Impact of Converter-based Technologies on Power System Stability: Challenges, Lessons Learnt and Recommendations.

Dharshana Muthumuni
Yousef Pipelzadeh
Wesley Mueller

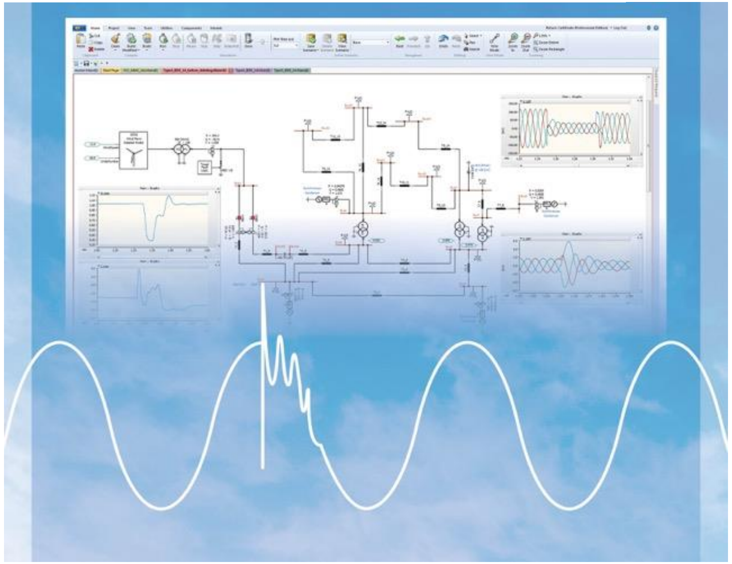
Abstract: The use of appropriate modelling tools can facilitate insights into the performance of low inertia (weaker) AC systems with high levels of renewable technologies, HVDC links and FACTs devices connected in close proximity. Phenomena's such as control interactions and sub-synchronous oscillations are a real challenge and a threat to power system stability and security. Phasor-based RMS simulation programme have key limitations to study weak grids with large penetration of renewables and HVDC links, and cannot accurately capture the transient interactions and events that could potentially lead to demand disconnection as recently experienced in the GB and Australian power system.
As part of lessons learnt from recent events in Australia, the electricity market operator AEMO, developed new and mandatory modelling requirements and guidelines for using Electromagnetic transient (EMT)-type simulation tools for studying large-scale power systems. Therefore, the entire Australian Power System has been developed in PSCAD to diagnose and reproduce the network response with high fidelity.

Manitoba Hydro International, as the developers of PSCAD™/EMTDC™ have provided consulting services, expert advice and in-depth training on electromagnetic transient (EMT) studies for over 40 years to utilities and manufacturers. This technical seminar highlights the importance of EMT modelling and demonstrates through real case studies the benefits of using EMT studies to address the challenges, lessons learnt and opportunities for accommodation of higher penetration and share of renewable energy in electricity grids.

Who we are

Manitoba Hydro International (MHI)

- Head Quarter in Canada and Technical Expert Presence in the UK
- Engineering Consulting
- Software development (PSCAD)



Outline

General Description of Challenges

- Inverter based interface to power systems
- EMT Studies – Background on EMT and RMS
- Connecting to weak grid locations
- Impact of transmission network characteristics

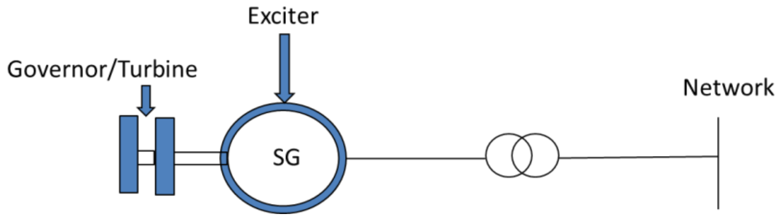
Brief Description of Selected Practical Cases (USA, UK and Australia)

- Control Interaction Issues
- Low frequency voltage oscillations
- Low inertia concerns - South Australian Blackout 2016
- Resonance issues and inverter response to network voltage and current transients
- Controls interactions and Torsional interaction (SSTI) concerns

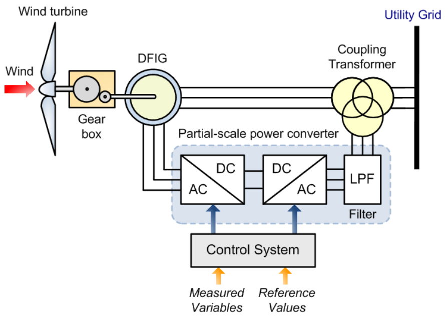
Wind Generators and influence of Transmission System Characteristics

- The characteristics of wind generators are much different from traditional synchronous machine based generation.
- Wind and PV generation is interfaced to the grid through power electronic devices
  - Fast control of P and Q
  - Natural ‘Inertia’ – not available from power electronic interfaced devices. Even with Type 3, the fast controls will regulate (maintain) the power to pre-set values.

- Nature of AC or HVDC transmission used to connect wind to the transmission grid (long ac cables, filters, weak grids, series compensation)

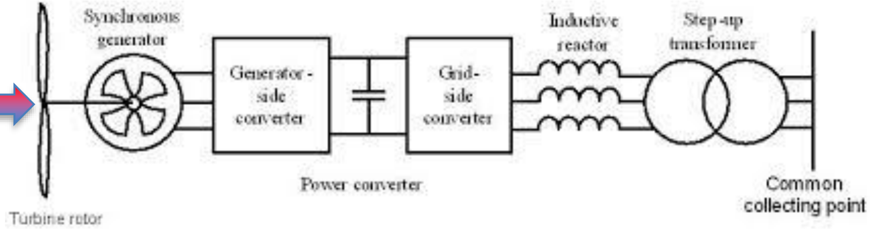


Synchronous generator based



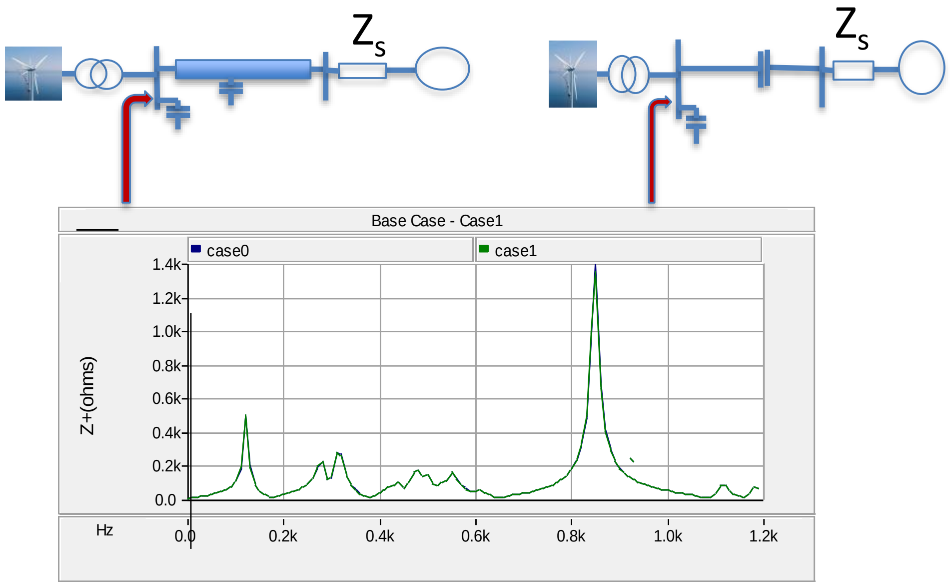
Wind Type 3

Wind Type 4



- Weak grid (Low short circuit current, high system impedance)
  - T3 and T4 controls depend on system voltage and current measurements as inputs
  - Weak grids : Changes in system quantities are harder to track following a system event.
    - Specially the change in voltage phase.
- Series compensated systems
  - Network resonance points in the sub synchronous frequency range (< 50 Hz)

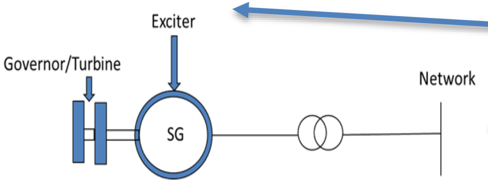
System Impedance Vs Frequency Plots



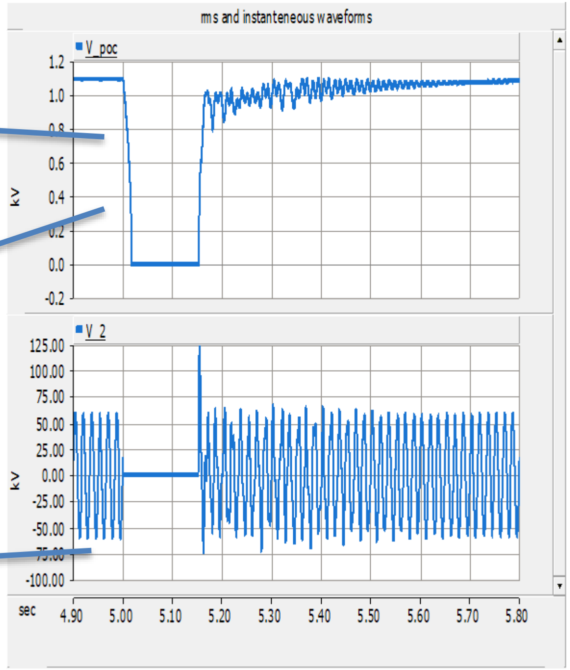
Wind Generators and Transmission characteristics

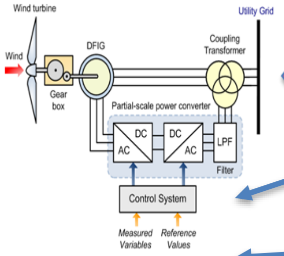
- The dynamic characteristics of wind and Solar PV installations are much different from traditional synchronous machine based generation.
- Nature of AC (or HVDC transmission) used to connect wind to the transmission grid (weak grids, series compensation, long ac cables, filters) has a significant impact on wind/solar PV response following system events

Inputs to generator controls:
RMS and instantaneous inputs to inverters



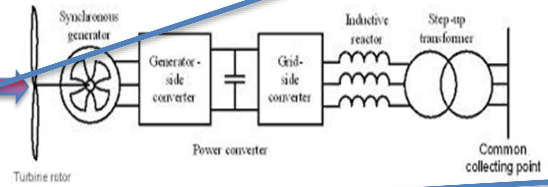
Synchronous generator based



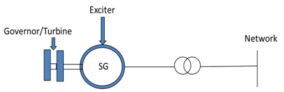


Wind Type 3

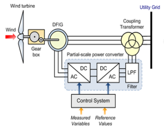
Wind Type 4



Wind Generators and Transmission characteristics

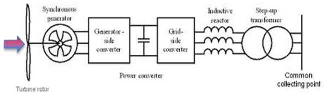


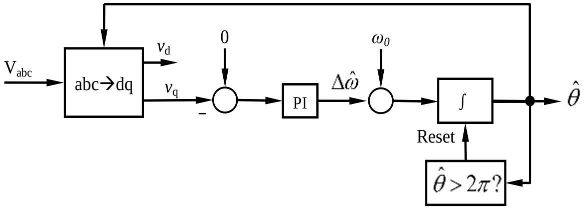
Synchronous generator based



Wind Type 3

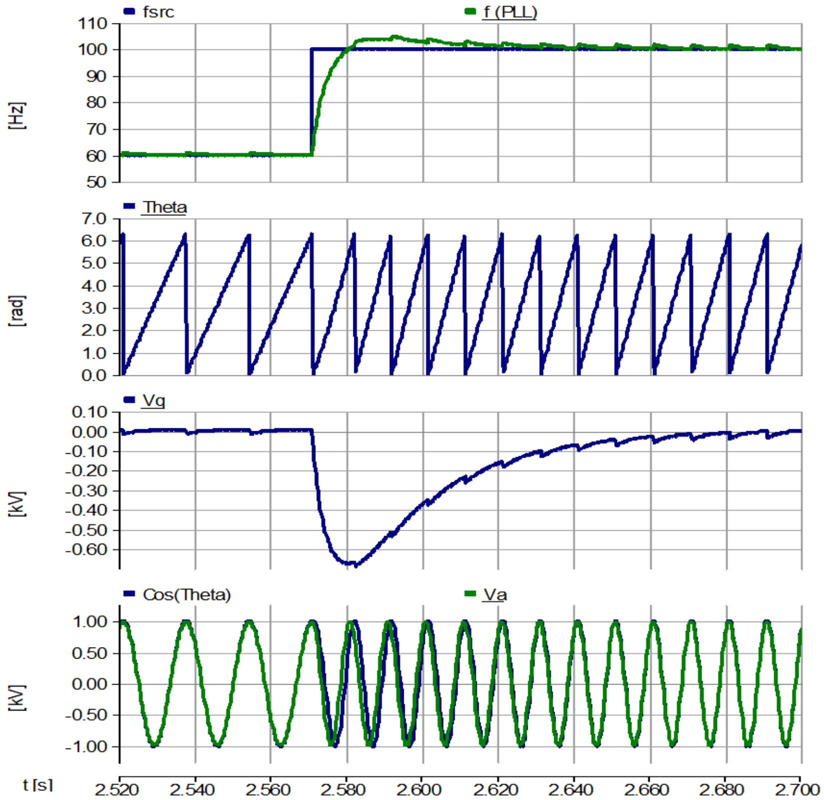
Wind Type 4



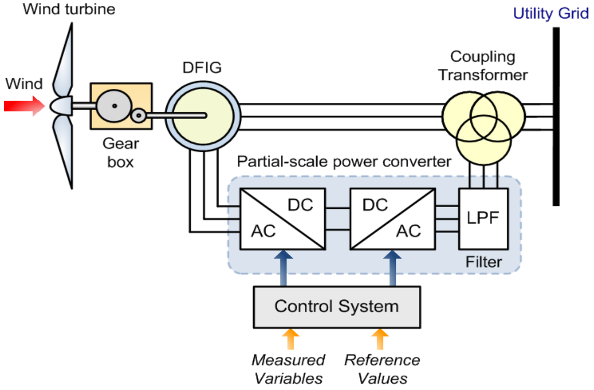


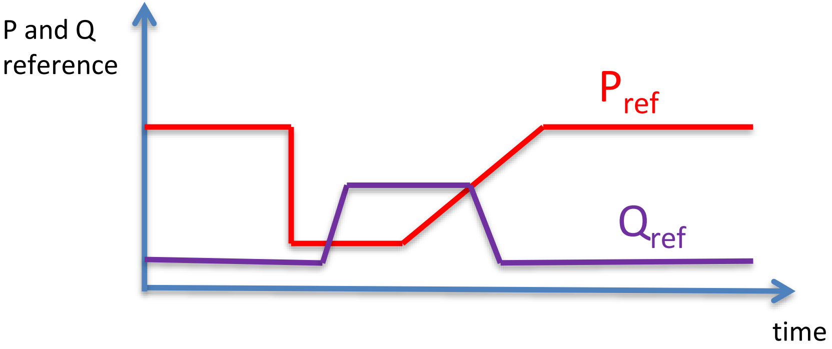
PLL Output to Inverter

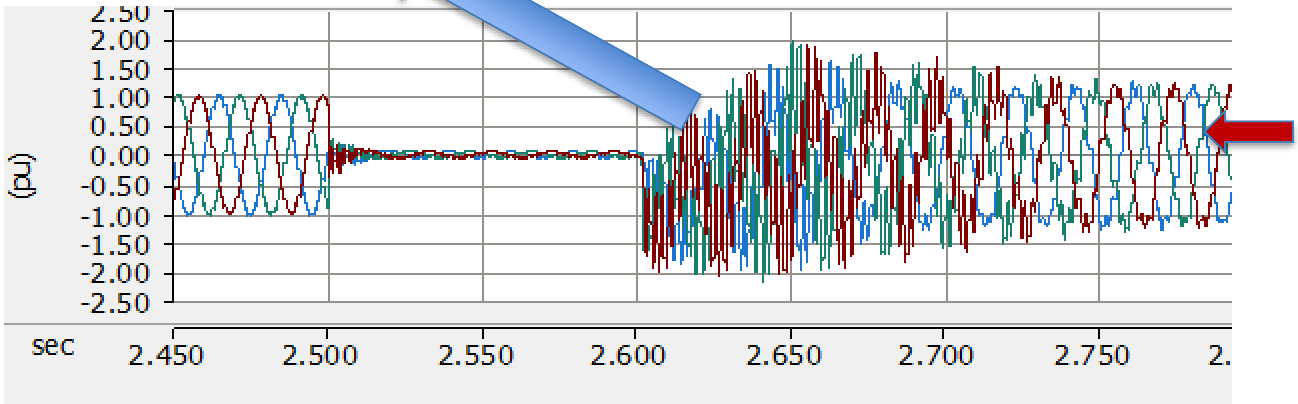
Input to PLL



Integration of wind power to weak grids – Example



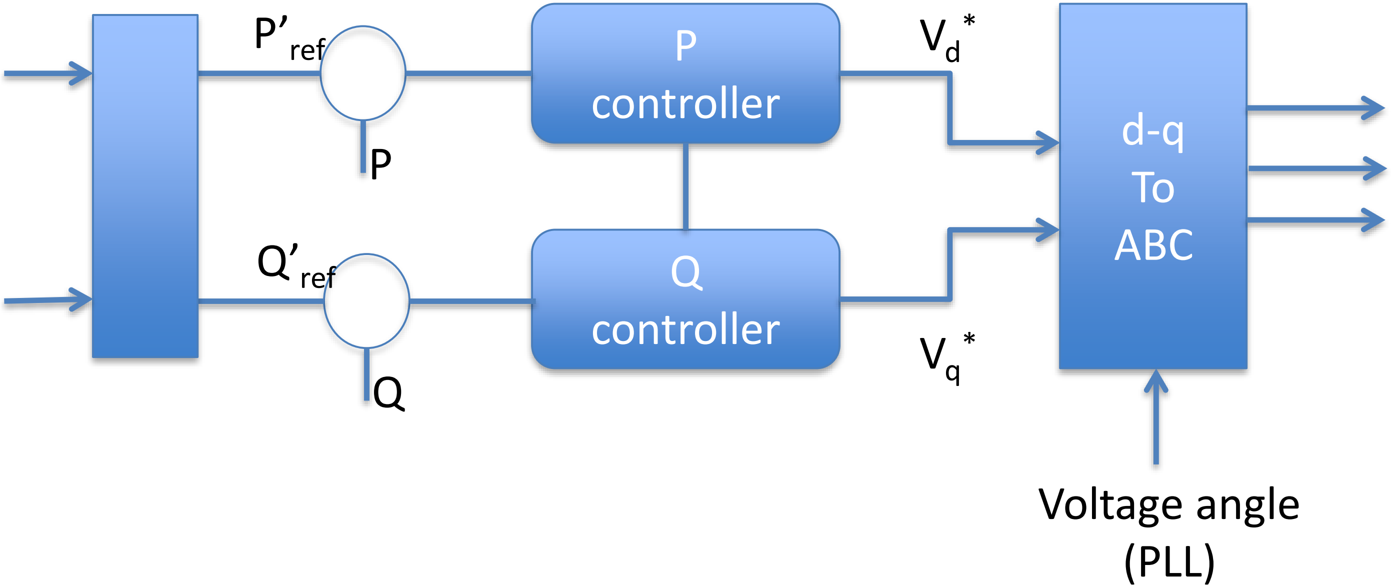




Bus voltage following a fault

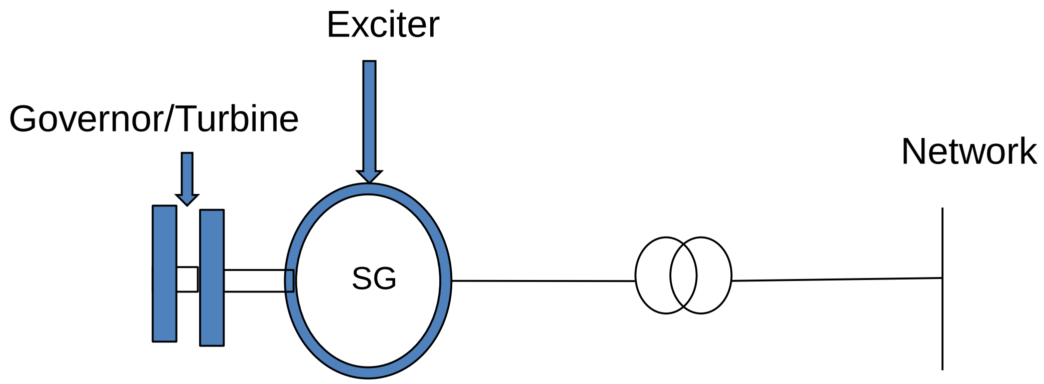
This voltage must be tracked and phase angle shifts estimated accurately and fast to ensure stable operation

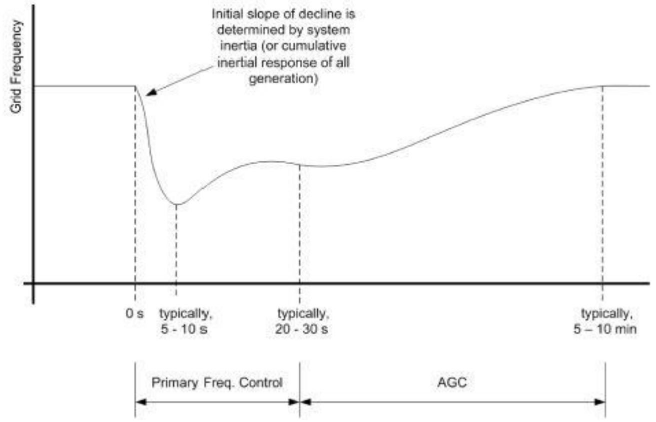
Integration of wind to weak grids – Example to highlight importance of system voltage tracking



EMT simulations must be used to accurately represent the response of the PLL and fast controls.

This is more of a concern in ‘weak grid interconnections’ and when there is significant penetration of renewables in an area.





The Synchronous generator response is determined by

- Machine electrical characteristics
- Exciter characteristics
- Governor / turbine
- Inertia of the rotating masses

The inertial response immediately follows the event

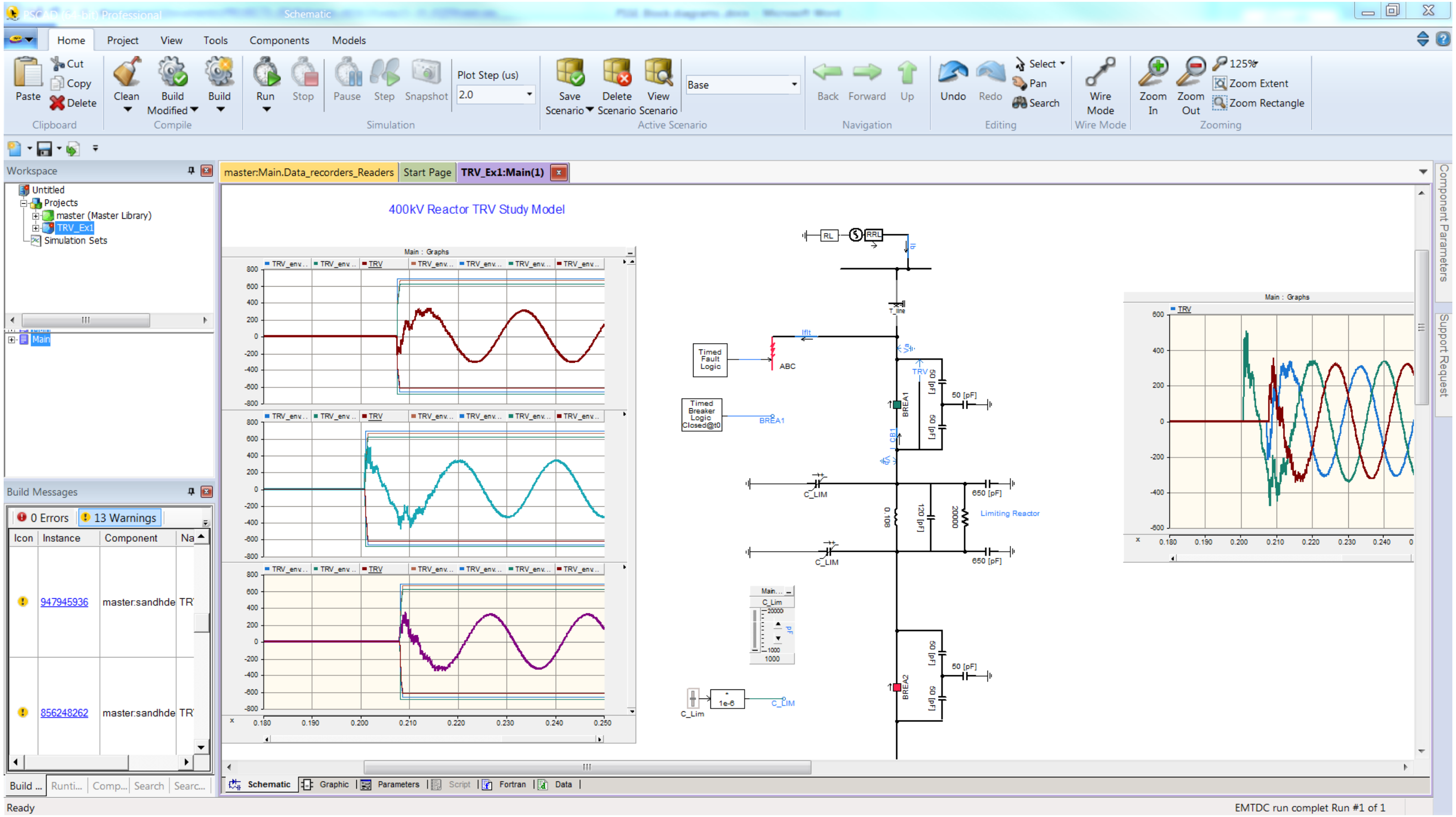
- The inertial response is due to the inertia of large synchronous generators
- Primary control - 20 -30 Sec
- Power electronic based generation does not provide the same style of ‘inertia’

EMT and RMS Simulation – Main Differences

PSCAD/EMTDC – The Industry Standard EMT Simulation Tool

pscad.com

Powered by Manitoba Hydro International Ltd.



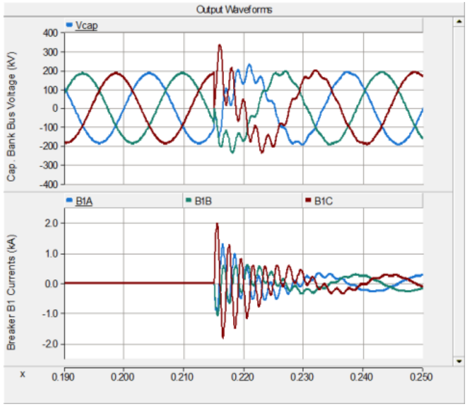
Transients and Steady State

Transients are initiated due to a change to the network topology

- Switching Events
- Faults and fault clearance
- Lightning
- Others

- Transient solution – influenced by
  - Harmonics
  - Non-linear effects
  - Frequency dependent effects
- Steady state solution
  - RMS Value of voltages and currents
    - Magnitude and phase

Example: Closing the breakers has initiated an electromagnetic transient. The energy exchange between L-C causes the oscillatory transient. Resistance in the circuit acts to damp the transient.



Transients and Steady State

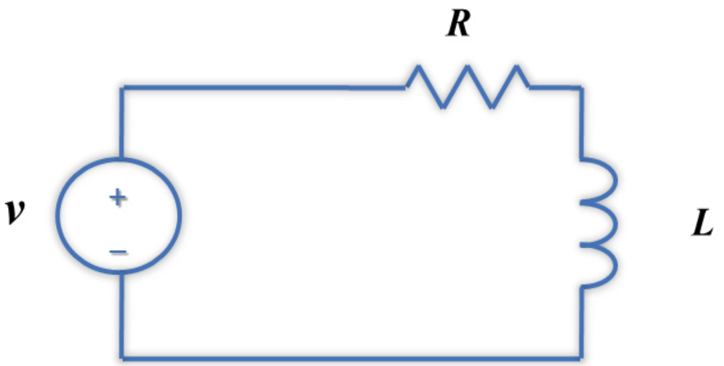
- RMS type simulations
  - Each solution based on phasor calculations
  - 50Hz/60 Hz representation of electric network
  - Network dynamics are not considered

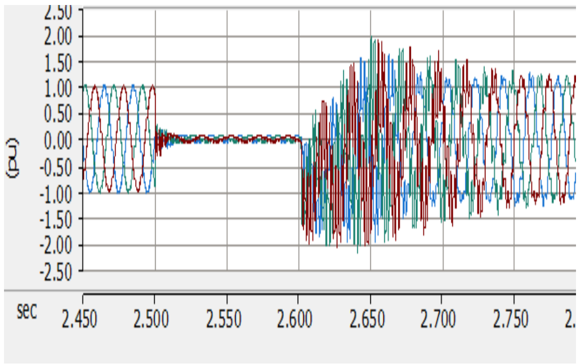
- Electro-Magnetic Transient Simulations (EMT)
  - Direct time domain solution of Differential Equations
  - Network dynamics are captured in the solution (results are based on the solution of the differential equations)

$$V(\omega) = R \cdot I(\omega) + j(L\omega) \cdot I(\omega)$$

2. π. 50

$$v(t) = R \cdot i(t) + L\frac{d}{dt}i(t)$$

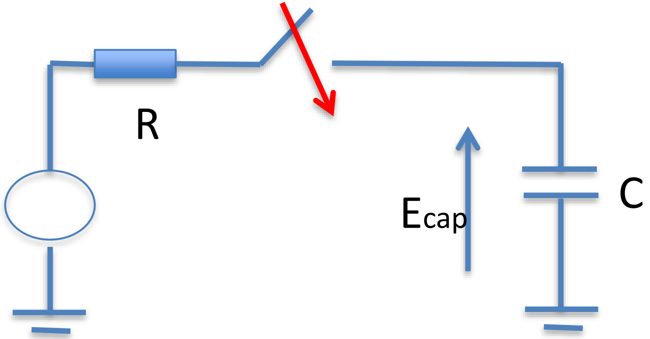


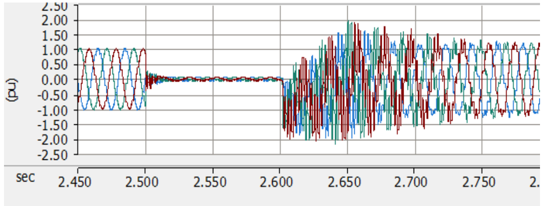


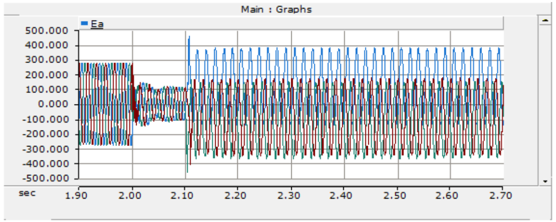
pscad.com
Powered by Manitoba Hydro International Ltd.

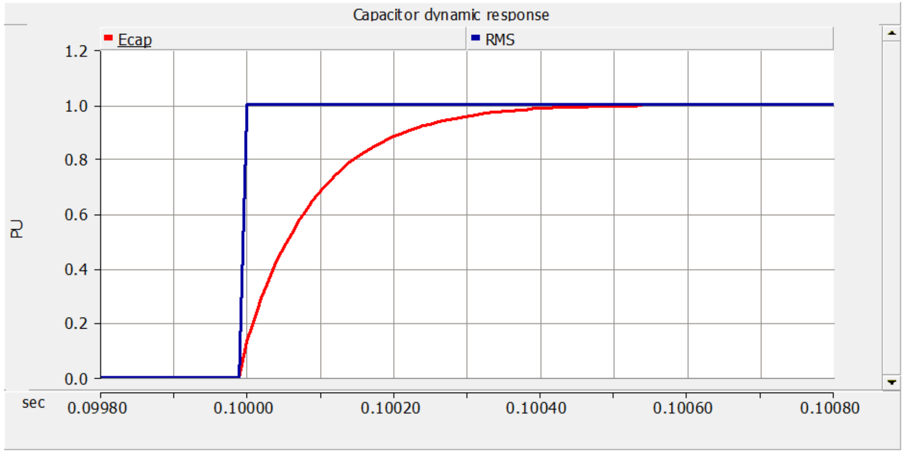
EMT Vs RMS response

Capacitor voltage response





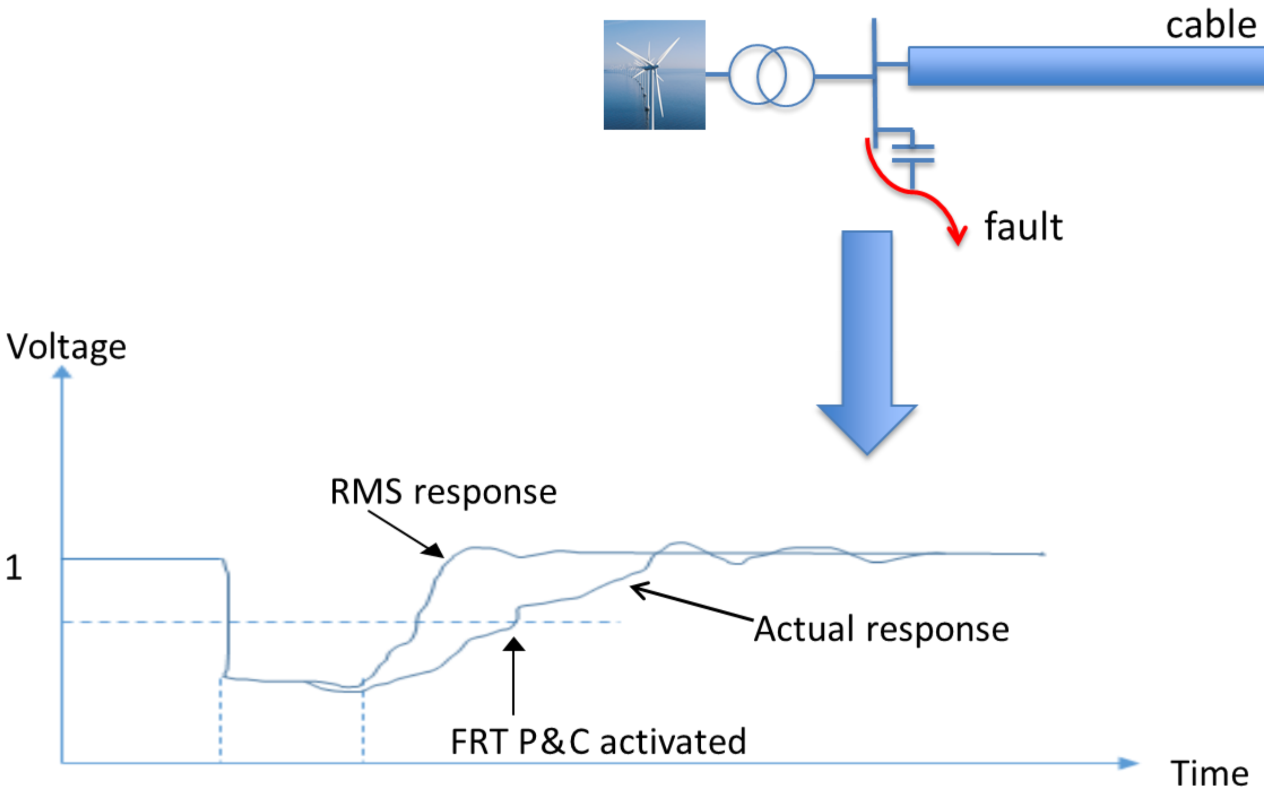




- Harmonics
- DC offset in currents and voltages are represented
- Fast controls of inverters can be better represented
- Interaction between fast acting power electronic devices can be studied
- However, emt simulations are slow compared to rms type simulations

EMT Vs RMS response - Example

Fault Ride Through response of a wind farm

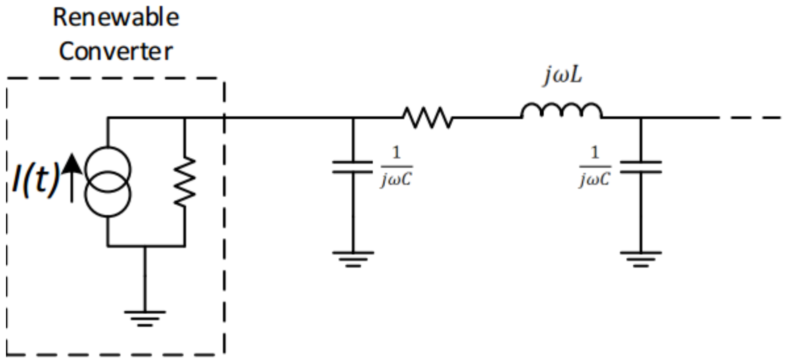


EMT vs. RMS Simulations

pscad.com
Powered by Manitoba Hydro International Ltd.

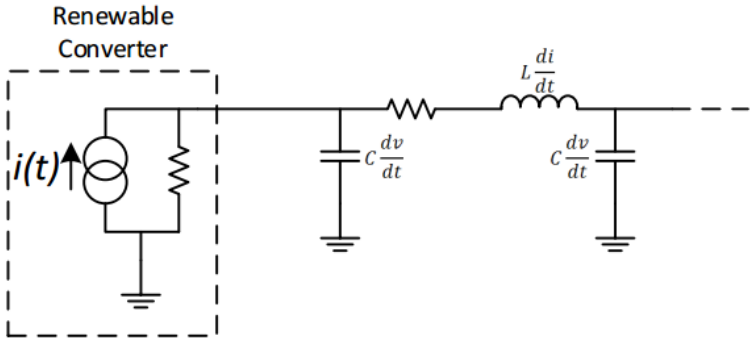
RMS

- Assume quasi-steady state
- Network transients neglected
- Fundamental phasor solution
- Positive sequence
- Large network possible



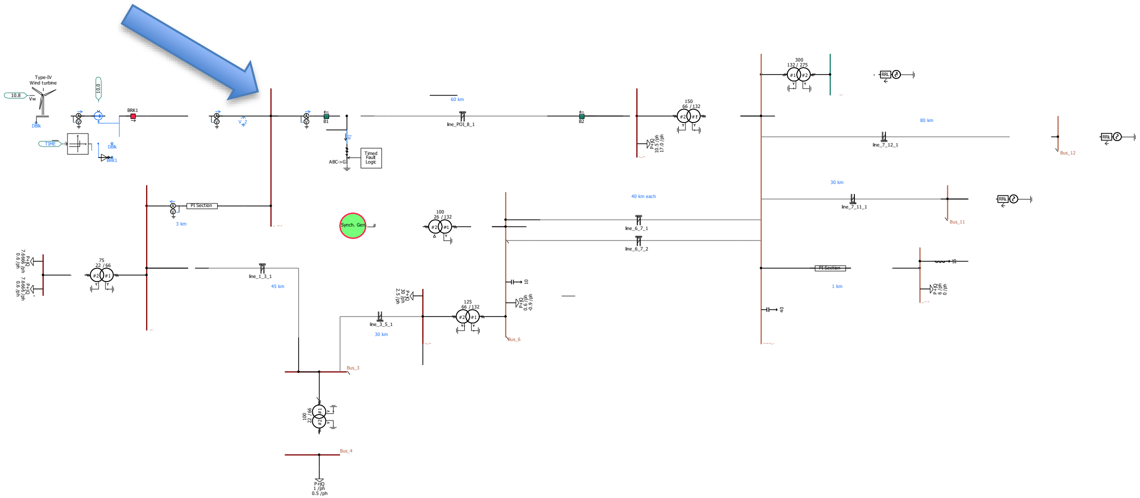
EMT

- Consider differential equations
- Numerical integration substitution
- Upper freq. depends on simulation time step (0~MHz)



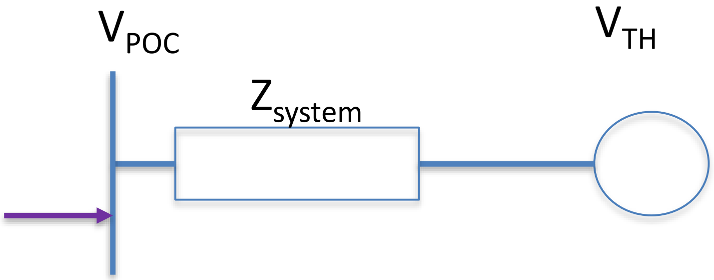
Weak Grids

Weak Grids – Low Short Circuit Ratio (SCR)



A ‘weak’ Point of connection (POC) (‘weak’ grid)

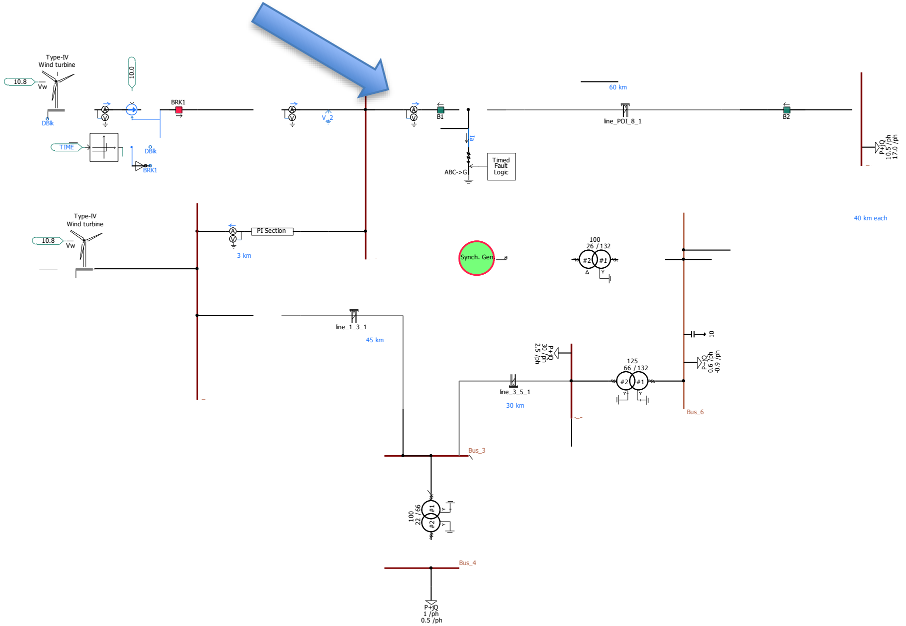
- Low short-circuit current level at POC
- High system impedance

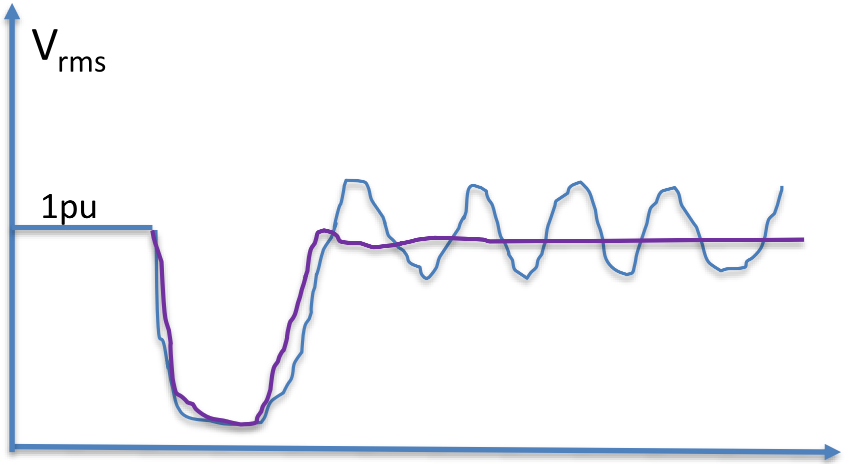


Injection of P and Q (Current) at a weak POC will lead to voltage variations at the bus

$$V_{POC} = I_{inj} \times Z_{system} + V_{TH}$$

Weak Grids – Undesirable interactions





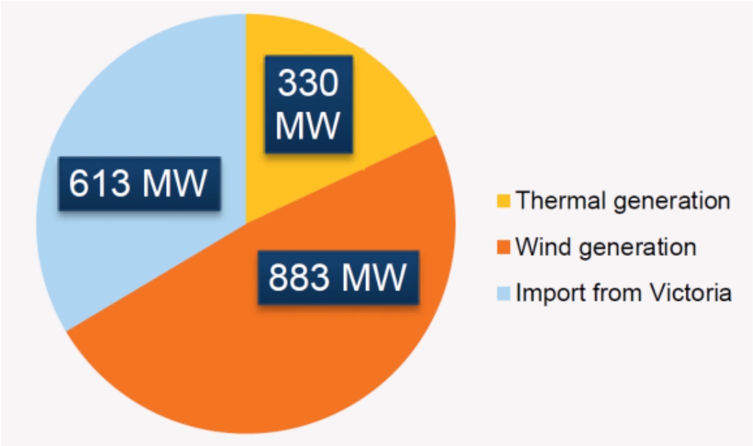
Injection of P and Q (Current) at a weak POC will lead to voltage variations at the bus

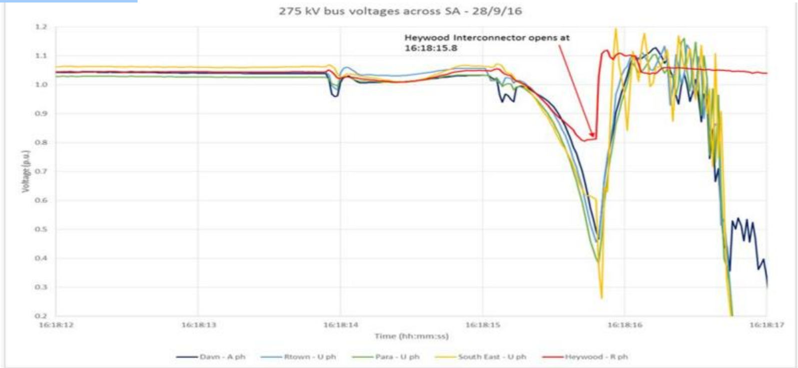
Small Q injection → 'large' Voltage change

Practical Examples

Example 1 – Black System South Australia – September 28, 2016

Example 3 – Black System South Australia – September 28, 2016





Event Description

- Extreme weather conditions resulted in five system faults on the SA transmission system in the 87 seconds between 16:16:46 and 16:18:13, with three transmission lines ultimately brought down

- In response to these faults, and the resulting six voltage disturbances, there was a sustained reduction of 456 MW of wind generation to the north of Adelaide.

- Increased flows on the Heywood Interconnector counteracted this loss of local generation by increasing flows from Victoria to SA

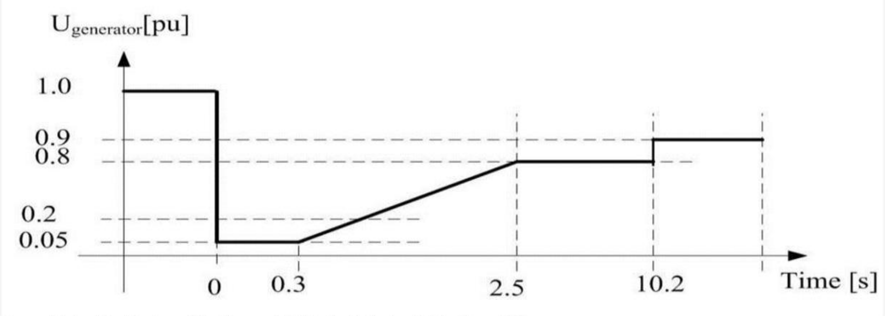
- This reduction in generation and increase of imports on the Interconnector resulted in the activation of Heywood Interconnector's automatic loss of synchronism protection, leading to the 'tripping' (disconnection) of both of the transmission circuits of the Interconnector. As a result, approximately 900 MW of supply from Victoria over the Interconnector was immediately lost.

- This sudden and large deficit of supply caused the system frequency to collapse more quickly than the SA Under-Frequency Load Shedding (UFLS) scheme was able to act.

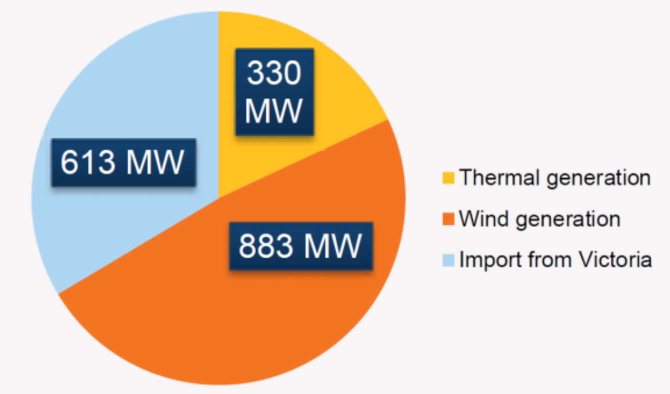
- Without any significant load shedding, the large mismatch between the remaining generation and connected load led to the system frequency collapse, and consequent Black System.

Fault ride through requirement of wind farms

- All wind farms met the ride through requirement for the number of faults within the short duration
- However, an additional protection that was not known to system operators got activated to trip some of the wind farms (more than 3-4 faults experienced within a pre defined short duration)



Source: Vestas Wind Systems A/S. *Advanced Grid Option 2, Vestas VCS turbines*, 2011.

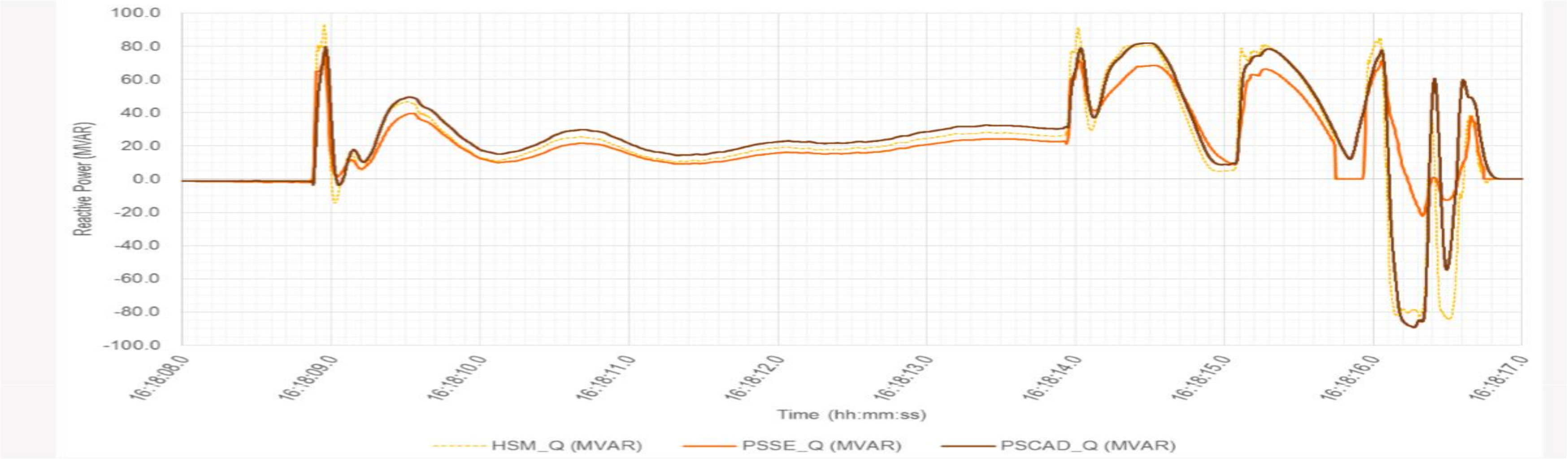


Lessons Learned and Recommendations

•**Generation Mix and System Inertia:**

- The system inertia on the SA side was not sufficient to maintain the frequency drop (once the Haywood interconnector tripped) and to make the under frequency load shedding (UFLS) effective.
- ‘Must run’ thermal generation may have to be identified.
- Synchronous condensers may be investigated as a potential solution if the thermal generation dispatch is expected to be low under specific load conditions.
- Load shedding

System Studies – Model validity

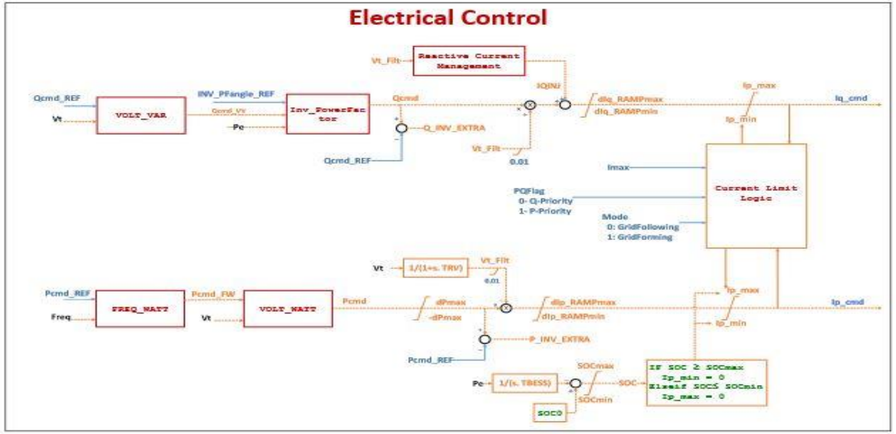


Reference:

BLACK SYSTEM SOUTH AUSTRALIA 28 SEPTEMBER 2016 - Report by AEMO

www.aemo.au

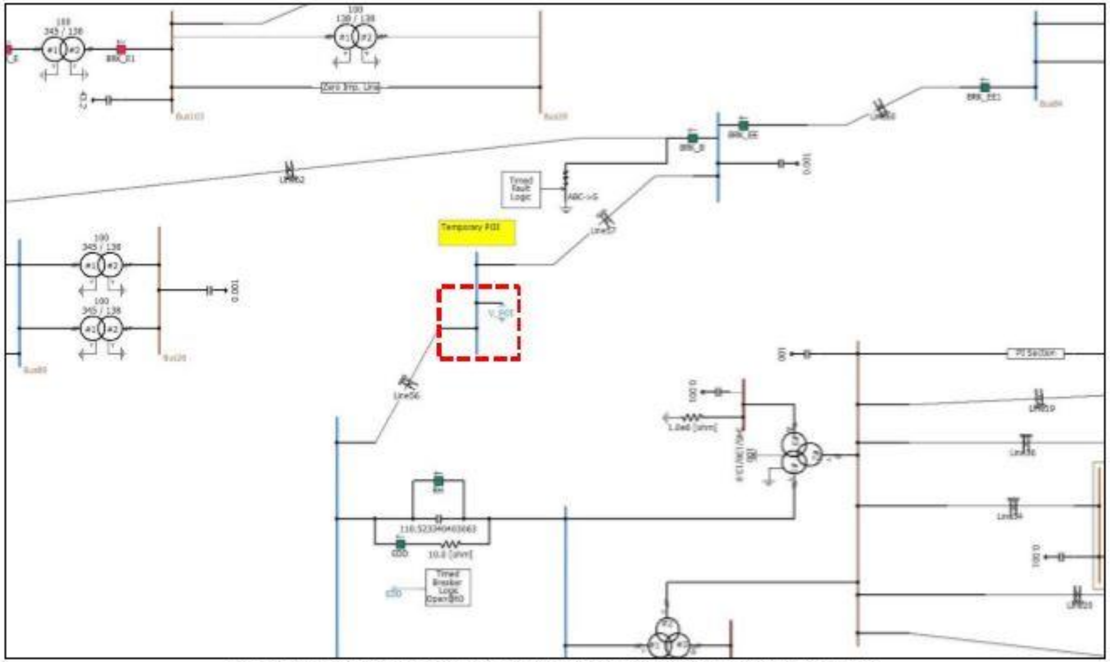
Hornsdale wind farm (300 MW) and Battery Energy Storage System – South Australia

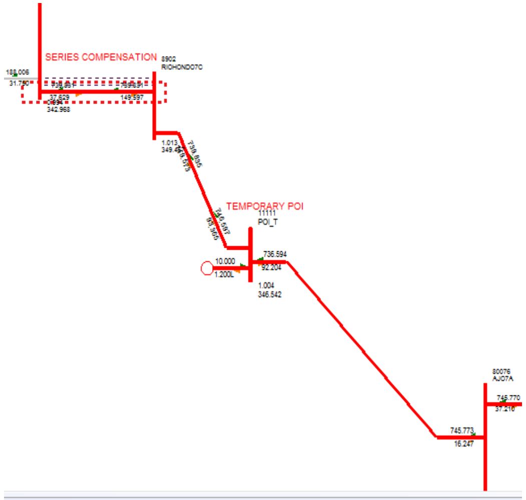


December 2017 – "Hornsdale Power Reserve, constructed by Tesla in South Australia, kicked in just 0.14 seconds (5-7 cycles) after a major plant, the Loy Yang station in the neighboring state of Victoria tripped"

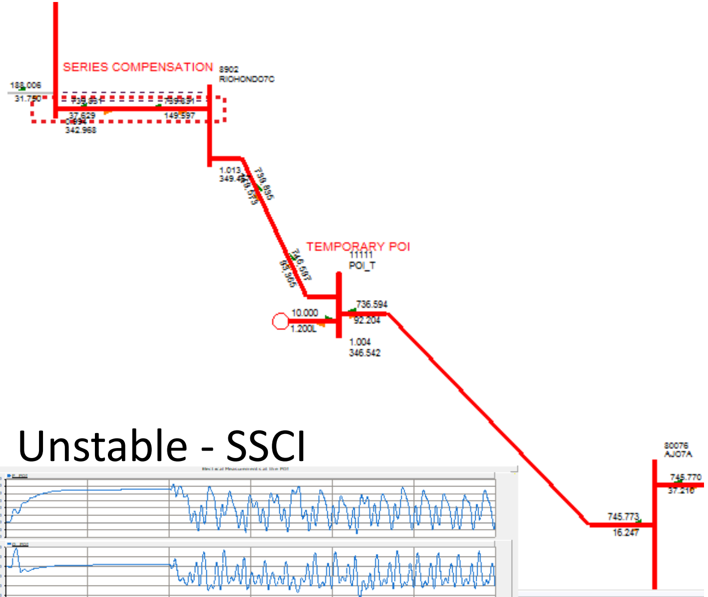
Example 2 –300 MW Wind Farm near Series Compensated 345 kV line – SSCI and Interaction with Network Transients

The series compensated line is tapped to facilitate the wind farm connection

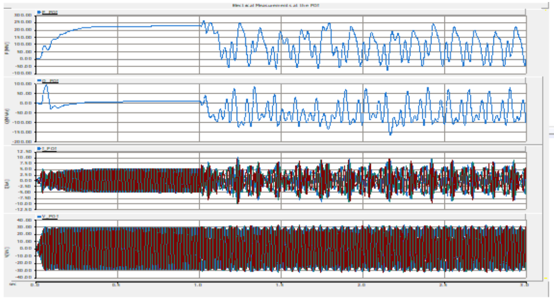




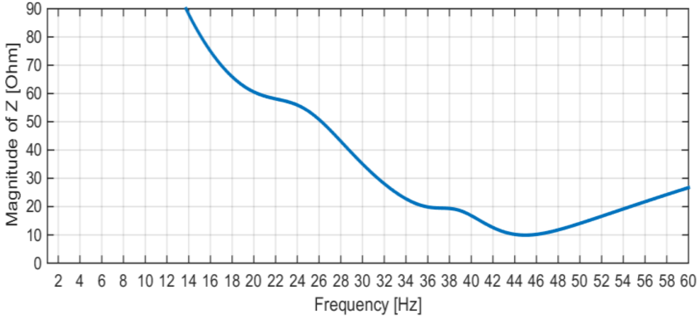
Issue No.1: Sub Synchronous Control Interaction - SSCI (more an issues with Type 3 wind)

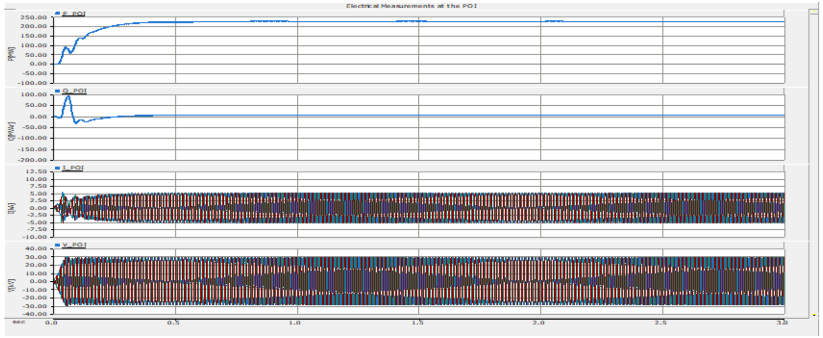


Unstable - SSCI

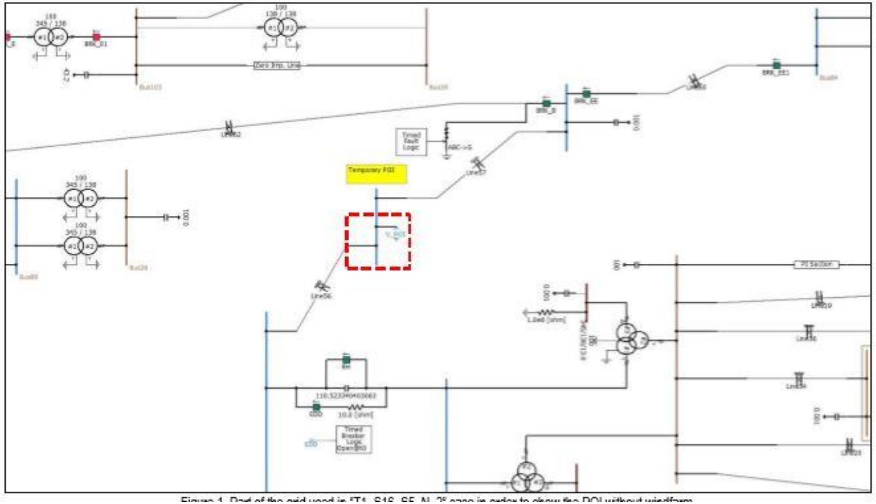


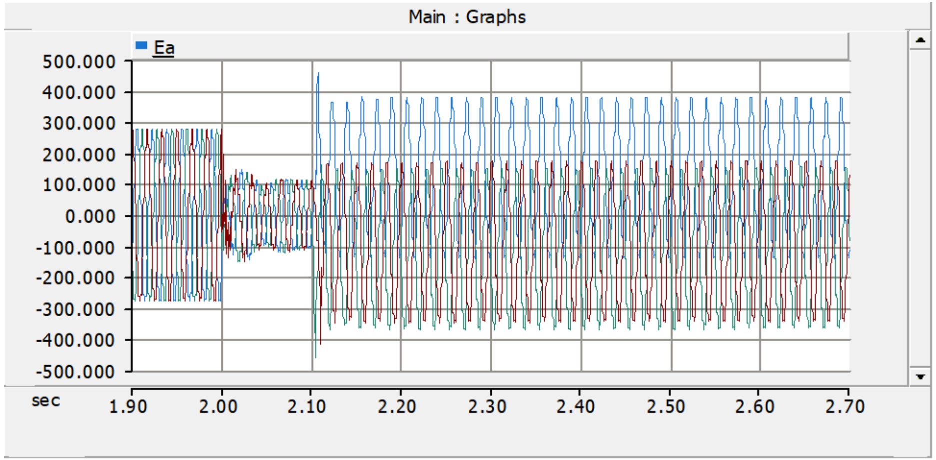
Network Impedance characteristics

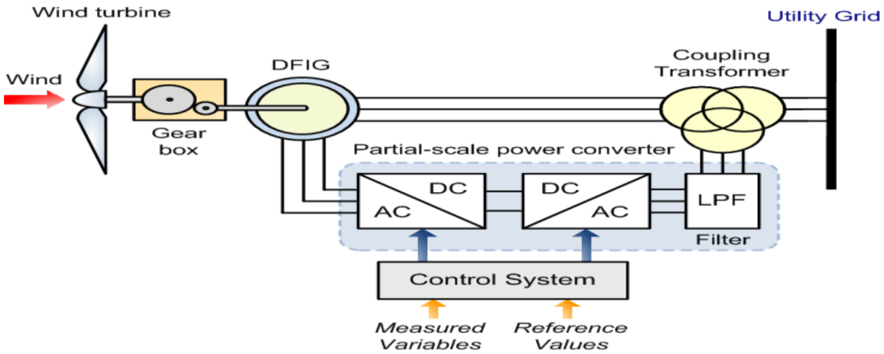




Issue No.2: Wind Inverter response to system transients



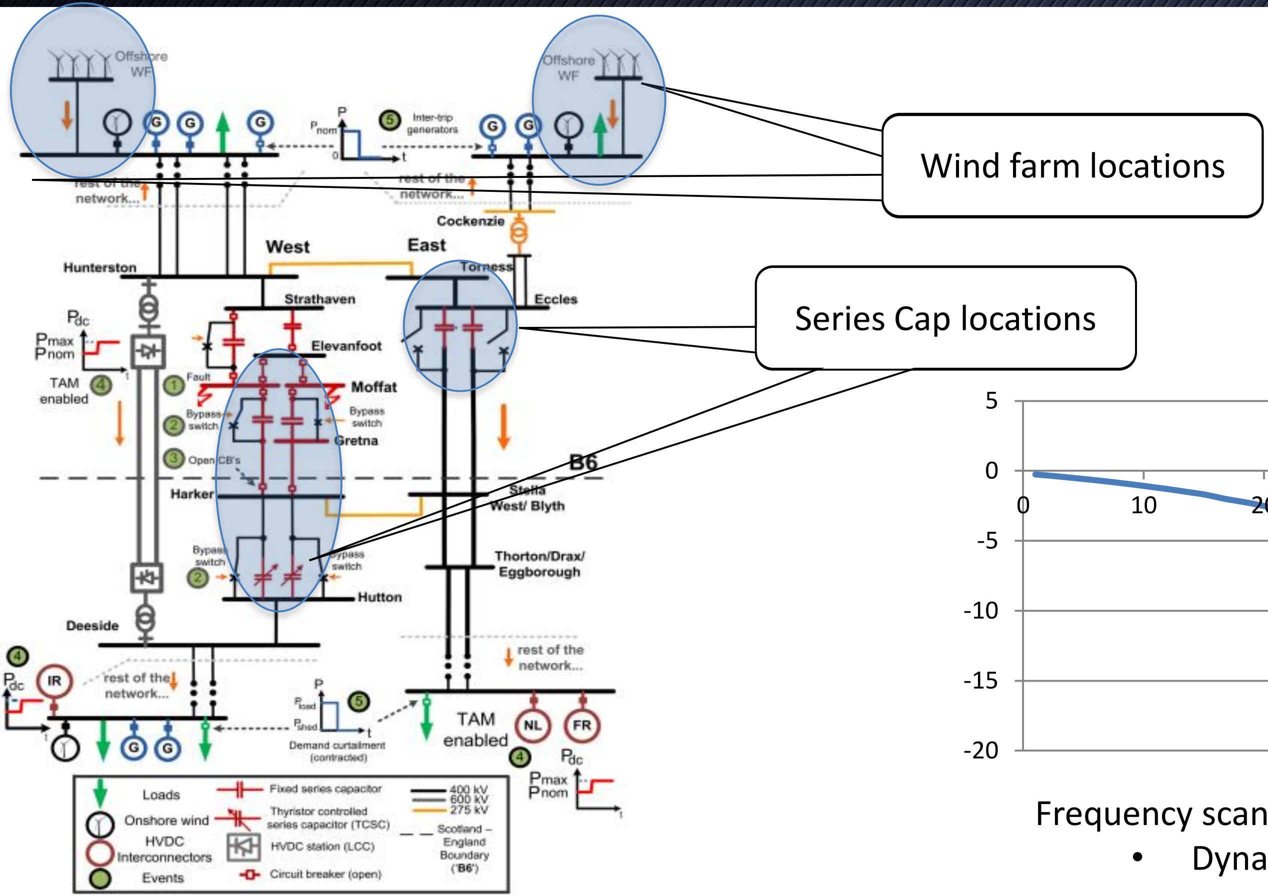


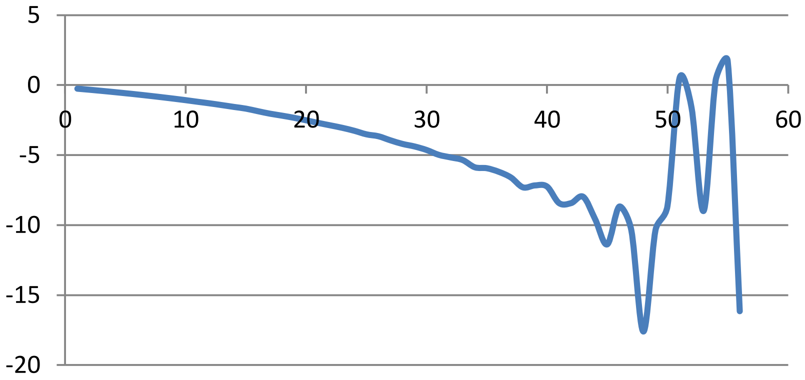


The DC offset in the POI voltage caused the inverter DC link voltage to rise.

- Poor network side damping
- Excessive energy in DC link chopper resistance (resulted in a trip)

Potential for sub synchronous oscillations between wind farms and series compensated lines in the UK

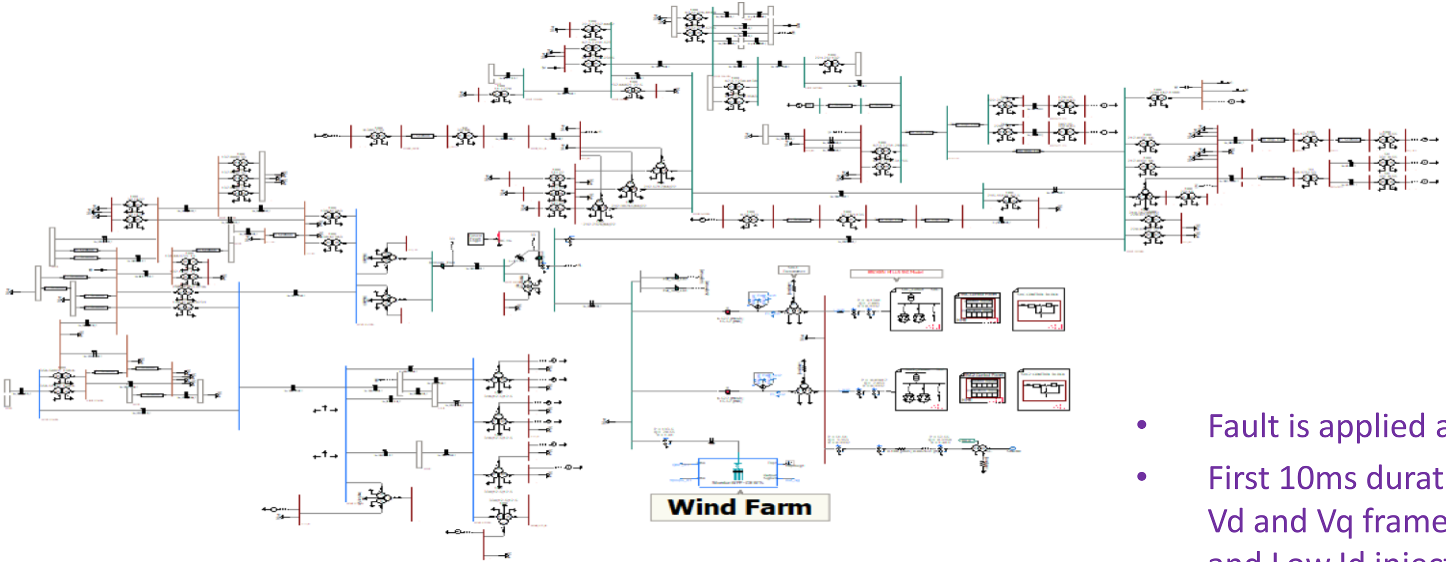


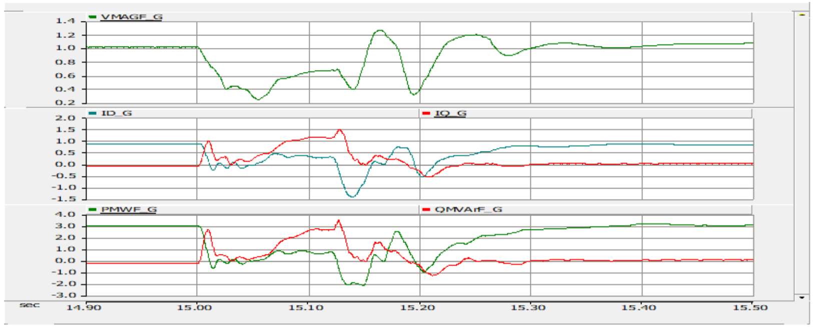


Frequency scan of Type 3 wind generator

- Dynamic Resistance vs Frequency

Example 3 – Multiple Inverter Based Devices in a Local Area – Control Interactions in a Weak Grid Area



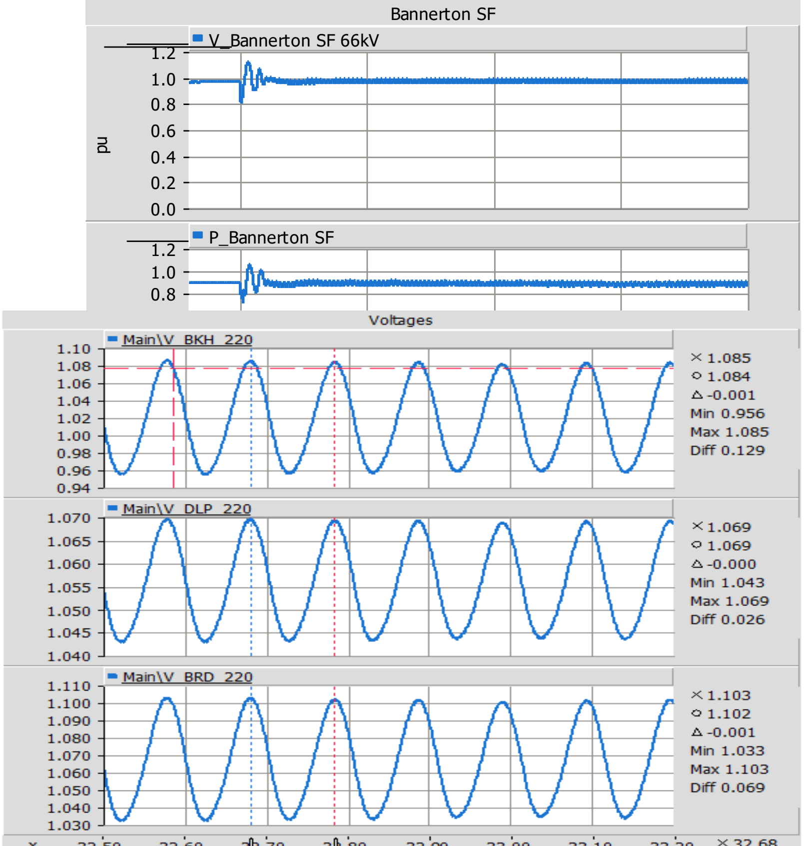


- Fault is applied at 15s for 120ms
- First 10ms duration fault: large rotation in Vd and Vq frame leads to high Iq injection and Low Id injection
- Next 50ms, inverter bring down Id and Iq to allow the PLL to relock to the phase.
- Last 60ms during the fault: inject Iq to support the system
- After fault release, PLL goes unstable and causes large voltage fluctuation

Example 4 – Low Frequency Voltage Oscillations – Weak Grid Issue

Example 2 – Low Frequency Voltage Oscillations (8- 10 Hz range)

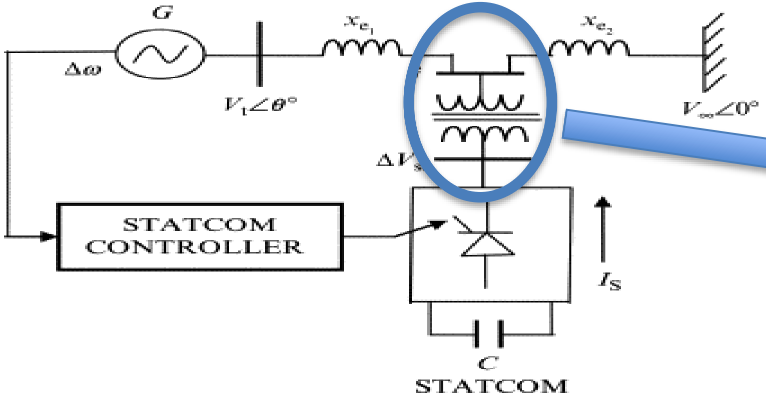
Low Frequency Voltage Oscillations – Interaction between multiple dynamic devices



Example 5 – Line Series Compensation – Fixed Capacitors Or power electronic inverter based solutions

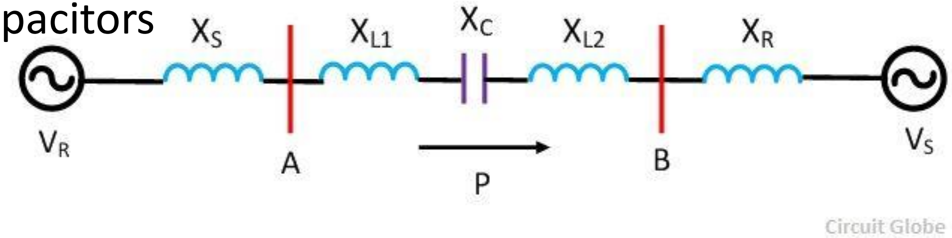
Series compensation – Power electronic based devices

FACTS Devices – Series Compensation

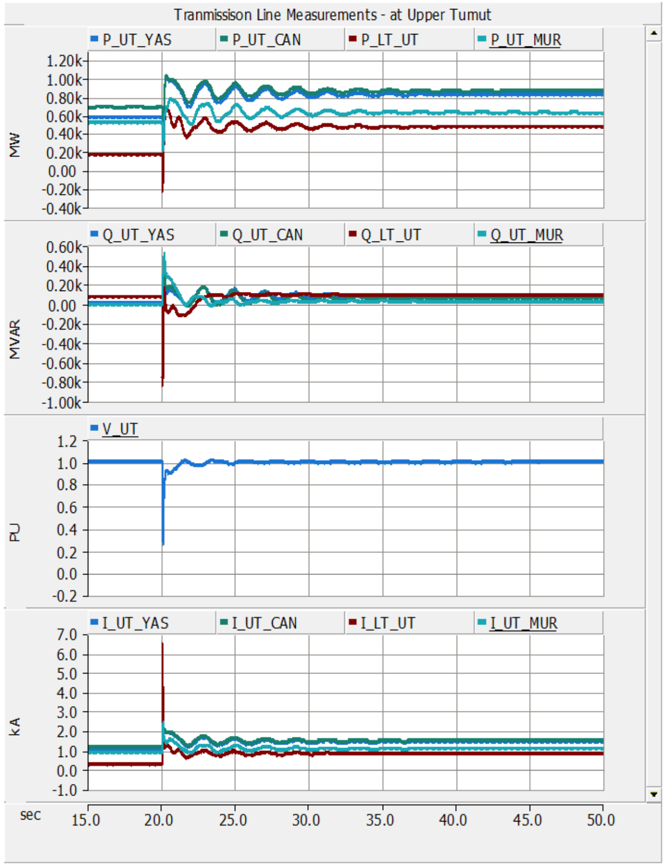


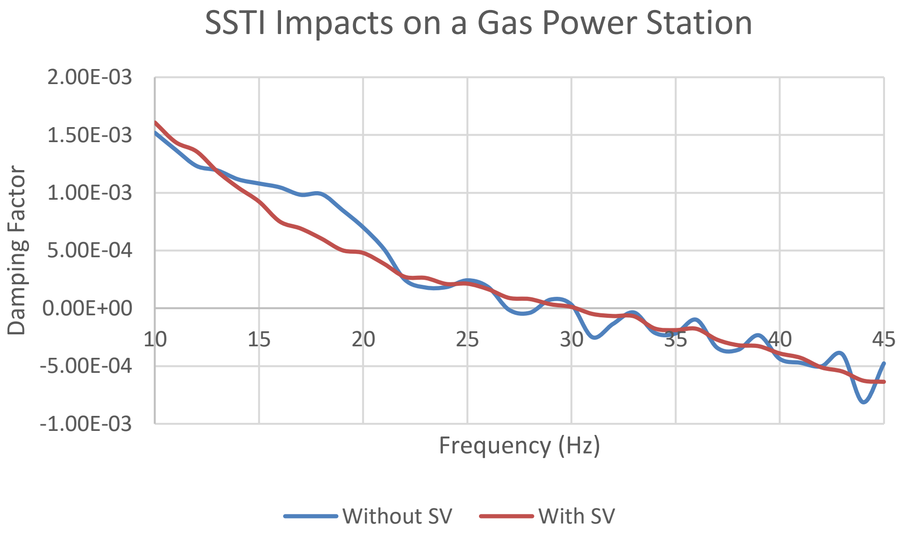
System

Series compensation of transmission lines - Series Capacitors

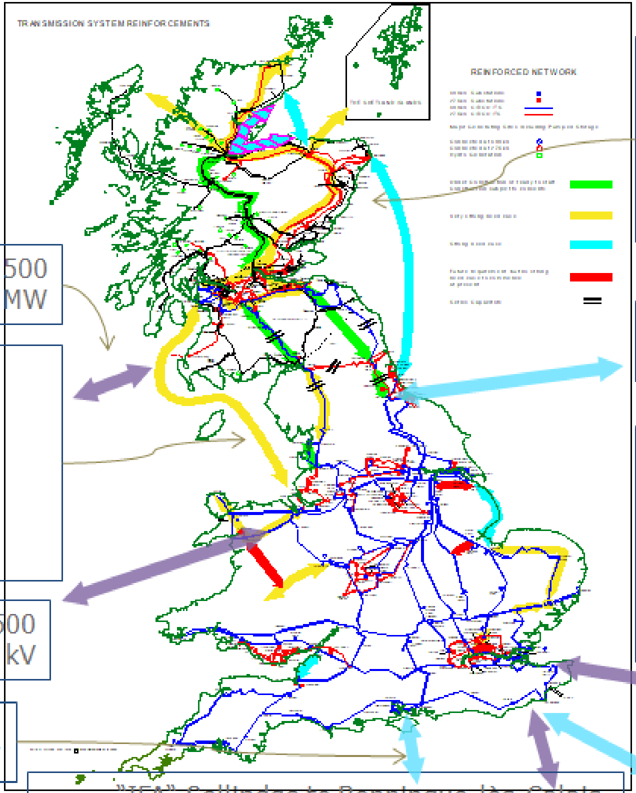


System Dynamic Response Study results





Transmission System Expansion and Interconnectors in the UK



"The Eastern Bootstrap"

HVDC Subsea Route Peterhead to Tyneside

Status unclear.

Ayrshire to NI, 500 MW

"NSN", 1,400 MW, Blythe to Norway 730km, 2€Bn

"The Western Bootstrap"

420 km HVDC Subsea Route Hunterston to Connah's Quay

Contract awarded to Siemens ±600 kV, 2,200 MW, CSC

"BritNed"

HVDC Subsea Route Kent to The Netherlands

Built by Siemens ±500 kV, 1,000 MW

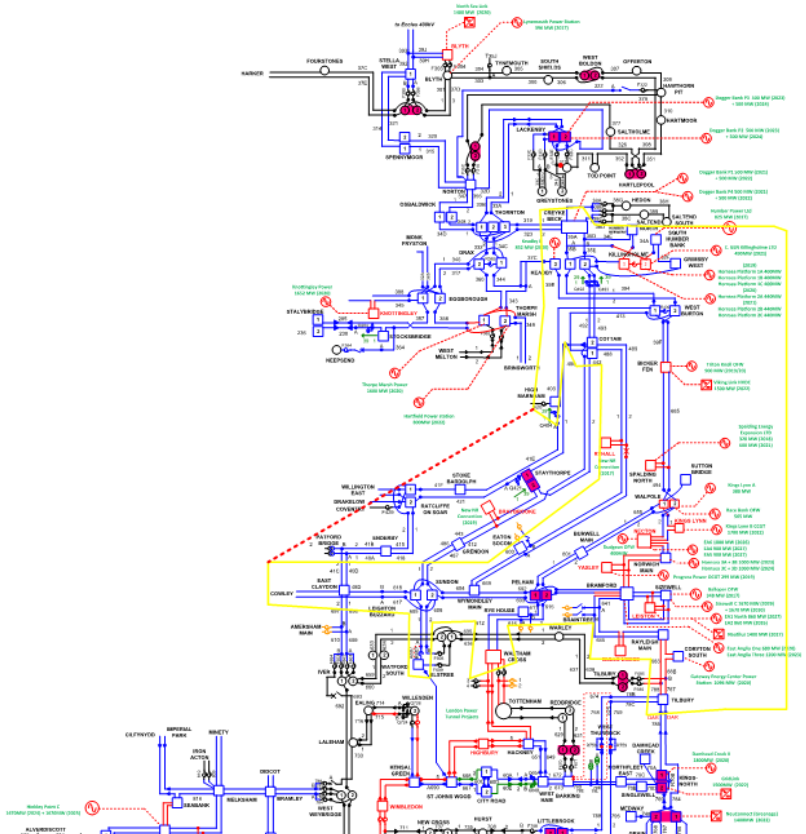
Deeside to Ireland, 500 MW, at ±200 kV

"IFA2"Chilling to Tourbe, 1,000 MW

"IFA" Sellindge to Bonningue-lès-Calais, 2,000 MW at ±270 kV CSC

"Nemo", 1,000 MW VSC

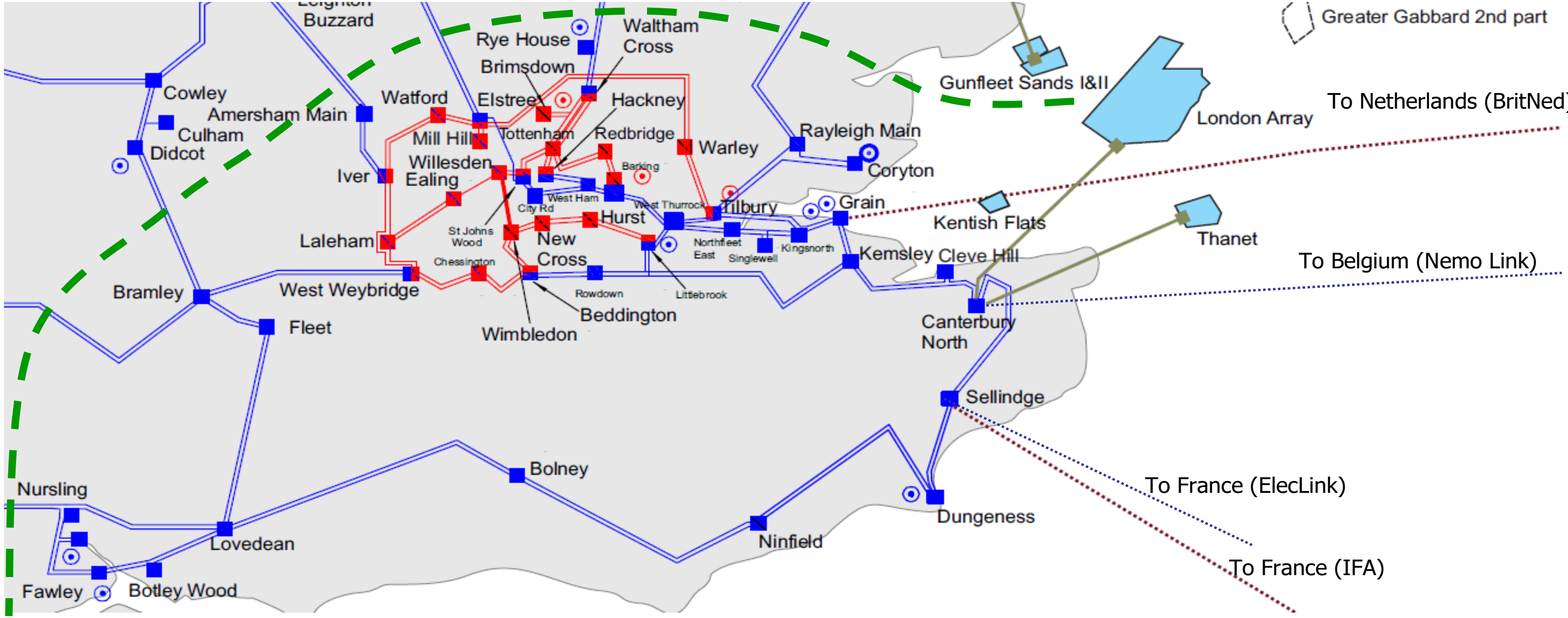
Reduced Network for Interaction Study



Example 6: – Control Interaction and SSTI Impacts - South East England

Potential Control Interaction and SSTI issues - South East England

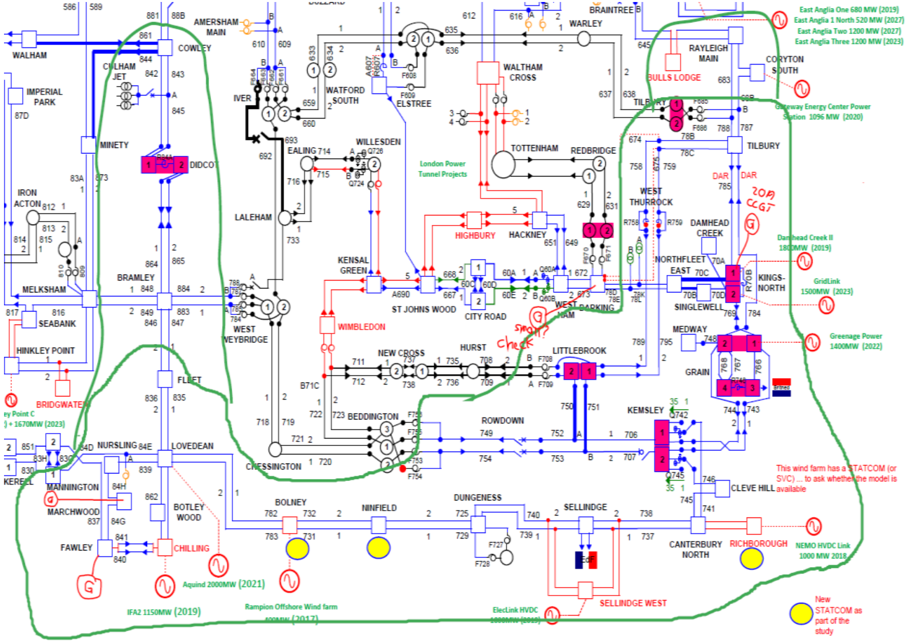
- South East England is where several HVDC interconnectors land and is a region that has little synchronous plants and even that is being displaced by offshore wind farms.
- Three STATCOMs commissioned to provide voltage support.
- The short circuit ratio is low and reactive current during a fault is sought.
- Control interactions and sub synchronous oscillations concerns given the 'weak grid'



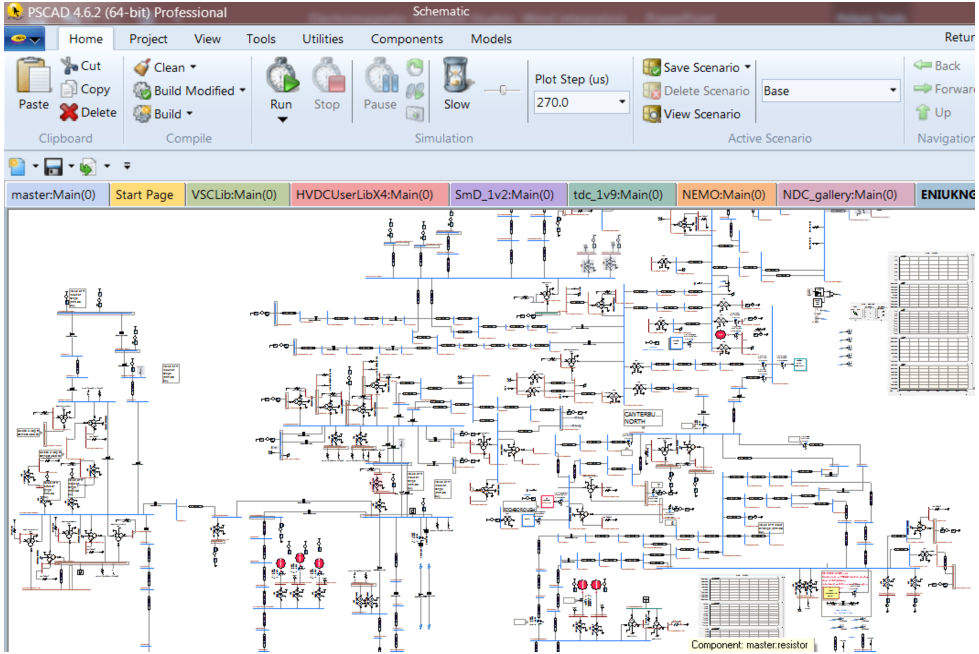
Potential Control Interaction and SSTI issues - South East England

pscad.com

Powered by Manitoba Hydro International Ltd.



- Modelling the entire South East England network including all vendor models for all HVDC, STATCOMS, Wind farms in EMT Platforms.



Model Validation of South East England between PSCAD and PF

pscad.com

Powered by Manitoba Hydro International Ltd.

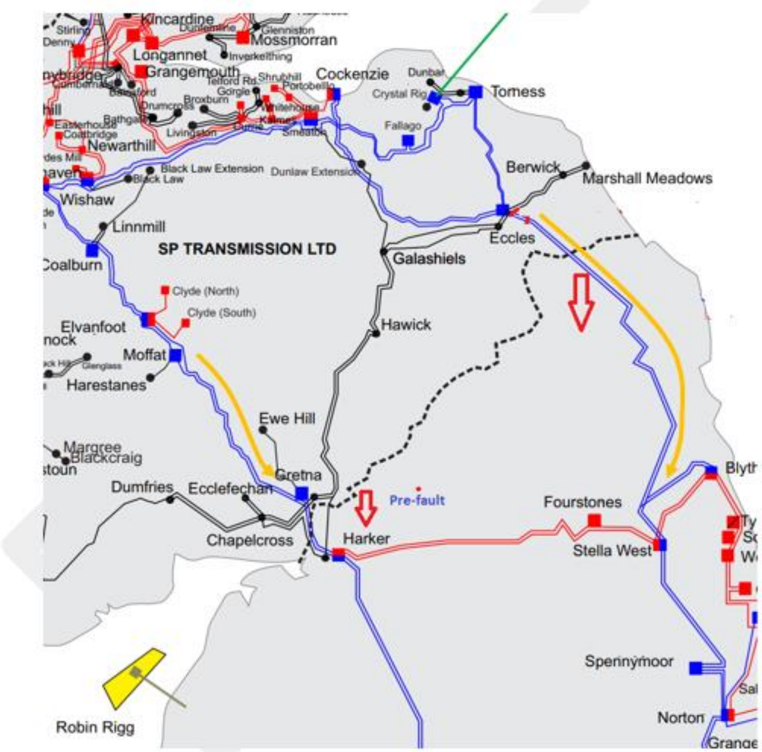
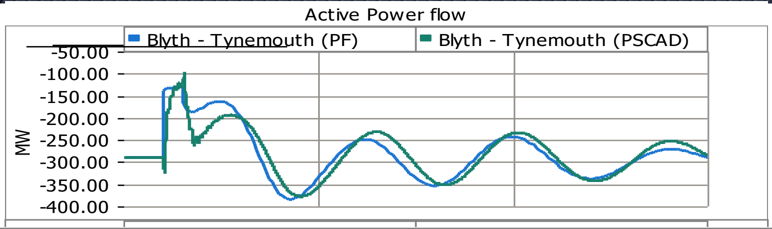
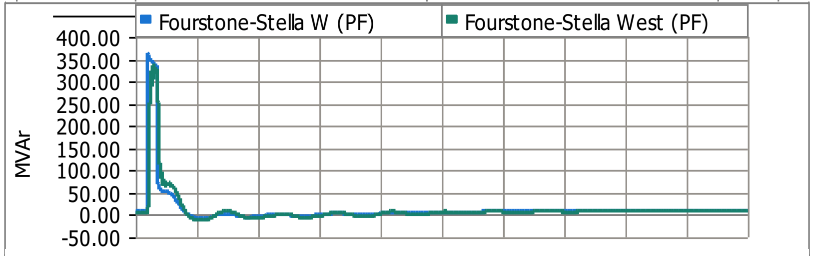
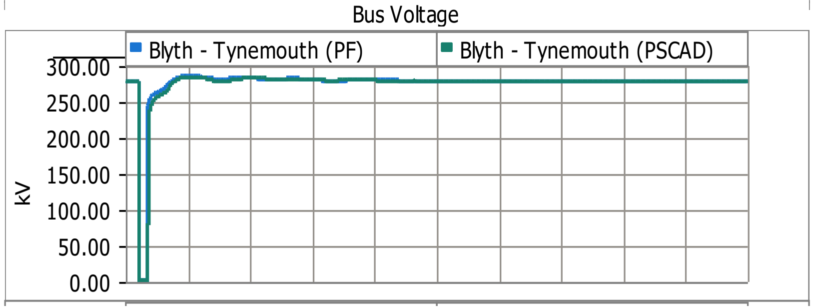


Figure 1: Two 400kV transmission corridors from Scotland to England







The full National Grid System model in Power Factory was validated against PSCAD

Example 7: Hornsea 3 Offshore Wind Power - System Interaction Studies

Offshore Wind Power Projects

UK Peak demand: 55,000 MW

UK Offshore installed wind capacity: 4,050 MW

UK Offshore wind under construction or approved: 11,000 MW

UK Onshore installed wind capacity: 8,080 MW

Plus other renewables by 2030: 25,000 MW

Firth of Forth– 3,600 MW

Dogger Bank – 7,200 MW

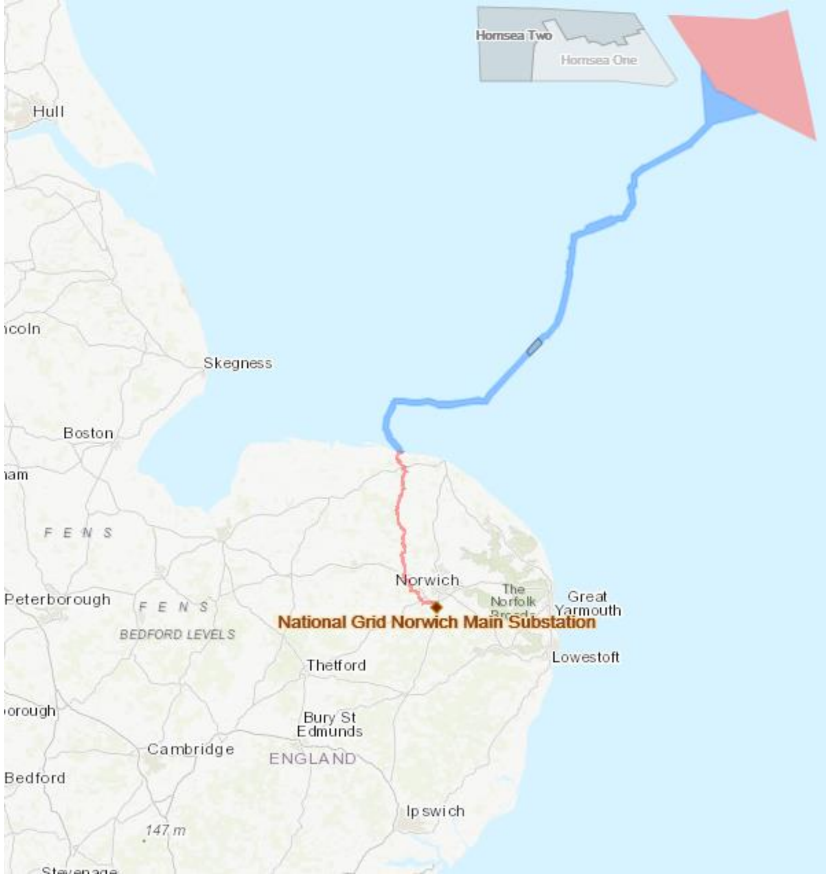
Hornsea 1– 1,200 MW
Hornsea 2– 1,800 MW
Hornsea 3

Great Gabbard – 504 MW - Operational

London Array – 640 MW - Operational

Thanet – 300 MW - Operational

Hornsea 3 Offshore Wind Power Projects: studies



Example 8: European Transmission Network Model Development for Transient Studies

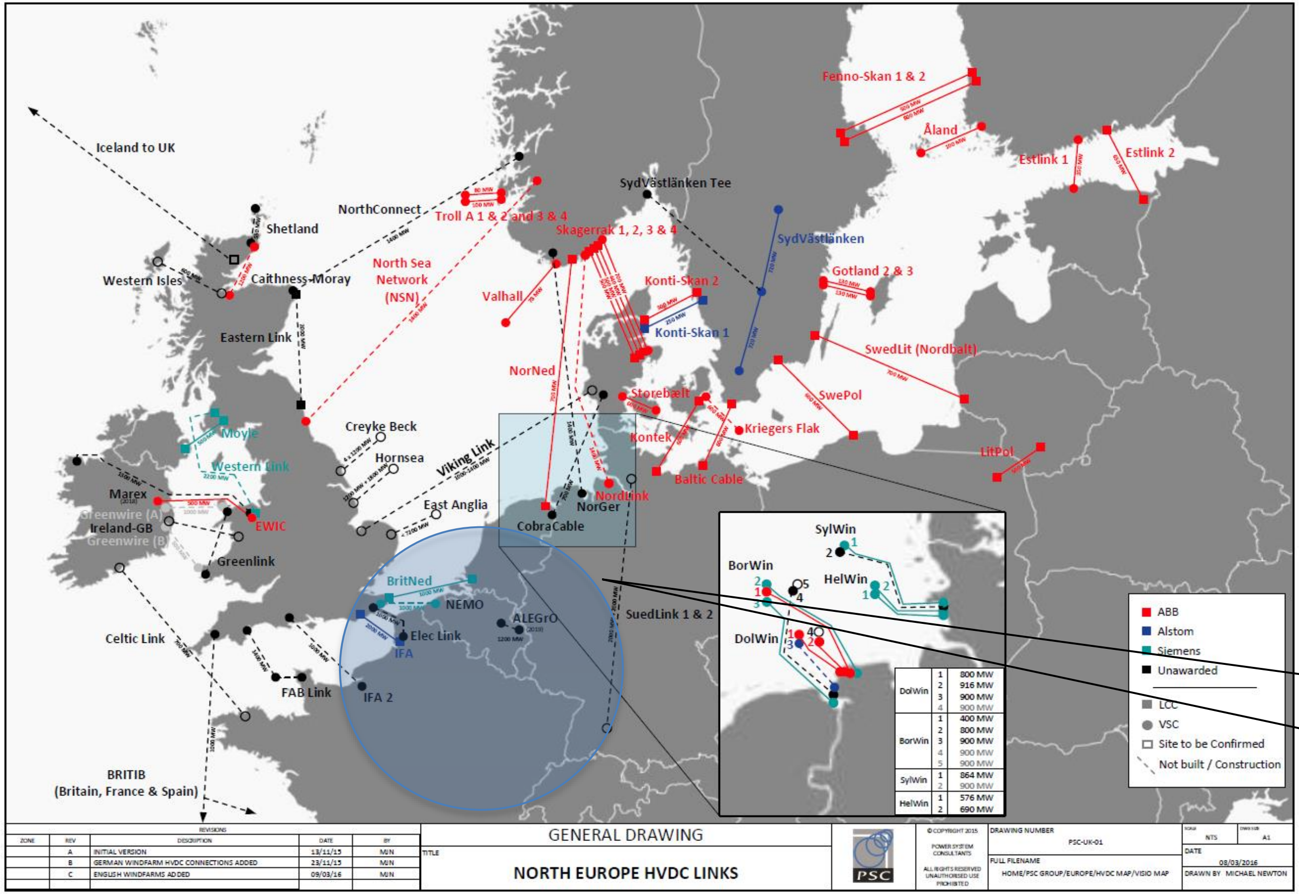
pscad.com

Powered by Manitoba Hydro International Ltd.

PSCAD

Transmission Upgrades - Belgium

pscad.com
Powered by Manitoba Hydro International Ltd.



Network model development for transient studies

Thank You

pscad.com

Powered by Manitoba Hydro International Ltd.