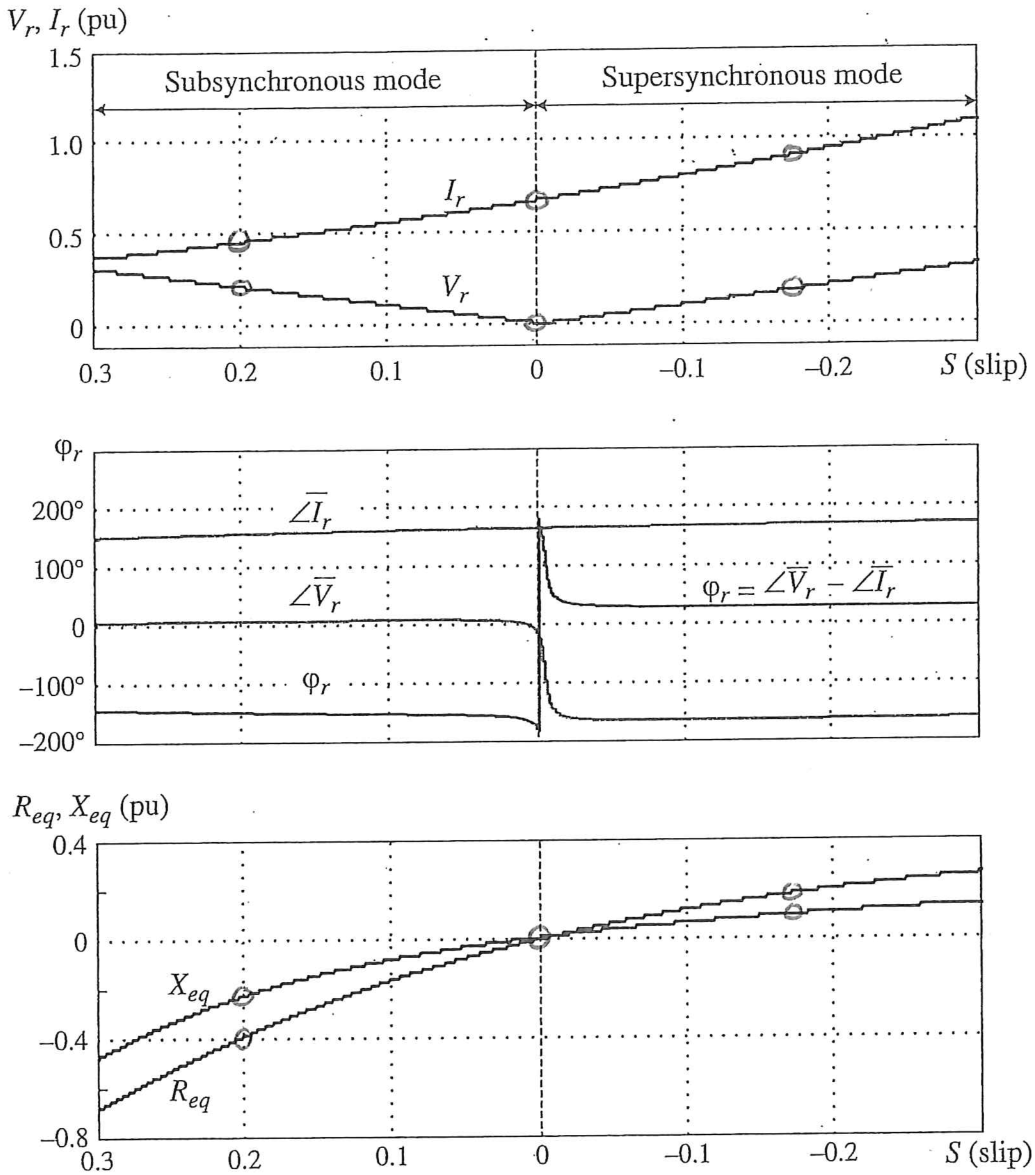

Figure 8-5. Rotor-side converter equivalent impedance ($PF_s = 1$).

Doubly Fed Induction Motor Example

Supersynchronous speed

$j := \sqrt{-1}$ $\quad m\Omega := 10^{-3}\cdot\Omega$

Given parameters

$R_s := 2.65\cdot m\Omega$ $\quad R_r := 2.63\cdot m\Omega$ $\quad L_{ls} := 168.7\cdot\mu H$ $\quad L_{lr} := 133.7\cdot\mu H$ $\quad L_m := 5.4749\cdot mH$ $\quad poles := 4$

Given operating conditions

$V_s := \frac{690}{\sqrt{3}}\cdot V$ $\quad T_m := -8185.1\cdot N\cdot m$ $\quad \omega_s := 2\cdot\pi\cdot 50\cdot\frac{rad}{sec}$ $\quad \omega_m := \frac{poles}{2}\cdot 1750\cdot\frac{\pi}{30}\cdot\frac{rad}{sec} = 366.519\,\frac{rad}{sec}$

$pf := 1.00$ $\quad s := \frac{\omega_s - \omega_m}{\omega_s} = -0.167$

From these parameters and operating conditions, calculate the equivalent circuit quantities.

$$I_s := \frac{V_s - \sqrt{V_s^2 - \frac{8\cdot R_s\cdot T_m\cdot\omega_s}{3\cdot poles}}}{2\cdot R_s} = -1068.2\,A \qquad \theta := acos(pf) = 0\,deg \qquad I_s := I_s\cdot e^{-j\cdot\theta}$$

$$V_m := V_s - I_s\cdot(R_s + j\cdot\omega_s\cdot L_{ls}) = (401.202 + 56.614i)\,V \qquad |V_m| = 405.177\,V \qquad arg(V_m) = 8.032\,deg$$

$$I_m := \frac{V_m}{j\cdot\omega_s\cdot L_m} = (32.915 - 233.259i)\,A$$

$$I_r := I_s - I_m = \left(-1.101\times 10^3 + 233.259i\right)A \qquad |I_r| = 1.126\times 10^3\,A \qquad arg(I_r) = 168.04\,deg$$

$I_{base} := 1225.1\cdot A$ $\quad I_{rr} := \frac{|I_r|}{I_{base}} = 0.919$

$$V_r := s\cdot V_m - I_r\cdot(R_r + j\cdot s\cdot\omega_s\cdot L_{lr}) = (-65.604 - 17.758i)\,V \qquad |V_r| = 67.965\,V \qquad arg(V_r) = -164.854\,deg$$

$V_{base} := 398.4\cdot V$ $\quad V_{rr} := \frac{|V_r|}{V_{base}} = 0.171$

$$Z_{eq} := \frac{V_r}{I_r} = (0.054 + 0.028i)\,\Omega \qquad R_{eq} := Re(Z_{eq}) = 53.751\,m\Omega \qquad X_{eq} := Im(Z_{eq}) = 27.513\,m\Omega$$

Steady State Analysis. Supersynchronous Operation.

$\omega_m = 366.519 \frac{rad}{sec}$ $\qquad |I_r| = 1125.6\,A \qquad arg(I_r) = 168.04\,deg$

Mechanical power to the generator (Negative means power from mechanical to electrical)

$$P_m := 3 \cdot \left(|I_r|\right)^2 \cdot \left(R_{eq} + R_r\right) \cdot \frac{(1-s)}{s} = -1500\,kW$$

Power delivered through the rotor and converter (Positive means power from machine to converter)

$$P_r := 3 \cdot \left(|I_r|\right)^2 \cdot R_{eq} = 204.29\,kW$$

Losses (Rotor and Stator)

$P_{I2Rr} := 3 \cdot \left(|I_r|\right)^2 \cdot R_r = 9.996\,kW$ $\qquad P_{I2Rs} := 3 \cdot \left(|I_s|\right)^2 \cdot R_s = 9.072 \times 10^3\,W$

Power delivered through the stator terminals (Negative means power from machine to grid)

$$P_s := Re\left(3 \cdot V_s \cdot \overline{I_s}\right) = -1.277 \times 10^3\,kW$$

Power delivered to the grid (stator and rotor components)

$$P_{grid} := P_s - P_r = -1.481 \times 10^6\,W$$

Checking losses two ways.

$P_m - P_{grid} = -19.067\,kW$ $\qquad P_{I2Rs} + P_{I2Rr} = 19.067\,kW$

Energy efficiency steady state

$$\eta := \frac{P_{grid}}{P_m} = 98.729\,\%$$

Synchronous speed

$j := \sqrt{-1}$ $m\Omega := 10^{-3} \cdot \Omega$

Given parameters

$R_s := 2.65 \cdot m\Omega$ $R_r := 2.63 \cdot m\Omega$ $L_{ls} := 168.7 \cdot \mu H$ $L_{lr} := 133.7 \cdot \mu H$ $L_m := 5.4749 \cdot mH$ $poles := 4$

Given operating conditions

$V_s := \frac{690}{\sqrt{3}} \cdot V$ $T_m := -6013.5 \cdot N \cdot m$ $\omega_s := 2 \cdot \pi \cdot 50 \cdot \frac{rad}{sec}$ $\omega_m := \omega_s + 10^{-9} \cdot \frac{rad}{sec}$

$pf := 1.00$ $s := \frac{\omega_s - \omega_m}{\omega_s} = -3.183 \times 10^{-12}$

$I_s := \frac{V_s - \sqrt{V_s^2 - \frac{8 \cdot R_s \cdot T_m \cdot \omega_s}{3 \cdot poles}}}{2 \cdot R_s} = -786.3\ A$ $\theta := acos(pf) = 0\ deg$ $I_s := I_s \cdot e^{-j \cdot \theta}$

$V_m := V_s - I_s \cdot (R_s + j \cdot \omega_s \cdot L_{ls}) = (400.455 + 41.671i)\ V$ $|V_m| = 402.618\ V$ $arg(V_m) = 5.941\ deg$

$I_m := \frac{V_m}{j \cdot \omega_s \cdot L_m} = (24.228 - 232.824i)\ A$

$I_r := I_s - I_m = (-810.498 + 232.824i)\ A$ $|I_r| = 843.276\ A$ $arg(I_r) = 163.973\ deg$

$I_{base} := 1225.1 \cdot A$ $I_{rr} := \frac{|I_r|}{I_{base}} = 0.688$

$V_r := s \cdot V_m - I_r \cdot (R_r + j \cdot s \cdot \omega_s \cdot L_{lr}) = (2.132 - 0.612i)\ V$ $|V_r| = 2.218\ V$ $arg(V_r) = -16.027\ deg$

$V_{base} := 398.4 \cdot V$ $V_{rr} := \frac{|V_r|}{V_{base}} = 5.567 \times 10^{-3}$

$Z_{eq} := \frac{V_r}{I_r} = (-2.63 \times 10^{-3} + 7.022i \times 10^{-13})\ \Omega$

$R_{eq} := Re(Z_{eq}) = -2.63\ m\Omega$ $X_{eq} := Im(Z_{eq}) = 7.022 \times 10^{-10}\ m\Omega$

Steady State Analysis. Synchronous Operation.

$\omega_m = 314.159 \frac{rad}{sec}$ $\quad |I_r| = 843.3\,A$ $\quad arg(I_r) = 163.973\,deg$

Mechanical power to the generator (Negative means power from mechanical to electrical)

$$P_m := 3\cdot(|I_r|)^2\cdot(R_{eq} + R_r)\cdot\frac{(1-s)}{s} = -945\,kW$$

Power delivered through the rotor and converter (Positive means power from machine to converter)

$$P_r := 3\cdot(|I_r|)^2\cdot R_{eq} = -5.611\,kW$$

Losses (Rotor and Stator)

$$P_{I2Rr} := 3\cdot(|I_r|)^2\cdot R_r = 5.611\,kW \qquad P_{I2Rs} := 3\cdot(|I_s|)^2\cdot R_s = 4.915\times 10^3\,W$$

Power delivered through the stator terminals (Negative means power from machine to grid)

$$P_s := Re\left(3\cdot V_s\cdot \overline{I_s}\right) = -939.684\,kW$$

Power delivered to the grid (stator and rotor components)

$$P_{grid} := P_s - P_r = -9.341\times 10^5\,W$$

Checking losses two ways.

$$P_m - P_{grid} = -10.526\,kW \qquad P_{I2Rs} + P_{I2Rr} = 10.526\,kW$$

Energy efficiency steady state

$$\eta := \frac{P_{grid}}{P_m} = 98.886\,\%$$

Subsynchronous speed

$j := \sqrt{-1}$ $m\Omega := 10^{-3} \cdot \Omega$

Given parameters

$R_s := 2.65 \cdot m\Omega$ $R_r := 2.63 \cdot m\Omega$ $L_{ls} := 168.7 \cdot \mu H$ $L_{lr} := 133.7 \cdot \mu H$ $L_m := 5.4749 \cdot mH$ $poles := 4$

Given operating conditions

$V_s := \frac{690}{\sqrt{3}} \cdot V$ $T_m := -3849 \cdot N \cdot m$ $\omega_s := 2 \cdot \pi \cdot 50 \cdot \frac{rad}{sec}$ $\omega_m := \frac{poles}{2} \cdot 1200 \cdot \frac{\pi}{30} \cdot \frac{rad}{sec} = 251.327 \frac{rad}{sec}$

$pf := 1.00$ $s := \frac{\omega_s - \omega_m}{\omega_s} = 0.2$

$$I_s := \frac{V_s - \sqrt{V_s^2 - \frac{8 \cdot R_s \cdot T_m \cdot \omega_s}{3 \cdot poles}}}{2 \cdot R_s} = -504.2\,A \quad \theta := acos(pf) = 0\,deg \quad I_s := I_s \cdot e^{-j \cdot \theta}$$

$$V_m := V_s - I_s \cdot (R_s + j \cdot \omega_s \cdot L_{ls}) = (399.708 + 26.722i)\,V \quad |V_m| = 400.6\,V \quad arg(V_m) = 3.825\,deg$$

$$I_m := \frac{V_m}{j \cdot \omega_s \cdot L_m} = (15.536 - 232.39i)\,A$$

$$I_r := I_s - I_m = (-519.737 + 232.39i)\,A \quad |I_r| = 569.326\,A \quad arg(I_r) = 155.909\,deg$$

$I_{base} := 1225.1 \cdot A$ $I_{rr} := \frac{|I_r|}{I_{base}} = 0.465$

$$V_r := s \cdot V_m - I_r \cdot (R_r + j \cdot s \cdot \omega_s \cdot L_{lr}) = (83.261 + 9.099i)\,V \quad |V_r| = 83.756\,V \quad arg(V_r) = 6.237\,deg$$

$V_{base} := 398.4 \cdot V$ $V_{rrr} := \frac{|V_r|}{V_{base}} = 0.21$

$$Z_{eq} := \frac{V_r}{I_r} = (-0.127 - 0.074i)\,\Omega \quad R_{eq} := Re(Z_{eq}) = -126.983\,m\Omega \quad X_{eq} := Im(Z_{eq}) = -74.285\,m\Omega$$

Steady State Analysis. Subsynchronous Operation.

$\omega_m = 251.327\,\frac{rad}{sec}$ $\quad |I_r| = 569.3\,A$ $\quad arg(I_r) = 155.909\,deg$

Mechanical power to the generator (Negative means power from mechanical to electrical)

$$P_m := 3\cdot\left(|I_r|\right)^2\cdot\left(R_{eq} + R_r\right)\cdot\frac{(1-s)}{s} = -484\,kW$$

Power delivered through the rotor and converter (Positive means power from machine to converter)

$$P_r := 3\cdot\left(|I_r|\right)^2\cdot R_{eq} = -123.477\,kW$$

Losses (Rotor and Stator)

$$P_{I2Rr} := 3\cdot\left(|I_r|\right)^2\cdot R_r = 2.557\,kW \qquad P_{I2Rs} := 3\cdot\left(|I_s|\right)^2\cdot R_s = 2.02\,kW$$

Power delivered through the stator terminals (Negative means power from machine to grid)

$$P_s := Re\left(3\cdot V_s\cdot \overline{I_s}\right) = -602.578\,kW$$

Power delivered to the grid (stator and rotor components)

$$P_{grid} := P_s - P_r = -479.1\,kW$$

Checking losses two ways.

$$P_m - P_{grid} = -4.578\,kW \qquad P_{I2Rs} + P_{I2Rr} = 4.578\,kW$$

Energy efficiency steady state

$$\eta := \frac{P_{grid}}{P_m} = 99.053\,\%$$

ECE 404 / 504

T & D Applications of Voltage Sourced Converters

Lesson 23

Due: Friday 8 March on campus; Monday 11 March off campus Engr Outreach

Doubly Fed Induction Generator : Induction machine with three phase windings on both stator and rotor; same number of poles on each;

Doubly fed machine has become popular for wind turbines; typically 30% or less of the energy goes through the variable speed drive

Stator: Energy from machine through transformer to grid

Rotor: Energy from machine through converter and transformer to grid

Power flow: Stator to grid unidirectional; rotor to grid bidirectional ; rotor power is typically <30% of stator power

SLIP!!

There is no class on Friday (next lesson). Compensatory time for the exam. Engr Outreach, there will be no video posted on Friday.