Renewable Energy and Distributed Generation

Doubly Fed Induction Generator WECS

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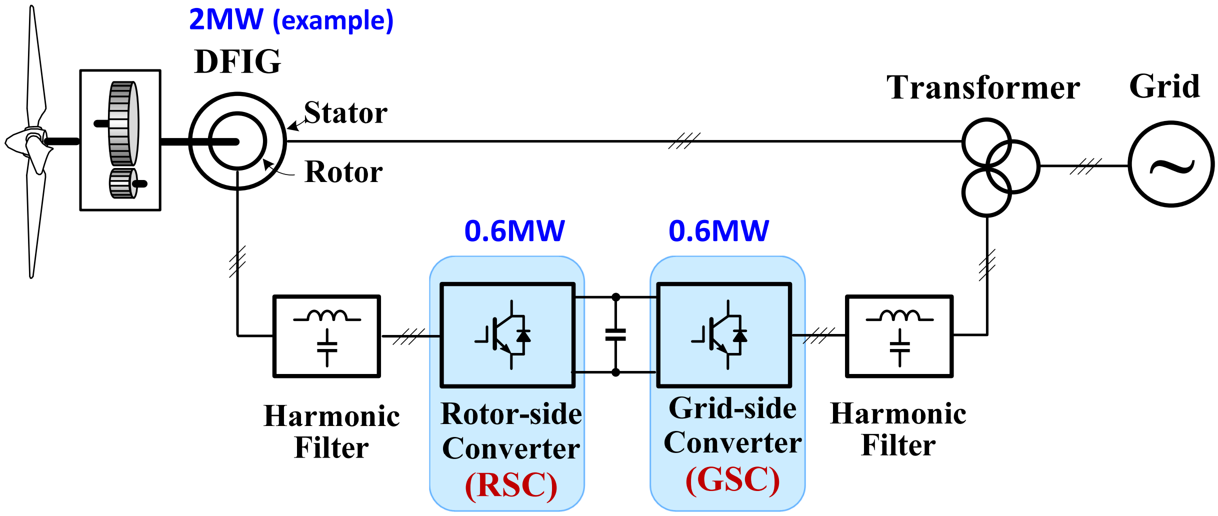
DFIG WECS

Main Topics

1. Introduction
2. Super- and Sub-synchronous Modes of Operation
3. DFIG Steady State Model
4. Steady State Analysis
5. Stator Voltage Oriented Control of DFIG WECS
6. DFIG WECS Start-up and Experiments

Introduction

System Configuration



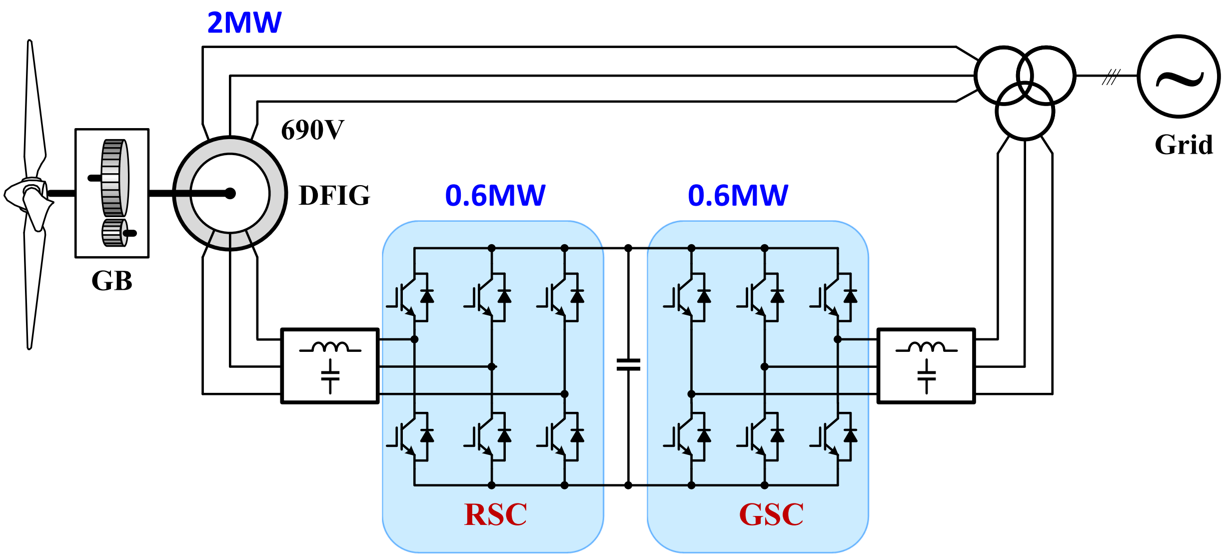
Block diagram of DFIG WECS

Main Feature:

The converter power rating is only around 30% of the generator rated power

Introduction

System Configuration

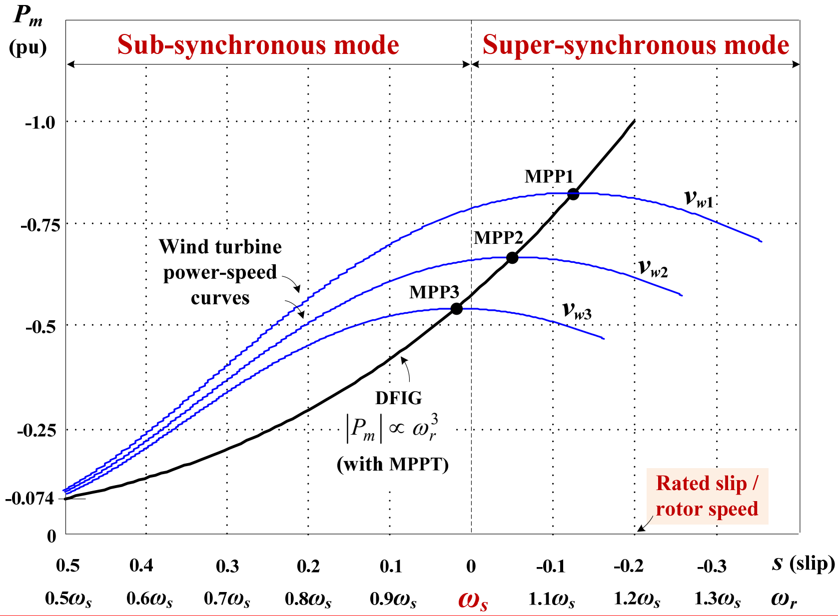


DFIG WECS with 2-level VSC

Super- and Sub-synchronous Operation

Power-speed Characteristics

- Rotor speed range: (0.7 ~ 1.3) ω_s
- ω_s is the synchronous speed of the generator



Sub-synchronous speed operation:

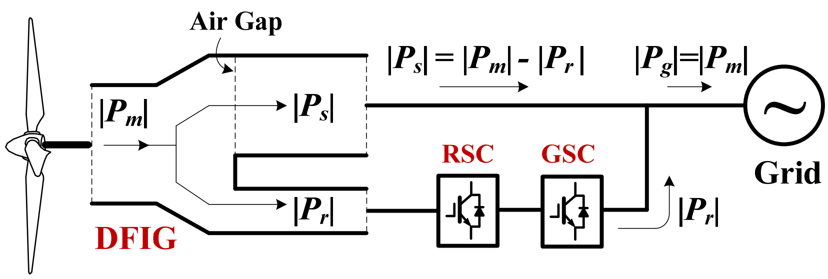
$\omega_r < \omega_s$

Super-synchronous speed operation:

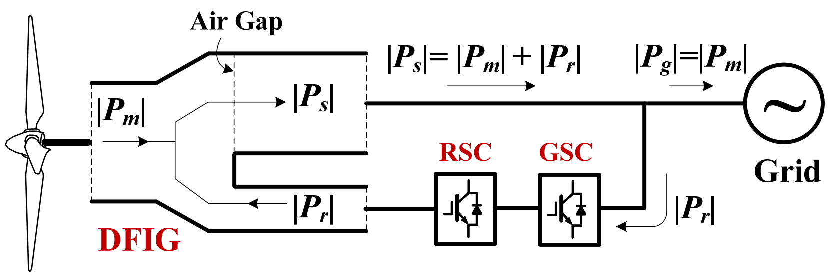
$\omega_r > \omega_s$

Super- and Sub-synchronous Operation

Power Flow in DFIG WECS



(a) Super-synchronous mode



(b) Sub-synchronous mode

Assumptions:
Power losses in DFIG and converters are ignored.

- P_m — mechanical power
- P_s — stator power
- P_r — rotor power
- P_g — grid power

Q: $|P_s| = |P_m| + |P_r|$

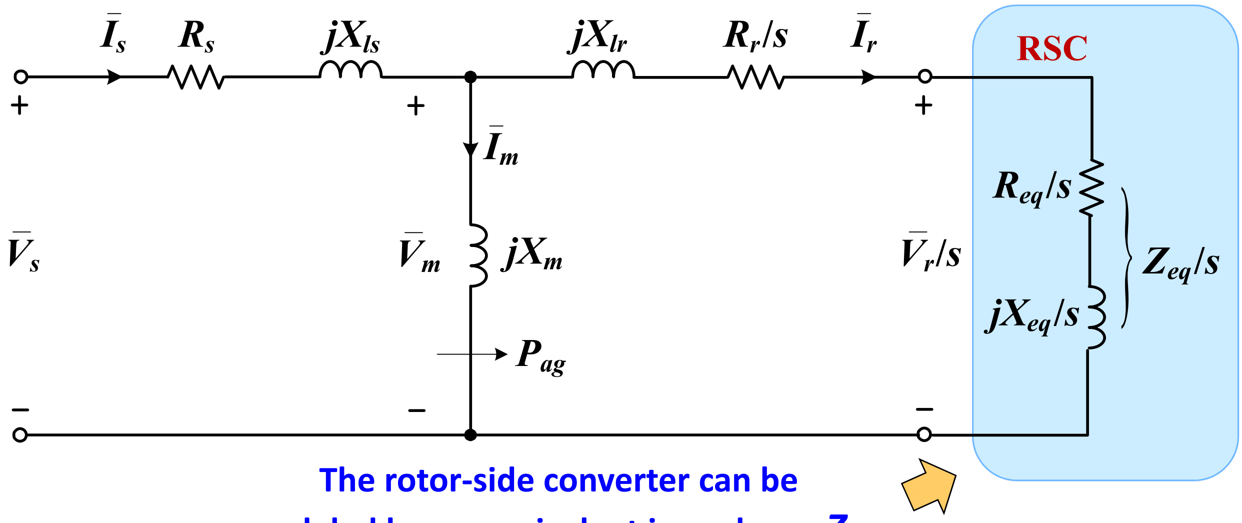
Is it too much for the stator?

Note: Power flow in the rotor and converters are bidirectional

DFIG Steady State Model

Equivalent Impedance of RSC

DFIG Steady-state Equivalent Circuit



The rotor-side converter can be modeled by an equivalent impedance Z_{eq}

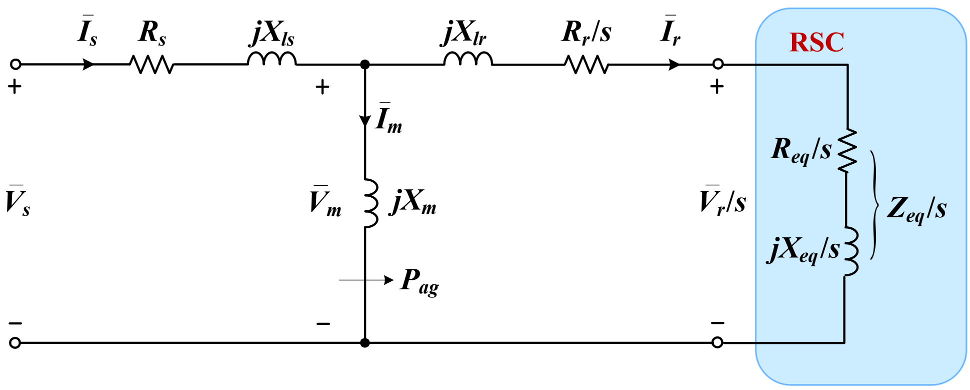
Q: How to find R_{eq} and X_{eq}?

DFIG Steady State Model

Equivalent Impedance of RSC

Q: How to find R_{eq} and X_{eq}?

Note:
The stator is connected to the grid.



Step 1 – Find I_s given V_s , ω_s and T_m (or P_m)

Step 2 – Find V_m and I_m

Step 3 – Find I_r and V_r

Step 4 – Find R_{eq} and X_{eq}

DFIG Steady State Model

Equivalent Impedance of RSC

The equivalent impedance of the converter is defined by

$$\bar{Z}_{eq} = R_{eq} + jX_{eq} = R_{eq} + j\omega_{sl}L_{eq}$$

Dividing by the slip yields:

$$\bar{Z}_{eq} / s = R_{eq} / s + j\omega_{sl}L_{eq} / s = R_{eq} / s + j\omega_s L_{eq}$$

where $\omega_{sl} = s\omega_s$

Step 1 – Find the stator current I_s

Assuming that the stator operates at a unity power factor, the air-gap power is given by

$$\boxed{P_{ag} = 3V_m I_s = 3(V_s - I_s R_s) I_s}$$ (from the equivalent circuit)

The air-gap power can also be defined by $\boxed{P_{ag} = \dfrac{\omega_s T_m}{P}}$ (from the machine theory)

Combining both: $\dfrac{\omega_s T_m}{P} = 3(V_s - I_s R_s) I_s \Rightarrow R_s I_s^2 - V_s I_s + \dfrac{\omega_s T_m}{3P} = 0$

DFIG Steady State Model

Equivalent Impedance of RSC

Solving for I_s:

$$R_s I_s^2 - V_s I_s + \frac{\omega_s T_m}{3P} = 0 \Rightarrow \boxed{I_s = \frac{V_s \pm \sqrt{V_s^2 - \dfrac{4R_s\omega_s T_m}{3P}}}{2R_s}}$$

Step 2 – Find V_m and I_m

The voltage across the magnetizing branch is

$$\bar{V}_m = \bar{V}_s - \bar{I}_s (R_s + j\omega_s L_{ls})$$

where $\bar{V}_s = V_s \angle 0°$ and $\bar{I}_s = I_s \angle 180°$ Note: The stator current angle of 180° is due to the generating mode and unity power factor operation.

The magnetizing current is $\bar{I}_m = \dfrac{\bar{V}_m}{j\omega_s L_m}$

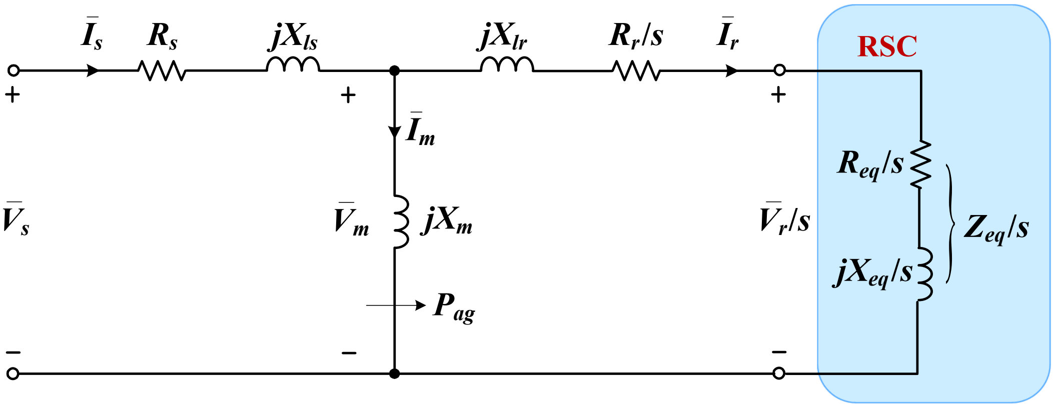
DFIG Steady State Model

Equivalent Impedance of RSC

Step 3 – Find I_r and V_r

$$\bar{I}_r = \bar{I}_s - \bar{I}_m$$

$$\bar{V}_r / s = \bar{V}_m - \bar{I}_r\left(\frac{R_r}{s} + j\omega_s L_{lr}\right) \quad \Rightarrow \quad \bar{V}_r = s\bar{V}_m - \bar{I}_r\left(R_r + js\omega_s L_{lr}\right)$$



DFIG Steady State Model

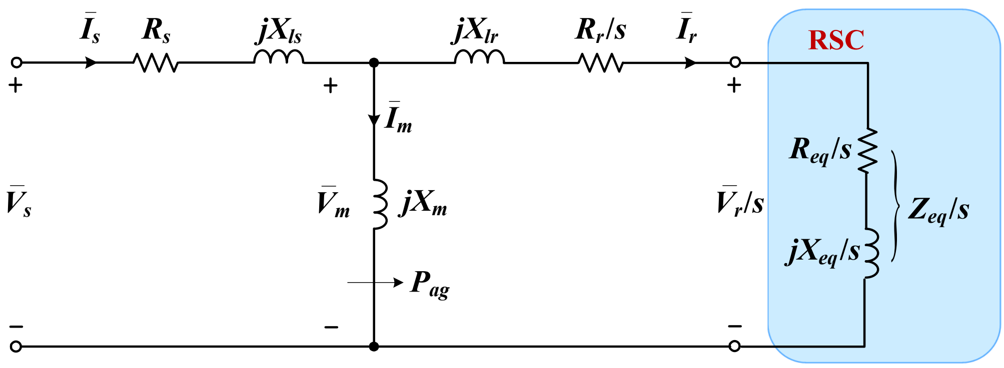
Equivalent Impedance of RSC

Step 4 – Find R_{eq} and X_{eq}

$$\frac{\bar{V}_r / s}{\bar{I}_r} = R_{eq} / s + jX_{eq} / s$$

from which

$$R_{eq} + jX_{eq} = \frac{\bar{V}_r}{\bar{I}_r}$$



DFIG Steady State Model

Case Study 1 – Equivalent Impedance of RSC

Consider:

- DFIG: 1.5MW/690V/1068A/50Hz/1750rpm
- Parameters given in Table B-5 of Appendix B
- Generator operates with an MPPT scheme
- Mechanical torque T_m is proportional to the square of the rotor speed
- Unity stator power factor operation

Q: Number of pole pairs?
A: $P = 2$

Investigate relationship between the rotor voltage, rotor current, and the equivalent impedance of the rotor-side converter when the DFIG operates at super-synchronous speed of 1750rpm

DFIG Steady State Model

Case Study 1 – Equivalent Impedance of RSC

DFIG operating at super-synchronous speed (1750 rpm, rated)

Stator current

Q: Synchronous speed?
A: 1500rpm.

$$I_s = \frac{V_s \pm \sqrt{V_s^2 - \dfrac{4R_s T_m \omega_s}{3P}}}{2R_s} = -1068.2\text{ A} \qquad \text{(the other solution } I_s = 1.514\times10^5\text{ A omitted)}$$

Rated torque due to the rated rotor speed of 1750rpm

where

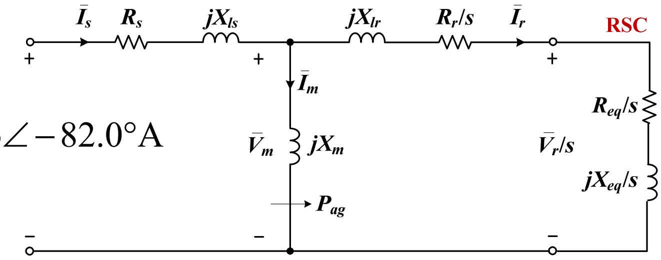
$$V_s = 690/\sqrt{3}\text{ V},\ \boxed{T_m = -8185.1\text{ N.m},}\ \omega_s = 2\pi\times50\text{ rad/sec},\ R_s = 6.25\text{ m}\Omega\ \text{ and } P = 2.$$

Voltage across the magnetizing branch

$$\begin{aligned}\overline{V}_m &= \overline{V}_s - \overline{I}_s\left(R_s + j\omega_s L_{ls}\right)\\ &= 690/\sqrt{3}\angle 0^\circ - 1068.2\angle 180^\circ \times (0.00625 + j100\pi\times 0.1687\times10^{-3})\\ &= 401.2 + j56.6 = 405.2\angle 8^\circ\ \text{ V}\end{aligned}$$

DFIG Steady State Model

Case Study 1 – Equivalent Impedance of RSC



Magnetizing current

$$\bar{I}_m = \frac{\bar{V}_m}{j\omega_s L_m} = 32.92 - j233.26 = 235.6\angle -82.0°\text{A}$$

The rotor current

$$\bar{I}_r = \bar{I}_s - \bar{I}_m = -1101.1 + j233.26 = 1125.6\angle 168.0°\text{A}$$

The rotor voltage

$$\bar{V}_r = s\bar{V}_m - \bar{I}_r\left(R_r + js\omega_s L_{lr}\right) = 67.97\angle -164.9°$$

where the slip is $s = (\omega_s - \omega_r)/\omega_s = -0.1667$

Finally, the equivalent impedance can be calculated by

$$\bar{Z}_{eq} = \bar{V}_r / \bar{I}_r = 0.05375\ \Omega + j0.2751 \quad \Rightarrow \quad \boxed{\begin{cases} R_{eq} = 0.05375\ \Omega \\ X_{eq} = 0.02751\ \Omega \end{cases}}$$

DFIG Steady State Model

Case Study 1 – Equivalent Impedance of RSC

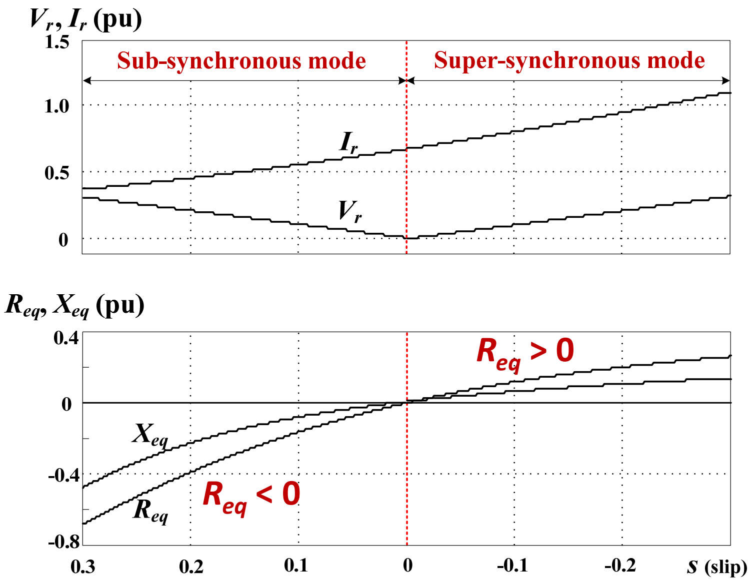
Question: When the DFIG operates at the synchronous speed (1500 rpm), how to calculate the mechanical torque?

$$\boxed{T_m = -(1500/\overset{\substack{\text{Rated}\\\text{mechanical}\\\text{speed}}}{\overset{\Downarrow}{1750}})^2 \times \overset{\substack{\text{Rated}\\\text{mechanical}\\\text{torque}}}{\overset{\Downarrow}{8.1851}}} = -6.0135\ \text{kN.m}$$

Why?

DFIG Steady State Model

Case Study 1 – Equivalent Impedance of RSC



Q: Physical meaning of positive and negative R_{eq} from the power flow point of view ?

A:

$R_{eq} > 0$ → rotor delivers power to the grid, super-synch mode;

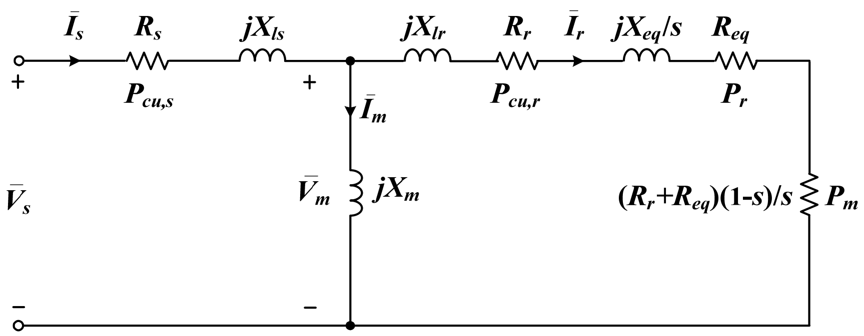
$R_{eq} < 0$ → rotor absorbs power from the grid, sub-synch mode;

See Fig. 8.3-6 on Slide 70

Steady State Analysis

Steady-state analysis

Consider the steady-state equivalent circuit



Neglecting rotational losses, the transferred and dissipated powers are

$$\begin{cases} P_m = 3I_r^2(R_r + R_{eq})(1-s)/s \\ P_r = 3I_r^2 R_{eq} \\ P_{cu,r} = 3I_r^2 R_r \\ P_{cu,s} = 3I_s^2 R_s \\ P_s = 3V_s I_s \cos\varphi_s \end{cases}$$

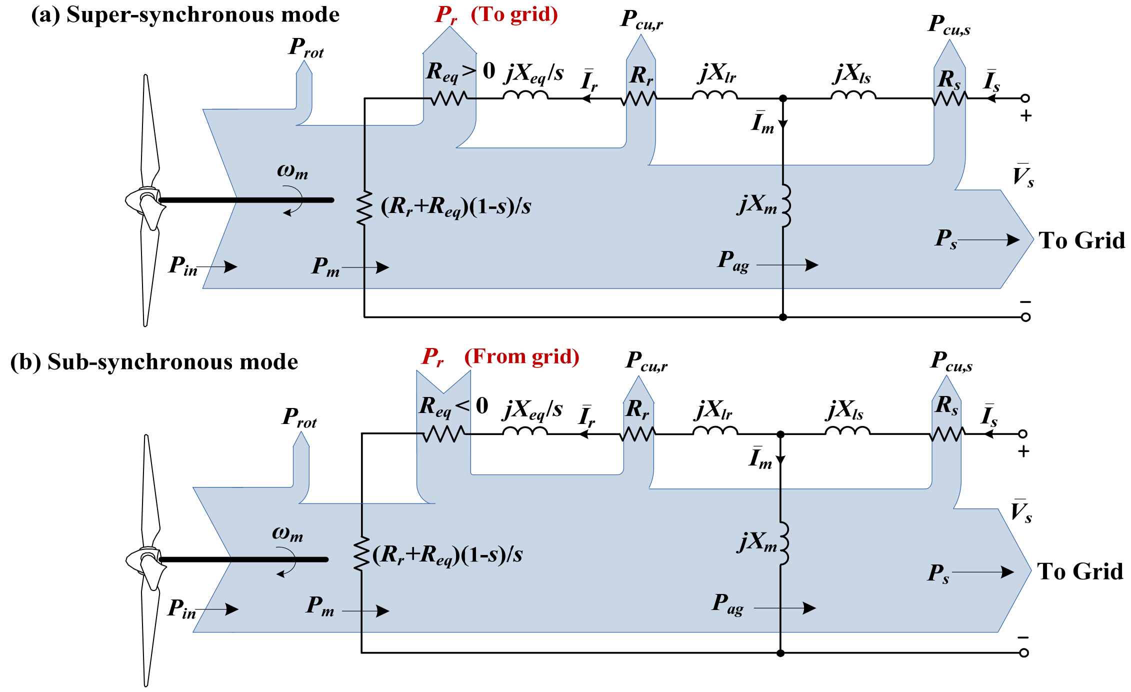
$$\left|P_g\right| = \begin{cases} \left|P_s\right| + \left|P_r\right| & \text{for super-synchronou mode} \\ \left|P_s\right| - \left|P_r\right| & \text{for sub-synchronou mode} \end{cases}$$

Power transferred to the grid

Steady State Analysis

Steady-state analysis

Power flow diagrams



Steady State Analysis

Case Study 2 – Steady-state Analysis with $PF_s = 1$

Consider the 1.5MW/690V DFIG operating under the same conditions as those in Case Study 1. Calculate the stator and rotor winding losses and the efficiency of the generator when it operates at the rotor speed of 1750rpm (super-synchronous mode).

With the rotor current calculated in Case Study 1, the mechanical power of the DFIG can be calculated by

$$P_m = 3I_r^2\left(R_{eq} + R_r\right)\left(1 - s\right)/s \quad \text{(from the equivalent circuit)}$$

$$= 3 \times 1125.6^2\left(0.05375 + 0.00263\right)\left(1 + 0.1667\right)/\left(-0.1667\right)$$

$$= -1500 \text{ kW}$$

Alternatively,

$$P_m = T_m\omega_m = -8185.1 \times 1750 \times 2\pi/60 = -1500\,\text{kW} \quad \text{(from the machine theory)}$$

Steady State Analysis

Case Study 2 – Steady-state Analysis with *PFs* = 1

The rotor power

$$P_r = 3(I_r)^2 R_{eq} = 3 \times 1125.6 \times 0.05375 = 204.29\,\text{kW}$$

The rotor and stator winding losses

$$P_{cu,r} = 3(I_r)^2 R_r = 10.0\,\text{kW}$$

$$P_{cu,s} = 3(I_s)^2 R_s = 9.07\,\text{kW}$$

Generating mode with unity PF

The stator active power

$$P_s = 3V_s I_s \cos\varphi_s = 690/\sqrt{3} \times 1068.2 \times \cos(180°) = -1276.64\,\text{kW}$$

Total power delivered to the grid

$$|P_g| = |P_s| + |P_r| = 1480.93\,\text{kW}$$

Efficiency:

$$\eta = P_g / P_m = 1480.93/1500 = 98.7\%$$

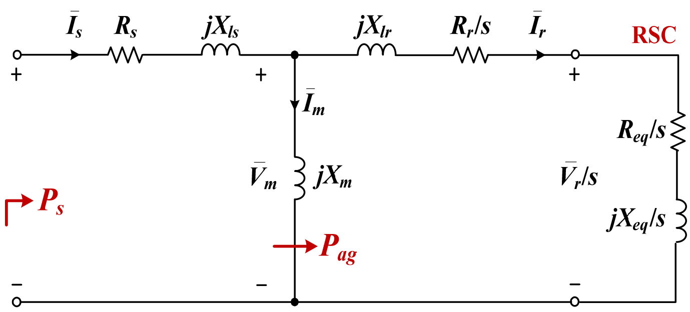
Steady State Analysis

Case Study 2 – Steady-state Analysis with *PFs* = 1

Simplified calculations

In large wind generators, the stator resistance is small (< 0.01pu).

Assumption: $R_s \approx 0$



The air-gap power

$$P_{ag} \approx P_s = 3\,V_s\,I_s \quad (PF_s = 1)$$

From electric machine theory:

$$P_{ag} = T_m \omega_s / P$$

from which the stator current can the be calculated by

$$I_s = \frac{T_m \omega_s / P}{3V_s}$$

With I_s calculated, all other analysis can be performed the same way as shown in Case Study 1.

Steady State Analysis

Case Study 2 – Steady-state Analysis

Calculations with leading and lagging power factor

With leading or lagging PF, the stator current can be calculated by

$$I_s = \frac{T_m \omega_s / P}{3V_s \boxed{\cos\varphi_s}}$$ **Leading or lagging PF**

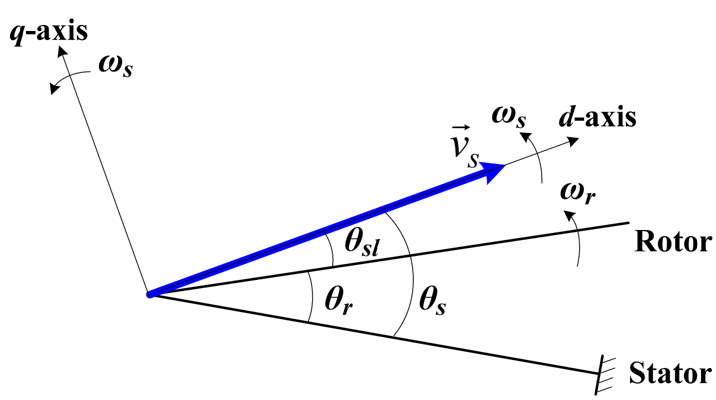
Following the same procedures given in Case Study 1, the calculated results with leading and lagging PF are as follows:

Stator PF	ω_m (rpm)	1200
	s (Slip)	0.2
Leading PF (0.95) $\varphi_s = -161.8°$	$\bar{V}_r$ [V]	$86.89\angle 5.7°$
	$\bar{I}_r$ [A]	$659.3\angle 142.2°$
	R_{eq} [Ω]	-0.0957
	X_{eq} [Ω]	-0.0906
Lagging PF (0.95) $\varphi_s = 161.8°$	$\bar{V}_r$ [V]	$80.65\angle 6.9°$
	$\bar{I}_r$ [A]	$525.2\angle 173.3°$
	R_{eq} [Ω]	-0.1493
	X_{eq} [Ω]	-0.0360

Stator Voltage Oriented Control

Principles of SVOC

- The stator of the DFIG is directly connected to the grid.
- Since stator voltage is fixed by the grid, it is convenient to use voltage oriented control (VOC) instead of field oriented control (FOC)
- Space vector diagram



Stator voltage vector aligned with the d-axis of the synch frame:

$$v_{qs} = 0$$
$$v_{ds} = v_s$$

Speed of the rotating frame:

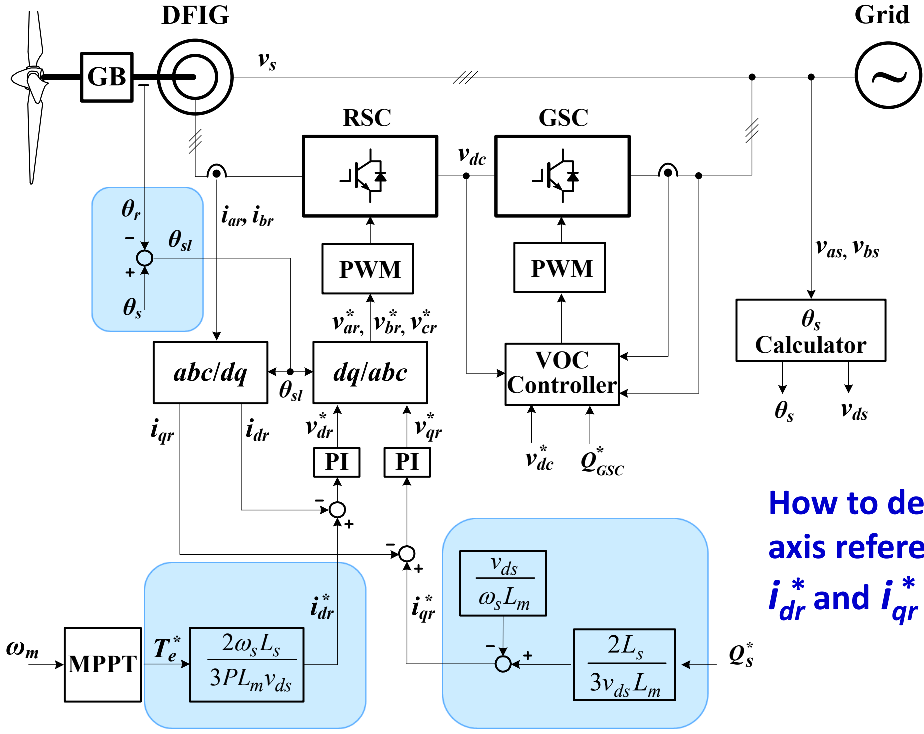
$$\omega_s = 2\pi f_s$$

Slip angle:

$$\theta_{sl} = \theta_s - \theta_r$$

Stator Voltage Oriented Control

Principles of SVOC – system block diagram



How to derive rotor *dq*-axis reference currents i_{dr}^* and i_{qr}^* ?

Stator Voltage Oriented Control

Principles of SVOC

Electromagnetic torque of the DFIG is given by

$$T_e = \frac{3PL_m}{2L_s}(-i_{qr}\lambda_{ds} + i_{dr}\lambda_{qs}) \qquad (8.56)$$

The dq-axis stator flux linkages can be found from its dq-axis equiv circuits:

$$\begin{cases} \lambda_{ds} = \dfrac{v_{qs} - R_s i_{qs}}{\omega_s} \\ \lambda_{qs} = -\dfrac{v_{ds} - R_s i_{ds}}{\omega_s} \end{cases} \qquad (8.59)$$

Substituting (8.59) to (8.56), and assuming R_s=0 and v_{qs}=0 for SVOC, we have

$$\boxed{T_e = -\frac{3PL_m}{2\omega_s L_s} i_{dr} v_{ds}} \qquad (8.62)$$

Note:
With a fixed stator voltage, torque can be controlled by d-axis rotor current.

Stator Voltage Oriented Control

Principles of SVOC

By definition, the active and reactive power are

$$\begin{cases} P_s = \frac{3}{2}(v_{ds} i_{ds} + v_{qs} i_{qs}) \\ Q_s = \frac{3}{2}(v_{qs} i_{ds} - v_{ds} i_{qs}) \end{cases}$$

With $v_{qs} = 0$ for SVOC,

$$\begin{cases} P_s = \frac{3}{2} v_{ds} i_{ds} \\ Q_s = -\frac{3}{2} v_{ds} i_{qs} \end{cases} \qquad (8.64)$$

Substituting (8.55) into (8.64) yields

$$\begin{cases} P_s = \frac{3}{2} v_{ds} \left(\frac{\lambda_{ds} - L_m i_{dr}}{L_s} \right) \\ Q_s = -\frac{3}{2} v_{ds} \left(\frac{\lambda_{qs} - L_m i_{qr}}{L_s} \right) \end{cases} \qquad (8.65)$$

Stator Voltage Oriented Control

Principles of SVOC

From (8.65)

$$\begin{cases} i_{dr} = -\frac{2L_s}{3v_{ds} L_m} P_s + \frac{1}{L_m} \lambda_{ds} \\ i_{qr} = \frac{2L_s}{3v_{ds} L_m} Q_s + \frac{1}{L_m} \lambda_{qs} \end{cases} \qquad (8.66)$$

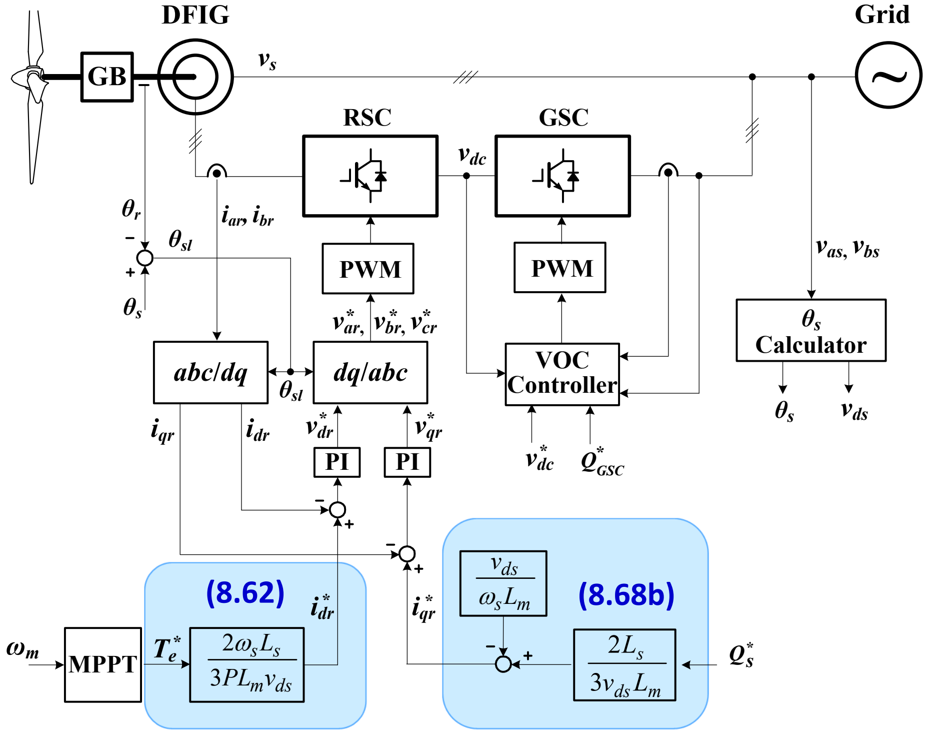
From (8.66)

$$i_{qr} = \frac{2L_s}{3v_{ds} L_m} Q_s - \frac{v_{ds}}{\omega_s L_m} \text{ (b)} \qquad (8.68)$$

Note: The stator active and reactive power can be controlled through rotor currents and voltages.

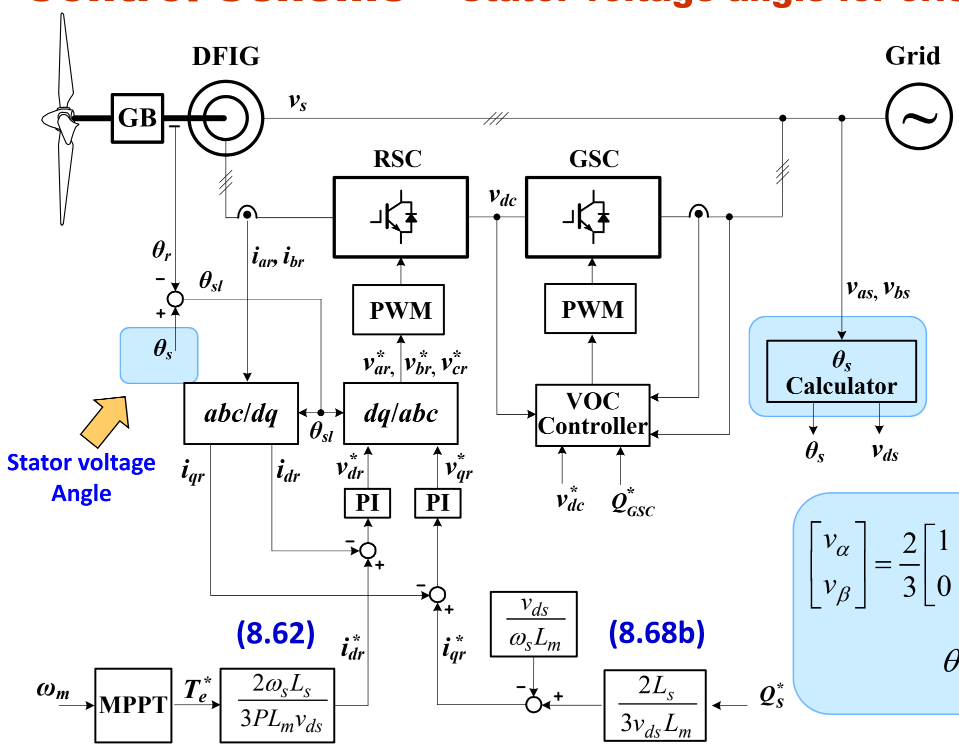
Stator Voltage Oriented Control

Control Scheme



Stator Voltage Oriented Control

Control Scheme – Stator voltage angle for orientation



$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix}$$

$$\theta_s = \tan^{-1}\frac{v_\beta}{v_\alpha}$$

Stator Voltage Oriented Control

Case Study 3 – Steady-state analysis of SVOC

With the same parameters of Case Study 1 and at 0.7pu wind speed

The mechanical torque of the generator is

$$T_m = -(\omega_{m,\text{pu}})^2 \times T_{m,R} = (0.7)^2 \times 8185 = -4010.7 \text{ N.m}$$

The stator current can be calculated by

$$I_s = \frac{V_s \pm \sqrt{V_s^2 - \dfrac{4R_s T_m \omega_s}{3P}}}{2R_s} = -525.3\text{A} \qquad (I_s = 1.509\times 10^5 \text{A omitted})$$

where

$$V_s = 690/\sqrt{3}\text{ V},\ \omega_s = 2\pi\times 50 \text{ rad/sec},\ R_s = 6.25 \text{ m}\Omega \text{ and } P = 2.$$

The voltage of the magnetizing branch is

$$\begin{aligned}\overline{V}_m &= \overline{V}_s - \overline{I}_s\left(R_s + j\omega_s L_{ls}\right)\\ &= 690/\sqrt{3}\angle 0° - 525.3\angle 180° \times (0.00625 + j100\pi\times 0.1687\times 10^{-3})\\ &= 399.8 + j27.8 = 400.7\angle 4.0° \text{ V}\end{aligned}$$

Stator Voltage Oriented Control

Case Study 3 – Steady-state analysis of SVOC

The magnetizing current is calculated by

$$\overline{I}_m = \frac{\overline{V}_m}{j\omega_s L_m} = 16.19 - j232.42 = 233.0\angle -86.0°$$

The rotor current is

$$\overline{I}_r = \overline{I}_s - \overline{I}_m = -541.50 + j232.42 = 589.27\angle 156.8°$$

The rotor voltage is determined by

$$\overline{V}_r = s\overline{V}_m - \overline{I}_r\left(R_r + js\omega_s L_{lr}\right) = 76.99\angle 6.5°$$

where $s = (\omega_s - \omega_r)/\omega_s = 0.1833$

Then the slip frequency at the 0.7 pu rotor speed is

$$\omega_{sl} = s\omega_s = 0.1833\times 2\pi\times 50 = 57.58 \text{ rad/sec}$$ **(9.165Hz)**

Stator Voltage Oriented Control

Case Study 3 – Steady-state analysis of SVOC

The peak values of the rotor voltage and rotor current are

$$\begin{cases} i_r = \sqrt{2} I_r = \sqrt{2} \times 589.27 = 833.25 \text{ A} & \boxed{(0.664 \text{ pu})} \\ v_r = \sqrt{2} V_r = \sqrt{2} \times 76.99 = 108.9 \text{ V} & \boxed{(0.273 \text{ pu})} \end{cases}$$

The rotor power factor angle is

$$\varphi_r = 6.5° - 156.8° = \boxed{-150.3°}$$

The equivalent impedance for the rotor-side converter is

$$\overline{Z}_{eq} = \overline{V}_r / \overline{I}_r = -0.11351\,\Omega + j - 0.06472\,\Omega$$

from which

$$\begin{cases} R_{eq} = -0.11351\ \Omega \\ X_{eq} = -0.06472\ \Omega \end{cases}$$

Stator Voltage Oriented Control

Case Study 3 – Steady-state analysis of SVOC

The mechanical power of the generator is

$$P_m = 3 I_r^2 \left(R_{eq} + R_r\right)\left(1 - s\right)/s$$

$$= 3 \times 589.27^2 \left(-0.11351 + 0.00263\right)\left(1 + 0.1833\right)/\left(-0.1833\right) = -514.50\ \text{kW}$$

Alternatively,

$$P_m = T_m \omega_m = -4010.7 \times 1750 \times 0.7 \times 2\pi / 60 = -514.50\,\text{kW}$$

The rotor power is

$$P_r = 3(I_r)^2 R_{eq} = 3 \times 589.27^2 \times (-0.11351) = -118.24\,\text{kW}$$

The rotor and stator winding losses are

$$P_{cu,r} = 3(I_r)^2 R_r = 2.74\,\text{kW}, \quad P_{cu,s} = 3(I_r)^2 R_s = 2.19\,\text{kW}$$

The stator active power is

Note: the DFIG operates as a generator with unity PF

$$P_s = 3 V_s I_s \cos\varphi_s = 690/\sqrt{3} \times 589.27 \times \cos(180°) = -627.81\,\text{kW}$$

Stator Voltage Oriented Control

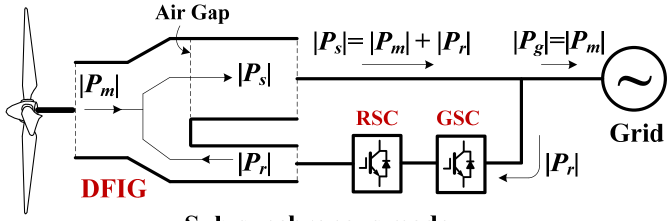
Case Study 3 – Steady-state analysis of SVOC

The total power delivered to the grid is

$$|P_g| = |P_s| - |P_r| = 627.81 - 118.24 = 509.57 \text{ kW}$$

The efficiency of the DFIG is then

$$\eta = |P_g| / |P_m| = 509.57 / 514.50 = 99.0\%$$



Sub-synchronous mode

The grid current is calculated by

$$|I_g| = \frac{|P_g|}{3V_g} = \frac{509.6 \times 10^3}{3 \times 398.4} = 426.37 \text{ A}$$

The peak grid current is

$$i_g = \sqrt{2}|I_g| = \sqrt{2} \times 426.37 = 603.0 \text{ A} \quad (0.48 \text{ pu})$$

The peak stator current is

$$i_s = \sqrt{2}|I_s| = \sqrt{2} \times 525.3 = 742.9 \text{ A} \quad (0.59\text{pu})$$

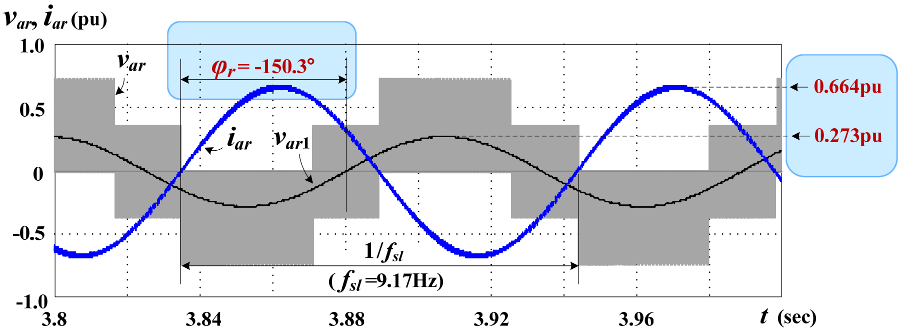
Q: Why is the grid current lower than stator current?

A: Because the grid power is equal to the stator power minus the rotor power in the sub-synch mode

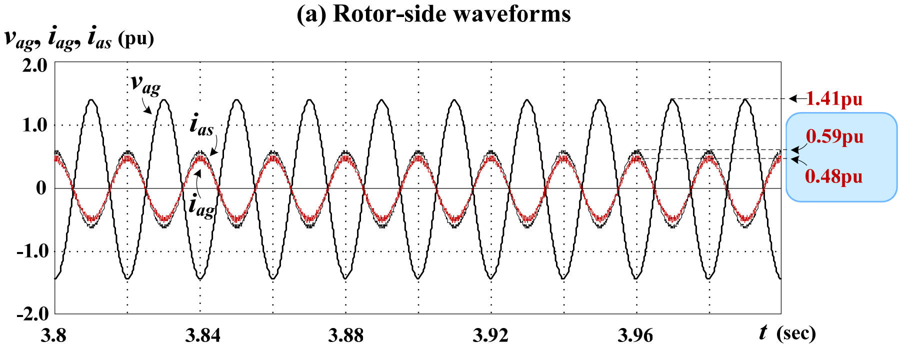
Stator Voltage Oriented Control

Case Study 3 – Steady-state analysis of SVOC

Verifying steady-state values by simulation



(a) Rotor-side waveforms

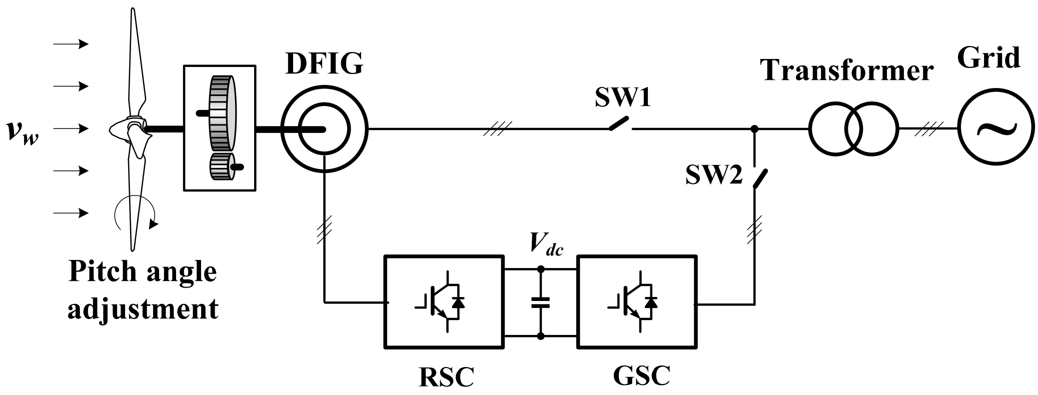


(b) Grid-side waveforms

DFIG Startup and Experiments

Startup Process

System block diagram



Initial parking state
- Switches SW1 and SW2 are open
- Turbine blades are pitched out of the wind
- Turbine does not rotate

DFIG Startup and Experiments

Startup Process

Step 1 – Stator voltage generation

- Mechanic safety brake is released
- Turbine blades are slightly pitched to produce starting torque
- Turbine and generator start to rotates
- SW2 is closed
- dc-link voltage is built by the GSC
- RSC provides excitation to the rotor and a rotating magnetic field is produced
- A 3-phase voltage is generated in the stator
- Torque reference is set to zero → no power is generated

DFIG Startup and Experiments

Startup Process

Step 2 – Synchronization

- The generated stator voltage/frequency are monitored and adjusted by RSC to match grid voltage/frequency for synchronization
- SW1 is closed when the synchronization is achieved
- The DFIG WECS is now connected to the grid

DFIG Startup and Experiments

Startup Process

Step 3 – Power generation

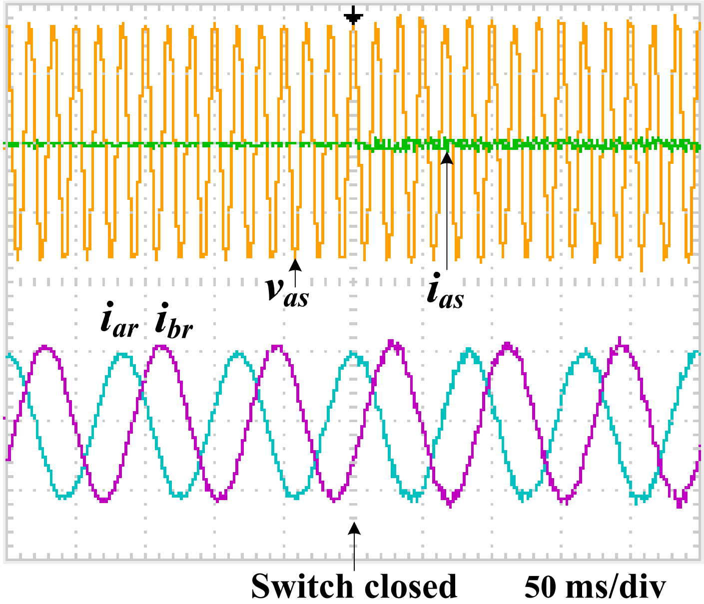
- The torque reference is increased from zero to a value by MPPT
- The blade pitch angle is adjusted to its optimal value
- The DFIG produces power to the grid
- The start-up process is completed

DFIG Startup and Experiments

Startup Process – Experimental Results

- Startup process with rotor speed at 0.8 pu (Steps 1 and 2 achieved)

- Results show Step 3 at which SW1 is closed



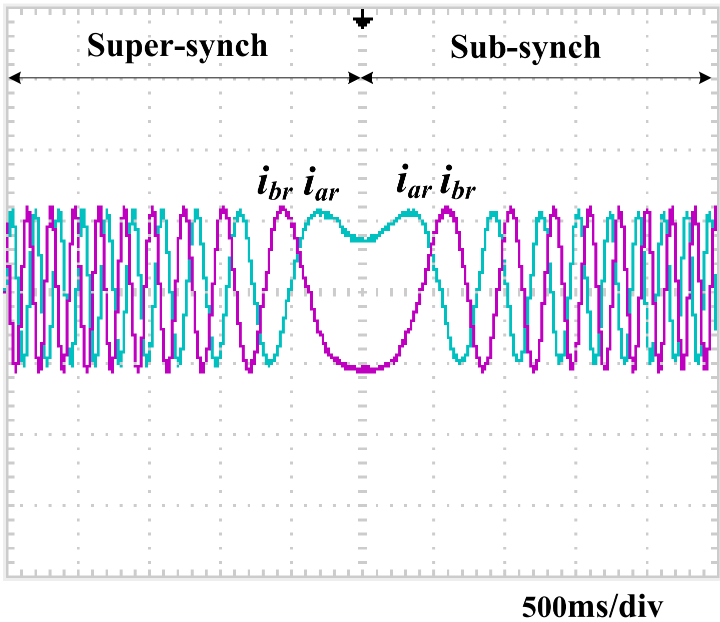
Stator current does not increase due to perfect synchronization

Ripple appears in stator current due to switching harmonics

DFIG Startup and Experiments

Startup Process – Experimental Results

Rotor currents during transition from super- to sub-synchronous speed



The rotor currents are DC when crossing synchronous speed

The Phase-*a* rotor current goes from lagging to leading the phase-*b* rotor current like seen in Case Study 4

Summary

1. Super- and Sub-synchronous Modes of Operation

Bidirectional power flow in the rotor circuit:

Super-synch operation: power delivered from the rotor to the grid

Sub-synch operation: power delivered from the grid to the rotor

Power flow in the stator circuit: always from the stator to the grid

2. DFIG Steady State Model

Derivation of R_{eq} and X_{eq} to represent the operation of the rotor-side converter

3. Steady State Analysis

Calculation of mechanical power, rotor power, losses, power factor, power delivered to the grid, and efficiency of the DFIG

4. Stator Voltage Oriented Control

SVOC principle, equations, steady state analysis, calculations

5. DFIG WECS Start-up Process

Discussed the start procedure of a DFIG WECS

Thanks