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

Kenneth Spiteri, Cyril Spiteri Staines, Maurice Apap
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.
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.
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
DFIM Steady-State Model

Power transferred through air-gap from stator:

\[ P_s = 3v_i i_s^* \]

Power transferred through air-gap from rotor:

\[ P_r = 3v_i i_r^* \]

Mechanical Power developed is:

\[ P_{mech} = P_s + P_r = P_s - sP_s = P_s(1-s) \]

\[ P_r = -3v_i i_s^* s \]

\[ P_r = -sP_s \]
Power Flow in a DFIM
DFIM dynamic model

DFIM Modelling in stator and rotor frames:

\[ v_{s_{αβ}} = R_s i_{s_{αβ}} + \frac{d(ψ_{s_{αβ}})}{dt} \]
\[ v_{r_{αβ'}} = R_r i_{r_{αβ'}} + \frac{d(ψ_{r_{αβ'}})}{dt} \]

DFIM Modelling in rotating dq frame:

\[ v_{s_{dq}} = R_s i_{s_{dq}} + \frac{d(ψ_{s_{dq}})}{dt} + jω_e ψ_{s_{dq}} \]
\[ v_{r_{dq}} = R_r i_{r_{dq}} + \frac{d(ψ_{r_{dq}})}{dt} + jω_{sl} ψ_{r_{dq}} \]
Aligning the synchronous frame to the stator $\Psi_s$, leads to:

$$\Psi_{sd} = \Psi_s \quad \Psi_{sq} = 0$$

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:

$$\nu_{Sd} = -\omega_e \Psi_{sq} = 0 \quad \nu_{Sq} = \omega_e \Psi_{sd}$$
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 \( \Psi_S \) and \( i_R \)

\[ v_{R_d} = R_R i_{R_d} + \frac{\partial L_R}{\partial t} \frac{d(i_{R_d})}{dt} - \delta L_R \omega_{sl} i_{R_q} \]
\[ v_{R_q} = R_R i_{R_q} + \frac{\partial L_R}{\partial t} \frac{d(i_{R_q})}{dt} + \omega_{sl} \left( \delta L_R i_{R_d} + \frac{L_O}{L_S} \Psi_{S_d} \right) \]

These equations can be used for PI current control design for SFO vector control.
DFIM Stator Field Orientated Vector Control Scheme

\( Q_S \propto i_{R_d} \)
\( P_S \propto -i_{R_q} \)
The stator active power is defined as: \( P_S = 3 \text{Re}(v_S i_S^*) \)

whereas the reactive power is defined as: \( Q_S = 3 \text{Im}(v_S i_S^*) \)

It can be shown after some mathematical manipulation that:

\[
P_S = -3 \frac{L_o}{L_s} i_{Rq} \Psi_S \omega_e \quad \text{\( (P_S \propto -i_{Rq}) \)}
\]

\[
Q_S = -3 \left( \frac{\Psi_S v_S}{L_s} - \frac{L_o v_S}{L_s} i_{Rd} \right) \quad \text{\( (Q_S \propto i_{Rd}) \)}
\]
Matrix Converter and Hardware Setup

The Matrix Converter and the DFIM Test Rig
Matrix Converter Circuit

UNIVERSITY OF MALTA

Three Phase Supply

Input Filter

Bidirectional Switch

Semikron SKM60GM123

RL-Load

Variable Voltage
Variable Frequency

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

DC Drive Sets System Speed

1.5 kW DFIM

DC machine

Speed Reference Console

DC Drive

Converter

Stator Current

PWM

Variac

Current Sensors

Grid Voltage & Rotor Current

Console

FPGA Interface Card

DSK C6713

HPI Interface

Host

Grid
Experimental Results
DFIM Stator Power Control

Stator Active and Reactive Power for step in $i_{Rq}$
DFIM Stator Power Control

Stator Active and Reactive Power for step in $i_{R_d}$
Variable Speed Operation

Operation Through Synchronous Speed: Automatic Rotor Current Reversal

Above Synchronous Speed

Below Synchronous Speed
Variable Speed Operation

Rotor Power Reversal During DFIM Speed Transition Through Synchronous Speed
Power Factor Control

Stator Reactive Power reduced to zero by step in $I_{rd}$ (maintaining constant Stator Flux)
Power Factor Control

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