





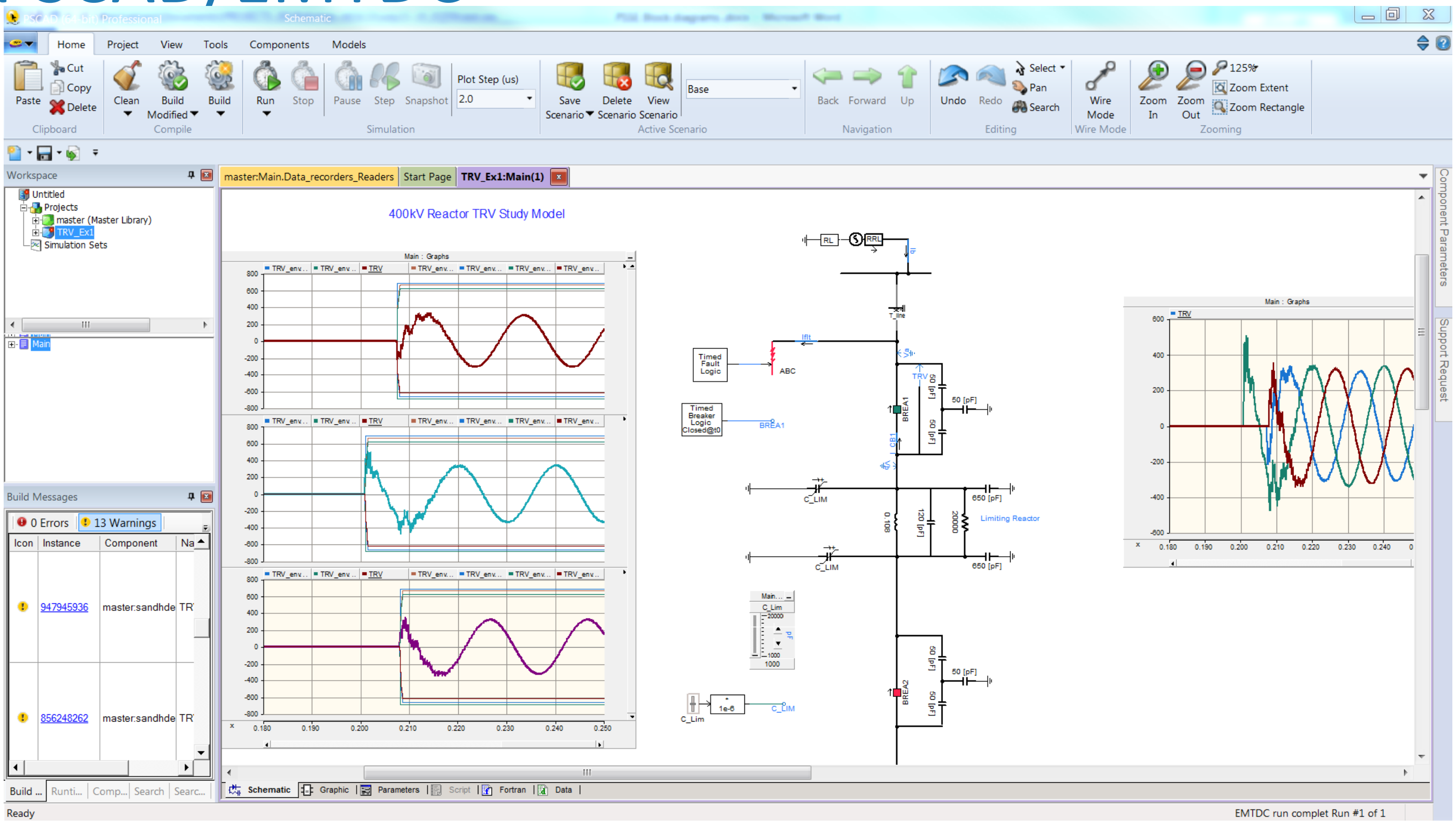

PSCAD

Introduction to Electromagnetic Transient Simulations and Applications

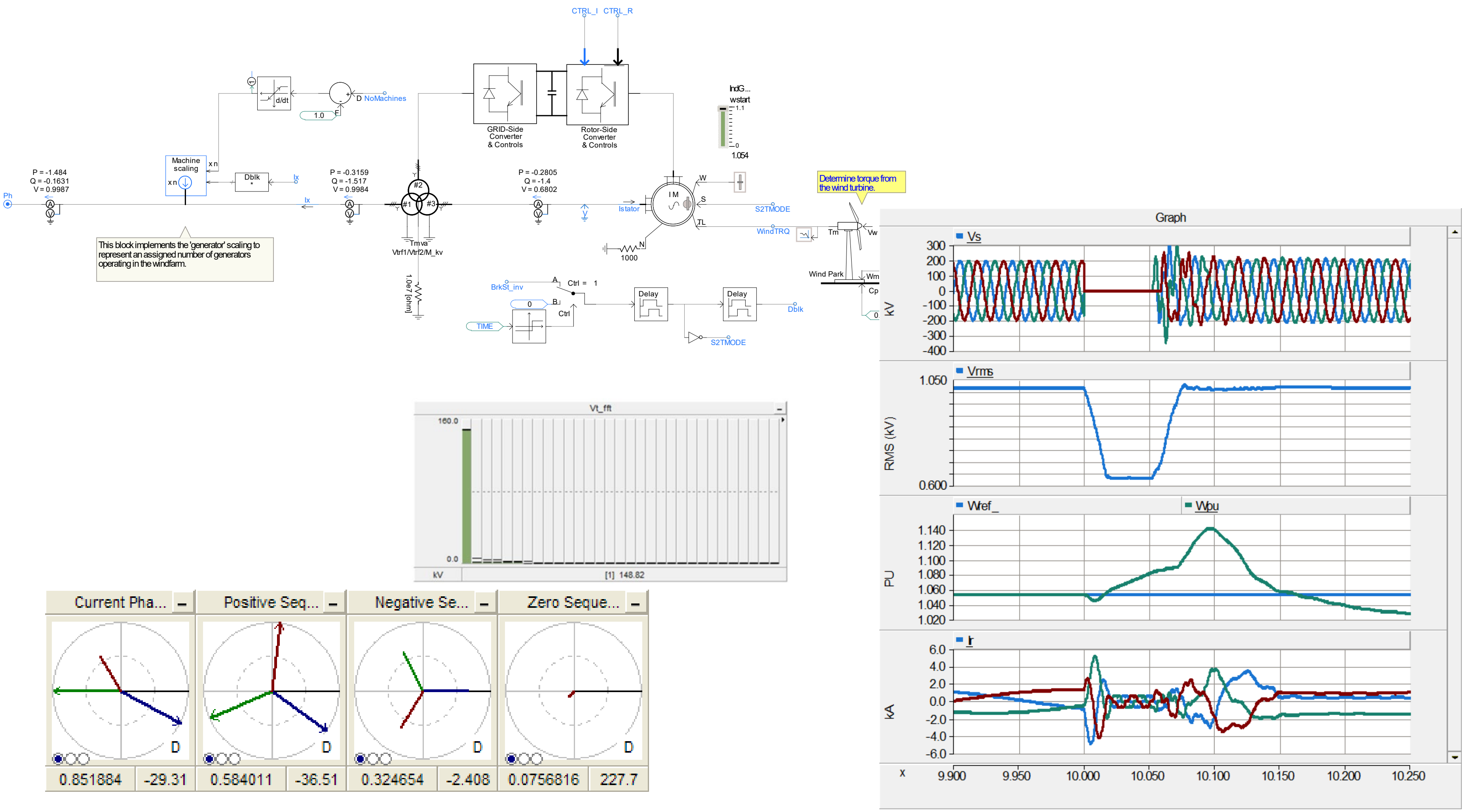
pscad.com

Manitoba
HYDRO INTERNATIONAL

Manitoba HVDC Research Centre Develops PSCAD/EMTDC



Limitless Applications



The Product

The time domain simulation engine, EMTDC, (originally developed at Manitoba Hydro) formed the basis of the simulation program.

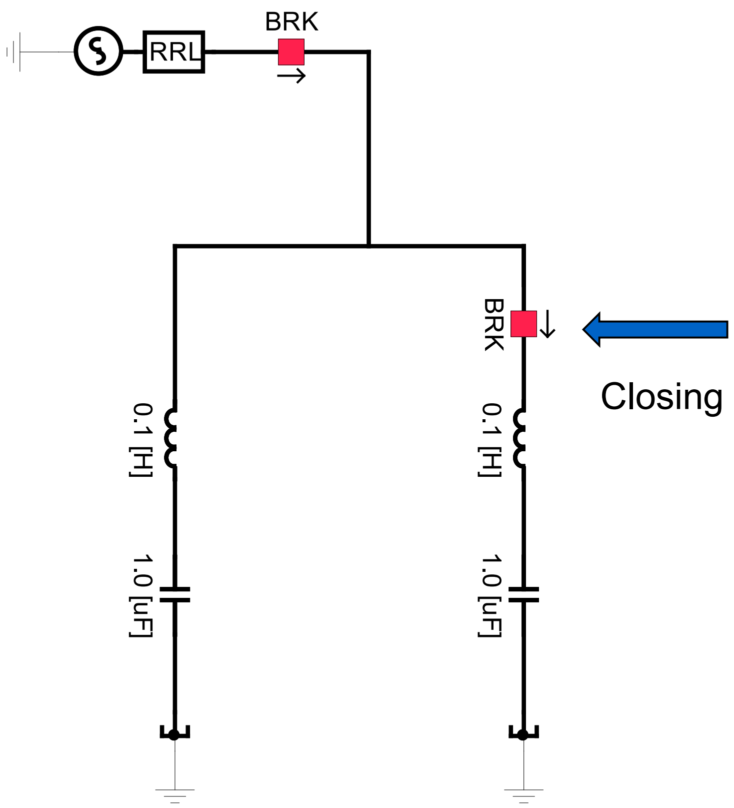
PSCAD (Power Systems Computer Aided Design) provides the user with control and visualization technologies to operate EMTDC.

Some Common Applications

- Switching Over-Voltage studies – arrester ratings
- Power System Lightning performance – BIL
- HVDC system design and operation studies
- Accurate modeling of FACTS and Power Electronics applications
- Sub-Synchronous Resonance
- Wind power and other renewable energy systems
- Protection System modeling and testing
- Dynamic/Transient Power System response
- Harmonic System response
- Distributed Generation Studies – wind power, solar, fuel cell, diesel…

Limited only by the imagination

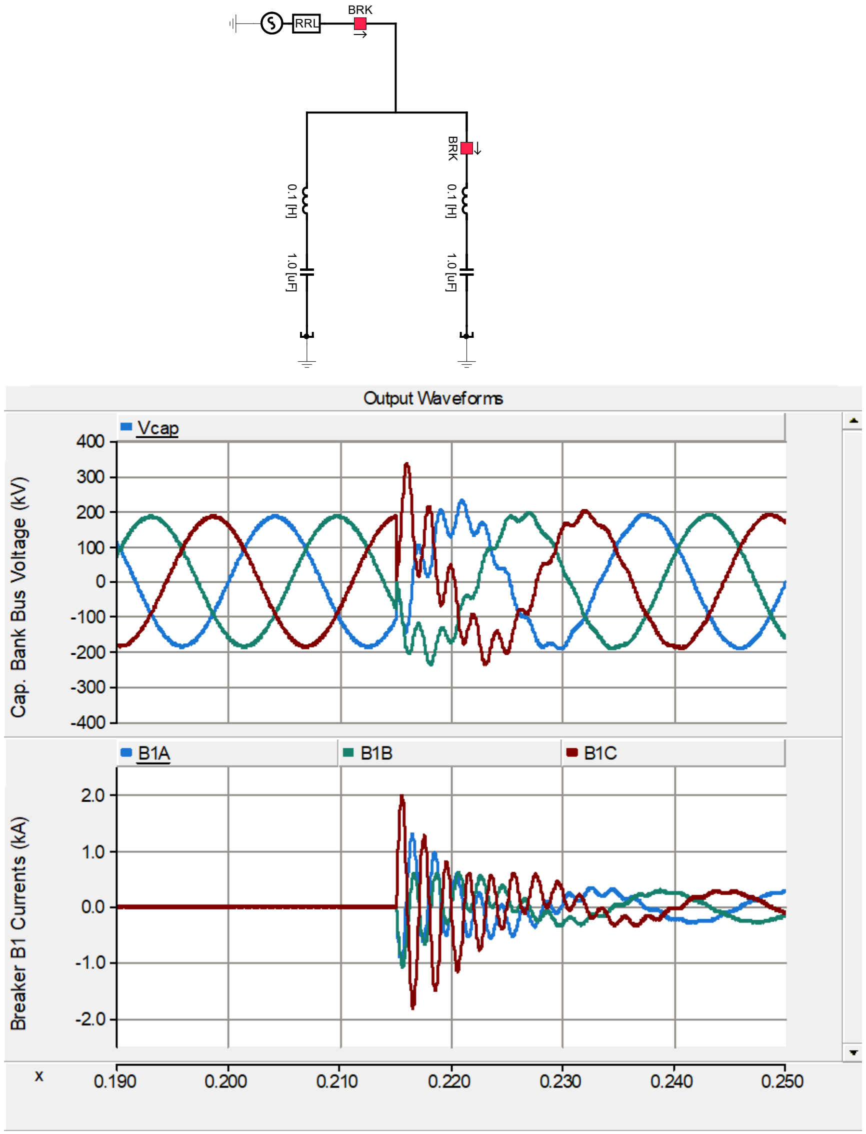
Transients and Steady State



Transient solution
- Harmonics
- Non-linear effects
- Frequency dependent effects

Steady state solution
- RMS Value

Transients and Steady State



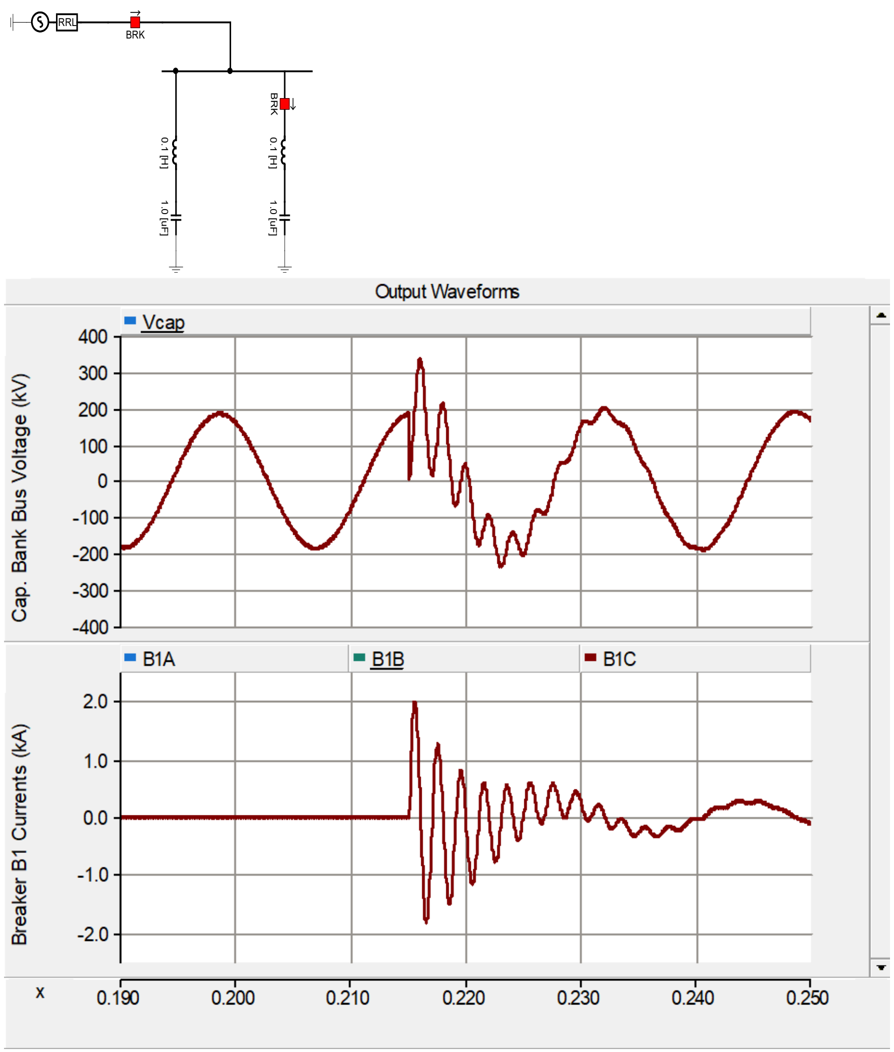
Transient solution

- Harmonics
- Non-linear effects
- Frequency dependent effects

Steady state solution

- RMS Value

Transients and Steady State



Transient

- High frequency
- Damped (short duration)

Transients and Steady State

Load Flow / Transient Stability

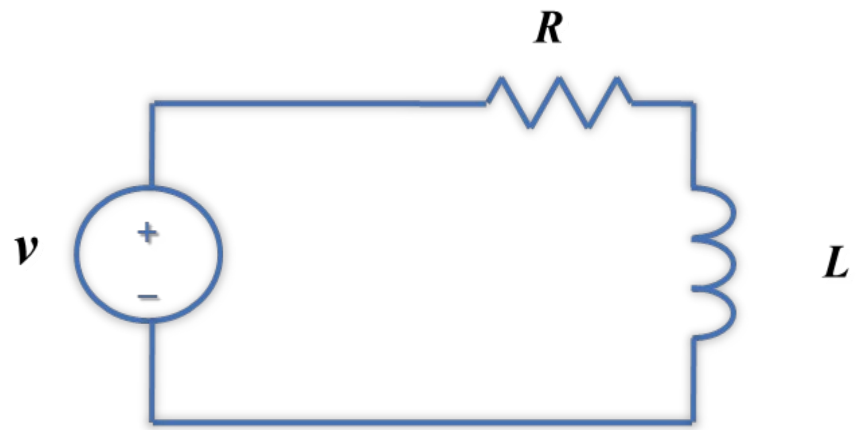
- Each solution based on phasor calculations

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

Electro-Magnetic Transients

- Direct time domain solution of Differential Equations

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



Machine equations

Stator Side

$$V_d = R_s . i_d + \frac{d}{dt}\lambda_d(t) - \lambda_q(t) . w_r$$

$$V_q = R_s . i_q + \frac{d}{dt}\lambda_q(t) + \lambda_d(t) . w_r$$

$$V_0 = R_0 . i_0 + \frac{d}{dt}\lambda_0(t)$$

Rotor Side

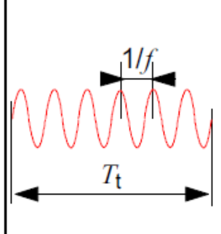
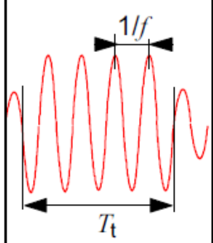
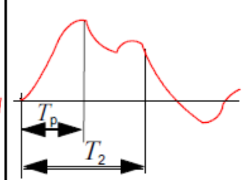
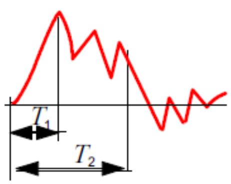
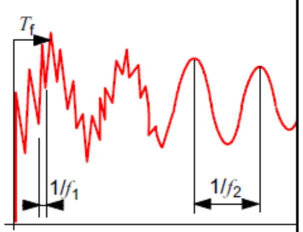
$$E_f = R_f . i_f + \frac{d}{dt}\lambda_f(t)$$

$$0 = R_{kd} . i_{kd} + \frac{d}{dt}\lambda_{kd}(t)$$

$$0 = R_{kq1} . i_{kq1} + \frac{d}{dt}\lambda_{kq1}(t)$$

$$0 = R_{kq2} . i_{kq2} + \frac{d}{dt}\lambda_{kq2}(t)$$

Dampers – 2 on Q-axis

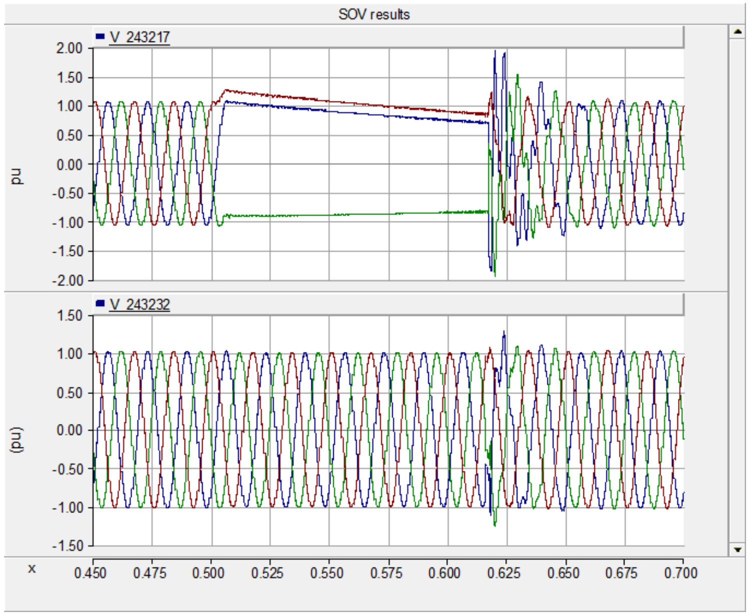
Class	Low frequency		Transient		
	Continuous	Temporary	Slow-front	Fast-front	Very-fast-front
Voltage or over-voltage shapes					
Range of voltage or over-voltage shapes	f = 50 Hz or 60 Hz T_t ≥3 600 s	10 Hz < f < 500 Hz 0,03 s ≤ T_t ≤ 3 600 s	20 µs < T_p ≤ 5 000 µs T_2 ≤ 20 ms	0,1 µs < T_1 ≤ 20 µs T_2 ≤ 300 µs	3 ns < T_f ≤ 100 ns 0,3 MHz < f_1 < 100 MHz 30 kHz < f_2 < 300 kHz

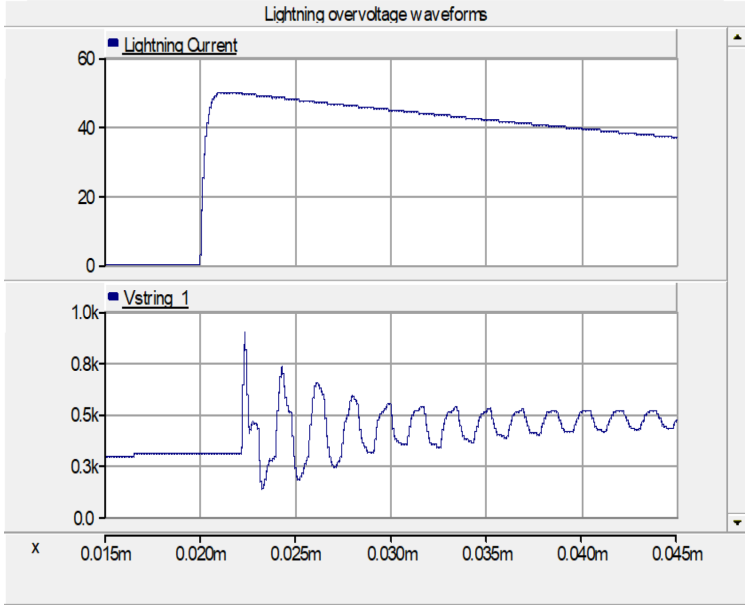
Why Study the short Transient period?

- Mainly to protect major equipment from insulation failure
- Ensure that main station equipment are protected from lightning induced voltage surges
- Ensure satisfactory operation of circuit breakers
- Design surge arresters
- Design current/voltage limiting devices (inrush reactors, ‘grading’ capacitors)
- Identify the ‘worst case’ (magnitude and duration of the transient)
- Identify and design mitigation methods

Electromagnetic Transients

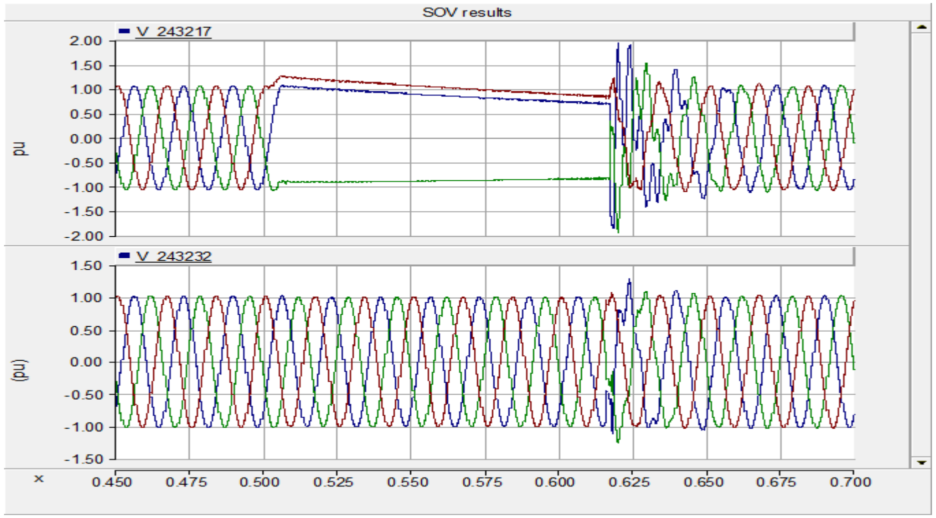
- Due to interaction between L-C elements in the network
  - Oscillations
  - Travelling waves
- Triggered by
  - Switching of lines, cables, transformers
  - Faults
  - Lightning





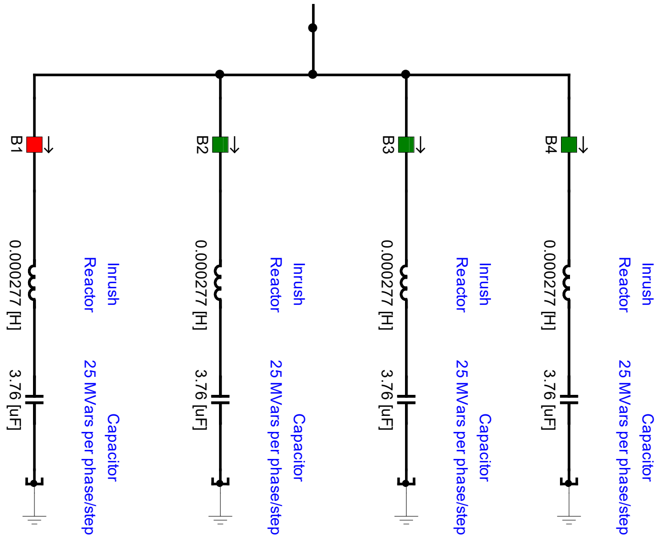
Transmission line and equipment switching

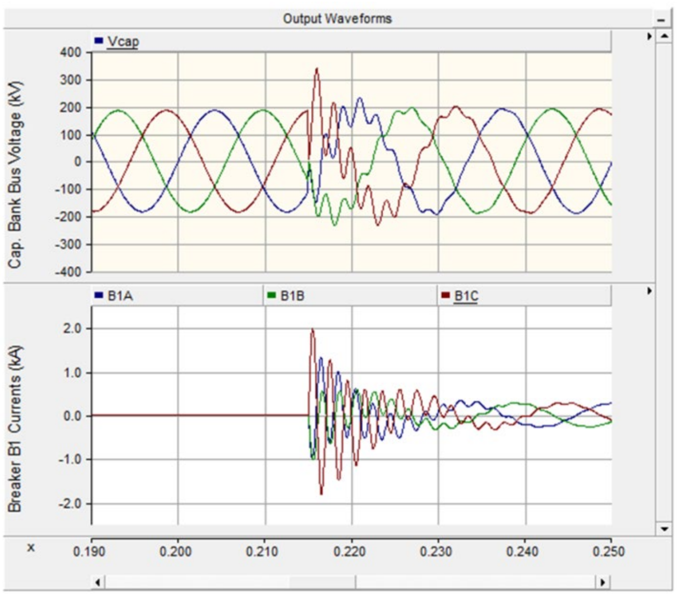
- Overvoltage magnitudes and equipment insulation levels
  - Surge arresters
- Statistical distribution of overvoltage magnitude
- Transmission line 'flash-over' rates
- Investigation of overvoltage mitigation methods



	E1	E2	E3	E4
Minimum:	364.6304	280.1849	332.9529	353.4259
Maximum:	395.8886	352.6374	413.6732	383.773
Mean:	379.7837	320.0234	375.2662	369.2719
Std Dev:	7.564519	17.03806	18.64495	7.544283
2% Level:	364.248	285.0315	336.9741	353.7778
98% Level:	395.3193	355.0153	413.5582	384.7659

Capacitor Bank Switching



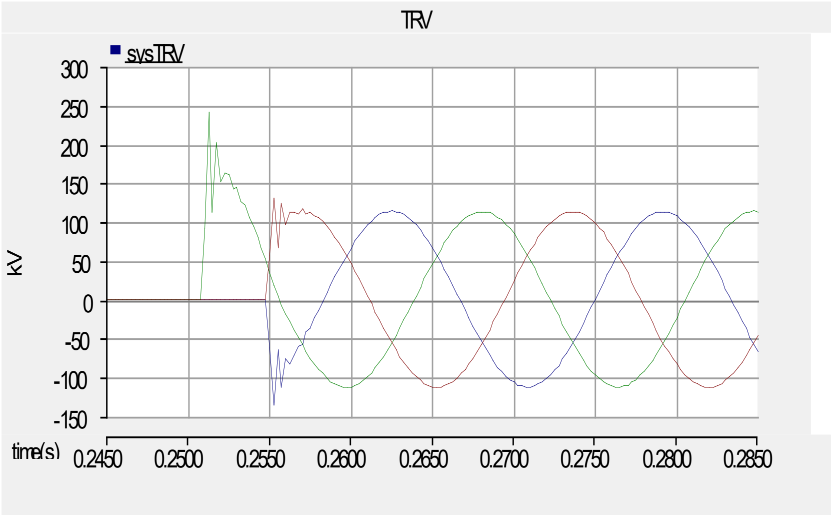


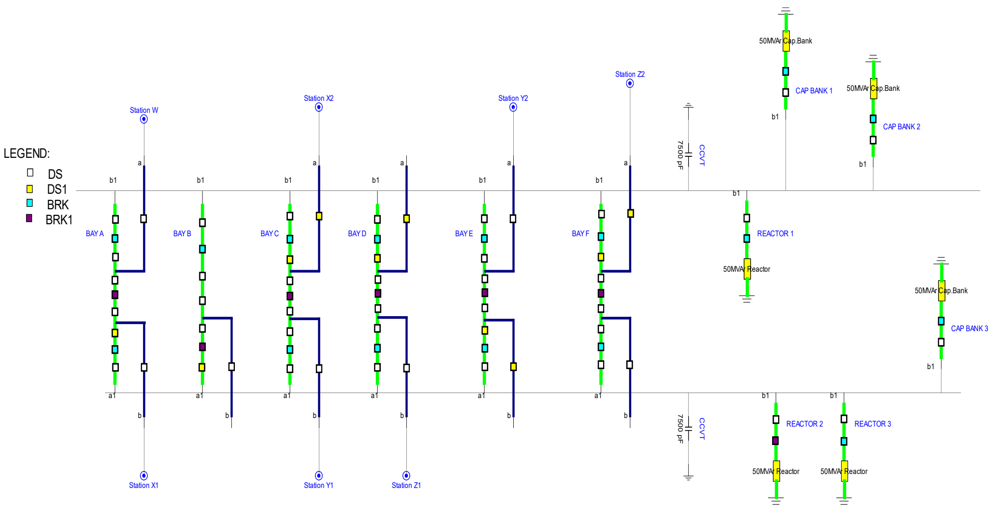
- Back to back switching
  - Inrush reactors
- Faults
  - Outrush reactors
- Cable energizing
- Resonance concerns

$$\frac{di}{dt}_{allow} = \frac{\sqrt{2} \cdot 40k \cdot 2\pi \cdot 60}{10^6} = 21.326 \frac{A}{\mu s}$$

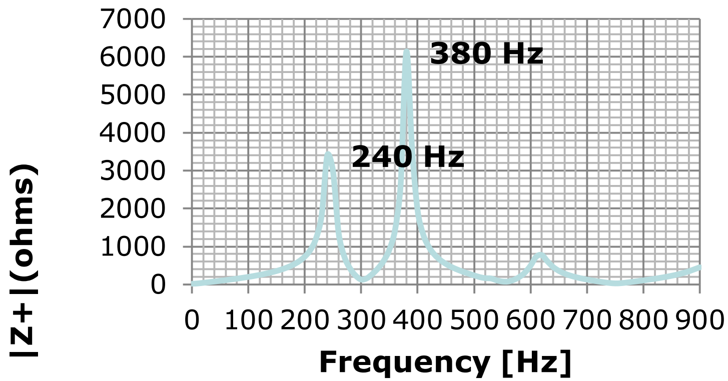
Circuit breaker Transient Recovery Voltage (TRV)

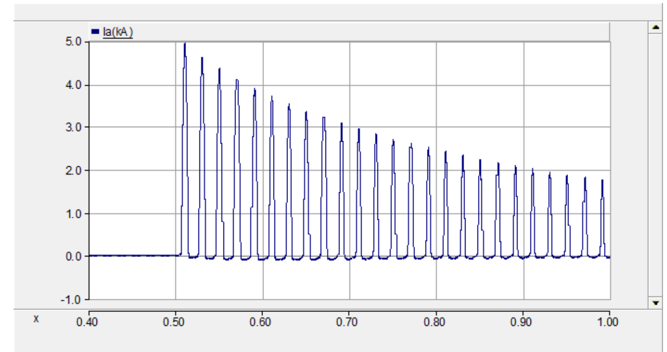
- TRV is the voltage developed across the breaker poles immediately after current interruption
- Fast event
- Simulation circuit should consider details of station equipment
- Breaker TRV withstand capability limits

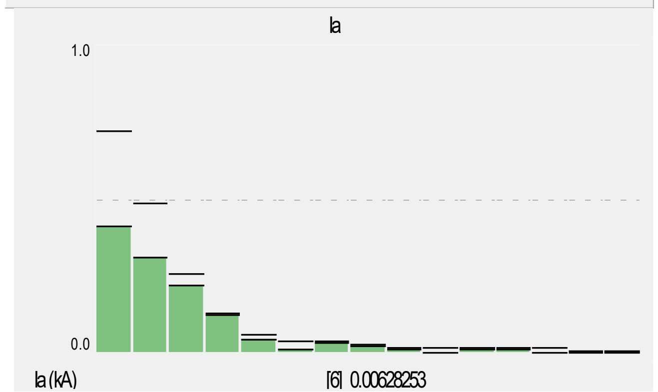




Transformer Energizing



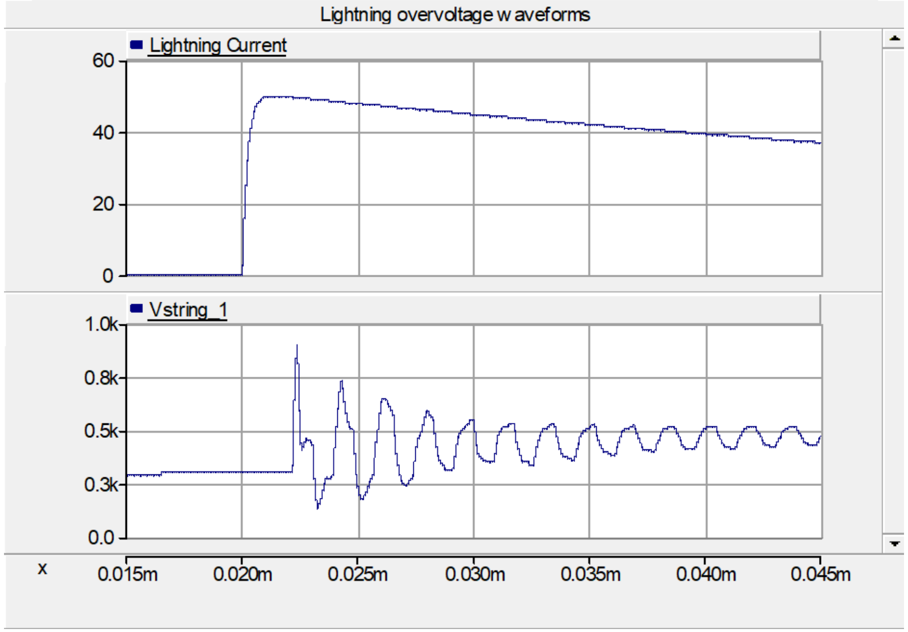




- Core saturation
- Inrush current and harmonics
  - Voltage dips
- Network characteristics - frequency scans
  - Over voltages due to harmonic resonance conditions

Lightning Overvoltages

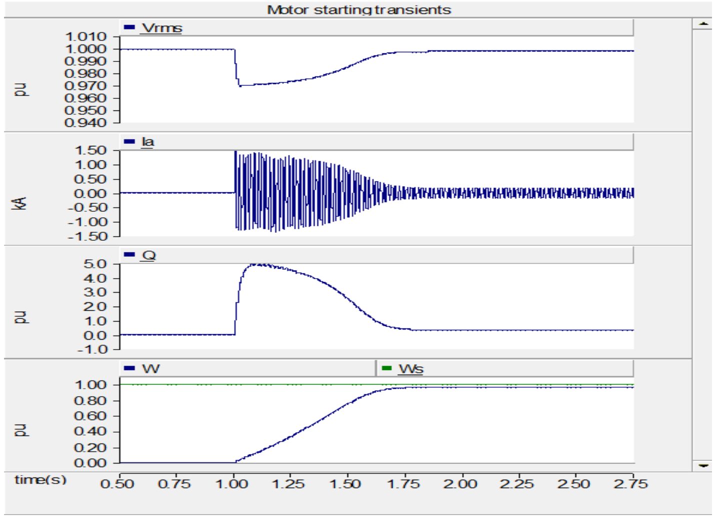
- Lightning overvoltage studies are required to:
  - Determine the required insulation levels of equipment (BIL)
  - Surge arresters size and location
  - Determine transmission line 'flashover' rates
    - Very Fast event
    - Simulation circuit should consider details of station equipment

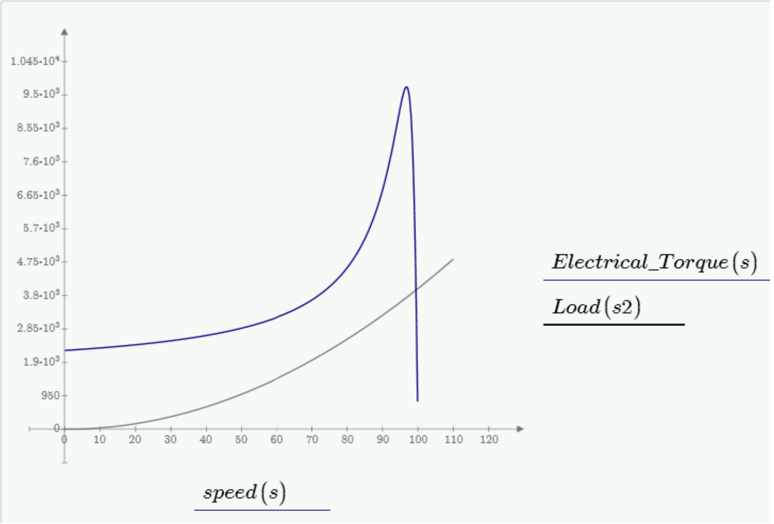


- How do we represent system equipment
  - Line segments
  - Towers
  - Insulators
  - Tower footing resistance
  - Flashover mechanism

Motor Starting

- Voltage dips and flicker caused by frequent starting of large motors at industrial plants is a power quality concern for utilities
  - Model data to match manufactures T-S and I-S curves
  - Impact of rotating inertia
  - Power System impedance characteristics near the interconnection point
  - Representation of load characteristics and the overall

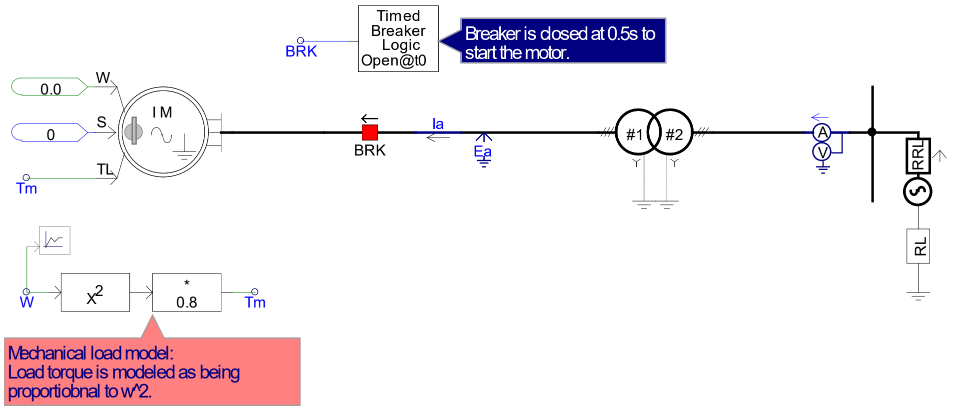


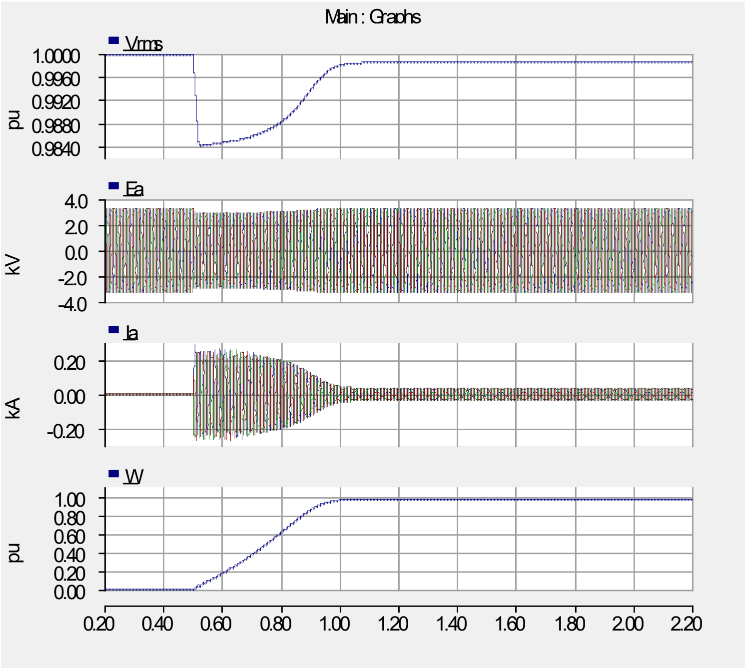


Transients and Steady State

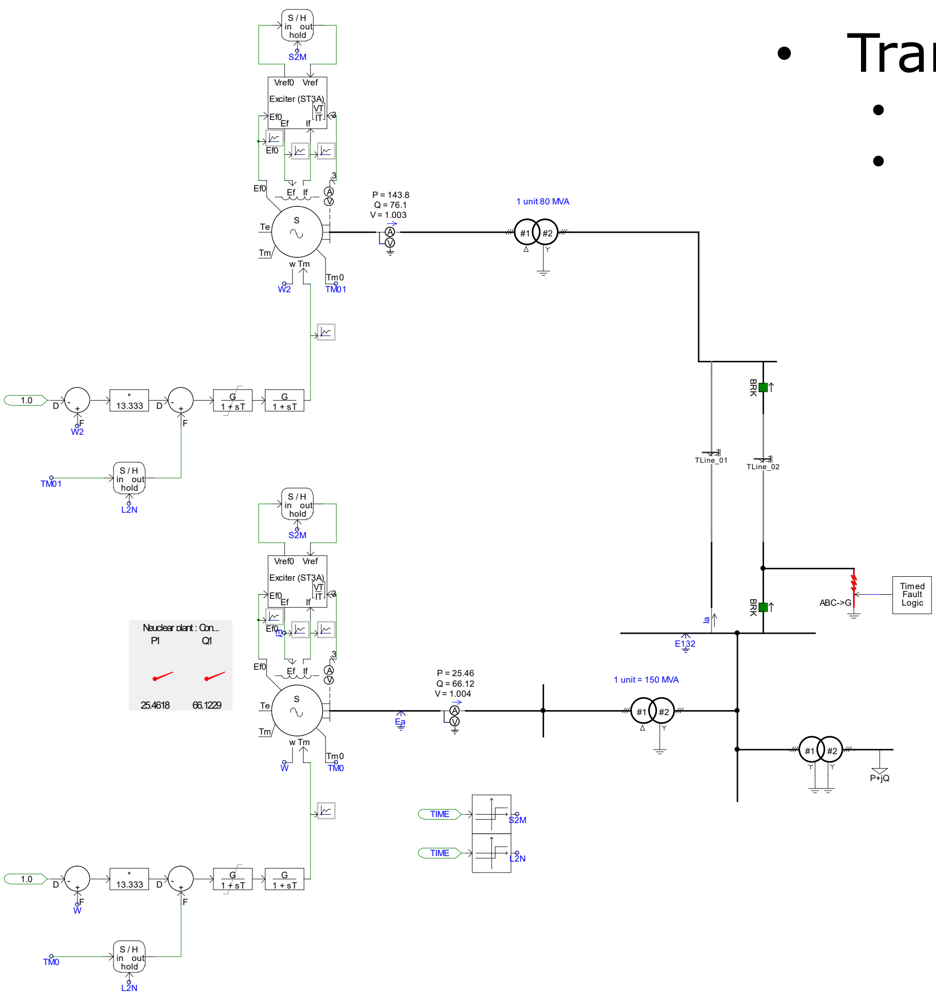
- Start-up of an induction motor
  - Slow Transient (electro-mechanical)

Motor starting - With a mehanical load connected to the shaft.

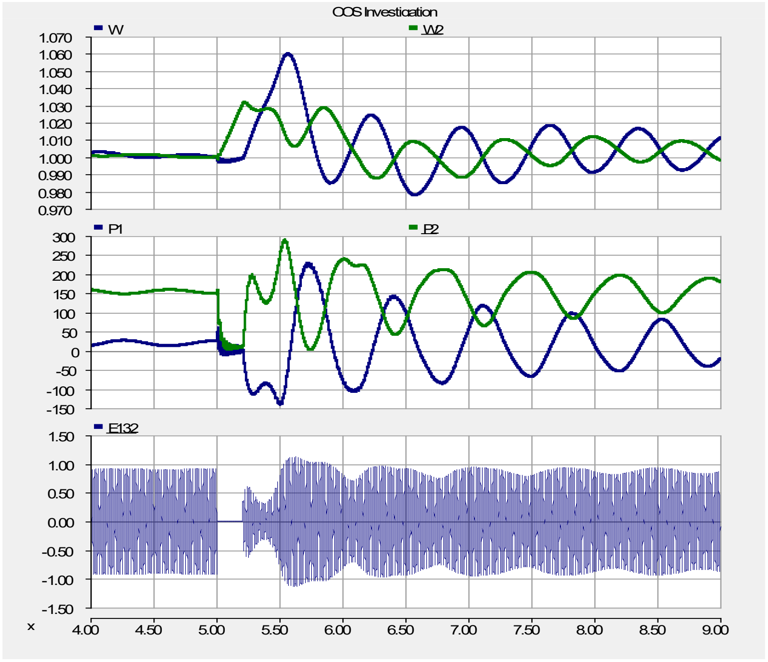




Transients and Steady State



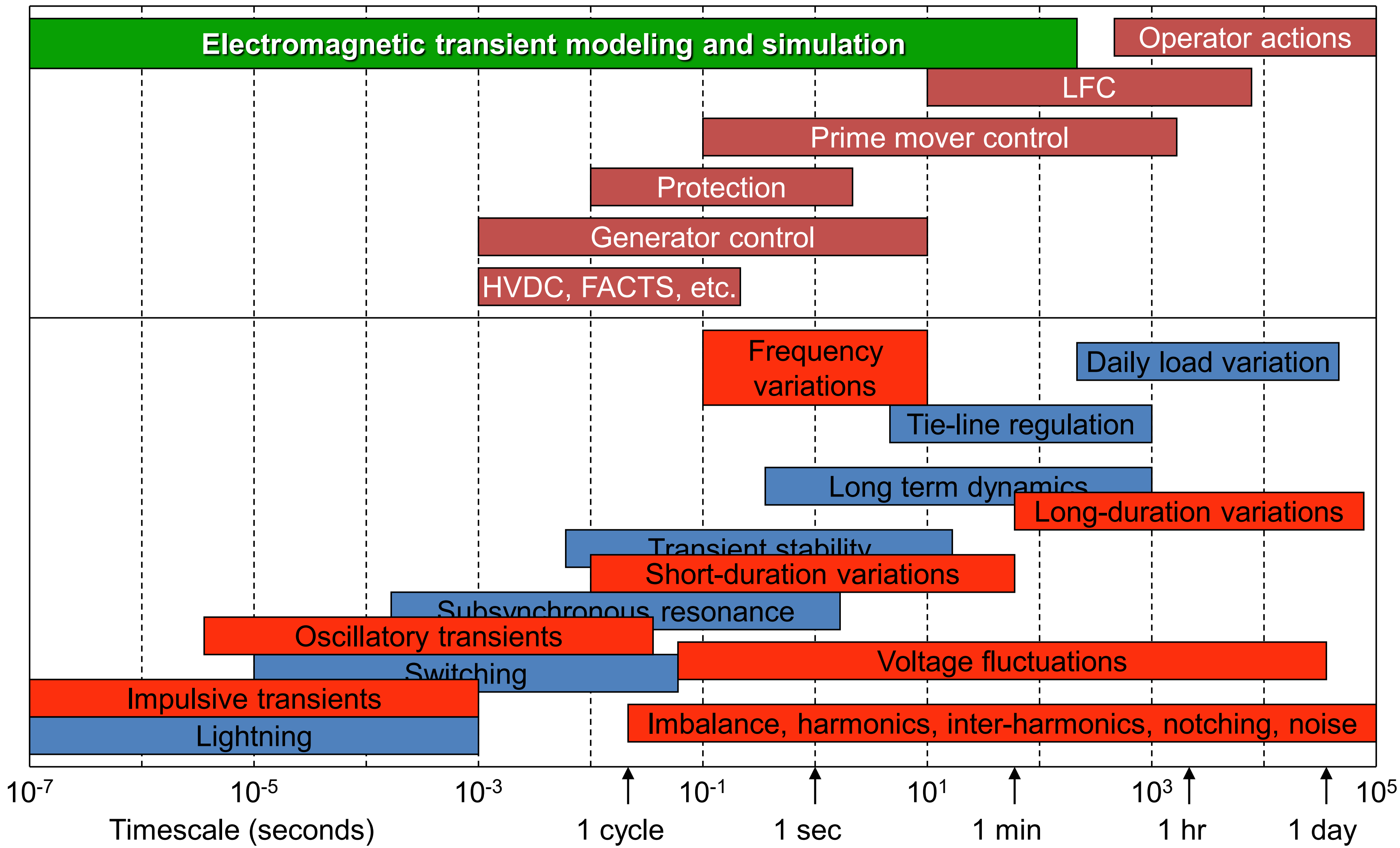
- Transient stability problem
  - Fault / clearance
  - Slow Transients (electro-mechanical)



Simulation studies for power system operation, planning, design

- Load flow (steady state – 60 Hz)
- Transient stability (slow variations- electro-mechanical)
- Small signal stability (operating point)
- Fault studies
- Electromagnetic transient studies (fast transients)

Time scales of power system phenomena



- Electrical transient occurs when there is a rapid exchange or flow of energy from one element to another
  - Interaction of energy stored in electric fields of capacitances and magnetic fields of inductances in electrical power systems
  - Initiated by a change to the network topology (connections)
  - Behaviour can be represented as set of first order differential equations

Electromagnetic transients are due to:

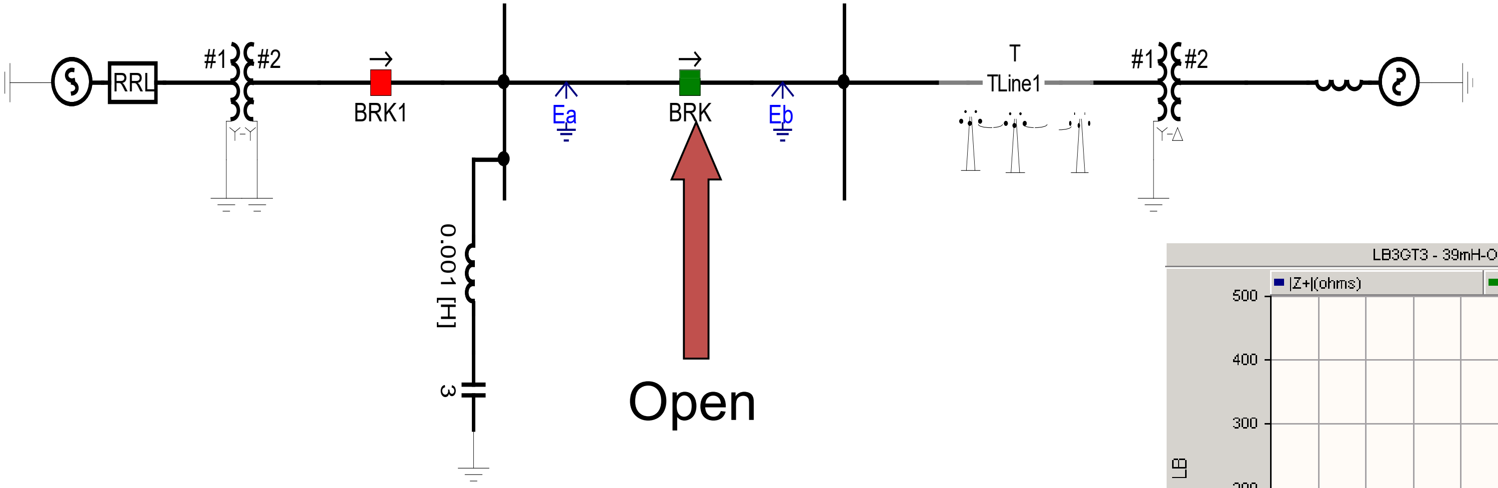
1. Oscillations in lumped circuit elements.

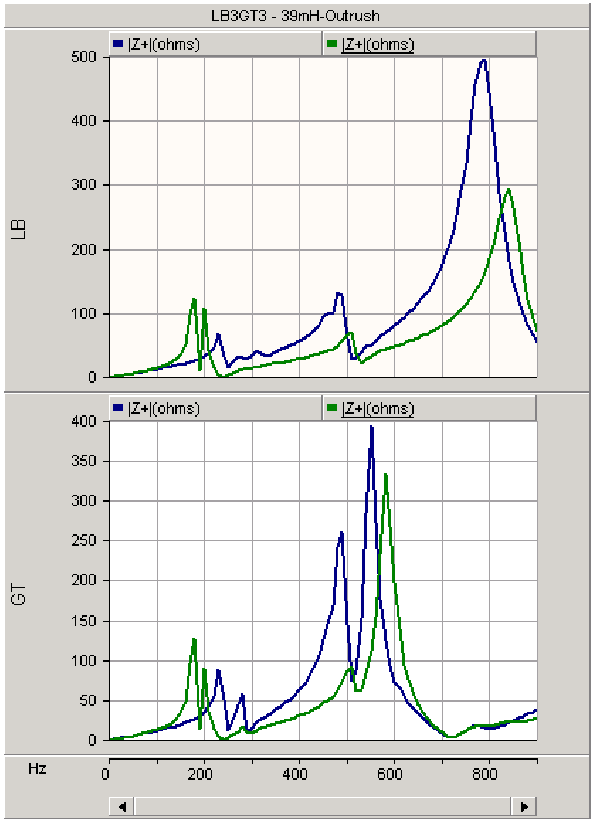
    - Rapid exchange of energy between inductive and Capacitive elements in the network

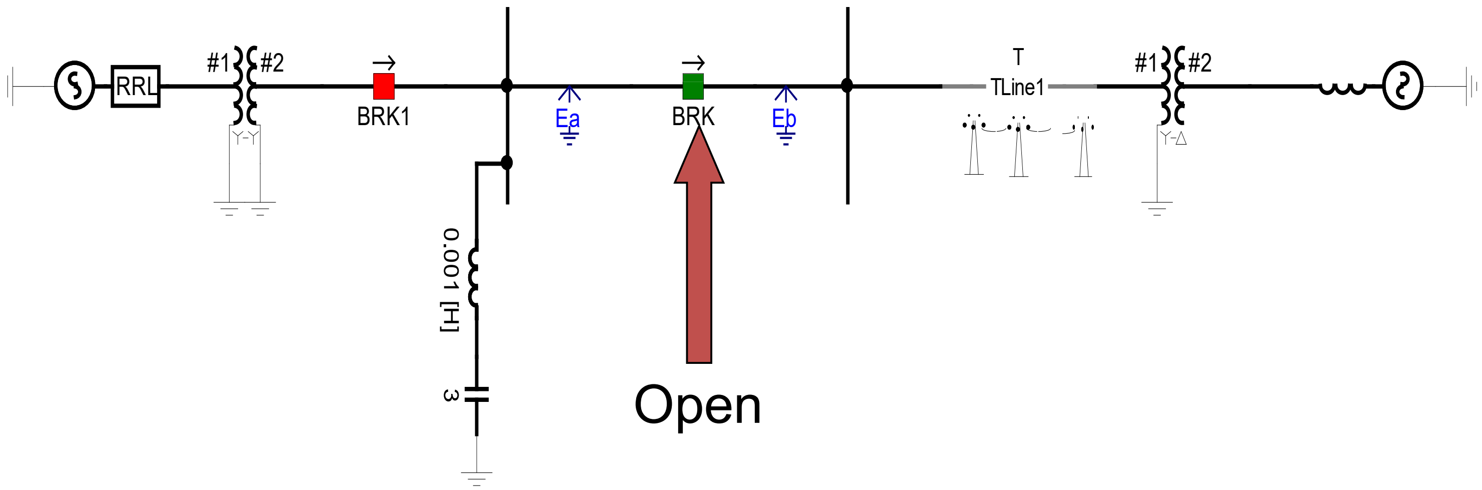
2. Travelling waves on transmission lines, Cables

3. Travelling waves on short Bus-bars (e.g. during Lightning)

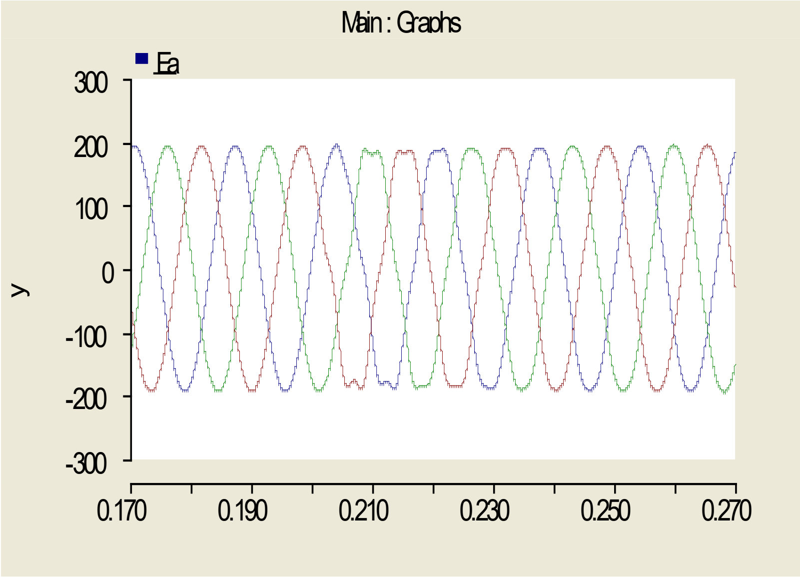
- Electrical transient occurs when there is a rapid exchange or flow of energy from one element to another
  - Interaction of energy stored in electric fields of capacitances and magnetic fields of inductances in electrical power systems
  - Initiated by a change to the network topology (connections)
    - Switching Events
      - Opening and closing
    - Faults
      - Inception and clearance
    - Lightning
    - Others


#1
#2
RRL
BRK1
Ea
BRK
Eb
T
TLine1
#1
#2
0.001 [H]
3
Open

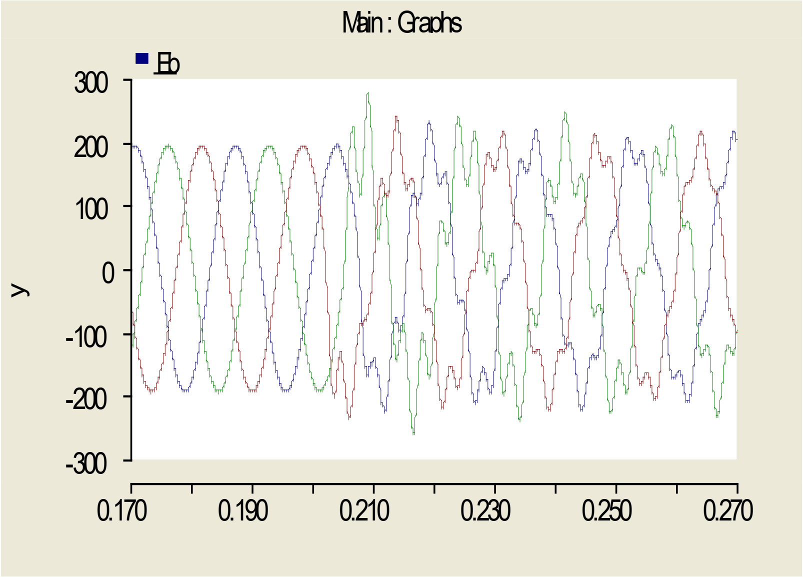

LB3GT3 - 39mH-Outrush
|Z+|(ohms)
|Z+|(ohms)
LB
GT
Hz
0
200
400
600
800



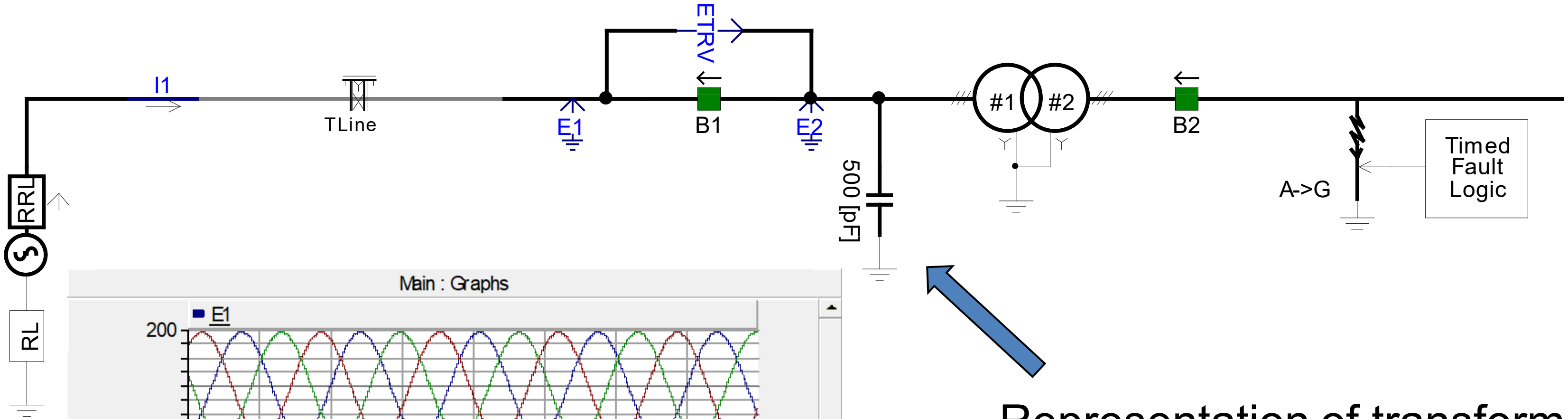
#1
#2
RRL
BRK1
Ea
BRK
Eb
T
TLine1
0.001 [H]
3
Open

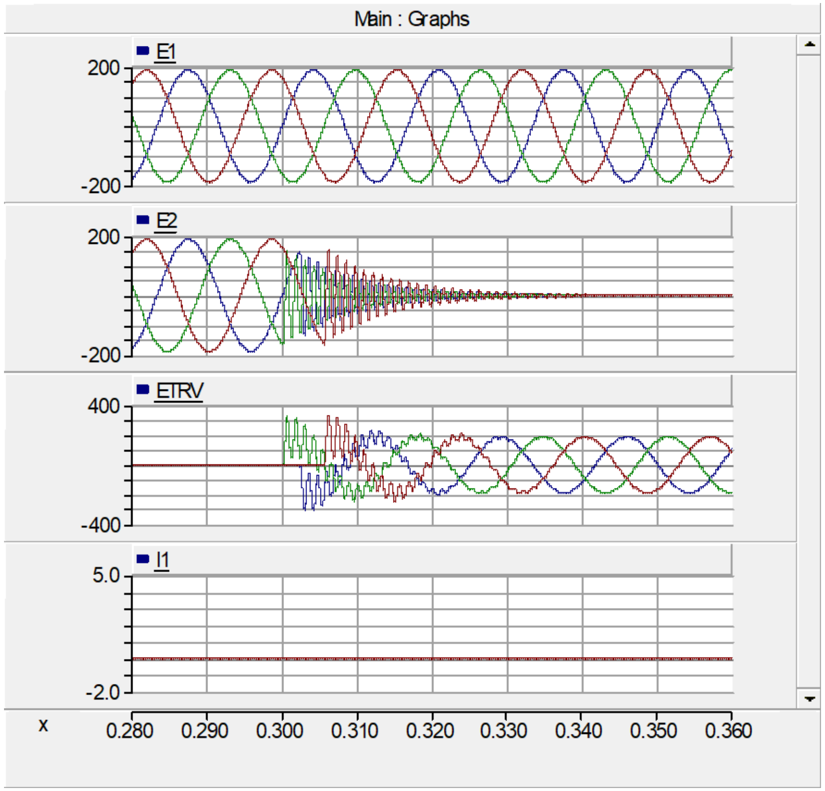


Main : Graphs
Ea
y



Main : Graphs
Eb
y



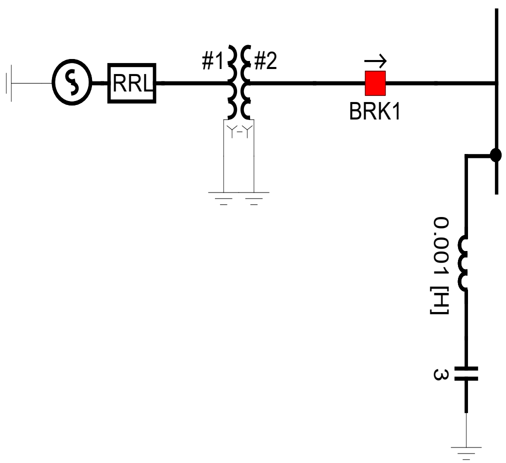


Representation of transformer bushing/stray capacitance

The nature of the transient is determined by the response of
R – L –C circuit elements

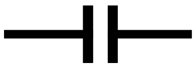
Basic R-L-C networks

Power system components:

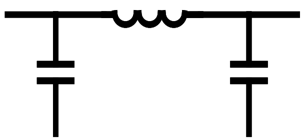


Transformers
Generators
Motors
Reactors

Capacitor Banks



Lines/Cables



Resistance – Losses, loads……..

Basic R-L-C networks

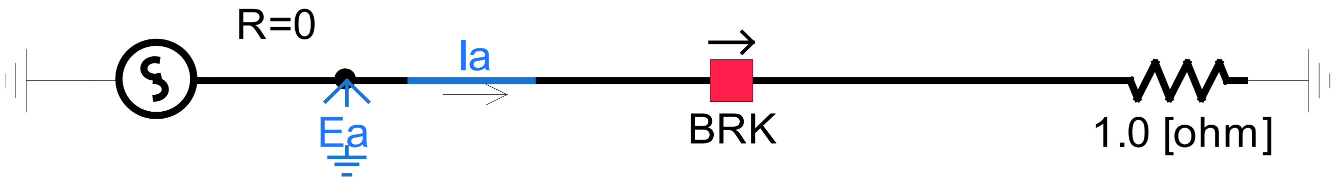
$$V = R \cdot I$$

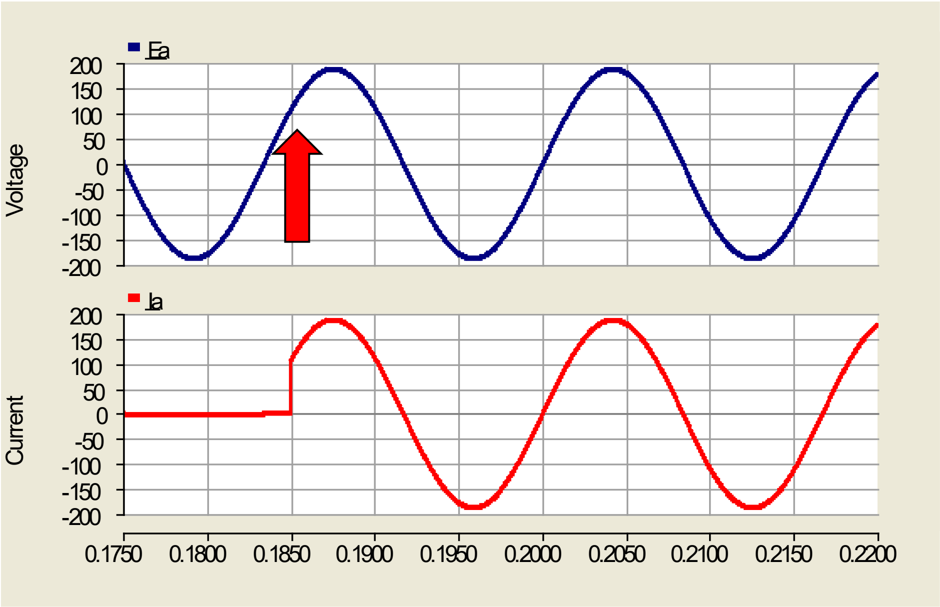
$$V = L\frac{di}{dt}$$

$$i = C\frac{dv}{dt}$$

Resistor – Dissipates energy

Inductor, Capacitor – Stores energy



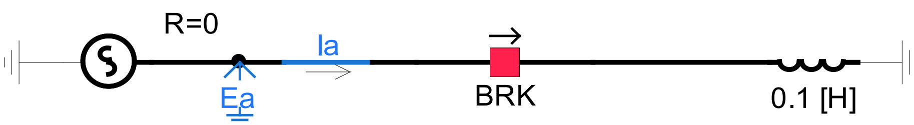


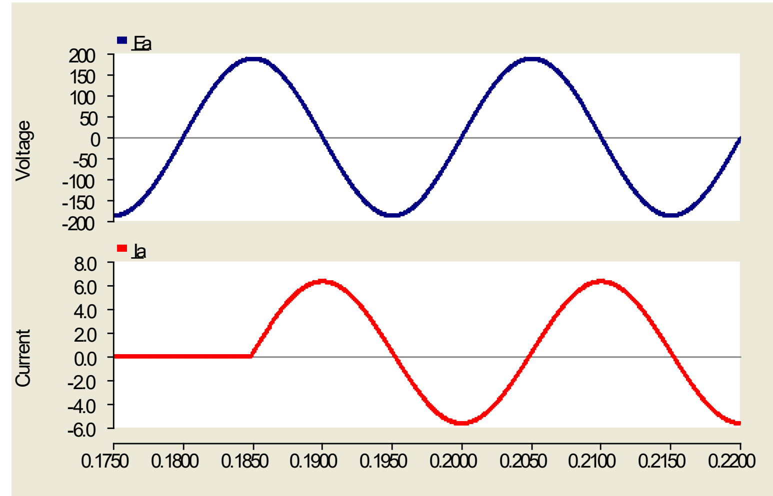
$$V = R \cdot I$$

Current follows the voltage waveshape.

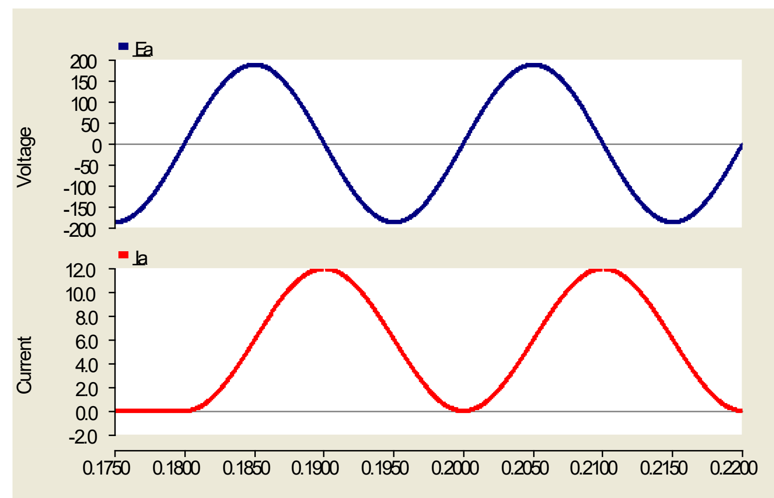
Point on wave impact:

- A simple example to illustrate the importance of 'sensitivity' analysis to find the 'worst case'.





$$V = L\frac{di}{dt} \qquad i = \frac{1}{L}\int V.dt$$

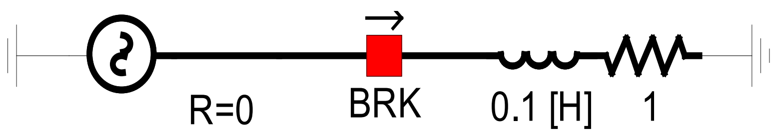


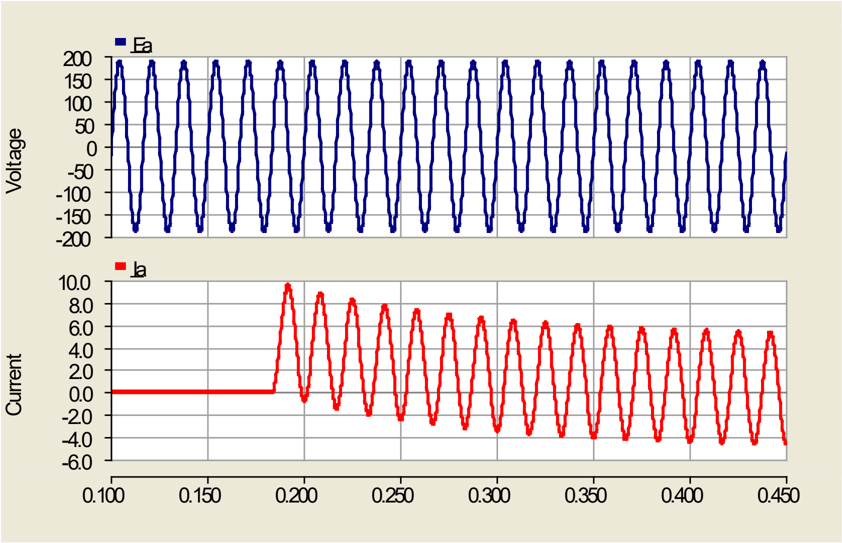
Integral is the area under the curve

$$Area = \int V.dt$$

Point on Wave Switching

- Transient is influenced by the point of the voltage waveform at the instant of disturbance (switching)





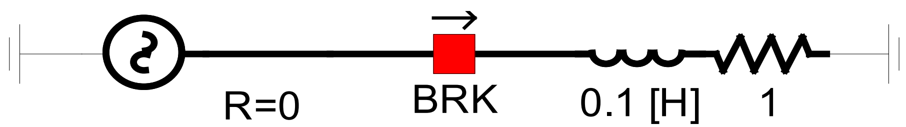
$$V = L\frac{di}{dt} + R.i$$

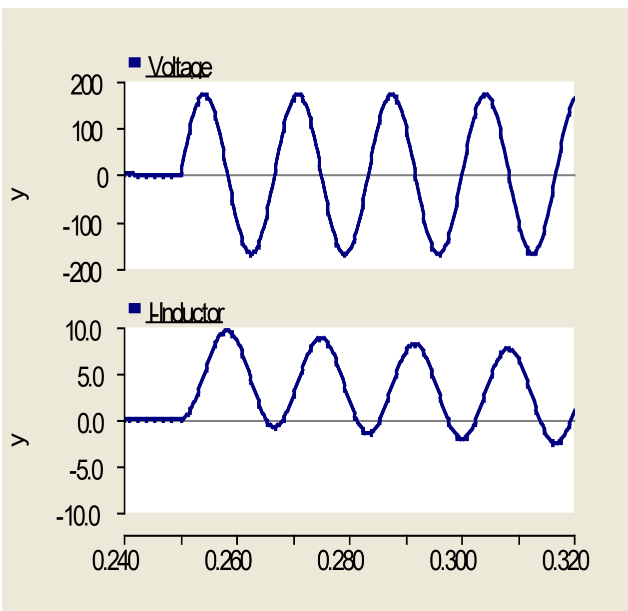
$$\tau = \frac{L}{R}$$

Damping – Due to losses and loads

Point on Wave Switching.

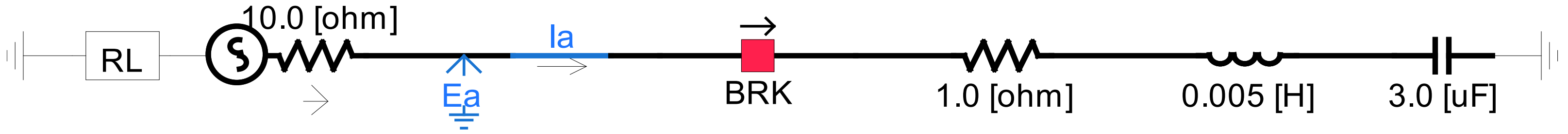
- Transient is influenced by the point of the voltage waveform at the instant of disturbance (switching)



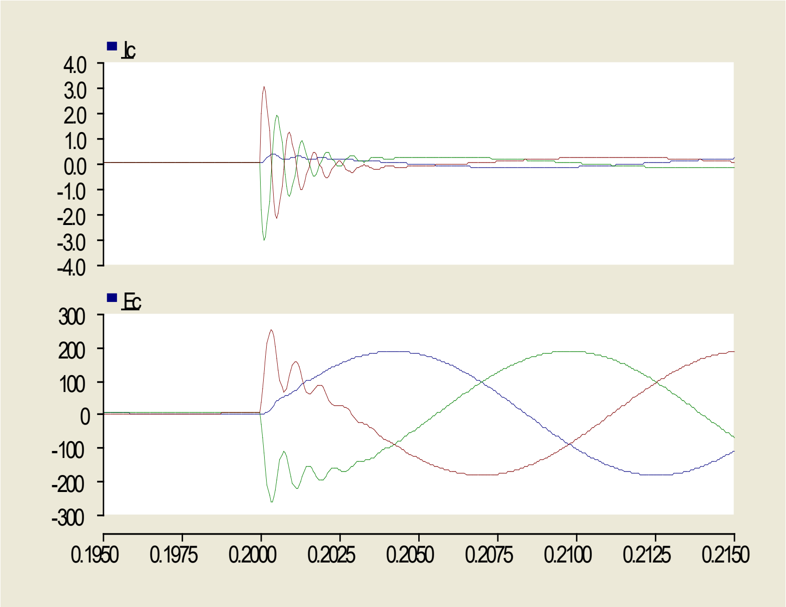


- Switching close to a Voltage zero is the worst case for a simple L-R network.

Note:
Damping is due to the resistance.
Time constant ➡ L/r



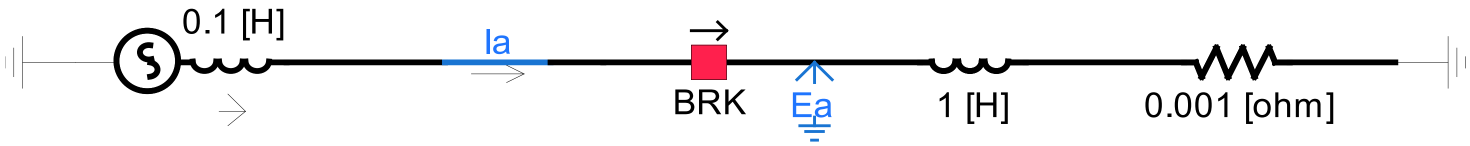
$$\frac{1}{2\pi\sqrt{LC}} = 1.299kHz$$

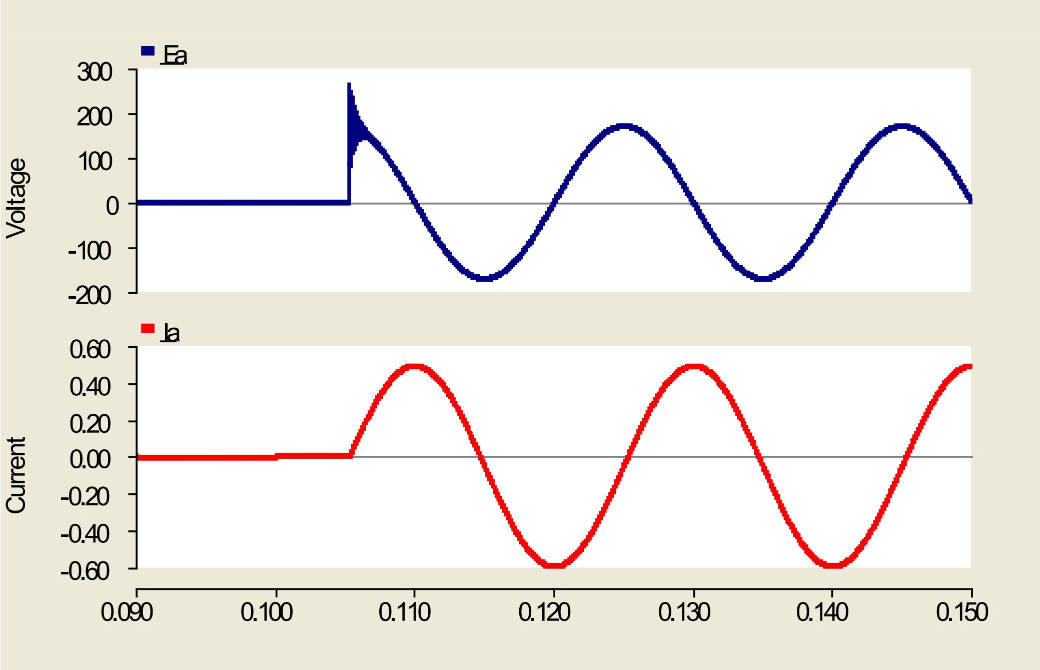


Oscillatory transients:

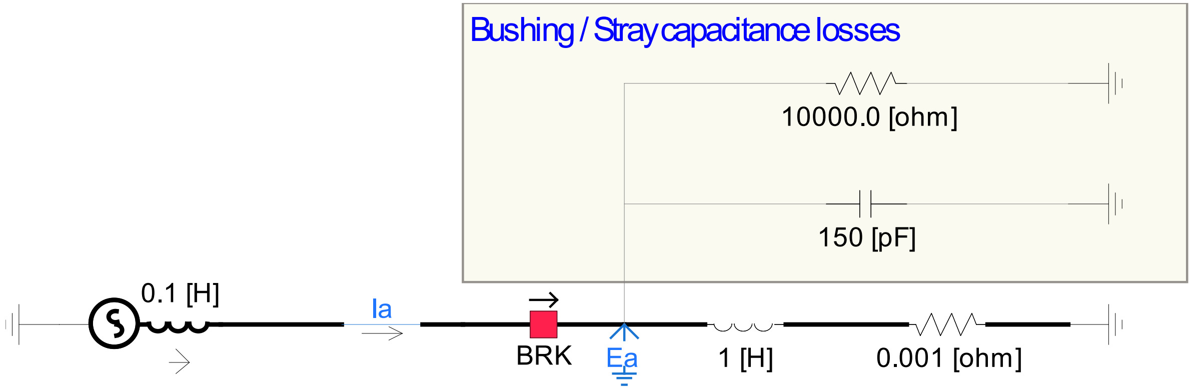
- Both **L *and* C** involved
- Damping is due to resistance
  - System losses
  - Loads

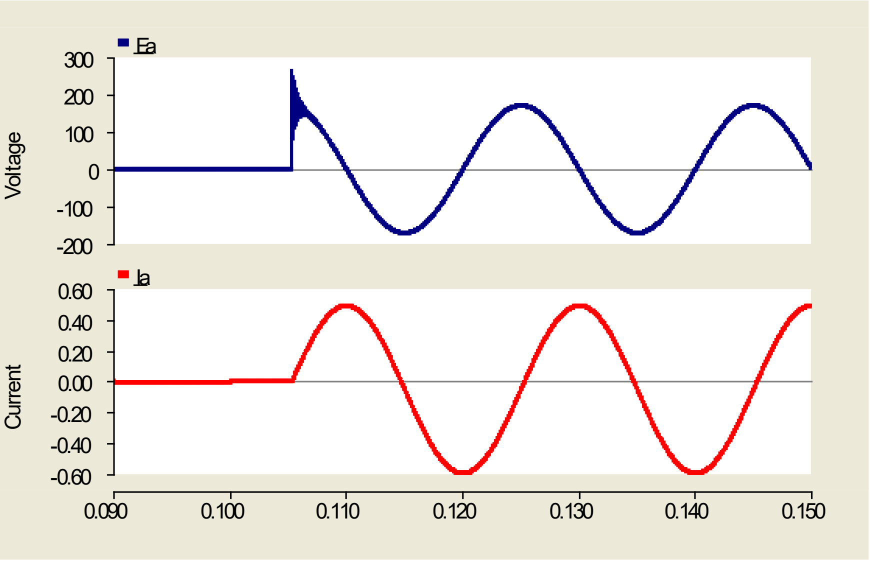
Reactor Switching





Why do we see oscillatory transients?





Why do we see oscillatory transients?

- Stray/Bushing capacitances
- Damped due to losses

Electromagnetic Transient Simulation Program

Electro-Magnetic Transient Programs:

- Direct time domain solution of Differential Equations using numerical methods
- Control systems are can be included in the simulations
- Solution time step must be small enough to capture the highest frequency of the transient we are interested in.
- Small part of the system may be considered in most studies.
- Power system components are modeled in more detail than any other applications

Power system components are modeled in more detail than any other applications:

- Detailed Machine models
- Detailed control system models
- Non linear effects (transformer core saturation)
- Coupling effects (Inductive/capacitive)
- Frequency dependent effects
- Distributed parameters for lines/cables (travelling wave models)

Power system components are modeled in more detail than any other applications:

This makes Electromagnetic transients suitable not only for fast electromagnetic transients.

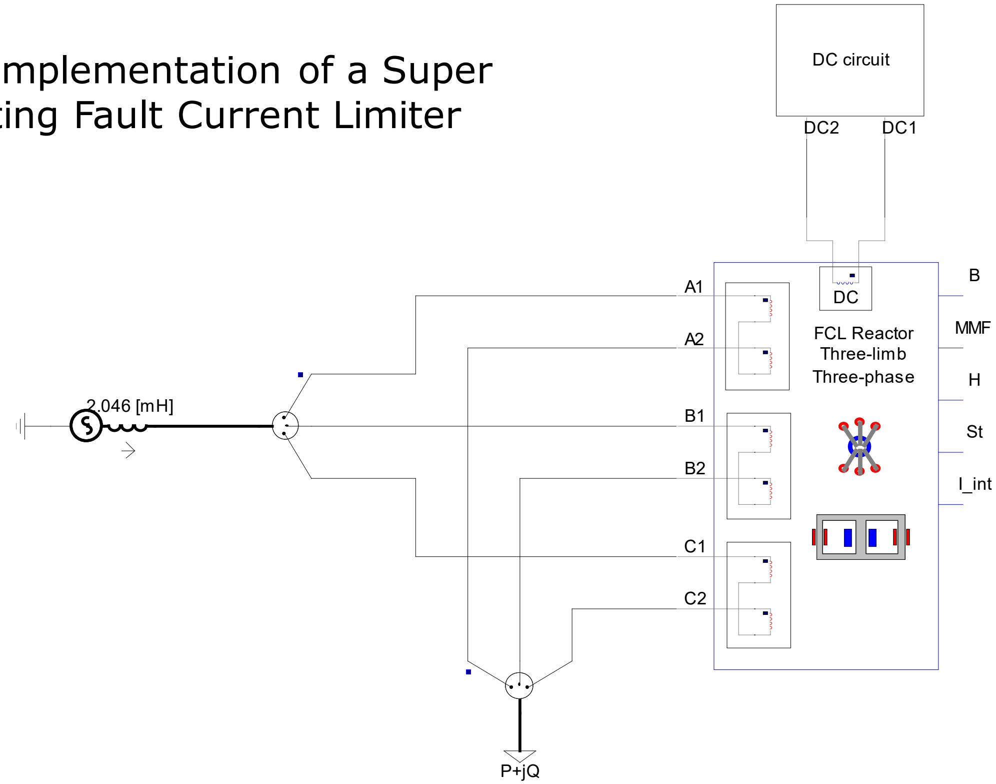
- AC/HVDC interactions
- Complex control system interactions
- Wind farm studies
- Sub Synchronous resonance studies (SSR)
- Voltage flicker issues
- Harmonic issues
- Other……….

- **Simulation time-step selection**
  - Fastest dynamic (highest frequency) that is to be simulated
    - e.g. $f_{highest}$ = 2 kHz, Δt = 50 μs (may work for switching transients)
  - TRV - 50 μs is too large. (Is there a ***Rule of thumb*** ????)
  - Smaller time-step ➔ take longer to complete simulation
- **Plot step selection**
  - Fastest dynamic to be plotted
- **Initialization or how to start a simulation**
  - Beware of the dynamics of all components in system
  - Need to wait until the slowest dynamic settles before introducing transient
- **Numerical stability**
  - Chatter removal
- **Interpolation / extrapolation techniques**
  - To match the exact switching instants of power electronic devices

PSCAD allows the users to develop custom models.

These can be used in a simulation along with any models from the main (MASTER) Library

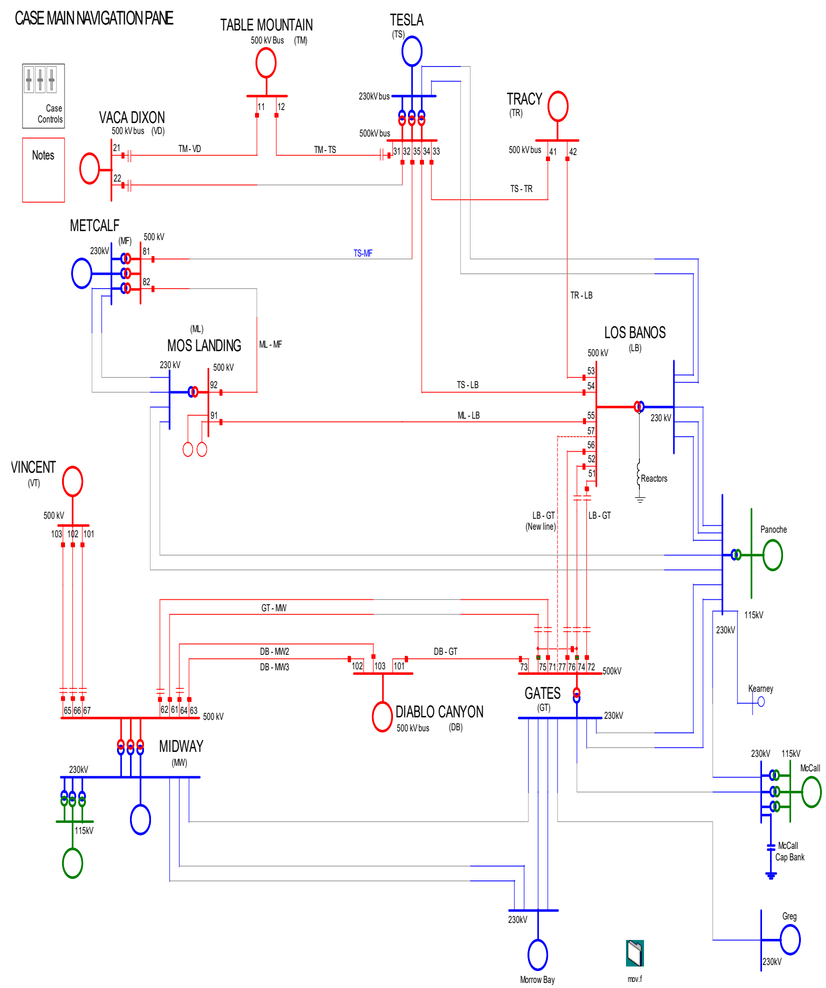
PSCAD implementation of a Super Conducting Fault Current Limiter



Model Validation

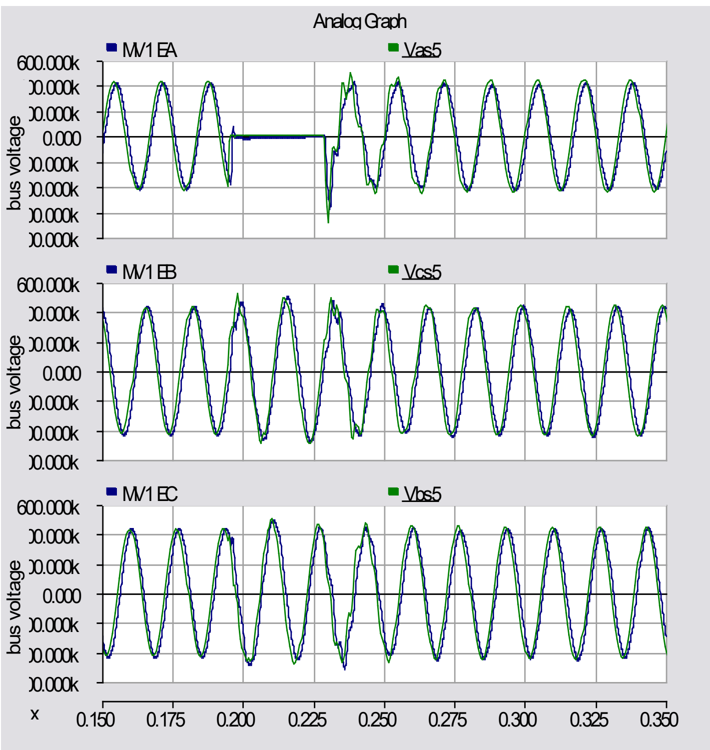
The model (500kV system model for a switching and protection study)was validated with the following methods.

- Load flow
- Fault level
- Fault recordings

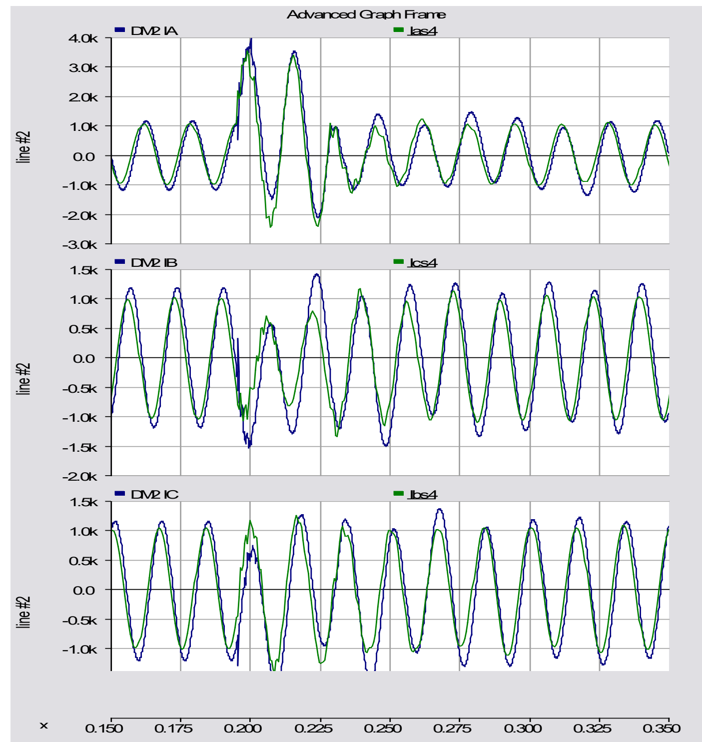


Model Validation

Fault recordings: Near the fault bus



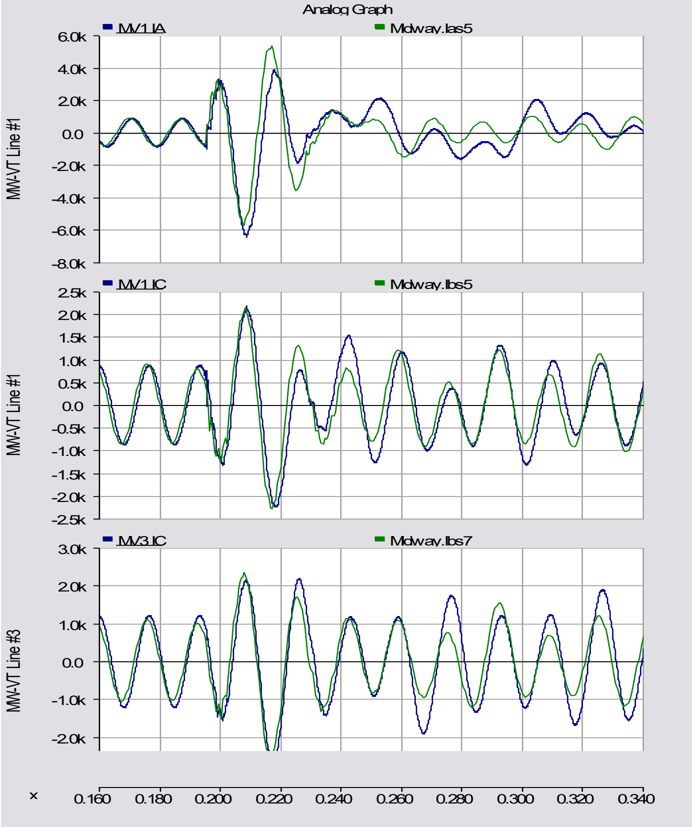
Voltages



Current

Fault recordings: At remote bus

Current



- The simulation shows the same trends
- Not all conditions are known at the instant of the fault.
  - Load flow
  - Point on wave
  - Reactors / capacitors ON or OFF

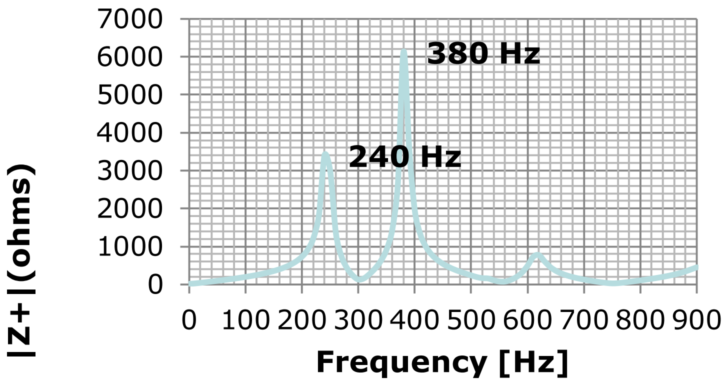
Selected Applications in Power Systems

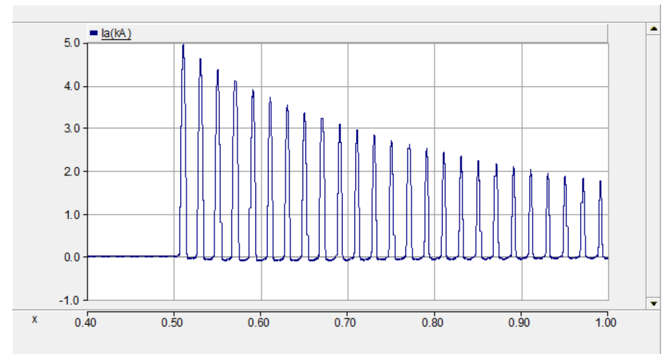
Selected Applications in Power Systems

1. Transformer energizing
2. Transmission line and equipment switching
3. Capacitor bank switching
4. Circuit breaker Transient Recovery Voltage (TRV)
5. Overvoltage caused by lightning strikes
6. Motor starting
7. Protection
8. Equipment failure – Post event investigations
9. Network resonance and Ferro resonance problems
10. Distributed generation studies
11. Power quality

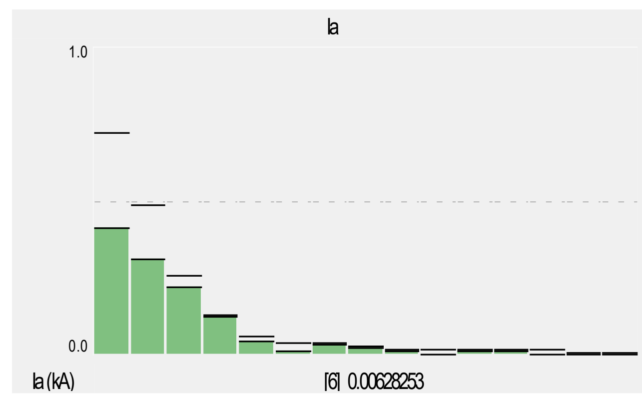
Many more……..

Transformer Energizing

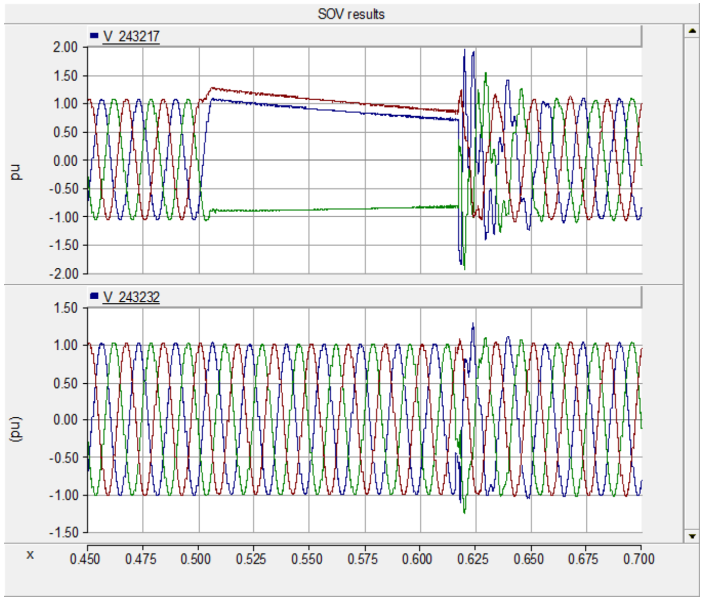




- Core saturation
- Inrush current and harmonics
  - Voltage dips
- Network characteristics - frequency scans
  - Over voltages due to harmonic resonance conditions



Transmission line and Equipment Switching

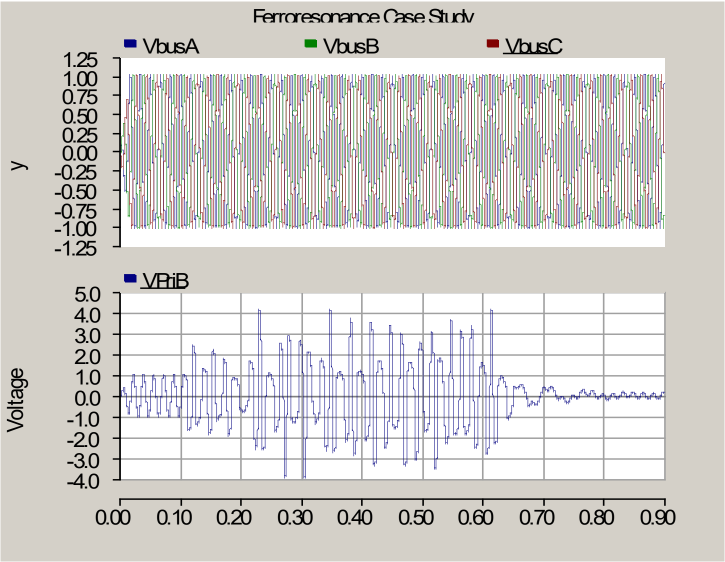


	E1	E2	E3	E4
Minimum:	364.6304	280.1849	332.9529	353.4259
Maximum:	395.8886	352.6374	413.6732	383.773
Mean:	379.7837	320.0234	375.2662	369.2719
Std Dev:	7.564519	17.03806	18.64495	7.544283
2% Level:	364.248	285.0315	336.9741	353.7778
98% Level:	395.3193	355.0153	413.5582	384.7659

- Overvoltage magnitudes and equipment insulation levels
  - Surge arresters
- Statistical distribution of overvoltage magnitude
- Transmission line ‘flash-over’ rates
- Investigation of overvoltage mitigation methods

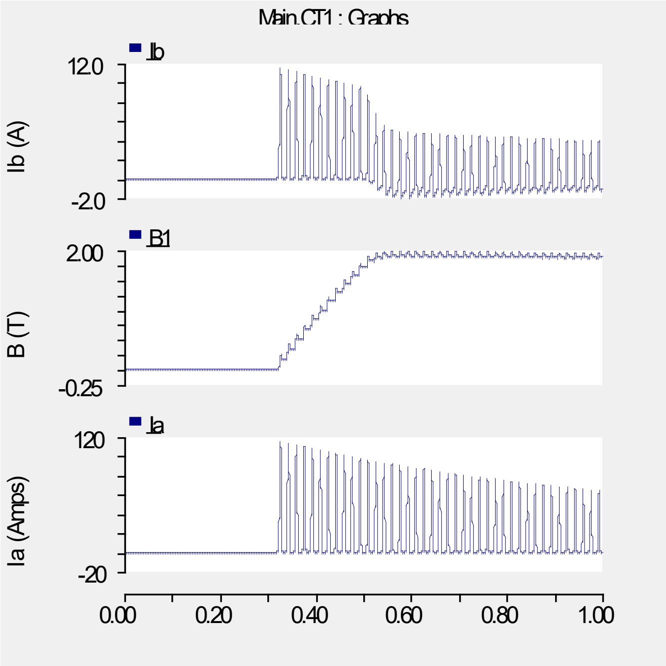
Ferro Resonance

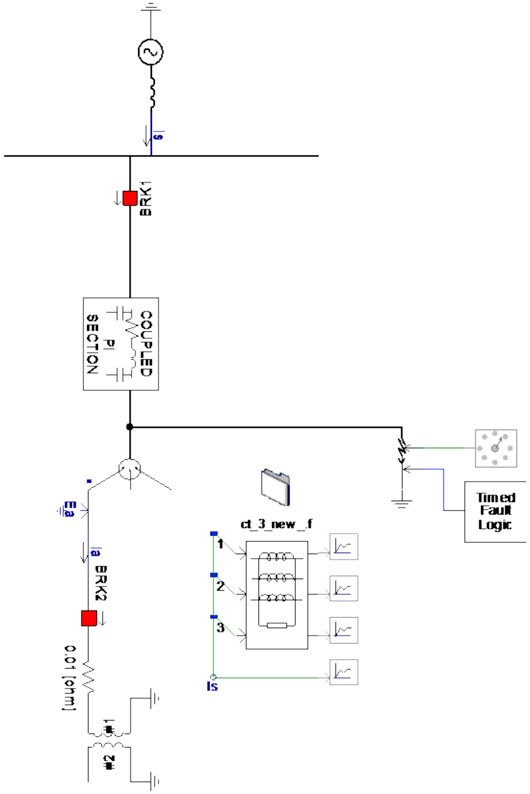
Many factors can lead to ferro-resonance situations. Transients simulations are necessary to identify possible problems.



CT Saturation

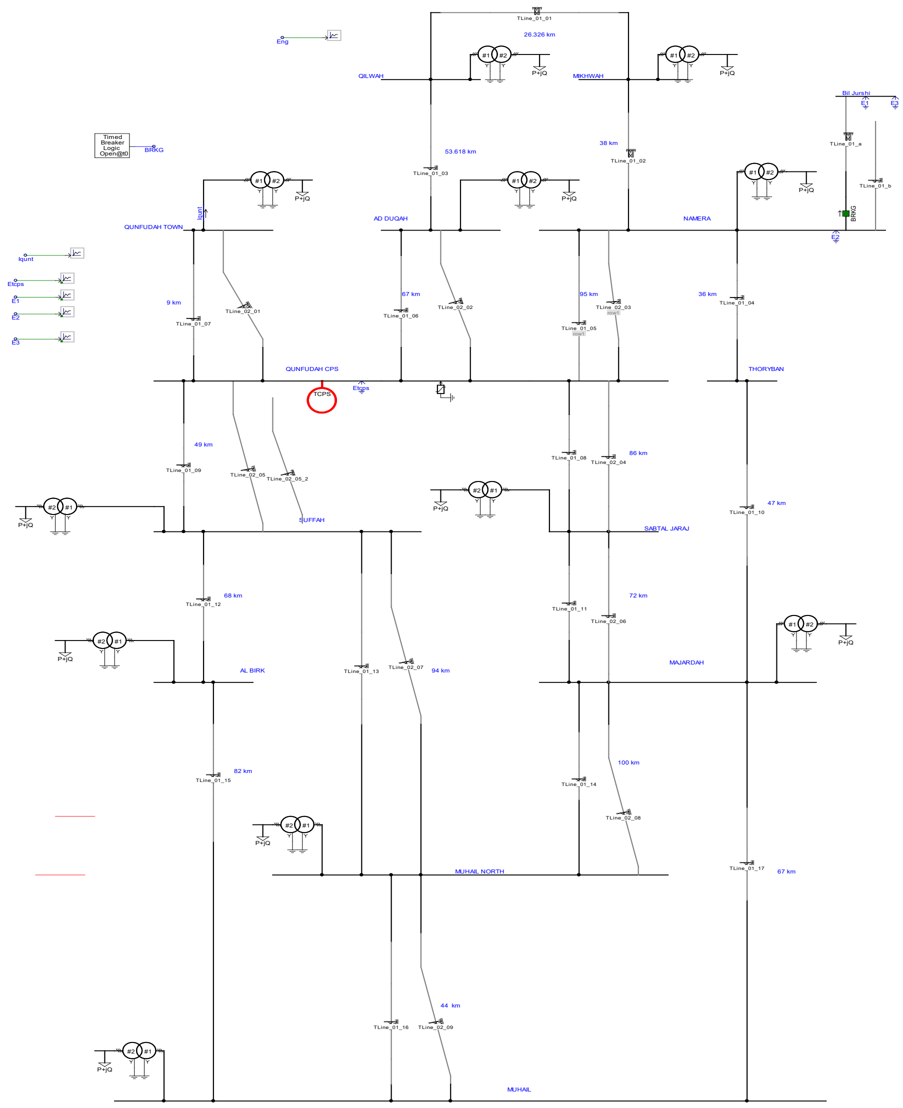
- Mal-operation of an earth fault relay during transformer energising.
- Inrush current caused unequal saturation of the 3 CTs, resulting in a 'burden' current.
  - ➢ CT of phase A saturated during energising of a single phase transformer in a distribution feeder



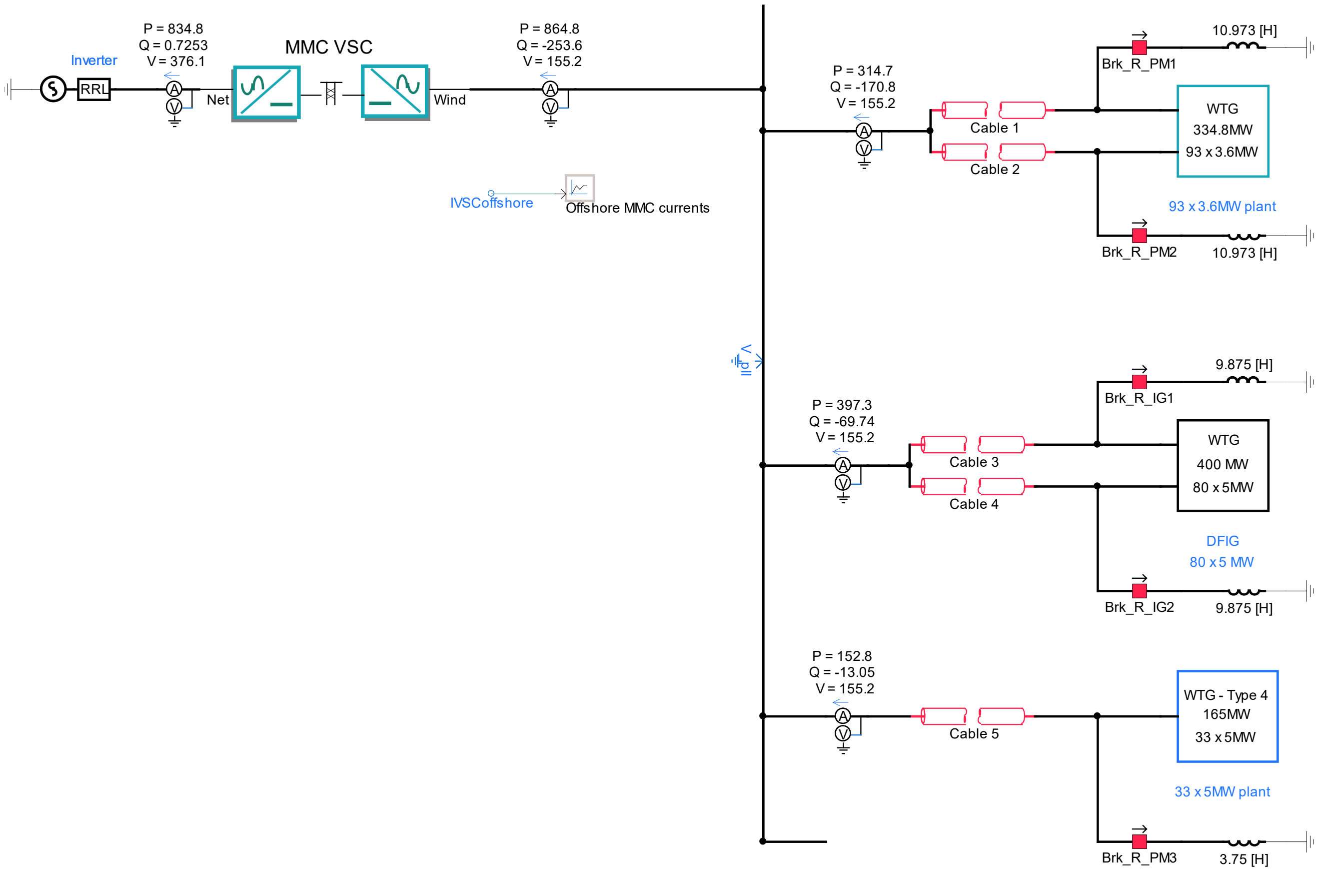


System Blackstart restoration studies

- Restoration steps are determined and documented – step by step.
- System single line drawings are used to illustrate each step
- Electrical studies are necessary to verify that the selected restoration actions (steps) can be implemented without damaging equipment.



Wind Integration



Thank you