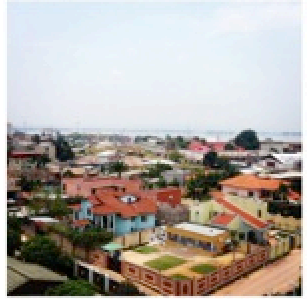
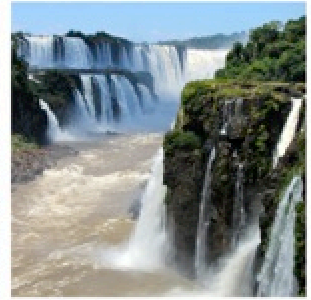
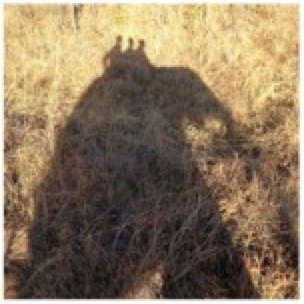
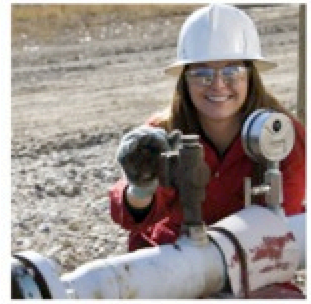





PSCAD

General Introduction to Electromagnetic Transient Simulations - Mathematical Background and Common Applications

Presenter: Dharshana Muthumuni

Manitoba HYDRO INTERNATIONAL

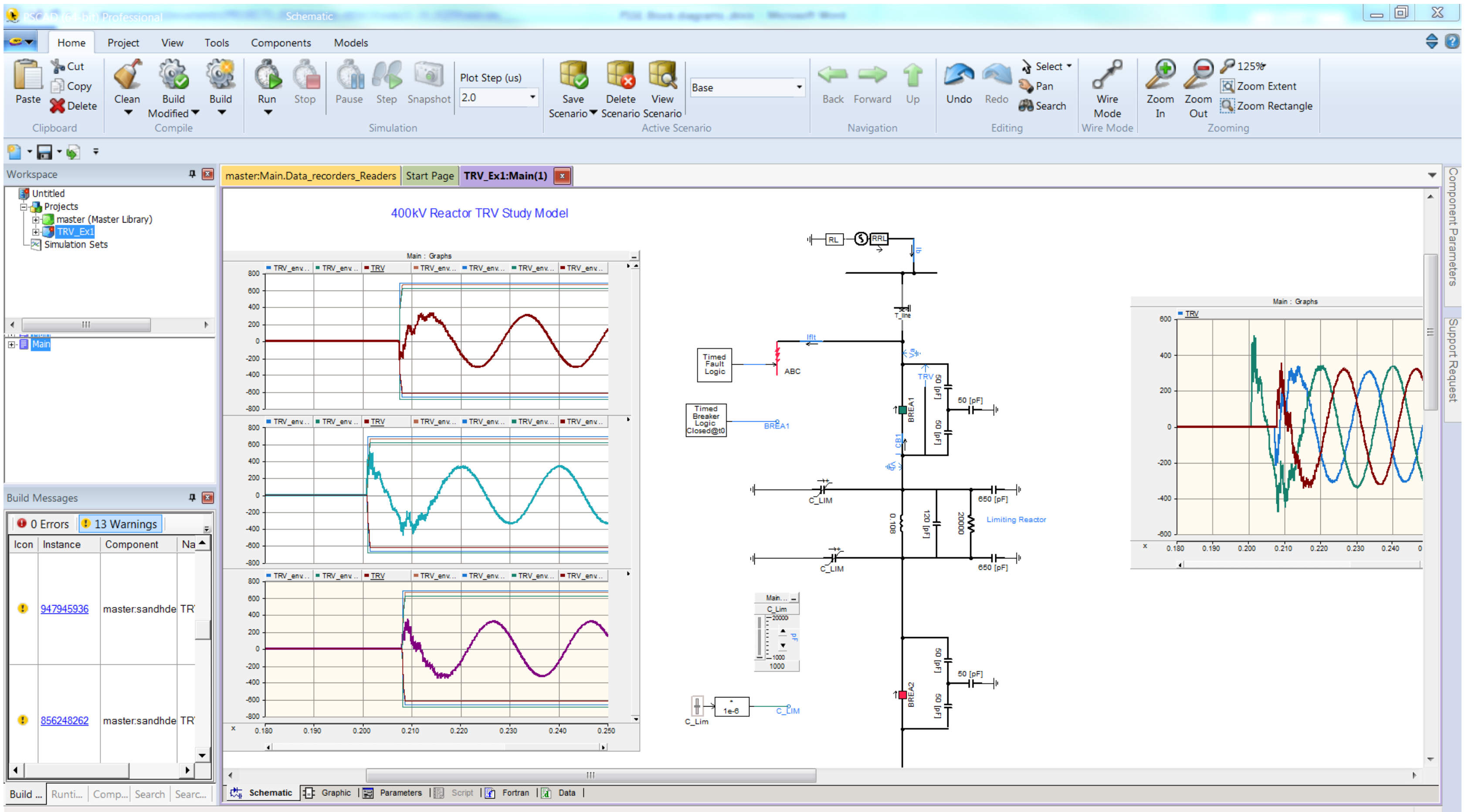
Introduction to the Fundamental Concepts of EMT Simulation and Circuit Solution Methods

- The key differences between EMT and RMS-type simulation solutions
- Electromagnetic transients in power systems
  - Characteristics
- Circuit equations and solution methods
  - State-space formulation
  - Dommel's method
- Techniques used for fast and accurate solutions
  - Sparse matrix
- Network Impedance Characteristics and transient response
- Practical simulation examples that highlight application areas

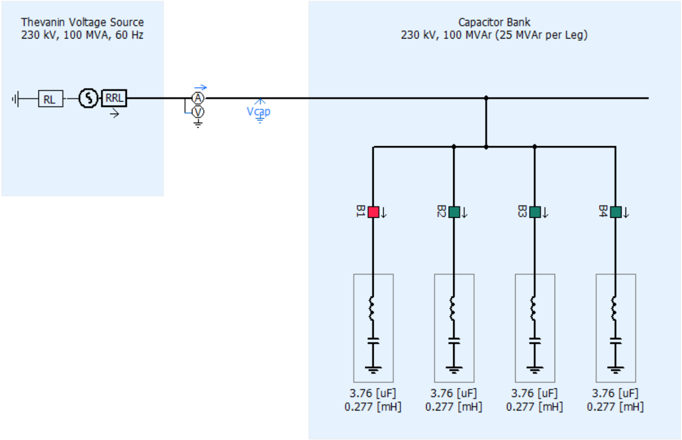
Common Applications

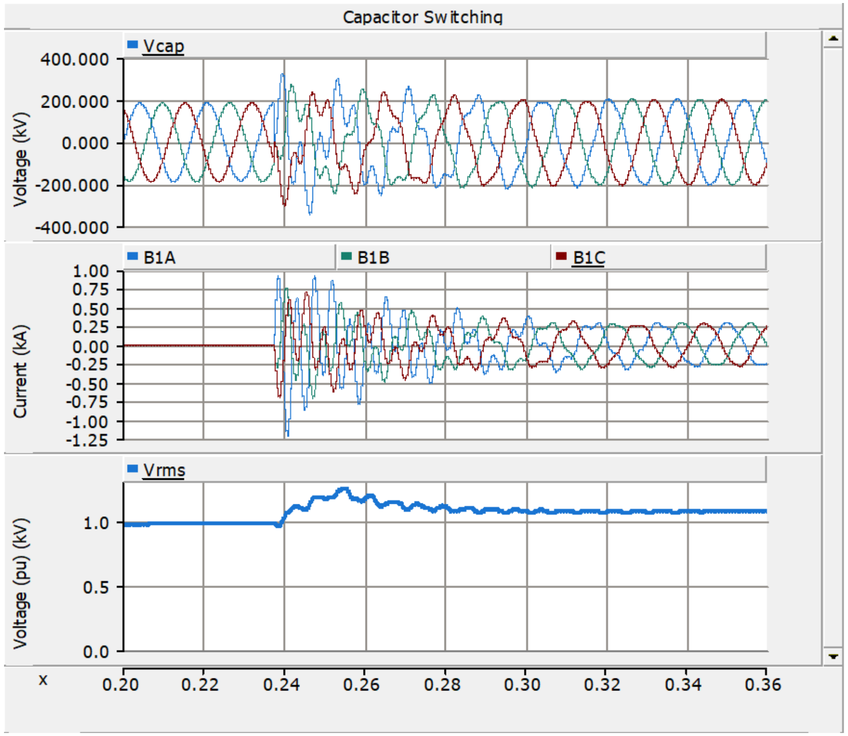
- Cable, line, station insulation design
  - Switching Over-Voltage studies – Arrester ratings
  - Power System lightning performance – BIL
  - Temporary Overvoltage studies (TOV)
  - Breaker Transient Recovery Voltage (TRV)
- Wind and Solar PV integration studies
  - Performance during faults
  - Interaction with other devices near the POI
  - FACTS technologies to support wind
  - Application of HVDC transmission (VSC, LCC)
- System Harmonic and power quality analysis
- Protection modeling and testing
- Sub-Synchronous Resonance

PSCAD/EMTDC – The Industry Standard EMT Program



EMT Solution





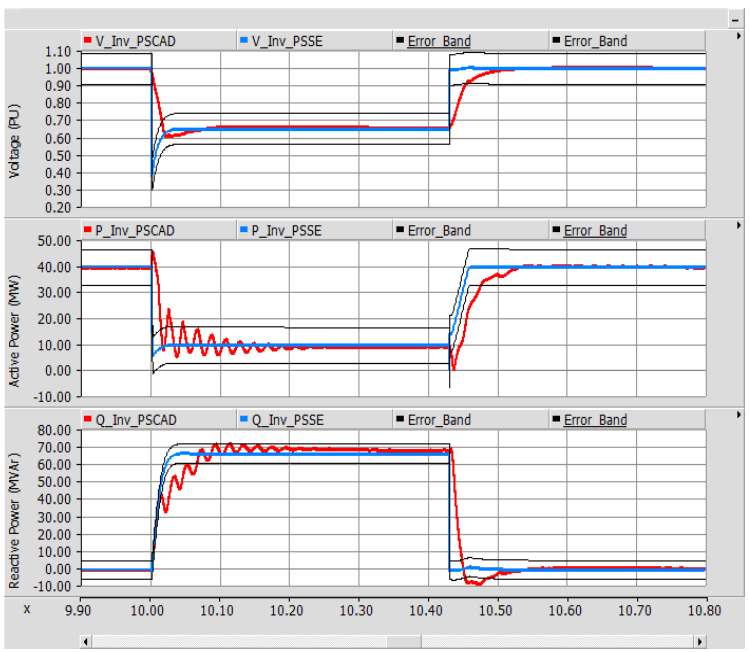
In an EMT simulation, the instantaneous values are calculated by solving time domain circuit equations.

- RMS quantities are derived from the instantaneous solution.

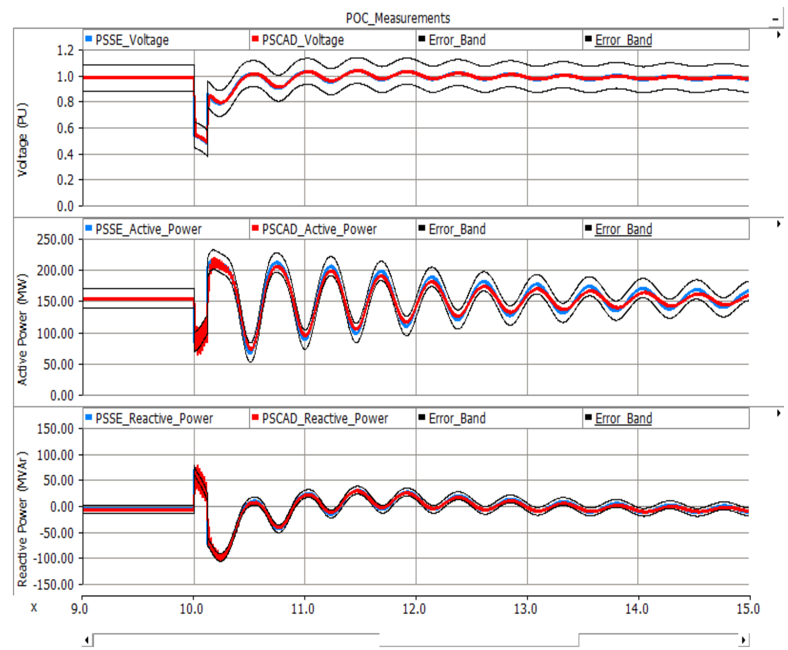
EMT and RMS Type Simulation Results

The results (even RMS quantities) are derived from two different methods of mathematical circuit solution techniques

Wind farm fault ride through

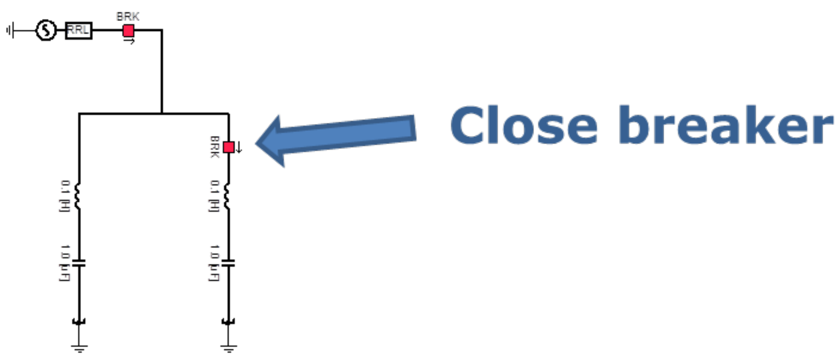


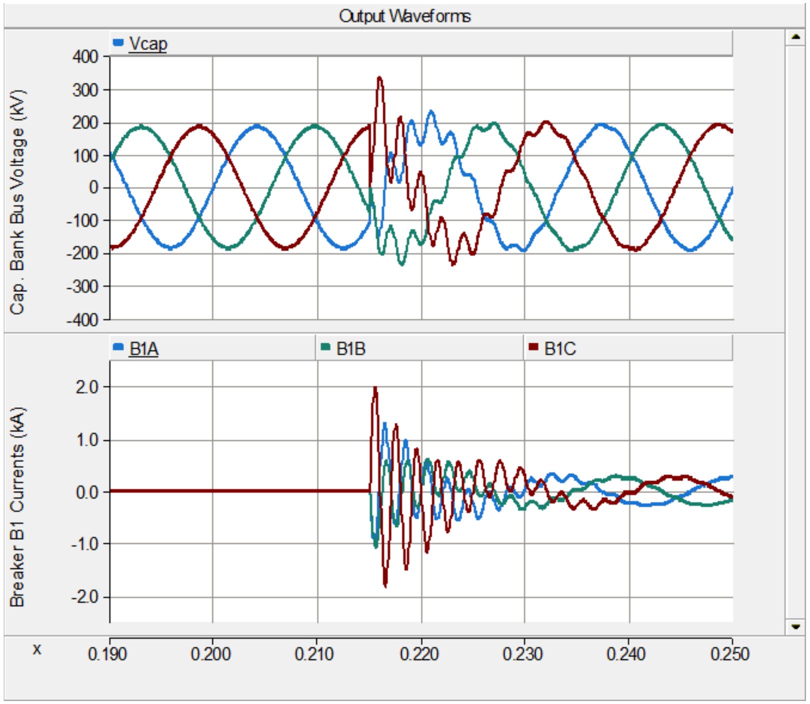
Synchronous generator fault ride through



Electromagnetic Transients in Power Systems - Characteristics

Example: Closing the breakers has initiated an electromagnetic transient

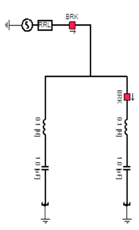




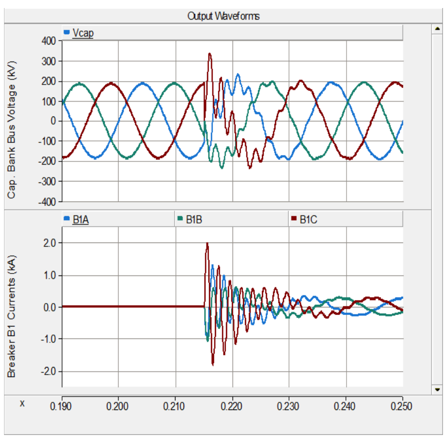
Electromagnetic Transients in Power Systems - Characteristics

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.



Close breaker



Transients are initiated due to a change to the network topology

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

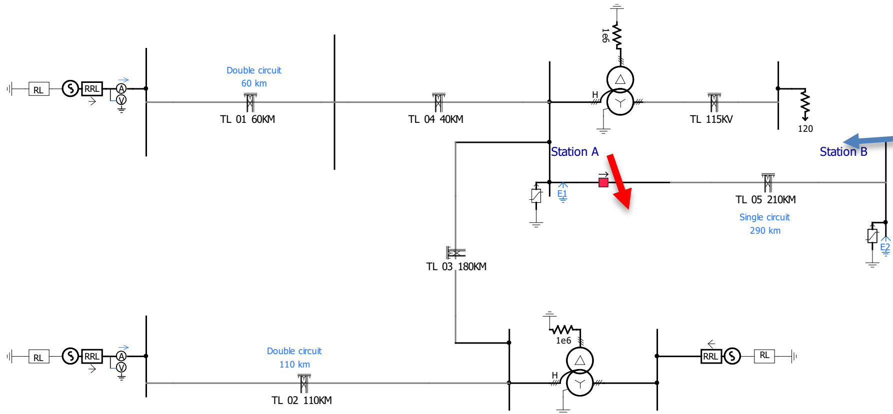
Electromagnetic Transients – General characteristics

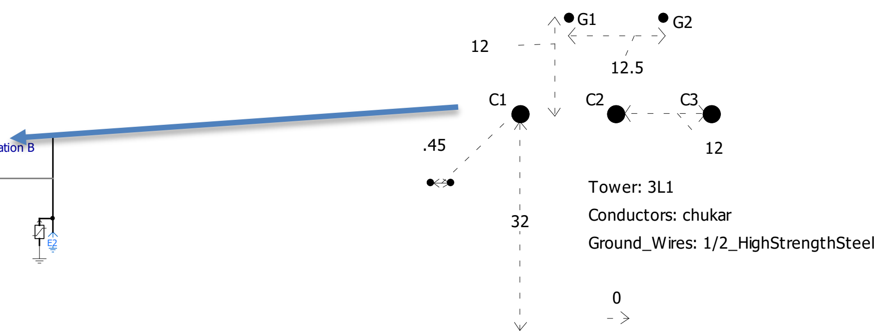
- High frequency oscillations ⟹ $f := \frac{1}{2 \cdot \pi \cdot \sqrt{L \cdot C}} = 503.292$
- Damped (short duration) ⟹ loads and losses

Steady state solution

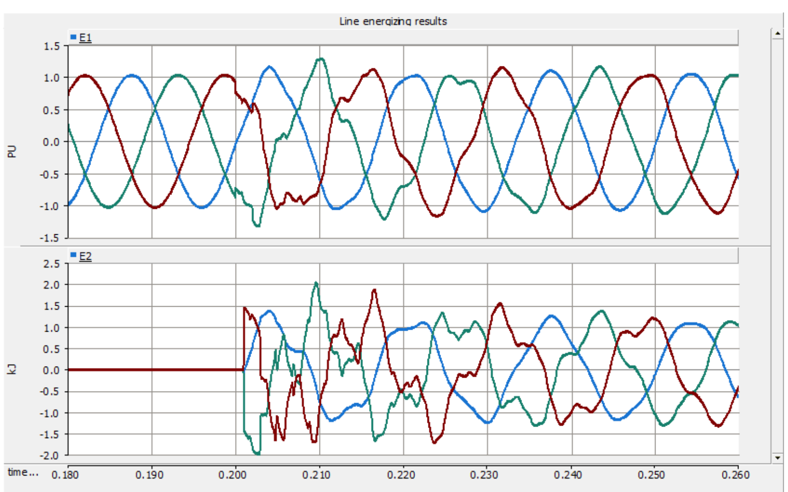
- **RMS Value of voltages and currents**
    - **Magnitude and phase**

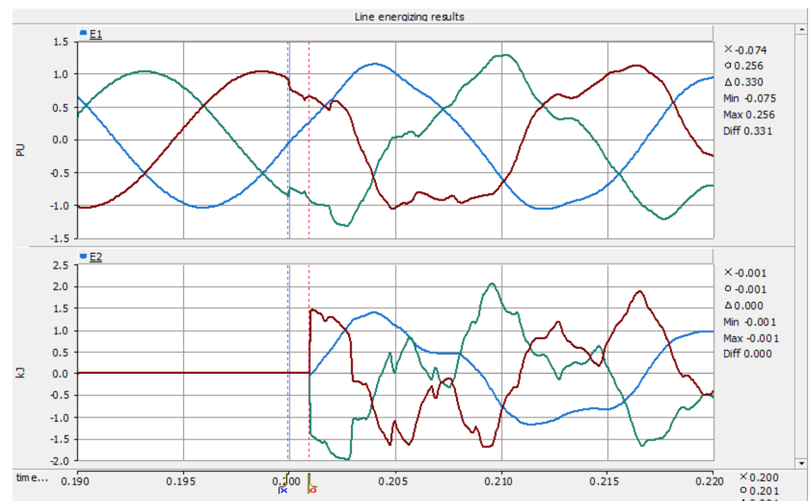
Electromagnetic Transients in Power Systems - Characteristics





Transmission Line 'travel time' (approx.) - 1 ms





EMT and RMS simulation – Main differences

Transients and Steady State Solution

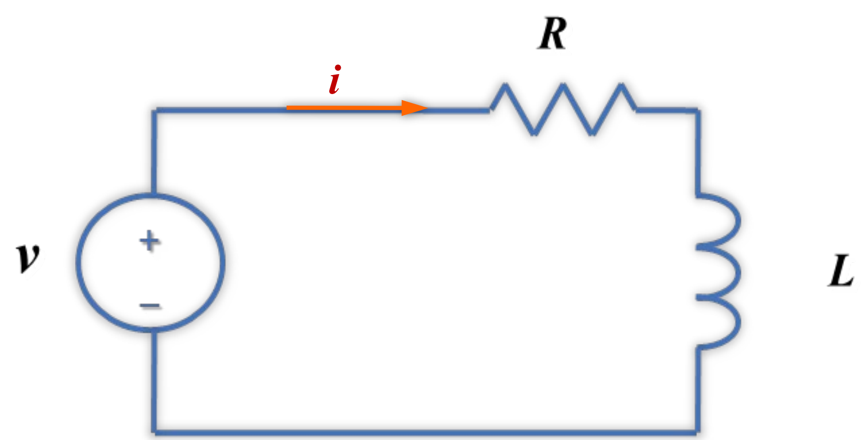
- Load Flow / Transient Stability
  - Each solution based on phasor calculations
    - PSSE, ETAP, PSLF, BPA

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

- 50 Hz solution on network side
- Good for low frequency electro mechanical oscillation studies.
- Difficult to represent power electronic converter response (wind, PV)
- Cannot represent ac system resonances

- Electro-Magnetic Transients
  - Direct time domain solution of Differential Equations
    - PSCAD, RTDS

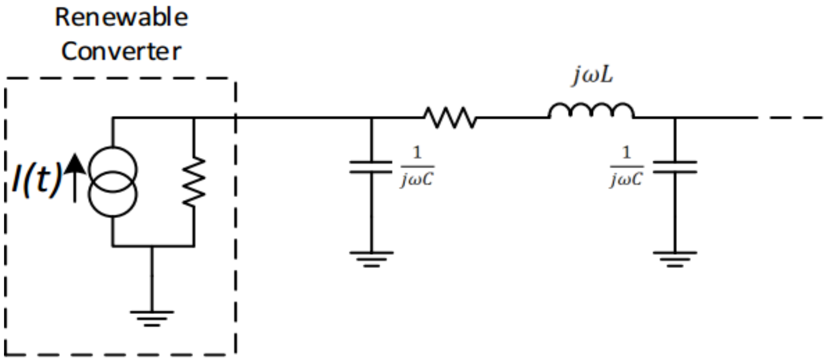
$$v(t) = R \cdot i(t) + L \frac{d}{dt} i(t)$$



Transients and Steady State Solution

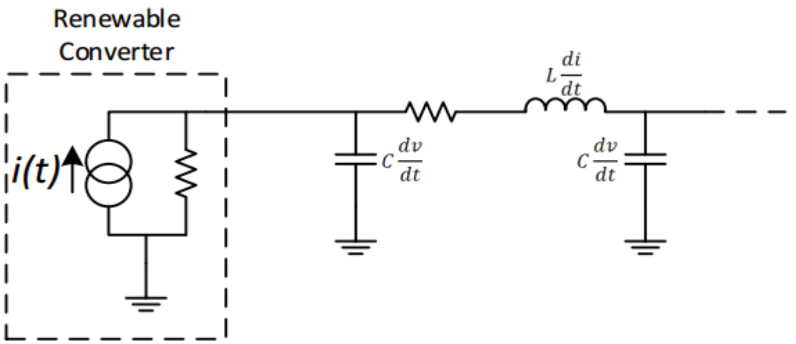
RMS

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

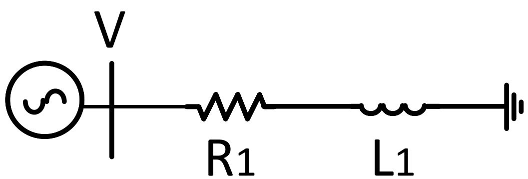


EMT

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



Time Domain Solution of Circuit Equations

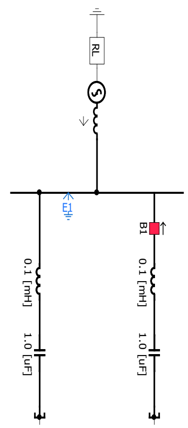


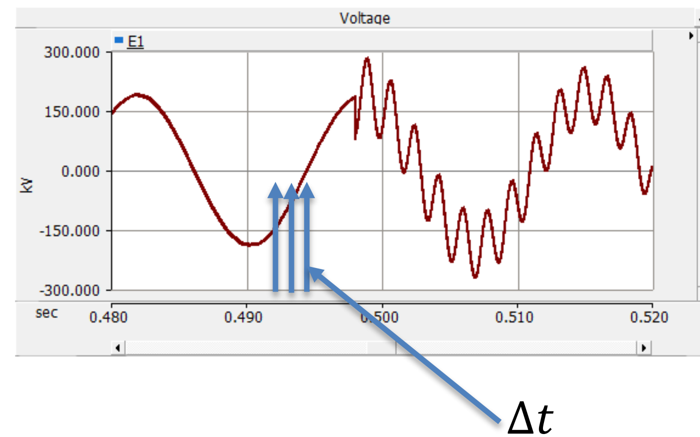
$$V = L\frac{dI}{dt} + R.I$$

$$\frac{V + V_0}{2} = \frac{L}{\Delta t}(I - I_0) + \frac{R}{2}(I + I_0)$$

$$V + V_0 = \frac{2L}{\Delta t}(I - I_0) + R(I + I_0)$$

$$V + \left[V_0 + \frac{2LI_0}{\Delta t} - R * I_0\right] = I\left(R + \frac{2L}{\Delta t}\right)$$





Circuit equations solved at time intervals - Δt

RMS Type Solution

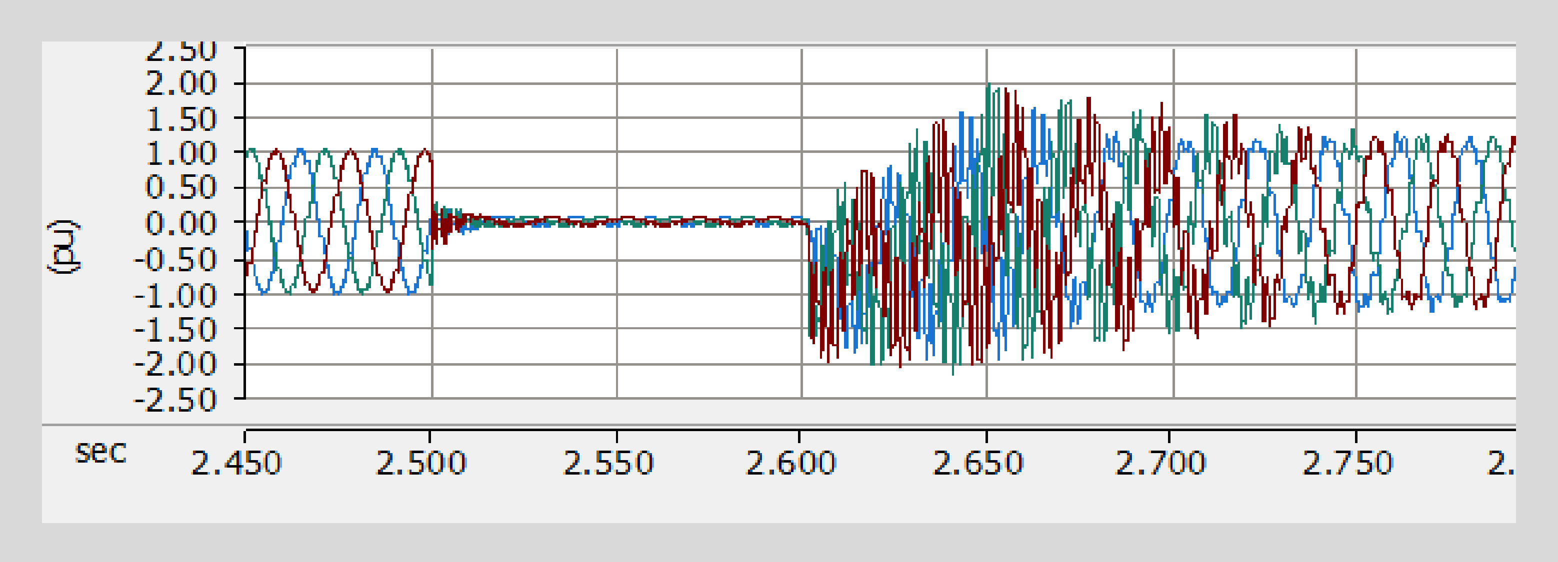
$$V = j.X.I + R.I$$

$$X = 2\pi f_0$$

EMT Vs RMS Response

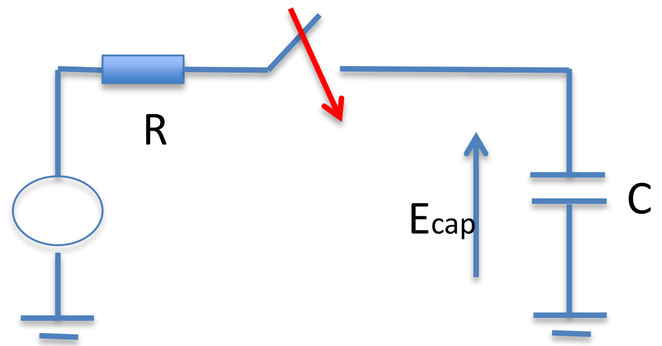
- Network (electric circuit) dynamics
  - Harmonics are represented
  - DC offset in currents and voltages are represented
- Fast controls of inverters can be better represented
- Interaction between fast acting power electronic devices can be studied

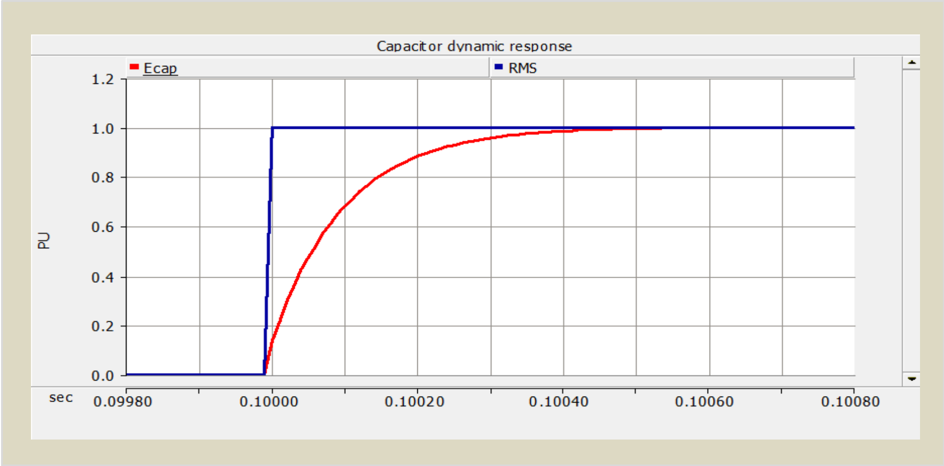
However, EMT simulations are slow compared to RMS type simulations



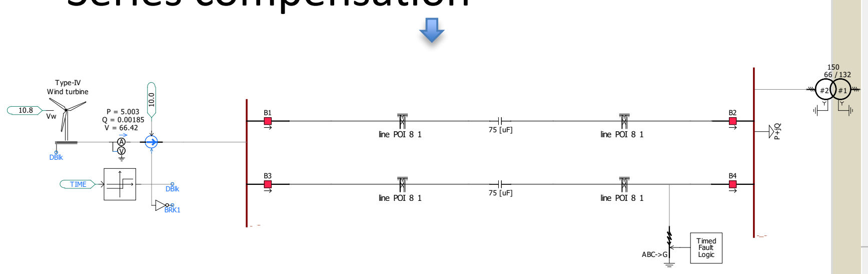
EMT Vs RMS Response – Capacitive Circuits

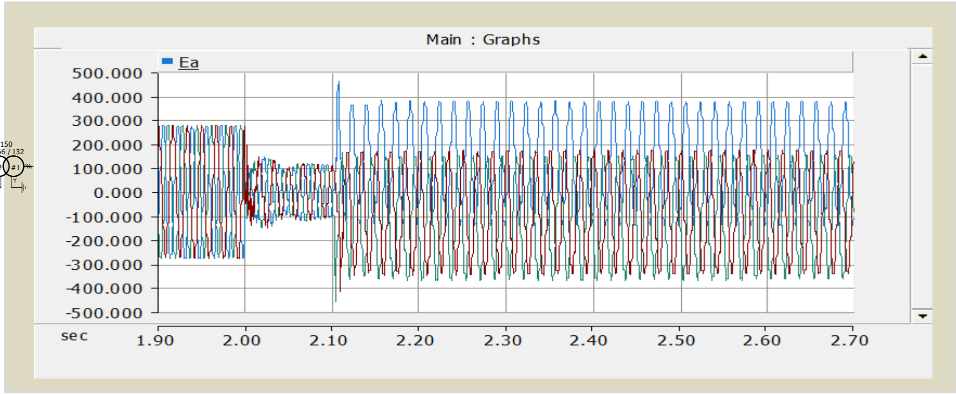
Capacitor voltage response



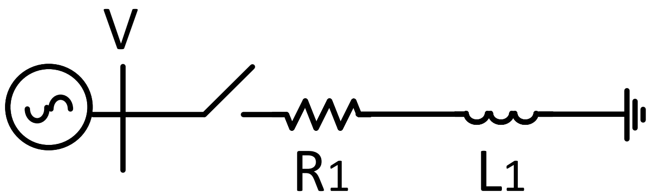


Series compensation



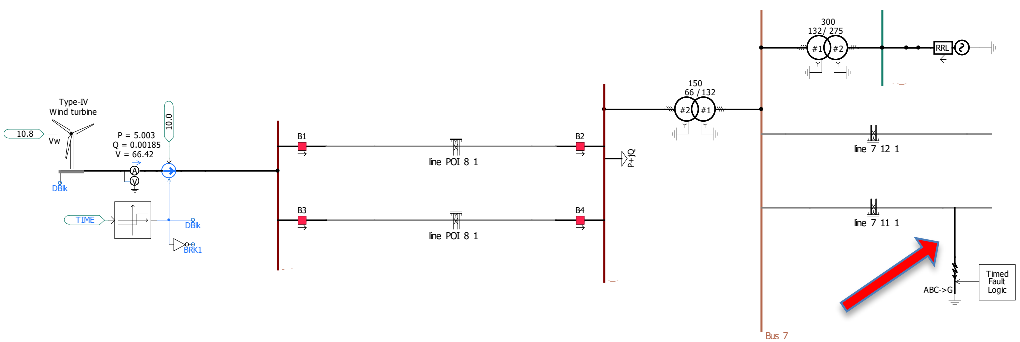


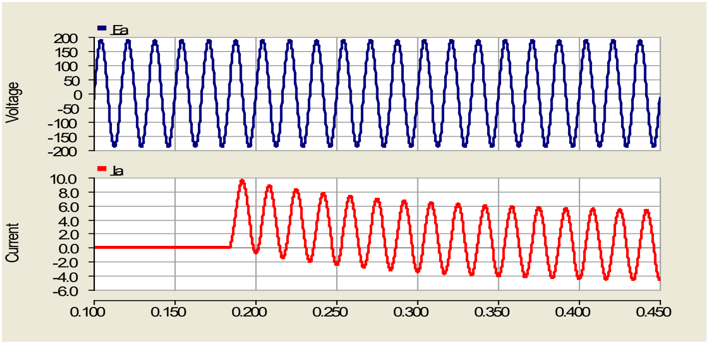
EMT Vs RMS Response – Inductive Circuits



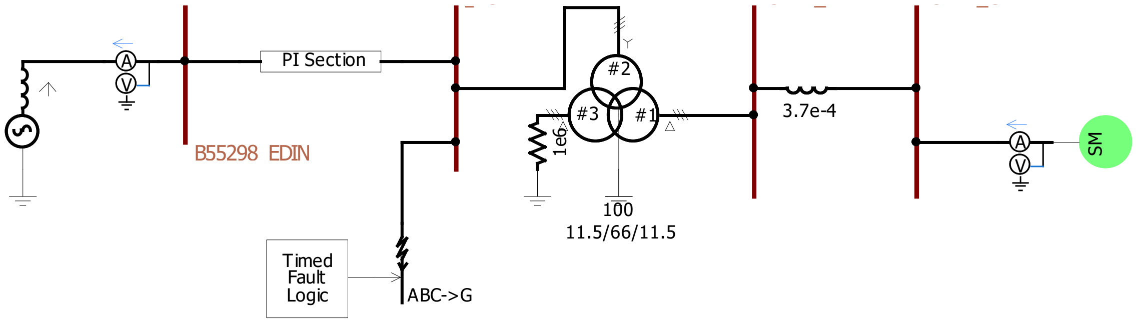
$$V = L\frac{di}{dt} + R.i$$

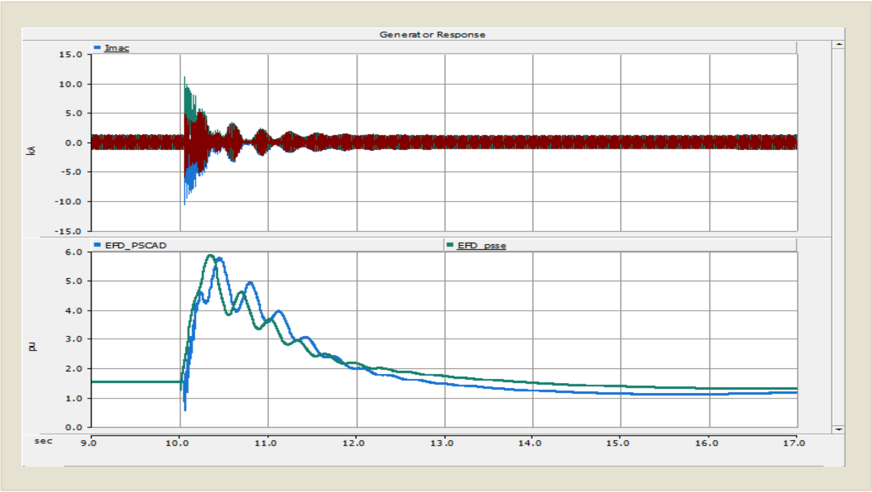
$$\tau = \frac{L}{R}$$

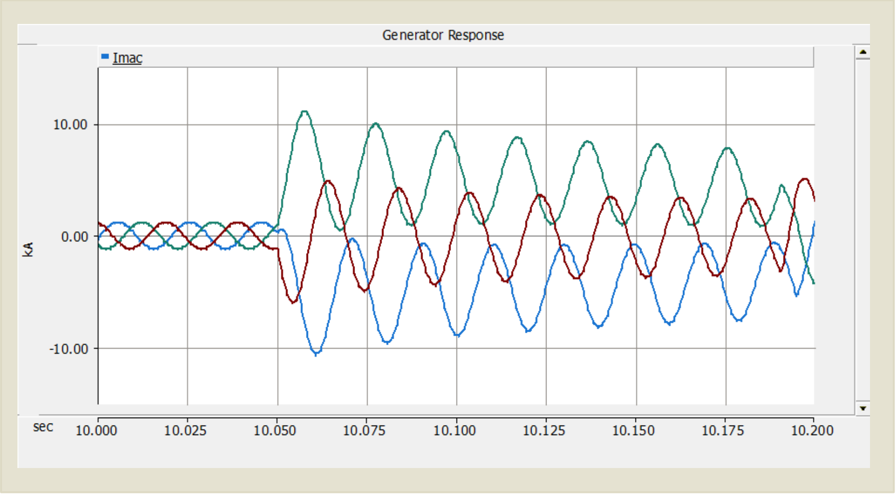




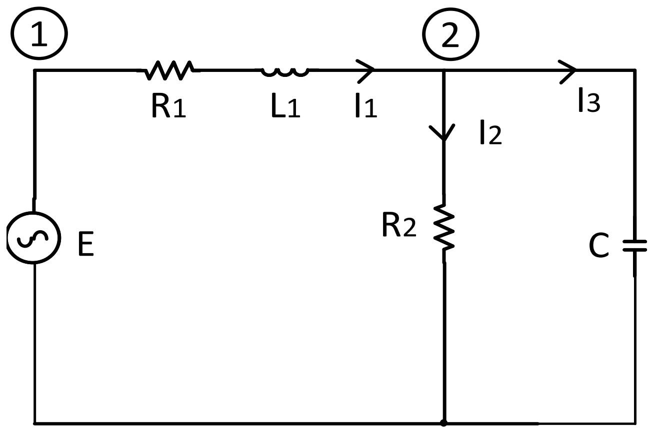
EMT Vs RMS response – Synchronous Machine Response







EMT Solution Methods: Circuit Equations – In State-Space form



$$E = I_1 . R_1 + L_1 \frac{dI_1}{dt} + V_2$$

$$V_2 = I_2 . R_2$$

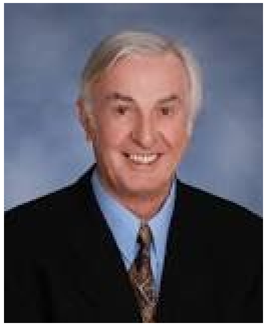
$$I_3 = C \frac{dV_2}{dt}$$

$$I_1 = I_2 + I_3$$

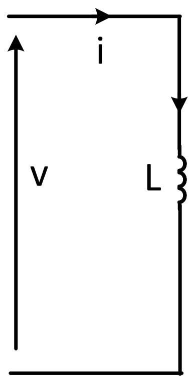
$$\begin{bmatrix} \frac{dV_2}{dt} \\ \frac{dI_1}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-1}{R_2 C} & \frac{1}{C} \\ \frac{-1}{L} & \frac{-R_1}{L} \end{bmatrix} \begin{bmatrix} V_2 \\ I_1 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{E}{L} \end{bmatrix}$$

$$[\dot{X}] = [A][X] + [B][U]$$

EMT Solution Methods: Dommel's EMT Formulation



Hermann W Dommel : Any circuit element may be represented using equivalent resistors and current sources

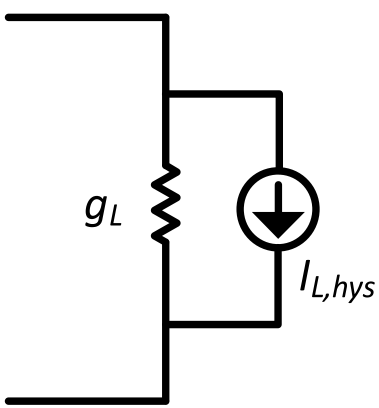


$$v = L\frac{di}{dt}$$

$$v = \frac{1}{L}\int_0^v v\,dt$$

$$i(t) = i(t-\Delta t) + \frac{1}{L}[\frac{v(t)+v(t-\Delta t)}{2}]\Delta t$$

$$i(t) = i(t-\Delta t) + \frac{\Delta t}{2L}v(t-\Delta t) + \frac{\Delta t}{2L}v(t)$$

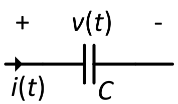


$$i(t) = i_{L,hys} + g_L.v(t)$$

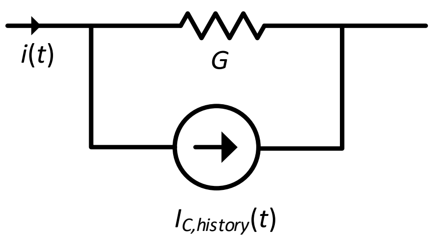
EMT Solution Methods: Dommel's EMT Formulation

Dommel's EMT Formulation: Any circuit element may be represented using equivalent resistors and current sources

Capacitor



$$i(t) = C\frac{dv(t)}{dt}$$

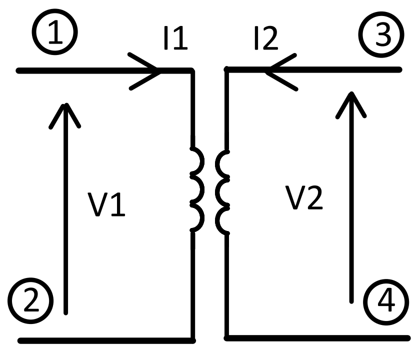


where,

$$\boldsymbol{G = \frac{2C}{\Delta t}}$$

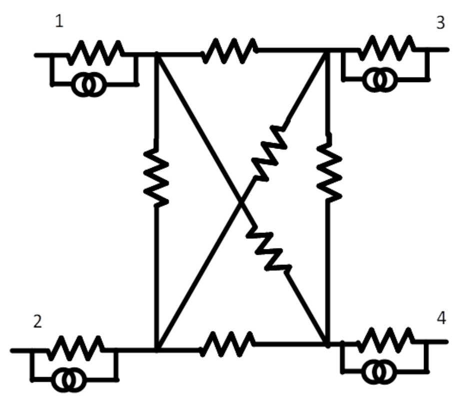
$$\boldsymbol{I_{C,history}(t) = -i(t-\Delta t) - Gv(t-\Delta t)}$$

Transformer – Magnetically coupled windings



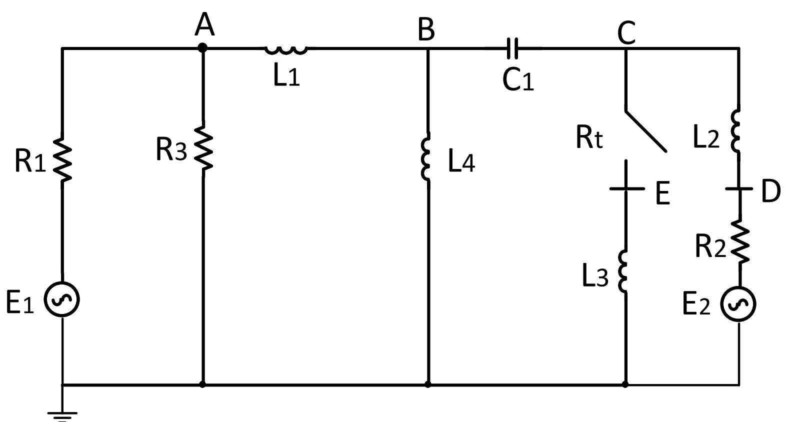
$$V_1 = L_1\frac{dI_1}{dt} + M\frac{dI_2}{dt}$$

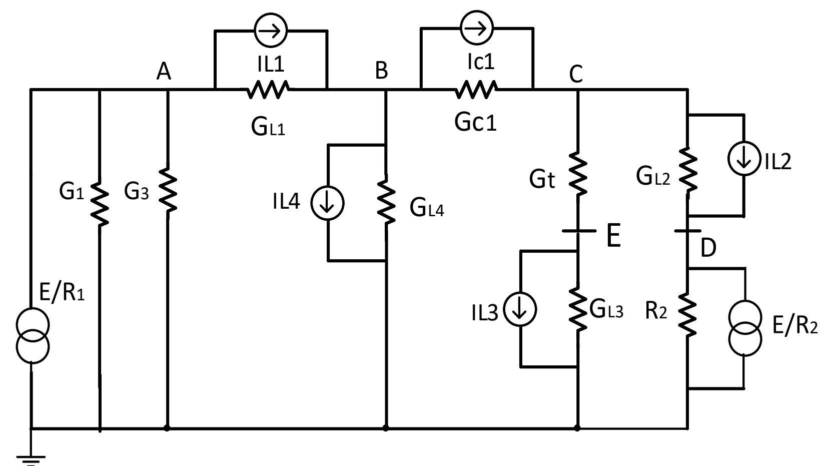
$$V_2 = L_2\frac{dI_2}{dt} + M\frac{dI_1}{dt}$$



EMT Solution Methods: Dommel's EMT Formulation

Dommel's EMT Formulation: Any circuit element may be represented using equivalent resistors and current sources



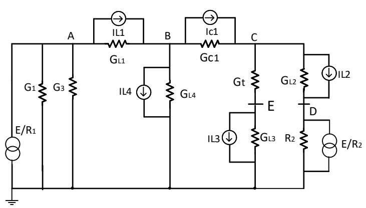


$$[I]nx1 = [Y]nxn[V]nx1$$

$$[V]=[Y]^{-1}[I]$$

EMT Solution Methods: Dommel's EMT Formulation

Dommel's EMT Formulation: Any circuit element may be represented using equivalent resistors and current sources



$$[I]nx1 = [Y]nxn[V]nx1$$

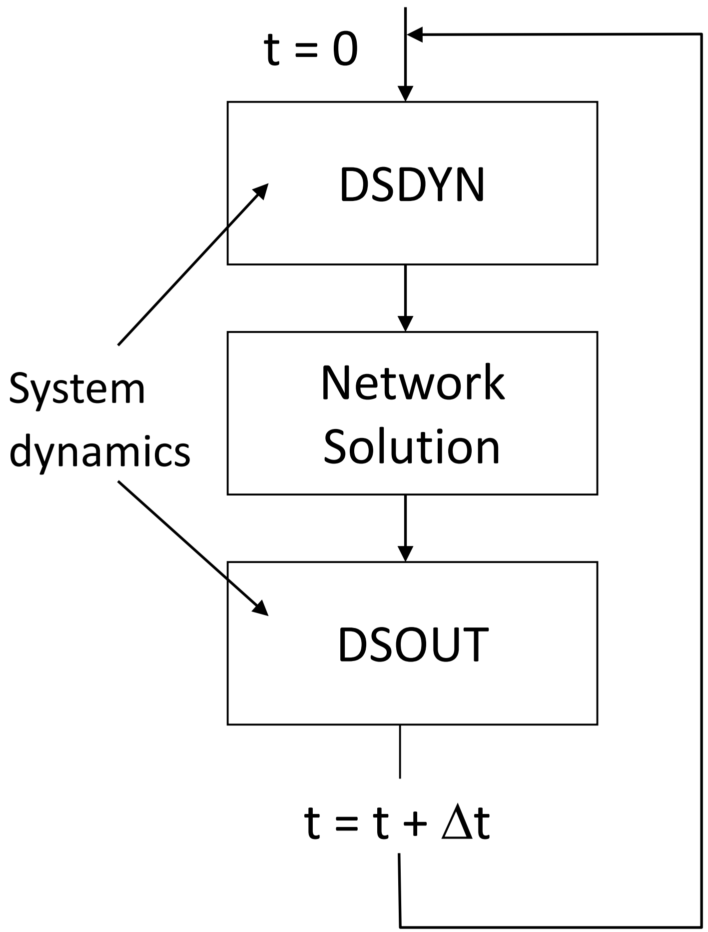
$$[V]=[Y]^{-1}[I]$$

$$\begin{bmatrix} V_A \\ V_B \\ V_C \\ V_D \\ V_E \end{bmatrix} = \begin{bmatrix} (G_1 + G_3 + G_{L1}) & -G_{L1} & 0 & 0 & 0 \\ -G_{L1} & (G_{L1} + G_{L4} + G_{C1}) & -G_{C1} & 0 & 0 \\ 0 & -G_{C1} & (G_{C1} + G_t + G_{L2}) & -G_{L2} & -G_t \\ 0 & 0 & -G_{C1} & (G_2 + G_{L2}) & 0 \\ 0 & 0 & -G_t & 0 & (G_t + G_3) \end{bmatrix}^{-1} \begin{bmatrix} \frac{E_1}{R_1} - I_{L1} \\ I_{L1} - I_{C1} - I_{L4} \\ I_{C1} - I_{L2} \\ I_{L2} - \frac{E_2}{R_2} \\ -I_{L3} \end{bmatrix}$$

System Y Matrix

- Algebraic equation
- Note the large number of zero elements in the Y matrix
- If L,R and C elements are constant, elements of the Y matrix does not change

EMT Solution Methods: Structure of EMTDC Solution Engine



DSDYN

- Solves the electrical component models and control systems models
- Compute the history current terms before the network solution is solved

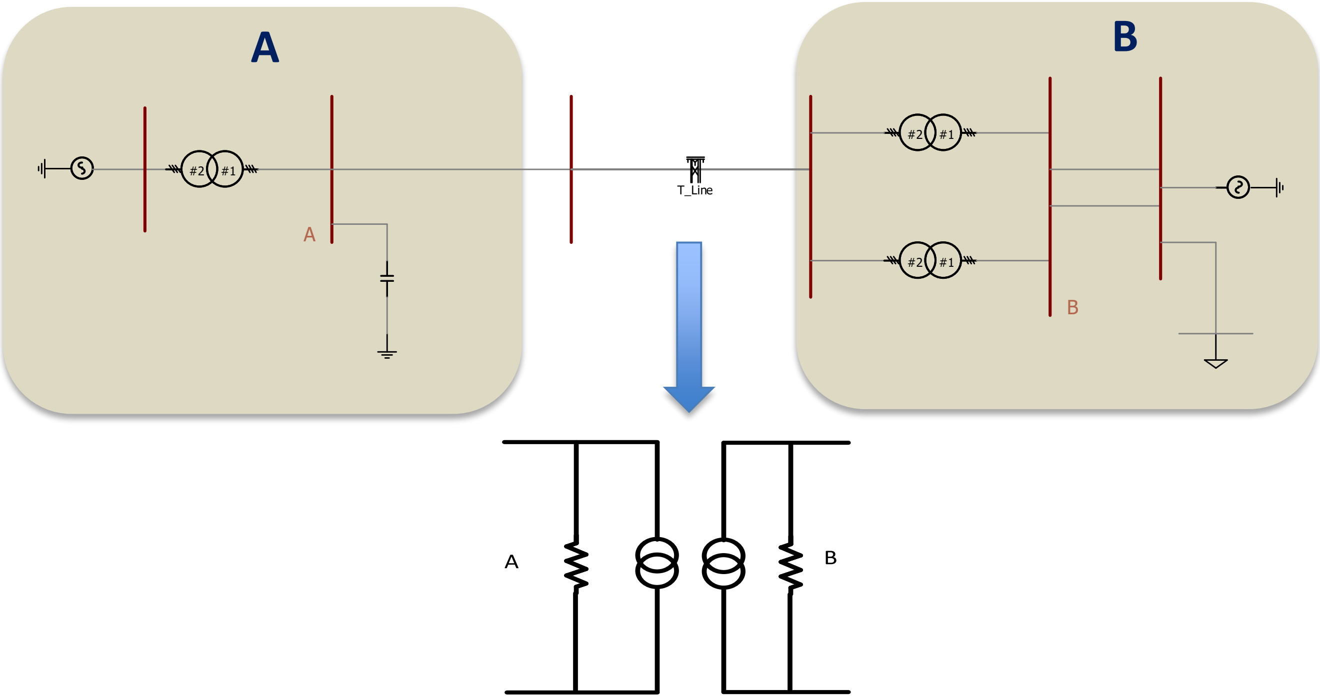
[I] = [Y] . [V]

DSOUT

- Output quantities after network solution is solved
  - Example: Compute RMS voltage, power……

Some Points to Remember……

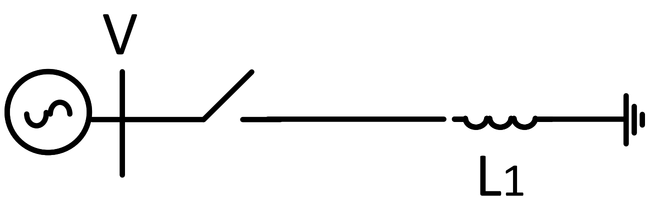
Representing Transmission Lines and Cables



- Transmission lines have inherent 'propagation delays'
- The networks at the two ends are eclectically 'de-coupled' due to the delay introduced by the line (over the duration of the calculation time step)
  - Ability to solve circuits A and B as independent circuits

Parametric Analysis – Example: Point on Wave (POW) Impact

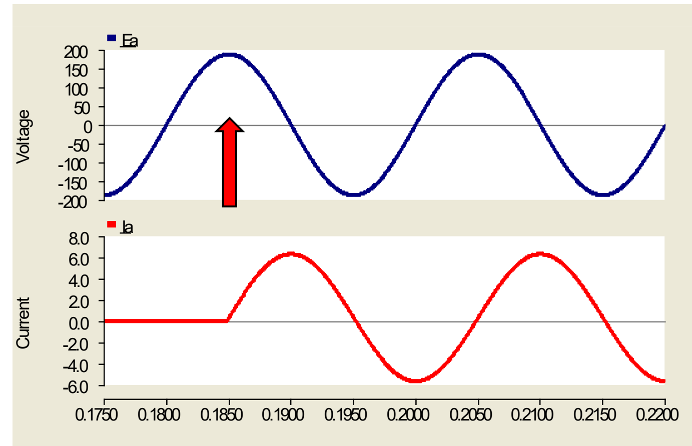
A simple example to illustrate the importance of 'sensitivity' analysis to find the 'worst case'.

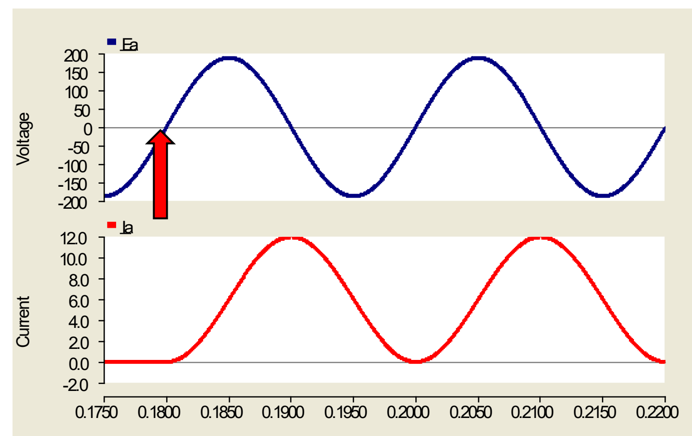


$$V = L\frac{di}{dt} \qquad i = \frac{1}{L}\int V.dt$$

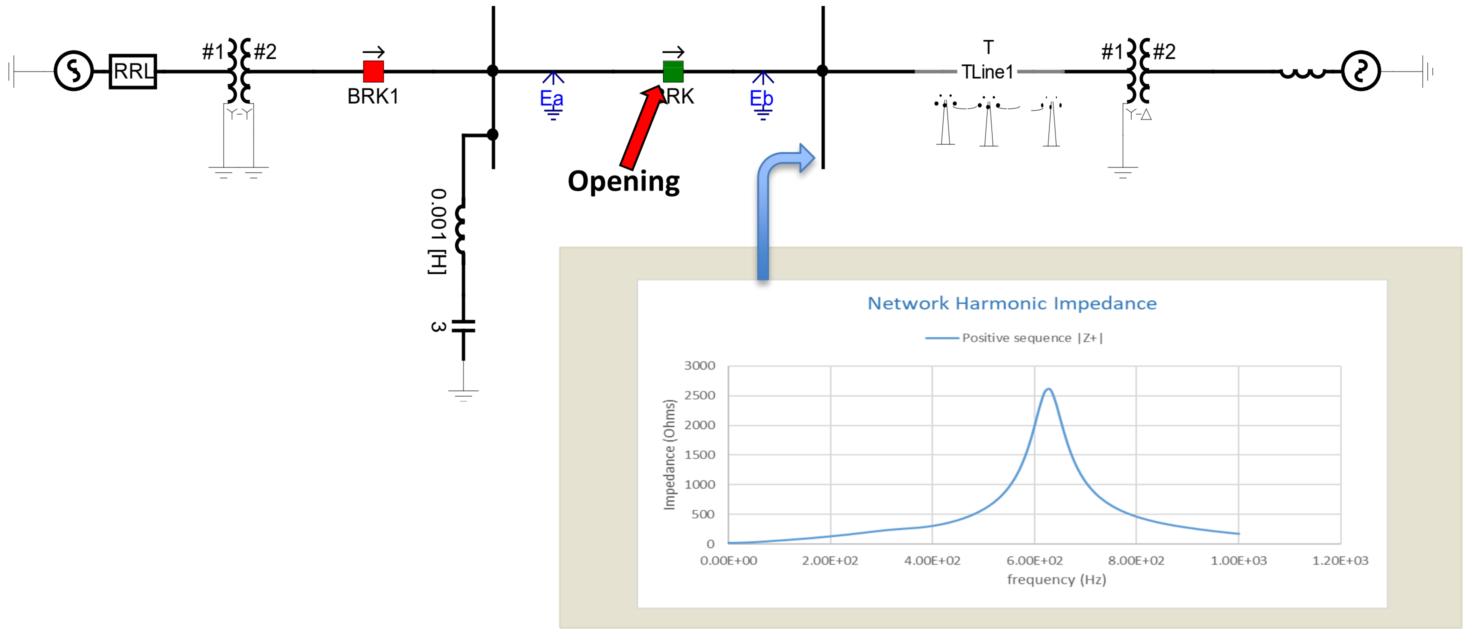
Integral is the area under the (voltage) curve

$$Area = \int V.dt$$

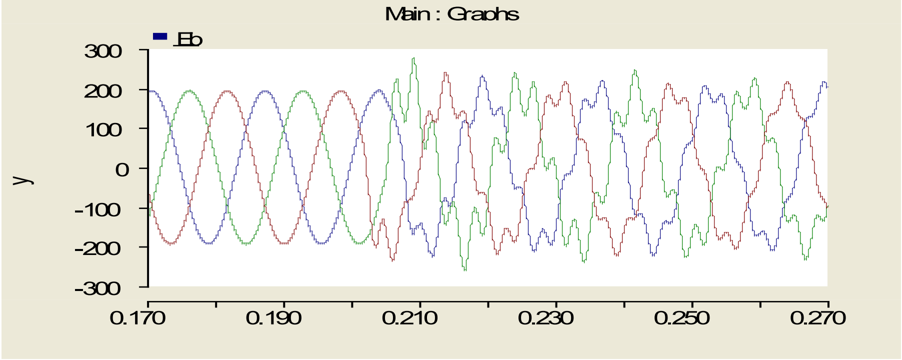




Network Characteristics: Network Impedance Scans



Dominant frequencies in the transient waveform co-relate to network resonance points

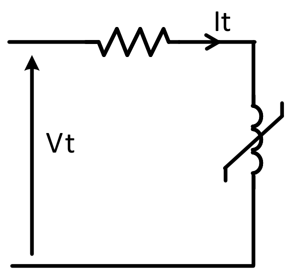


Illustrative Simulation Examples

1. Capacitor Switching
2. Transient Recovery Voltage (TRV)
3. Line Energizing
4. Transformer Energizing
5. Lightning Overvoltage study example
6. Black Start restoration Study example
7. Ferro Resonance
8. Sub Synchronous Torsional Interactions (SSTI)
9. Wind/ PV Dynamic response
10. Synchronous machine response

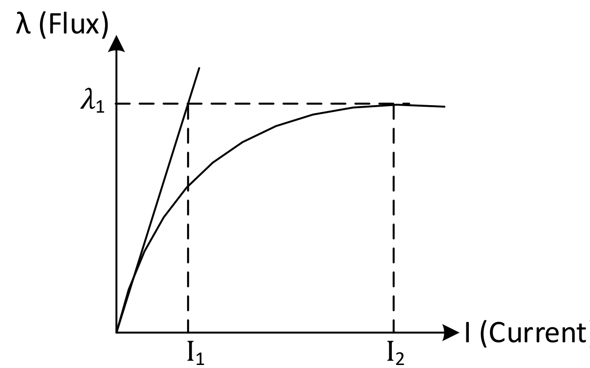
Modeling Non-Linear Elements

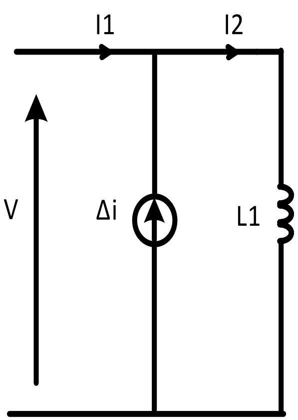
An iron core inductor example (representing iron saturation) – represented with a linear inductor in shunt with a current source



$$V = N\frac{d\varphi}{dt} = \frac{d\lambda}{dt}$$

$$\lambda = \int V\, dt$$

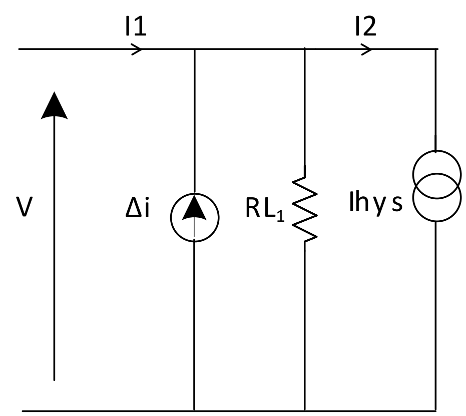




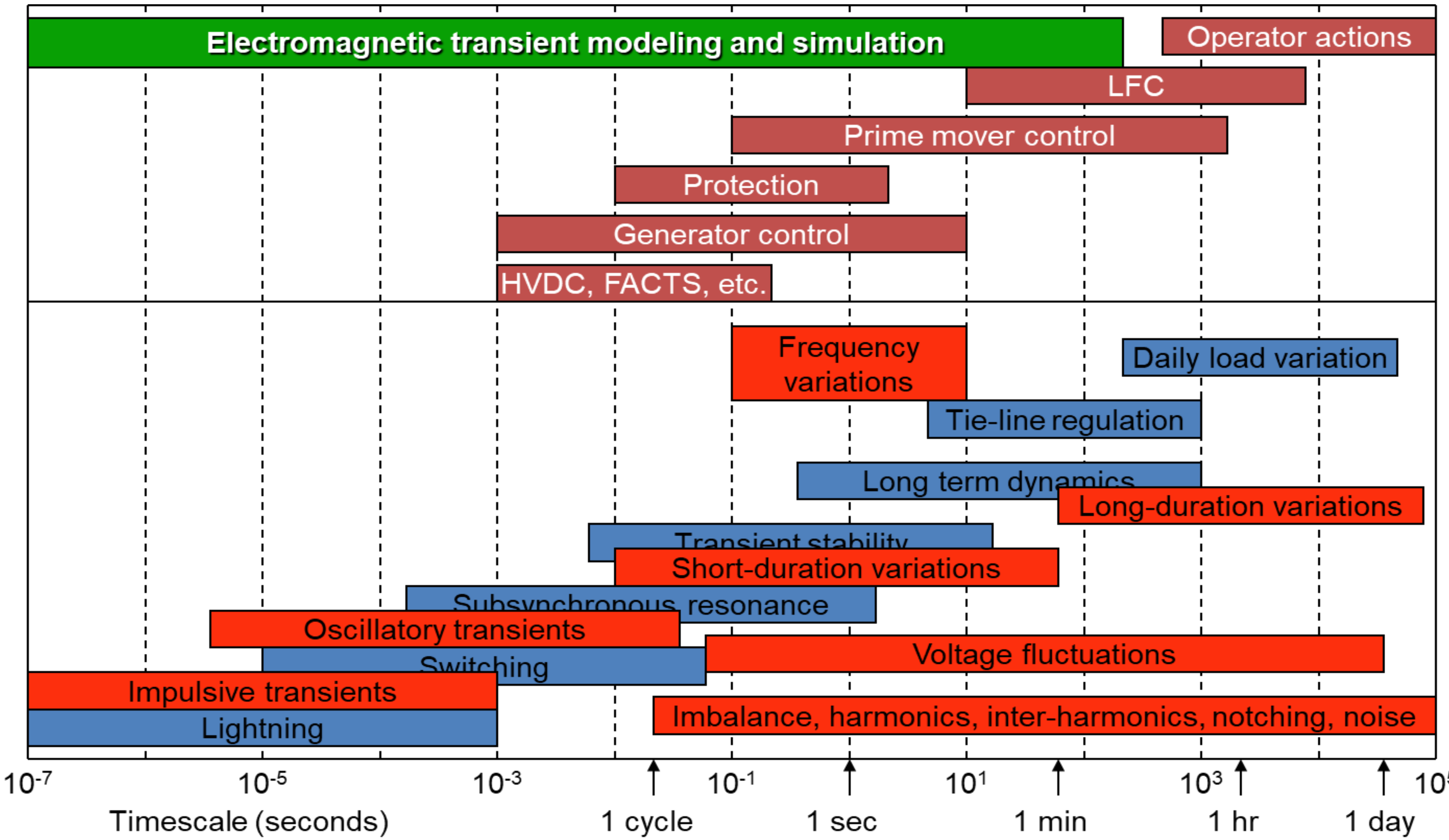
$$\Delta i = i_1 - i_2$$

$$L_1 = \frac{\lambda_1}{I_1}$$

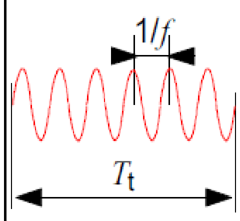
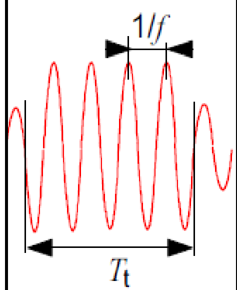
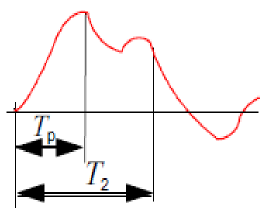
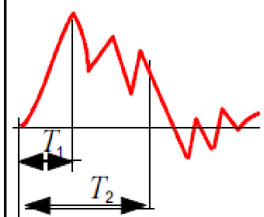
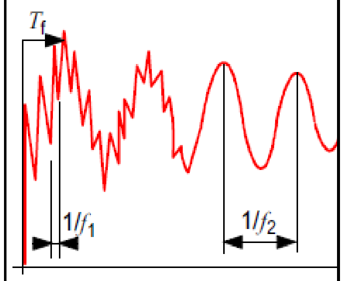
Dommel's form



Time Scales of Power System Phenomena



Characterization of Transient Phenomena

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 $T_t \geq 3\,600$ s	10 Hz < f < 500 Hz $0{,}03 \text{ s} \leq T_t \leq 3\,600$ s	$20\ \mu s < T_p \leq 5\,000\ \mu s$ $T_2 \leq 20$ ms	$0{,}1\ \mu s < T_1 \leq 20\ \mu s$ $T_2 \leq 300\ \mu s$	$3 \text{ ns} < T_f \leq 100$ ns $0{,}3 \text{ MHz} < f_1 < 100$ MHz $30 \text{ kHz} < f_2 < 300$ kHz

Thank you

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