Electromagnetic Transient Studies – Applications in Wind Integration

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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
Main components

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
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
Common Applications

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)

- 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

Traditional Applications

‘Non-Traditional’ Applications
Common 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

![Graph showing TRV time and voltage](image)

**LEGEND:**
- DS
- DS1
- BRK
- BRK1

**System Diagram:**
- Station W
- Station X1
- Station X2
- Station Y1
- Station Z1
- Station Z2
- Station Y2
- BAY A
- BAY B
- BAY C
- BAY D
- BAY E
- BAY F
- REACTOR 1
- CAP BANK 1
- CAP BANK 2
- REACTOR 2
- REACTOR 3
- CAP BANK 3

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Transformer Energizing

- Core saturation
  - Inrush current and harmonics
    - Voltage dips
  - Network characteristics - frequency scan
  - Over voltages due to harmonic resonance conditions
Lightning Over voltages: Protect equipment and limit faults due to back flashover.
Wind farm fault response
Wind farm fault response

Governor/Turbine → Exciter → SG → Network

Graphs showing current and voltage levels over time.
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

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)
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
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
EMT and RMS Simulation – main differences
Transients and Steady State

- Load Flow / Transient Stability
  - Each solution based on phasor calculations

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

- Electro-Magnetic Transients
  - Direct time domain solution of Differential Equations

\[ v(t) = R \cdot i(t) + L \frac{d}{dt} i(t) \]
Capacitor voltage response
Fault Ride Through response of a wind farm

- RMS response
- Actual response
- FRT P&C activated
- Voltage
- Time
- Fault
- Cable
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.

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
Wind Generator Types

Q-axis (rotating)

D-axis (rotating)

\(\phi\) - Stator flux

Rotor position

Stator phase A axis (stationary)

\(I_q\)

\(I_d\)

Slip angle
Position of the Flux Vector

Identification of main stator flux by integrating stator voltage after removal of resistive drop. The washout filter removes any dc component from the integrated flux without significantly affecting the phase.

Very important signal - present location of rotating stator flux determining the relative difference between stator flux and rotor position for resolving the rotor currents.

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
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 Temporal over voltages (TOV) on wind farm collector cables
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 WTGs
  - Serious TOV concern
  - WTGs should be able to limit this TOV through protection and control action
  - Cable capacitance and number of tripped WTG units affect TOV
TOV on isolated collector feeders

- Fault on the 110 kV side
Fault ride through of the wind farm

Stable case

Unstable case
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).

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.
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 an 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

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 grid has necessitated ‘Series Compensated (SC)’ Transmission lines

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

- Negative damping
Wind Integration: SSCI involving T3 Wind units
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
Wind Integration: SSCI involving T3 Wind units

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