Renewable Energy and Distributed Generation

# Topic 6
# Variable-speed Induction Generator WECS

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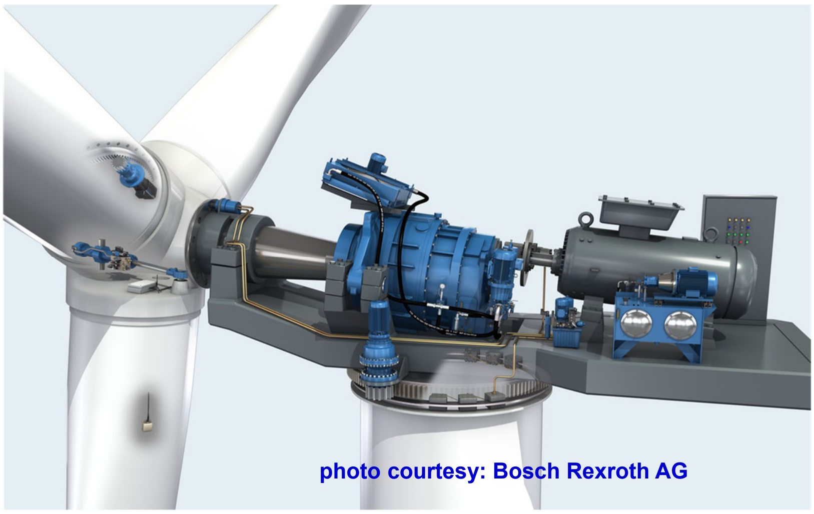


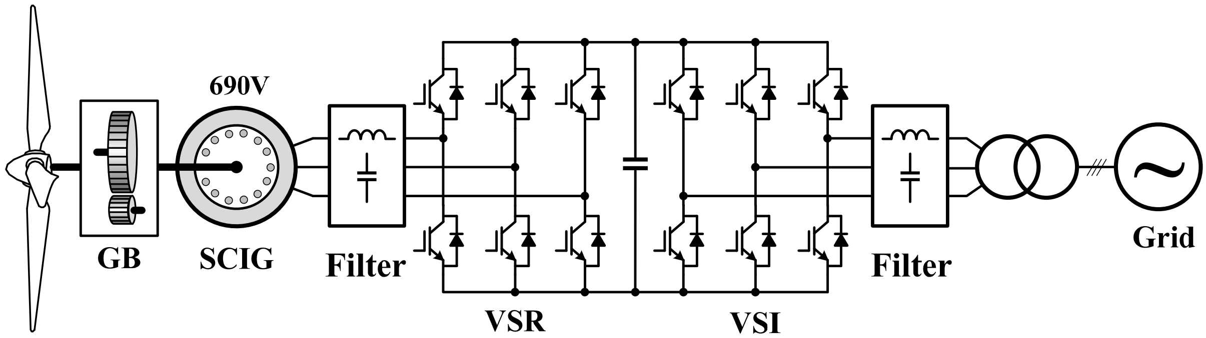

# Variable-speed IG WECS

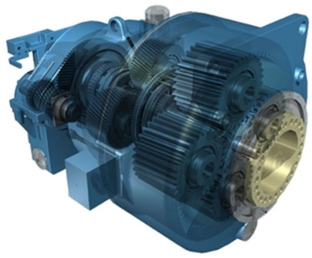
## Main Topics

1. Introduction
2. Direct Field Oriented Control (FOC)
3. Indirect Field Oriented Control
4. Introduction to Direct Torque Control (DTC)

# Introduction

## System Configuration



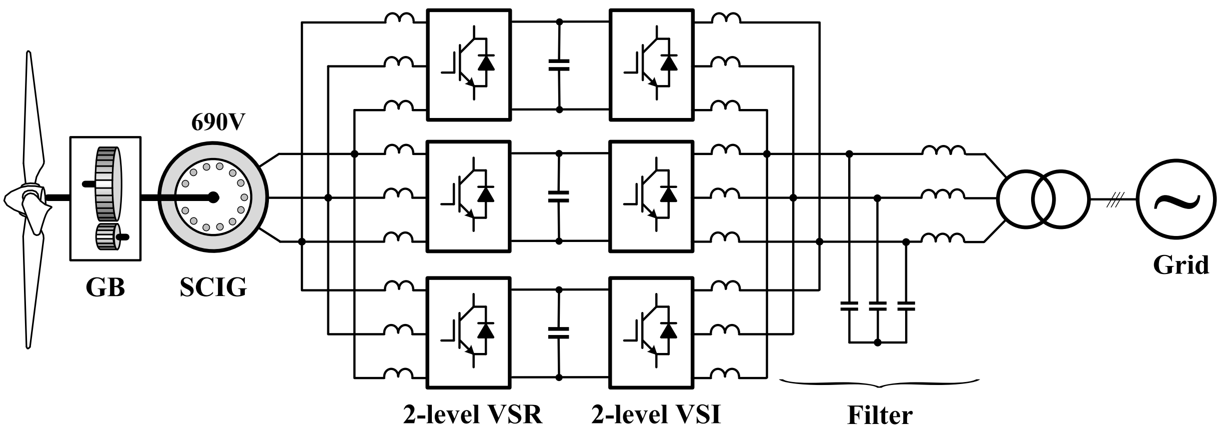
Gearbox

SCIG



# Introduction

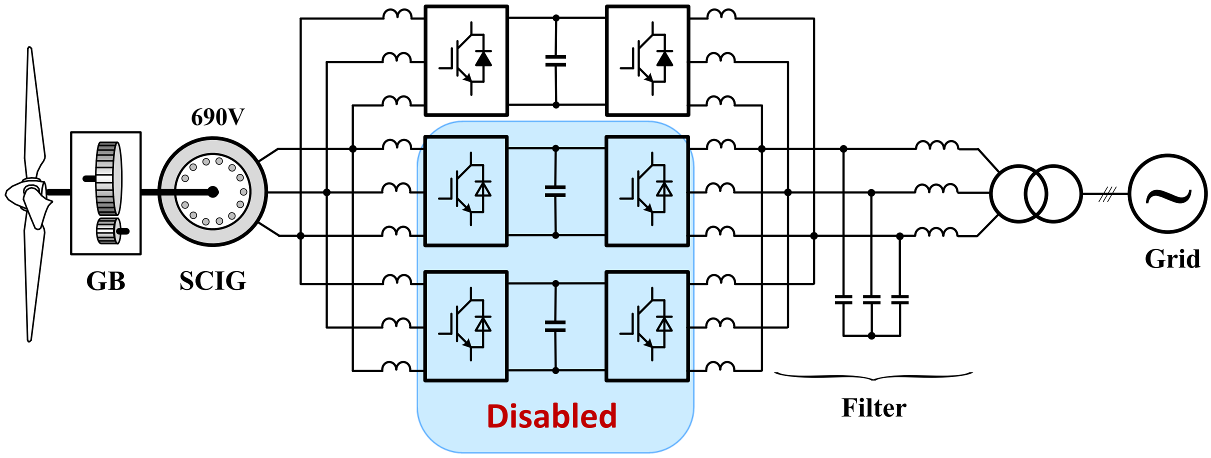
## System Configuration – Megawatt WECS




- Converters are connected in parallel for megawatt power capacity
- Converters can be turned off at lower wind speeds

# Introduction

## System Configuration – Megawatt WECS




**Example - Below rated operating conditions**

- Each converter is rated 0.75MW. Total power of the system is 2.25MW
- With wind speed of 0.6pu, captured power is $0.6^3 \times 2.25 = 0.49$MW
- At a wind speed of 0.6pu, two converter channels may be disabled. Why?



# Introduction

## Classification of FOC

**Field Orientation:**

In the rotor flux synchronous frame

**Direct FOC:**

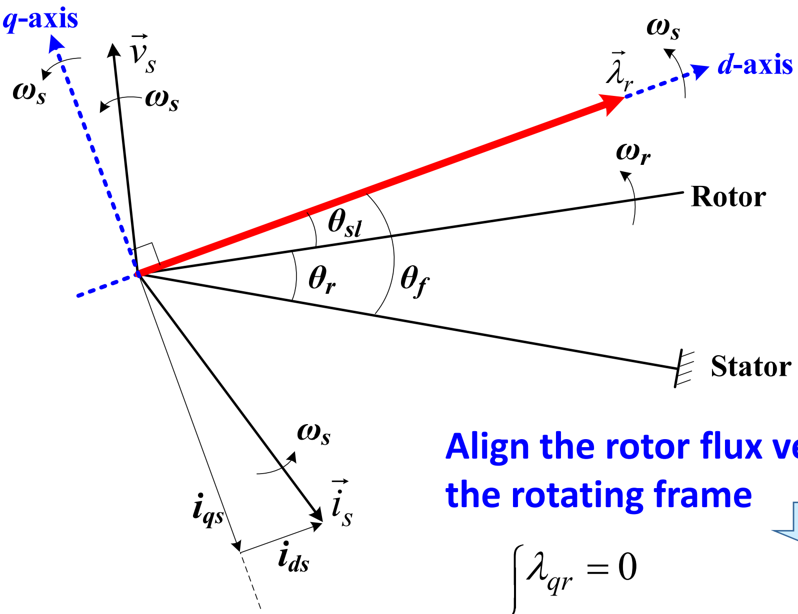
The rotor flux angle is obtained from measured generator terminal voltage and current

**Indirect FOC:**

The rotor flux angle is obtained from measured rotor position angle and calculated slip angle

# Direct FOC

## Field Orientation




$\theta_r$ – Rotor angle
$\theta_{sl}$ – slip angle
$\theta_f$ – Rotor flux angle

$\theta_f = \theta_r + \theta_{sl}$

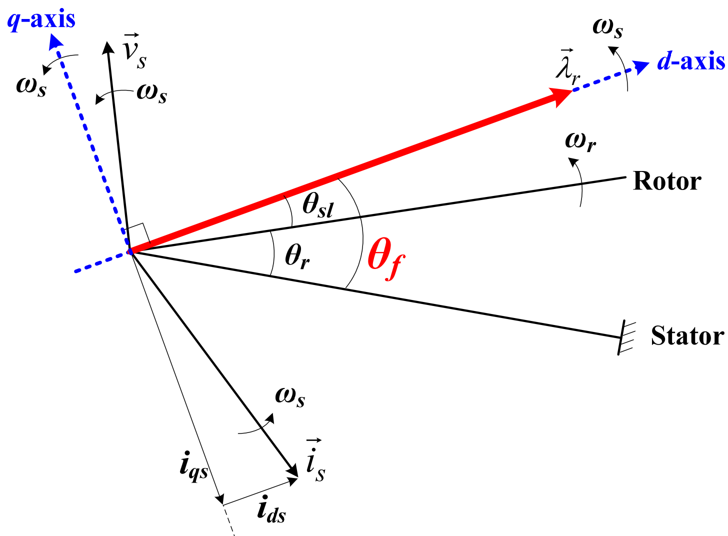
Align the rotor flux vector with the d-axis of the rotating frame

$$\begin{cases} \lambda_{qr} = 0 \\ \lambda_{dr} = \sqrt{(\lambda_r)^2 - (\lambda_{qr})^2} = \lambda_r \end{cases}$$



# Direct FOC

## Field Orientation




Simplified torque equation:

$$\begin{cases} \lambda_{qr} = 0 \\ \lambda_{dr} = \sqrt{(\lambda_r)^2 - (\lambda_{qr})^2} = \lambda_r \end{cases}$$

$$T_e = \frac{3PL_m}{2L_r}(i_{qs}\lambda_{dr} - i_{ds}\lambda_{qr})$$

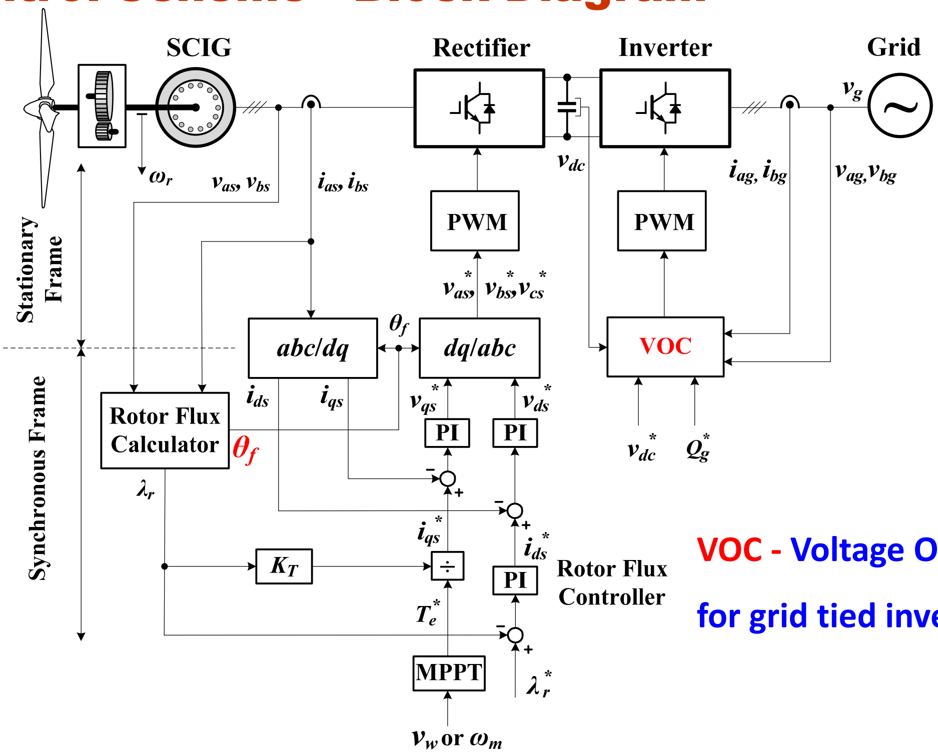
$$\boxed{T_e = K_T\, i_{qs}\lambda_r}$$

where $K_T = \dfrac{2PL_m}{3L_r}$

**Note:** One of the important tasks in the FOC scheme is to identify the rotor flux angle $\theta_f$ for field orientation.

# Direct FOC

## Control Scheme - Block Diagram

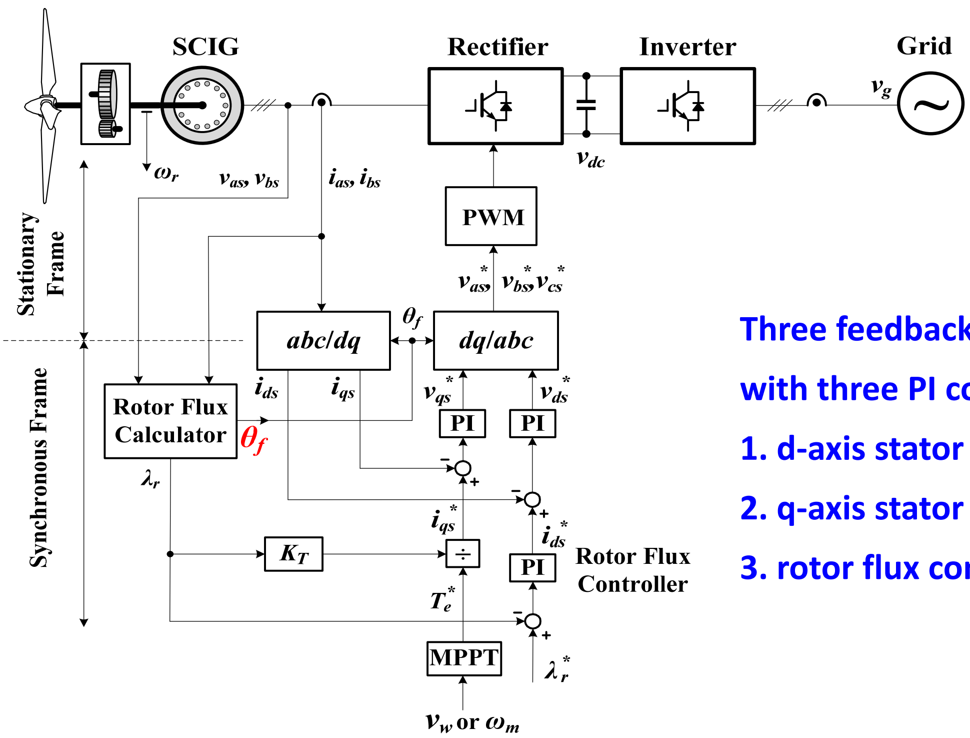



VOC - Voltage Oriented Control for grid tied inverter.



# Direct FOC

## Principle of Direct FOC

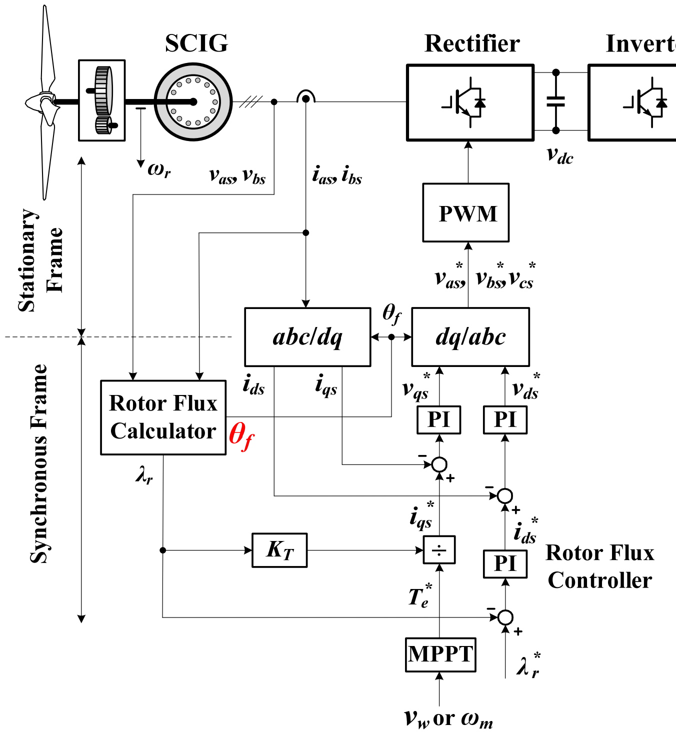



Three feedback control loops with three PI controllers:

1. d-axis stator current control
2. q-axis stator current control
3. rotor flux control

# Direct FOC

## Principle of Direct FOC




**Reference frame transformation:**

**Use rotor flux angle $\theta_f$ for transformation between the stationary and synchronous frames.**

**Q: Which synchronous frame?**

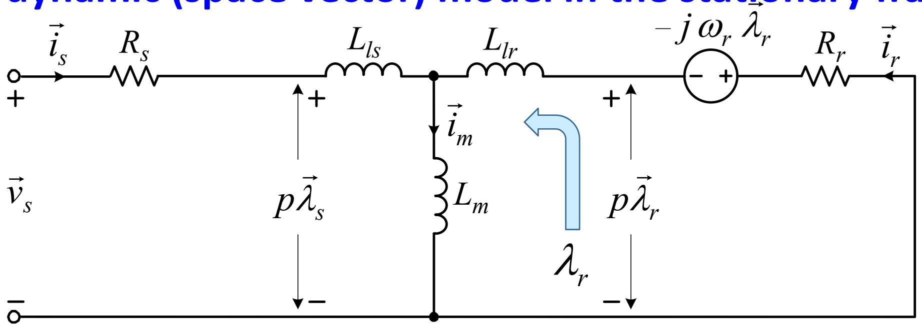
**A: Rotor flux synchronous frame**



# Direct FOC

## Rotor Flux Calculator

**SCIG dynamic (space vector) model in the stationary frame**




**The stator flux vector**

$$\vec{\lambda}_s = \int (\vec{v}_s - R_s \vec{i}_s) dt$$

**Q: Which frame is used for the IG model?**

**A: Stator (stationary) frame.**

**The rotor flux vector** $\vec{\lambda}_r = L_{lr}\vec{i}_r + L_m \vec{i}_m = L_r \dfrac{\vec{\lambda}_s - L_s \vec{i}_s}{L_m} + L_m \vec{i}_s = \dfrac{L_r}{L_m}\left(\vec{\lambda}_s - \sigma L_s \vec{i}_s\right)$

**where σ is the total leakage factor** $\sigma = 1 - \dfrac{L_m^2}{L_s L_r}$

# Direct FOC

## Rotor Flux Calculator

**The rotor flux expression** $\vec{\lambda}_r = \frac{L_r}{L_m}\left(\vec{\lambda}_s - \sigma L_s \vec{i}_s\right)$ **(from the previous slide)**

**Decomposing the rotor flux into the d- and q-axis components**

$$\begin{cases} \lambda_{dr} = \dfrac{L_r}{L_m}\left(\lambda_{ds} - \sigma L_s i_{ds}\right) \\ \lambda_{qr} = \dfrac{L_r}{L_m}\left(\lambda_{qs} - \sigma L_s i_{qs}\right) \end{cases}$$

**Can be directly measured**

**The magnitude and angle of the rotor flux:**

$$\begin{cases} \lambda_r = \sqrt{\lambda_{dr}^2 + \lambda_{qr}^2} \\ \theta_f = \tan^{-1}\dfrac{\lambda_{qr}}{\lambda_{dr}} \end{cases}$$

Feature: $\lambda_r$ and $\theta_f$ are identified from measured $\vec{v}_s$ , $\vec{i}_s$ and generator parameters ( $L_s$ , $L_r$ , $L_m$ and $R_s$ )



# Direct FOC

## Rotor Flux Calculator

**The d- and q-axis rotor flux:**

$$\begin{cases} \lambda_{dr} = \dfrac{L_r}{L_m}\left(\boxed{\lambda_{ds}} - \sigma L_s i_{ds}\right) \\ \lambda_{qr} = \dfrac{L_r}{L_m}\left(\boxed{\lambda_{qs}} - \sigma L_s i_{qs}\right) \end{cases}$$

**(from the previous slide)**

**How to find/measure $\lambda_{ds}$ and $\lambda_{qs}$ ?**

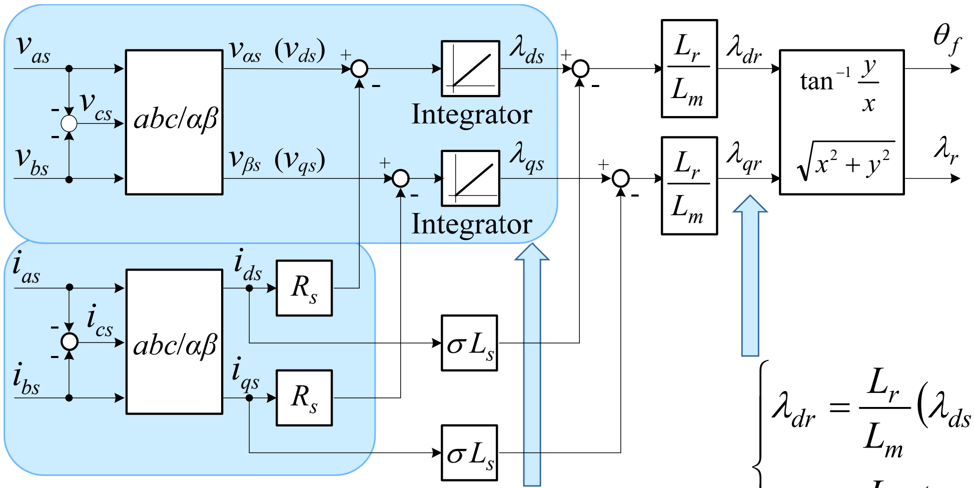
$$\vec{\lambda}_s = \int\left(\vec{v}_s - R_s \vec{i}_s\right)dt \Rightarrow \begin{cases} \lambda_{ds} = \int\left(v_{ds} - R_s i_{ds}\right)dt \\ \lambda_{qs} = \int\left(v_{qs} - R_s i_{qs}\right)dt \end{cases}$$

**Can be directly measured**

# Direct FOC

## Rotor Flux Calculator

### Block diagram of Rotor Flux Calculator




$$\begin{cases} \lambda_{dr} = \dfrac{L_r}{L_m}\left(\lambda_{ds} - \sigma L_s i_{ds}\right) \\ \lambda_{qr} = \dfrac{L_r}{L_m}\left(\lambda_{qs} - \sigma L_s i_{qs}\right) \end{cases}$$

$$\begin{cases} \lambda_{ds} = \int \left(v_{ds} - R_s\, i_{ds}\right) dt \\ \lambda_{qs} = \int \left(v_{qs} - R_s\, i_{qs}\right) dt \end{cases}$$



# Direct FOC

## Case Study 1 – Start up Transient Analysis

**Investigation:** The start-up transient process of a 2.3MW/690V SCIG WECS (Table B-1, Appendix B)

**Wind speed:** Rated

**Control Scheme:** Direct FOC scheme

**Starting procedures:**

1. The mechanical safety brake is released
2. The turbine and generator speeds are brought up from zero to their rated value by the wind
3. A step rotor flux (rated ) reference is applied
4. The rotor flux starts to build up. After it reaches its rated value, a step torque reference (rated) is applied
5. The system delivers its rated power to the grid

# Direct FOC

## Case Study 1 – Start up Transient Analysis

**Assumption**

1. The generator speed does not change during the transients since the mechanical system of the wind turbine is much slower than the electrical system.

2. The dc voltage is kept constant by the grid-tied inverter: A constant dc voltage source is used in the simulation



# Direct FOC

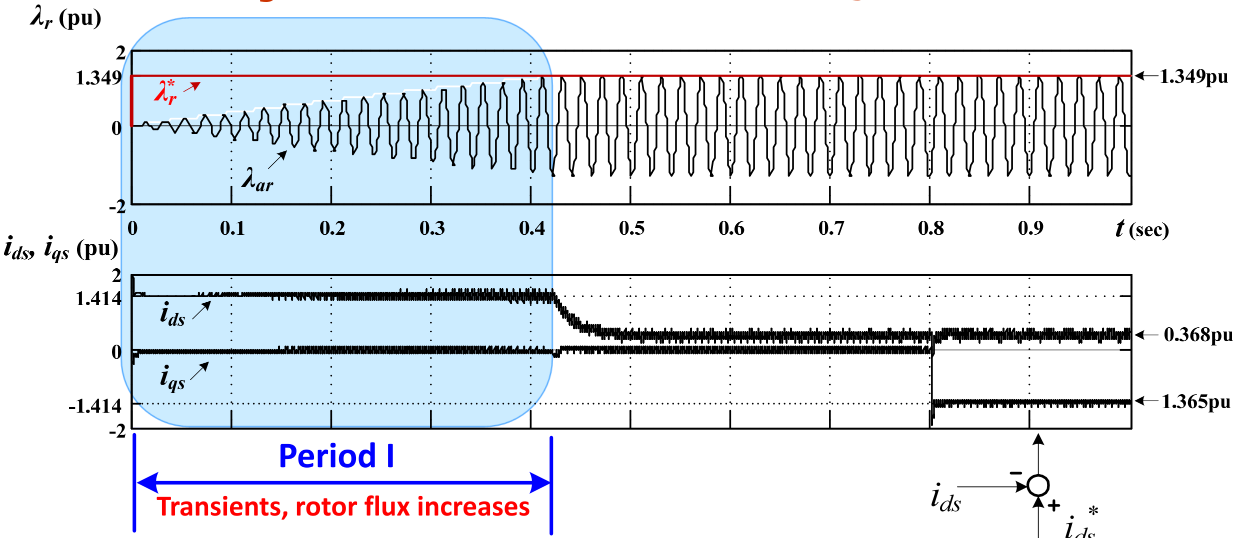
## Case Study 1 – Start up Transient Analysis

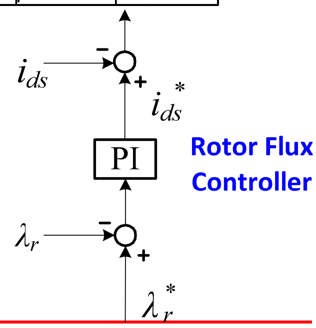
### System Parameters

| | | |
|---|---|---|
| Induction Generator | Generator Ratings:<br>2.3MW/690V/50Hz/1512rpm<br>2168A/14.67kN.m | Generator parameters:<br>Table B-1 (Appendix B) |
| Generator-side Converters | Converter Type | Two-level VSC |
| | Modulation Scheme | Space vector modulation |
| | Switching Sequence | Seven segment; Table 4-4 |
| | Switching Frequency | 2kHz |
| DC Voltage | Fixed | $V_{dc}$ = 1220V (3.06pu) |

# Direct FOC

## Case Study 1 – Start up Transient Analysis




**Q:** $i_{ds}^*$ is set at its rated value by the PI controller (saturated) during start up. Why?

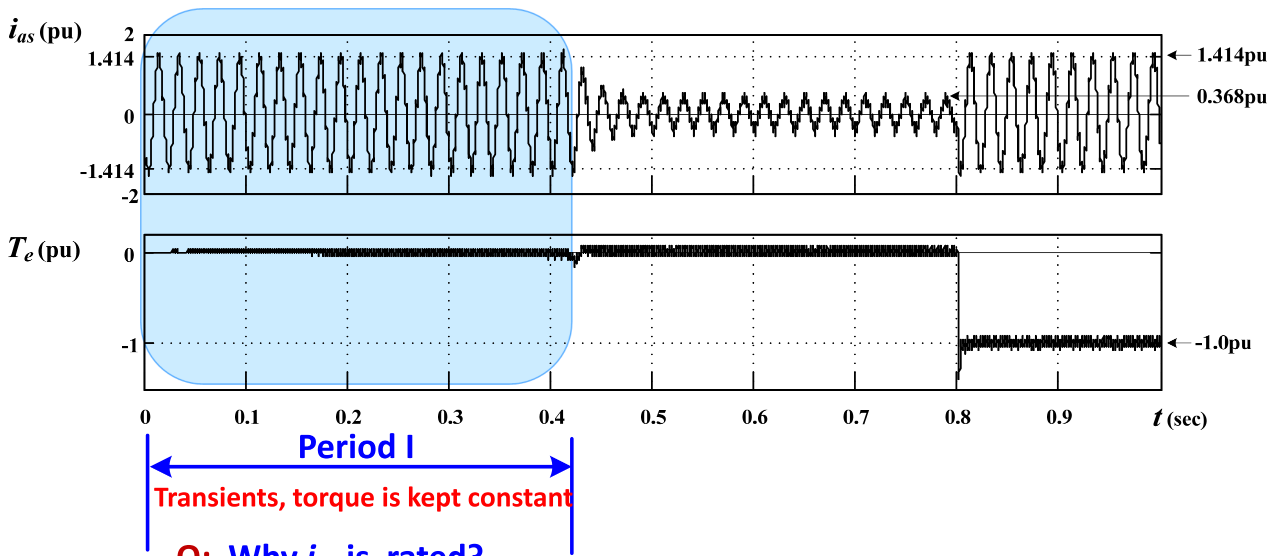
**A:** To be discussed in class

$\lambda_r$ increases at its maximum rate



# Direct FOC

## Case Study 1 – Start up Transient Analysis




**Q:** Why $i_{as}$ is rated?

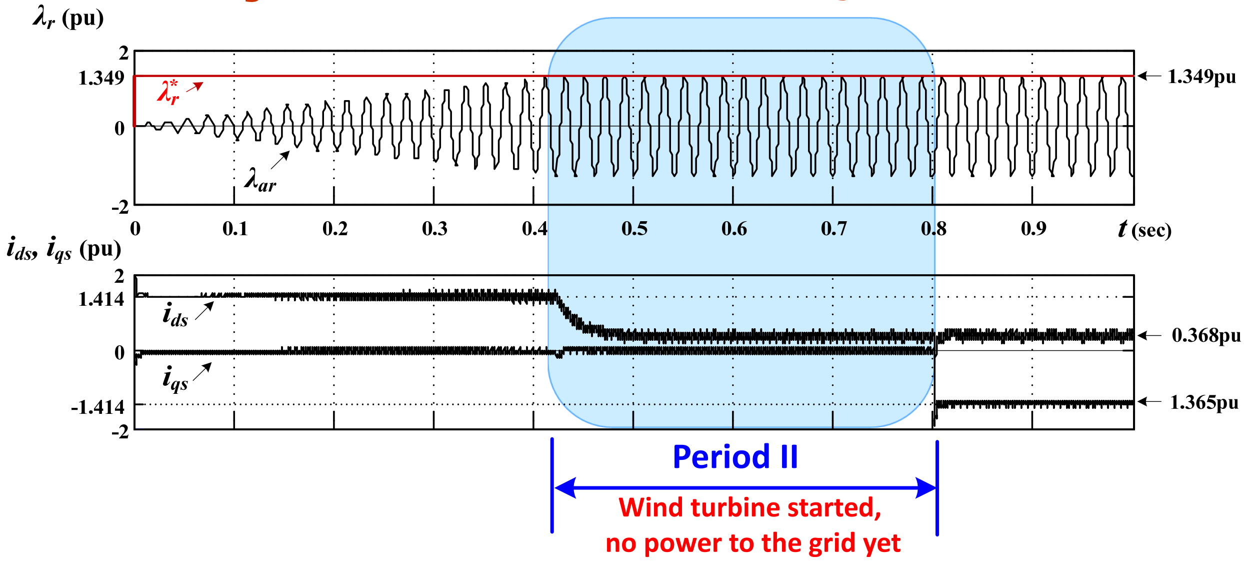
**A:** To be discussed in class

**Q:** Why $T_e = 0$?

**A:** To be discussed in class

# Direct FOC

## Case Study 1 – Start up Transient Analysis




Q: $i_{ds}$ is reduced. Why?

A: The Rotor Flux Controller is out of saturation

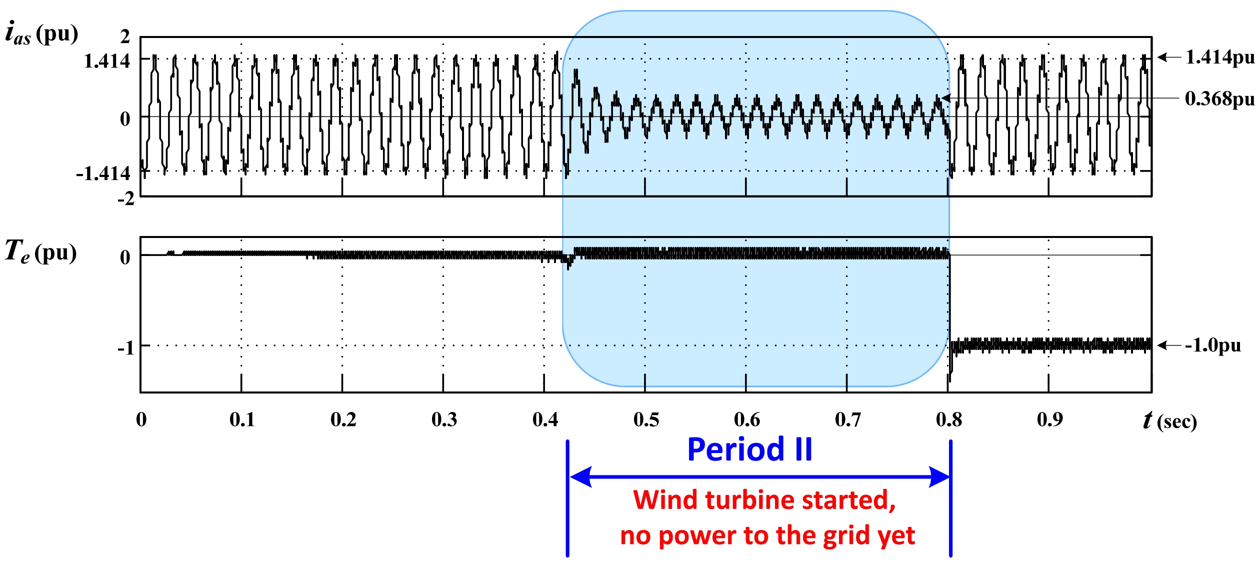
Q: $i_{ds}$ = 0.368pu. Why?

A: $i_{ds}$ is the magnetizing current



# Direct FOC

## Case Study 1 – Start up Transient Analysis

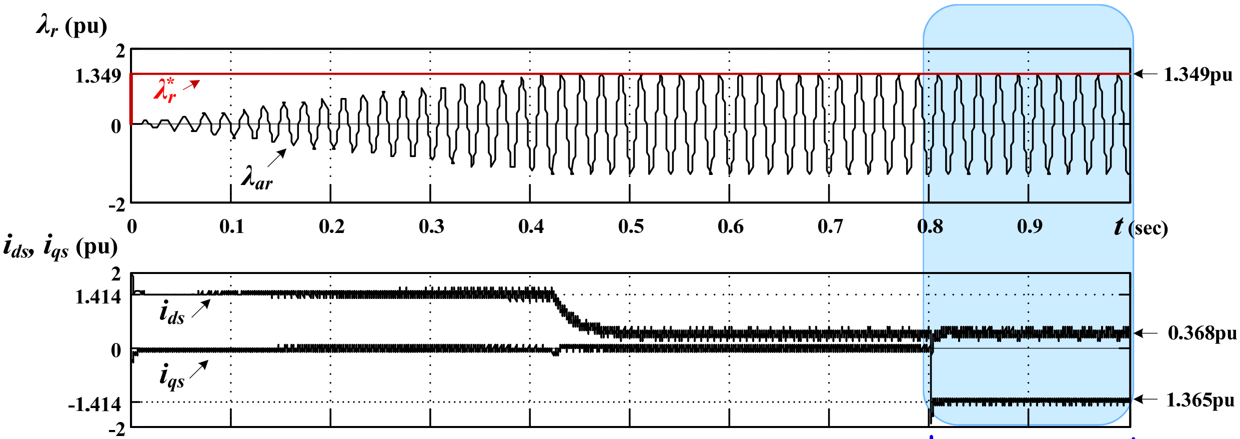



Q: Why the stator current $i_{as}$ is 0.368pu?

A: To be discussed in class

# Direct FOC

## Case Study 1 – Start up Transient Analysis




Period III

Rated power to the grid

The rms value of the stator current:

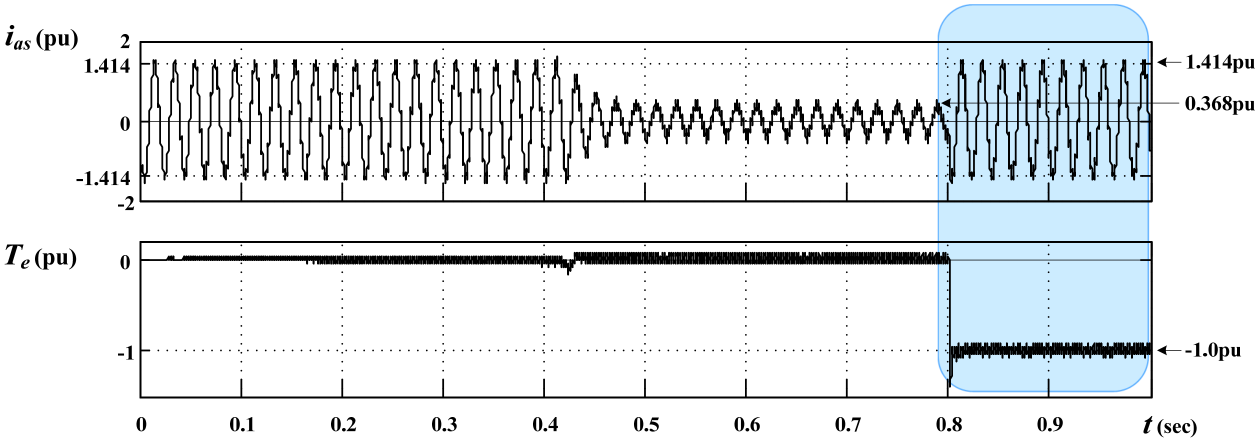
$$I_{as} = \sqrt{i_{ds}^2 + i_{qs}^2} \,/\, \sqrt{2}$$

$$= \sqrt{0.368^2 + 1.365^2} \,/\, \sqrt{2} = 1.0\text{pu (rated)}$$



# Direct FOC

## Case Study 1 – Start up Transient Analysis




Period III

Rated power to the grid

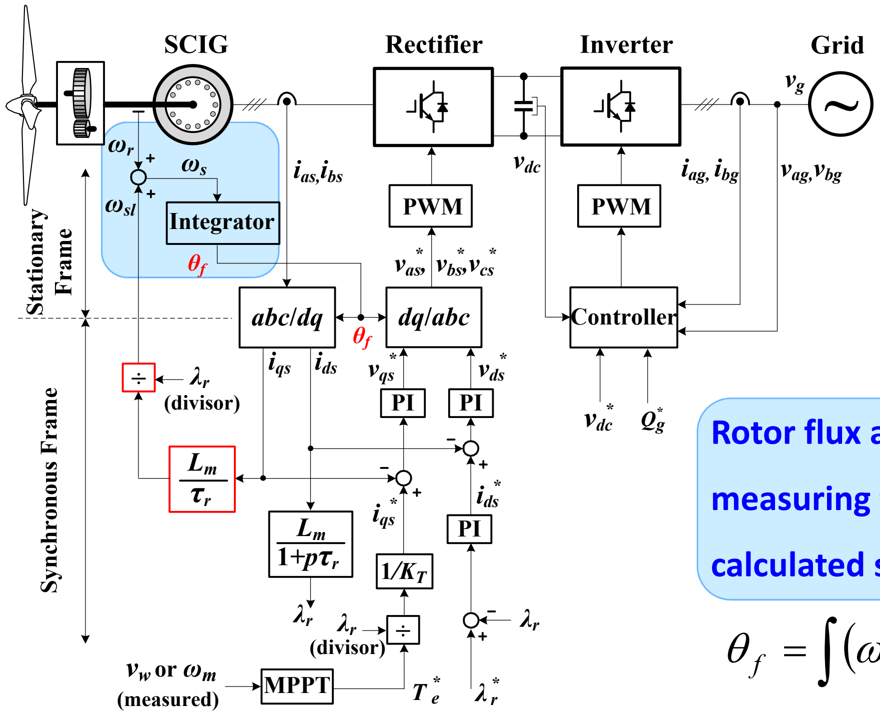
$I_{as}$ (rms) = $i_{as}$ /sqrt (2) = 1.414/sqrt(2) = 1pu

Torque reference $T_e^*$= -1pu (rated)

$T_e$ = -1pu (rated)

# Indirect FOC

## Principle of Indirect FOC



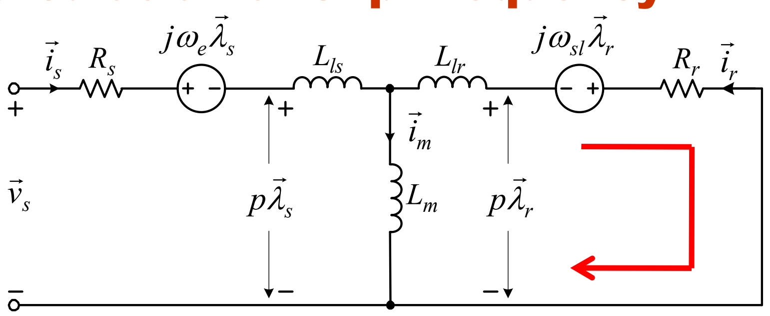

Rotor flux angle is obtained by measuring the rotor speed and calculated slip

$$\theta_f = \int (\omega_r + \omega_{sl}) dt$$



# Indirect FOC

## Calculation of Slip Frequency




Space vector model for IG in the synchronous frame

$$p\vec{\lambda}_r = -R_r\,\vec{i}_r - j\omega_{sl}\,\vec{\lambda}_r$$

Substituting the rotor current $\vec{i}_r = \dfrac{1}{L_r}\left(\vec{\lambda}_r - L_m\,\vec{i}_s\right)$ into the above equation

$$p\vec{\lambda}_r = -\frac{R_r}{L_r}\left(\vec{\lambda}_r - L_m\vec{i}_s\right) - j\omega_{sl}\,\vec{\lambda}_r$$

**Note:** $\vec{\lambda}_r = L_r\vec{i}_r + L_m\vec{i}_s$

# Indirect FOC

## Calculation of Slip Frequency

$$p\vec{\lambda}_r = -\frac{R_r}{L_r}\left(\vec{\lambda}_r - L_m\vec{i}_s\right) - j\omega_{sl}\,\vec{\lambda}_r$$ (from the previous slide)

from which

$$\vec{\lambda}_r\left(1+\tau_r(p+j\omega_{sl})\right) = L_m\vec{i}_s$$

where $\tau_r$ is the rotor time constant, defined by

$$\tau_r = L_r / R_r$$

Decomposing into dq-axis components and letting $\lambda_{qr} = 0$ and $\lambda_{dr} = \lambda_r$ due to the field orientation:

$$\begin{cases} \lambda_r\left(1+p\tau_r\right) = L_m i_{ds} \\ \omega_{sl}\,\tau_r\,\lambda_r = L_m i_{qs} \end{cases}$$

Note:

$$\vec{\lambda}_r = \lambda_{dr} + j\lambda_{qr}$$

$$\vec{i}_s = i_{ds} + ji_{qs}$$



# Indirect FOC

## Calculation of Slip Frequency

$$\omega_{sl}\,\tau_r\,\lambda_r = L_m i_{qs}$$ (from the previous slide)

$$\boxed{\omega_{sl} = \frac{L_m}{\tau_r\,\lambda_r} i_{qs}}$$

Measured q-axis stator current

Slip frequency

# Indirect FOC

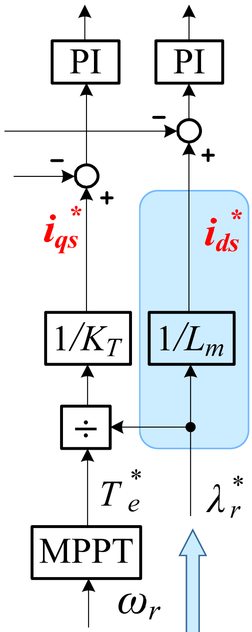
## Calculation of dq-axis Reference Currents

$$\lambda_r(1+p\tau_r)=L_m i_{ds}$$ **(from the previous slide)**

$$i_{ds}^* = \frac{(1+p\tau_r)}{L_m}\lambda_r^*$$

Since $\lambda_r^*$ is normally kept constant during operation $(p\lambda_r^*=0)$, the above equation can be simplified to

$$\boxed{i_{ds}^* = \frac{1}{L_m}\lambda_r^*}$$






# Indirect FOC

## Calculation of dq-axis Reference Currents

**Torque equation:**

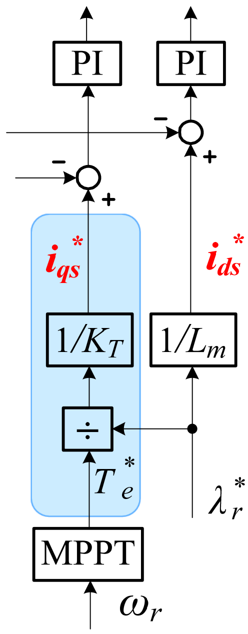
$$T_e = \frac{3PL_m}{2L_r}\left(i_{qs}\lambda_{dr} - i_{ds}\lambda_{qr}\right)$$

**Replacing** $\lambda_{qr}=0$ **and** $\lambda_{dr}=\lambda_r$ **yields**

$$i_{qs}^* = T_e^* \frac{2L_r}{3PL_m\lambda_r}$$

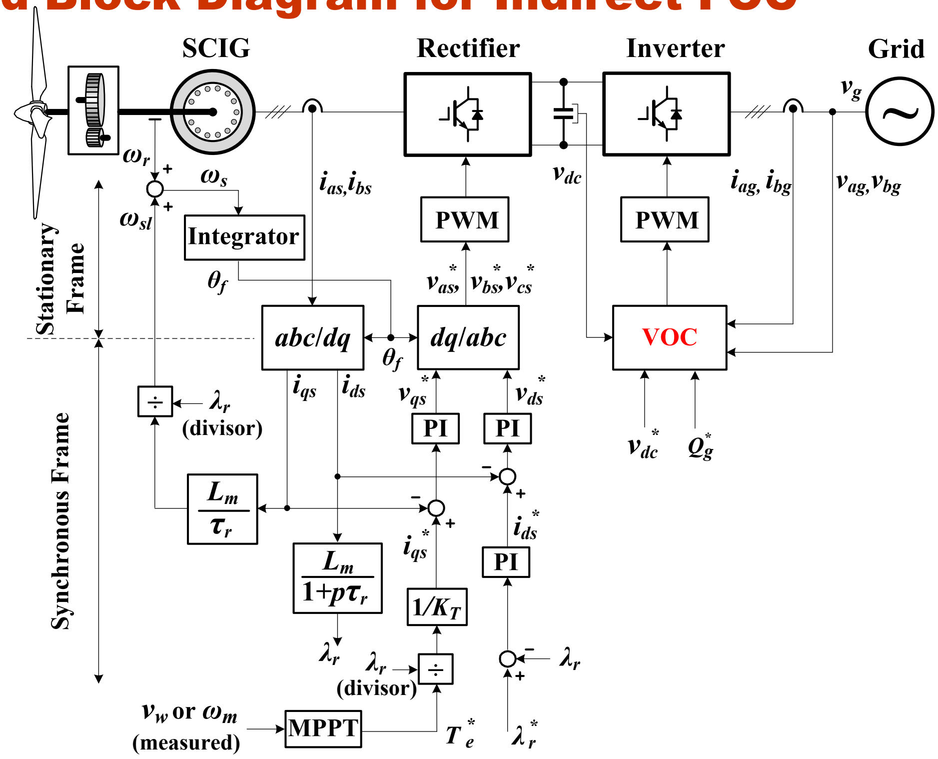
**or** $$\boxed{i_{qs}^* = \frac{1}{K_T\lambda_r}T_e^*}$$

**where** $$K_T = \frac{3PL_m}{2L_r}$$



# Indirect FOC

## Derived Block Diagram for Indirect FOC






# Indirect FOC

## Steady-state Analysis of IG WECS

**Note:** With FOC, the rotor flux is kept constant.

### Calculation Procedures

| | |
|---|---|
| **Given:** Rotor flux linkage [Wb] | $\lambda_r$ (Rated, controlled by FOC) |
| **Given:** Rotor speed [rad/sec] | $\omega_m$ (based on wind speed) |
| 1. Electromagnetic torque [N.m] | $T_e = T_m$ (from the $T_m - \omega_m$ profile) |
| 2. *d*-axis current [A] | $i_{ds} = \dfrac{\lambda_r}{L_m}$ |
| 3. *q*-axis current [A] | $i_{qs} = \dfrac{T_e}{K_T \lambda_r} = \dfrac{2L_r}{3PL_m} \dfrac{T_e}{\lambda_r}$ |
| 4. Stator current [A] | $i_s = \sqrt{i_{ds}^2 + i_{qs}^2}$ |
| 5. Slip frequency [rad/sec] | $\omega_{sl} = \dfrac{L_m}{\tau_r \lambda_r} i_{qs} = \dfrac{R_r L_m}{L_r \lambda_r} i_{qs}$ |

# Indirect FOC

## Steady-state Analysis of IG WECS

| | |
|---|---|
| 6. Stator frequency [rad/sec] | $\omega_s = \omega_r + \omega_{sl}$ |
| 7. Slip | $s = \dfrac{\omega_{sl}}{\omega_s}$ |
| 8. Generator impedance [Ω] | $\bar{Z}_s = R_s + jX_{ls} + jX_m // (\frac{R_r}{s} + jX_{lr})$ |
| 9. Stator current (rms) [A] | $\bar{I}_s = i_s / \sqrt{2} \angle 0°$ (Reference phasor) |
| 10. Stator voltage (rms) [V] | $\bar{V}_s = \bar{I}_s \bar{Z}_s = V_s \angle \varphi$ |
| 11. Stator power factor angle | $\varphi_s = \angle \bar{V}_s - \angle \bar{I}_s = \varphi$ |



# Indirect FOC

## Case Study 3 – Steady-state analysis of IG WECS

Consider a 2.3MW/690V induction generator wind energy system in Case Study 1.

**Given:**
The generator operates at 0.7pu rotor speed

1. The turbine mechanical torque:

$$T_m = T_{m,R} \times 0.7^2 = -14{,}740 \times 0.7^2 = -7.2226 \text{ kN.m}$$

2. The rotor flux is kept at its rated value of 1.7106Wb by the FOC scheme.

   The d-axis current is:

$$i_{ds} = \frac{\lambda_r}{L_m} = \frac{1.7106}{2.1346 \times 10^{-3}} = 801.4 \text{ A} \quad (0.369 \text{ pu})$$

# Indirect FOC

## Case Study 3 – Steady-state analysis of IG WECS

**3. The q-axis stator current:**

$$i_{qs} = \frac{2L_r}{3PL_m}\frac{T_e}{\lambda_r} = \frac{2\times 2.1995\times 10^{-3}}{3\times 2\times 2.1346\times 10^{-3}}\cdot\frac{-7222.6}{1.7106} = -1450.2\ \text{A} \quad (-0.669\ \text{pu})$$

**4. the peak stator current:**

$$i_s = \sqrt{i_{ds}^2 + i_{qs}^2} = \sqrt{801.4^2 + 1450.2^2} = 1656.9\ \text{A} \quad (0.764\ \text{pu})$$

**5. The slip frequency:**

$$\omega_{sl} = \frac{R_r L_m}{L_r\ \lambda_r} i_{qs} = \frac{1.497\times 10^{-3}\times 2.1346\times 10^{-3}}{2.1995\times 10^{-3}\times 1.7106}\times(-1450.2) = -1.2317\ \text{rad/sec}$$

**6. The stator frequency**

$$\omega_s = \omega_r + \omega_{sl} = (1512\times 0.7)(2\pi/60)P - 1.2317 = 220.4\ \text{rad/sec}$$ (35.08 Hz)



# Indirect FOC

## Case Study 3 – Steady-state analysis of IG WECS

**7. The slip:**

$$s = \frac{\omega_{sl}}{\omega_s} = -5.588\times 10^{-3}$$

**8. The rms value of the stator current:**

$$\bar{I}_s = i_s/\sqrt{2}\angle 0° = 1171.6\angle 0°\text{A}$$

**8. The generator impedance:**

$$\bar{Z}_s = R_s + jX_{ls} + jX_m // (\frac{R_r}{s} + jX_{lr}) = 0.2349\angle 144.9°\ \Omega$$

**10. The rms stator voltage can be calculated by:**

$$\bar{V}_s = \bar{I}_s\bar{Z}_s = V_s\angle\varphi = 275.2\angle 144.9°\ \text{V}$$

# Introduction to Direct Torque Control

## Principle of DTC

**Direct torque control (DTC):**
**The generator torque $T_e$ is directly controlled by the torque angle $\theta_T$**

$$T_e = \frac{3P}{2}\frac{L_m}{\sigma L_s L_r}\lambda_s \lambda_r \sin\theta_T$$

3. The generator toque is then controlled by the torque angle

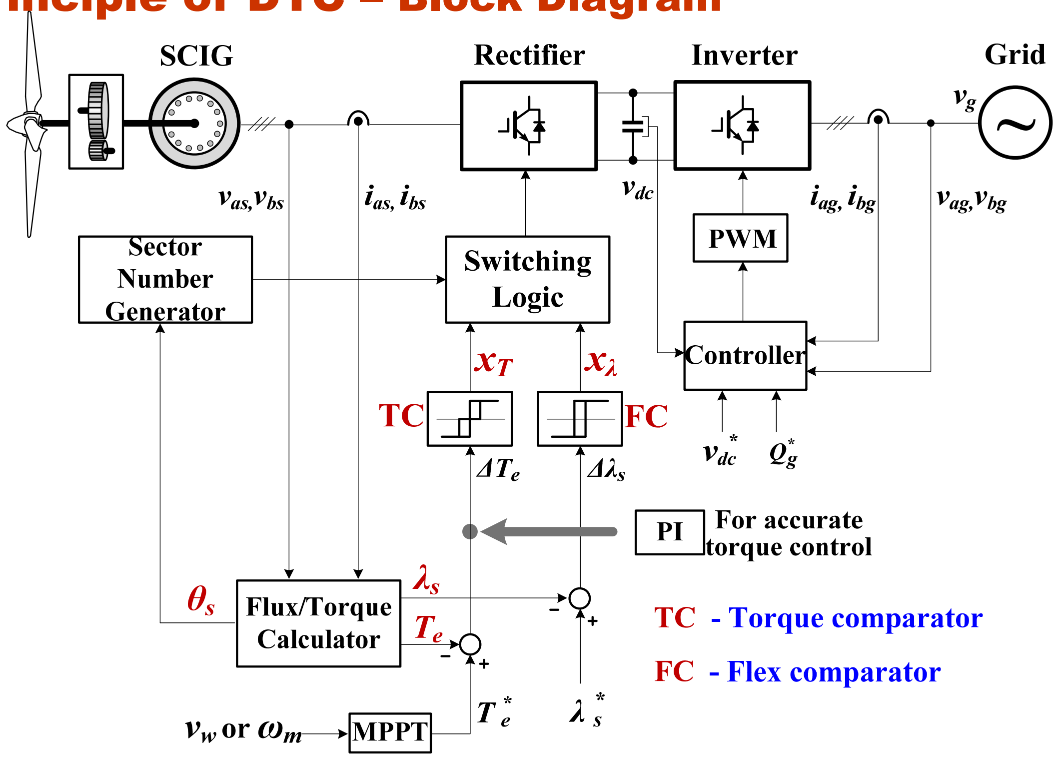
2. Rotor flux linkage is almost constant if the stator flux is kept constant.

1. Stator flux linkage is kept constants by the controller



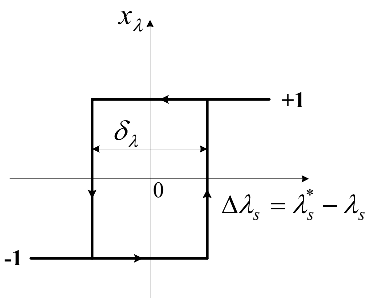
# Introduction to Direct Torque Control

## Principle of DTC – Block Diagram

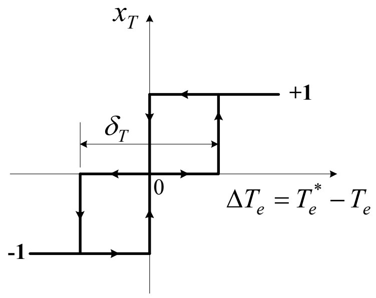


# Introduction to Direct Torque Control

## Switching Logic




(a) Flux comparator




(b) Torque comparator

Switching table for $\vec{\lambda}_s^*$ rotating in the clockwise direction

| Comparator output | | Sector | | | | | |
|---|---|---|---|---|---|---|---|
| $x_\lambda$ | $x_T$ | I | II | III | IV | V | VI |
| 1 | +1 | $\vec{V}_6$ [POP] | $\vec{V}_5$ [OOP] | $\vec{V}_4$ [OPP] | $\vec{V}_3$ [OPO] | $\vec{V}_2$ [PPO] | $\vec{V}_1$ [POO] |
| | 0 | $\vec{V}_0$ [PPP] | $\vec{V}_0$ [OOO] | $\vec{V}_0$ [PPP] | $\vec{V}_0$ [OOO] | $\vec{V}_0$ [PPP] | $\vec{V}_0$ [OOO] |
| | -1 | $\vec{V}_2$ [PPO] | $\vec{V}_1$ [POO] | $\vec{V}_6$ [POP] | $\vec{V}_5$ [OOP] | $\vec{V}_4$ [OPP] | $\vec{V}_3$ [OPO] |
| -1 | +1 | $\vec{V}_5$ [OOP] | $\vec{V}_4$ [OPP] | $\vec{V}_3$ [OPO] | $\vec{V}_2$ [PPO] | $\vec{V}_1$ [POO] | $\vec{V}_6$ [POP] |
| | 0 | $\vec{V}_0$ [OOO] | $\vec{V}_0$ [PPP] | $\vec{V}_0$ [OOO] | $\vec{V}_0$ [PPP] | $\vec{V}_0$ [OOO] | $\vec{V}_0$ [PPP] |
| | -1 | $\vec{V}_3$ [OPO] | $\vec{V}_2$ [PPO] | $\vec{V}_1$ [POO] | $\vec{V}_6$ [POP] | $\vec{V}_5$ [OOP] | $\vec{V}_4$ [OPP] |



# Introduction to Direct Torque Control

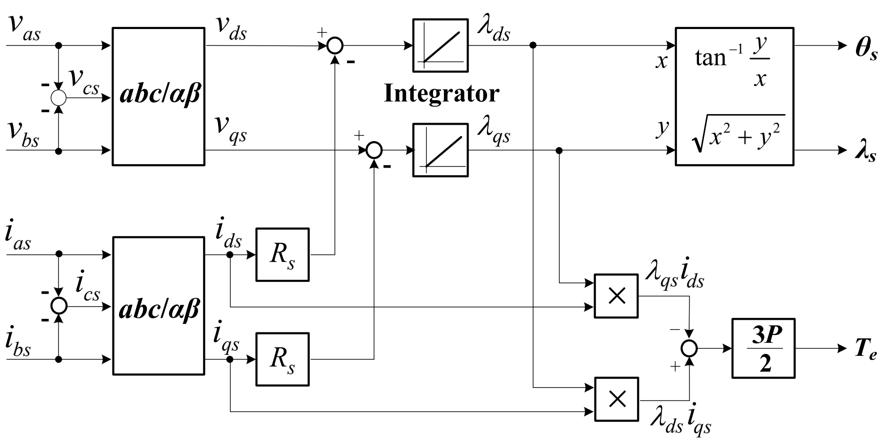
## Stator Flux and Torque Calculator

$$\vec{\lambda}_s = \lambda_{ds} + j\lambda_{qs} = \int (v_{ds} - R_s i_{ds})dt + j\int (v_{qs} - R_s i_{qs})dt$$

$$\begin{cases} \lambda_s = \sqrt{\lambda_{ds}^2 + \lambda_{qs}^2} \\ \theta_s = \tan^{-1}\left(\dfrac{\lambda_{qs}}{\lambda_{ds}}\right) \end{cases}$$

$$T_e = \frac{3P}{2}(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds})$$

Algorithm of stator flux and torque identification




Block diagram of stator flux and torque calculator

# Introduction to Direct Torque Control

## Case Study 4 – Transient Analysis of an SCIG WECS

| | |
|---|---|
| Investigation: | The transient process of a 2.3MW/690V SCIG WECS |
| Control Scheme: | DTC scheme |
| Wind Speed: | Step change from 0.7 pu to 1.0 pu |

1. The stator flux keeps constant.
2. The absolute value of the angle between stator flux and rotor flux vector is increased.



# Introduction to Direct Torque Control

## Case Study 4 – Transient Analysis of an SCIG WECS

### System Parameters

| | | |
|---|---|---|
| Induction generator | Generator ratings: 2.3MW/690V/50Hz/1512rpm 2168A/14.67kN.m | Generator parameters: Table B-1 (Appendix B) |
| System input variables | Stator flux reference (rated) | $\lambda_s^* = 1.803\ \text{Wb}$ (1.422 pu) |
| | Initial generator torque at wind speed of 8.4m/s (0.7pu) | $T_m = -7222.6\ \text{N.m}\ \ (0.49\ \text{pu})$ |
| | Step change in wind speed at $t$ = 0.1 sec | $v_w$ = 12 m/sec (1.0 pu) |
| DTC scheme | Control scheme | Fig. 7-14 with the torque PI controller implemented |
| | Flux tolerance band | $\delta_\lambda$ = 0.01 pu |
| | Torque tolerance band | $\delta_T$ = 0.08 pu |
| | Switching Frequency | Around 2.7kHz at 0.7pu rotor speed and 2kHz at rated rotor speed |

# Introduction to Direct Torque Control

## Case Study 4 – Transient Analysis of an SCIG WECS

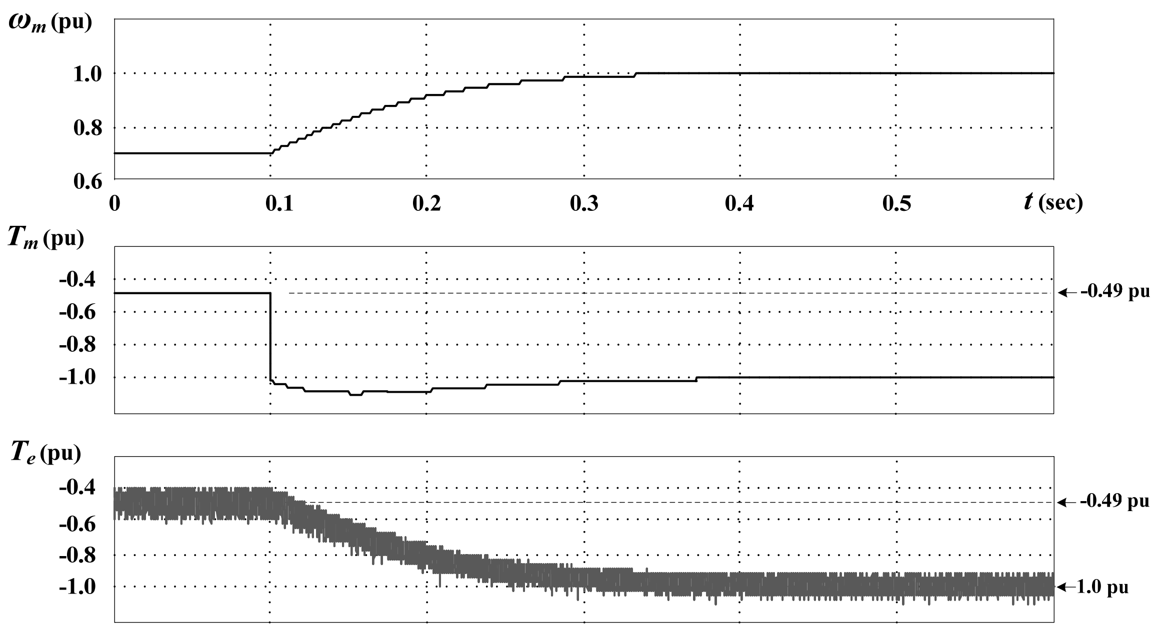
### System Parameters

| | | |
|---|---|---|
| Generator-side converter | Converter type | Two-level voltage source |
| | Modulation scheme | Not applicable |
| Grid-side converter | Replaced by a dc voltage source with a fixed dc voltage | $V_{dc}$ = 1220 V (3.06 pu) |
| Stator flux calculator | Algorithm | Fig. 7-16 |
| PI controller | Torque control loop | Yes |
| | Stator flux loop | No |
| Reference frame transformation | Not applicable | |



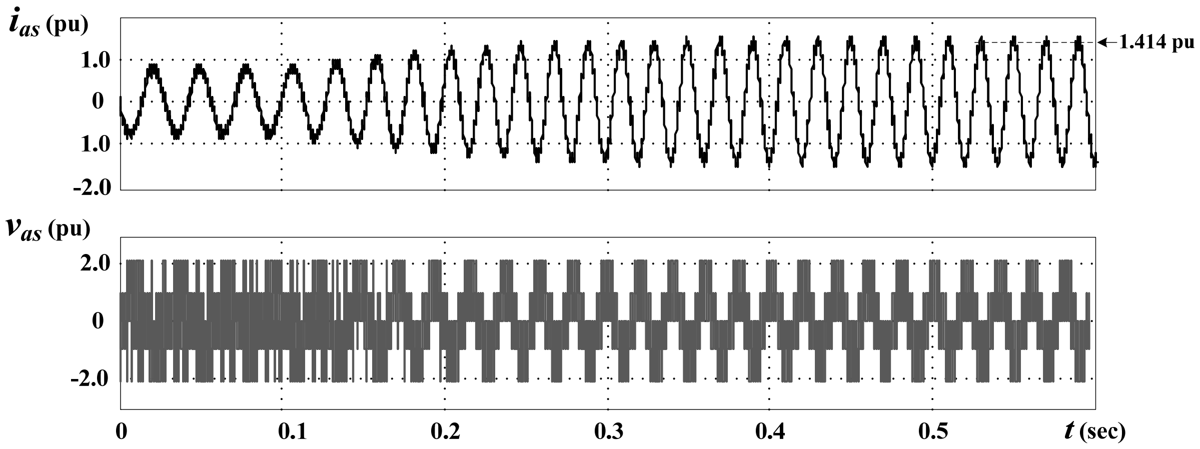
# Introduction to Direct Torque Control

## Case Study 4 – Transient Analysis of an SCIG WECS



# Introduction to Direct Torque Control

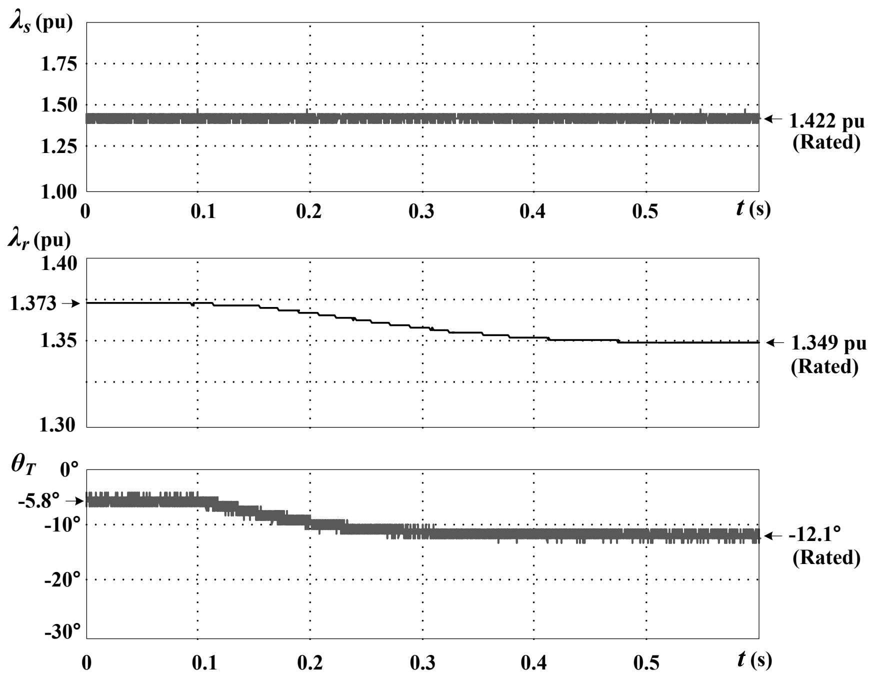
## Case Study 4 – Transient Analysis of an SCIG WECS






# Introduction to Direct Torque Control

## Case Study 4 – Transient Analysis of an SCIG WECS



# Introduction to Direct Torque Control

## Comparison to the FOC Schemes

1. The DTC scheme has similar or better dynamic performance than the FOC schemes
2. The DTC scheme does not use any modulation schemes or reference frame transformation (simple control scheme)
3. The DTC scheme may generate more torque ripples
4. Both DTC and FOC schemes are widely used in industry



# Thanks