MANITOBA HVDC RESEARCH CENTRE,
a Division of Manitoba Hydro International Ltd.

Electromagnetic Transient Studies – Applications in Wind Integration

November 2016

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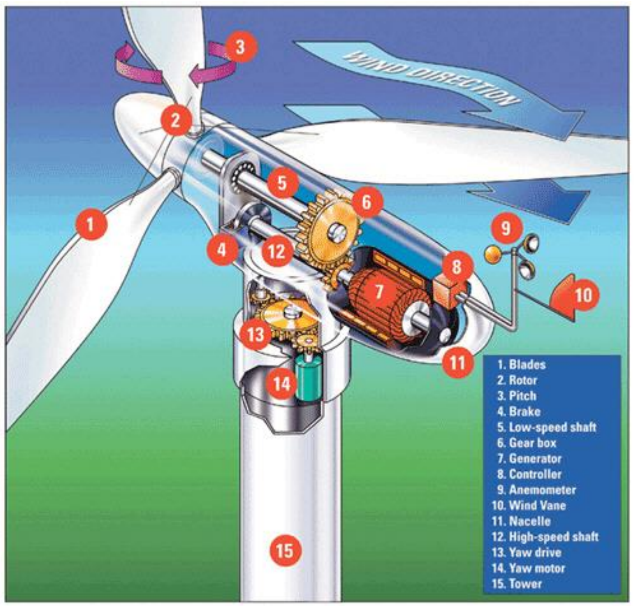
Studies for Wind Integration Planning, Operation and Design

- Load flow (steady state – 50 Hz)
- Transient stability (slow variations – electro-mechanical)
- Small signal stability (operating point)
- Fault studies
- Harmonics
- Electromagnetic transient studies (fast transients)

General Introduction

- PV and Wind integration do present challenges
  - Variable nature of the prime energy source – PV or wind
  - PV and Wind generators behave very differently from conventional generators based on synchronous machines
  - Remote location of PV/wind farm sites
  - Need to interconnect to ‘weak’ grids
    - Low short-circuit ratio (High system impedance)
    - Series compensated lines
    - Offshore wind connected via long cables



Example: 3.5 MW rating

Blade Dia: 110 m

Wind speed:
3.5 – 14 – 25 m/s

DFIG : IGBT based

Speed : 8.5 – 15.3 rpm

Main components

Outline

- Introduction – Applications: related to wind integration
- EMT simulation tools – PSCAD/EMTDC
- EMT and RMS simulations – brief discussion (Main differences)
- Wind Generator Types and their characteristics
- Why use EMT simulations for 'specific' wind dynamic performance studies
- Example cases: practical applications
- Important models and features of PSCAD for wind related studies
- Illustration of selected PSCAD examples

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Common Applications – Renewable Energy

- Cable, line, station insulation design
    - Switching Over-Voltage studies – Arrester ratings
    - Power System lightning performance – BIL
    - Temporary Overvoltage studies (TOV)
    - Breaker Transient Recovery Voltage (TRV)

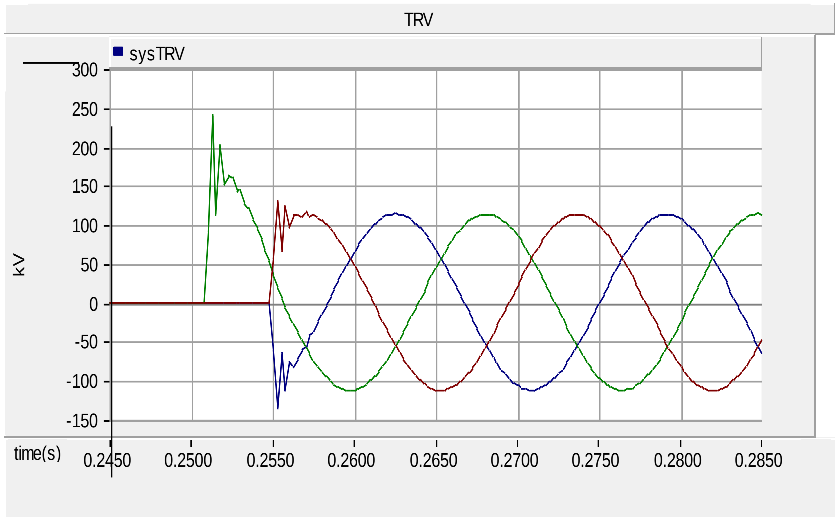
Traditional Applications

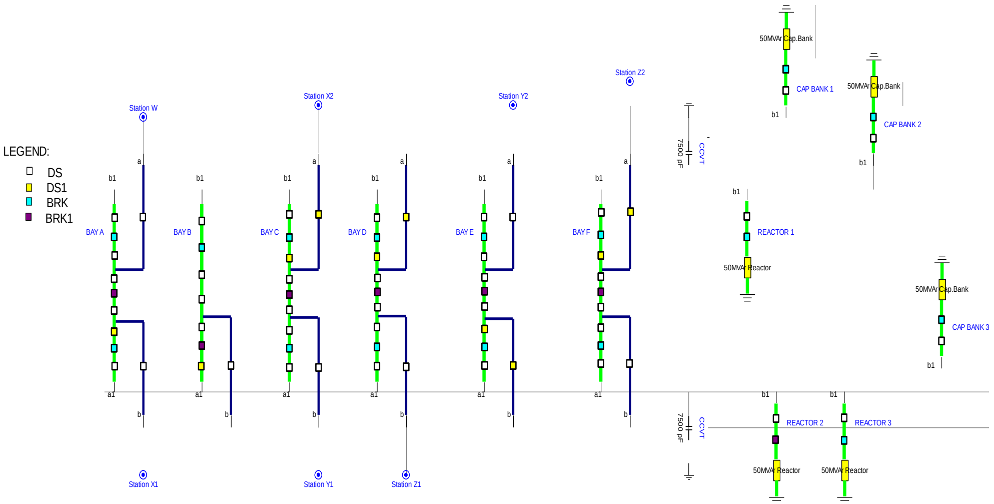
- Wind and Solar PV integration studies
    - Performance during faults
    - Interaction with other devices near the POI
    - FACTS technologies to support wind
    - Application of HVDC transmission (VSC, LCC)
- System Harmonic and power quality analysis
- Protection System modeling and testing
- Sub-Synchronous Resonance

'Non –Traditional' Applications

Circuit Breaker Transient Recovery Voltage (TRV)

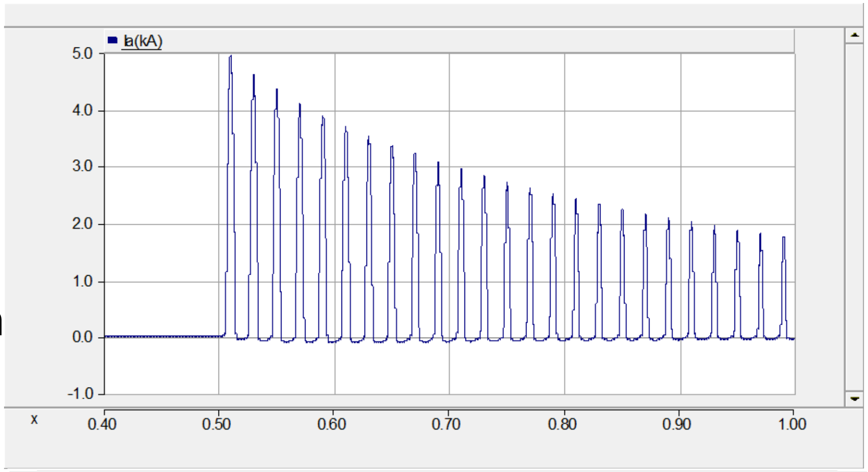
- TRV is the voltage developed across the breaker poles immediately after current interruption
- Fast event
- Simulation circuit should consider details of station equipment
- Breaker TRV withstand capability limits

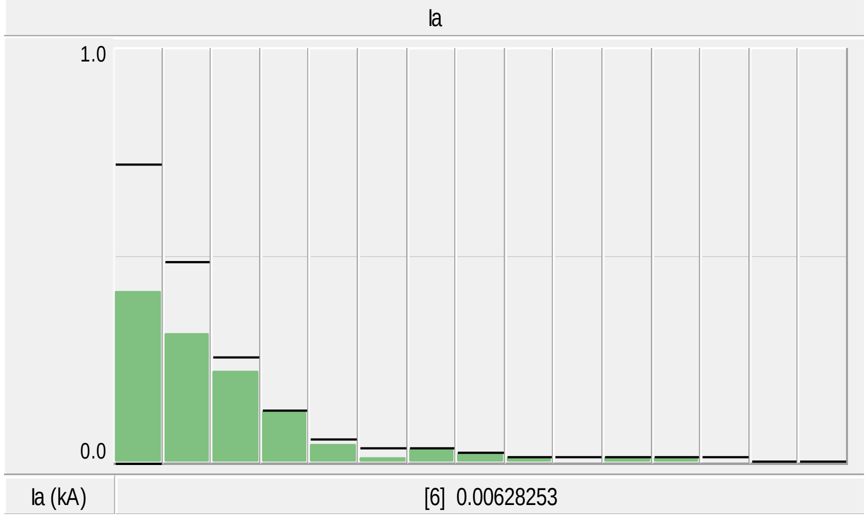


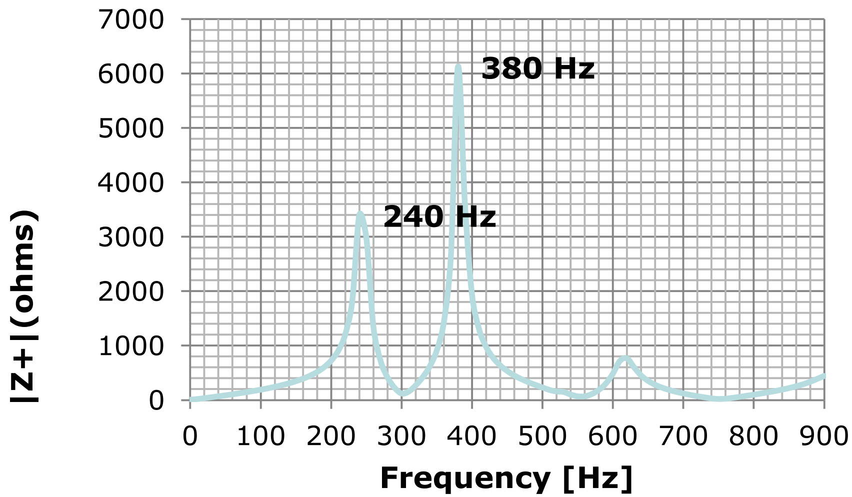


Transformer Energizing

- Core saturation
  - Inrush current and harmonics
    - Voltage dips
- Network characteristics - frequency scan
  - Over voltages due to harmonic resonance conditions







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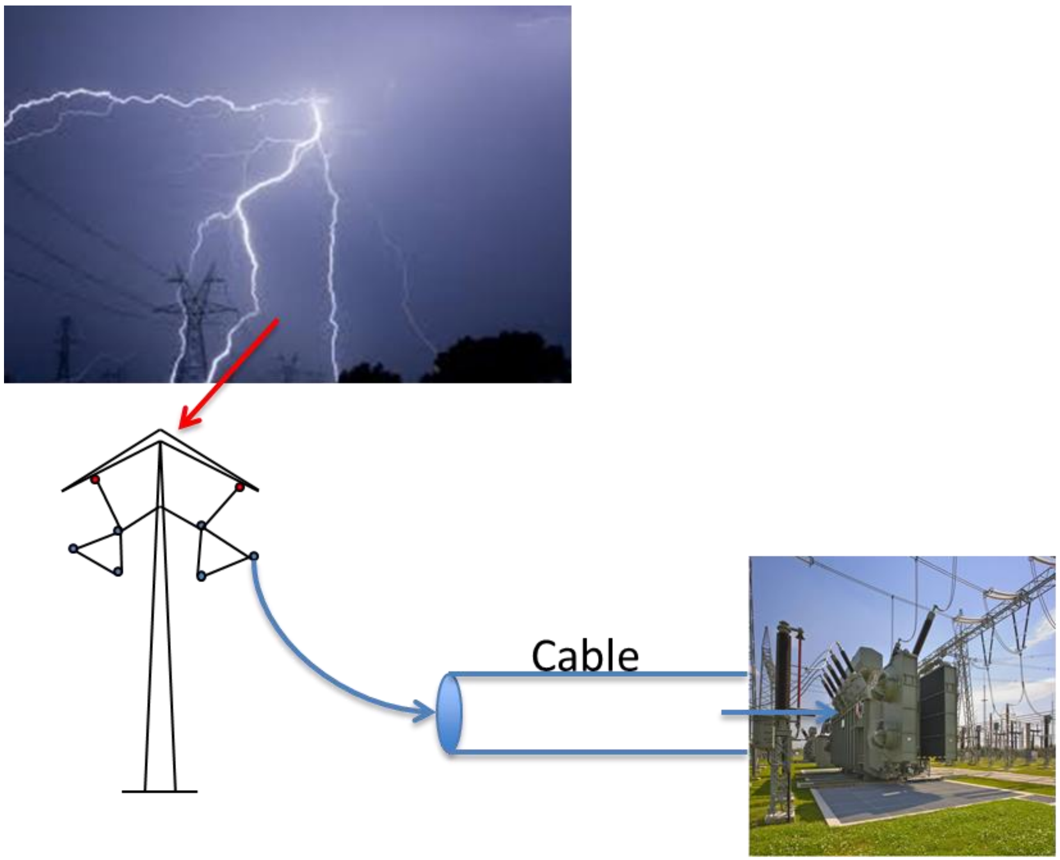
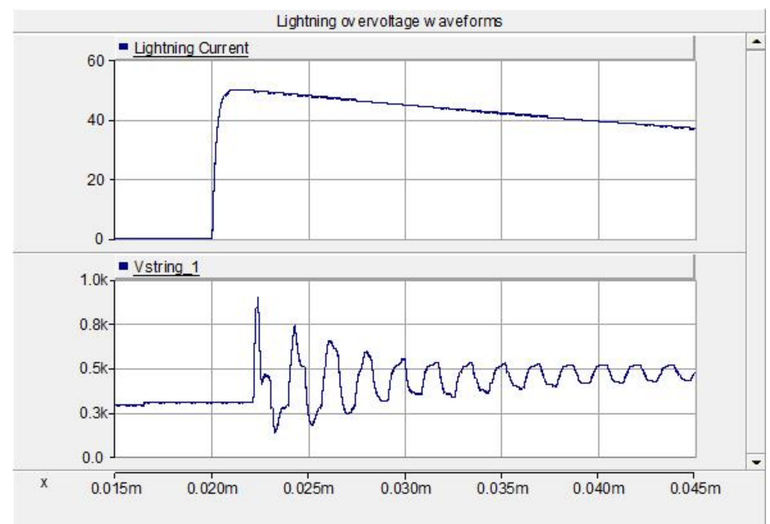
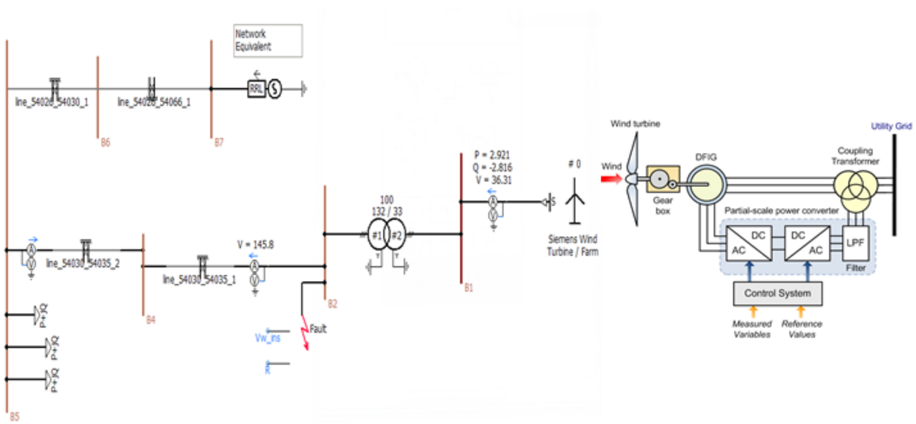
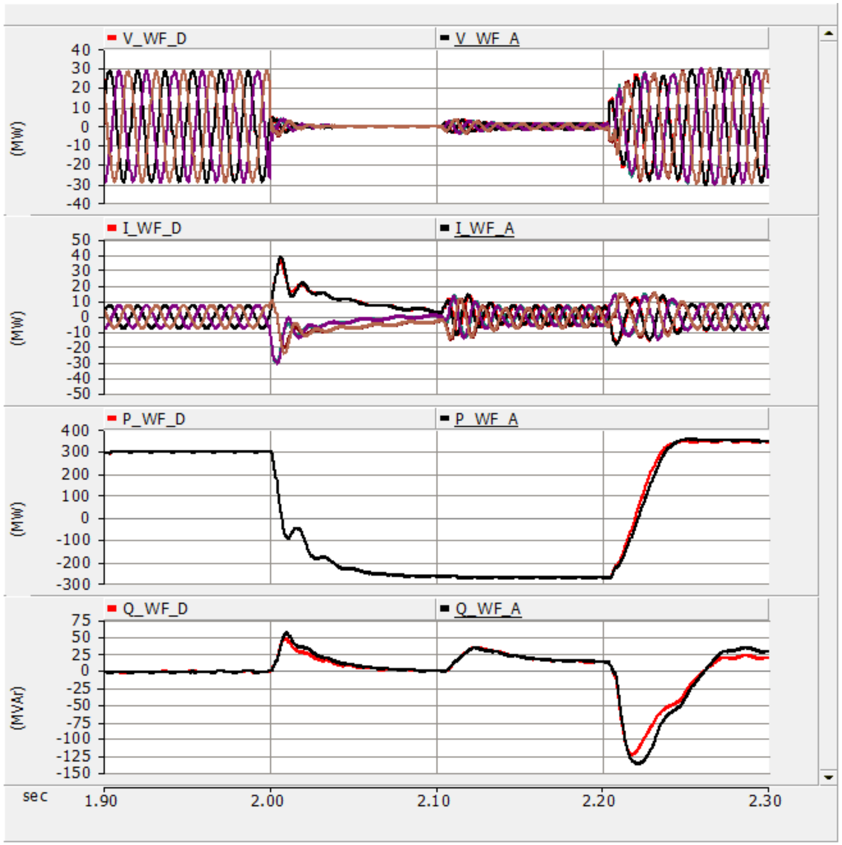
Lightning Over voltages : Protect equipment and limit faults due to back flashover



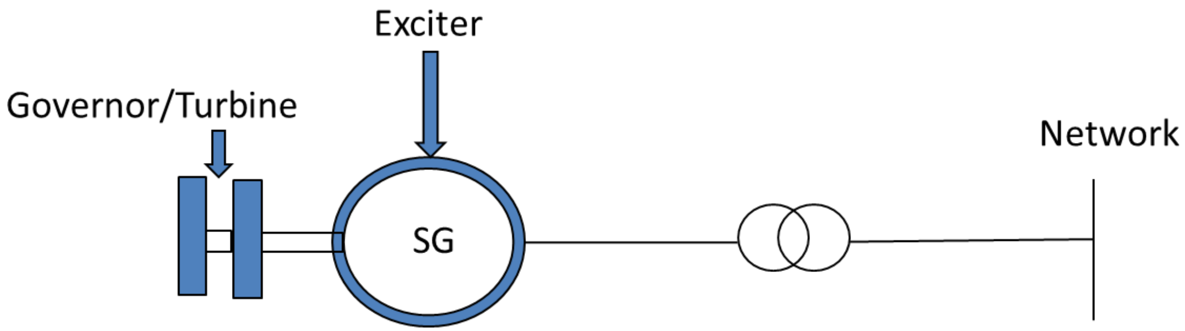


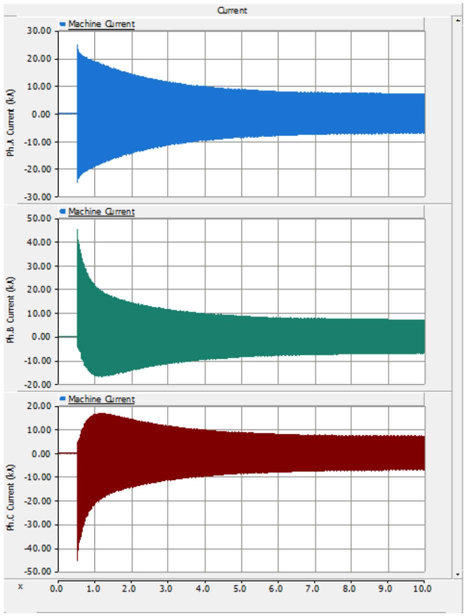
Wind farm fault response

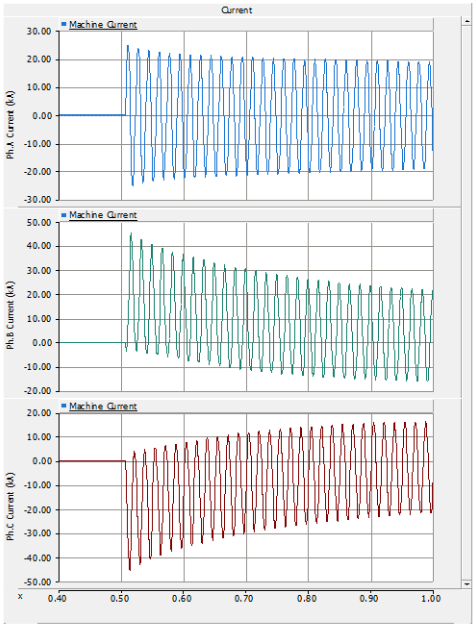




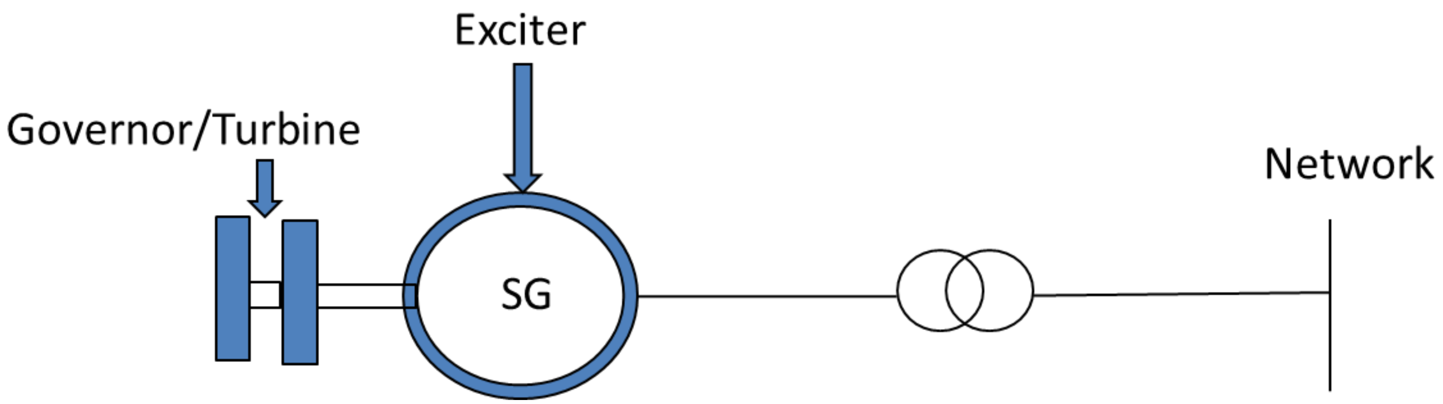
Wind farm fault response





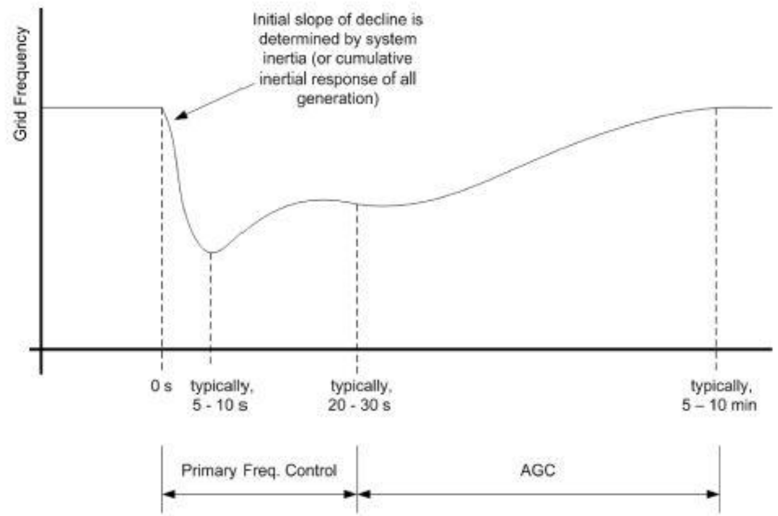


Characteristics of conversional Synchronous Generators



- The Synchronous generator response is determined by
  - Machine electrical characteristics
  - Exciter characteristics
  - Governor / turbine
  - Inertia of the rotating masses

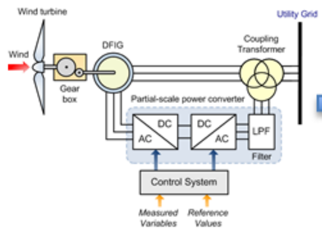
Characteristics of Synchronous Generators



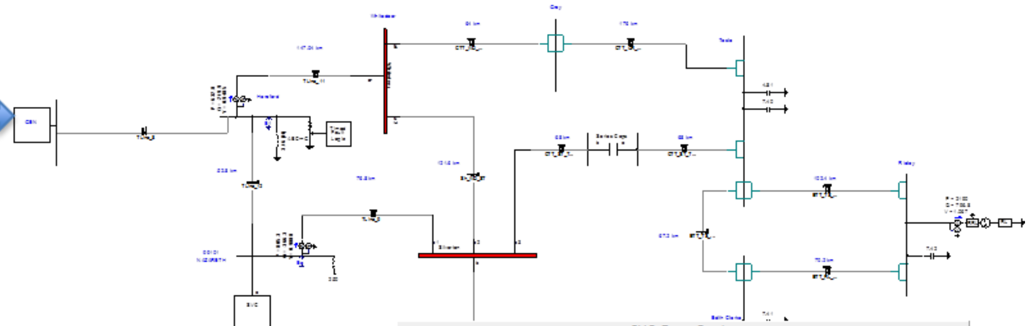
- The response immediately follows the event
- Primary control - 20 -30 Sec
- Secondary - 5 -10 minutes.
- The inertial response is due to the inertia of large synchronous generators

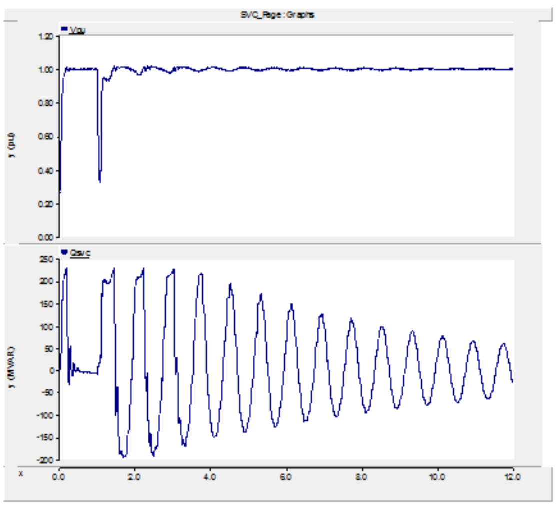
- The Synchronous generator response is determined by
  - Machine electrical characteristics
  - Exciter characteristics
  - Governor / turbine
  - Inertia of the rotating masses

Control Interactions between nearby wind farms/FACTS/Generators

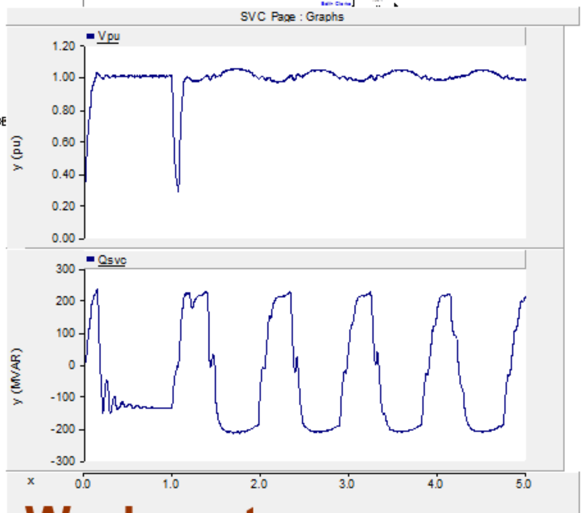


POI





Strong system response



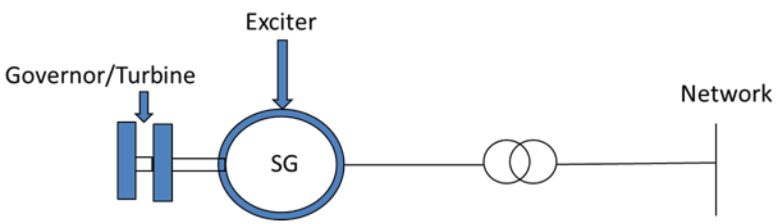
Weak system response

EMT Applications

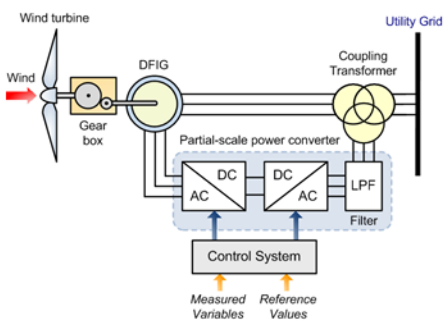
- ‘Traditional’ applications
- ‘Non Traditional’ Applications
  - The characteristics of wind generators are much different from traditional synchronous machine based generation
  - Nature of AC or HVDC transmission used to connect wind to the transmission grid

Wind Generators and Transmission

- The characteristics of wind generators are much different from traditional synchronous machine based generation.
- Nature of AC or HVDC transmission used to connect wind to the transmission grid (long ac cables, filters, weak grids, series compensation)

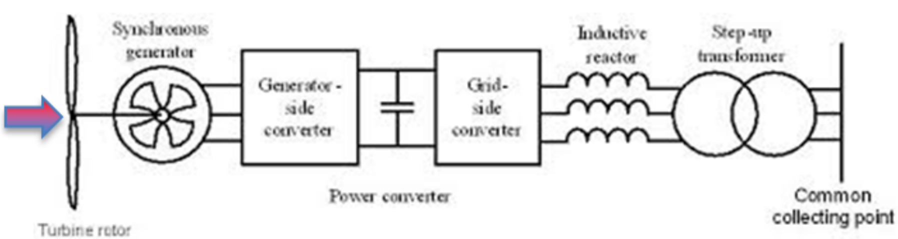


Synchronous generator based



Wind Type 3

Wind Type 4



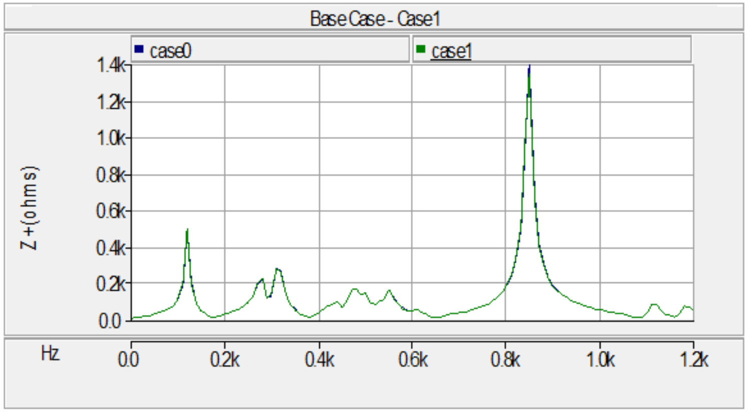
Network Characteristics

- 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.
    - Especially the change in voltage phase.

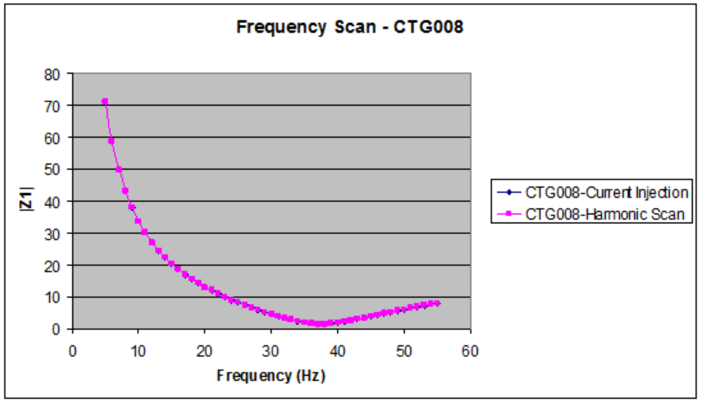
- Series compensated systems
  - Network resonance points in the sub synchronous frequency range (< 50 Hz)

Network Characteristics

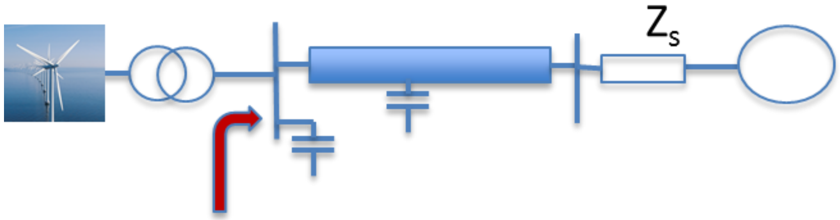
System Impedance Vs Frequency Plots

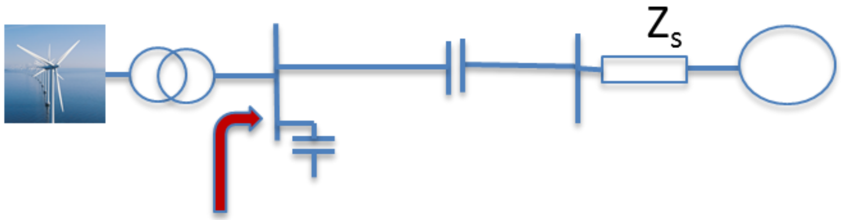


Typical



Series compensated system

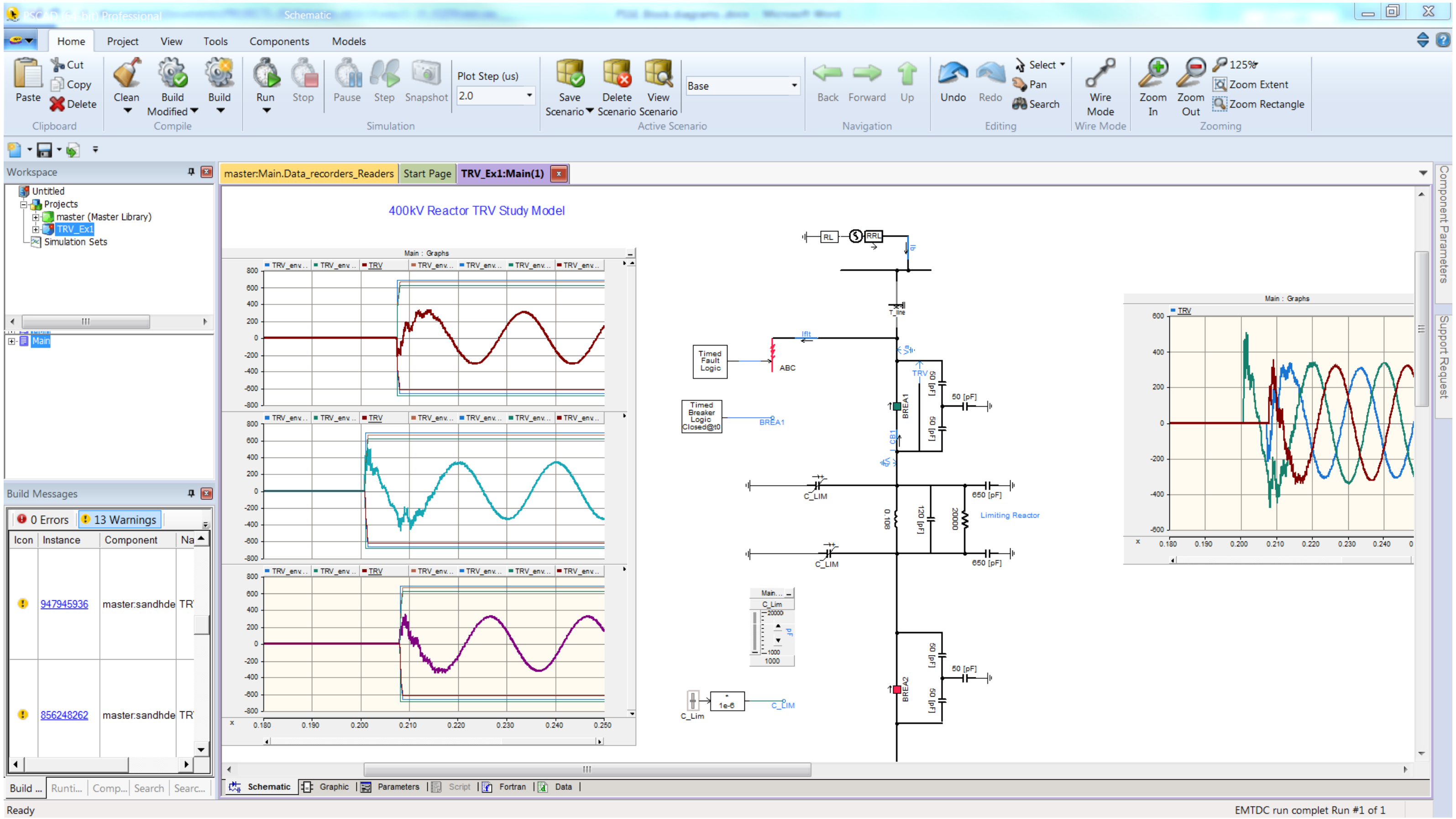




EMT Simulation Tools

Electromagnetic Transient simulations

PSCAD/EMTDC


Home
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Models
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Paste
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Clean
Build Modified
Build
Run
Stop
Pause
Step
Snapshot
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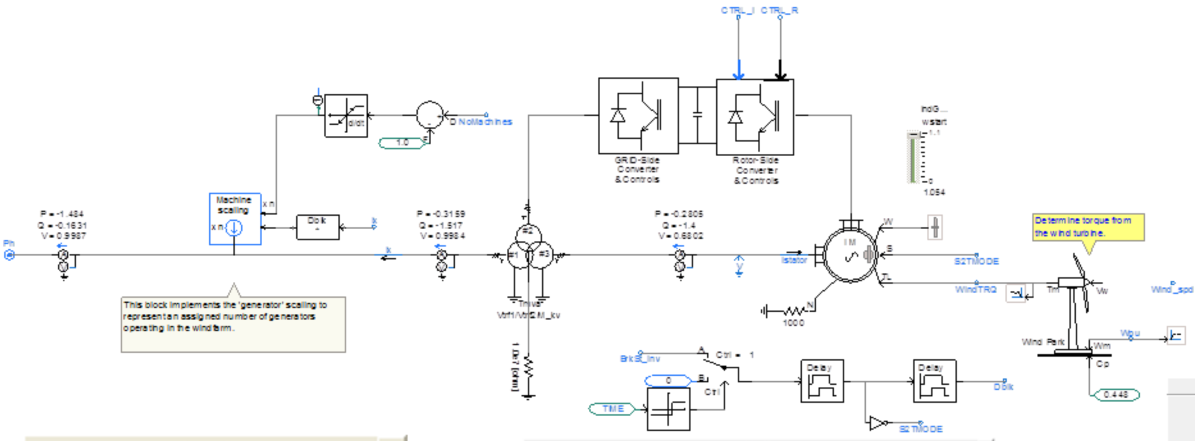
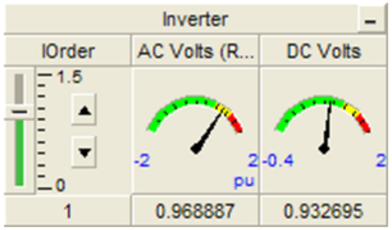
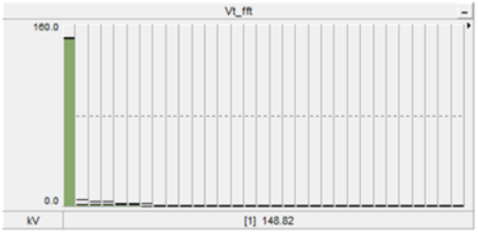
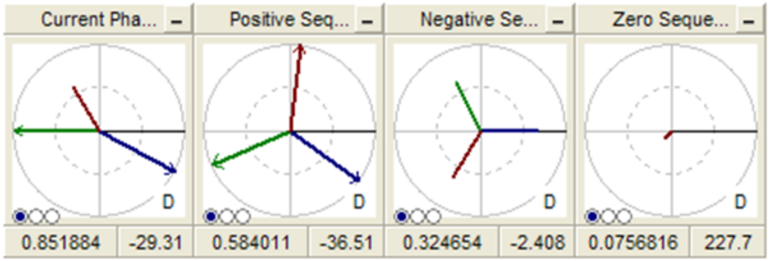
2.0
Save Scenario
Delete Scenario
View Scenario
Base
Back
Forward
Up
Undo
Redo
Select
Pan
Search
Wire Mode
Zoom In
Zoom Out
125%
Zoom Extent
Zoom Rectangle
Clipboard
Compile
Simulation
Active Scenario
Navigation
Editing
Zooming
Workspace
Untitled
Projects
master (Master Library)
TRV_Ex1
Simulation Sets
Main
Build Messages
0 Errors
13 Warnings
Icon
Instance
Component
947945936
master:sandhde
856248262
master:sandhde
master:Main.Data_recorders_Readers
Start Page
TRV_Ex1:Main(1)
400kV Reactor TRV Study Model
Main : Graphs
Timed Fault Logic
Timed Breaker Logic Closed@t0
C_LIM
650 [pF]
50 [pF]
Limiting Reactor
Schematic
Graphic
Parameters
Script
Fortran
Data
Component Parameters
Support Request
Ready
EMTDC run complet Run #1 of 1

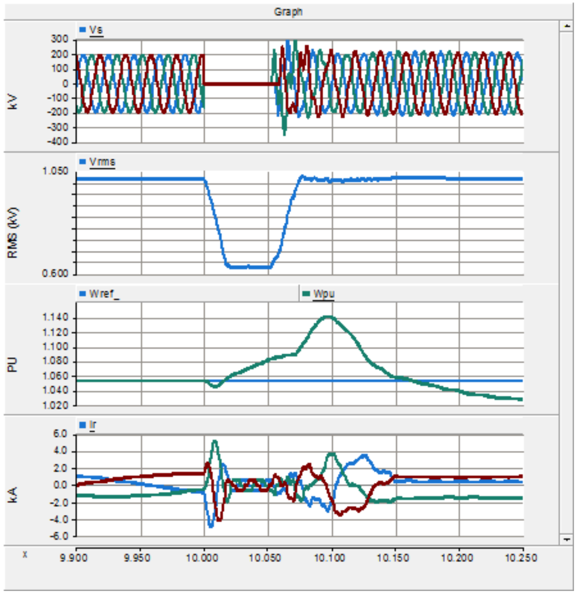
Wide Range of Applications









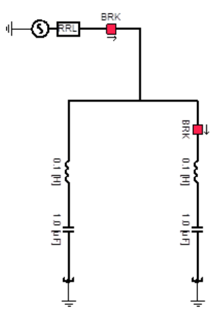


Transients and Steady State

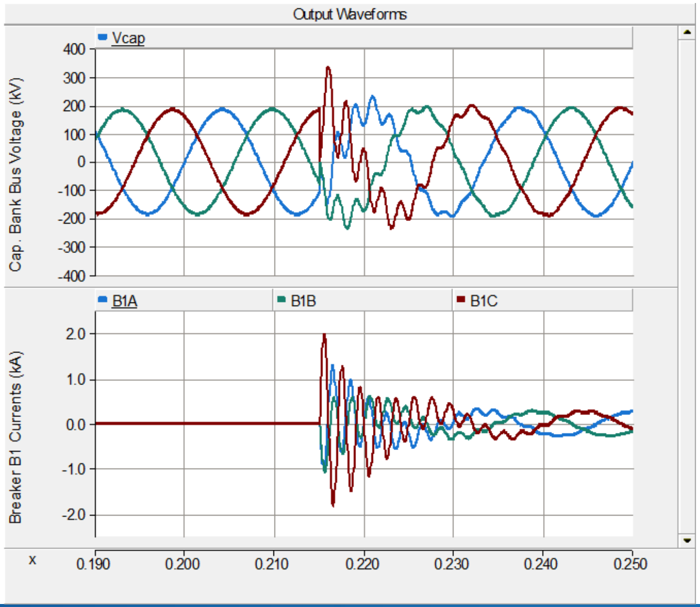
Transients are initiated due to a change to the network topology (connections)

- Switching Events
- Faults
- Lightning
- Others

- Transient solution
  - Harmonics
  - Non-linear effects
  - Frequency dependent effects
- Steady state solution
  - RMS Value
  - Magnitude and phase



Close breaker



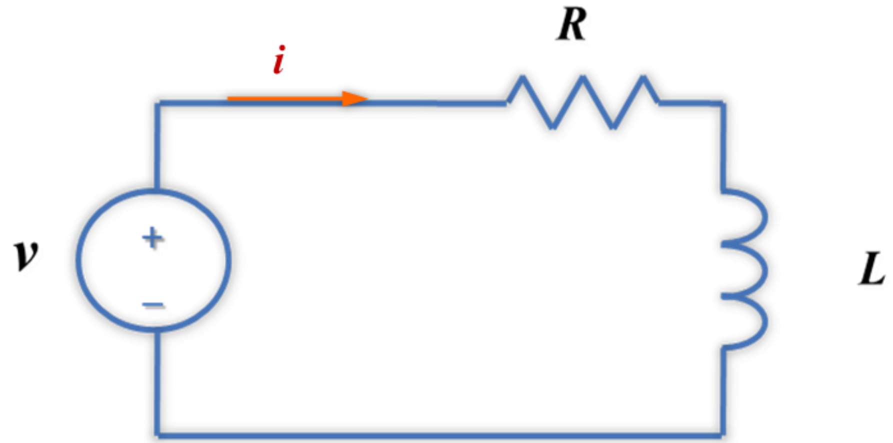
EMT and RMS Simulation – main differences

Transients and Steady State

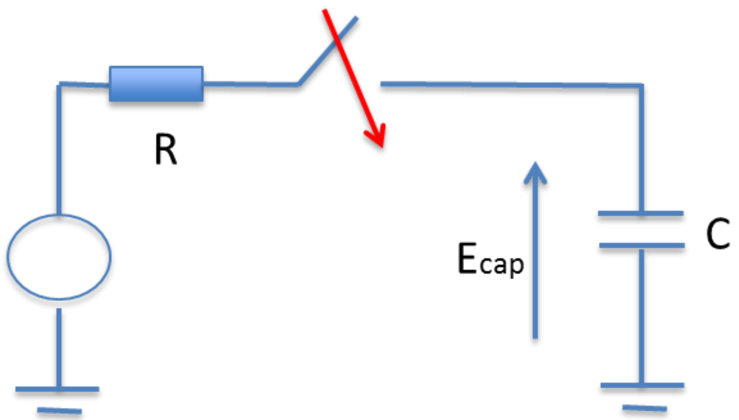
- Load Flow / Transient Stability
  - Each solution based on phasor calculations
- Electro-Magnetic Transients
  - Direct time domain solution of Differential Equations

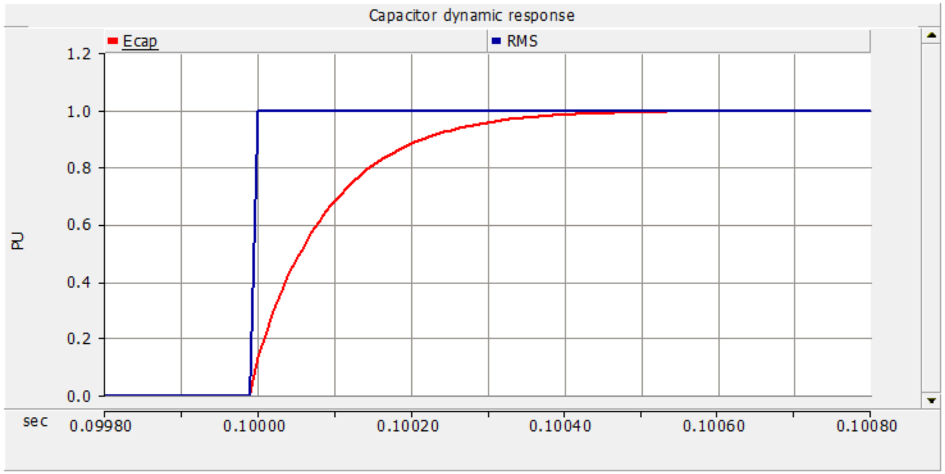
$$V(\omega) = R \cdot I(\omega) + j(L\omega) \cdot I(\omega)$$

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



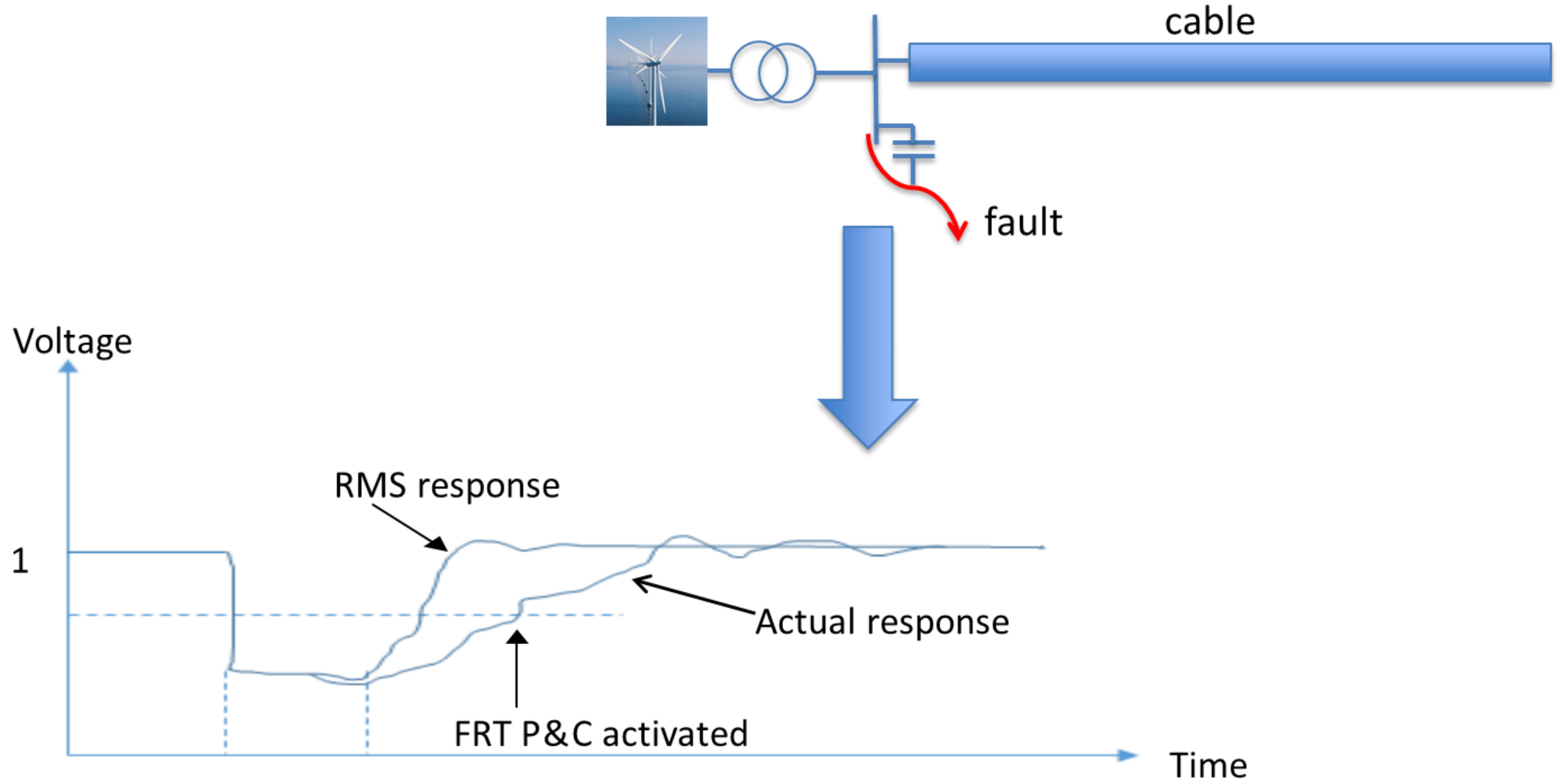
Capacitor voltage response





EMT Vs RMS response - 02

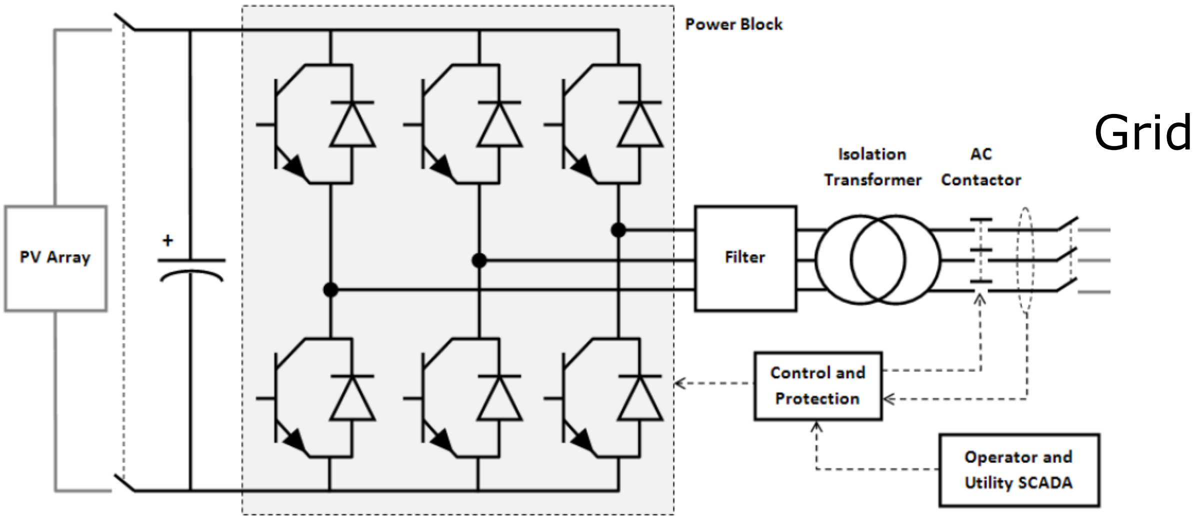
Fault Ride Through response of a wind farm



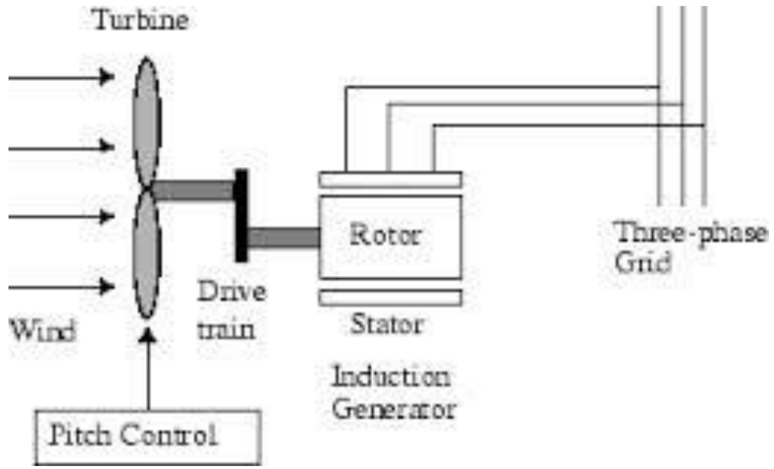
Wind generator Types

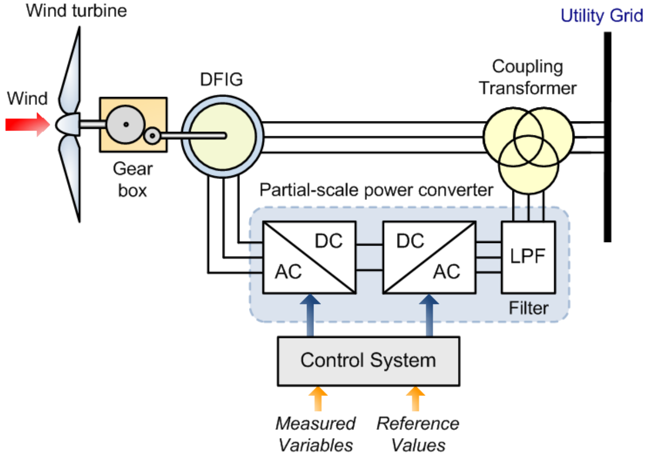
Wind Generator Types

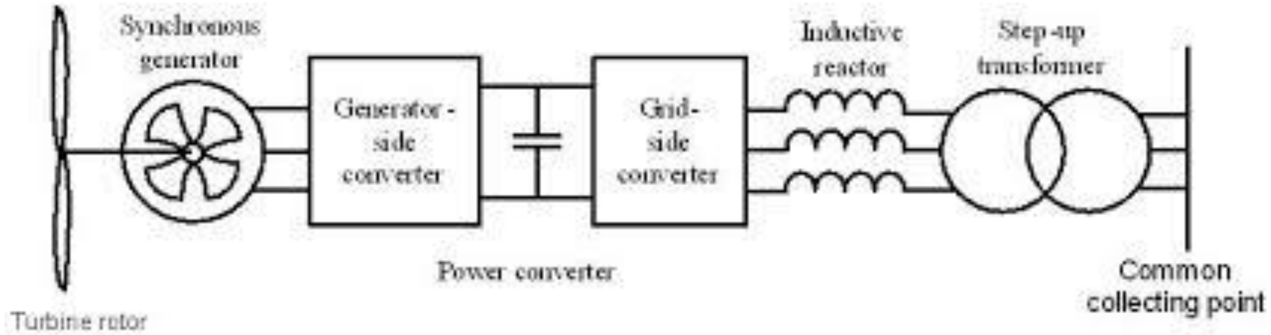
- Type 1 – Induction machine based
- Type 2– Induction machine with external rotor resistance control
- Type 3 – Induction machine/power electronic converters
- Type 4 – Induction, PM, Synchronous machine / Power electronic converters



Wind Generator Types

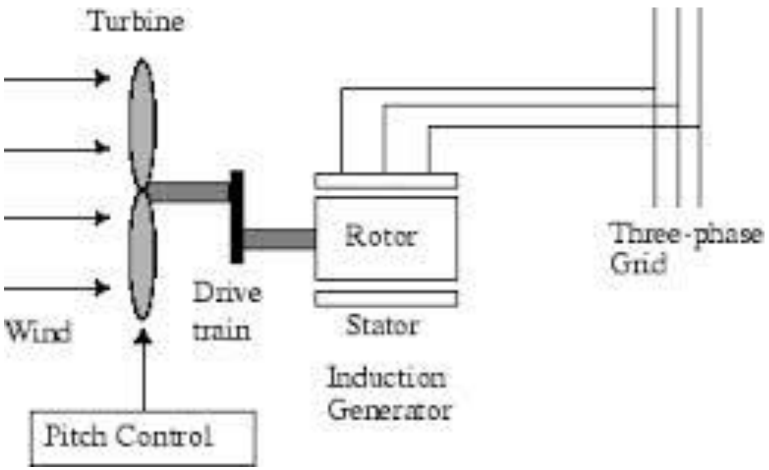






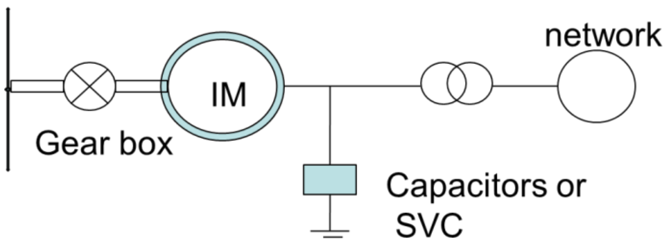
Wind Generator Types

- Type 1 and Type 2
  - Direct connected (to grid) induction machines
    - Simple scheme, Complex control systems not involved,
      - Poor response during faults and other system events

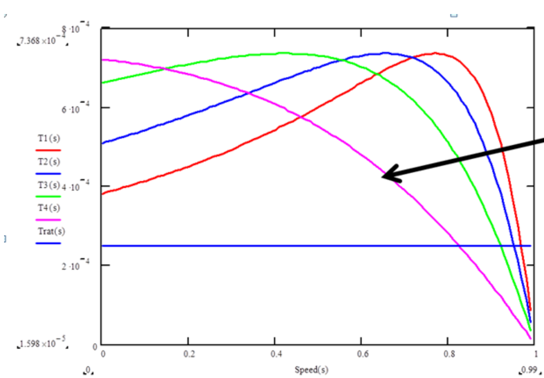


Wind Generator Types

Direct connected induction machine:

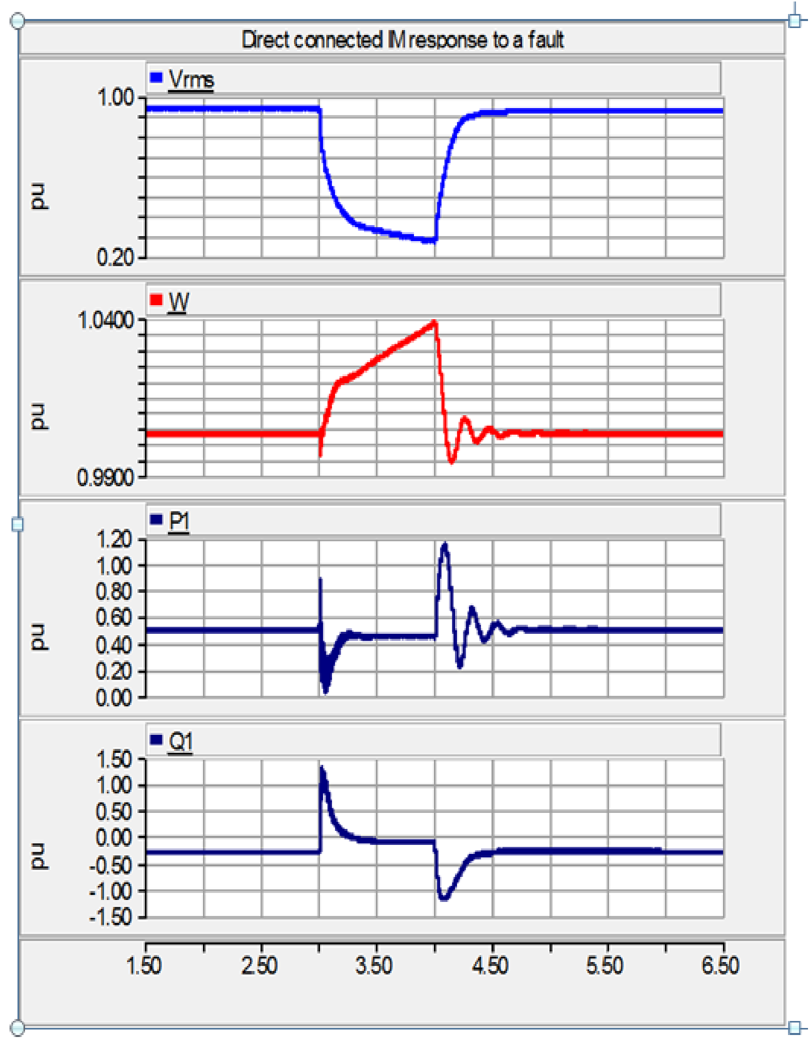


- No slip rings/brushes,
- Squirrel cage machine has a simple robust construction
- Less maintenance
- 'Fixed speed' operation



R_{rotor} increasing

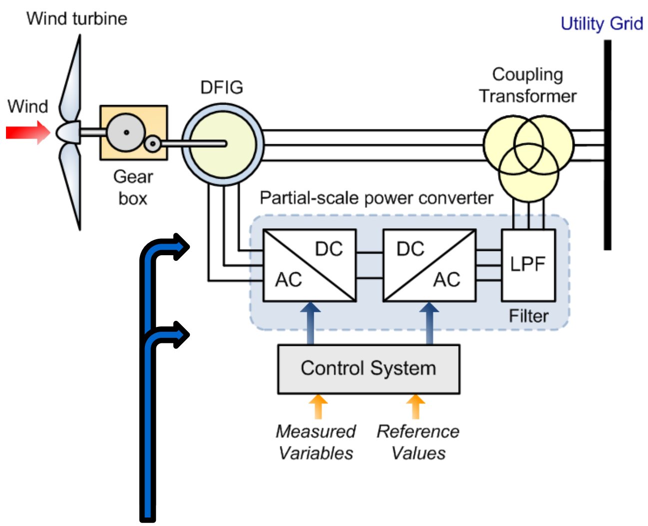
Typical speed variation:
+/- 5%

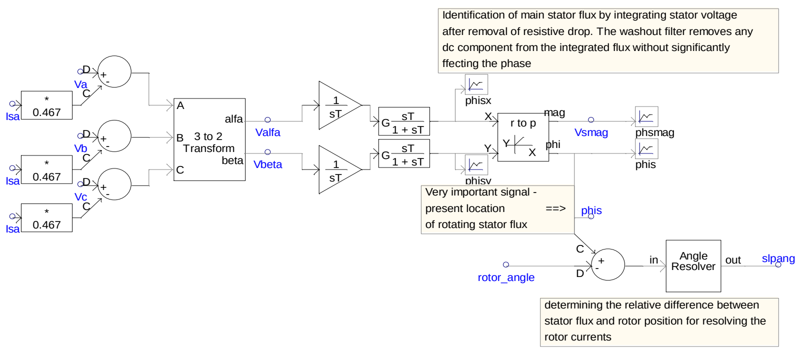


Wind Generator Types

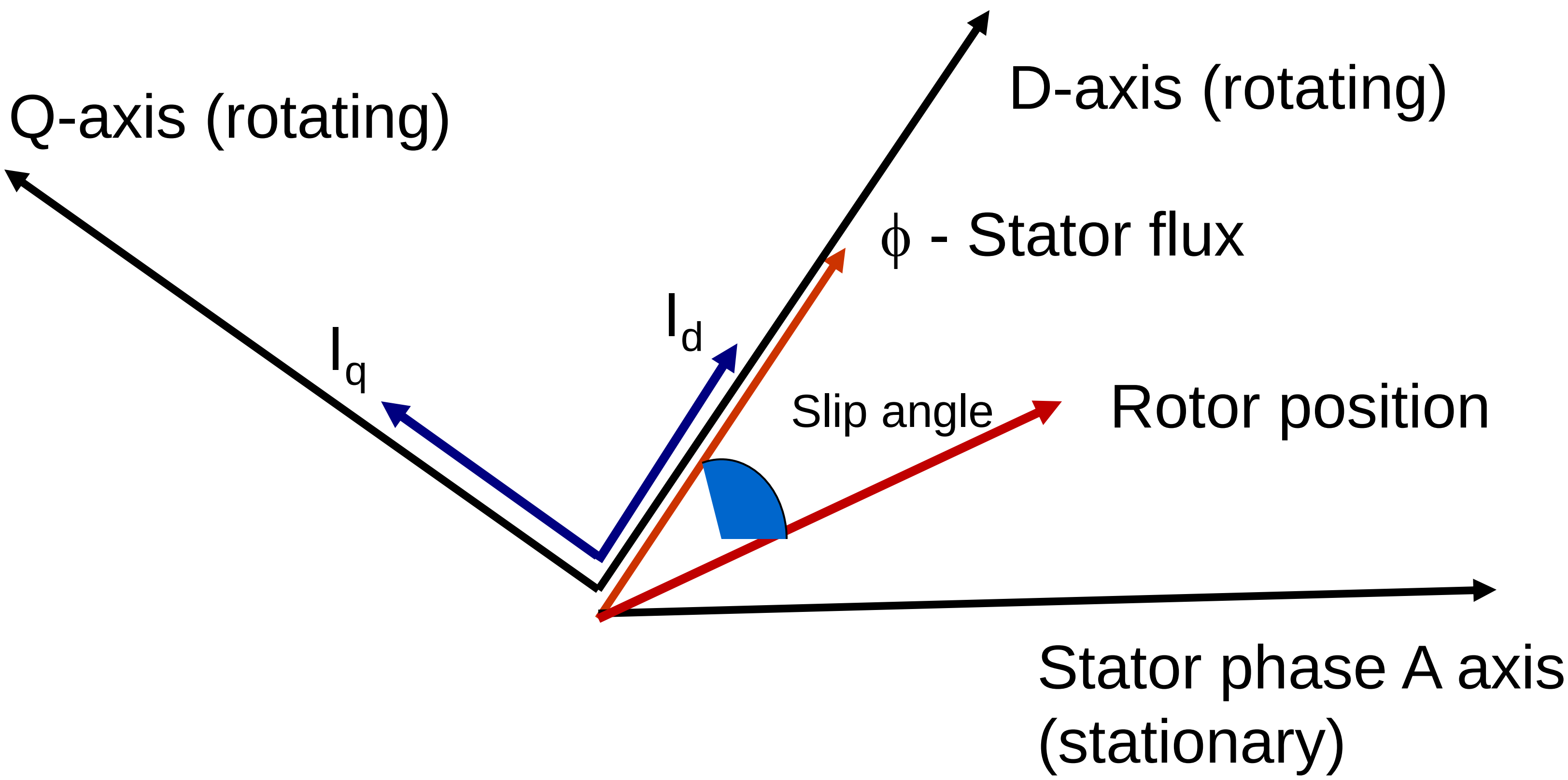
Type 3: Doubly Fed Induction Generator (DFIG)

- Complex control /measurement systems and power electronic converters are required to make this scheme work.
    - Much improved response during fault recovery
    - Ability to control of P and Q
    - Complex controls can interact with the transmission system with negative impact
        - Proper control tuning necessary (specially in weak grid situations)





Inject 'controlled' currents to rotor => magnitude, phase and frequency


Q-axis (rotating)
D-axis (rotating)
ϕ - Stator flux
I_d
I_q
Slip angle
Rotor position
Stator phase A axis (stationary)

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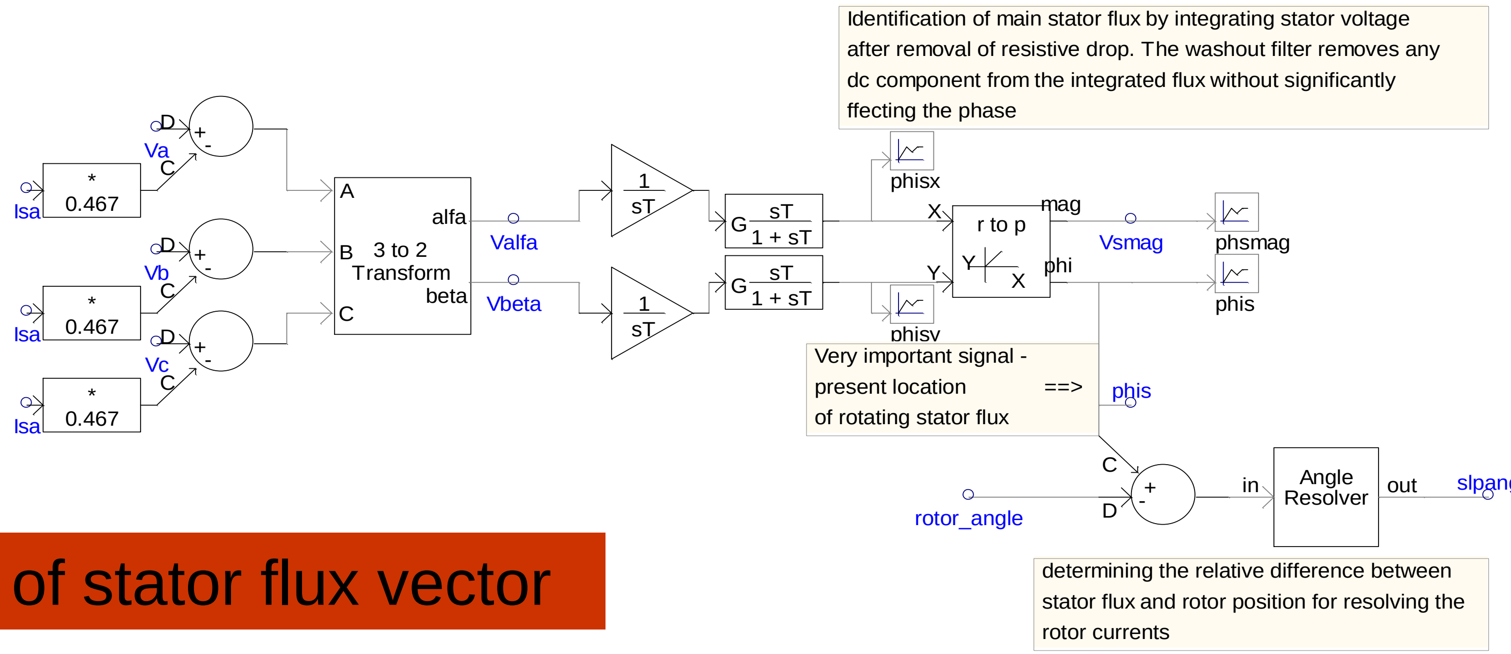
Position of the Flux Vector

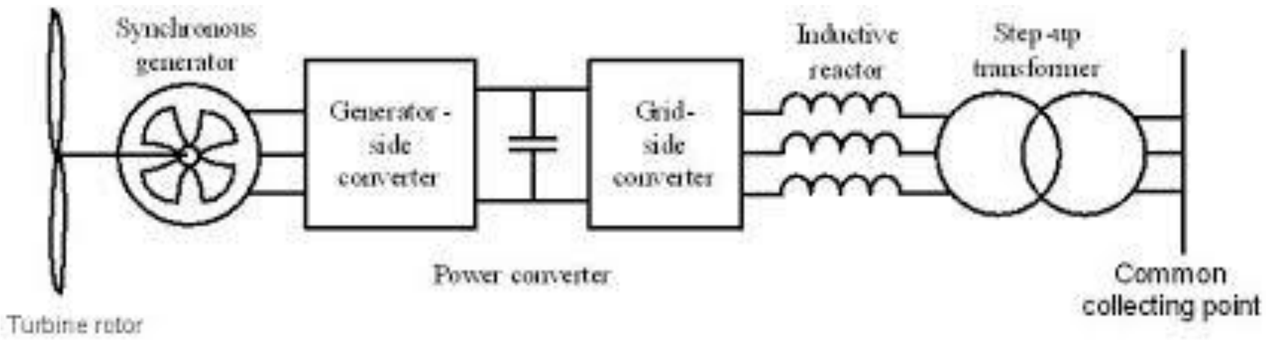


Estimation of stator flux vector

Implementation is easier in the Alfa - Beta Fame.

Wind Generator Types

- Type 4: Back to Back converter based
  - Also depend on Complex control /measurement systems and power electronic converters Much improved response during fault recovery
    - One notable difference compared to type 3: machine decoupled from ac system via the Back to back converter.

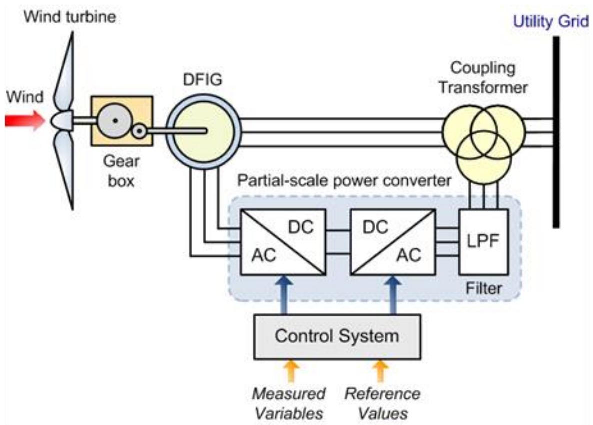


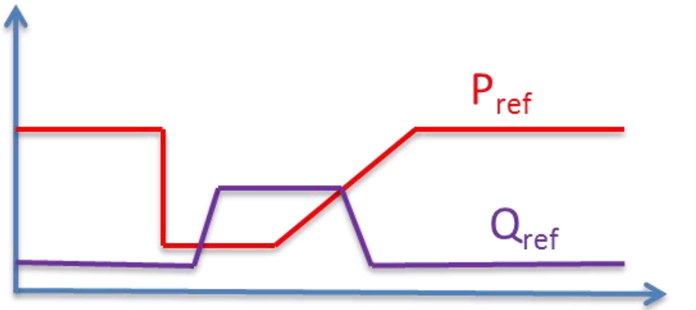
Grid Integration of Power Electronic Based Generation

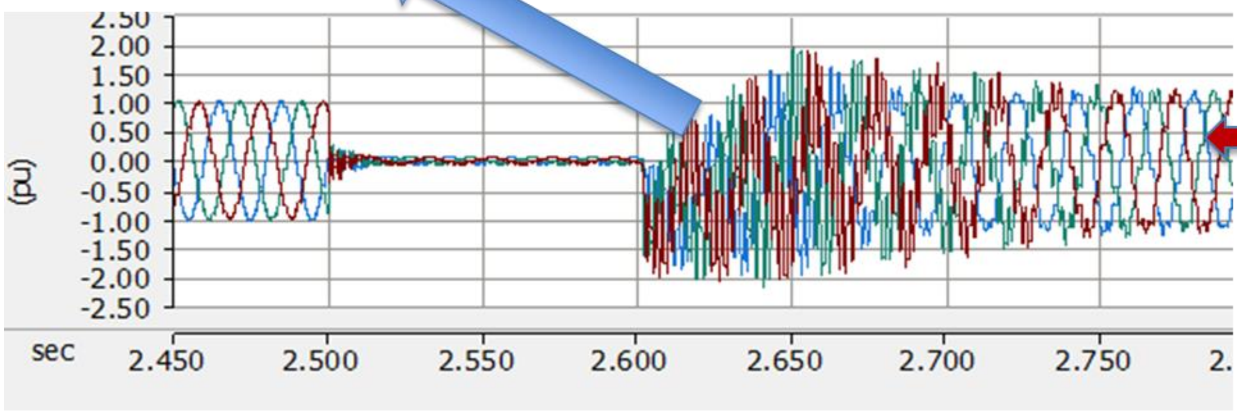
- Solar PV, Type 3 and Type 4 renewable integration type use power electronic inverters.
- Inverter performance depend on the fast and accurate measurement of the Bus voltage phase angle
    - This is a challenge in ‘weak’ system

Why EMT for ‘specific’ wind integration studies

Integration of wind power to weak grids – overall response and grid code compliance







Bus voltage following a fault

Integration of wind to weak grids – overall response and grid code compliance

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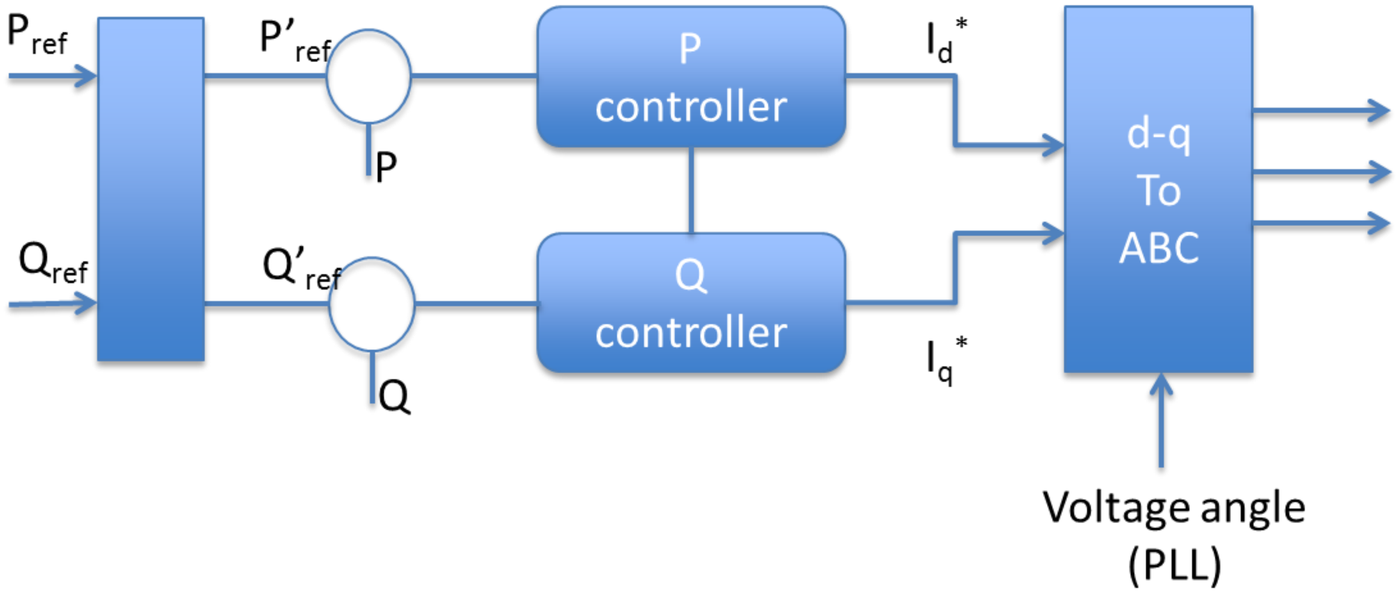
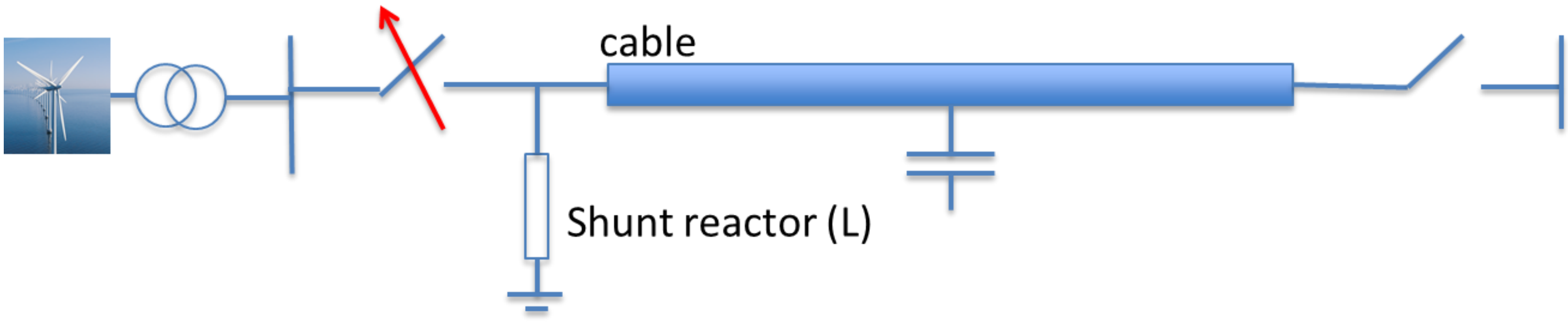
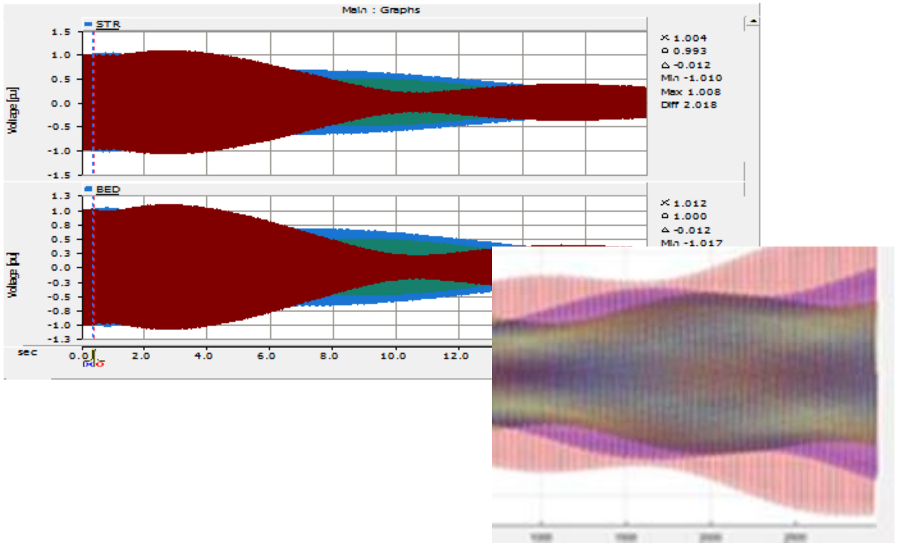


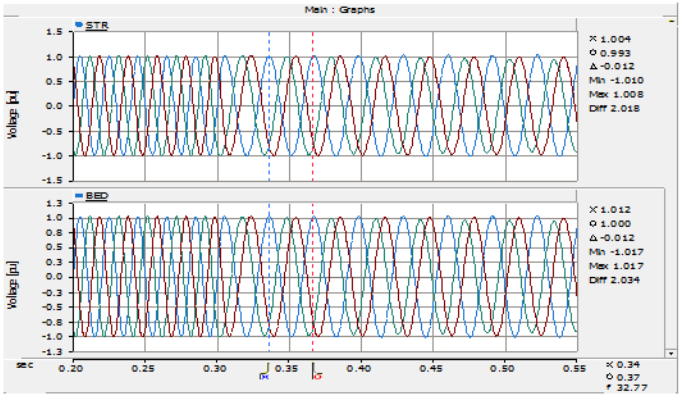
EMT simulations must be used to accurately represent the response of the PLL and fast controls.

This is more of a concern in 'weak grid interconnections'

AC Cables and Network Characteristics

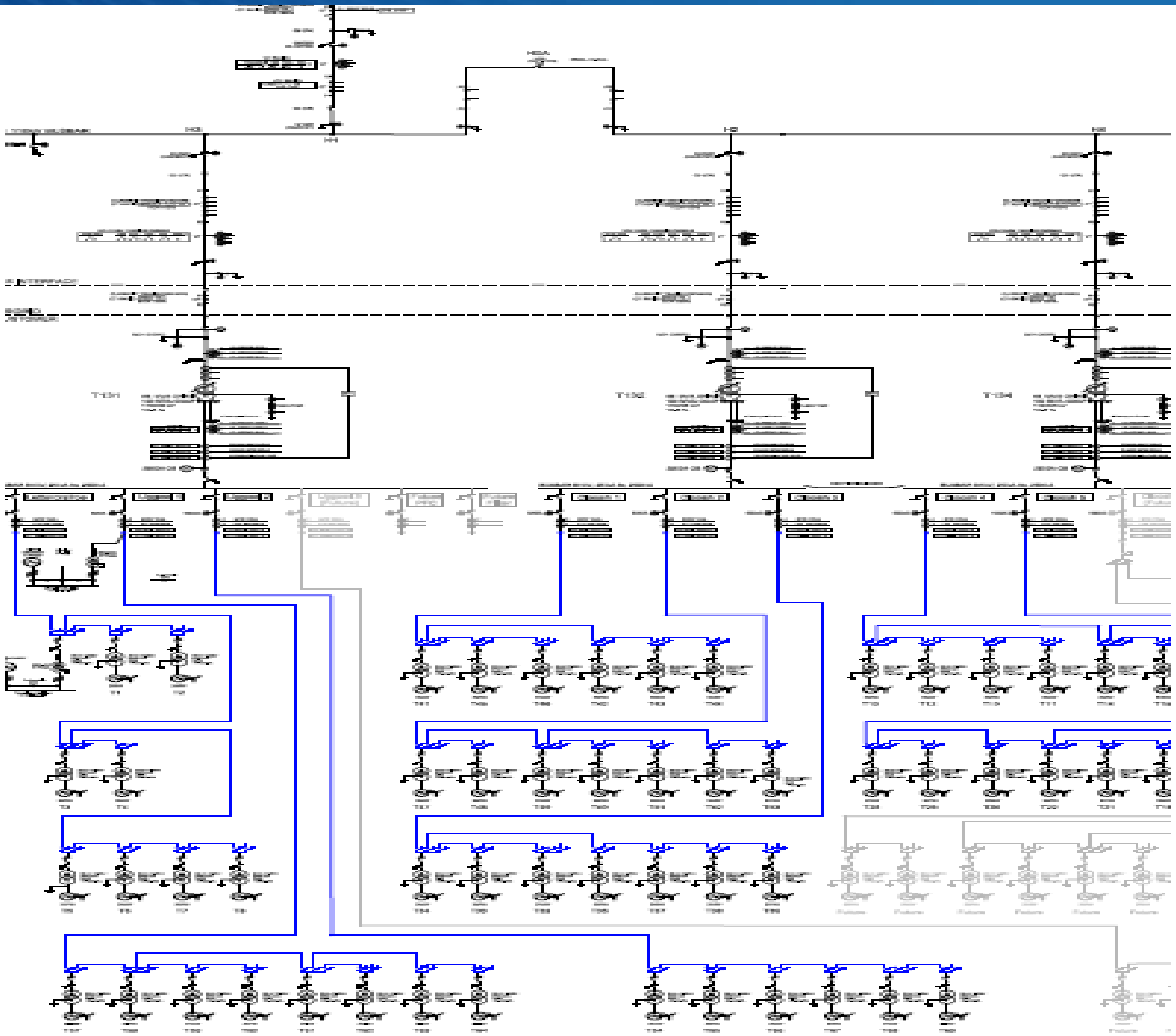






Practical Examples

Example 1 Temporary over voltages (TOV) on wind farm collector cables



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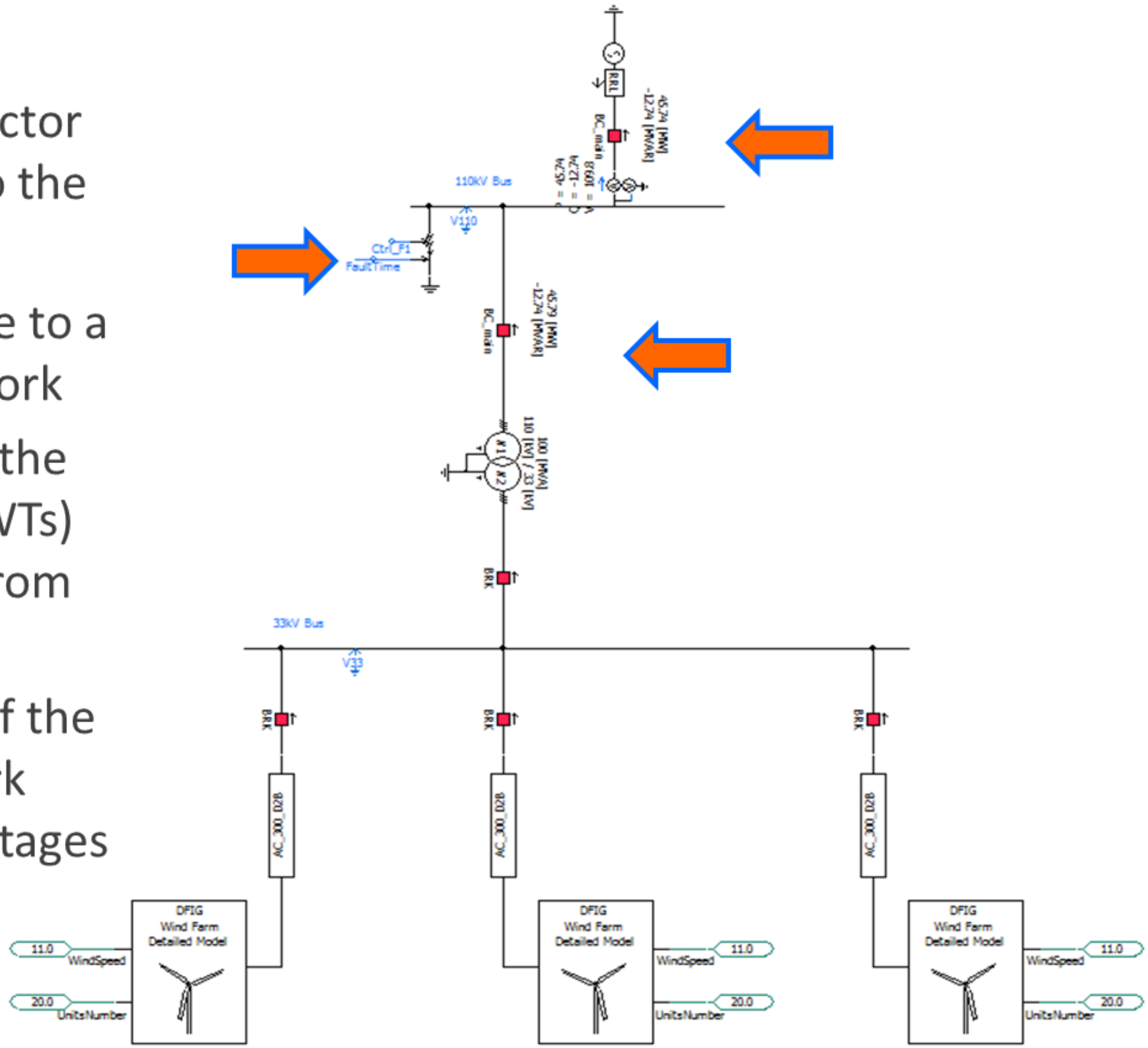
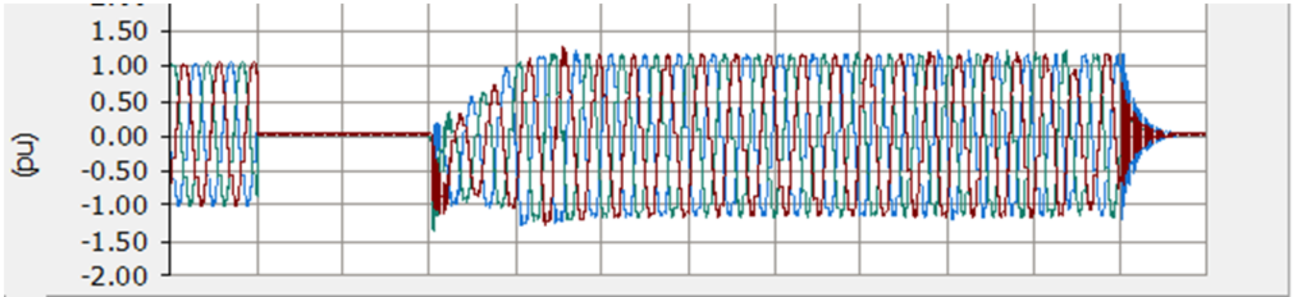
Study Model – Temporary Over Voltages (TOV)

- Wind farm and collector system connected to the power grid
- Breakers opened due to a fault on the ac network
  - Breakers isolate the wind turbines (WTs) and the cables from the grid
  - Rapid increase of the collector network and terminal voltages of WTs



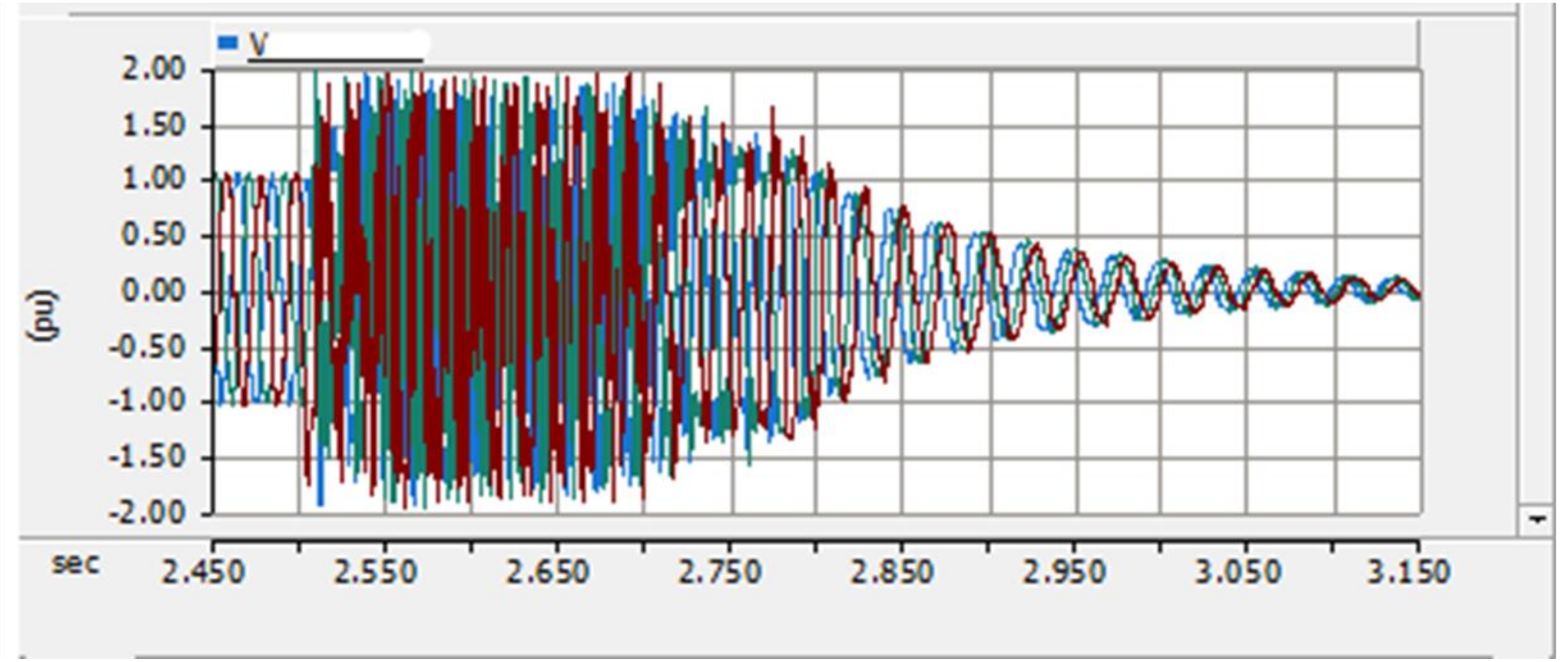
TOV on isolated collector feeders

- Rapid increase of the collector network and terminal voltages of WTs
  - Serious TOV concern
  - WTGs should be able to limit this TOV through protection and control action
  - Cable capacitance and number of tripped WTG units effect TOV



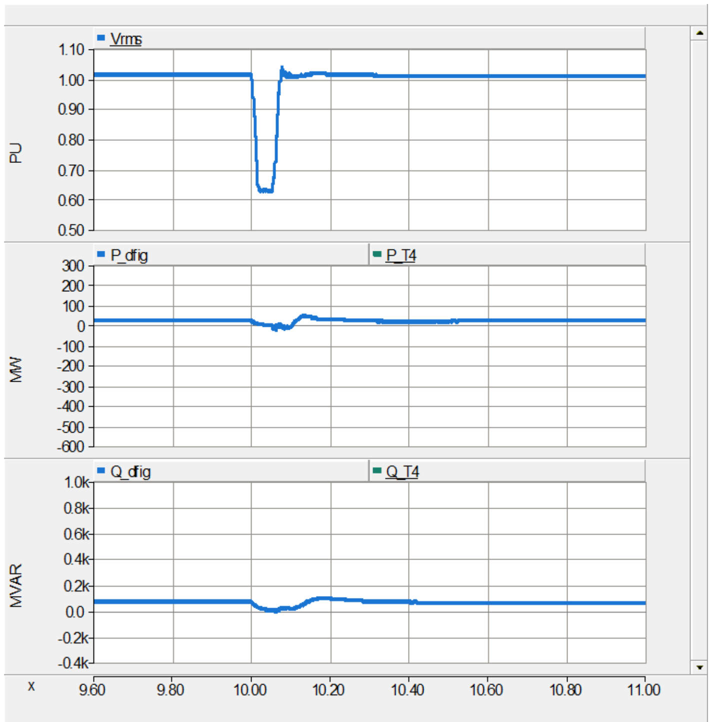
TOV on isolated collector feeders

- Fault on the 110 kV side

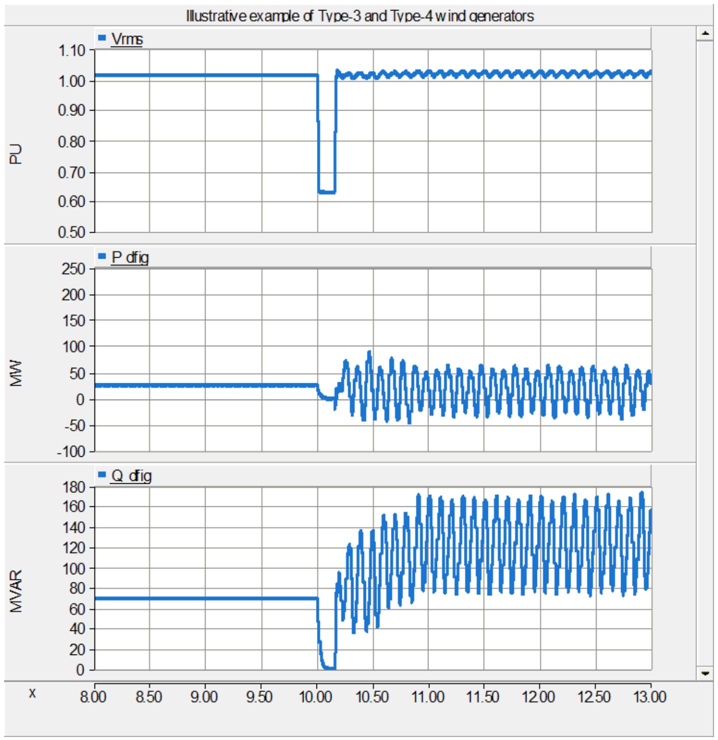


Fault ride through of the wind farm

•



Stable case



Unstable case

Representation of WTGs for simulation studies in PSCAD

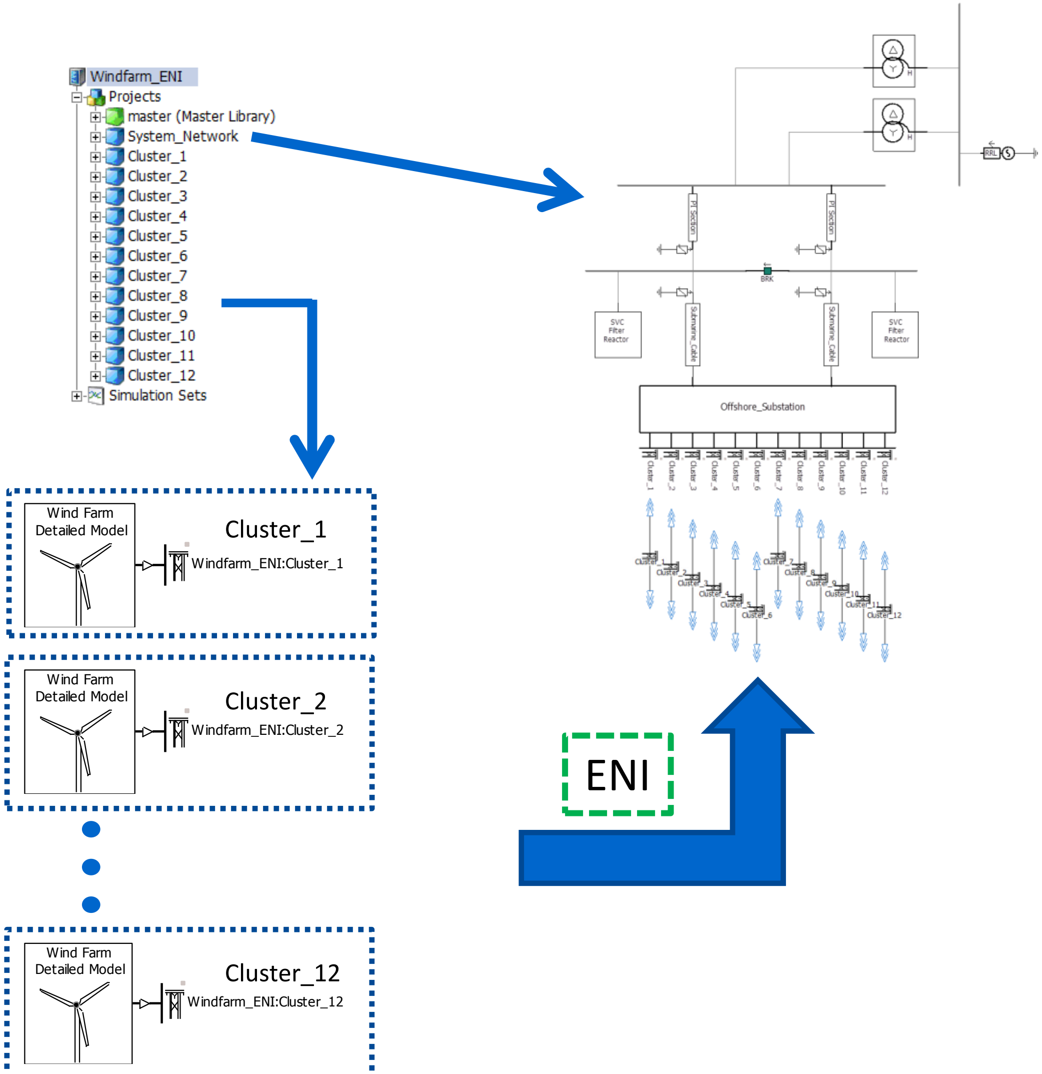
Do we have to model all WTG units in a wind farm

- Model aggregation for system level studies (1 WTG per feeder ?)
- Represent multiple WTG's on a feeder for specific transient studies)

PSCAD/EMTDC feature

- Electric Network Interface (ENI) **=>**where parallel processing capability of computers is utilised to break an electric system (with many WTGs for example) into smaller cases.

Electric Network Interface (ENI)

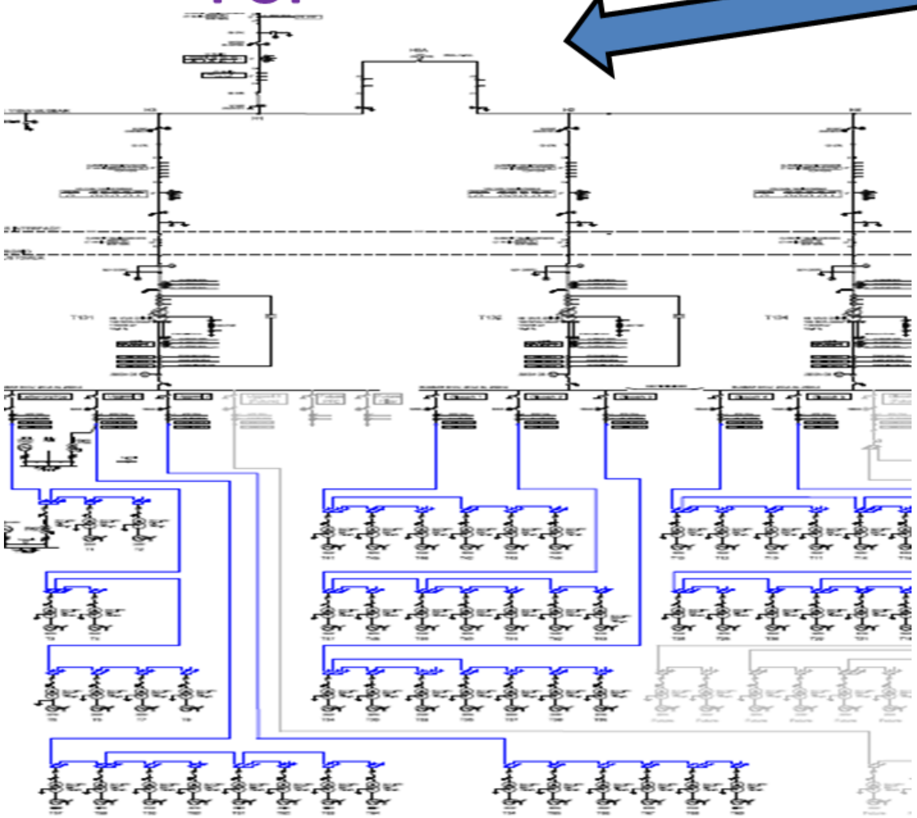


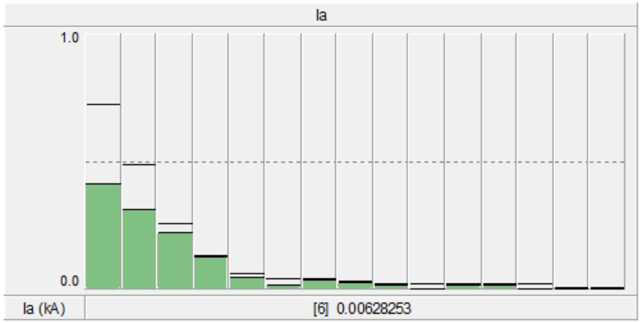
- ENI provide a way to break large electric networks into subnetworks, interconnect them, and run each as a separate process, on an individual processor core.
- This example shows 12 Detailed PSCAD Wind farm models connected to the network through Electric Network Interface (ENI).
- Each detailed model is representing one or few wind farm turbine generators.

Example 2 – Harmonic Performance

What are the harmonic impact at POI and customer load locations (THD).

POI





Harmonics injected from the converter based wind (or PV) penetrated to the POI and utility network via the array cables or lines.

Harmonic Model of a WTG

V_h - Harmonic voltage source

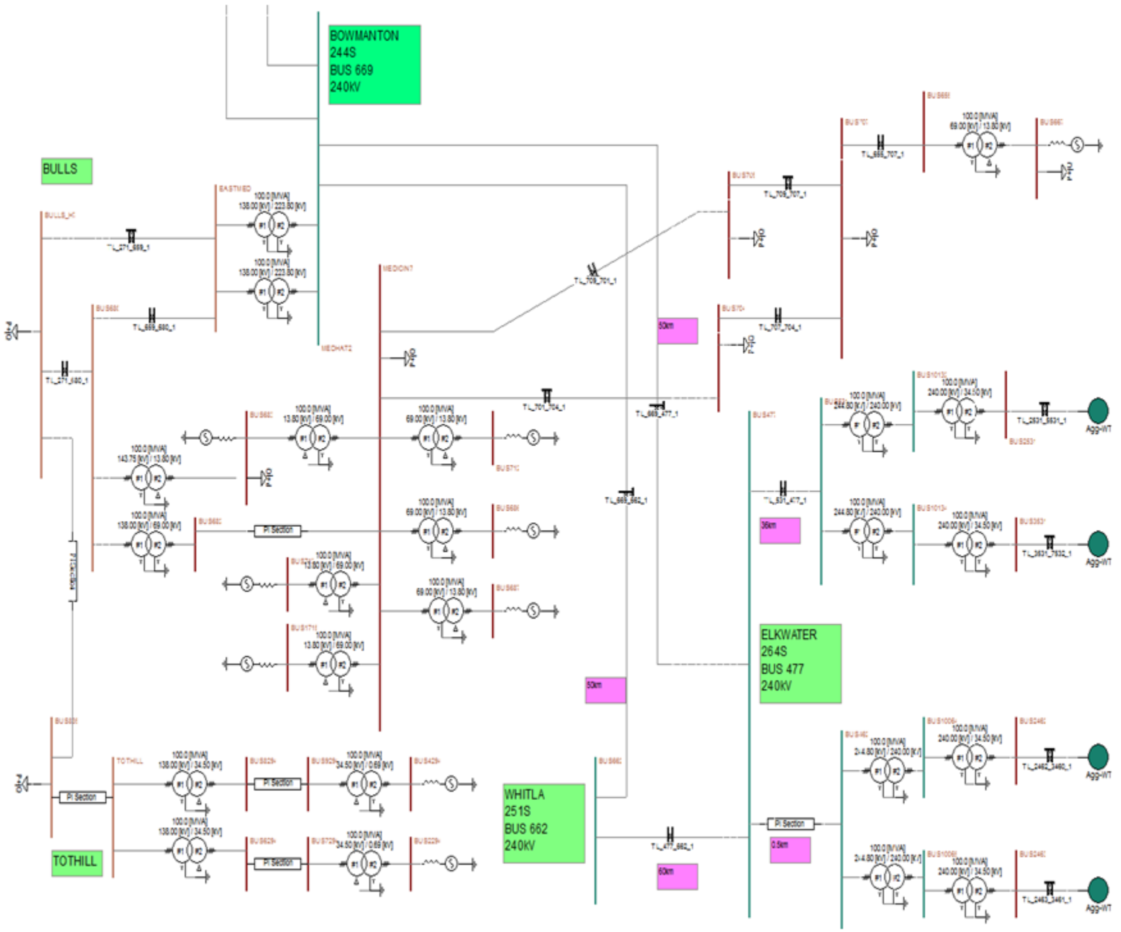
Z_h - Harmonic impedance (frequency dependent)

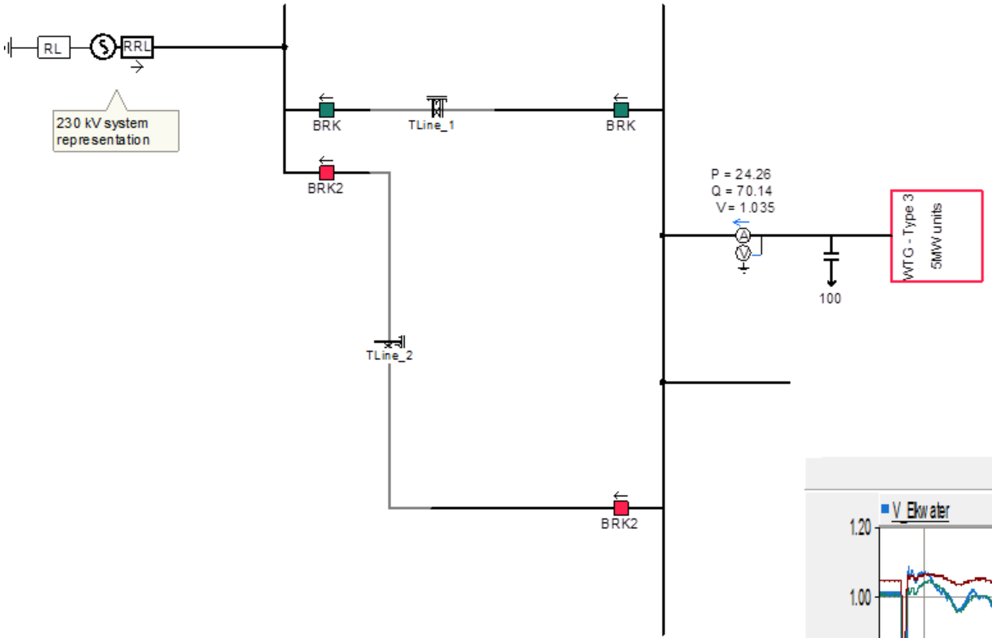
The simplified harmonic source parameters are derived based on detailed EMT model response and (potentially) validated through field measurements

Example 3 – Wind Farm Response During Faults

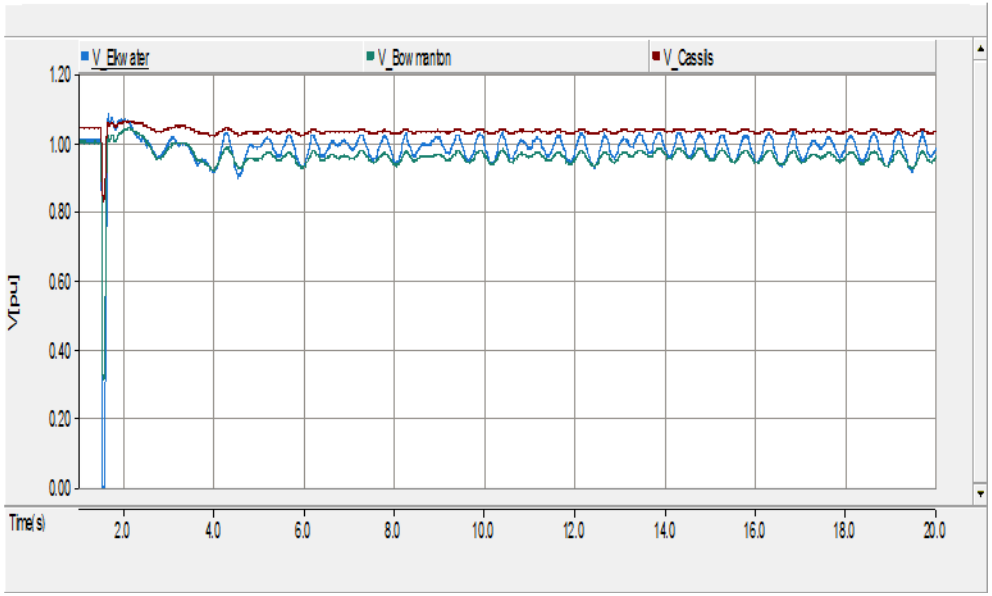
Wind Integration: 400 MW Wind Farm (Canada)

- Wind farm: 400 MW – Type 3
- Weak Grid Interconnection
- Difficulty meeting grid interconnection requirements
  - Tripping of wind farm following a system fault
  - Unacceptable oscillation following system events.





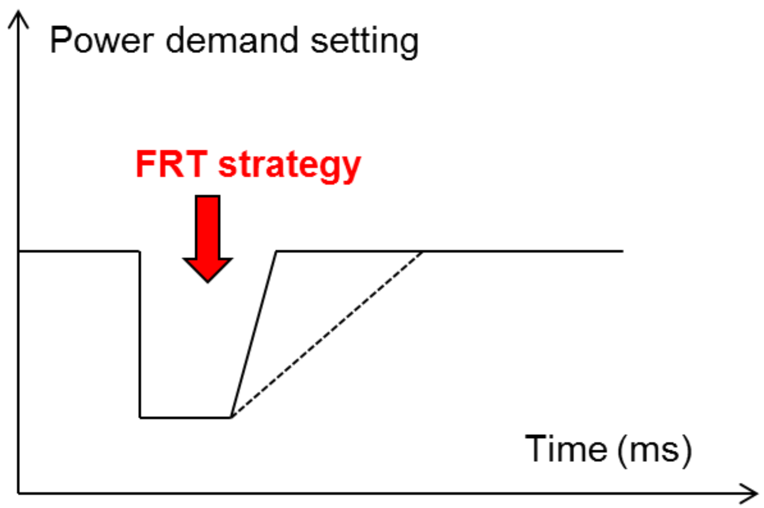
RL
S
RRL
230 kV system representation
BRK
TLine_1
BRK
BRK2
P = 24.26
Q = 70.14
V= 1.035
A
V
100
WTG - Type 3
5MW units
TLine_2
BRK2

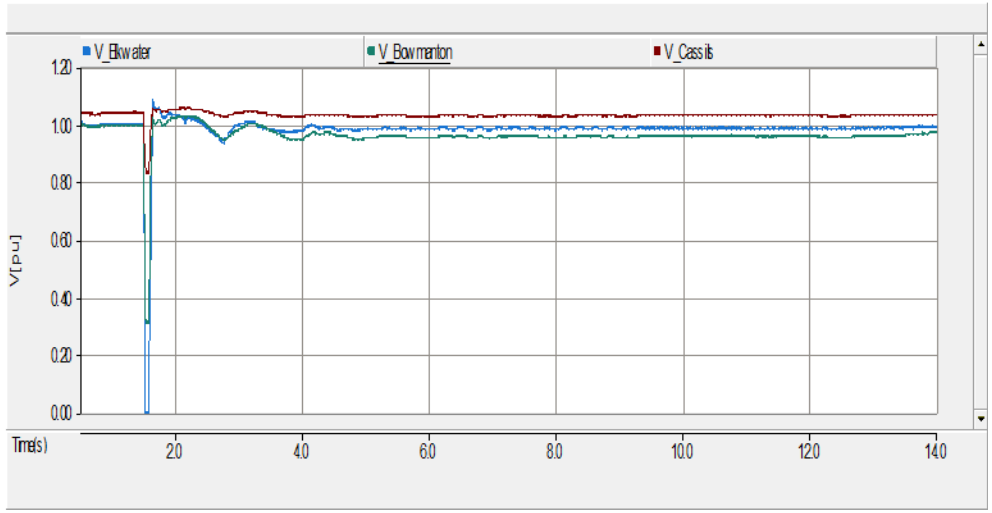


V_Elkwater
V_Bowmanton
V_Cassils
V[pu]
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Time(s)
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0

Wind Integration: 400 MW Wind Farm (Canada)

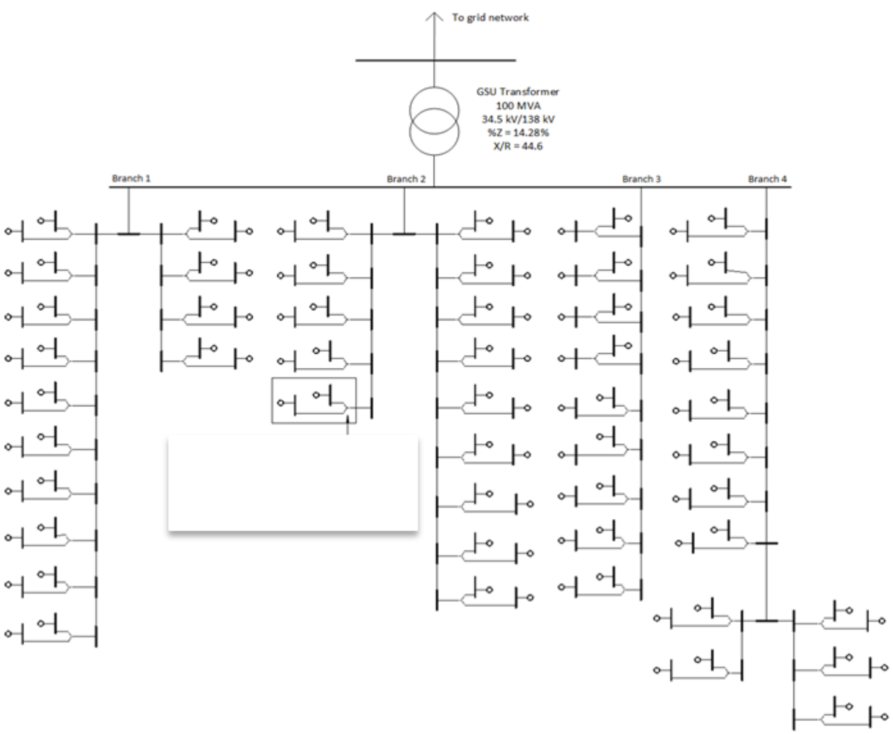
- Solution through control and protection modifications
  - Most cost effective solution(‘FREE’)
  - STATCOM,SVC or Synch. Condenser based solutions – Costly.

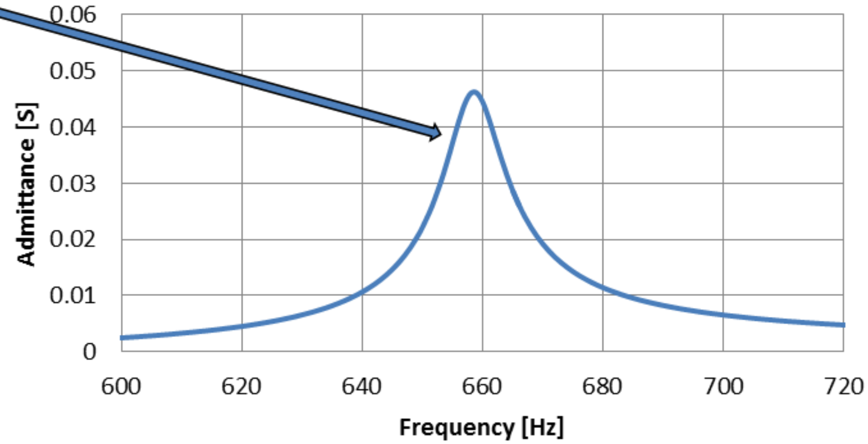




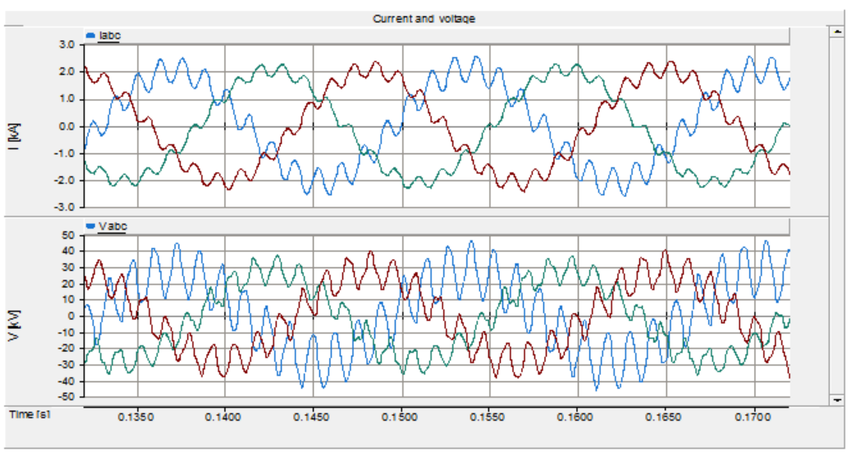
Example 4 – Converter Based Generation – Interconnection Issues due to Harmonic Interactions

Electric system network resonance characteristics



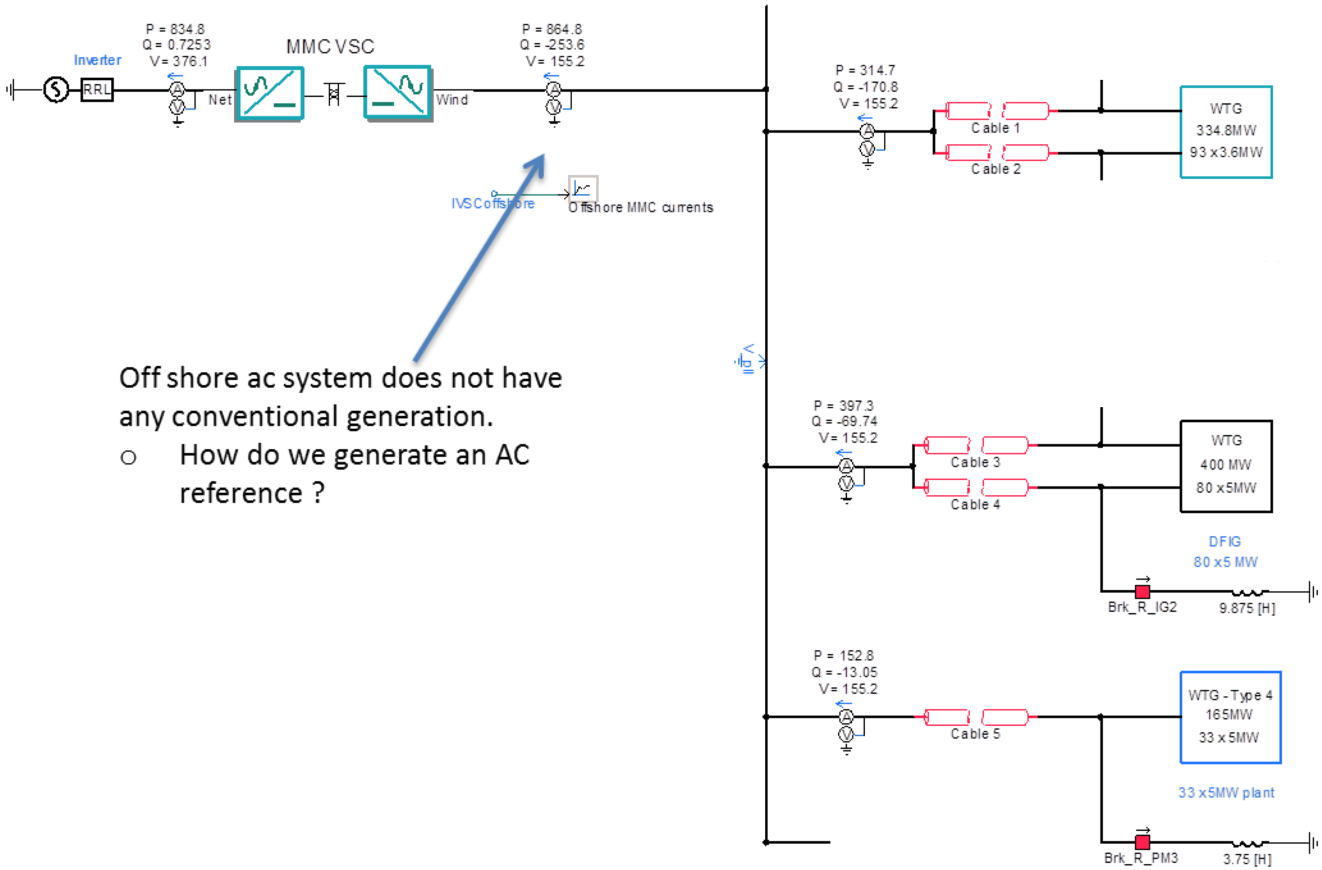


Voltage distortion due to harmonic interaction



Example 5 – VSC Transmission for Offshore Wind

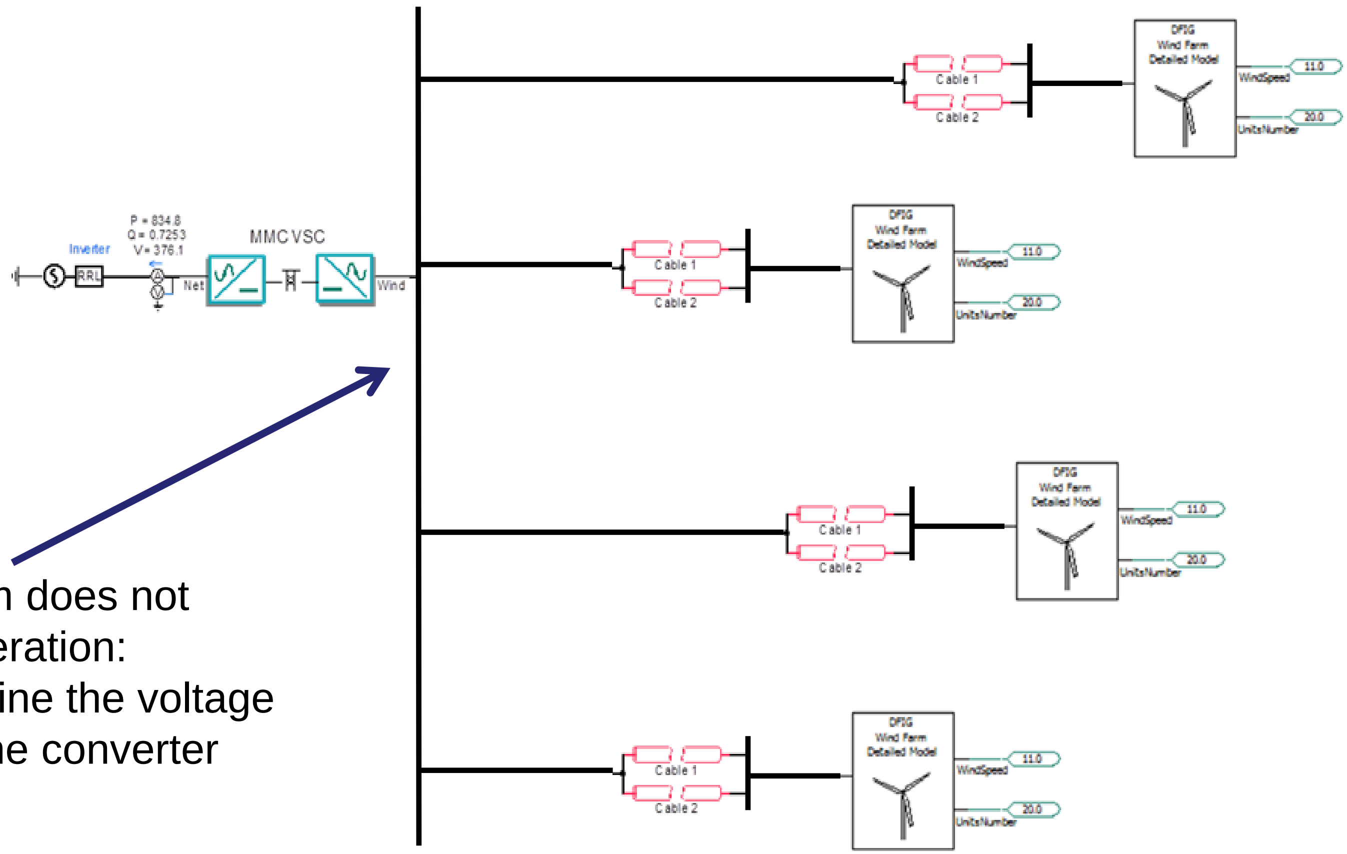
Design and performance verification of an off shore wind farms connected to VSC- HVDC (over 750 MW capacity)



Off shore ac system does not have any conventional generation.

- How do we generate an AC reference ?

Design and performance verification of a offshore wind farm connected through a VSC –HVDC link (Over 750 MW)

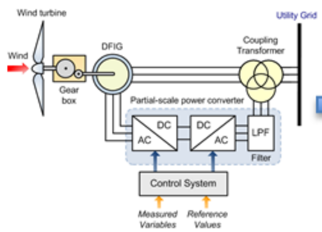


The offshore AC system does not have conventional generation:

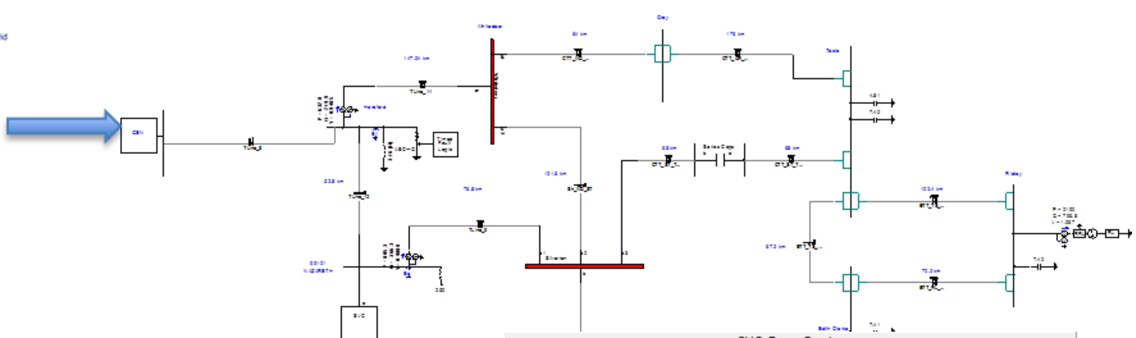
- How do we define the voltage reference for the converter controls

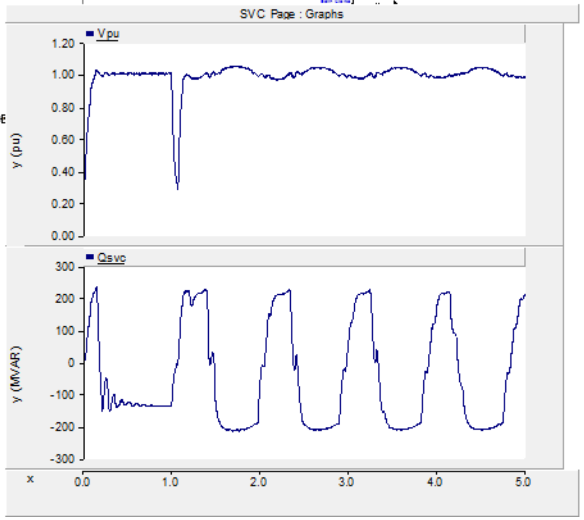
Example 6 – Control Interactions

Control Interactions between nearby by wind farms/ FACTS/Generators



POI





EMT simulations are required to verify acceptable operation.

- *Two or more 'fast' voltage controllers*
- *'Weak' POI ?*
- *Comparable Q controls responses ?*

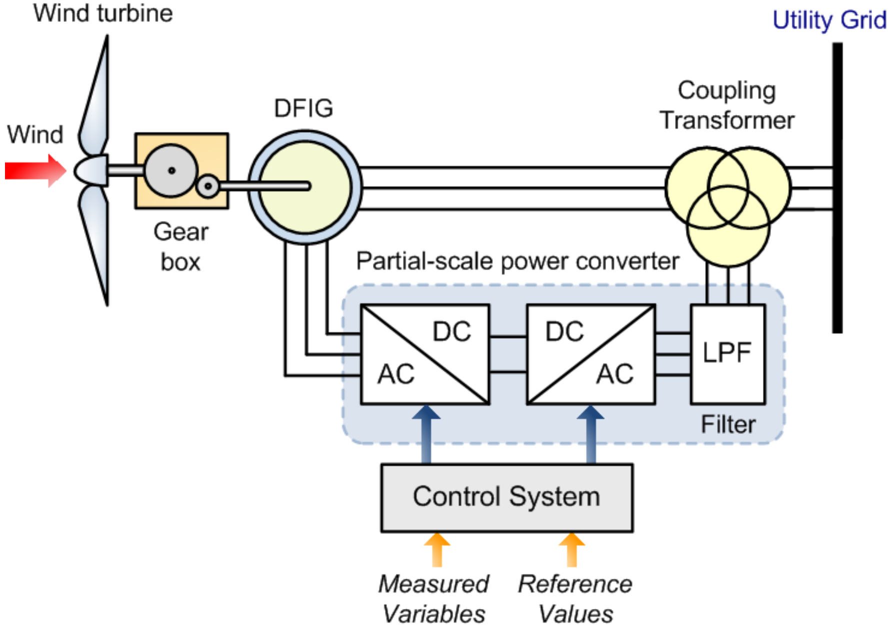
Example 7 – Sub Synchronous Control Instability (SSCI)

Wind Integration: SSCI involving T3 Wind units

- Modern wind turbines use power electronic converters (connected to the generator) to improve performance

- Wind farms located far from the ac gird has necessitated ‘Series Compensated (SC)’ Transmission lines

- Problem: DFIG controls act to ‘amplify’ sub synchronous currents entering the generator
- Negative damping



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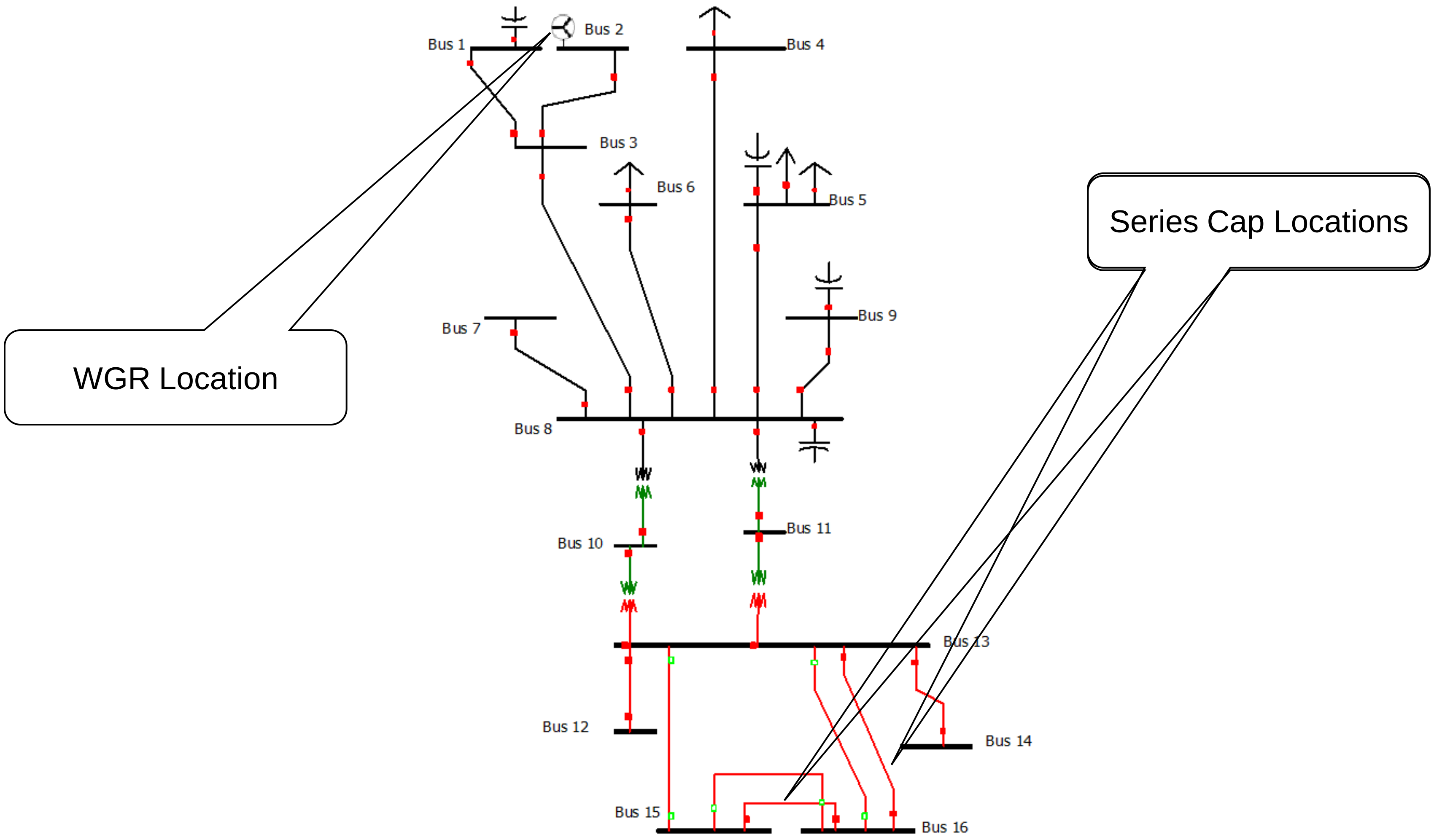
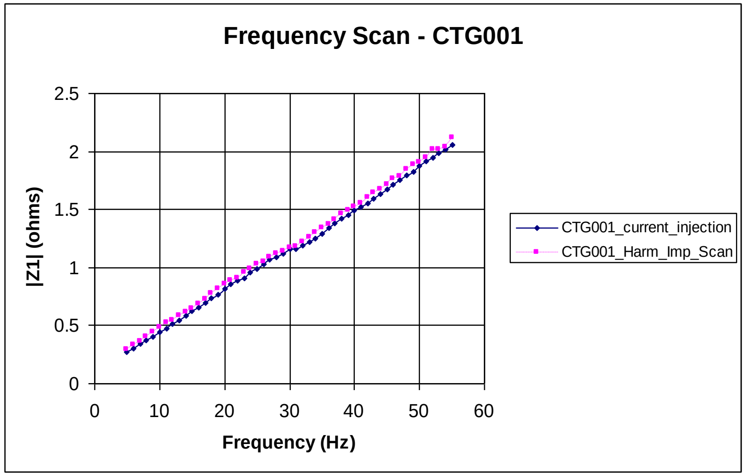
Wind Integration: SSCI involving T3 Wind units



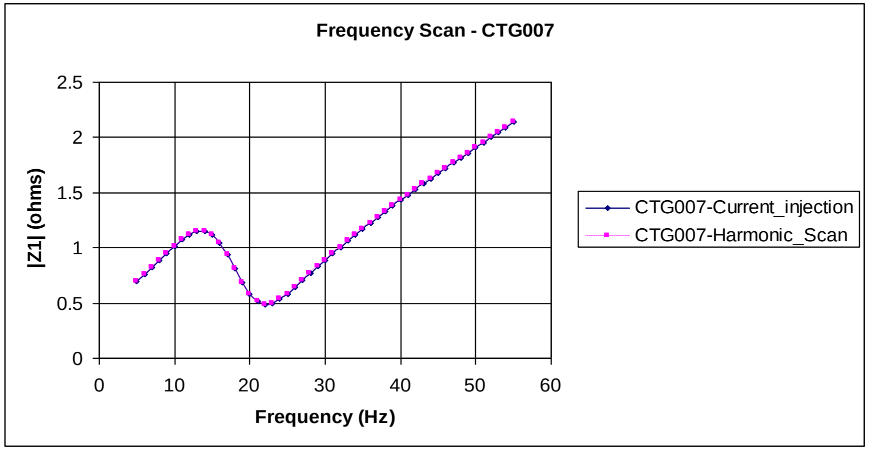
System side frequency scan results

Trend of system side frequency scans similar for CTG#1 through CTG#5

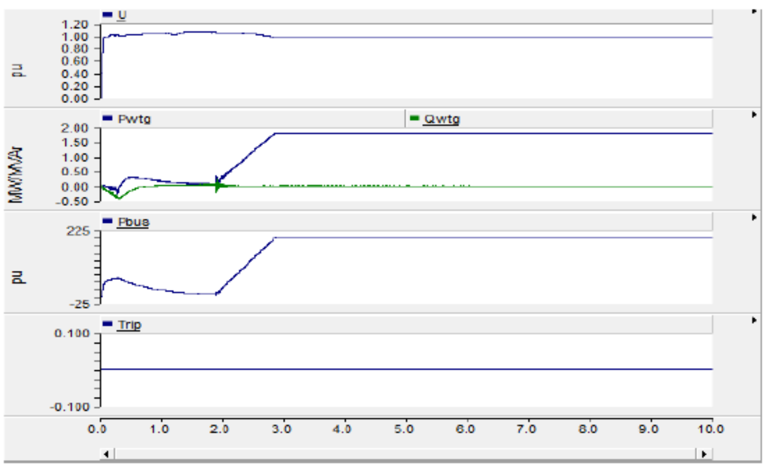
Near Radial Condition



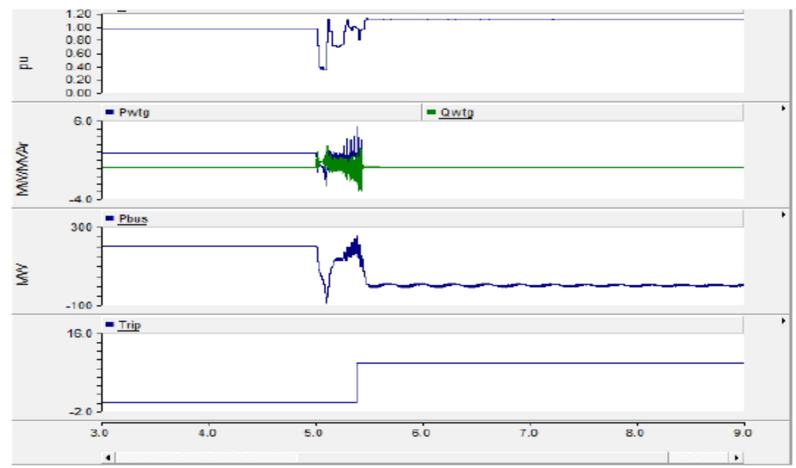
System Side Scans, CTG#1



System Side Scans, CTG#7



EMT Simulation Results, CTG#1



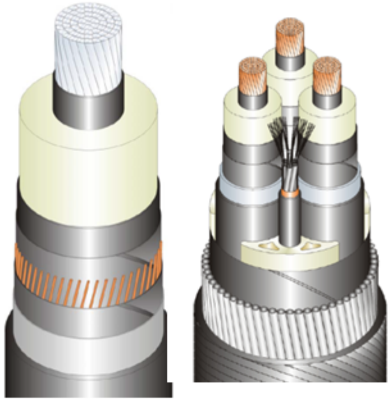
EMT Simulation Results, CTG#8

EMT Models and Tool Features

Simulation models for wind interconnection studies

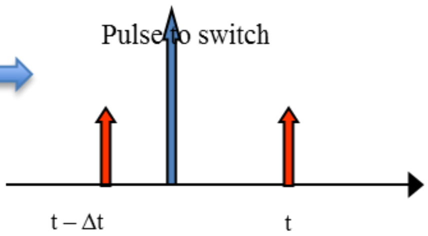
Cables:

- Accurate over a wide frequency range (DC correction, passivity- stable models)
- Finite defence techniques to handle non standard conductor cross sections



Power electronics:

- Accurate representation of switching instant.



Machine models:

- Induction, PM ……

Ability to simulate 'large' systems or many WTG units

- Parallel processing features

WTG model – What do we need to perform specific studies

- Detailed ‘specific’ model of the WTG – from the vendor (likely available in ‘blackbox’ form)
- A ‘grey’ model as opposed to a ‘blackbox’
  - Trip signals as an output
  - Access to inputs (wind speed, P and Q set points,…)
- Ability to ‘copy-paste’ multiple instances of the WTG model
- Scalable to represent multiple WTG’s in a wind farm

Thank you