Power Control of Doubly Fed Induction Machine using a Rotor Side Matrix Converter

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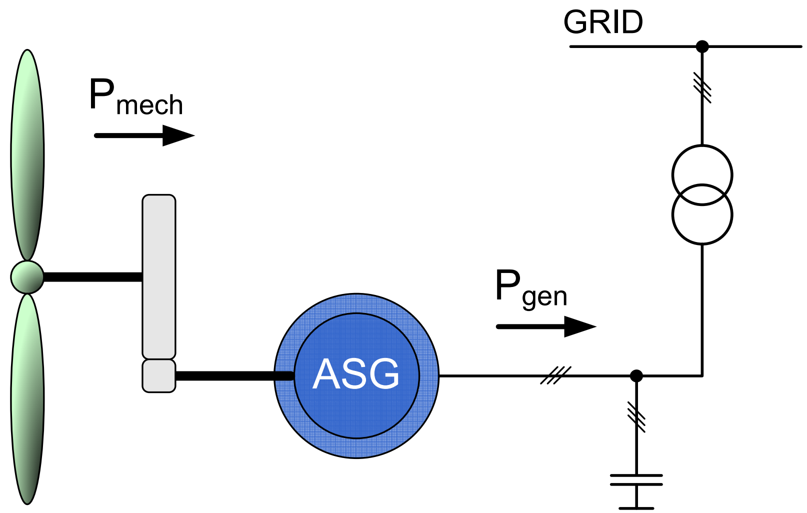
Presentation Outline

- Wind Grid-Connected Systems
- Doubly Fed Induction Machine
- Matrix Converter and Experimental Rig
- Results

Overview of

Wind Grid-Connected Systems

Fixed Speed direct on line generator



- Direct on line. No expensive power electronics converter needed.
- Mechanical control (complex & expensive)
  - Blades pitch angle Control.
    - Maximum power point tracking not possible.
  - Hydro-Dynamically controlled gearbox.
    - Continuously controllable variable gear box ratio.
    - Maximum power point tracking possible.

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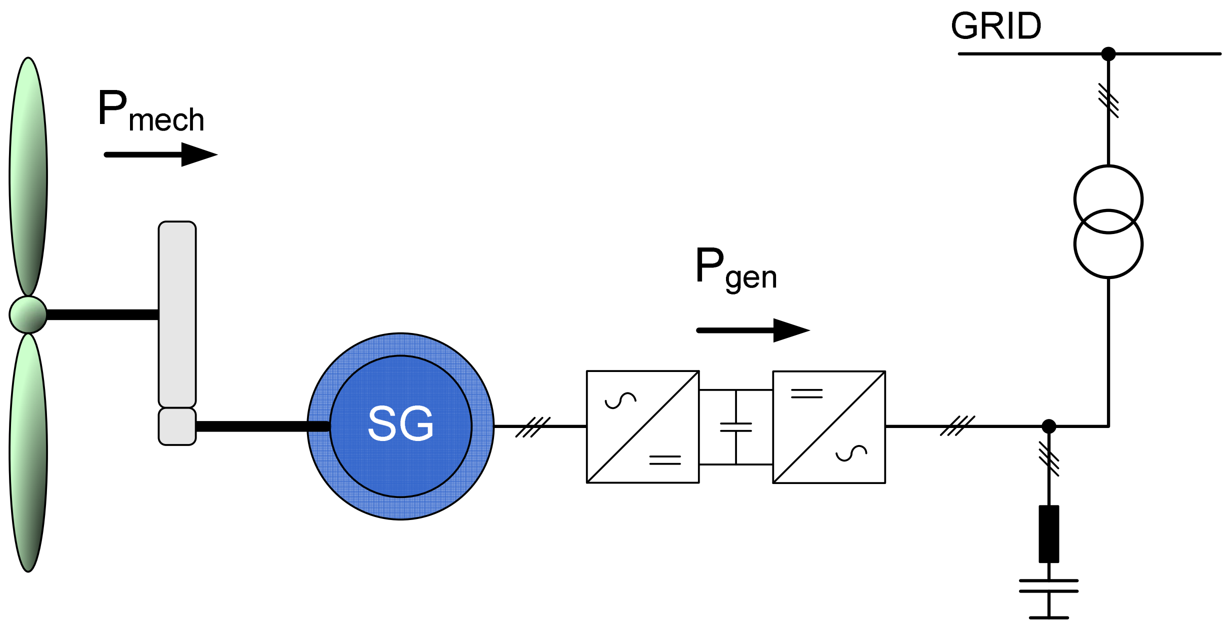
Wind Grid-Connected Systems

Adjustable Speed Using Synchronous Generator



- Mechanical control system is kept simple, hence less expensive.
- Adjustable Speed Drive allows for Maximum Power Operation.
- Generator produces variable-frequency AC power.
- A power electronics converter is needed.
  - Power converter has to be rated 100% of total system VA.

Wind Grid-Connected Systems

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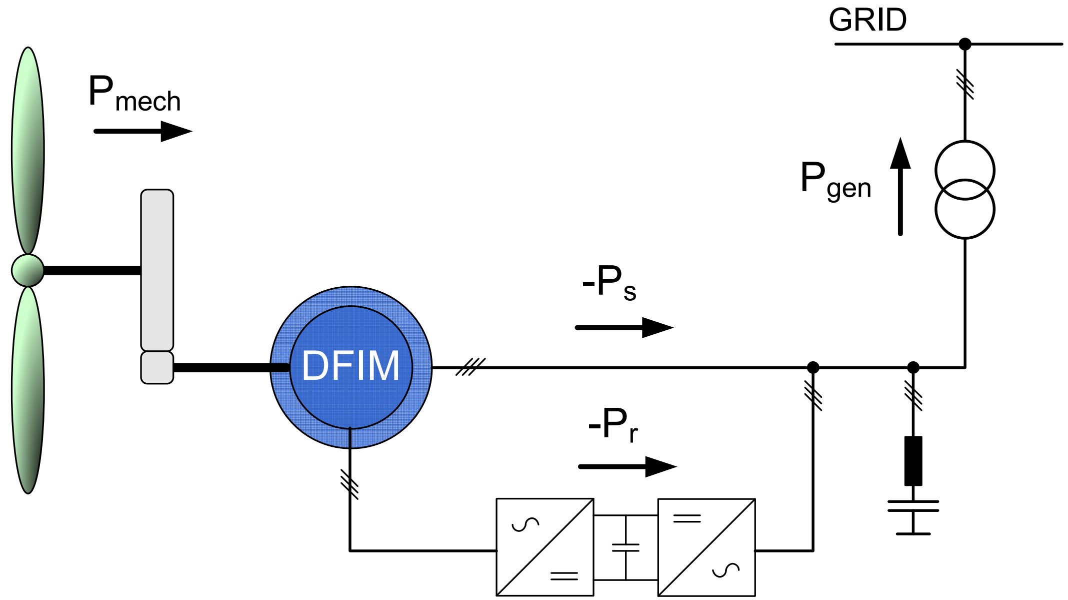
Adjustable Speed Using Doubly Fed Induction Generator



- Mechanical control system is kept simple, hence less expensive.
- Adjustable Speed Drive allows for Maximum Power Operation.
- Generator produces fixed-frequency fixed-voltage AC power.
- A power electronic converter is only needed to supply the slip power.
  - Power converter typically rated 25% of total system VA (less expensive).

Vector Control of the Doubly Fed Induction Machine

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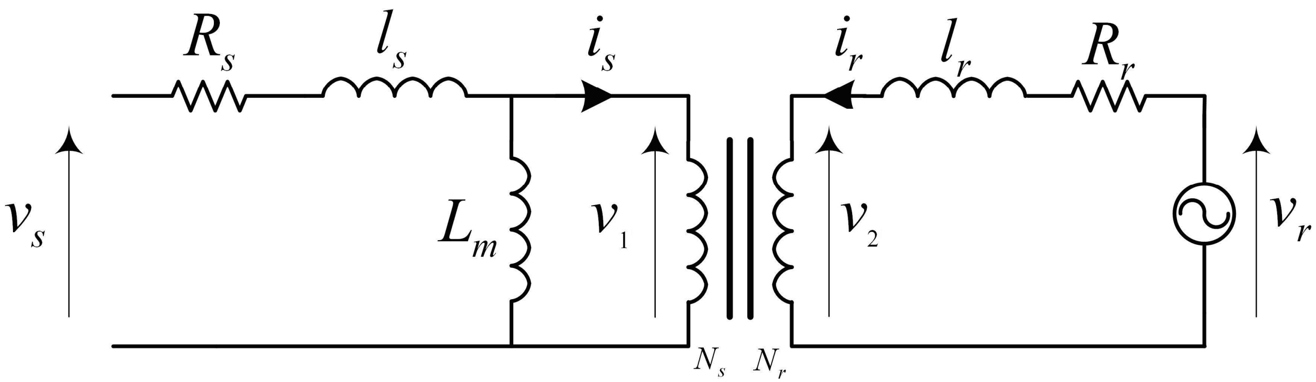
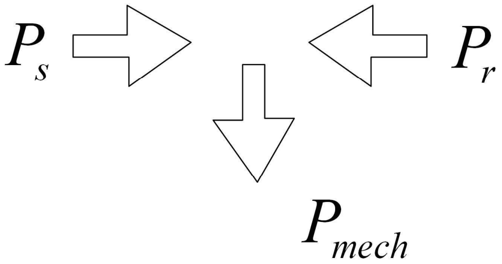
DFIM Steady-State Model



Power transferred through air-gap from stator:

$$P_s = 3 v_1 i_s^{*}$$



Power transferred through air-gap from rotor:

$$P_r = 3 v_2 i_r^{*}$$

$$P_r = 3\left(\frac{v_1 s}{N_{sr}}\right)\left(-i_s^{*} N_{sr}\right)$$

$$P_r = -3 v_1 i_s^{*} s$$

$$P_r = -s P_s$$

Mechanical Power developed is:

$$P_{mech} = P_s + P_r$$

$$P_{mech} = P_s - sP_s = P_s\left(1 - s\right)$$

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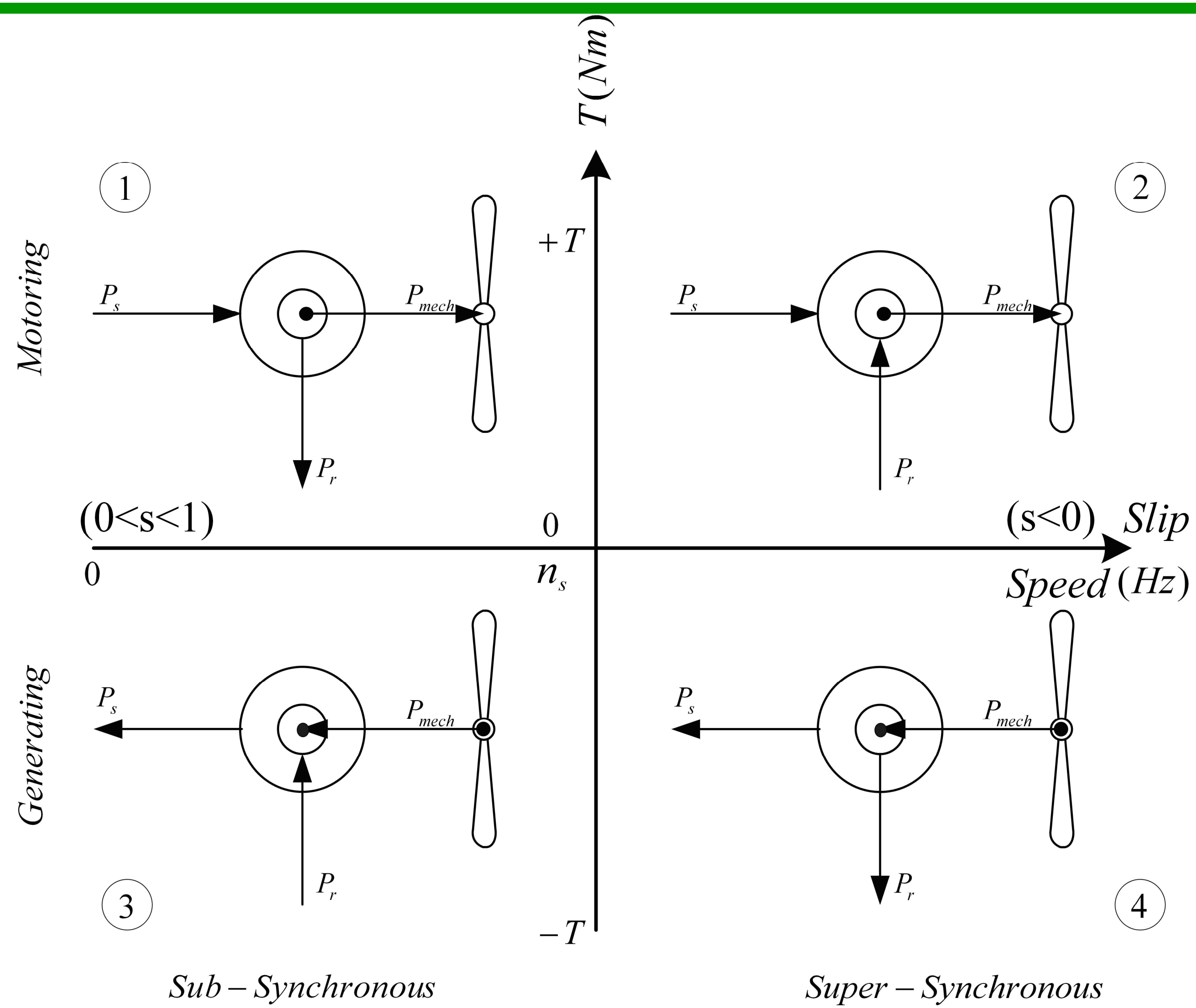
Power Flow in a DFIM



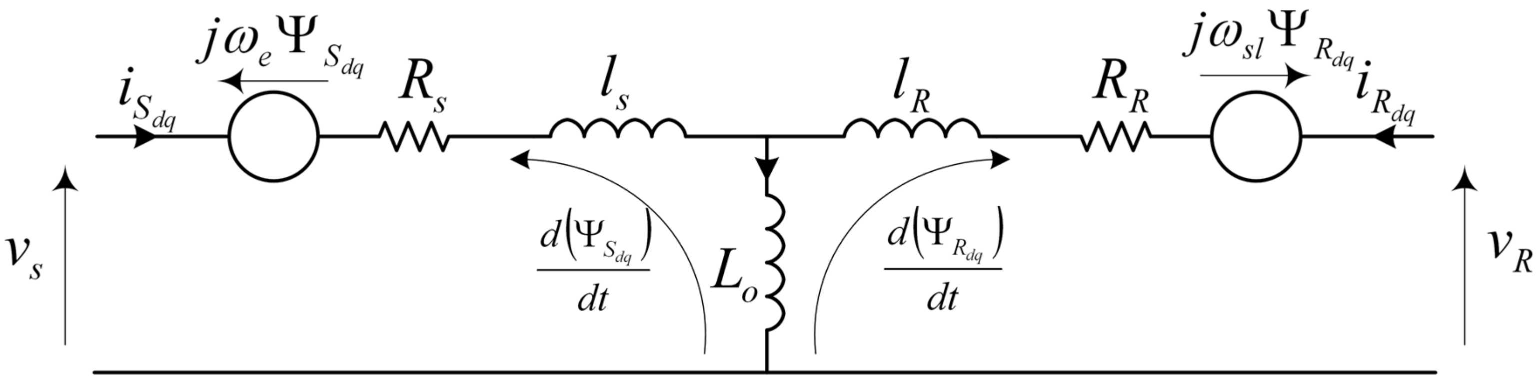
DFIM dynamic model

DFIM Modelling in stator and rotor frames:

$$v_{S_{\alpha\beta}} = R_S i_{S_{\alpha\beta}} + \frac{d\left(\Psi_{S_{\alpha\beta}}\right)}{dt} \qquad v_{R_{\alpha'\beta'}} = R_R i_{R_{\alpha'\beta'}} + \frac{d\left(\Psi_{R_{\alpha'\beta'}}\right)}{dt}$$

DFIM Modelling in rotating dq frame:

$$v_{S_{dq}} = R_S i_{S_{dq}} + \frac{d\left(\Psi_{S_{dq}}\right)}{dt} + j\omega_e \Psi_{S_{dq}} \qquad v_{R_{dq}} = R_R i_{R_{dq}} + \frac{d\left(\Psi_{R_{dq}}\right)}{dt} + j\omega_{sl} \Psi_{R_{dq}}$$



DFIM Stator Field Orientated Vector Control

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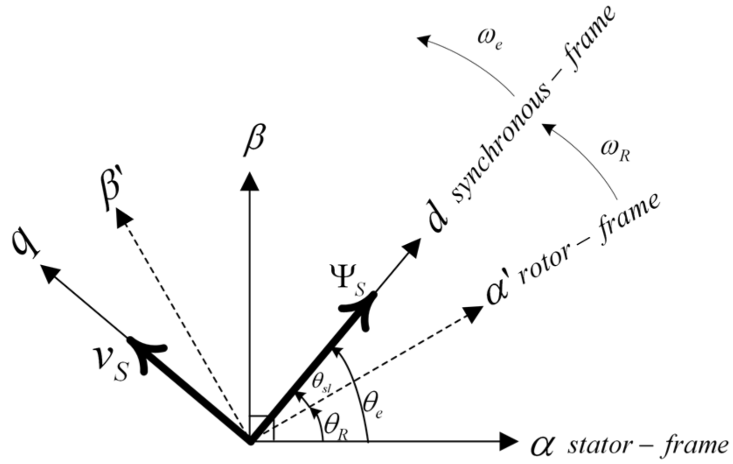

- Aligning the synchronous frame to the stator Ψ_S, leads to:

$$\Psi_{S_d} = \Psi_S \qquad \Psi_{S_q} = 0$$

- Neglecting stator resistance and assuming steady state grid supply the stator flux vector becomes constant in the dq frame and the stator dynamic equations may be written as:

$$v_{S_d} = -\omega_e \Psi_{S_q} = 0 \qquad\qquad v_{Sq} = \omega_e \Psi_{S_d}$$

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DFIM SFO Vector Control
Rotor Dynamic Equations

Using the flux relationships:

$$\Psi_S = L_S i_S + L_O i_R$$

$$\Psi_R = L_R i_R + L_O i_S$$

the rotor dynamic equations may be arranged in terms of Ψ_S and i_R

$$v_{R_d} = \underbrace{R_R i_{R_d} + \delta L_R \frac{d\left(i_{R_d}\right)}{dt}}_{Linear} \underbrace{- \delta L_R \omega_{sl} i_{R_q}}_{Coupling}$$

$$v_{R_q} = \underbrace{R_R i_{R_q} + \delta L_r \frac{d\left(i_{R_q}\right)}{dt}}_{Linear} \underbrace{+ \omega_{sl}\left(\delta L_R i_{R_d} + \frac{L_O}{L_S}\Psi_{S_d}\right)}_{Coupling}$$

These equations can be used for PI current control design for SFO vector control.

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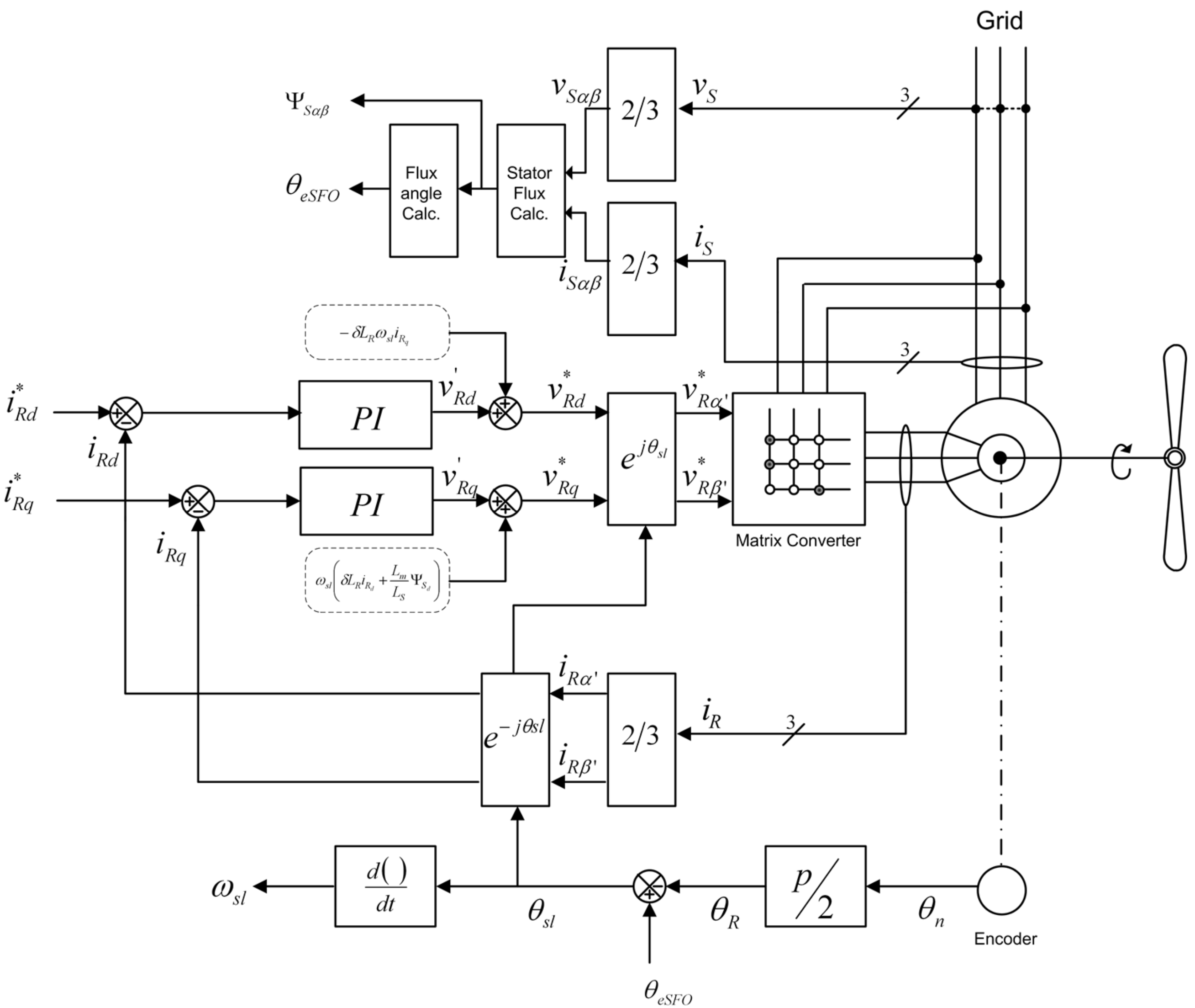
DFIM Stator Field Orientated Vector Control Scheme

$(Q_S \propto i_{R_d})$

$(P_S \propto -i_{R_q})$



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DFIM
Indirect Stator Power Control

- The stator active power is defined as: $P_S = 3\,\mathrm{Re}(v_S i_S^*)$
- whereas the reactive power is defined as: $Q_S = 3\,\mathrm{Im}(v_S i_S^*)$
- It can be shown after some mathematical manipulation that:

$$P_S = -3\frac{L_O}{L_S} i_{R_q} \Psi_S \omega_e \qquad (P_S \propto -i_{R_q})$$

$$Q_S = -3\left(\frac{\Psi_S v_S}{L_S} - \frac{L_O v_S}{L_S} i_{R_d}\right) \qquad (Q_S \propto i_{R_d})$$

The Matrix Converter and the DFIM Test Rig

Matrix Converter Circuit

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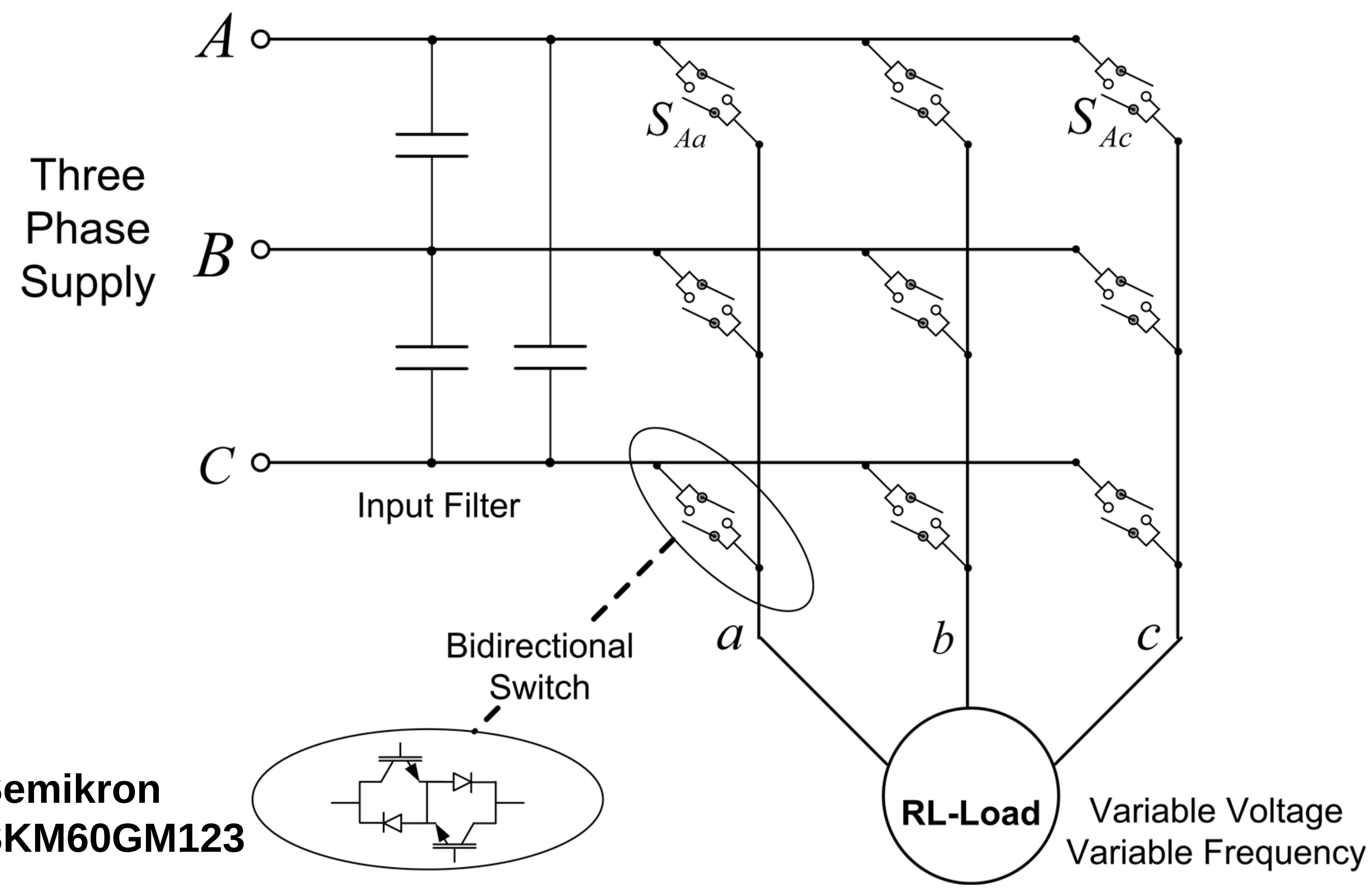
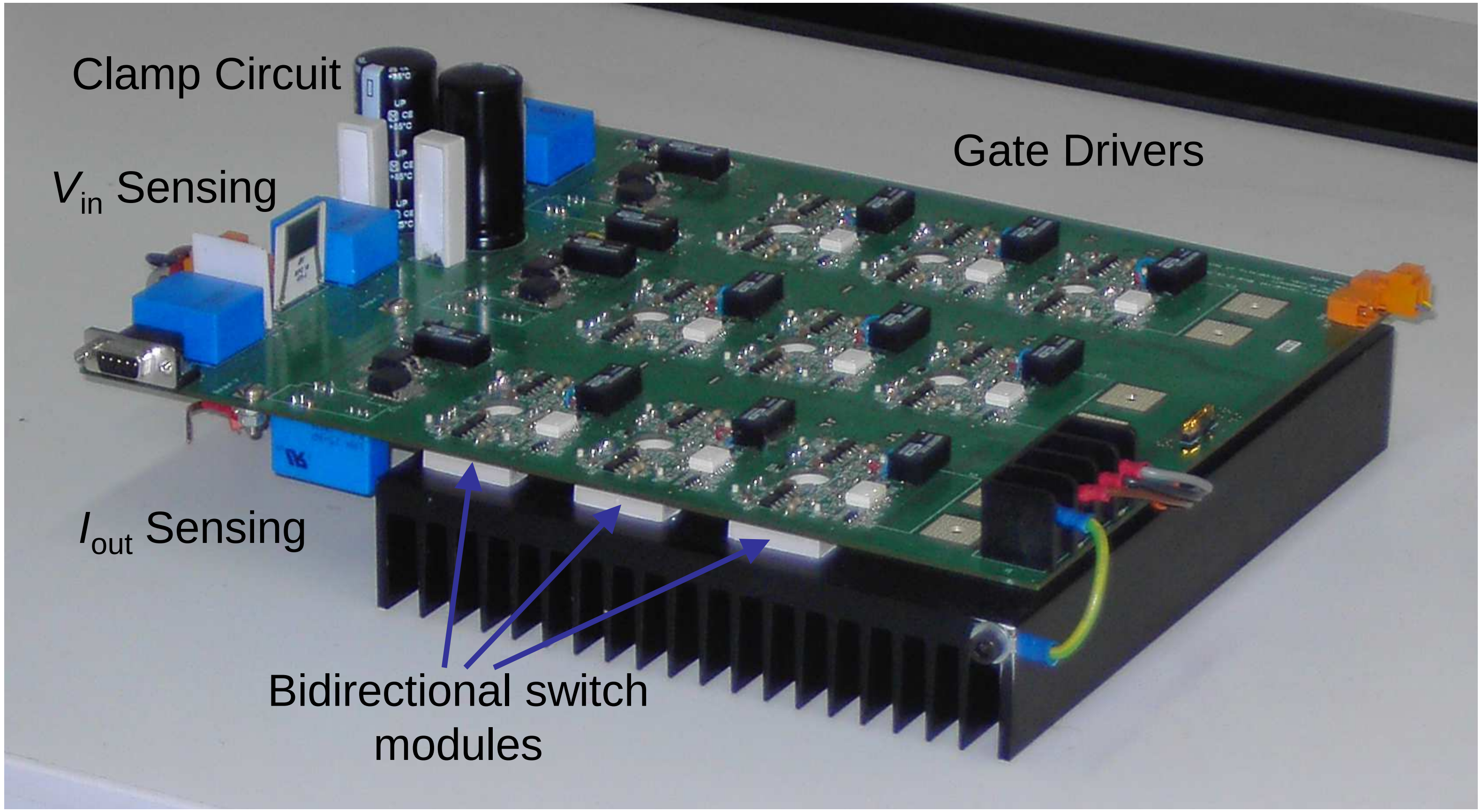


Semikron SKM60GM123

Matrix Converter Properties

- Each output phase can be connected to any input phase at any time
- Direct Conversion (no power storage elements)
  - Power In = Power Out at all times
- Bidirectional power flow due to bidirectional switches
- Sinusoidal input currents due to PWM control and input filter
- Input power factor can be set as desired – this includes operation at PF=1

7.5kW Matrix Converter Circuit



Experimental Setup

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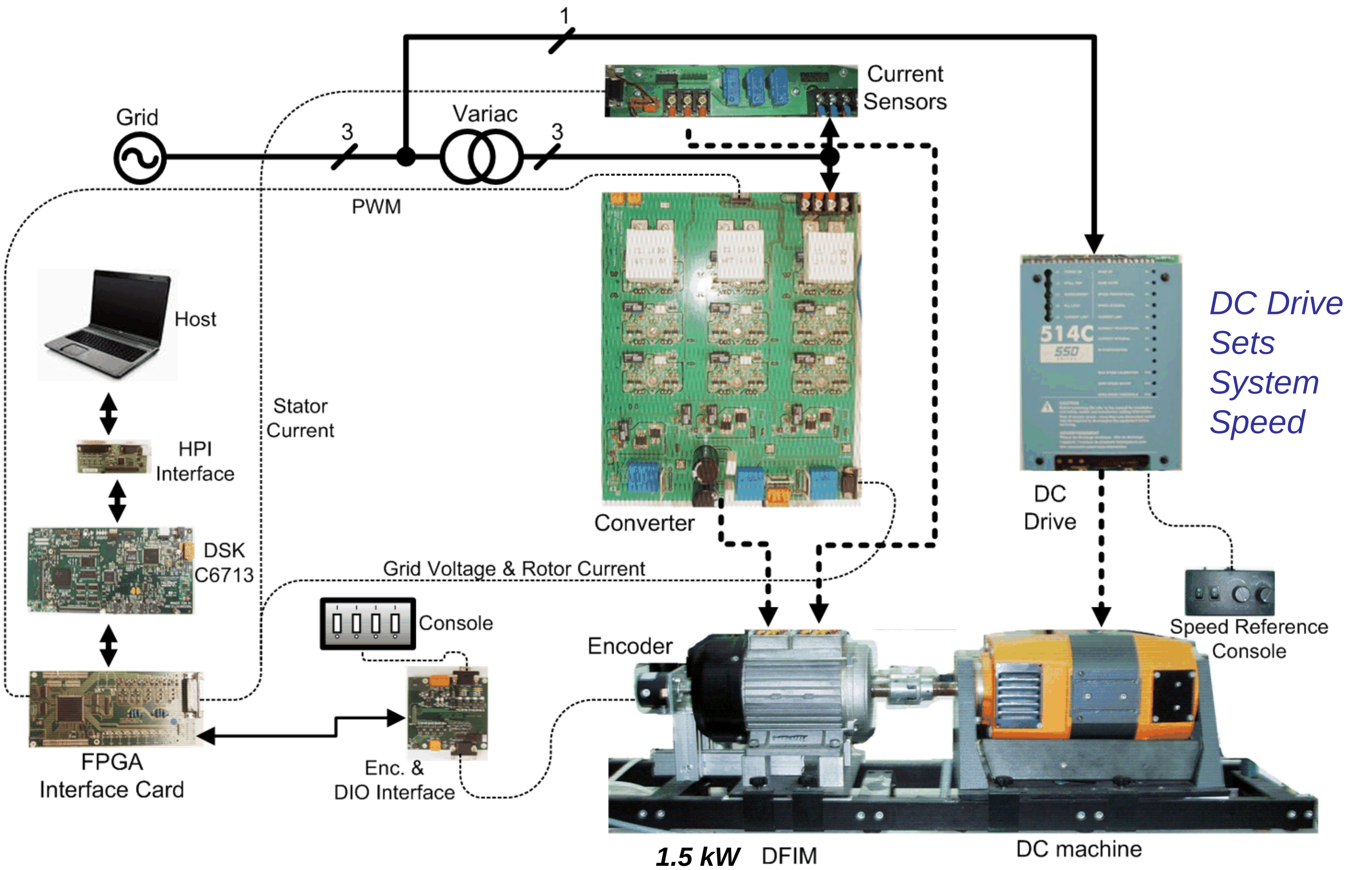

Experimental Results

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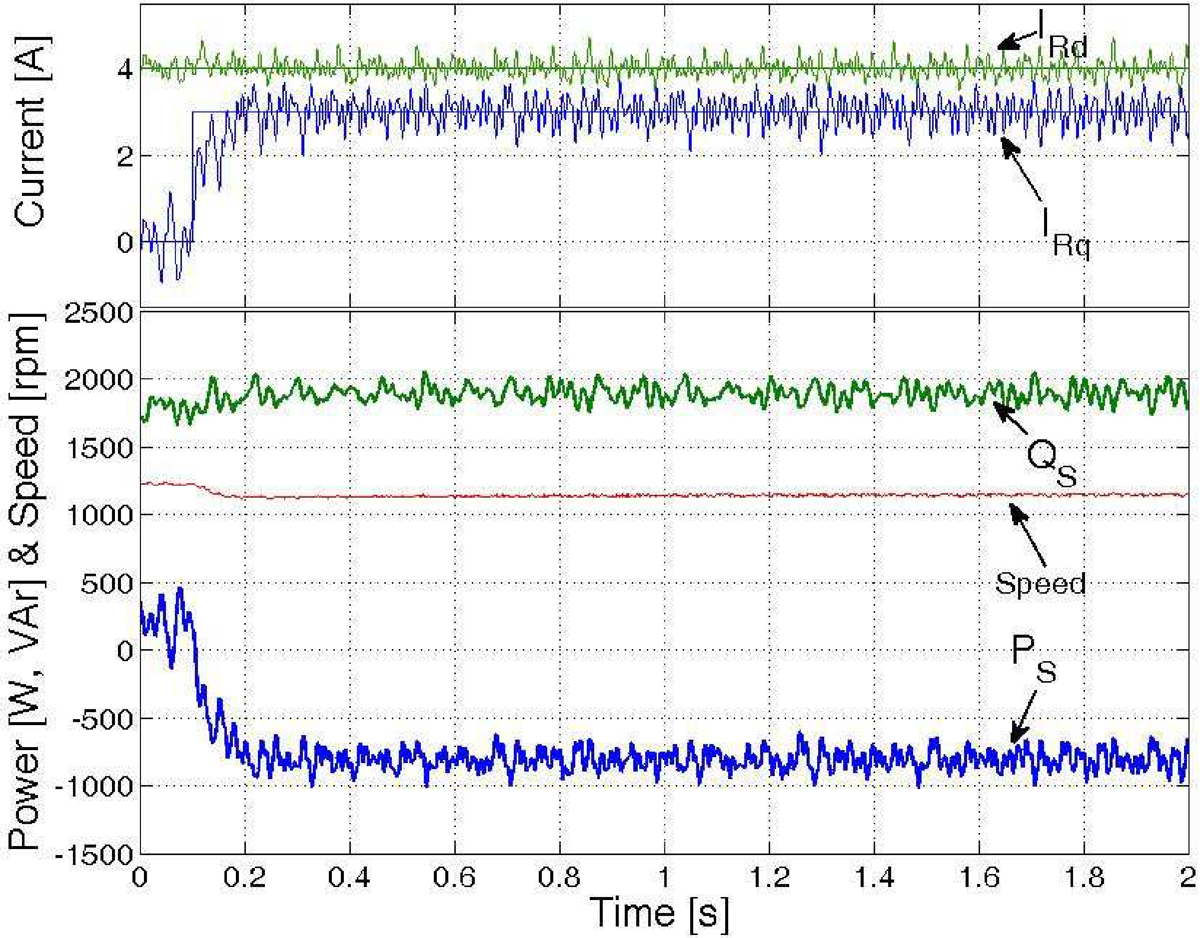
DFIM Stator Power Control

Stator Active and Reactive Power for step in i_{R_q}



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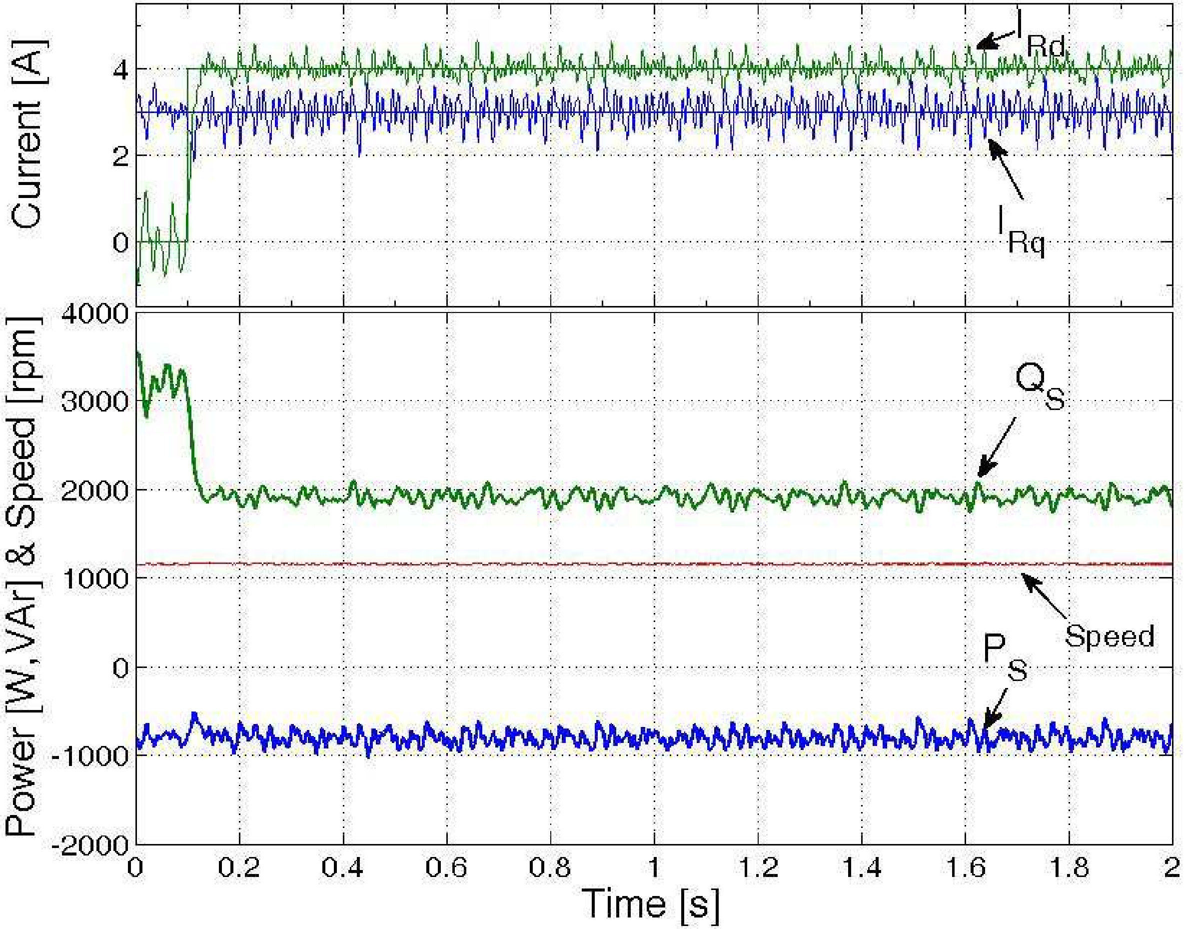
DFIM Stator Power Control

Stator Active and Reactive Power for step in i_{R_d}



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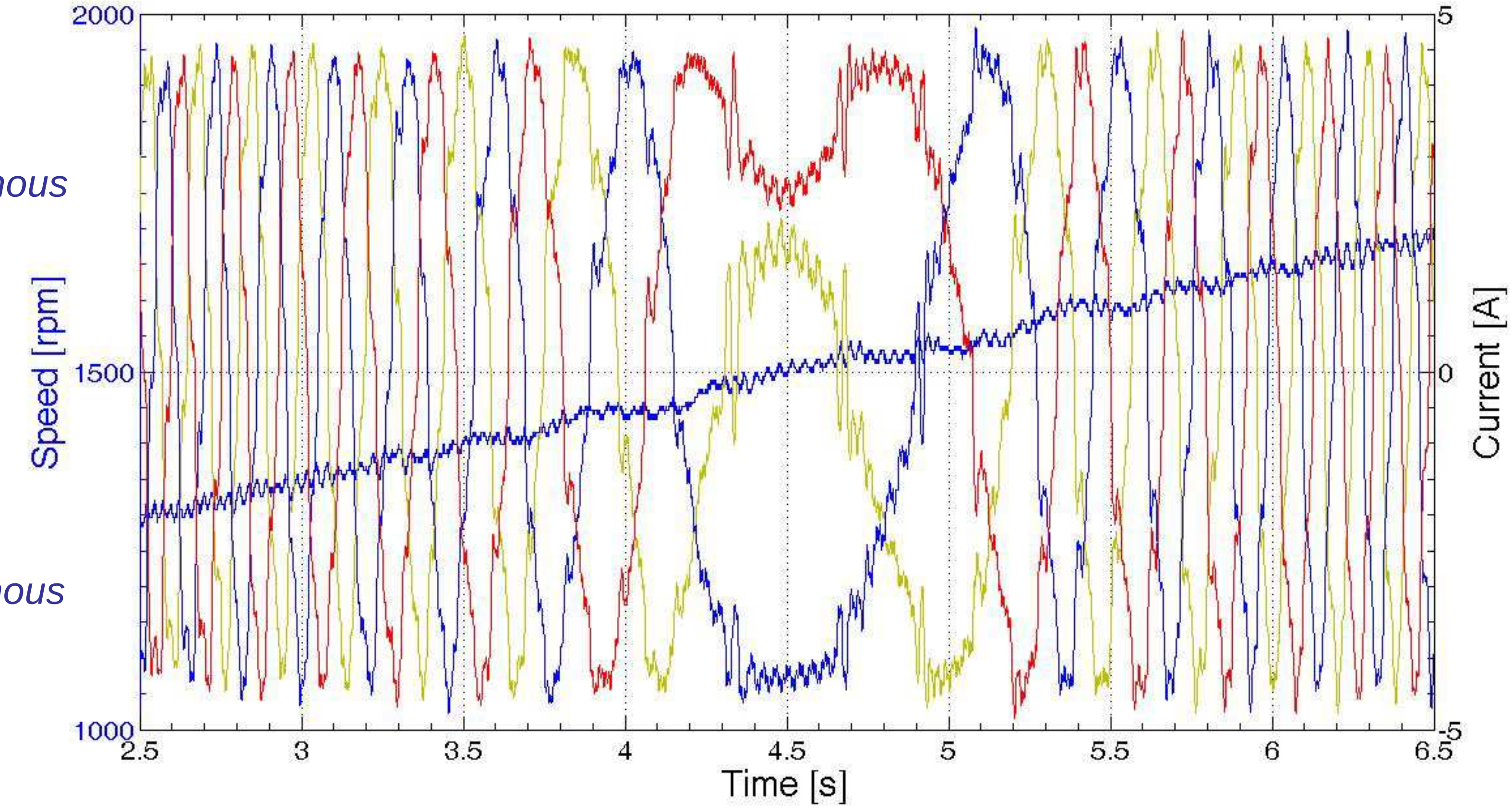
Variable Speed Operation

Operation Through Synchronous Speed: Automatic Rotor Current Reversal

Above Synchronous Speed

Below Synchronous Speed



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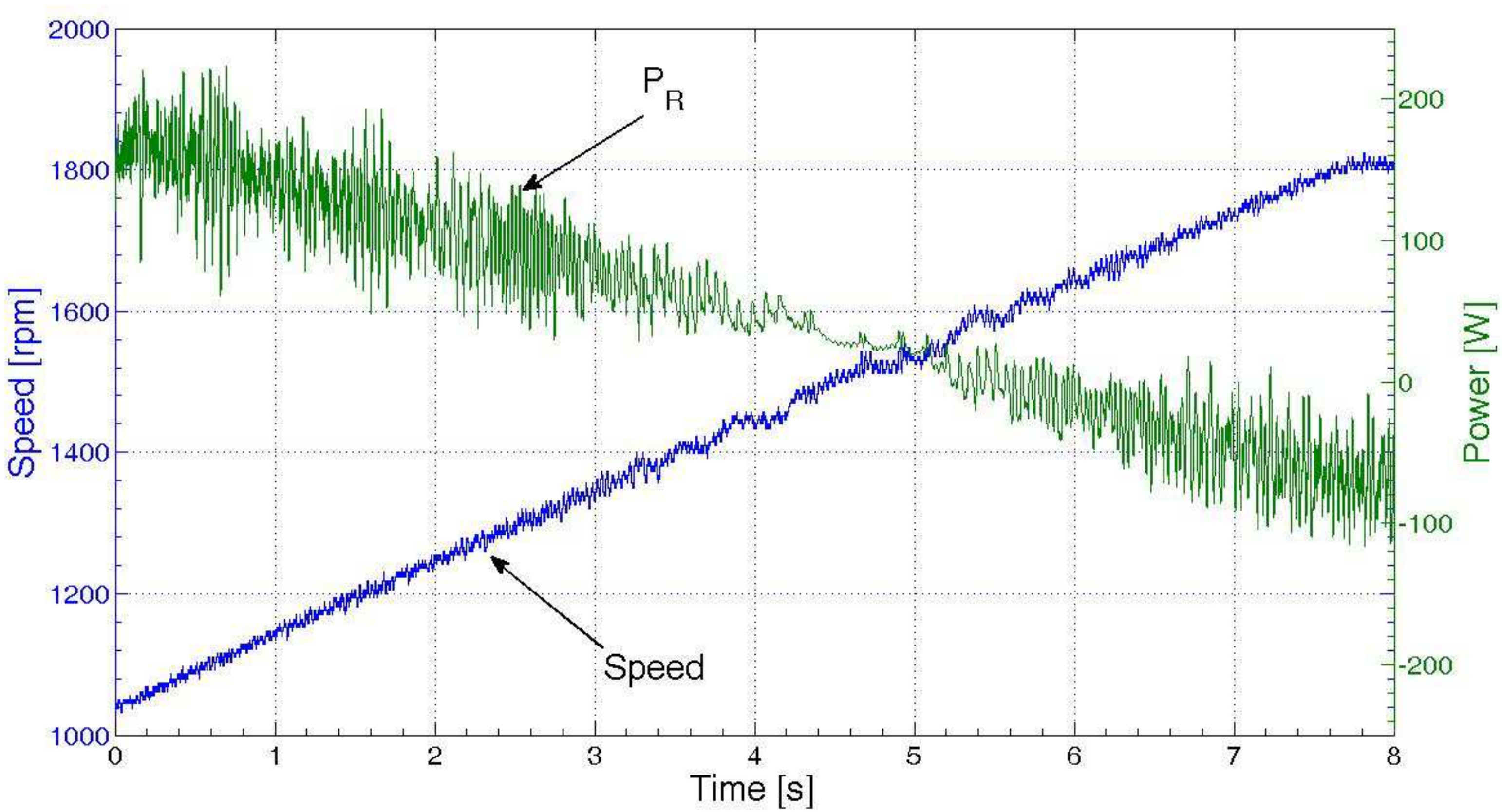
Variable Speed Operation

Rotor Power Reversal During DFIM Speed Transition Through Synchronous Speed



Power Factor Control

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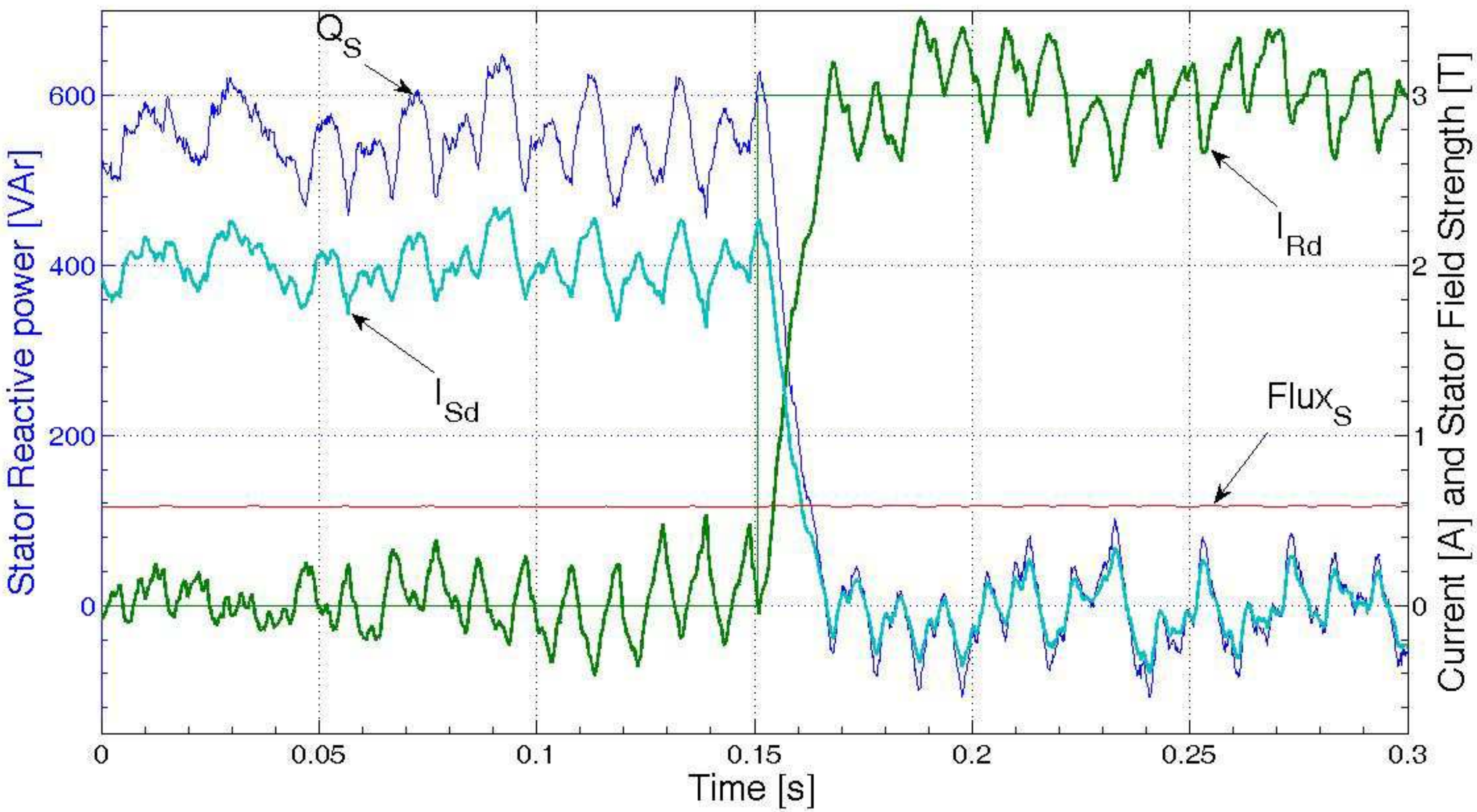
Stator Reactive Power reduced to zero by step in Ird
(maintaining constant Stator Flux)



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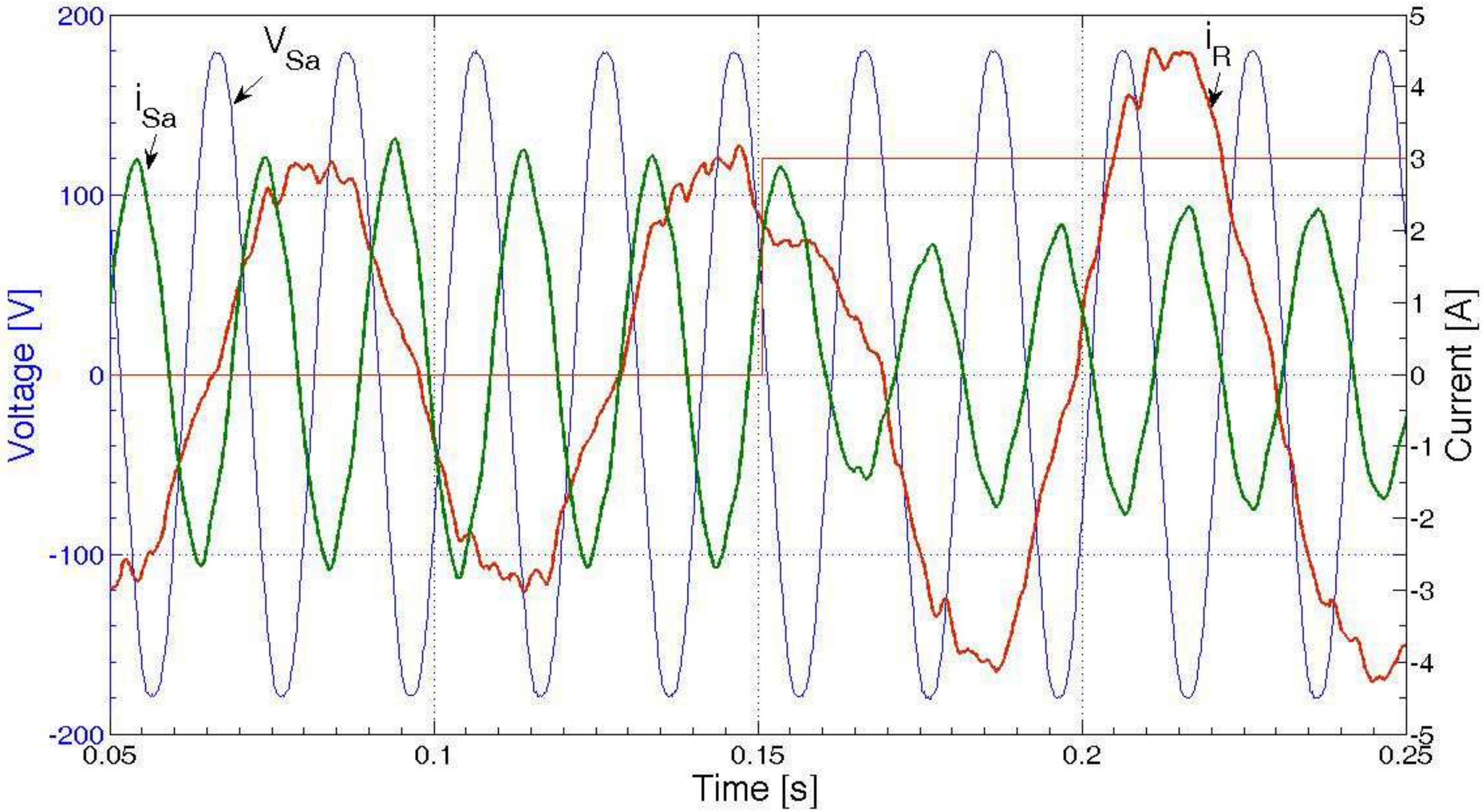
Power Factor Control

Stator Voltage & Current and Rotor Current
for a step reduction of Stator Reactive Power to zero



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Conclusions

- Application of matrix converter drive applied to DFIM stator power control for a Wind Energy System
- Matrix Converter used to control rotor circuit of DFIM using SFO vector control
- Results demonstrate control of stator power to grid during tests whilst speed is controlled by dc drive acting as prime mover