# EE-565 - W15
# DOUBLY FED INDUCTION MACHINES

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# DOUBLY FED INDUCTION MACHINE (I)

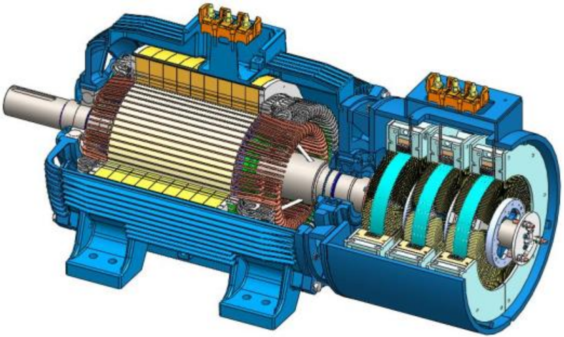


**Figure 1** Doubly fed induction machine.

- 3-phase wound stator - normally connected to AC grid of frequency - $\omega_{stator}$
- 3-phase wound rotor - fed by converter, through slip-rings - $\omega_{rotor}$
- mechanical speed of rotor (electrical equivalent) - $\omega_{mech}$

Multiple names are used:

- **WRIM (WRIG)** - Wound Rotor Induction Motor (Generator)
- **DFIM (DFIG)** - Doubly Fed Induction Motor (Generator)
- **DOIM (DOIG)** - Double Output Induction Motor (Generator)

Comparison:

- **Stator** - Similar to SM and IM stator
- **Rotor** - Wound with 3 slip rings

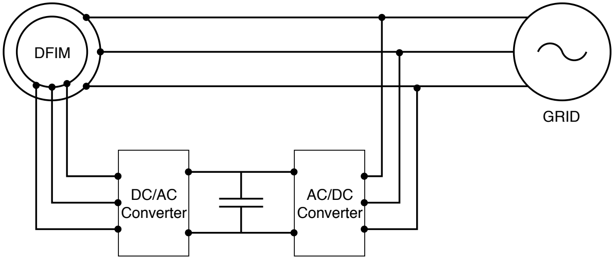



**Figure 2** Doubly fed induction machine.

**Figure 3** DFIM is used in: (top) hydro applications, (bottom) wind applications (less and less now).

Operation possibilities:

$$\omega_{mech} = \omega_{stator} \pm \omega_{rotor} \qquad \omega_{mech} = \Omega_{mech} p$$

- + sign indicates a **subsynchronous** operation mode $\omega_{mech} < \omega_{stator}$
- - sign indicates a **supersynchronous** operation mode $\omega_{mech} > \omega_{stator}$

Slip:

$$S = \frac{\omega_{rotor}}{\omega_{stator}} = \frac{\omega_{stator} - \omega_{mech}}{\omega_{stator}}$$

- $S > 0$ indicates a subsynchronous operation
- $S < 0$ indicates a supersynchronous operation

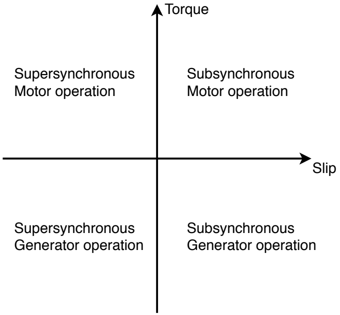



**Figure 4** Four quadrant operation

# OPERATION REGIONS OF DFIM (II)

Power delivery:

- Majority of active power comes from the stator
- However, in supersynchronous operation a good part comes from the rotor

With limited speed (slip) range of the DFIM: $S_{max}$

$$\omega_{mech_{max}} = \omega_{m_{max}} = \omega_s \left(1 + |S_{max}|\right)$$

Maximum power at maximum speed:

$$P_{max} = T\omega_{m_{max}} = T\omega_s \left(1 + |S_{max}|\right)$$

$$P_{max} = P_s + P_{r_{max}} = P_s + |S_{max}|P_s$$

- DFIM is electrically designed for $P_s$ at $\omega_s$
- DFIM is mechanically designed for $P_{max}$ at $\omega_{m_{max}}$
- Rotor side converter ratings are reduced - cost effective solution

Typically $S_{max} \cong 0.2 - 0.3$

In hydro or wind application this offer sufficient regulation capabilites

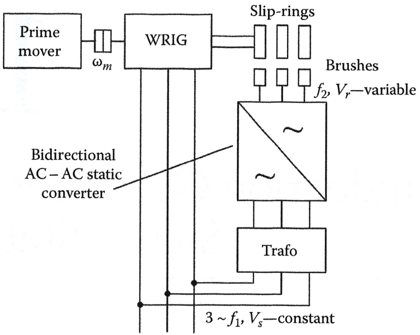



**Figure 5** DFIM setup

# OPERATION REGIONS OF DFIM (III)

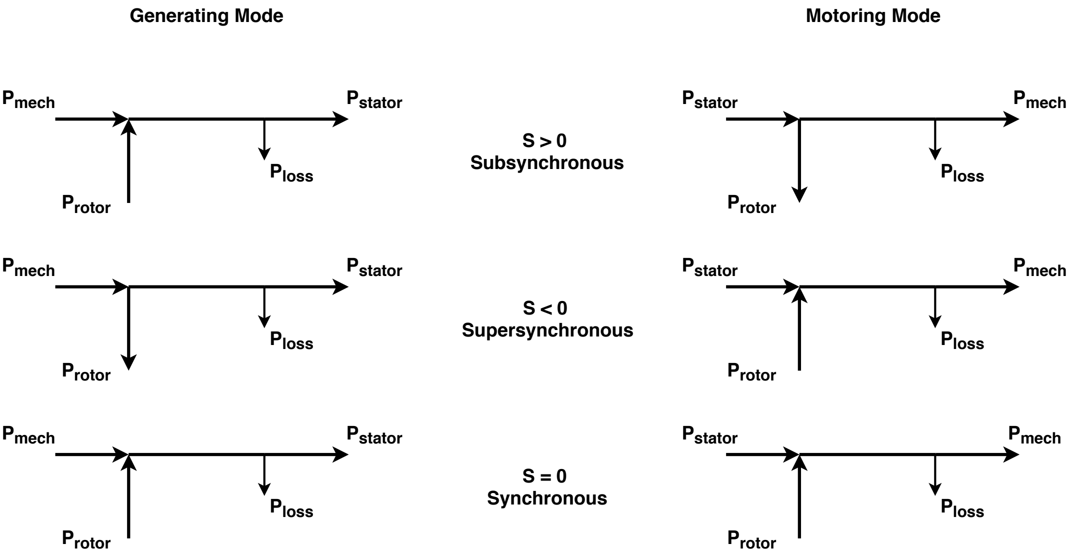



**Figure 6** Various operating modes

- Stator voltage:

$$U_{s_{abc}} = R_{s_{abc}} I_{s_{abc}} + \frac{d\Psi_{s_{abc}}}{dt}$$

- Rotor voltage:

$$U_{r_{abc}} = R_{r_{abc}} I_{r_{abc}} + \frac{d\Psi_{r_{abc}}}{dt}$$

- Combined:

$$|U_{sr_{abc}}| = |R_{sr_{abc}}||I_{sr_{abc}}| + \frac{d|\Psi_{sr_{abc}}|}{dt}$$

Where:

$$|R_{sr_{abc}}| = Diag|R_s, R_s, R_s, R_r^r, R_r^r, R_r^r|$$

$$|U_{sr_{abc}}| = Diag|U_{s_a}, U_{s_b}, U_{s_c}, U_{r_a}^r, U_{r_b}^r, U_{r_c}^r|^T$$

$$|I_{sr_{abc}}| = Diag|I_{s_a}, I_{s_b}, I_{s_c}, I_{r_a}^r, I_{r_b}^r, I_{r_c}^r|^T$$

$$|\Psi_{sr_{abc}}| = Diag|\Psi_{s_a}, \Psi_{s_b}, \Psi_{s_c}, \Psi_{r_a}^r, \Psi_{r_b}^r, \Psi_{r_c}^r|^T$$

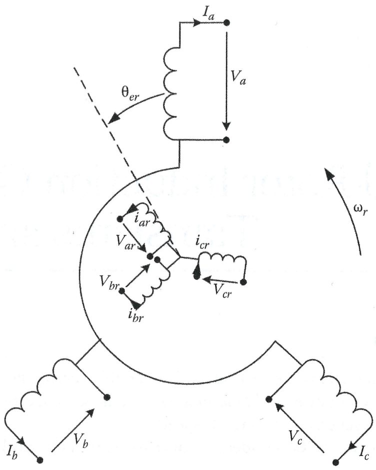



**Figure 7** DFIG phase circuits

- Relation between flux and current:

$$\left|\Psi_{sr_{abc}}\right| = \left|L_{sr_{abc}}(\theta_{er})\right|\left|I_{sr_{abc}}\right|$$

- with:

$$\left|L_{sr_{abc}}(\theta_{er})\right| =$$

$$= \begin{bmatrix} L_{ls}+L_{os} & -\frac{L_{os}}{2} & -\frac{L_{os}}{2} & M\cos(\theta_e r) & M\cos\left(\theta_e r+\frac{2\pi}{3}\right) & M\cos\left(\theta_e r-\frac{2\pi}{3}\right) \\ -\frac{L_{os}}{2} & L_{ls}+L_{os} & -\frac{L_{os}}{2} & M\cos\left(\theta_e r-\frac{2\pi}{3}\right) & M\cos(\theta_e r) & M\cos\left(\theta_e r+\frac{2\pi}{3}\right) \\ -\frac{L_{os}}{2} & -\frac{L_{os}}{2} & L_{ls}+L_{os} & M\cos\left(\theta_e r+\frac{2\pi}{3}\right) & M\cos\left(\theta_e r-\frac{2\pi}{3}\right) & M\cos(\theta_e r) \\ M\cos(\theta_e r) & M\cos\left(\theta_e r-\frac{2\pi}{3}\right) & M\cos\left(\theta_e r+\frac{2\pi}{3}\right) & L_{lr}+L_{or} & -\frac{L_{or}}{2} & -\frac{L_{or}}{2} \\ M\cos\left(\theta_e r+\frac{2\pi}{3}\right) & M\cos(\theta_e r) & M\cos\left(\theta_e r-\frac{2\pi}{3}\right) & -\frac{L_{or}}{2} & L_{lr}+L_{or} & -\frac{L_{or}}{2} \\ M\cos\left(\theta_e r-\frac{2\pi}{3}\right) & M\cos\left(\theta_e r+\frac{2\pi}{3}\right) & M\cos(\theta_e r) & -\frac{L_{or}}{2} & -\frac{L_{or}}{2} & L_{lr}+L_{or} \end{bmatrix}$$

Where:

$-\frac{L_{os}}{2}$ and $-\frac{L_{or}}{2}$ are derived from $L_{os}\cos\left(\frac{2\pi}{3}\right)$ and $L_{or}\cos\left(\frac{2\pi}{3}\right)$

$-\frac{L_{os}}{2}$ and $-\frac{L_{or}}{2}$ are the constant mutual inductances on the stator and the rotor

Power balance:

$$|U_{sr_{abc}}||I_{sr_{abc}}| = |R_{sr_{abc}}||I_{sr_{abc}}|^2 + \frac{d|\Psi_{sr_{abc}}|}{dt}|I_{sr_{abc}}|$$

$$|U_{sr_{abc}}||I_{sr_{abc}}| = \underbrace{|R_{sr_{abc}}||I_{sr_{abc}}|^2}_{1} + \underbrace{\frac{d}{dt}\left(\frac{1}{2}|I_{sr_{abc}}|^T|L_{sr_{abc}}(\theta_{er})||I_{sr_{abc}}|\right)}_{2} + \underbrace{\frac{1}{2}|I_{sr_{abc}}|^T\frac{d}{d\theta_{er}}|L_{sr_{abc}}(\theta_{er})||I_{sr_{abc}}|\frac{d\theta_{er}}{dt}}_{3}$$

- Part 1: Winding power losses
- Part 2: Stored magnetic energy variation in time
- Part 3: Electromagnetic power

Electromagnetic power:

$$P_{elm} = \frac{1}{2}|I_{sr_{abc}}|^T\frac{d}{d\theta_{er}}|L_{sr_{abc}}(\theta_{er})||I_{sr_{abc}}|\omega_r = T_e\frac{\omega_r}{p_1}$$

Electromagnetic torque:

$$T_e = \frac{p_1}{2}|I_{sr_{abc}}|^T\left|\frac{dL_{sr_{abc}}(\theta_{er})}{d\theta_{er}}\right||I_{sr_{abc}}|$$

# DFIM MODELLING - DQ FRAME (I)

Using Park transformation:

$$\underline{I_s^k} = I_{sd}^k + I_{sq}^k = \frac{2}{3}\left(I_{sa} + I_{sb}e^{j\frac{2\pi}{3}} + I_{sc}e^{-j\frac{2\pi}{3}}\right)e^{-j\theta_k}$$

$$\underline{I_r^k} = I_{rd}^k + I_{rq}^k = \frac{2}{3}\left(I_{ra} + I_{rb}e^{j\frac{2\pi}{3}} + I_{rc}e^{-j\frac{2\pi}{3}}\right)e^{-j(\theta_k-\theta_{er})}$$

Reduce rotor to stator variables:

$$a_{rs} \cong \frac{1}{|S_{max}|} \qquad K_{rs} = \frac{V_{r_N}}{V_{s_N}|S_{max}|} \qquad 0 < |S_{max}| < 0.3$$

- $a_{rs}$: stator to rotor turn ratio
- $K_{rs} = \frac{M}{L_{os}}$
- $|S_{max}|$: maximum slip (defined by the datasheet)

From rotor to stator variables:

$$I_{r_{abc}} = I_{r_{abc}}^r K_{rs} \qquad V_{r_{abc}} = \frac{V_{r_{abc}}^r}{K_{rs}}$$

$$R_r = \frac{R_r^r}{K_{rs}^2} \qquad L_{rl} = \frac{L_{rl}^r}{K_{rs}^2}$$

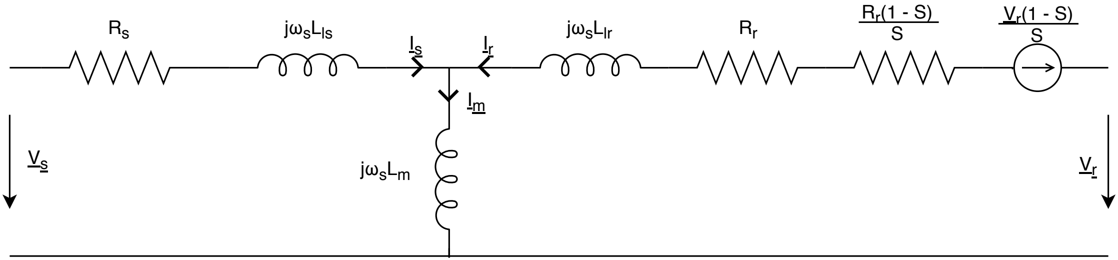



**Figure 8** DFIM equivalent model

Choosing the right reference frame:

$$\underline{U}_{s_{dq}} = R_s \underline{I}_{s_{dq}} + \frac{d\underline{\Psi}_{s_{dq}}}{dt} + j\omega_k \underline{\Psi}_{s_{dq}} \qquad \underline{U}_{r_{dq}} = R_r \underline{I}_{r_{dq}} + \frac{d\underline{\Psi}_{r_{dq}}}{dt} + j(\omega_k - \omega_m)\underline{\Psi}_{r_{dq}}$$

- Stator coordinates: $\omega_k = 0$
- Rotor coordinates: $\omega_k = \omega_m$
- **Synchronous coordinates:** $\omega_k = \omega_s$

# MODELING - DQ FRAME (I)

Stator and rotor fluxes:

$$\underline{\Psi}_{s_{dq}} = L_s \underline{I}_{s_{dq}} + L_m \underline{I}_{r_{dq}} \qquad \underline{\Psi}_{r_{dq}} = L_r \underline{I}_{r_{dq}} + L_m \underline{I}_{s_{dq}}$$

Where:

$$L_s = L_m + L_{ls} \qquad L_r = L_m + L_{lr}$$

Power:

$$P_s = \frac{3}{2} Real(\underline{U_s I_s}^*) = \frac{3}{2} R_s I_{s_d}^2 + Real\left(\frac{3}{2} \frac{d\underline{\Psi}_s}{dt} \underline{I_s}^*\right) + \underbrace{Real\left(\frac{3}{2} j\omega_b \underline{\Psi_s I_s}^*\right)}_{P_{elm}}$$

Electromagnetic torque:

$$\begin{aligned} T_e = \frac{p_1}{\omega_b} &= Real\left(\frac{3}{2} j\omega_b \underline{\Psi_s I_s}^*\right) \\ &= \frac{3}{2} p_1 Imag\left(\underline{\Psi_s I_s}^*\right) \\ &= \frac{3}{2} p_1 \left(\Psi_{s_q} I_{s_d} - \Psi_{s_d} I_{s_q}\right) \end{aligned}$$

# OPERATION AT THE POWER GRID (I)

$$\underline{U_s} = R_s\underline{I_s} + \frac{d\Psi_s}{dt} + j\omega_s\left(L_s\underline{I_s} + L_m\underline{I_r}\right)$$

$$\underline{U_r} = R_r\underline{I_r} + \frac{d\Psi_r}{dt} + jS\omega_s\left(L_r\underline{I_r} + L_m\underline{I_s}\right) = U_r\left(\cos\delta + j\sin\delta\right)$$

Steady state equations & assumption $R_s = 0$:

$$\underline{U_s} = j\omega_s\left(L_s\underline{I_s} + L_m\underline{I_r}\right)$$

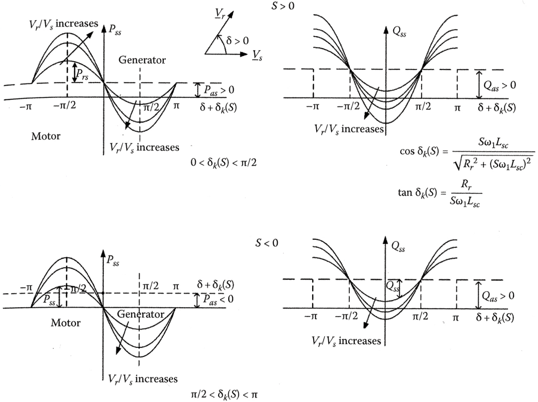
$$\underline{U_r} = R_r\underline{I_r} + jS\omega_s\left(L_r\underline{I_r} + L_m\underline{I_s}\right) = U_r\left(\cos\delta + j\sin\delta\right)$$

Eliminating $I_s$:

$$\left(R_r + jS\omega_s\left(L_r - \frac{L_m^2}{L_s}\right)\right)\underline{I_r} = U_r\left(\cos\delta + j\sin\delta\right) - SU_s\frac{L_m}{L_s}$$

With $\sigma = 1 - \frac{L_m^2}{L_sL_r}$:

$$\underline{I_r} = \frac{\left(U_r\cos\delta + jU_r\sin\delta - SU_s\frac{L_m}{L_s}\right)\left(R_r - jS\omega_s\sigma L_r\right)}{R_r^2 + \left(S\omega_s\sigma L_r\right)^2}$$



$$\cos\delta_k(S) = \frac{S\omega_s\sigma L_r}{\sqrt{R_r^2 + (S\omega_s\sigma L_r)^2}} \qquad \sin\delta_k(S) = \frac{R_r}{\sqrt{R_r^2 + (S\omega_s\sigma L_r)^2}} \qquad \tan\delta_k(S) = \frac{R_r}{S\omega_s\sigma L_r}$$

The angle $\delta_k$ depends on the Slip $S$ and the rotor resistance $R_r$:

$$\begin{aligned}
\delta_k &= 0 && for \quad |S\omega_s\sigma L_r| \gg R_r \\
\delta_k &= \frac{\pi}{2} && for \quad S = 0 \\
0 < \delta_k &< \frac{\pi}{2} && for \quad S > 0 \\
\frac{\pi}{2} < \delta_k &< \pi && for \quad S < 0
\end{aligned}$$

Operation at $S = 0$

$$P_s = -3U_sU_r\frac{L_m}{R_rL_s}\sin\left(\delta + \frac{\pi}{2}\right)$$

$$Q_s = \frac{3U_s^2}{\omega_sL_s} - 3U_sU_r\frac{L_m}{R_rL_s}\cos\left(\delta + \frac{\pi}{2}\right)$$

$$P_s + jQ_s = 3U_s I_s^* = 3L_m \frac{U_s}{L_s}\left(\frac{jU_s}{\omega_s L_m} - I_r^*\right)$$

Inserting the expression for $I_r$:

$$P_s + jQ_s = 3U_s I_s^* = 3\frac{jU_s^2}{\omega_s L_s} - 3L_m \frac{U_s}{L_s}\frac{\left(U_r \cos\delta - jU_r \sin\delta - SU_s \frac{L_m}{L_s}\right)(R_r + jS\omega_s\sigma L_r)}{R_r^2 + (S\omega_s\sigma L_r)^2}$$

Dividing into active and reactive power:

$$P_s = \underbrace{-3U_s U_r \frac{L_m}{L_s}\frac{\sin(\delta + \delta_k(S))}{\sqrt{R_r^2 + (S\omega_s\sigma L_r)^2}}}_{P_{ss}} + \underbrace{3U_s^2\left(\frac{L_m}{L_s}\right)^2 \frac{R_r S}{R_r^2 + (S\omega_s\sigma L_r)^2}}_{P_{as}}$$

$$Q_s = \frac{3U_s^2}{\omega_s L_s}\left(1 + \underbrace{\frac{(S\omega_s L_m)^2\sigma L_r}{\left(R_r^2 + (S\omega_s\sigma L_r)^2\right)L_s}}_{Q_{as}}\right) \underbrace{- 3U_s U_r \frac{L_m}{L_s}\frac{\cos(\delta + \delta_k(S))}{\sqrt{R_r^2 + (S\omega_s\sigma L_r)^2}}}_{Q_{ss}}$$

$$P_r^r + jQ_r^r = 3U_r I_r^*$$

Inserting the expression for $I_r$:

$$P_r^r + jQ_r^r = 3\left(U_r \cos\delta + jU_r \sin\delta\right) \frac{\left(U_r \cos\delta - jU_r \sin\delta - SU_s \frac{L_m}{L_s}\right)\left(R_r + jS\omega_s \sigma L_r\right)}{R_r^2 + \left(S\omega_s \sigma L_r\right)^2}$$

Dividing into active and reactive power:

$$P_r^r = \underbrace{\frac{3U_r^2 R_r}{R_r^2 + \left(S\omega_s \sigma L_r\right)^2}}_{P_{loss}^r} + \underbrace{3U_s U_r \frac{L_m}{L_s} \frac{S \sin\left(\delta + \delta_k(S)\right)}{\sqrt{R_r^2 + \left(S\omega_s \sigma L_r\right)^2}}}_{P_{as}^r}$$

$$Q_r^r = \underbrace{\frac{3U_r^2 S\omega_s \sigma L_r}{R_r^2 + \left(S\omega_s \sigma L_r\right)^2}}_{Q_{absorbed}^r} - \underbrace{3U_s U_r \frac{L_m}{L_s} \frac{S \cos\left(\delta + \delta_k(S)\right)}{\sqrt{R_r^2 + \left(S\omega_s \sigma L_r\right)^2}}}_{Q_s^r}$$

Main purpose:

- Keep the DC-link voltage constant

Voltage equations across the inductor:

$$\begin{bmatrix} U_{a_s} \\ U_{b_s} \\ U_{c_s} \end{bmatrix} = R \begin{bmatrix} I_{a_s} \\ I_{b_s} \\ I_{c_s} \end{bmatrix} + L \begin{bmatrix} \frac{dI_{a_s}}{dt} \\ \frac{dI_{b_s}}{dt} \\ \frac{dI_{c_s}}{dt} \end{bmatrix} + \begin{bmatrix} U_{a_1} \\ U_{b_1} \\ U_{c_1} \end{bmatrix}$$

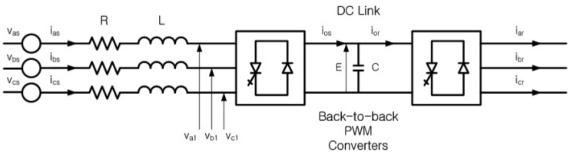



**Figure 9** GSC control schematics

In dq reference frame, the voltage equations become:

$$U_{d_s} = RI_{d_s} + L\frac{dI_{d_s}}{dt} - \omega_e LI_{q_s} + U_{d1}$$

$$U_{q_s} = RI_{q_s} + L\frac{dI_{q_s}}{dt} + \omega_e LI_{d_s} + U_{q1}$$

The supply flux angle is calculated:

$$\theta_e = \int \omega_e dt = \tan^{-1} \frac{U_\beta}{U_\alpha}$$

Aligning the d-axis along the stator-voltage angle leads to:

$$U_{q_s} = 0$$

$$P_s = \frac{3}{2} V_{d_s} I_{d_s}$$

$$Q_s = -\frac{3}{2} U_{d_s} I_{q_s}$$

# DFIG CONTROL GRID SIDE CONVERTER (II)

The DC-link equations:

$$E I_{os} = 3 U_d I_d \qquad U_d = \frac{m_1}{2\sqrt{2}} E$$

$$I_{os} = \frac{3}{2\sqrt{2}} m_1 I_d \qquad C\frac{dE}{dt} = I_{os} - I_{or}$$

The DC-link voltage can be controlled by $I_d$

The voltage equations become:

$$U_{d_1} = -\underbrace{\left(RI_{d_s} + L\frac{dI_{d_s}}{dt}\right)}_{=U'_d} + \underbrace{\omega_s L I_{q_s} + U_{d_s}}_{=U_{d1}^{comp}}$$

$$U_{q1} = -\underbrace{\left(RI_{q_s} + L\frac{dI_{q_s}}{dt}\right)}_{=U'_q} - \underbrace{\omega_s L I_{d_s}}_{=U_{q1}^{comp}}$$

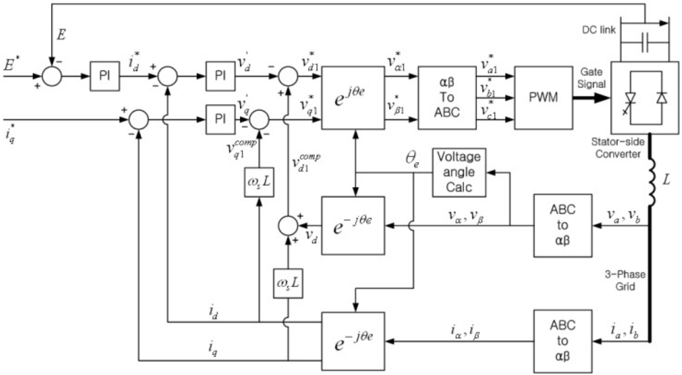



**Figure 10** GSC control schematics

Main purpose:

- Control speed
- Control active & reactive power on the rotor

Aligning the stator flux on the d-axis the equations become:

- Flux equations:

$$\Psi_{s_d} = L_s I_{s_d} + L_m I_{r_d} \qquad 0 = \Psi_{s_q} = L_s I_{s_q} + L_m I_{r_q}$$

$$\Psi_{r_d} = L_r I_{r_d} + L_m I_{s_d} \qquad \Psi_{r_q} = L_r I_{r_q} + L_m I_{s_q}$$

- from these equations:

$$I_{r_q} = -\frac{L_s}{L_m} I_{s_q} \qquad \Psi_{r_q} = L_r I_{r_q} - L_m \frac{L_s}{L_m} I_{r_q} = \left(1 - \frac{L_m^2}{L_s L_r}\right) L_r I_{r_q}$$

- Stator voltage equations:

$$\underline{U}_{s_{dq}} = R_s \underline{I}_{s_{dq}} + \frac{d\underline{\Psi}_{s_{dq}}}{dt} + j\omega_b \underline{\Psi}_{s_{dq}}$$

$$U_{s_d} = R_s I_{s_d} + \frac{d\Psi_{s_d}}{dt} = R_s I_{s_d} + L_s \frac{dI_{s_d}}{dt} + L_m \frac{dI_{r_d}}{dt}$$

$$U_{s_q} = R_s I_{s_q} + \omega_s \Psi_{s_d} = R_s I_{s_q} + \omega_s \left(L_s I_{s_d} + L_m I_{r_d}\right)$$

# DFIG CONTROL ROTOR SIDE CONVERTER (II)

Starting from:

$$\underline{U}_{r_{dq}} = R_r \underline{I}_{r_{dq}} + \frac{d\underline{\Psi}_{r_{dq}}}{dt} + j(\omega_b - \omega_m)\underline{\Psi}_{r_{dq}}$$

The rotor voltage equations become:

$$\begin{aligned}
U_{r_d} = R_r I_{r_d} + \frac{d\Psi_{r_d}}{dt} - (\omega_s - \omega_m)\Psi_{r_q} &= R_r I_{r_d} + L_r \frac{dI_{r_d}}{dt} + L_m \frac{dI_{s_d}}{dt} - \omega_{slip}\sigma L_r I_{r_q} \\
&= R_r I_{r_d} + L_r \frac{dI_{r_d}}{dt} + L_m \left(\frac{1}{L_s}\left(U_{s_d} - I_{s_d} R_s - L_m \frac{dI_{r_d}}{dt}\right)\right) - \omega_{slip}\sigma L_r I_{r_q} \\
&= R_r I_{r_d} + \left(L_r - \frac{L_m^2}{L_s}\right)\frac{dI_{r_d}}{dt} + \frac{L_m}{L_s}\left(U_{s_d} - \left(\frac{1}{L_s}(\Psi_{s_d} - L_m I_{r_d})\right)R_s\right) - \omega_{slip}\sigma L_r I_{r_q} \\
&= \underbrace{\left(R_r + \frac{L_m^2}{L_s^2}R_s\right)I_{r_d} + \underbrace{\left(L_r - \frac{L_m^2}{L_s}\right)}_{\sigma L_r}\frac{dI_{r_d}}{dt}}_{U'_{r_d}} + \underbrace{\frac{L_m}{L_s}\left(U_{s_d} - \frac{R_s}{L_s}\Psi_{s_d}\right) - \omega_{slip}\sigma L_r I_{r_q}}_{U_{r_d}^{comp}}
\end{aligned}$$

Finally:

$$U_{r_d} = U'_{r_d} + U_{r_d}^{comp}$$

# DFIG CONTROL ROTOR SIDE CONVERTER (III)

Transforming the q component of the rotor voltage:

$$
\begin{aligned}
U_{r_q} = R_r I_{r_q} + \frac{d\Psi_{r_q}}{dt} + (\omega_s - \omega_m)\Psi_{r_d} &= \underbrace{R_r I_{r_q} + \sigma L_r \frac{dI_{r_q}}{dt}}_{U'_{r_q}} + \omega_{slip}\left(L_r I_{r_d} + L_m I_{s_d}\right) \\
&= U'_{r_q} + \omega_{slip}\left(L_r I_{r_d} + L_m\left(\frac{1}{L_s}\left(\Psi_{s_d} - L_m I_{r_d}\right)\right)\right) \\
&= U'_{r_q} + \omega_{slip}\left(\left(L_r - \frac{L_m^2}{L_s}\right) I_{r_d} + \frac{L_m}{L_s}\Psi_{s_d}\right) \\
&= U'_{r_q} + \underbrace{\omega_{slip}\sigma L_r I_{r_d} + \omega_{slip}\frac{L_m}{L_s}\Psi_{s_d}}_{U_{r_q}^{comp}}
\end{aligned}
$$

Finally:

$$U_{r_q} = U'_{r_q} + U_{r_q}^{comp}$$

# DFIG CONTROL ROTOR SIDE CONVERTER (IV)

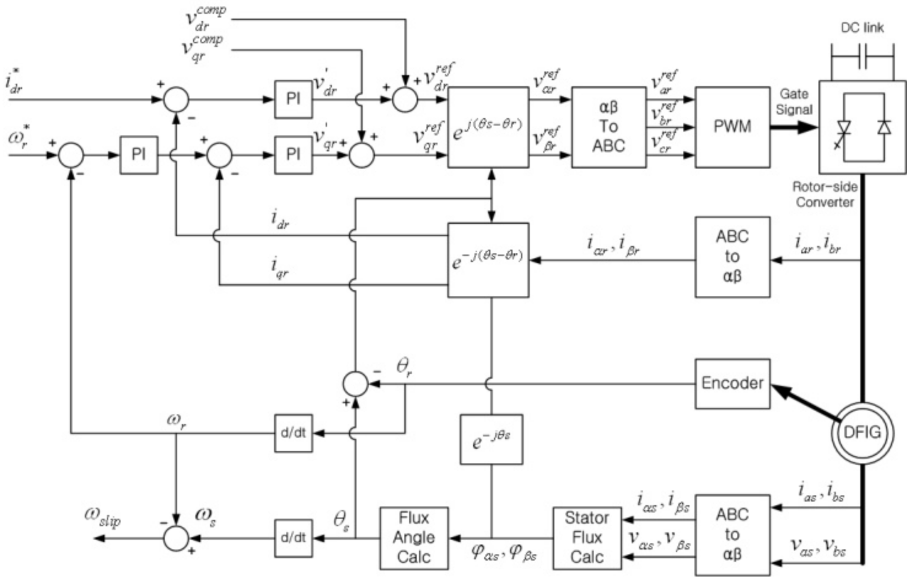



**Figure 11** GSC control schematics

Synchronisation is done in 3 Phases:

**Phase 1:** Acceleration to $\omega_{mech} > \omega_s(1 - |S_{max}|)$

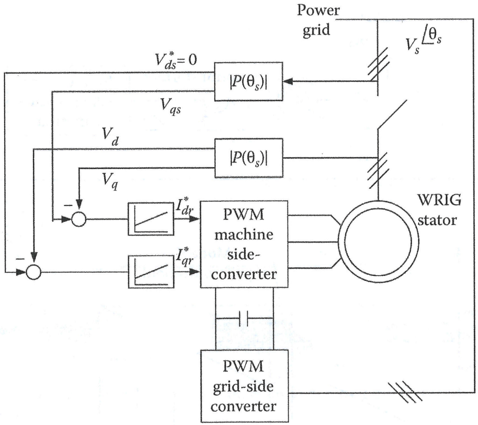
- Stator is short-circuited
- Operation principle as for a rotor fed induction machine

**Phase 2:** Open stator short-circuit

- Machine decelerates slowly
- Start synchronisation process

**Phase 3:** Close connection to the grid

- Frequency, Phase and Amplitude must match



# COMPARISON

## Disadvantages of DFIM

- Rotor slip rings require more maintenance
- Complex control for the RSC
- Limited current rating in case of grid fault

## Advantages of DFIM

Grid Synchronisation:

- Fast grid synchronisation
- Flexible grid synchronisation
- Fast de- and reconnection to the Grid

Flexibility:

- Speed variation allows better tracking of optimal power point
- Variable speed pumping for optimized efficiency

Reduced rotor side converter rating