Variable-speed Synchronous Generator WECS

Zheng Wang Professor
School of Electrical Engineering
Southeast University

Contact Info
Email: zwang@seu.edu.cn

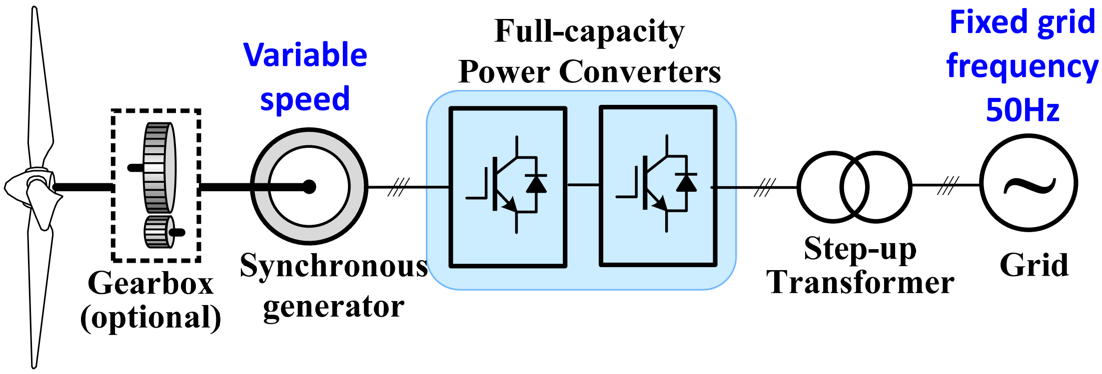
Variable-speed SG WECS

Main Topics

1. Introduction
2. Control Schemes for Synchronous Generators
3. Control of SG WECS
4. DC/DC Boost Converter Fed SG WECS
5. Grid-side Reactive Power Control

Introduction

System Configuration



Variable speed SG based WECS

The grid and generator are “decoupled” by the power converters

Control Schemes for SG

Control Schemes for SG

1. Zero d-axis current control (ZDC)
2. Maximum torque per ampere control (MTPA)

Control Schemes for SG

Zero d-axis Current Control (ZDC)

Make the d-axis stator current zero by the controller:

$$\begin{cases} \vec{i}_s = i_{ds} + ji_{qs} = ji_{qs} \\ i_s = \sqrt{i_{ds}^2 + i_{qs}^2} = i_{qs} \end{cases} \qquad \text{for} \;\; i_{ds} = 0$$

$\vec{i}_s$ - stator current space vector

i_s - peak value of the stator current

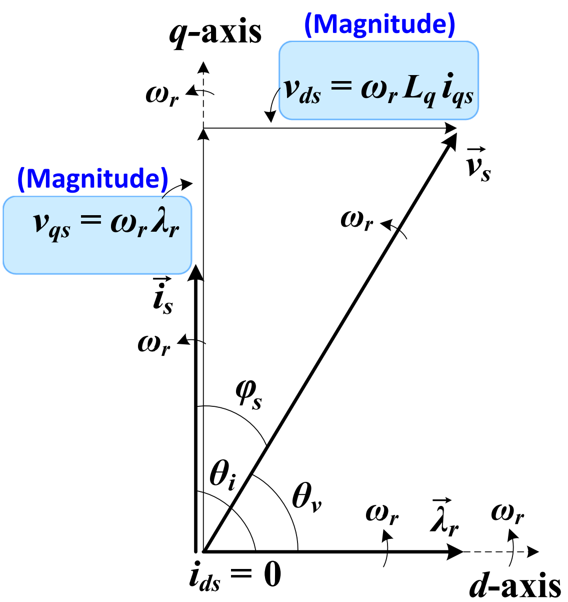
Electromagnetic torque : $T_e = \frac{3}{2} P \left(\lambda_r \, i_{qs} - \left(L_d - L_q \right) i_{ds} i_{qs} \right)$

With ZDC: $T_e = \frac{3}{2} P \lambda_r i_{qs} = \frac{3}{2} P \lambda_r i_s$

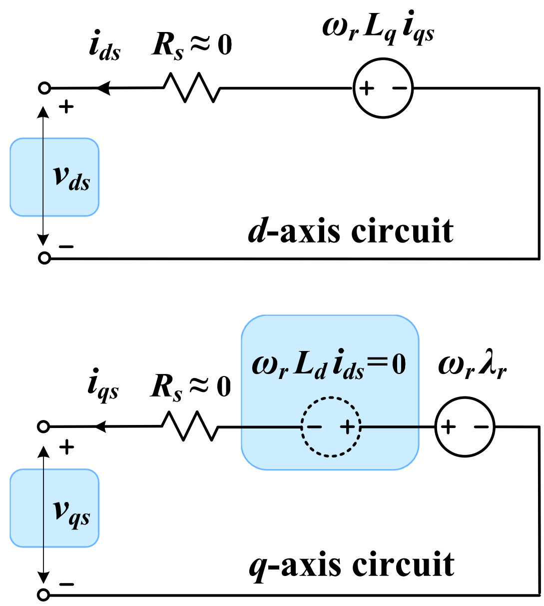
With constant rotor flux, and torque is proportional to the stator current.

Control Schemes for SG

Zero d-axis Current Control (ZDC)



Vector diagram



SG steady-state model

Control Schemes for SG

Maximum Toque Per Ampere Control (MTPA)

$$T_e = \frac{3}{2}P\left[\lambda_r\, i_{qs} - \left(L_d - L_q\right) i_{ds} i_{qs}\right]$$

Analysis: For a given rotor flux, torque is a function of stator *dq*- axis currents

→ It is possible to produce a given torque with minimum stator current.

$$i_{ds} = \sqrt{i_s^2 - i_{qs}^2}$$

$$T_e = \frac{3}{2}P\left[\lambda_r\, i_{qs} - \left(L_d - L_q\right)\left(\sqrt{i_s^2 - i_{qs}^2}\right) i_{qs}\right]$$

$$\boxed{\frac{dT_e}{di_{qs}}} = \frac{3P}{2}\left(\lambda_r - \left(L_d - L_q\right) i_{ds} + \left(L_d - L_q\right) i_{qs}^2 \frac{1}{\sqrt{i_s^2 - i_{qs}^2}}\right) \boxed{= 0}$$

Control Schemes for SG

Maximum Toque Per Ampere Control (MTPA)

To find MTPA:

$$\lambda_r - \left(L_d - L_q\right) i_{ds} + \left(L_d - L_q\right)\frac{i_{qs}^2}{i_{ds}} = 0$$

$$\boxed{i_{ds} = \frac{\lambda_r}{2\left(L_q - L_d\right)} + \sqrt{\frac{\lambda_r^2}{4\left(L_q - L_d\right)^2} + i_{qs}^2} \qquad L_d \neq L_q}$$

Q: What if $L_d = L_q$?

A: It becomes ZDC

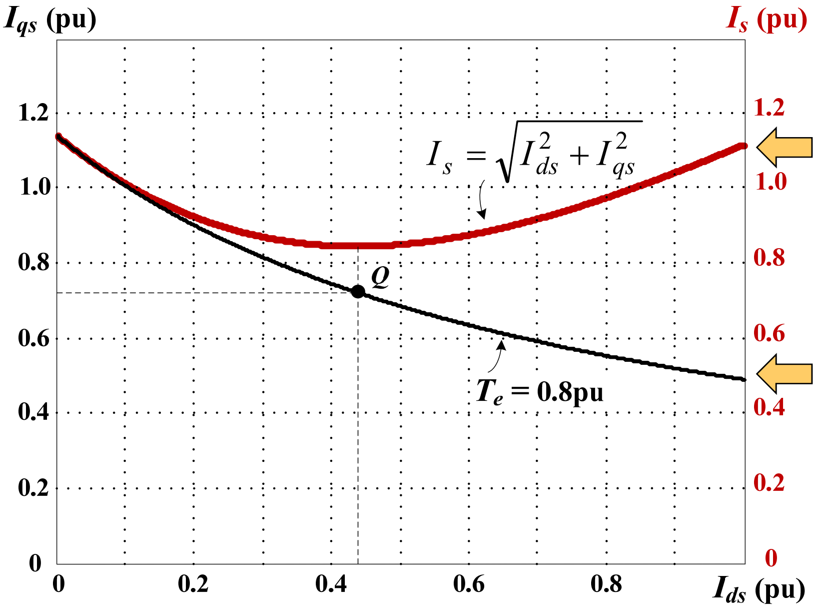
When the above condition is satisfied, the SG operates with MTPA

Q: How to find i_{qs}? **A:** Solve the following equations simultaneously:

$$\begin{cases} T_e = \frac{3}{2}P\left(\lambda_r\, i_{qs} - \left(L_d - L_q\right) i_{ds}\, i_{qs}\right) \\ i_{ds} = \frac{\lambda_r}{2\left(L_d - L_q\right)} + \sqrt{\frac{\lambda_r^2}{4\left(L_q - L_d\right)^2} + i_{qs}^2} \end{cases} \quad \text{for } L_d \neq L_q \qquad (9.13)$$

Control Schemes for SG

Maximum Toque Per Ampere Control (MTPA)



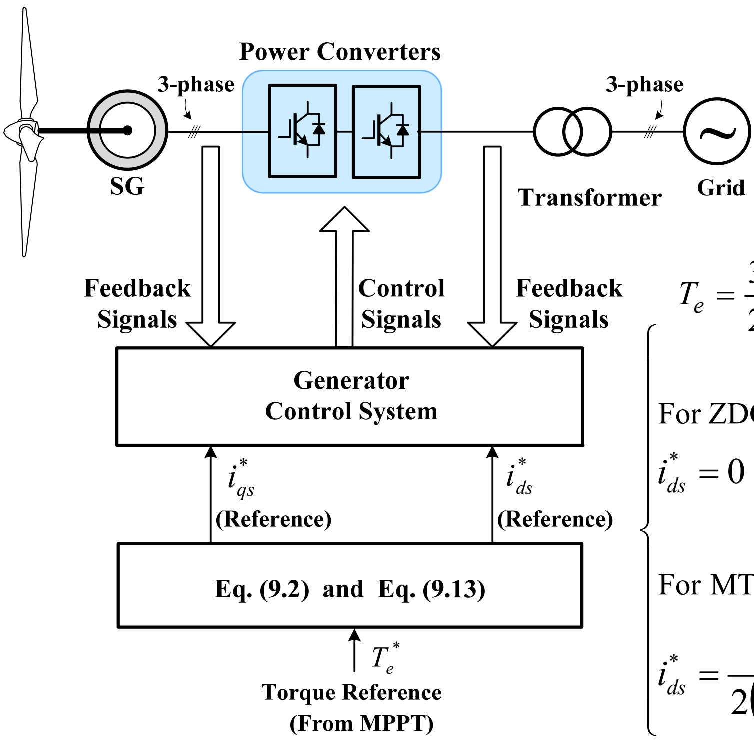
Trajectory of the stator current at $T_e = 0.8$pu

i_s versus i_{ds} for given T_e

i_{qs} versus i_{ds} for given T_e

Control Schemes for SG

Implementation of ZDC and MTPA



$$T_e = \frac{3}{2}P\left[\lambda_r\, i_{qs} - \left(L_d - L_q\right) i_{ds} i_{qs}\right] \quad \textbf{(9.2)}$$

For ZDC control :

$$i_{ds}^* = 0$$

For MTPA control :

$$i_{ds}^* = \frac{\lambda_r}{2\left(L_q - L_d\right)} + \sqrt{\frac{\lambda_r^2}{4\left(L_q - L_d\right)^2} + i_{qs}^2} \quad \textbf{(9.13b)}$$

Control Schemes for SG

Example 1 – SG with ZDC Control

Consider a 2.45MW/4000V/490A/58.459kN.m/53.3Hz non-salient PMSG operating at the rated condition with zero d-axis current control. Generator parameters are assumed.

The electrical rotor speed and mechanical torque at the rated conditions:

$$\begin{cases} \omega_r = 2\pi f_s = 2\pi \times 53.3 = 334.89 \text{ rad/sec} \ \ (1.0 \text{ pu}) \\ T_m = 58.459 \text{ kN.m} \ \ (1.0 \text{ pu}) \end{cases}$$

The dq-axis stator currents:

$$\begin{cases} i_{ds} = 0 \quad \text{for ZDC} \\ i_{qs} = \dfrac{T_e}{1.5 \times P \times \lambda_r} = \dfrac{58.459 \times 10^3}{1.5 \times 8 \times 7.03} = 692.96 \text{ A} \end{cases}$$

The rms stator current:

$$I_s = i_s / \sqrt{2} = \sqrt{i_{ds}^2 + i_{qs}^2} / \sqrt{2} = 692.96 / \sqrt{2} = 490.0 \text{ A} \quad (1.0 \text{ pu})$$

Control Schemes for SG

Example 1 – SG with ZDC Control

The dq-axis stator voltages:

$$\begin{cases} v_{ds} = -I_d R_s + \omega_r L_q i_{qs} = 2279.38 \text{ V} \\ v_{qs} = -i_{qs} R_s - \omega_r L_d i_{ds} + \omega_r \lambda_r = 2338.97 \text{ V} \end{cases}$$

The rms stator voltage:

$$V_s = v_s / \sqrt{2} = \sqrt{v_{ds}^2 + v_{qs}^2} / \sqrt{2} = 3265.9 / \sqrt{2} = 2309.37 \text{ V} \quad (1.0 \text{ pu})$$

The angle of the stator voltage and current vectors:

$$\begin{cases} \theta_v = \tan^{-1} \dfrac{v_{qs}}{v_{ds}} = 0.798 \text{ rad} \quad (45.74°) \\ \theta_i = \tan^{-1} \dfrac{i_{qs}}{i_{ds}} = \pi / 2 \ \text{ rad} \quad (90°) \end{cases}$$

The stator power factor angle:

$$\varphi_s = \theta_v - \theta_i = -0.7725 \text{ rad} \quad (\text{-}44.26°)$$

Control Schemes for SG

Example 1 – SG with ZDC Control

The stator power factor:

$$PF_s = \cos\varphi_s = \cos(-44.26°) = 0.716$$

The stator output active power:

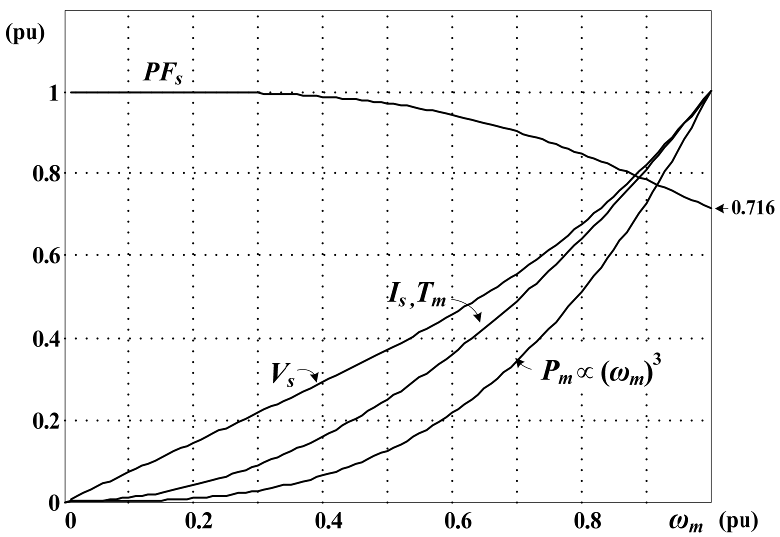
$$P_s = 3V_s\, I_s \cos\varphi_s = 2431.2\ \text{kW}$$

The above analysis can be extended to the full speed range, see next slide.

Control Schemes for SG

Example 1 – SG with ZDC Control

Non-salient PMSG (2.45MW/4000V)



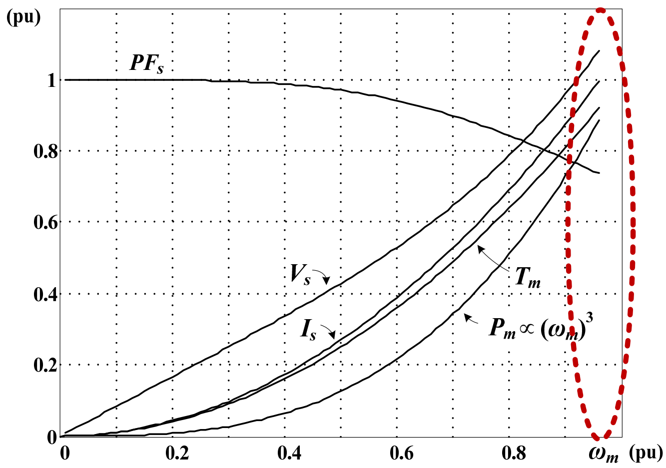
Non-salient PMSG

Note: The ZDC scheme can work for the full speed range of a non-salient PMSG

Control Schemes for SG

Example 1 – SG with ZDC Control

Salient-pole PMSG, (2MW/690V)



Salient-pole PMSG

Note: The ZDC scheme is NOT applicable for the salient PMSG since the full operation range cannot be achieved.

Control Schemes for SG

Example 2 – SG with MTPA Control

Given: 2MW/690V/1868A salient PMSG with MTPA scheme. The generator parameters are assumed.

The electrical rotor speed and mechanical torque at the rated conditions:

$$\begin{cases} \omega_r = 2\times\pi\times 11.25\ \text{Hz} = 70.69\ \text{rad/sec}\ \ (1.0\ \text{pu}) \\ T_m = 852.78\ \text{kN.m}\ \ (1.0\ \text{pu}) \end{cases} \Rightarrow \quad T_e = T_m = 852.78\text{kN.m}\ \text{ in steady state}$$

Solve the following equations for dq-axis stator currents:

$$\begin{cases} T_e = \dfrac{3}{2}P\left(\lambda_r\, i_{qs} - \left(L_d - L_q\right) i_{ds}\, i_{qs}\right) \\ i_{ds} = \dfrac{\lambda_r}{2\left(L_d - L_q\right)} + \sqrt{\dfrac{\lambda_r^2}{4\left(L_q - L_d\right)^2} + i_{qs}^2} \end{cases} \text{for } L_d \neq L_q \Rightarrow \begin{cases} i_{ds} = 892.14\ \text{A}\ \ (0.4777\ \text{pu}) \\ i_{qs} = 2486.1\ \text{A}\ \ (1.3311\ \text{pu}) \end{cases}$$

The rms stator current: $I_s = i_s/\sqrt{2} = \sqrt{i_{ds}^2 + i_{qs}^2}/\sqrt{2} = 1867.8\ \text{A}\ \ (1.0\ \text{pu})$

Control Schemes for SG

Example 2 – SG with MTPA Control

The *dq*-axis stator voltage:

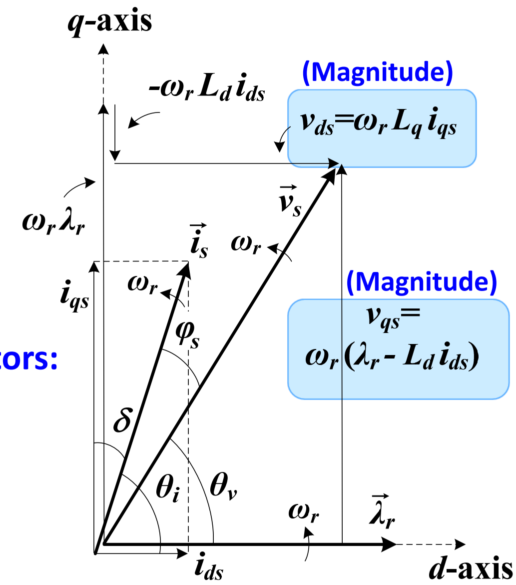
$$\begin{cases} v_{ds} = -i_{ds}R_s + \omega_r L_q i_{qs} = 405.3\ \text{V} \\ v_{qs} = -i_{qs}R_s - \omega_r L_d i_{ds} + \omega_r \lambda_r = 391.3\ \text{V} \end{cases}$$

The rms stator voltage:

$$V_s = v_s/\sqrt{2} = \sqrt{v_{ds}^2 + v_{qs}^2}/\sqrt{2} = 398.4\ \text{V} \quad (1.0\ \text{pu})$$

The angles of the stator voltage and current vectors:

$$\begin{cases} \theta_v = \tan^{-1}\dfrac{v_{qs}}{v_{ds}} = 0.7678\ \text{rad} \quad (43.99°) \\ \theta_i = \tan^{-1}\dfrac{i_{qs}}{i_{ds}} = 1.2263\ \text{rad} \quad (70.26°) \end{cases}$$



Control Schemes for SG

Example 2 – SG with MTPA Control

The power factor angle and power factor:

$$\varphi_s = \theta_v - \theta_i = 0.7678 - 1.2263 = -0.4585\ \text{rad} \quad (-26.27°)$$

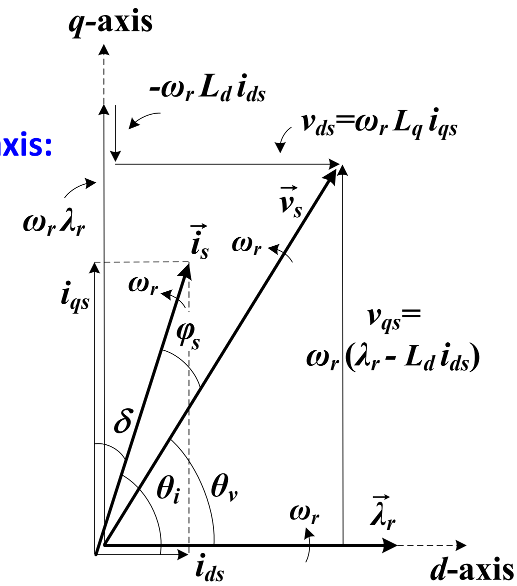
$$PF_s = \cos\varphi_s = \cos(-26.27°) = 0.8967$$

The angle of the stator current with respect to *q*-axis:

$$\delta = \frac{\pi}{2} - \theta_i = \frac{\pi}{2} - 1.2263 = 0.3445\ \text{rad} \quad (19.74°)$$

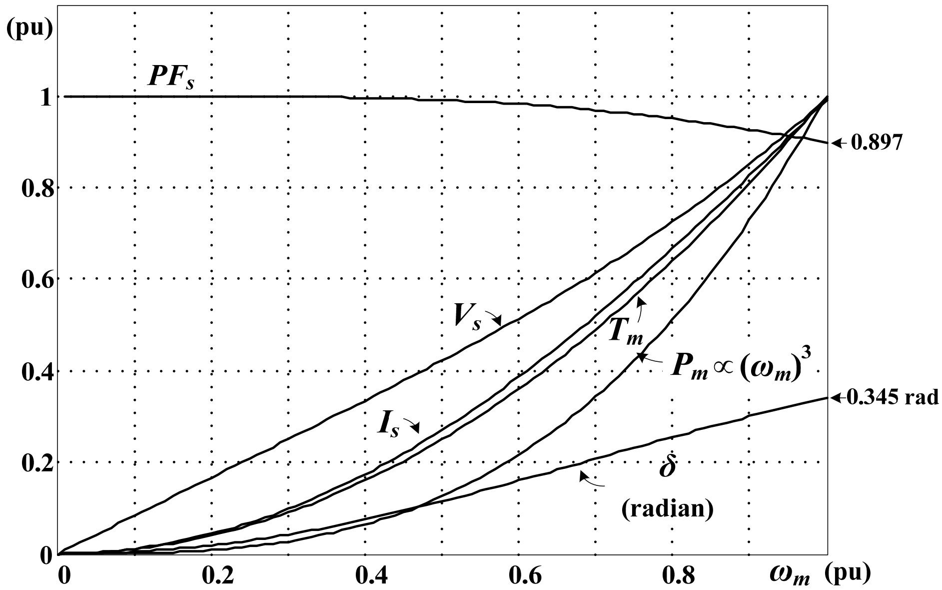
The stator output active power:

$$P_s = 3V_s\, I_s \cos\varphi_s = 2001.6\ \text{kW}$$



Control Schemes for SG

Example 2 – SG with MTPA Control



Characteristics of salient PMSG with MTPA scheme

Control Schemes for SG

Summary - ZDC and MTPA

Generator Type	Control Scheme
Non-salient generator	ZDC Scheme
Salient-pole generator	MTPA Scheme

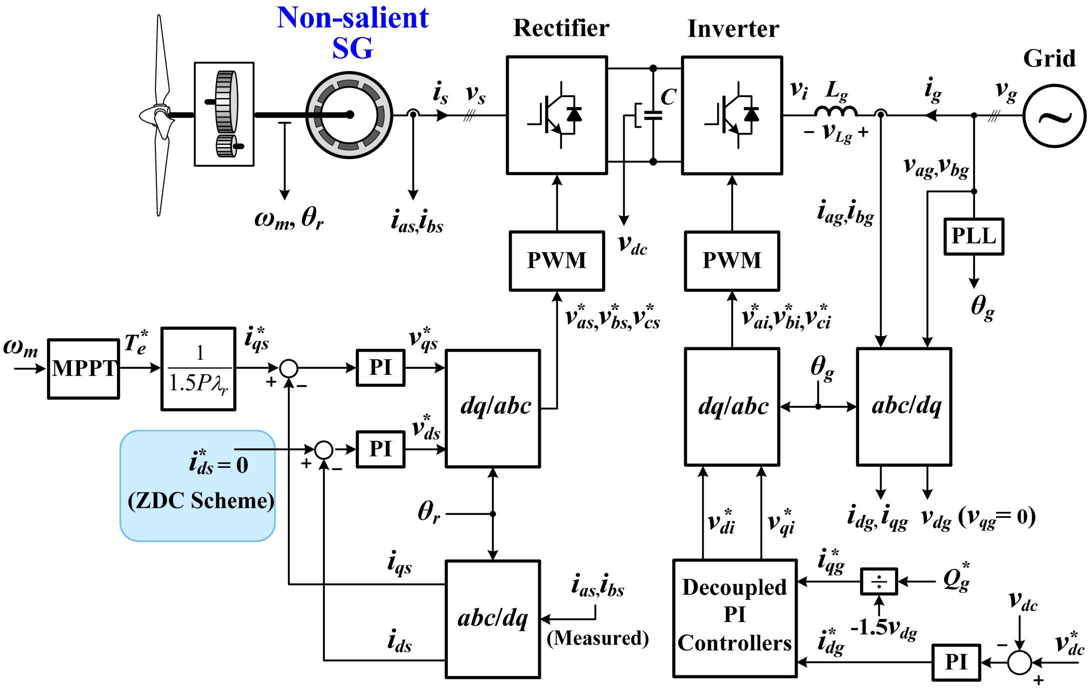
Control of SG WECS

Main Topics

1. ZDC control of non-salient SG WECS
2. MTPA control of salient SG WECS

Control of SG WECS

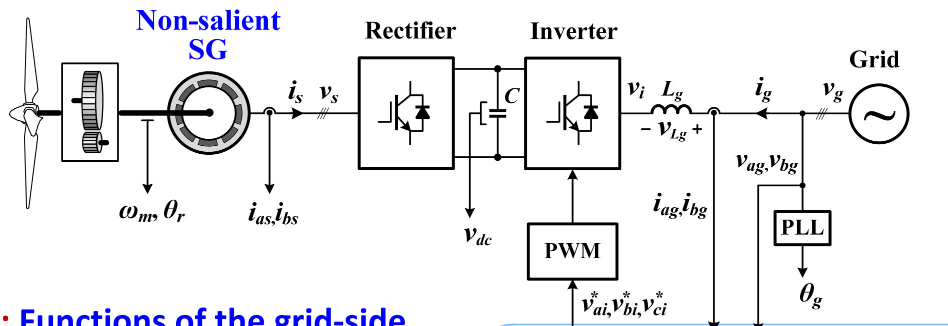
ZDC control of SG WECS



System Block Diagram

Control of SG WECS

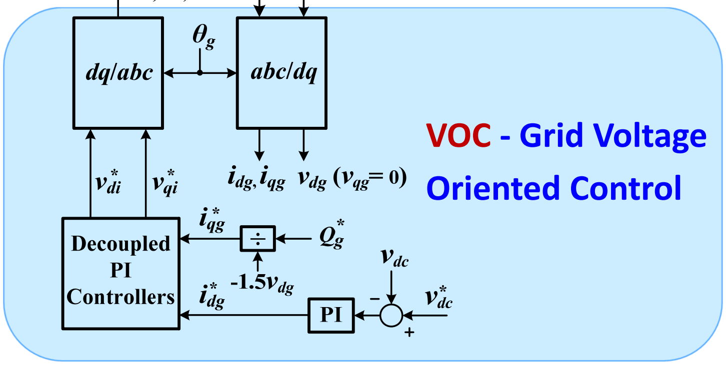
ZDC Control of SG WECS – Inverter Control



Q: Functions of the grid-side converter?

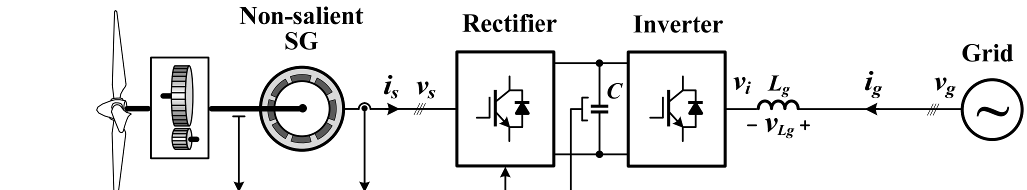
A: i) for dc voltage control

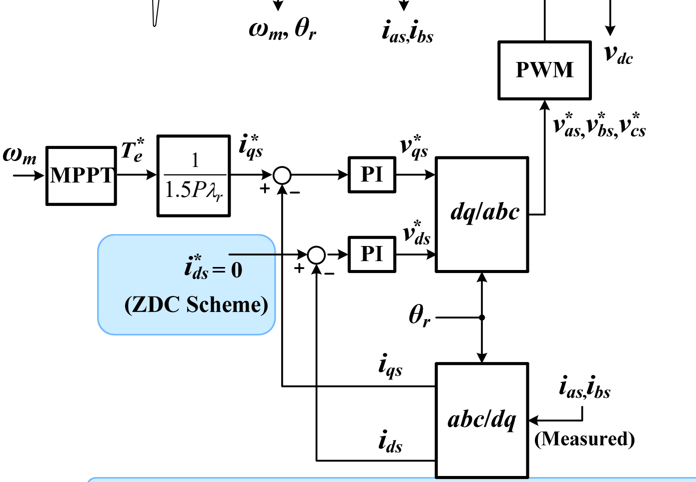
ii) for grid-side reactive power control



Control of SG WECS

ZDC Control of SG WECS – Rectifier Control





Q: Function of the generator-side converter?

A: Control active power (MPPT)

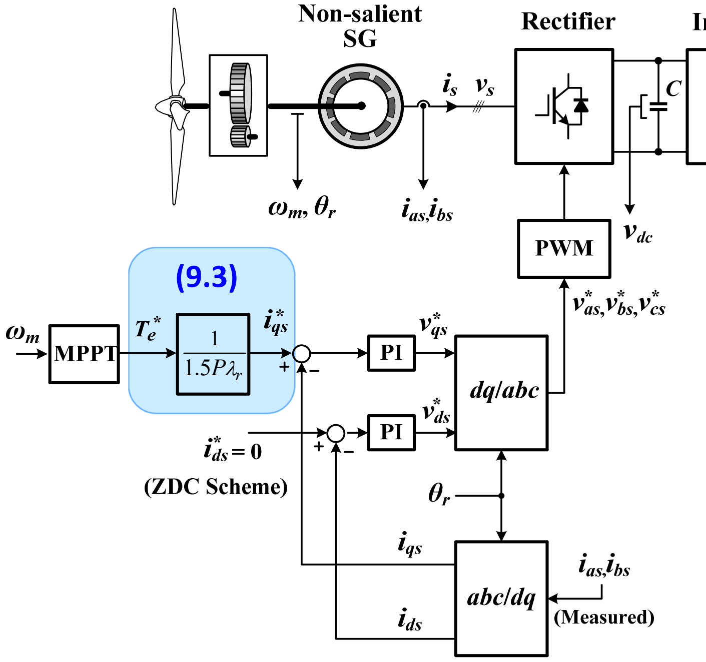
θ_r - Rotor angle, detected and used for field orientation

i_{as} i_{bs} i_{cs} - Stator current, detected

Generator Control: Zero d-axis (ZDC) current control → $i^*_{ds} = 0$

Control of SG WECS

ZDC Control of SG WECS – Rectifier Control

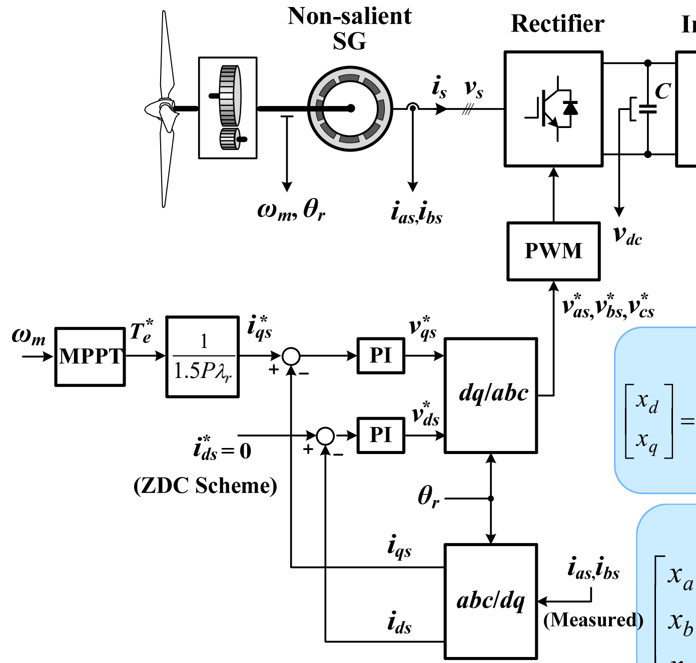


$$T_e = \frac{3}{2} P \lambda_r i_{qs} \qquad (9.3)$$

i_{qs}, i_{ds} – are tightly controlled via two PI controllers

Control of SG WECS

ZDC Control of SG WECS – Rectifier Control



***abc/dq* transformation:**

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta_r & \cos(\theta_r - 2\pi/3) & \cos(\theta_r - 4\pi/3) \\ -\sin\theta_r & -\sin(\theta_r - 2\pi/3) & -\sin(\theta_r - 4\pi/3) \end{bmatrix} \cdot \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}$$

***dq/abc* transformation:**

$$\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} = \begin{bmatrix} \cos\theta_r & -\sin\theta_r \\ \cos(\theta_r - 2\pi/3) & -\sin(\theta_r - 2\pi/3) \\ \cos(\theta_r - 4\pi/3) & -\sin(\theta_r - 4\pi/3) \end{bmatrix} \cdot \begin{bmatrix} x_d \\ x_q \end{bmatrix}$$

Control of SG WECS

Case Study 1 – ZDC for non-salient SG

Generator parameters (Based on generator-side per unit system)		
Rated Shaft Input Power	2.45 MW	
Rated Stator Line-Line Voltage	3950V	
Rated Stator Phase Voltage	2280 V (rms)	1.0 pu
Rated Stator Current	490A (rms)	1.0 pu
Rated Rotor Speed	400 rpm	1.0 pu
Rated Torque	58.6 kN•m	1.0 pu
Rated Stator Frequency	53.3Hz	1.0 pu
Number of Pole pairs P	8	
Rated Rotor Flux Linkage λ_r	7.043 Wb (peak)	0.732 pu
Stator Resistance R_s	0.024 Ω	0.005 pu
d-axis Synchronous Inductance L_d	9.5 mH	0.687 pu
q-axis Synchronous Inductance L_q	9.5 mH	0.687 pu

Control of SG WECS

Case Study 1 – ZDC for non-salient SG

System parameters

DC Link Parameters (Based on generator-side per unit system)		
DC Capacitor C	1700 μF	4.0 pu
DC Link Voltage Reference	7045 V	3.05pu
Grid-side Parameters (Based on grid-side per unit system)		
Rated Active Power to the Grid (PF = 1)	2.44 MW	1.0 pu
Rated Grid Phase Voltage	2280 V (rms)	1.0 pu
Rated Stator Current	356 A	1.0 pu
Grid Frequency	60 Hz	1.0 pu
Filter Inductance	3.4 mH	0.2 pu
Line Resistance	0.032 Ω	0.005 pu

Control of SG WECS

Case Study 1 – ZDC for non-salient SG

Operating Conditions:

1) The system starts when the speed of the turbine is brought to its rated value by the wind, at which the power converter system is activated.

2) To start the system smoothly, the torque reference is increased linearly from zero to its rated value in 1.0sec

3) The wind speed is rated. The SG operates at the rated condition after the start.

Assumption:

All the power losses in the system are neglected.

Control of SG WECS

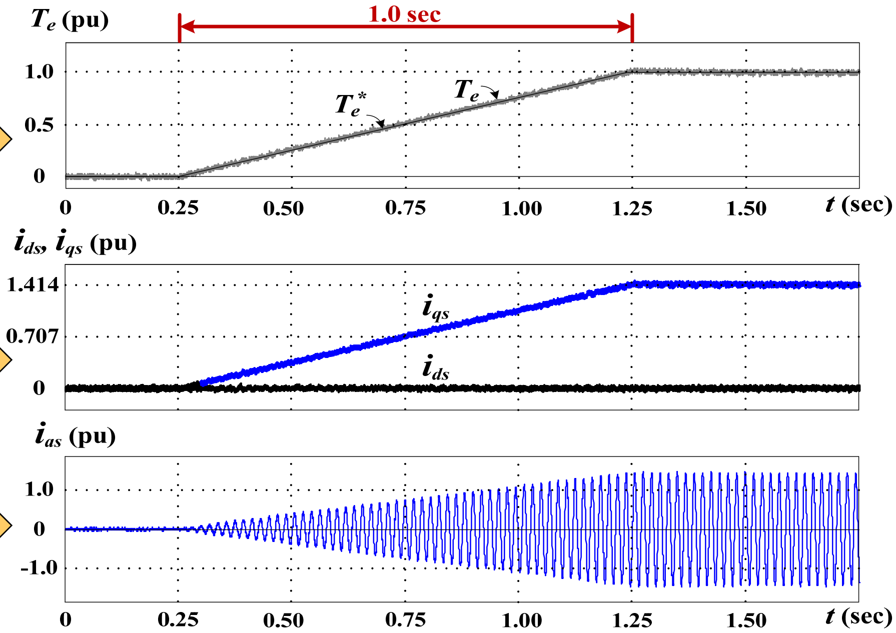
Case Study 1 – ZDC for non-salient SG

Simulation (Generator Control)

i_{qs} is proportional to torque. Why?

i_{ds} is zero during transients. Why?

Stator current (phase a)

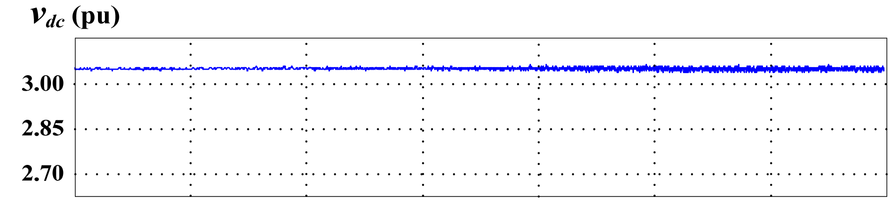


(a) Generator-side waveforms

At t = 0.25 sec, the torque reference T^*_e starts to increase. The generator torque Te follows its reference and ramps up to its rated value (1pu) at 1.25 sec.

Control of SG WECS

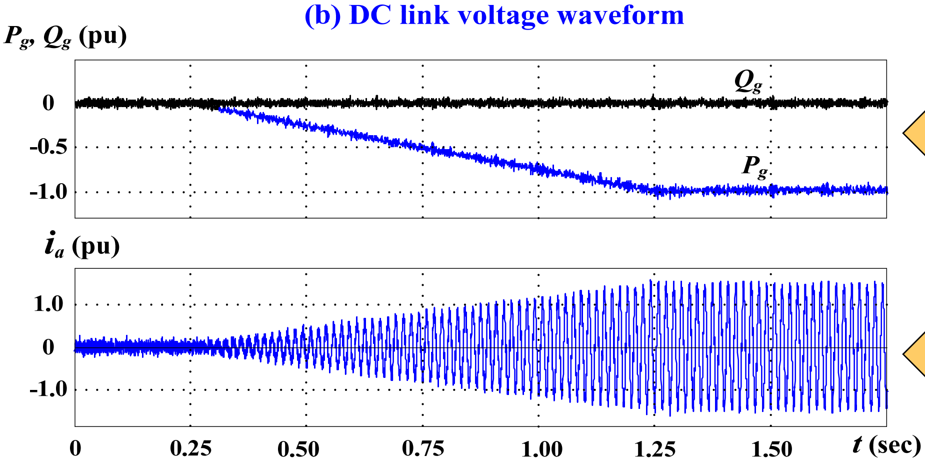
Case Study 1 – ZDC for non-salient SG



(b) DC link voltage waveform

DC link voltage

Q: How to keep the dc Voltage constant?



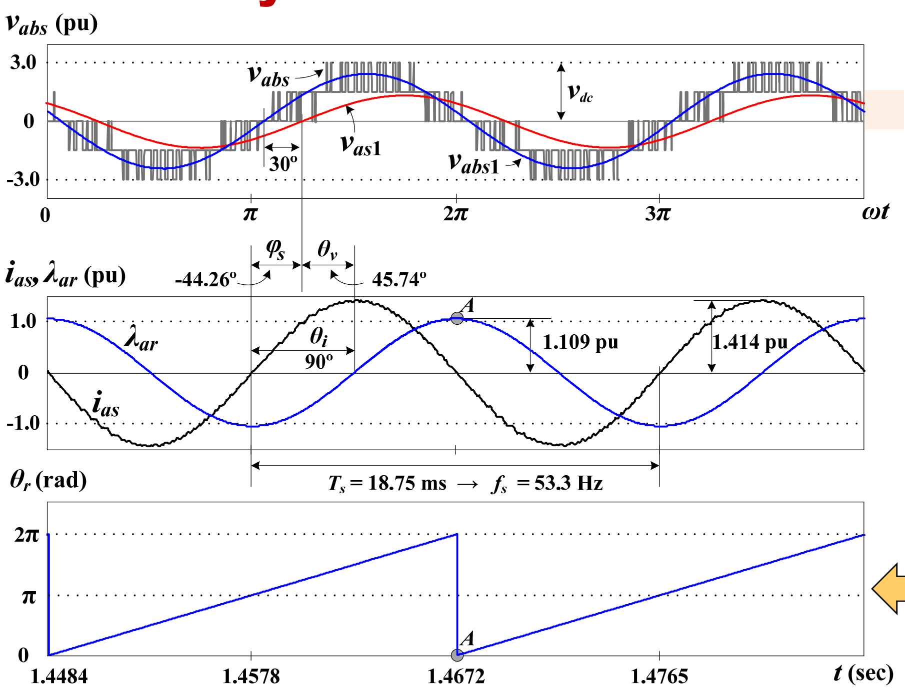
(c) Grid-side waveforms

Grid-side active and reactive power ($Q^* = 0 \rightarrow Q = 0$)

Grid-side current (phase a)

Control of SG WECS

Case Study 1 – ZDC for non-salient SG



Generator-side waveforms

- 3-level NPC converter
- Line-to-line voltage: 5 levels

Fundamental voltage:

Blue trace: V_{abs1}

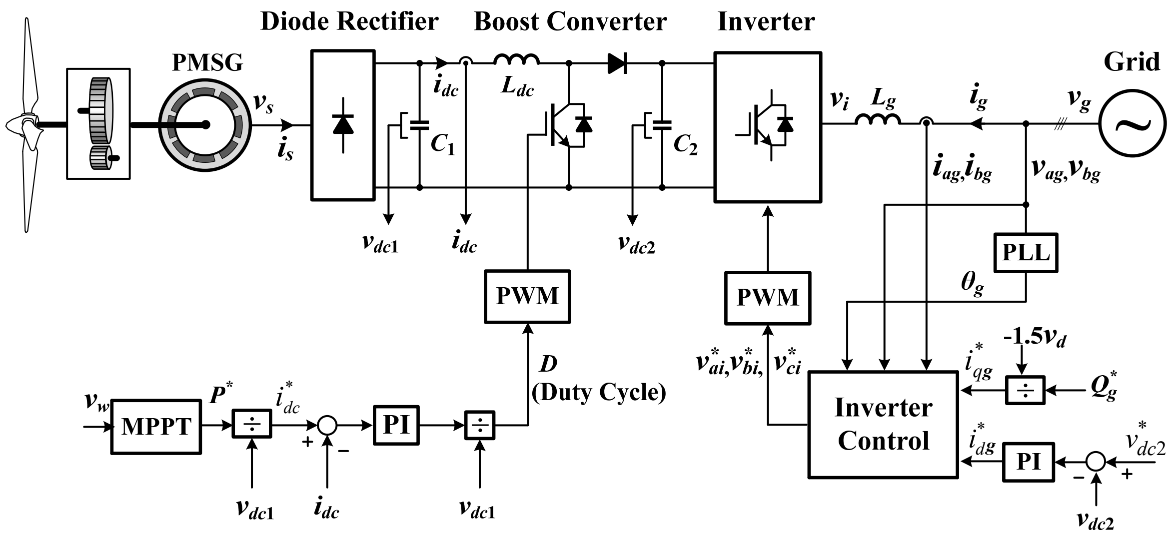
Red trace: V_{as1}

φ_s – Generator power factor angle (-44.26°)

Rotor flux angle

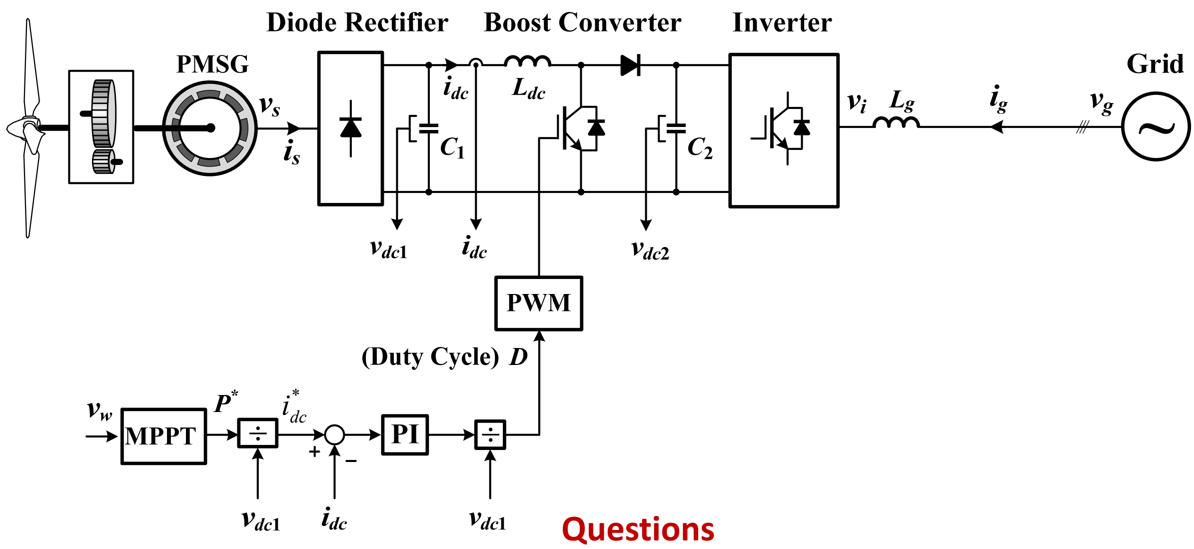
Boost Converter Fed SG WECS

Block Diagram



Boost Converter Fed SG WECS

Control of Boost Converter

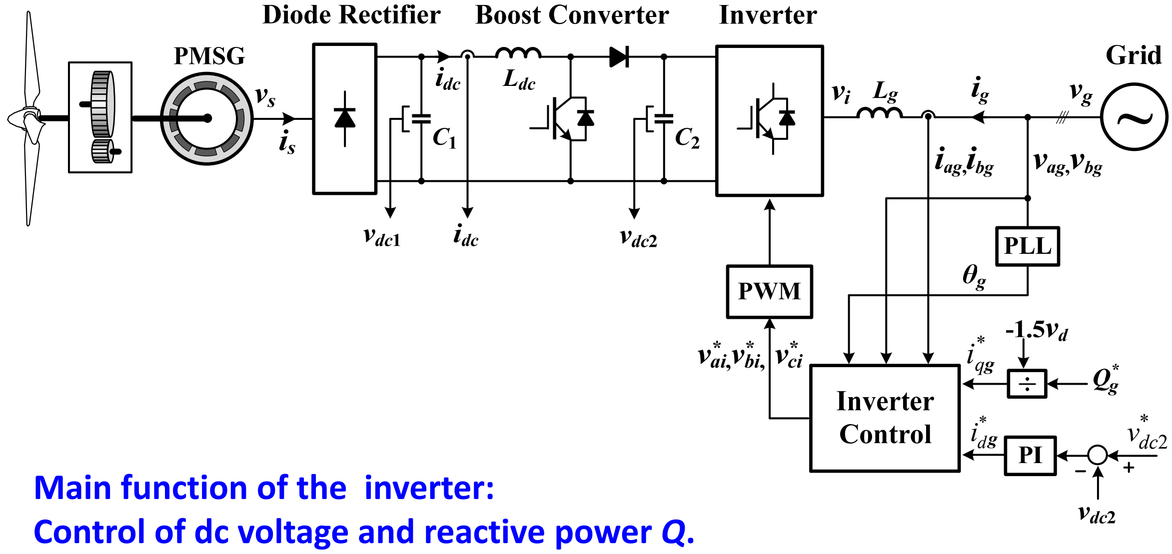


Questions

Main function of the boost converter?

Boost Converter Fed SG WECS

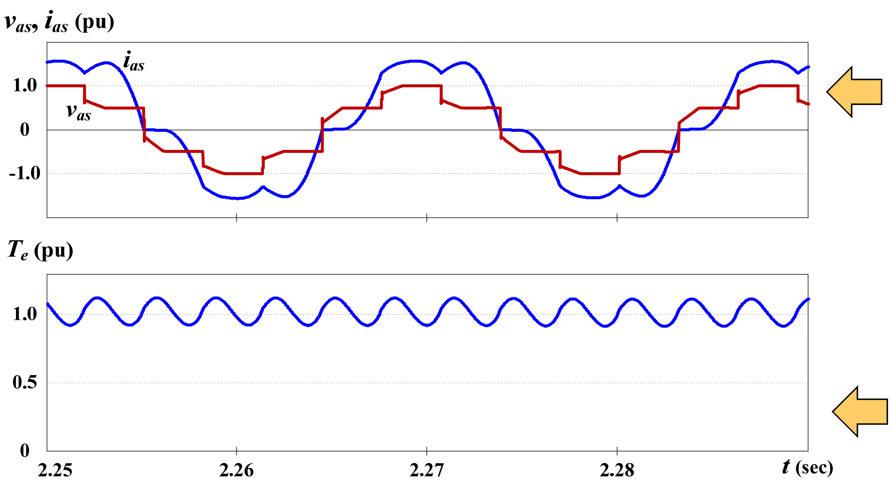
Control of Grid-side Converter



Main function of the inverter:
Control of dc voltage and reactive power *Q*.

Boost Converter Fed SG WECS

Steady-state Waveforms (simulation)



Q: Why the stator current contains harmonics?

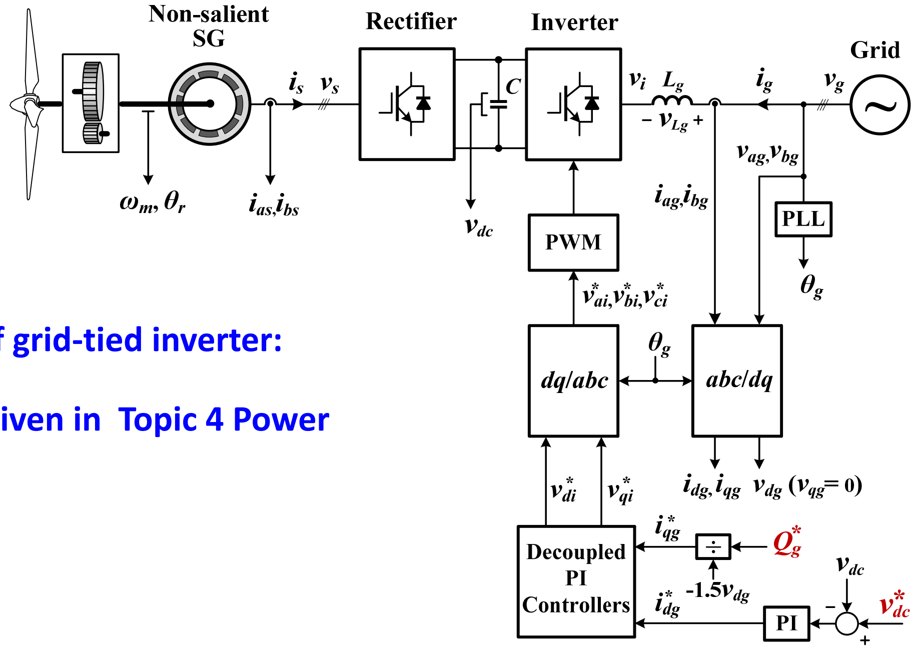
A: Because of the diode rectifier.

Q: Why the torque contains ripples?

A: Because of the harmonics in the stator current.

Grid-side Reactive Power Control

Block Diagram



Operation of grid-tied inverter:

See details given in Topic 4 Power Converters

Grid-side Reactive Power Control

Case Study 4 – Reactive Power Analysis

Given: **Inverter power rating: 2.44MVA/690V**

Assumption:

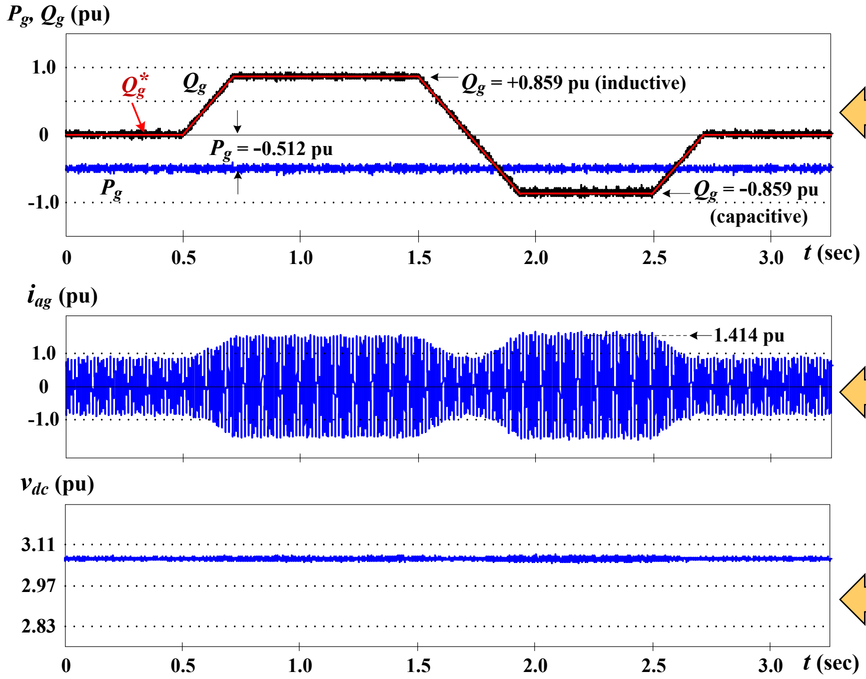
Inverter is ideal with no power losses

For a rotor speed of 0.8 pu, the grid-side active power and maximum reactive power that the inverter can provide can be calculated by

$$\begin{cases} P_g = \left(\omega_{r,\text{pu}}\right)^3 = 0.8^3 = 0.512 \text{ pu} \qquad (1.25\text{MW}) \\ Q_{g,\max} = \pm\sqrt{S_g^2 - P_g^2} = \pm\sqrt{1 - P_g^2} = \pm 0.859 \text{ pu} \quad (\pm 2.10\text{MVAR}) \end{cases}$$

Grid-side Reactive Power Control

Case Study 4 – Reactive Power Analysis



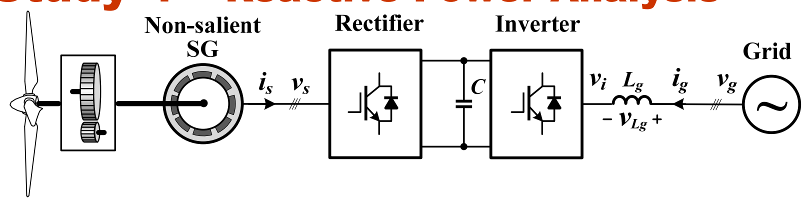
Active and reactive power to the grid

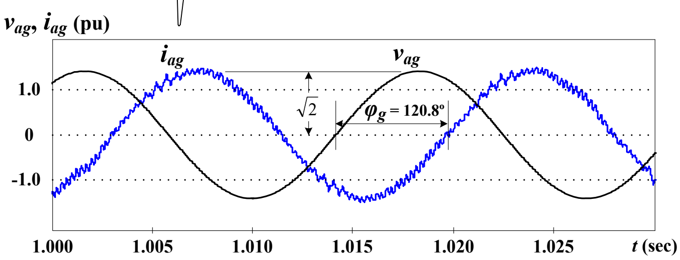
Grid current

DC voltage (Kept constants by the controller)

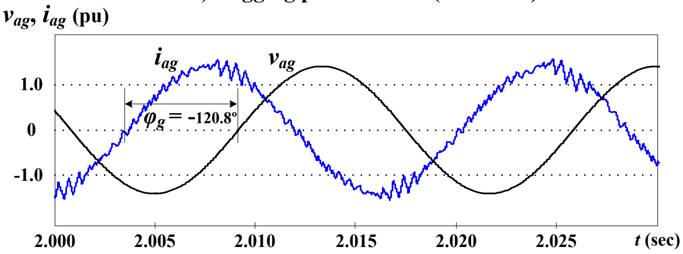
Grid-side Reactive Power Control

Case Study 4 – Reactive Power Analysis

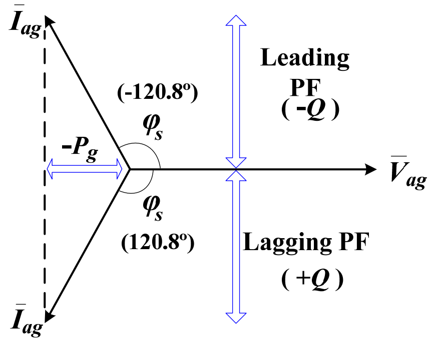




a) Lagging power factor (inductive)



b) Leading power factor (capacitive)



c) Phasor diagram

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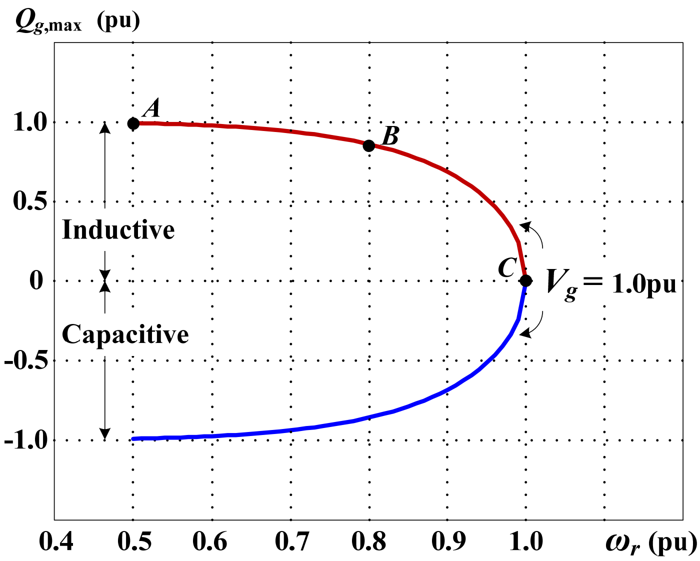
Maximum Reactive Power



$$Q_g = \pm\sqrt{S^2 - P^2} = \pm\sqrt{1 - P^2}\,\text{pu}$$

S is the power rating of the grid-side converter

Point A: ω_r = 0.5pu,
$P = (\omega_r)^3$ = 0.125pu, Q = 0.992pu

Point B: ω_r = 0.8pu,
$P = (\omega_r)^3$ = 0.512pu, Q = 0.859pu

Point C: ω_r = 1pu,
$P = (\omega_r)^3$ = 1pu, Q = 0pu

Q: Why $P = (\omega_r)^3$?

Summary

1. Control Schemes for Synchronous Generators
   Principle of two schemes: ZDC and MTPA controls

2. Control of SG WECS
- ZDC control of non-salient SG WECS
  Control block diagram, transient analysis, steady state analysis
- MTPA control of salient SG WECS
  Control block diagram, transient analysis, steady state analysis

3. Boost Converter Fed SG WECS
   System configuration, control block diagram, simulations

4. Grid-side Reactive Power Control
   Control block diagram, inductive/capacitive reactive power, case study, simulations

Thanks