Modelling and Control of Wind Power Systems

Durham
University

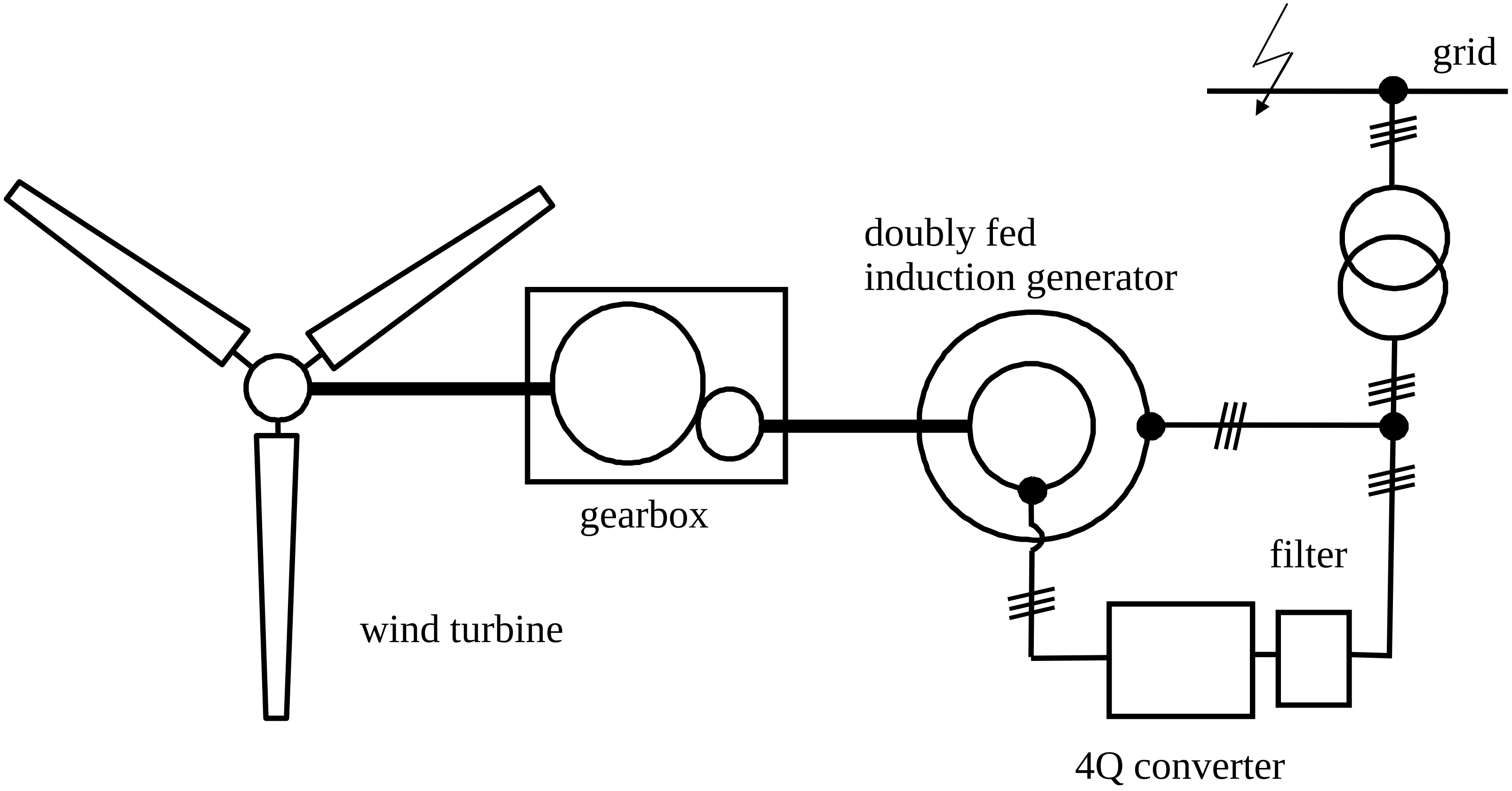
School of Engineering
and Computing Sciences

Presentation Plan

This presentation intends to introduce basic concepts of wind power system control through 3 case studies:

Case 1: doubly fed induction generator (DFIG)
grid fault ride-through control
Case 2: grid inverter control with unbalanced grid
voltage
Case 3: DFIG wind farm connection using LCC
HVDC link

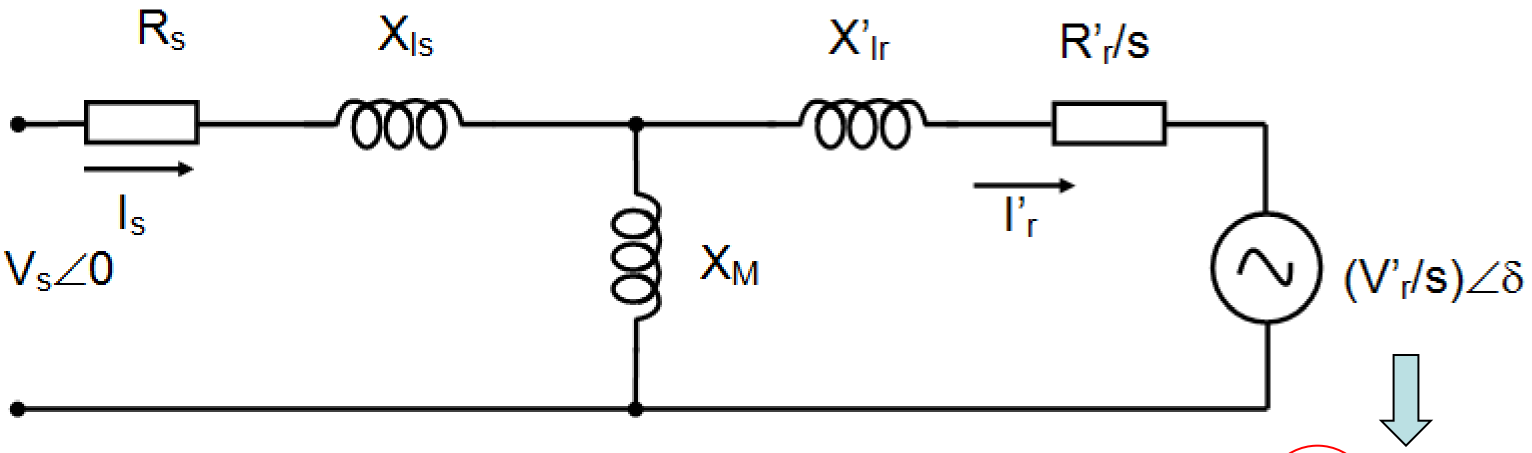
Case 1: DFIG control



The configuration and working principle of DFIG:

- rotor supply frequency (and voltage) is controlled to control the speed.
- speed varies ±30% around synchronous speed to limit the converter rating.
- the speed range is enough because power is very low below minimum speed.

Case 1: DFIG control

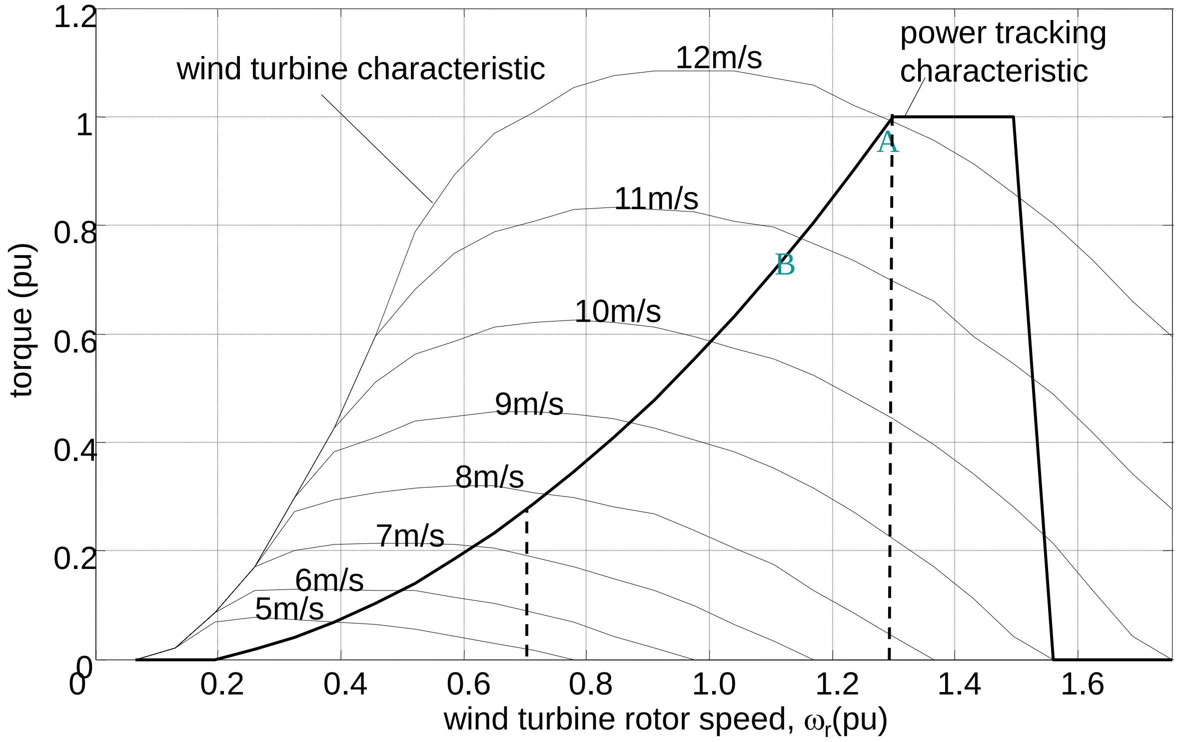


$$\enclose{circle}{V'_r} + \frac{1-s}{s} V'_r$$

The equivalent circuit of DFIG:

- induction machine is like transformer with two sets of magnetically coupled windings.
- however rotor cuts the flux at the slip frequency.
- the frequency ratio only affects the voltage but not the current. Therefore rotor side impedance is further referred to the stator side by (1/s) instead of $(1/s)^2$. It is also for this reason rotor power is $P_r=sP_s$.

Case 1: DFIG control



Maximum power tracking control in normal operation:

- it is necessary to control the generator torque according to rotational speed.
- given turbine characteristics, it is not necessary to measure wind velocity.
- rotational speed is proportional to wind velocity to maintain optimum λ.

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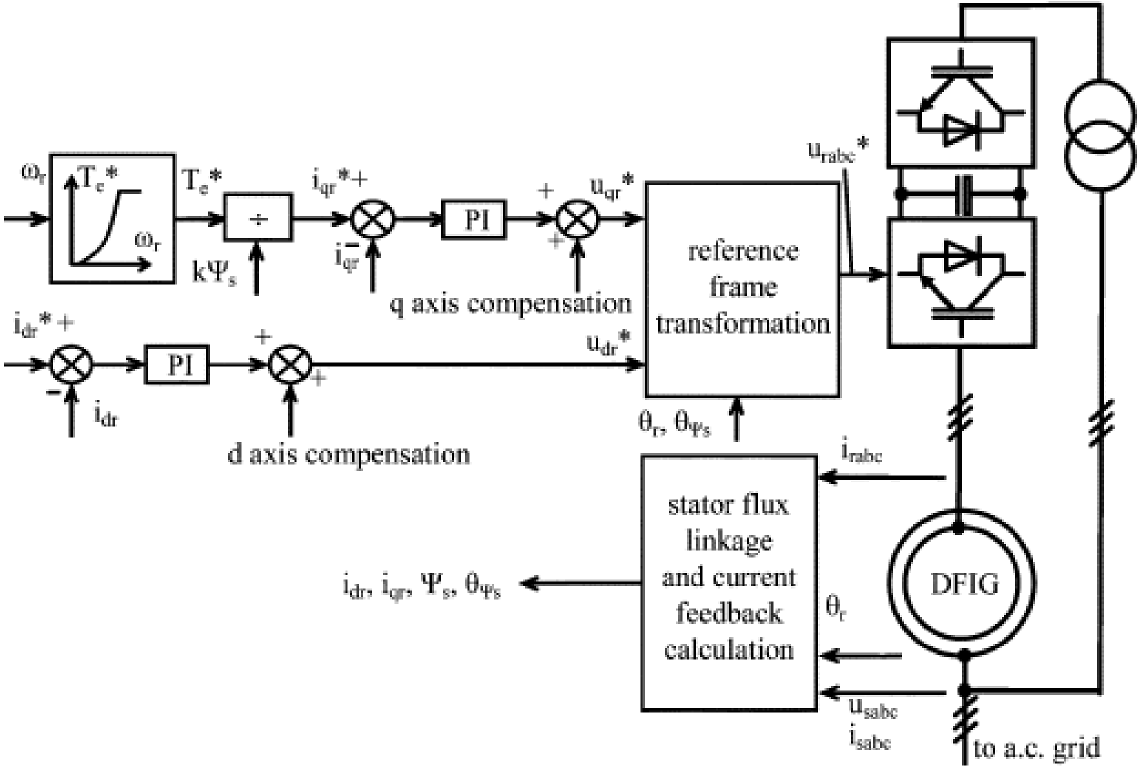
Case 1: DFIG control



$$\psi_{sabc} = \int (u_{sabc} - R_s i_{sabc})dt$$

A vector control scheme orientated to stator flux linkage space vector:

Case 1: DFIG control

Numerical Example:

A 690 V, 2 MW DFIG generator have the following per unit parameters (based on 690 V, 2 MVA). The 4-pole generator operates ±30% around the synchronous speed and reaches the 2 MW stator power at the maximum speed.

stator resistance: R_s=0.09841 p.u.
stator leakage inductance: L_{ls}=0.1248 p.u.
rotor resistance: R_r=0.00549 p.u.
rotor leakage inductance: L_{lr}=0.09955 p.u.
magnetizing inductance: L_m=3.9527 p.u.

Determine the following quantities for the DFIG at the maximum speed.

(i) stator power,
(ii) rotor power, and
(iii) total generator power.

Solution:

Stator power: P_s=2 MW, the continuous power rating depends on voltage and current ratings of the stator winding

Rotor power: P_r=0.3x2 MW=0.6 MW, out from rotor at super-synchronous speed

Total power: P_t=2 MW+0.6 MW = 2.6 MW

Case 1: DFIG control

Provision of magnetising current:

Base impedance: $Z_b = (690\ \text{V})^2 / 2\ \text{MVA} = 0.238\ \text{ohm}$

Magnetising reactance: $X_m = 3.9527\ \text{pu} \times 0.238\ \text{ohm} = 0.94\ \text{ohm}$, per phase

Magnetising current: $I_m = (690\ \text{V}/\sqrt{3})/0.94\ \text{ohm} = 424\ \text{A}$

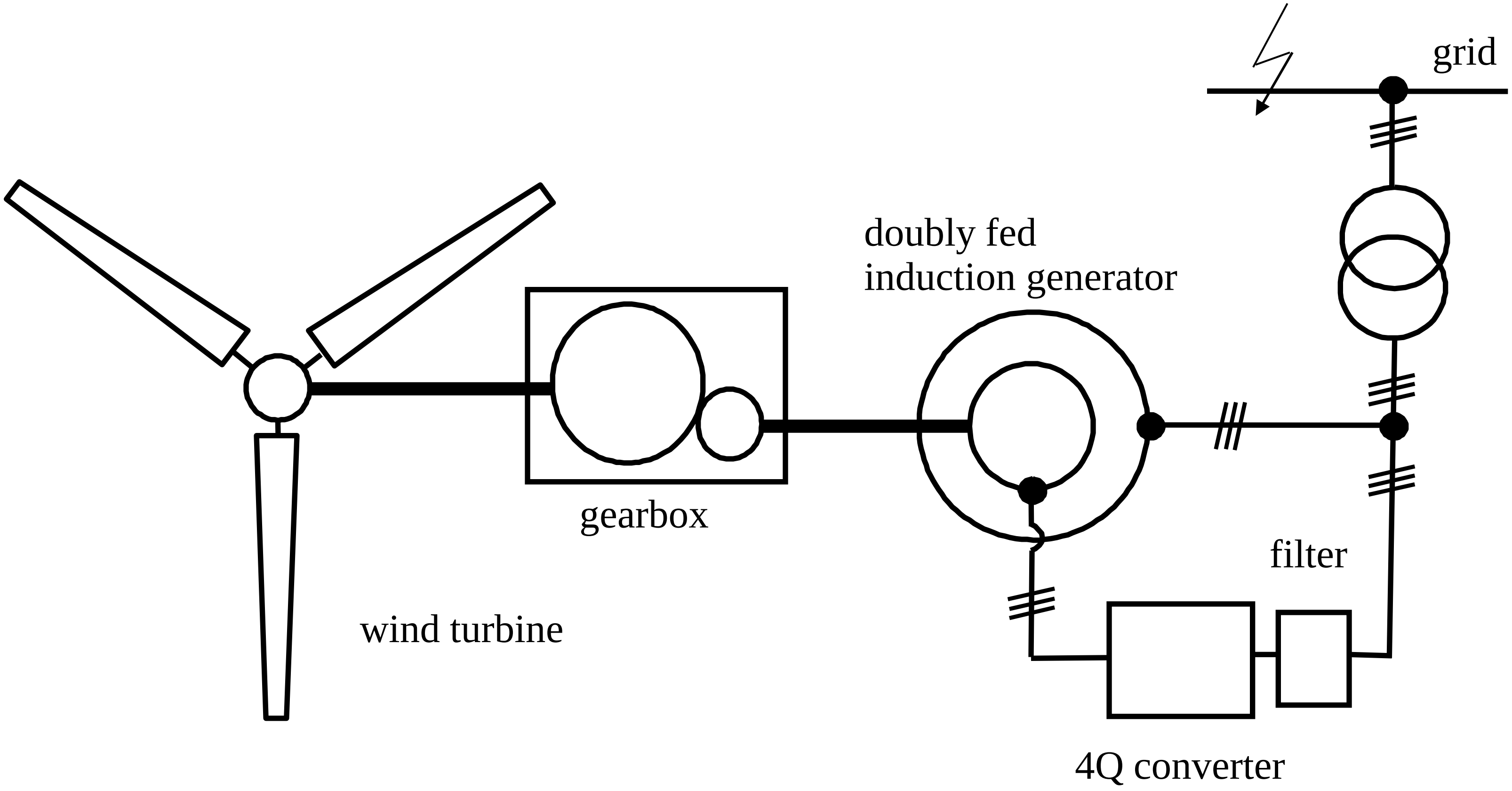
Compare to rated stator current:

$I = 2\ \text{MW}/(\sqrt{3} \times 690\ \text{V}) = 1673\ \text{A}$

The magnetising current is not insignificant!

- Should this be provided from stator or rotor side?
- How to provide reactive power control?

Case 1: DFIG control



Grid fault (low voltage) ride-through (LVRT) challenge:

- rotor initially cut flux at slip speed (maximum 30% of synchronous speed).
- at grid fault, some flux components stop rotating or reverse direction, cutting rotor windings at much higher speed and causing over voltage and current. This is again to read Faraday's law backwards.

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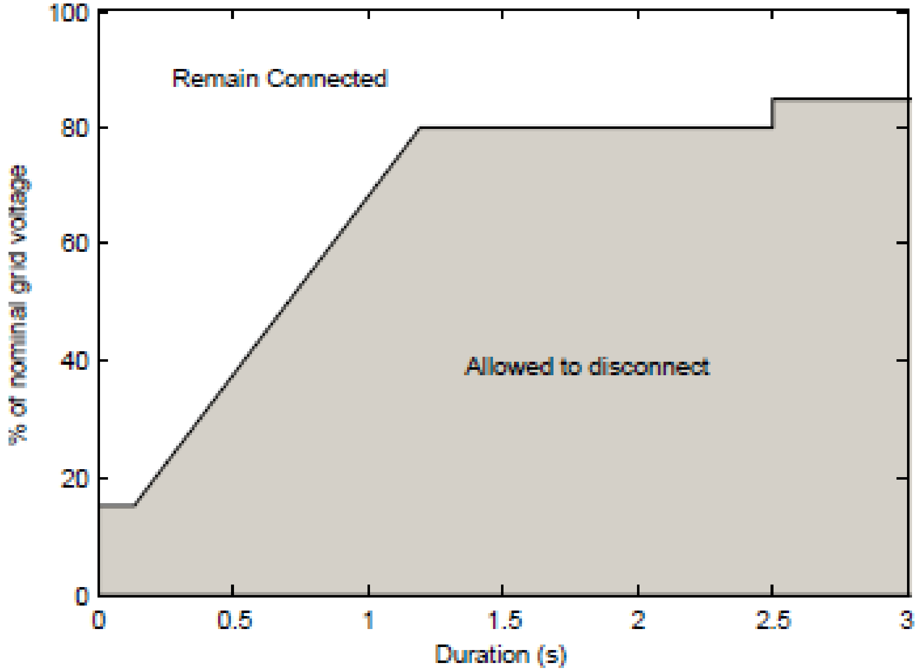
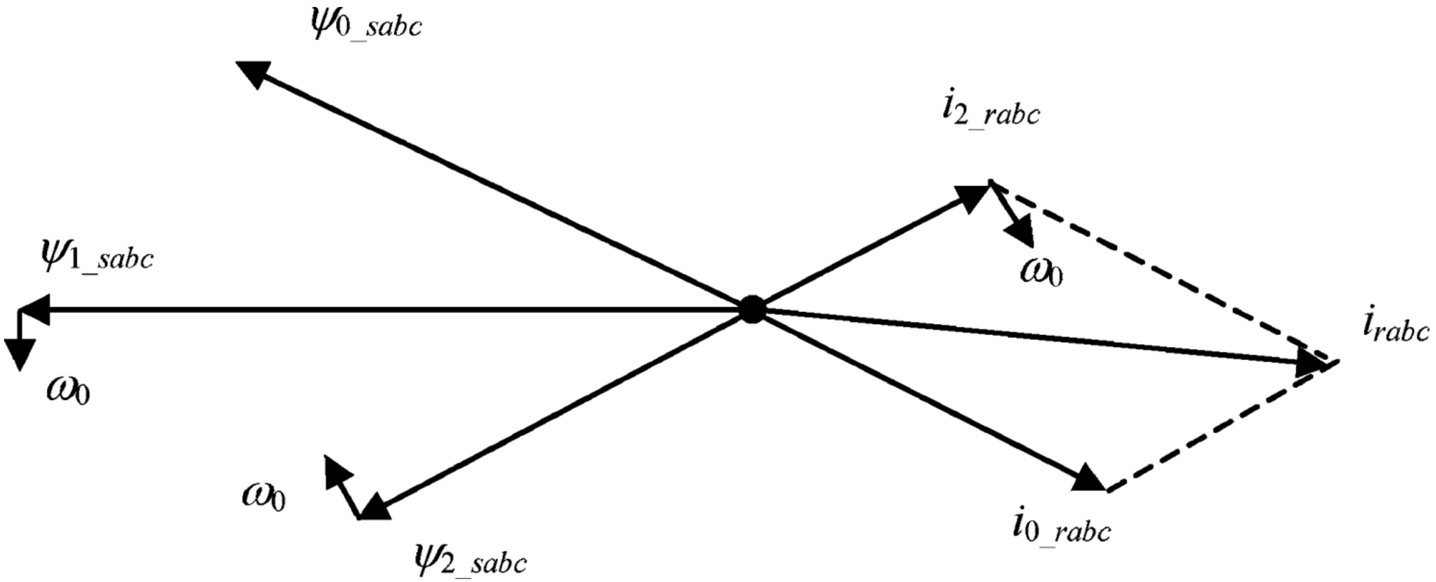
Case 1: DFIG control



Why grid fault ride-through requirement in Grid Code?

- this is necessary as wind power represents a significant portion of generation.
- some companies and countries are considering ‘storm ride-through’.

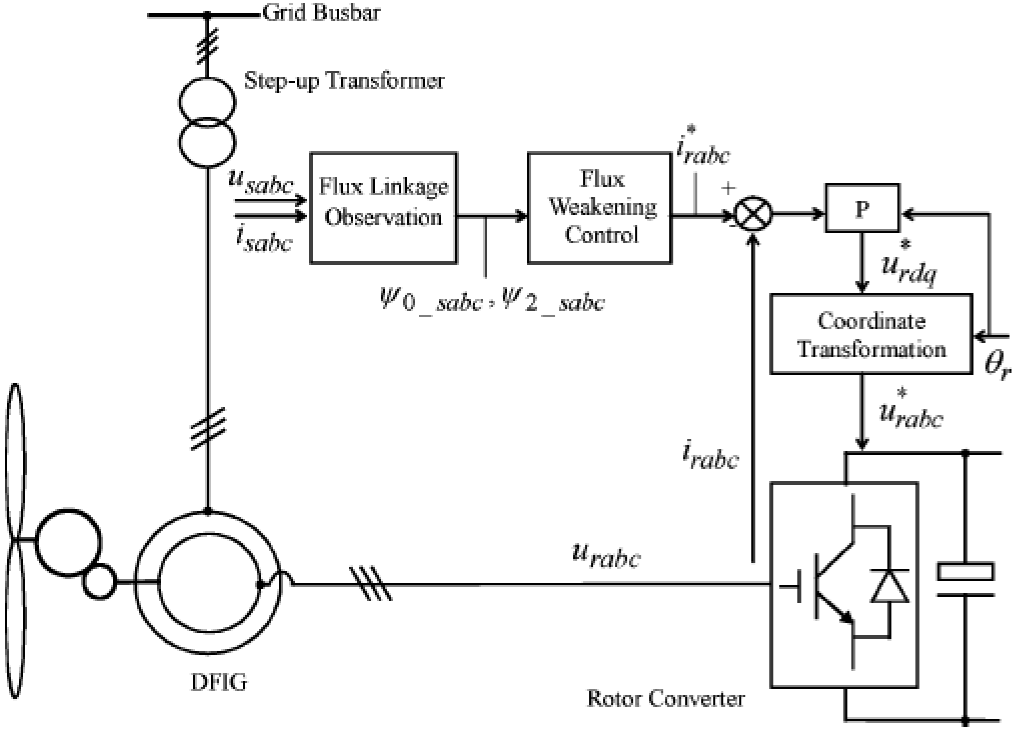
Case 1: DFIG LVRT control



A control scheme by Dawei Xiang in his PhD work at Durham:

- rotor current is controlled to counteract the undesired flux components.
- this is similar to flux suppression control in a synchronous machine.

Case 1: DFIG LVRT control

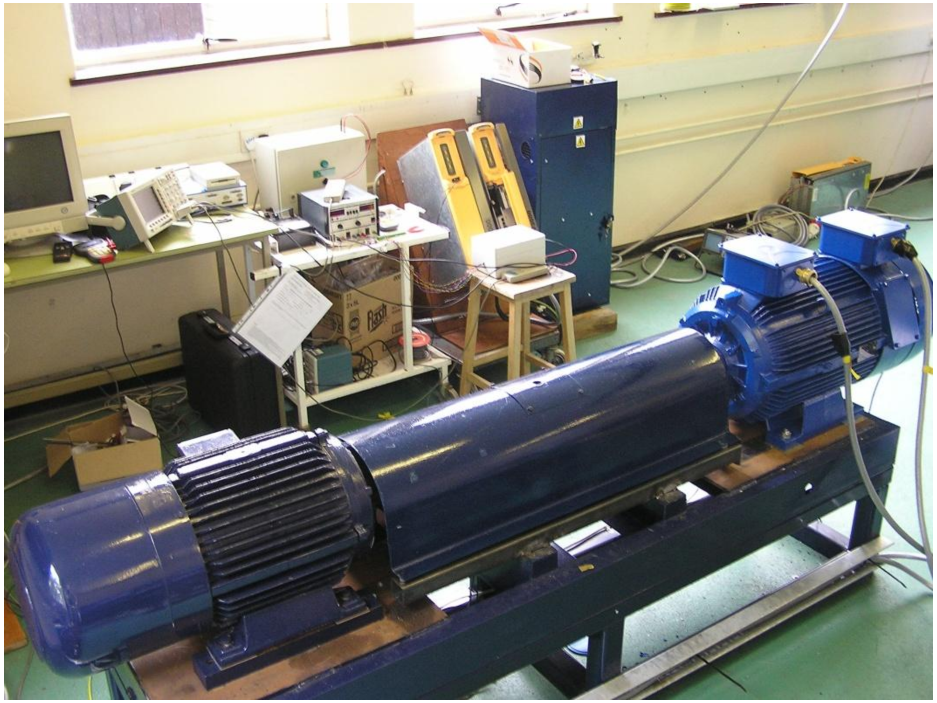


The implemented control scheme:

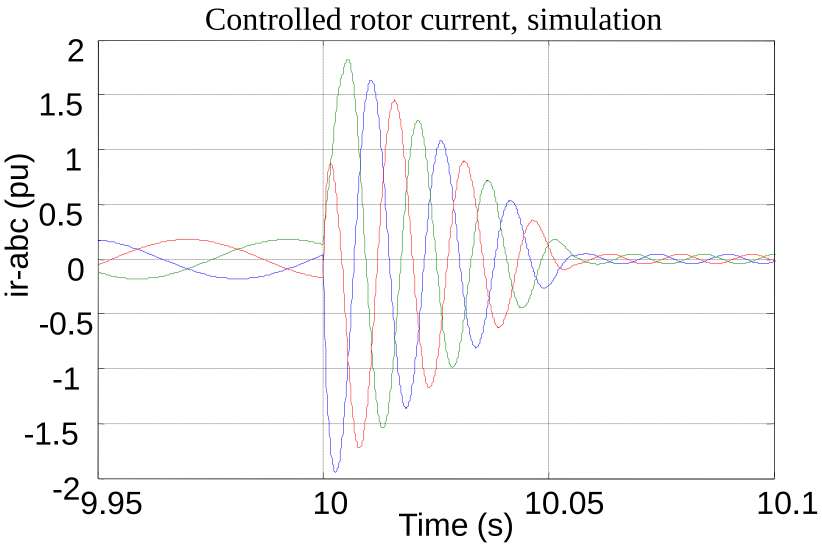
- current control actions are derived in a rotating reference frame, in which 3 -phase sine wave are turned into dc in the steady state.
- the change of rotor position has to be taken into account.

Case 1: DFIG LVRT control

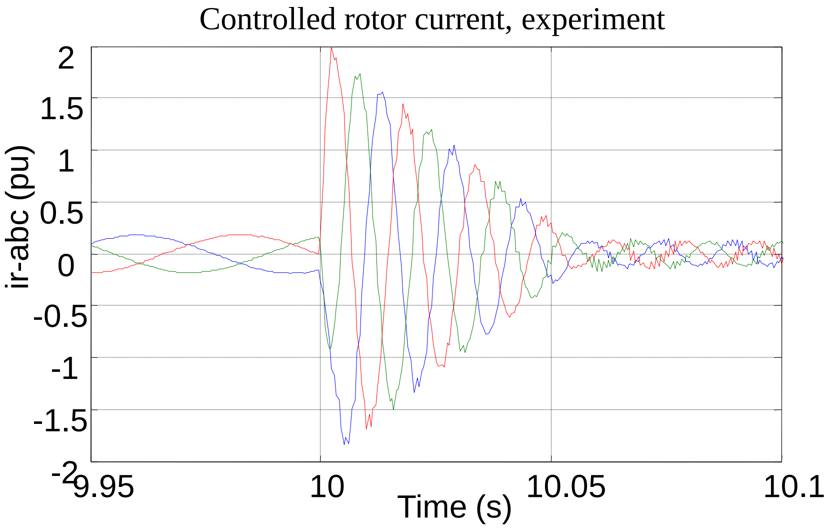
Grid fault ride-through by DFIG – test rig



Experiment verifies the control method and the simulation model which is then used to predict the behaviour of full scale turbines.



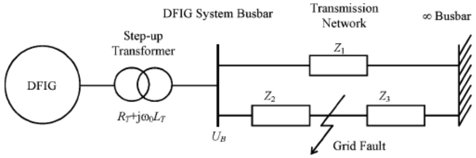
Controlled rotor current, simulation



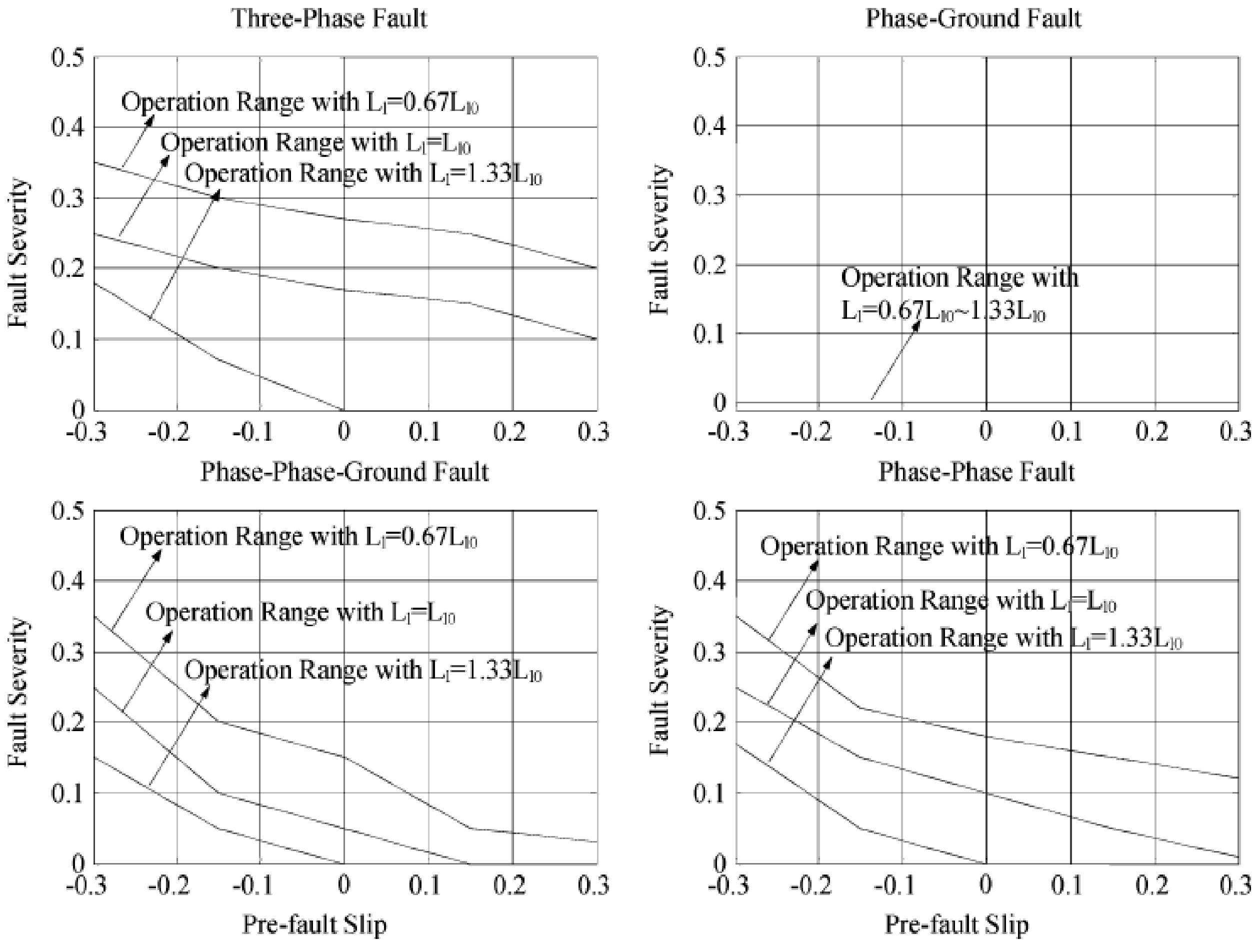
Controlled rotor current, experiment

Case 1: DFIG LVRT control

Definition of fault severity

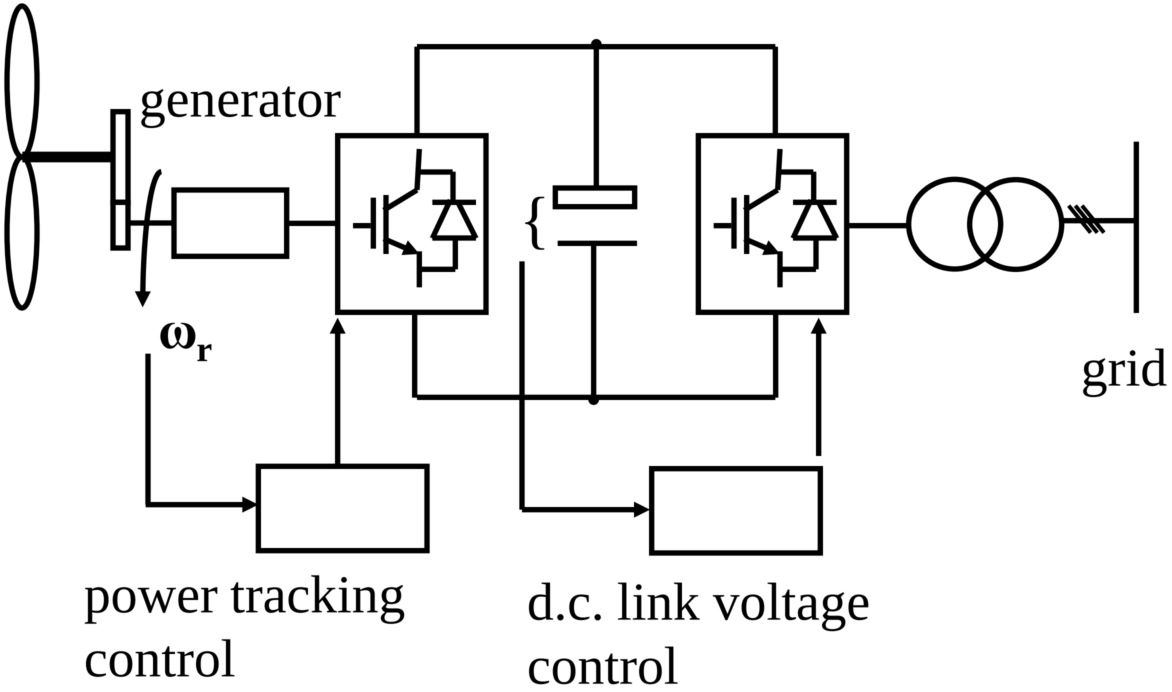


$$K_{\mathrm{f}} = \frac{Z_2}{Z_2 + Z_3}$$



Feasibility region for LVRT predicted by simulation

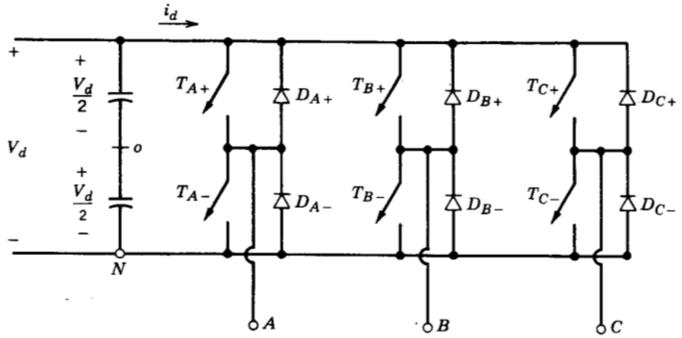
Case 2: Grid inverter control

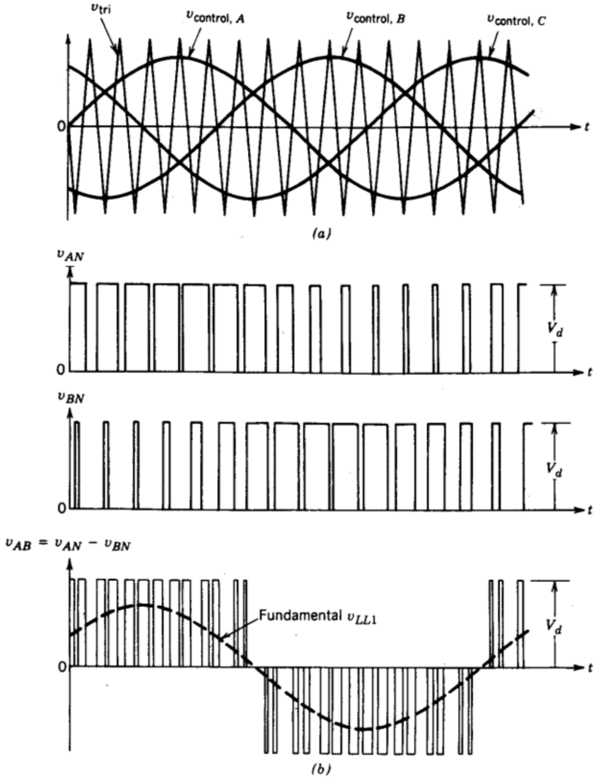


Grid fault ride-through challenge:

- unbalanced faults cause 2nd order harmonics on the d.c. side
- d.c. link capacitors are constrained in size by nacelle space

Case 2: Grid inverter control



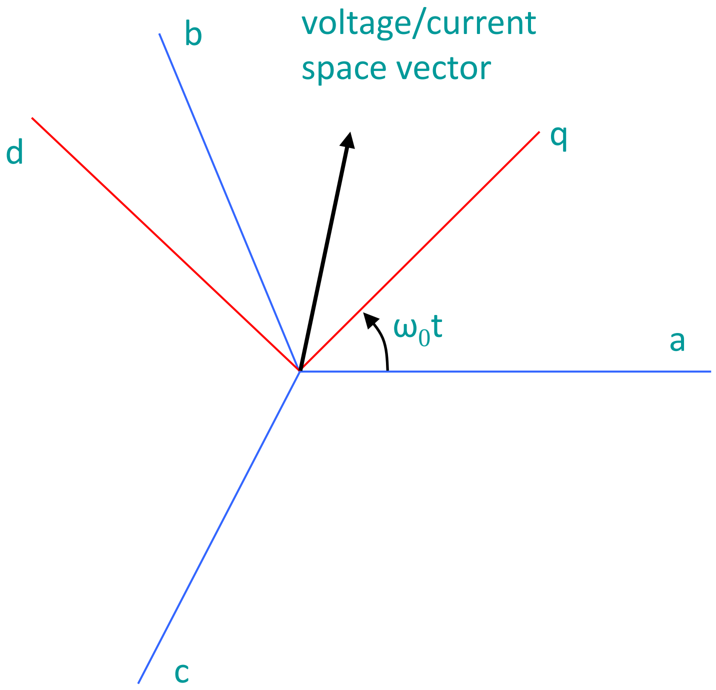


Configuration of a voltage source converter (VSC):

- each output phase (A, B, or C) can be connected to V_{dc}+ or V_{dc}- disregarding the phase current direction.
- a train of pulses with variable widths are produced to synthesize the desired sinusoidal voltage in each phase.
- the neg-sequence impedance of a VSC is virtually zero.

Case 2: Grid inverter control

Definition of reference frames



where

ω_0 - angular speed of dq reference frame with respect to stationary abc reference frame, usually corresponding to 50 or 60 Hz.

The use of coordinate transformation:

- 3-phase quantities can be expressed in space vectors
- quantities become d.c. in proper rotating reference frames

Case 2: Grid inverter control

Representations of 3φ inductor – time domain

$$v_a = L\frac{di_a}{dt} \quad v_b = L\frac{di_b}{dt} \quad v_c = L\frac{di_c}{dt}$$

or in space vectors $$v_{abc} = L\frac{di_{abc}}{dt}$$

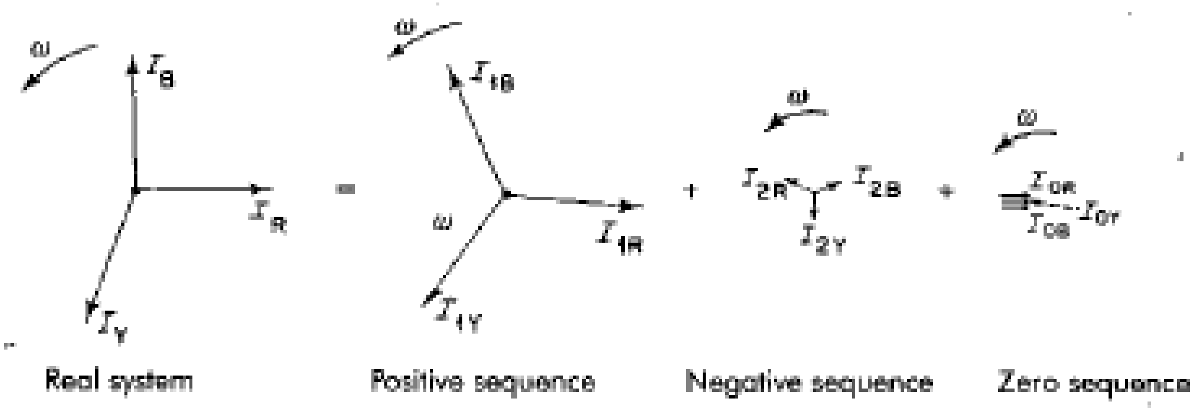
coordinate transformation 2→3:

$$v_{abc} = v_{dq}e^{j\omega_0 t} \quad i_{abc} = i_{dq}e^{j\omega_0 t}$$

$$v_d = \omega_0 L i_q + L\frac{di_d}{dt}$$

$$v_q = -\omega_0 L i_d + L\frac{di_q}{dt}$$

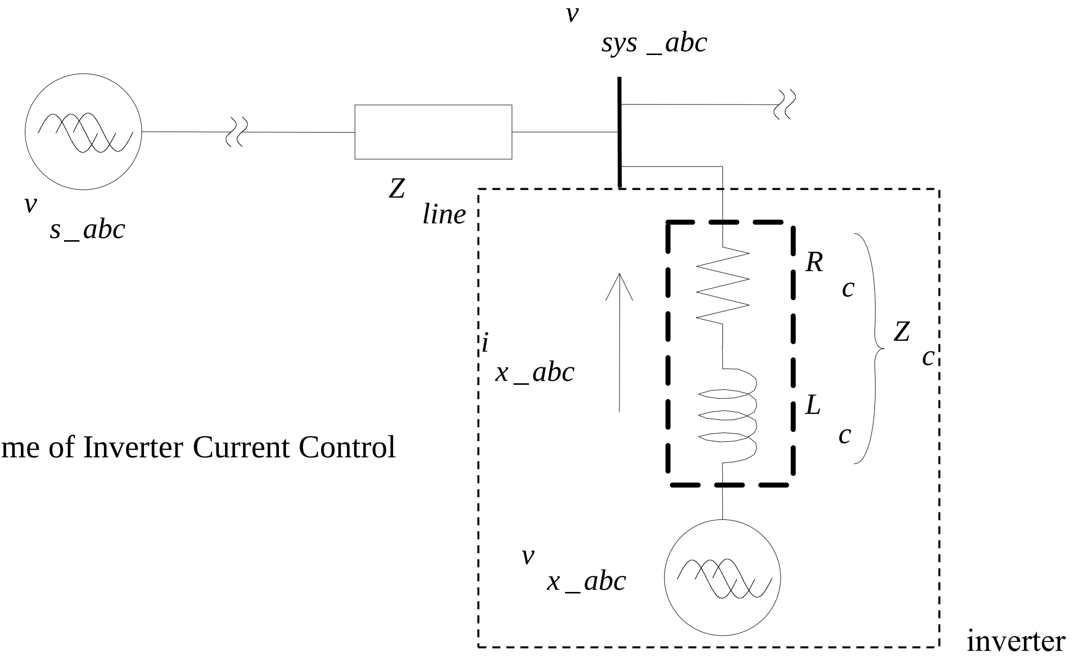
Case 2: Grid inverter control



The concept of symmetrical components:

- 3-phase quantities (of same frequency) can be considered as the sum of the +, - and 0 – sequence components.
- network analysis can be carried out for each sequence and the results are then superimposed.
- the concept can be extended to space vectors in reference frames rotating in opposite directions; 0-sequence is ignored.

Case 2: Grid inverter control



Scheme of Inverter Current Control

Positive sequence

$$\begin{aligned} v_{x\_dq0}(t) &= v_{sys\_dq0}(t) \\ &+ PI\left[i_{ref\_dq0}(t) - i_{x\_dq0}(t)\right] \\ &+ PI\left\{\begin{matrix} -\omega L_c\left[i_{ref\_q}(t) - i_{x\_q}(t)\right] \\ \omega L_c\left[i_{ref\_d}(t) - i_{x\_d}(t)\right] \\ 0 \end{matrix}\right\} \end{aligned}$$

Negative sequence

$$\begin{aligned} v^{n}_{x\_dq0}(t) &= v^{n}_{sys\_dq0}(t) \\ &+ PI^{n}\left[i^{n}_{ref\_dq0}(t) - i^{n}_{x\_dq0}(t)\right] \\ &+ PI^{n}\left\{\begin{matrix} \omega L_c\left[i^{n}_{ref\_q}(t) - i^{n}_{x\_q}(t)\right] \\ -\omega L_c\left[i^{n}_{ref\_d}(t) - i^{n}_{x\_d}(t)\right] \\ 0 \end{matrix}\right\} \end{aligned}$$

Case 2: Grid inverter control

Scheme of Inverter Current Control

Control objective

$$P^{total} = \frac{3}{2}\left(v_d i_d + v_q i_q + v_d^n i_d^n + v_q^n i_q^n\right) = P_{ref}$$

$$Q^{total} = \frac{3}{2}\left(v_d i_q - v_q i_d + v_d^n i_q^n - v_q^n i_d^n\right) = 0$$

$$P^{2nd} = \frac{3}{2}\left(v_d^n i_d + v_q^n i_q + v_d i_d^n + v_q i_d^n\right) = 0$$

$$Q^{2nd} = \frac{3}{2}\left(v_d^n i_q - v_q^n i_d - v_d i_q^n + v_q i_d^n\right) = 0$$

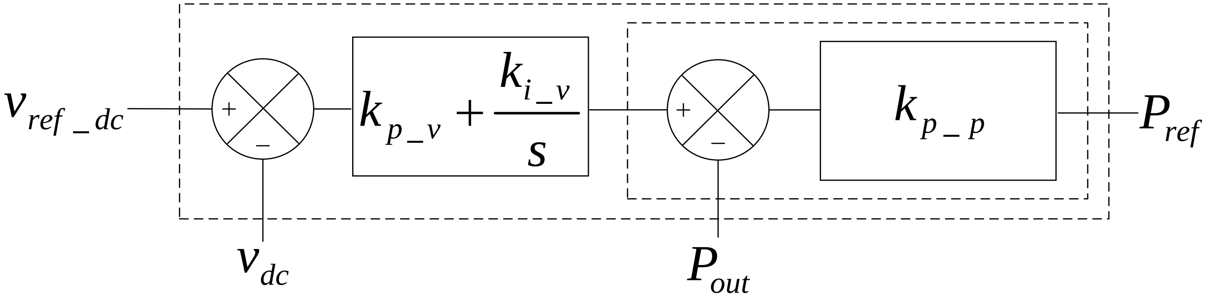
Equation (13)

$$\mathrm{i}_{\mathrm{ref\_d}} = \frac{2}{3}\mathrm{P}_{\mathrm{ref}} \frac{\mathrm{v}_{\mathrm{sys\_d}}}{(\mathrm{v}_{\mathrm{sys\_d}}{}^2 + \mathrm{v}_{\mathrm{sys\_q}}{}^2) + (\mathrm{v}^{\mathrm{n}}_{\mathrm{sys\_d}}{}^2 + \mathrm{v}^{\mathrm{n}}_{\mathrm{sys\_q}}{}^2)}$$

$$\mathrm{i}_{\mathrm{ref\_q}} = \frac{2}{3}\mathrm{P}_{\mathrm{ref}} \frac{\mathrm{v}_{\mathrm{sys\_q}}}{(\mathrm{v}_{\mathrm{sys\_d}}{}^2 + \mathrm{v}_{\mathrm{sys\_q}}{}^2) + (\mathrm{v}^{\mathrm{n}}_{\mathrm{sys\_d}}{}^2 + \mathrm{v}^{\mathrm{n}}_{\mathrm{sys\_q}}{}^2)}$$

$$\mathrm{i}^{\mathrm{n}}_{\mathrm{ref\_d}} = -\frac{2}{3}\mathrm{P}_{\mathrm{ref}} \frac{\mathrm{v}^{\mathrm{n}}_{\mathrm{sys\_d}}}{(\mathrm{v}_{\mathrm{sys\_d}}{}^2 + \mathrm{v}_{\mathrm{sys\_q}}{}^2) - (\mathrm{v}^{\mathrm{n}}_{\mathrm{sys\_d}}{}^2 + \mathrm{v}^{\mathrm{n}}_{\mathrm{sys\_q}}{}^2)}$$

$$\mathrm{i}^{\mathrm{n}}_{\mathrm{ref\_q}} = -\frac{2}{3}\mathrm{P}_{\mathrm{ref}} \frac{\mathrm{v}^{\mathrm{n}}_{\mathrm{sys\_q}}}{(\mathrm{v}_{\mathrm{sys\_d}}{}^2 + \mathrm{v}_{\mathrm{sys\_q}}{}^2) - (\mathrm{v}^{\mathrm{n}}_{\mathrm{sys\_d}}{}^2 + \mathrm{v}^{\mathrm{n}}_{\mathrm{sys\_q}}{}^2)}$$



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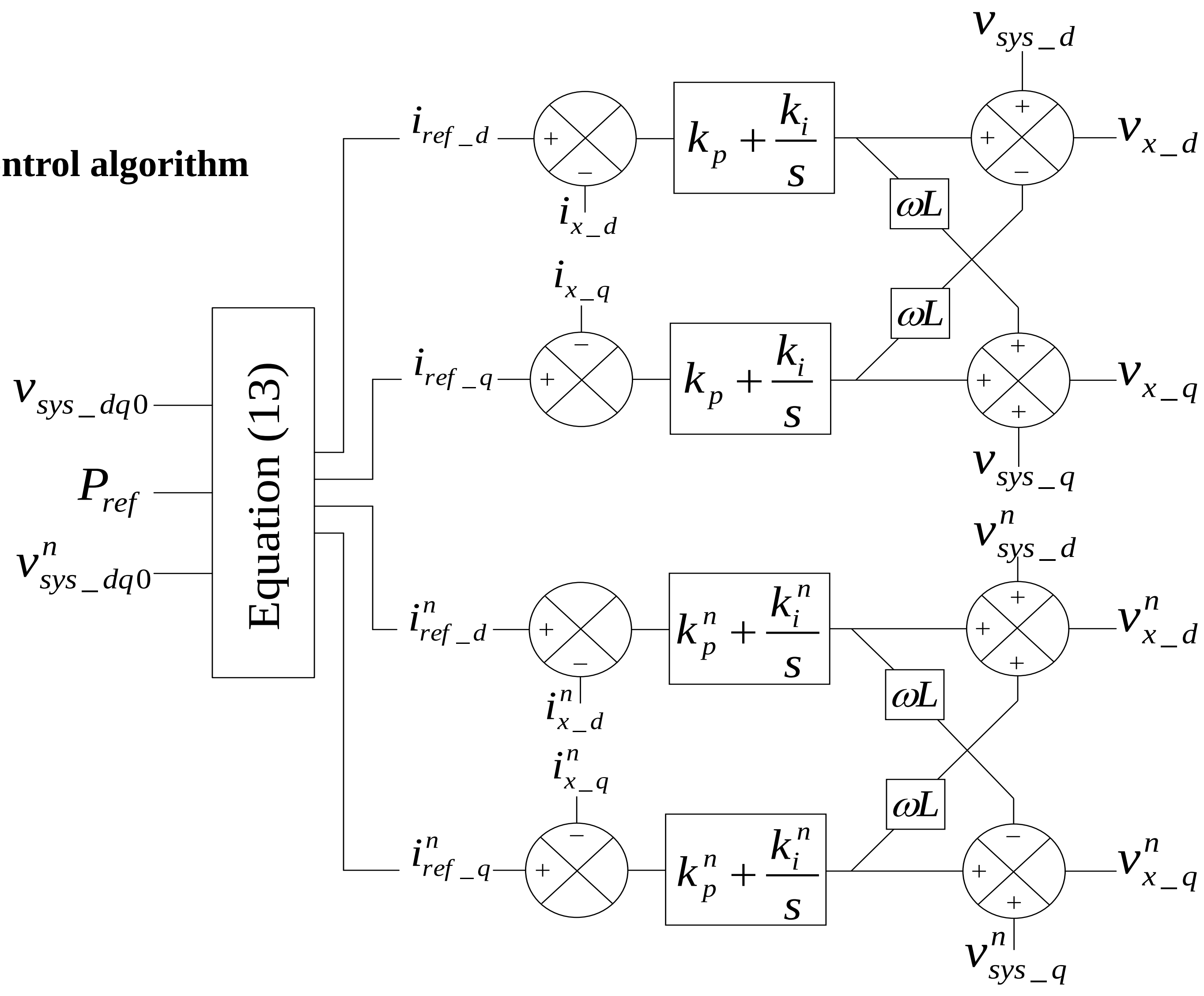
Case 2: Grid inverter control

Current control algorithm



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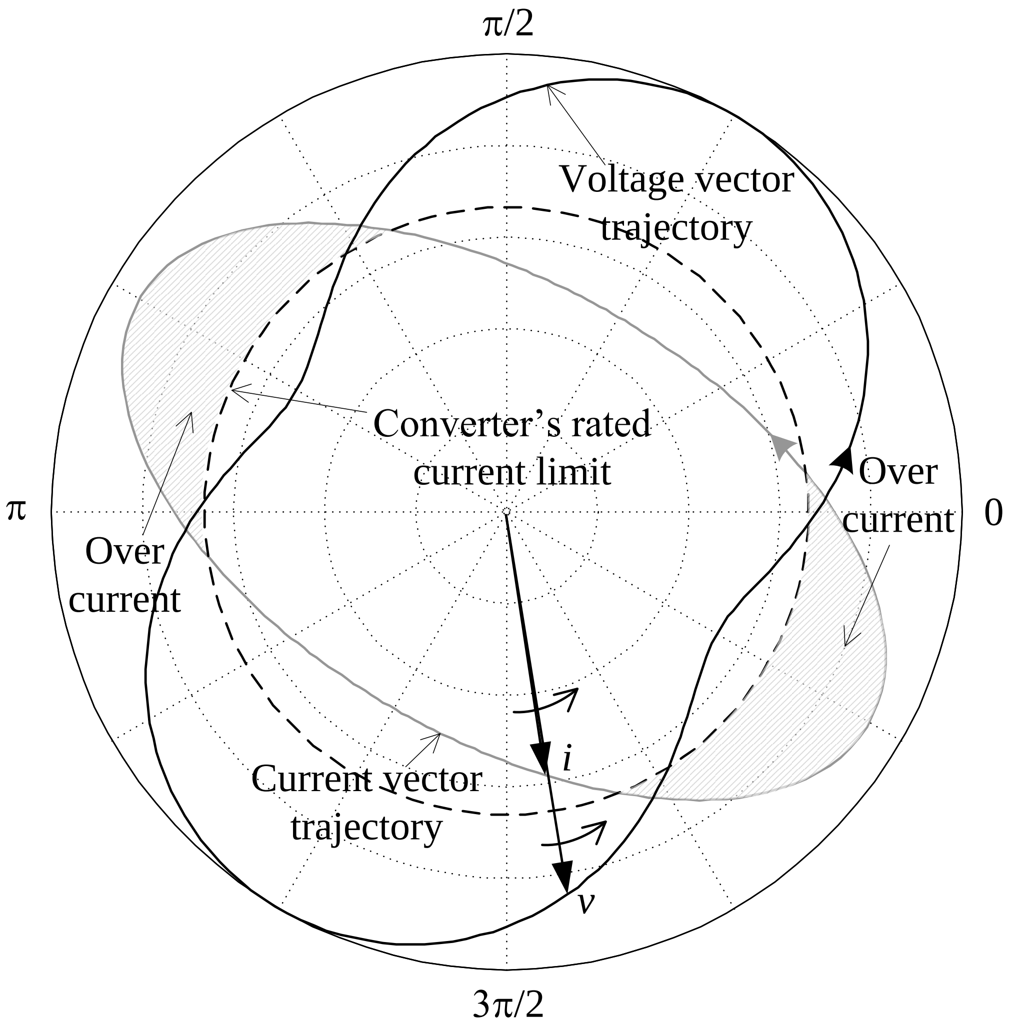
Case 2: Grid inverter LVRT control

Inverter o/p voltage and current trajectories during unbalanced grid fault



Maximum inverter current

$$I_{max} = \frac{P_{inv}}{3/2(|V^p| - |V^n|)}$$

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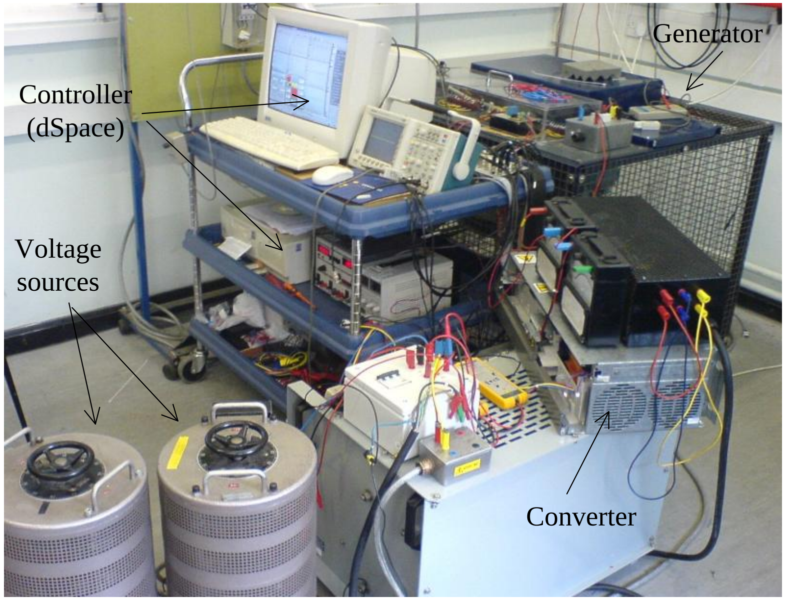
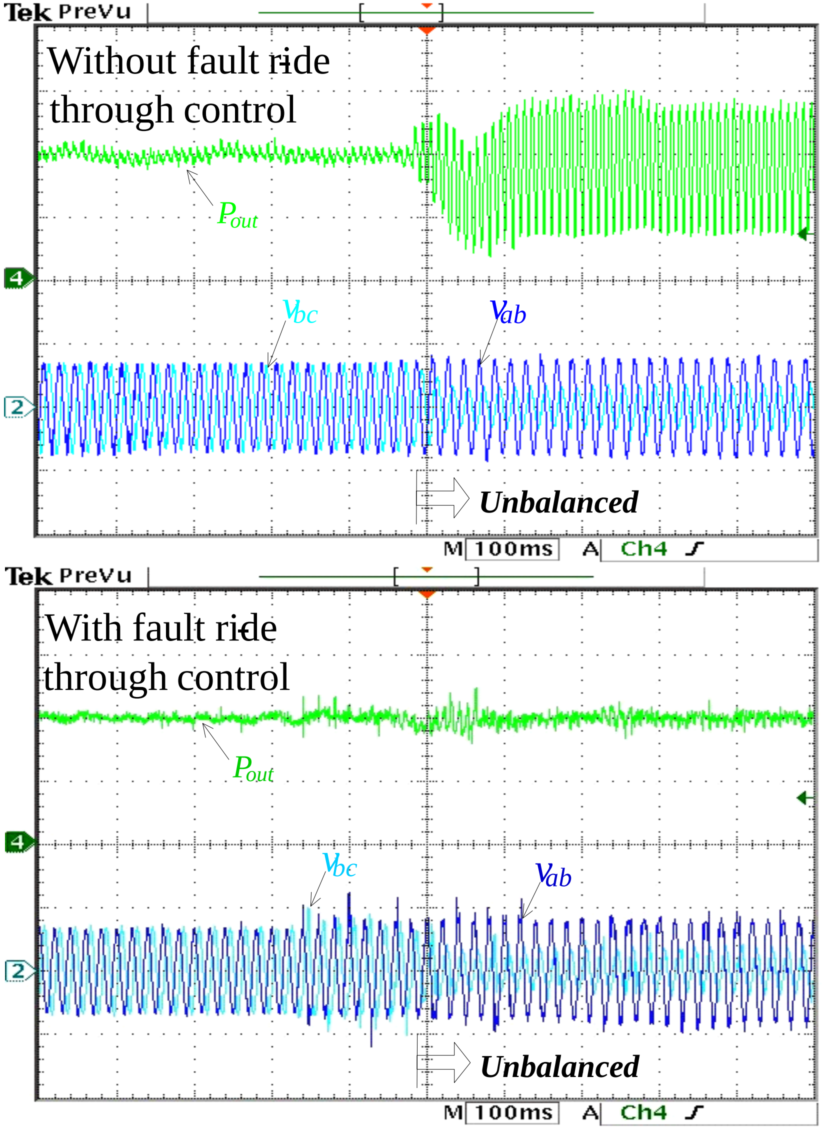
Case 2: Grid Inverter control



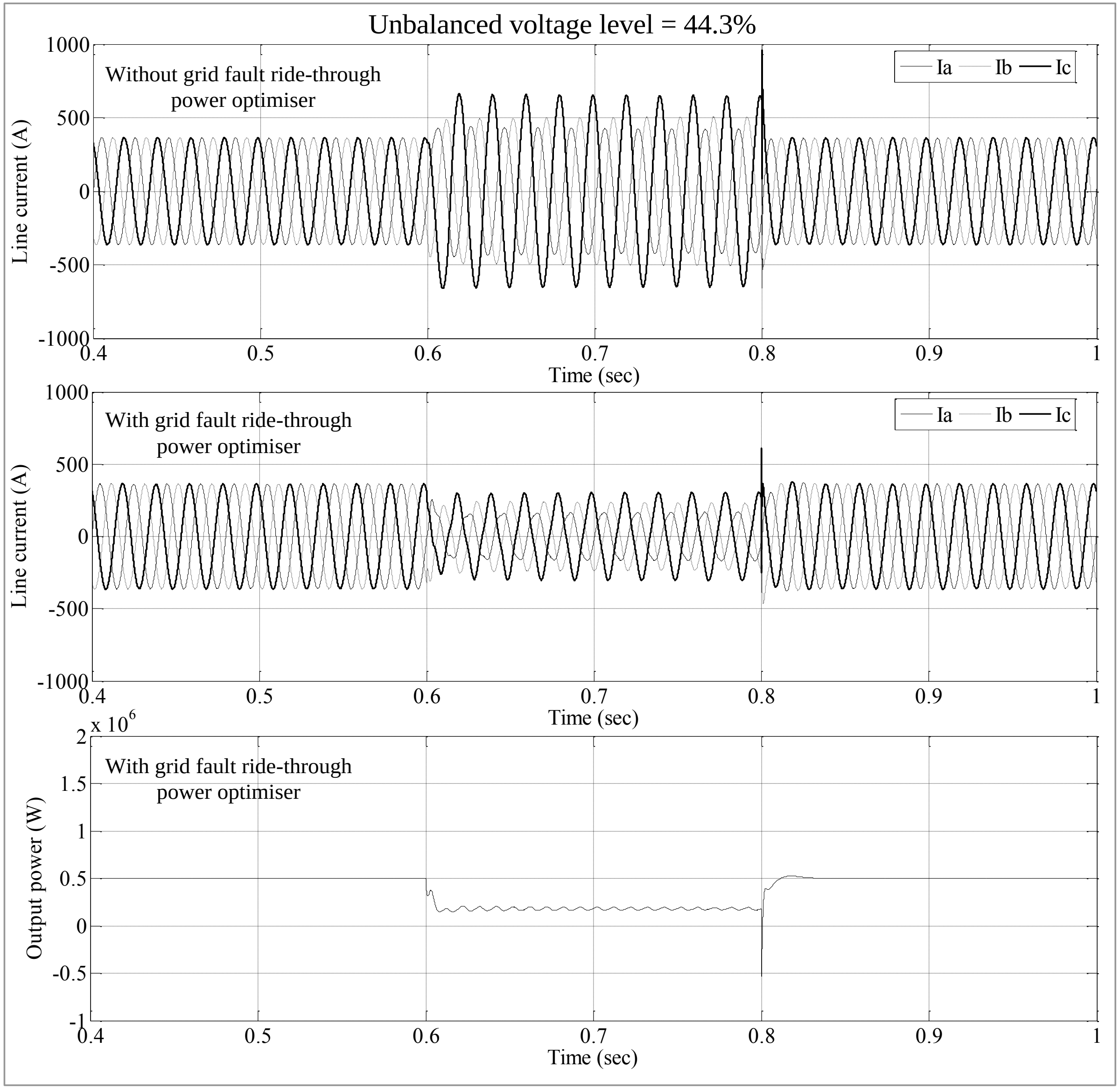
Inverter grid fault ride-through control

Ch1 – V_{ab} (25 V/div) @ t = 10 ms/div
Ch2 – V_{bc} (25 V/div) @ t = 10 ms/div
Ch4 – P_{out} (50 W/div) @ t = 10 ms/div



Case 2: Grid Inverter control

Simulation result with current limit



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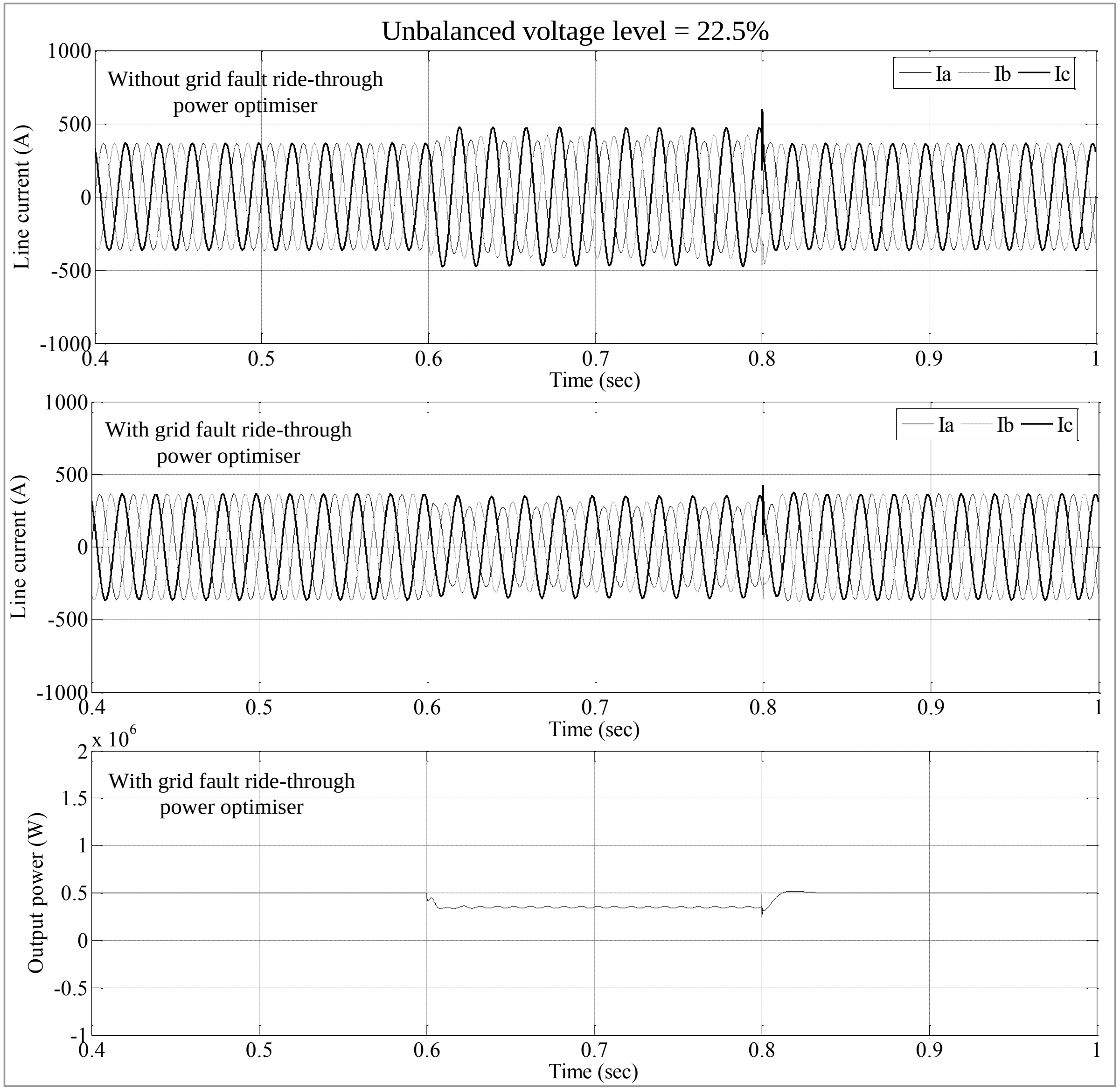
Case 2: Grid Inverter LVRT control

Simulation result with current limit



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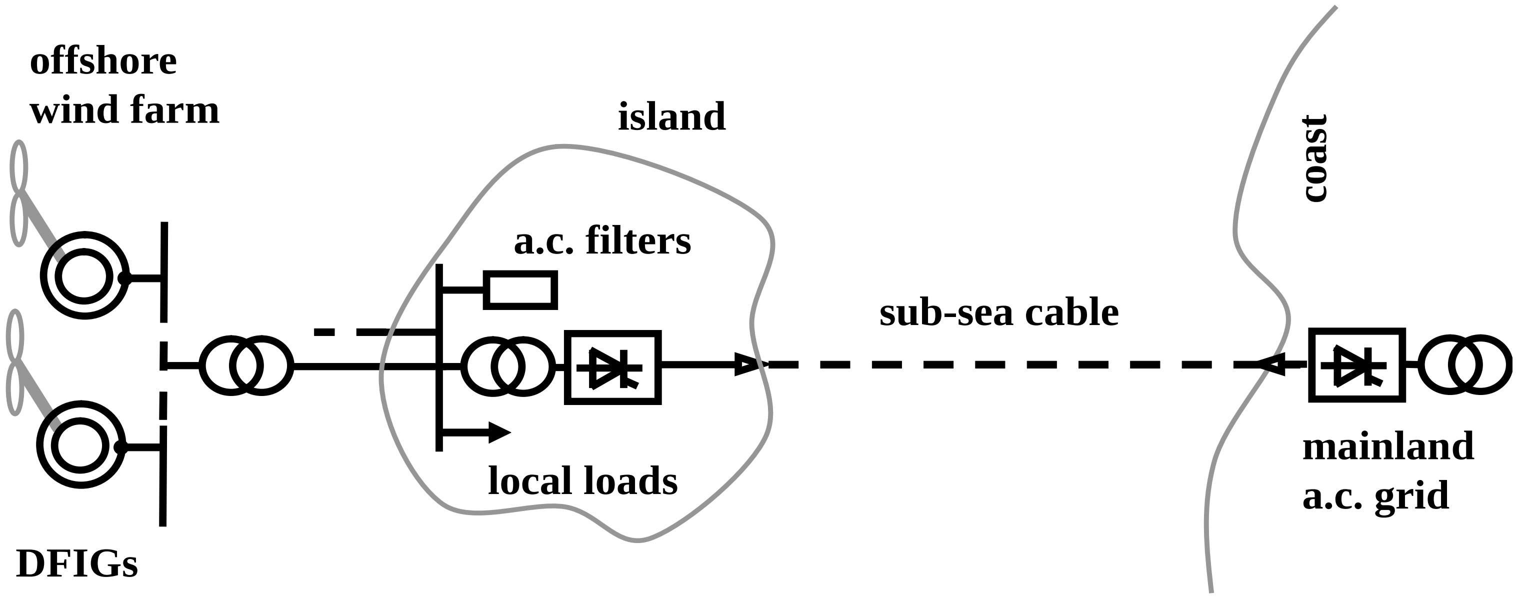
Case 3: DFIG with LCC HVDC



- planned offshore wind farm: 1000 MW, ~100 km offshore
- HVDC can not define an a.c. voltage source for the stator side of DFIG.
- solution: DFIG control is for power tracking; HVDC is responsible for local voltage and frequency control: $V/\omega = \psi$

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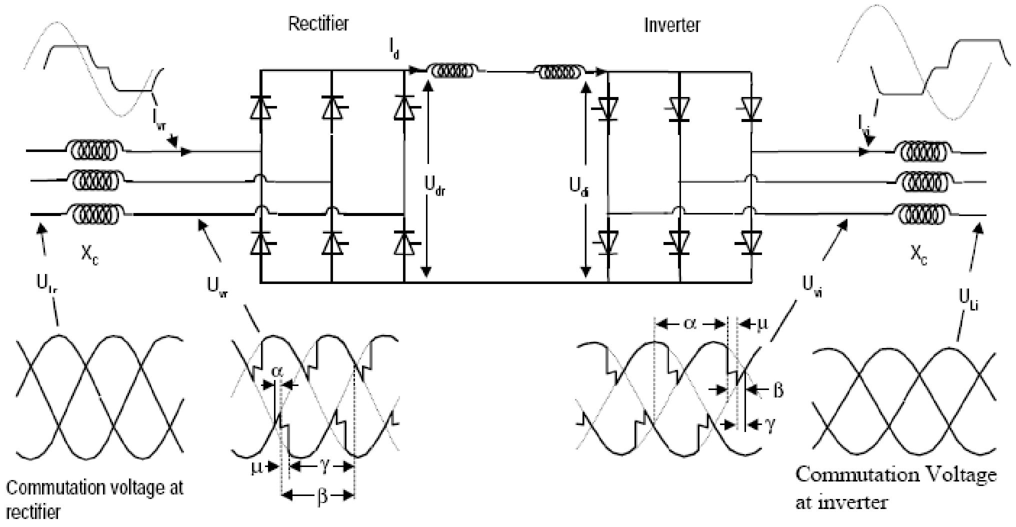
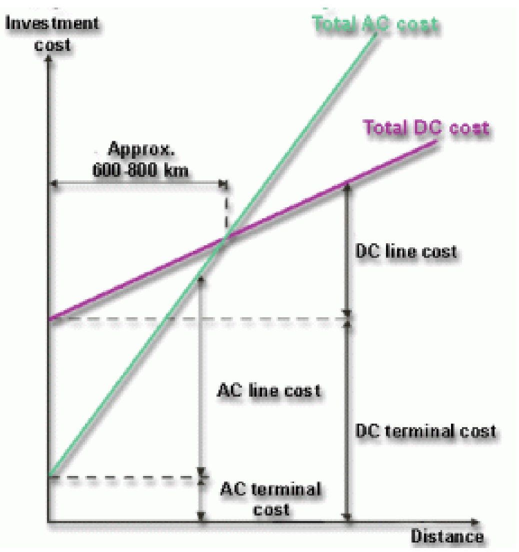
Case 3: DFIG with LCC HVDC





Why HVDC?

- the concept of break even distance
- charging reactive power of 400 kV a.c. cable transmission (data from Weedy):

charging current 23.86 A/km

charging reactive power for 50 km cable

$\sqrt{3}$x400 kVx(23.86 Ax50) = 826.5 MVAr

rated current 1600 A

rated capacity $\sqrt{3}$x400 kVx1600 A = 1108.48 MVA

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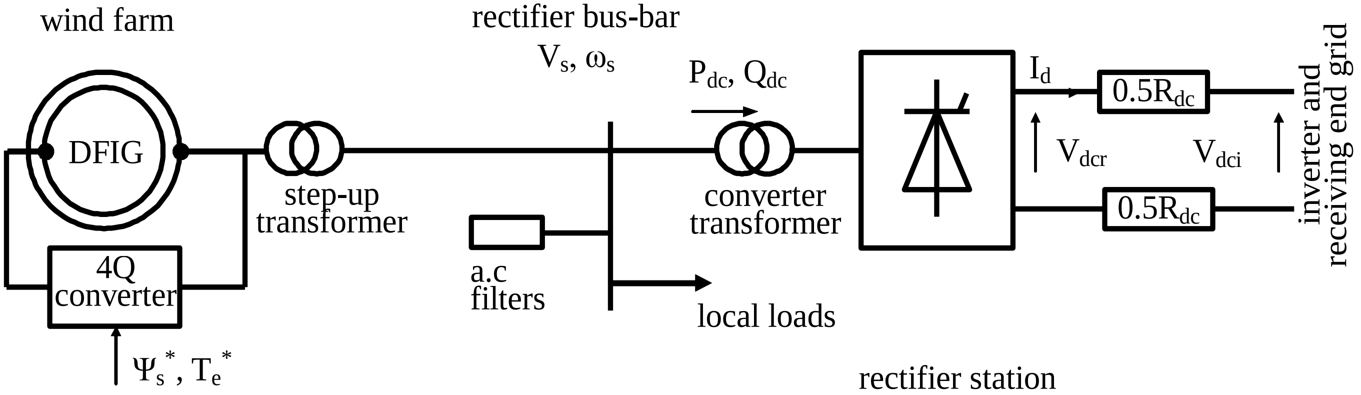
Case 3: DFIG with LCC HVDC

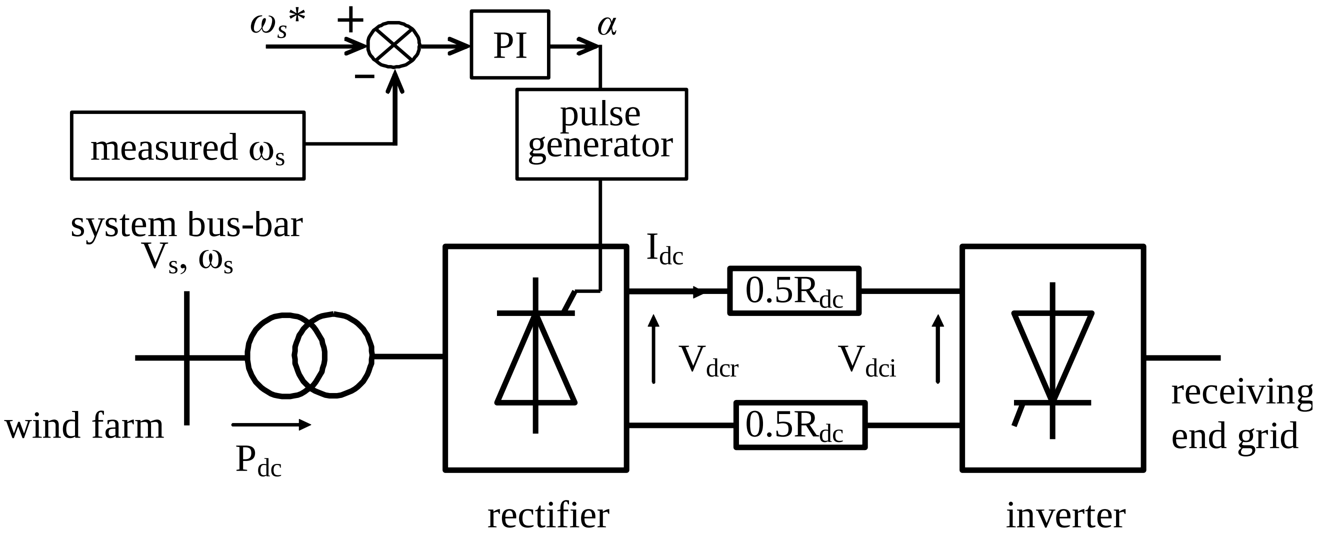


Machine characteristic: $V = \sqrt{3}\psi_s\, \omega_s$

HVDC (12 pulse) characteristic: $V_{dcr} = 2 \times 1.35 V_s \cos\alpha - 2R_c \cdot I_{dc}$

V_{dcr} is determined by the amount of power to deliver.

Case 3: DFIG with LCC HVDC



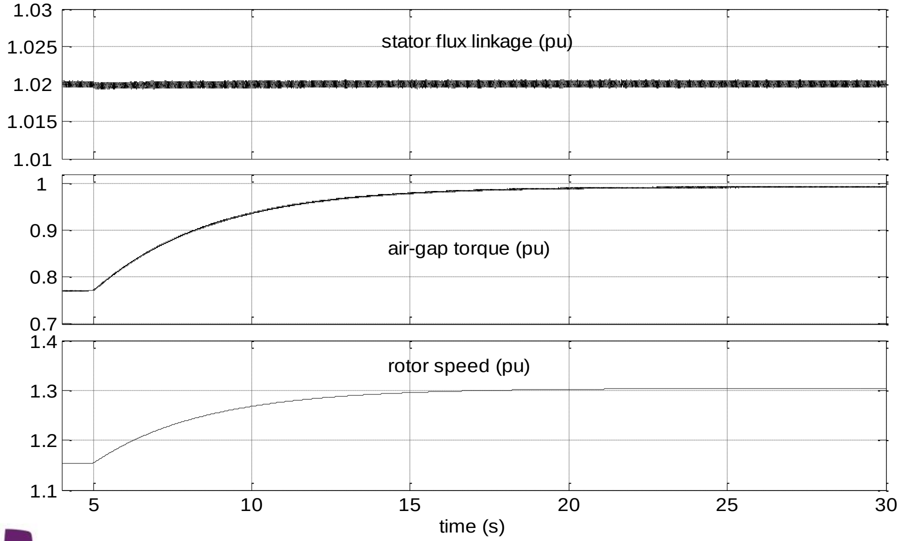
The firing delay angle of HVDC rectifier is adjusted to set the local frequency and voltage. By doing this, the HVDC will take away the generator power minus local load.

Case 3: DFIG with LCC HVDC

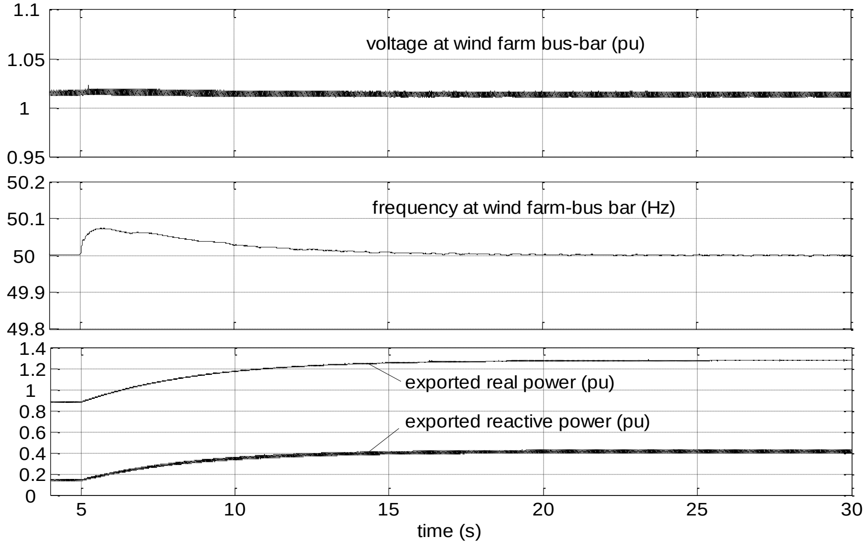
Response to a step change of wind speed from 11 m/s to 12 m/s.

For a 910 MW wind farm.
Base capacity: 770 MW.

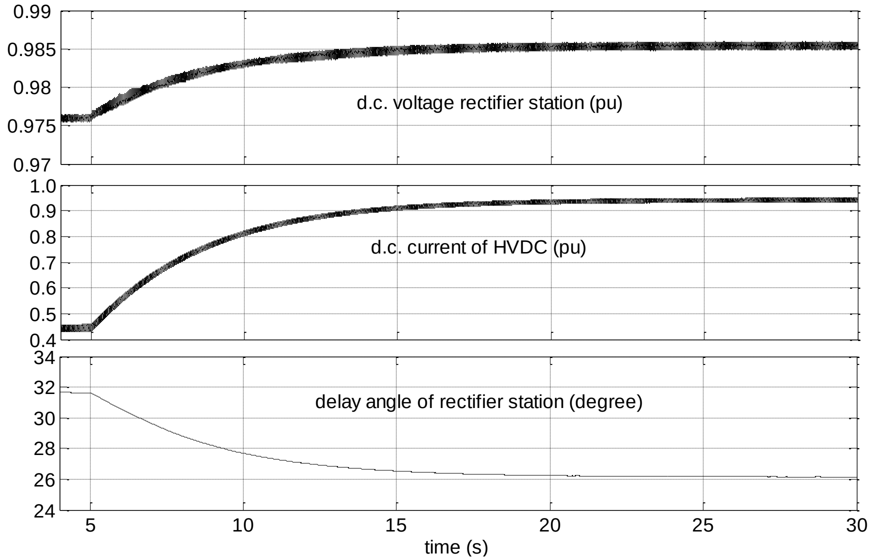
(a) DFIG variables



(b) wind farm variables



(c) HVDC variables



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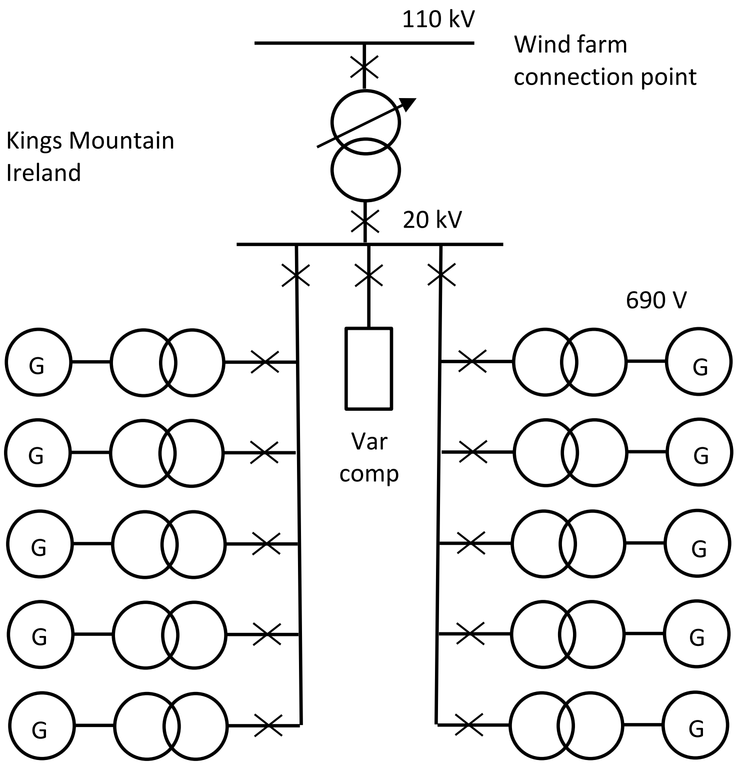
Terry's on-going work

Onshore Power Collection Scheme



- 10 x 2.6 MW DFIG turbines
- generator terminal voltage is 690 V, limited by the voltage rating of IGBTs
- voltage stepped up to 20 kV for cable connection to 110 kV substation
- maximum generator current: 2200 A down to 76 A
- turbine units are grouped to save cable runs

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Terry’s on-going work

Different in Offshore Wind Farms

- distance between turbines is usually greater due to larger wake effect.
- turbine unit is larger due to higher installation and supporting structure cost.
- there is very limited experience about offshore substations.

These lead to greater power transmitted over longer distances; a higher voltage level is needed as the collection voltage.

Horn Rev Offshore Substation

Terry’s on-going work

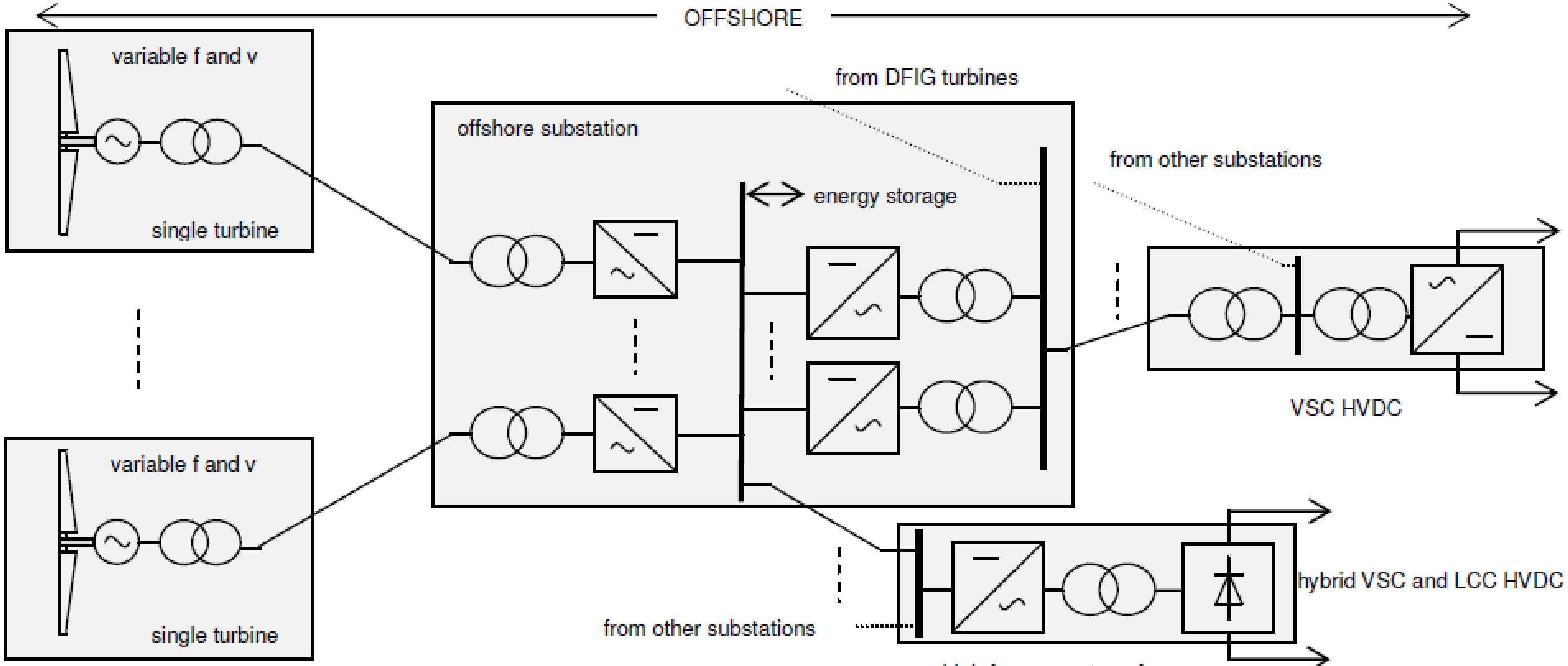

Figure 2

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Terry’s on-going work

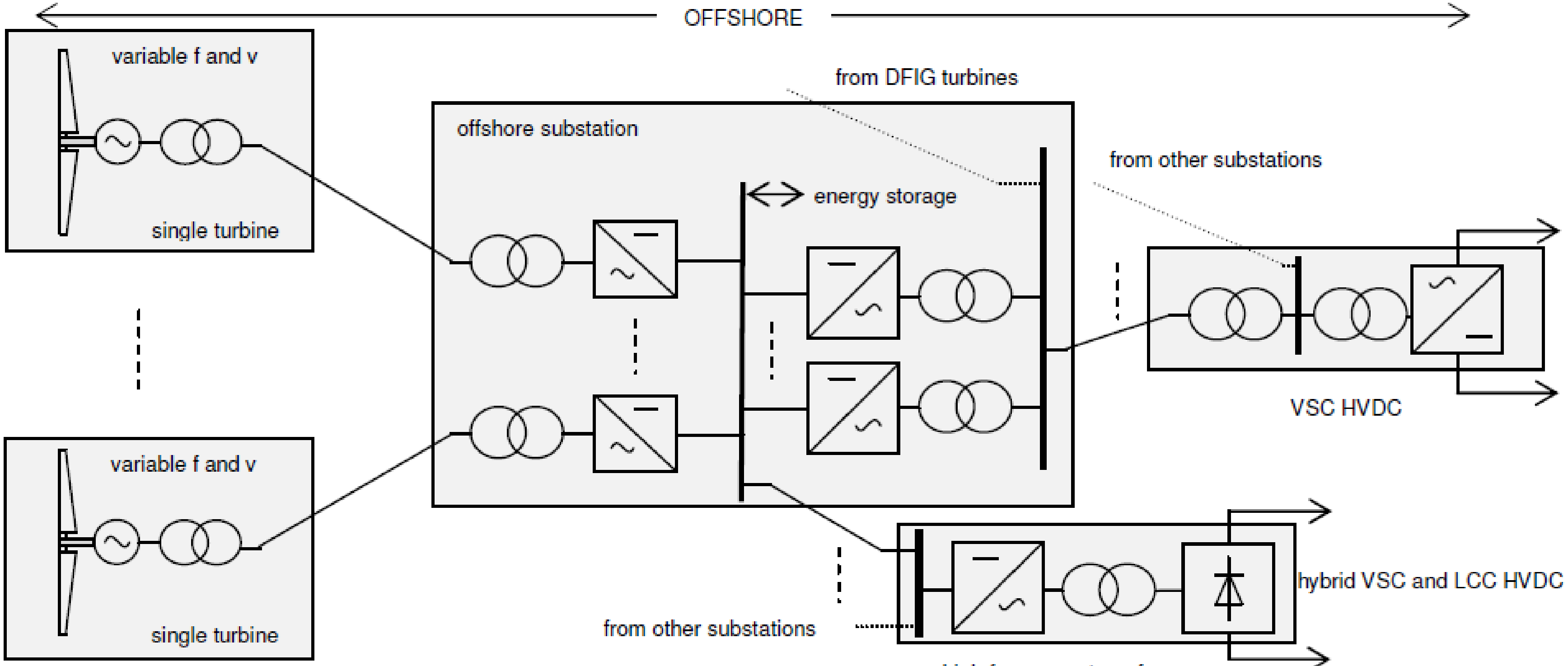

Figure 2

Thank you