INTERCONNECTION INNOVATION e-XCHANGE
U.S. DEPARTMENT OF ENERGY

EMT Bootcamp for BES IBR Studies
Part 1: Plant-Level Emphasis
| 8/3/23

An initiative spearheaded by the Solar Energy Technologies Office and the Wind Energy Technologies Office

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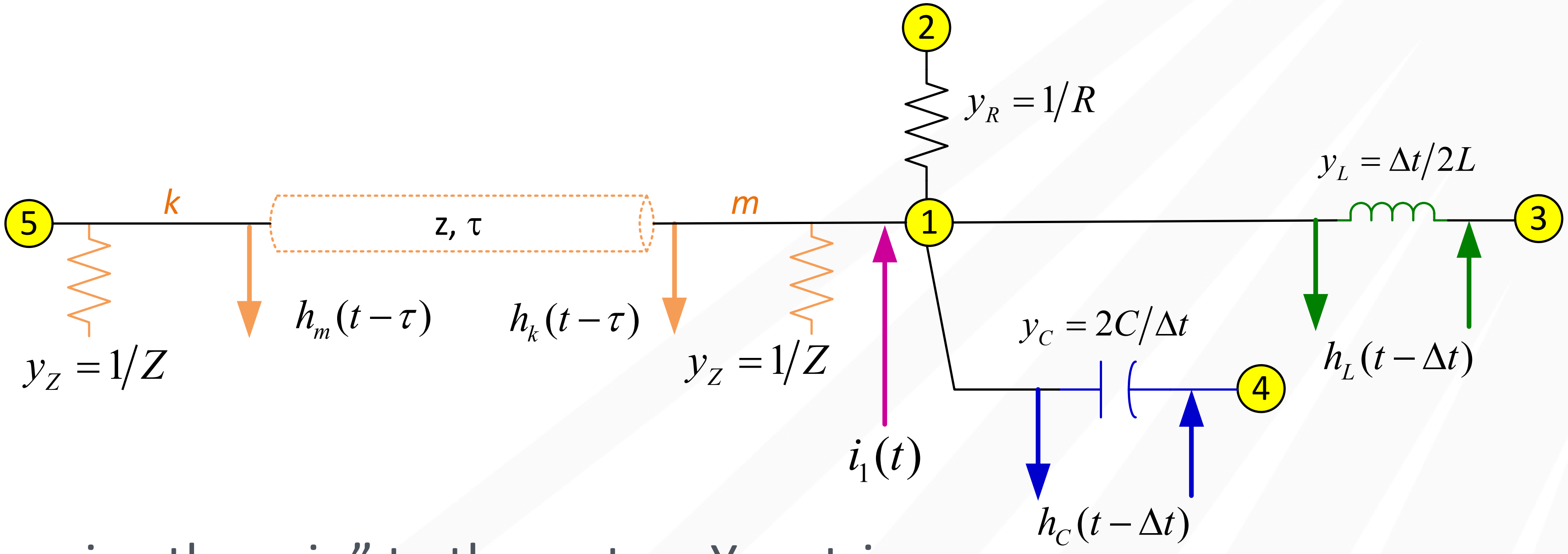
How an EMT solver works with trapezoidal integration and a system admittance (Y) matrix.



"Stamping these in" to the system Y matrix:

$$\begin{bmatrix} y_Z + y_R + y_L + y_C & -y_R & -y_L & -y_C & 0 \\ -y_R & y_R & 0 & 0 & 0 \\ -y_L & 0 & y_L & 0 & 0 \\ -y_C & 0 & 0 & y_C & 0 \\ 0 & 0 & 0 & 0 & y_Z \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \\ v_5 \end{bmatrix} = \begin{bmatrix} i_1 - h_k - h_L - h_C \\ 0 \\ h_L \\ h_C \\ -h_m \end{bmatrix}$$

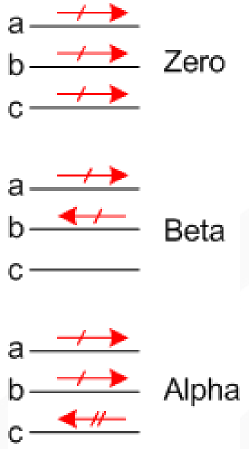
Suggested reference: https://doi.org/10.1109/PROC.1974.9550

Constant-parameter distributed line models rely on modal decomposition matrices with real-number elements.

For three-phase balanced lines, instead of symmetrical components:

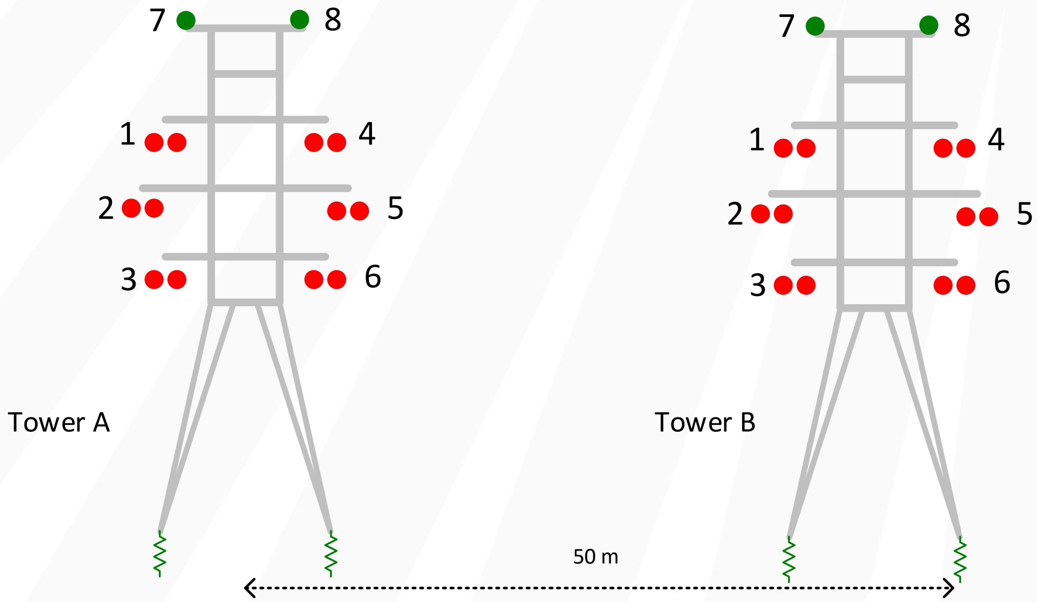
$$\mathbf{I_p} = \mathbf{T_i I_m}$$

$$\mathbf{T_i} = \begin{pmatrix} 1/\sqrt{3} & 1/\sqrt{2} & 1/\sqrt{6} \\ 1/\sqrt{3} & -1/\sqrt{2} & 1/\sqrt{6} \\ 1/\sqrt{3} & 0 & -2/\sqrt{6} \end{pmatrix}$$



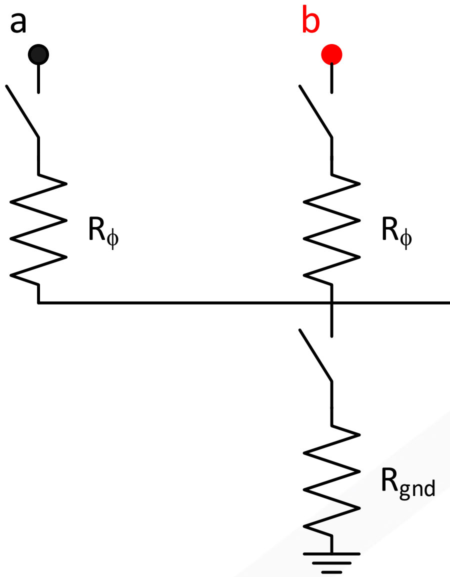
We can represent this transmission path as:

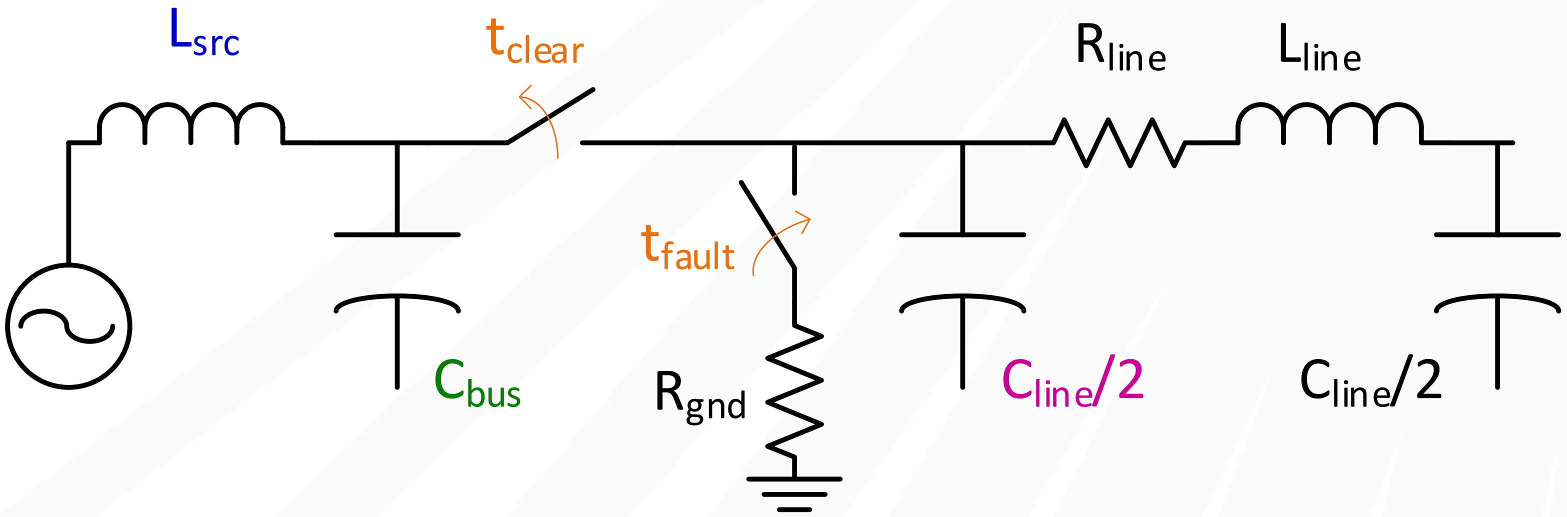
- *Four balanced three-phase lines*
  - *Optionally with zero-sequence coupling*
- *A "twelve-phase" unbalanced line*
  - *Optionally add the ground wires*
- *Two double-circuits, and other combinations in between*



Suggested references: https://doi.org/10.1109/TPAS.1985.319051 and https://doi.org/10.1109/61.772350

Representing faults and fault clearing operations.

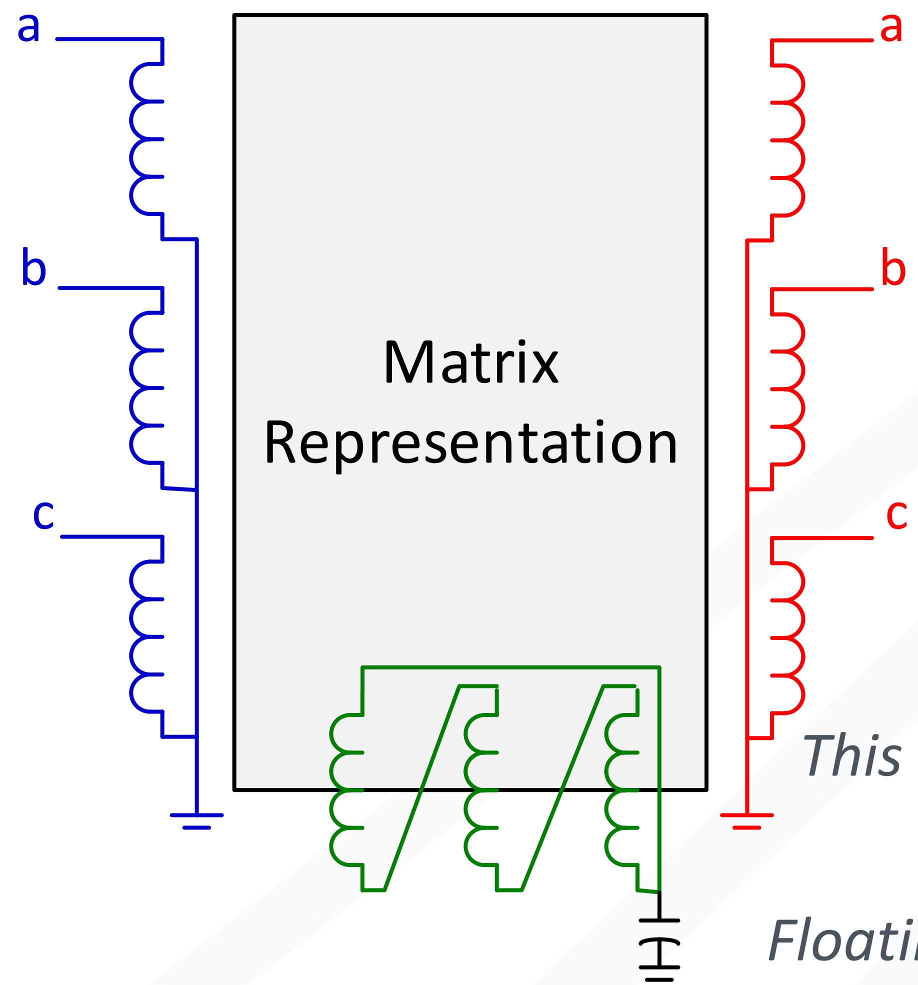




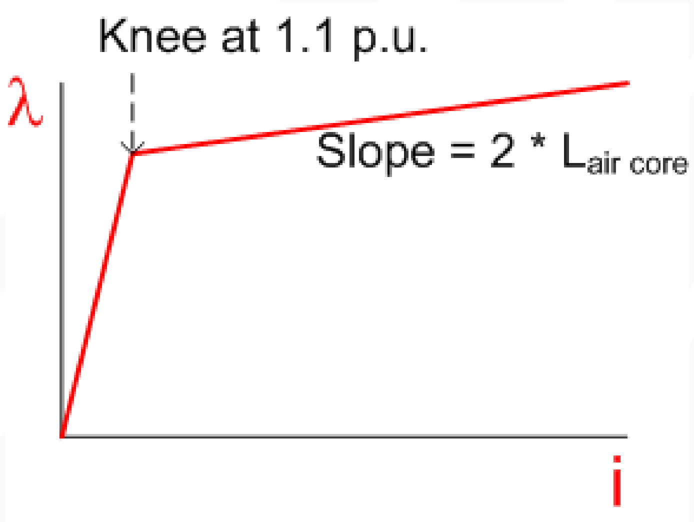
- Voltage across $C_{line}/2$ can't change instantaneously; $\tau = 0.5 * R_{gnd} * C_{line}$ governs the discharge.
- Current through L_{src} can't change instantaneously, so, interruption occurs at a natural current zero.
- C_{bus} determines the transient recovery voltage (TRV).

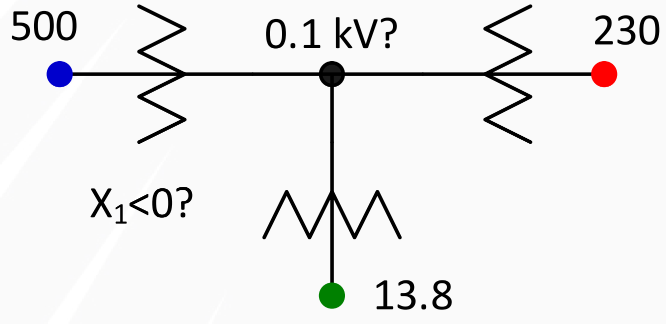
Suggested references: https://doi.org/10.1109/TPWRD.2005.848726

EMT transformer models include multiple windings, neutral connections, saturation, and high-frequency characteristics.



Saturation is separate.





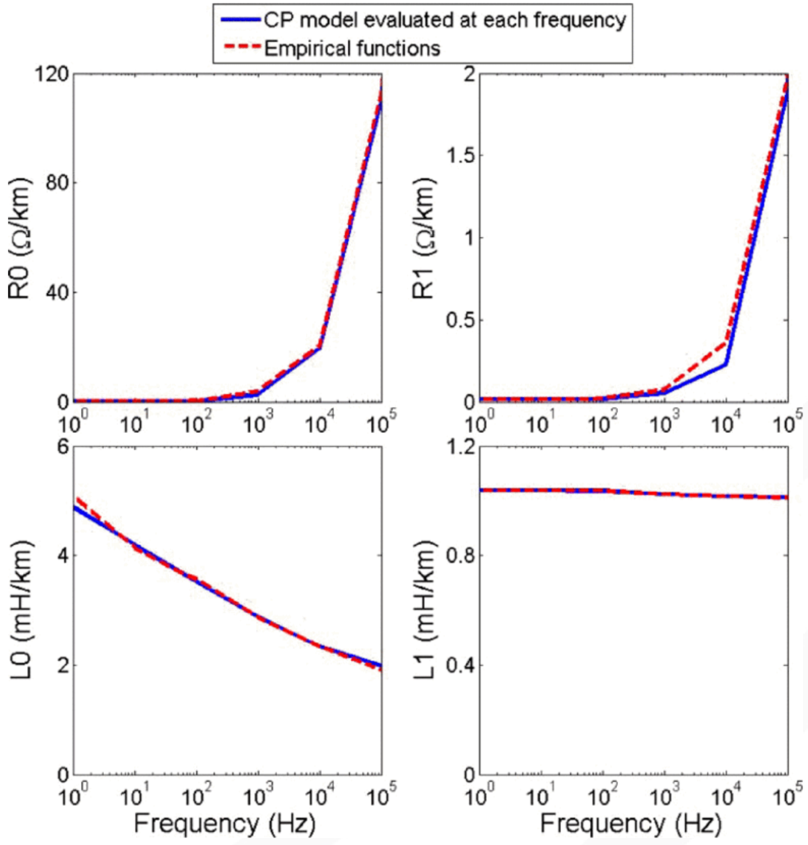
Legacy Power Flow Model

This is Yyd, but autotransformer connections can be made.

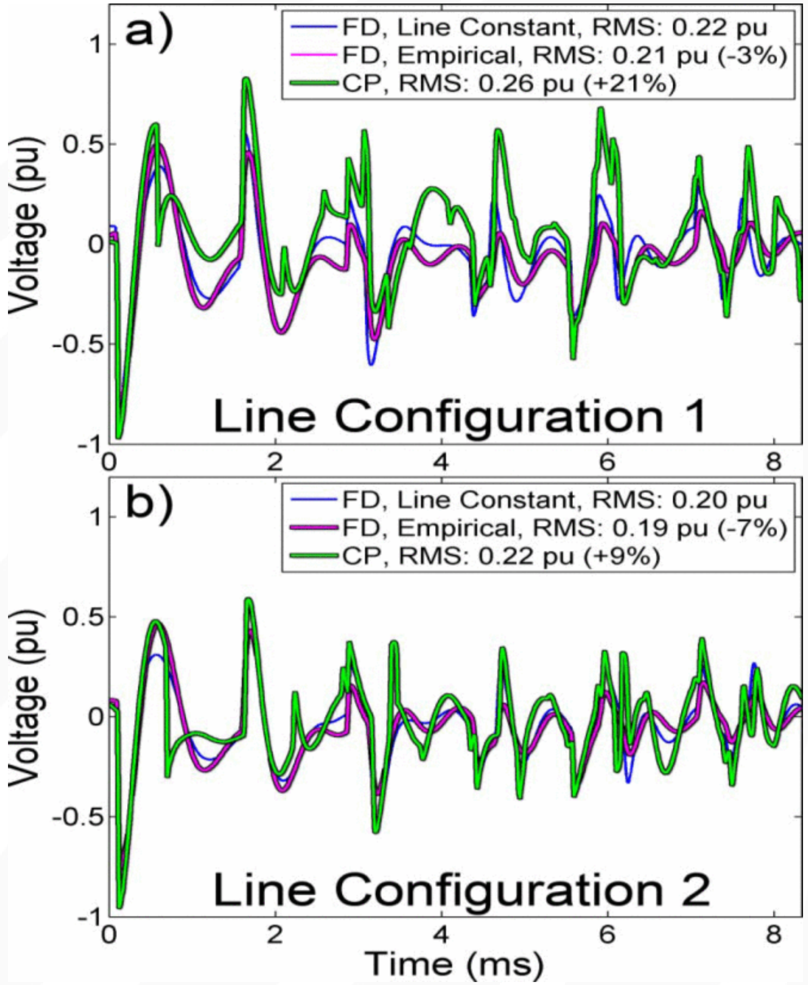
Floating delta is not allowed.

Suggested references: https://doi.org/10.1109/TPWRD.2005.848752 and https://doi.org/10.1109/TPAS.1982.317184

What is the meaning of frequency dependence in lines?



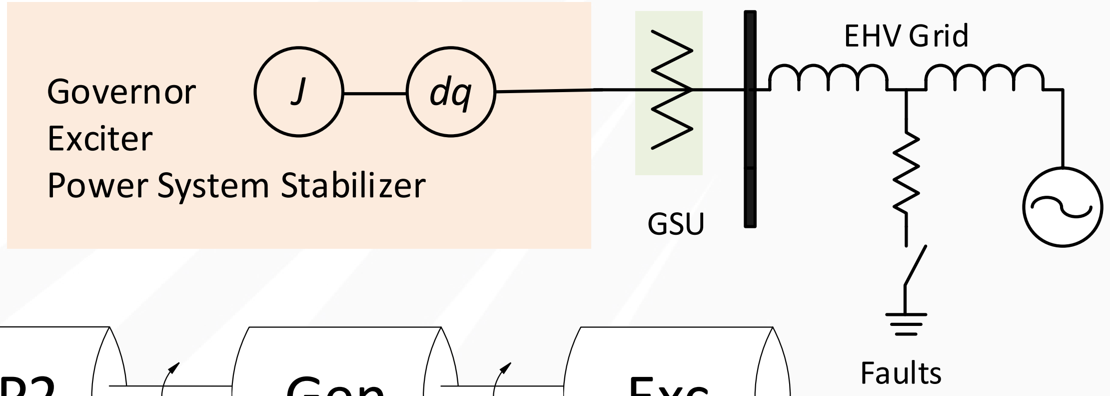
Source: https://doi.org/10.1109/TDC.2008.4517264

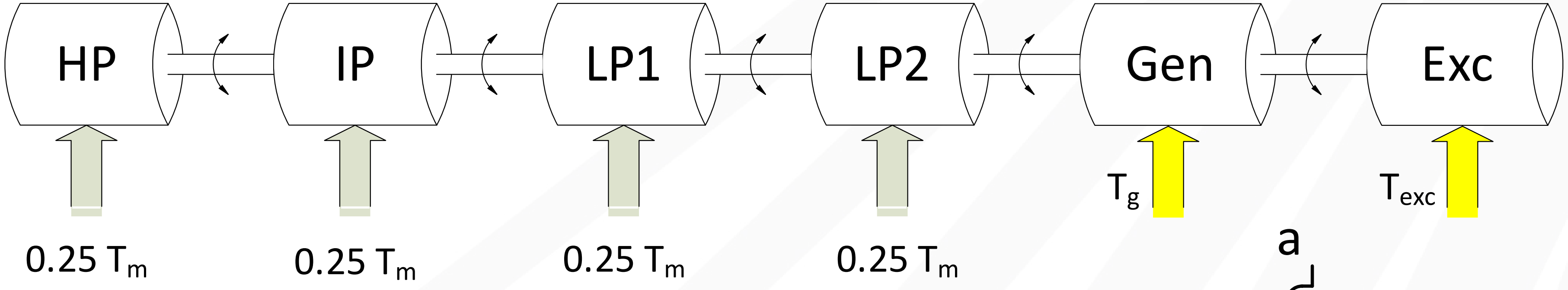


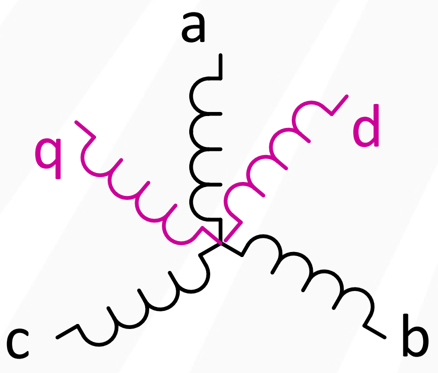
Suggested references: https://doi.org/10.1109/TPWRD.2005.848678 and https://doi.org/10.1109/TPWRD.2005.848774 (cables).

EMT machine models include stator flux transients, saturation, shaft torsionals and unbalanced operation.

<u>For control block diagrams</u>: see IEEE 421.5, Power System Dynamic Performance (PSDP) Committee reports, your dynamics program user manual, etc.

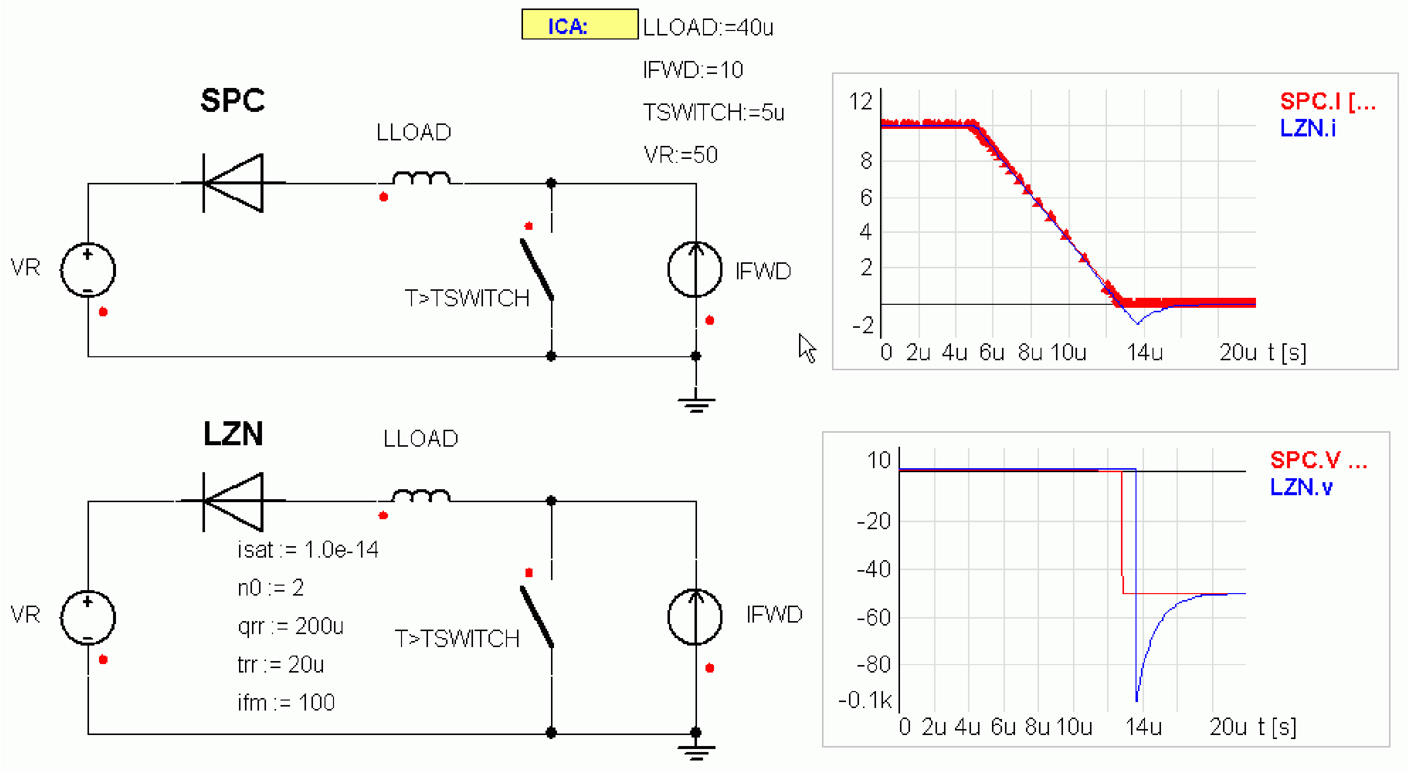






Suggested references: https://doi.org/10.1109/TPWRD.2005.848725, https://doi.org/10.1109/61.473358 and https://doi.org/10.1109/61.517533

“Compact” model of a power electronic switching device; a diode with reverse recovery voltage and switching losses.



$$i(t) = \frac{(q_E - q_M)}{T_M}$$

$$0 = \frac{dq_M}{dt} + \frac{q_M}{\tau} - \frac{(q_E - q_M)}{T_M}$$

$$q_E = I_S \tau \left[\exp\left(\frac{v}{nV_T}\right) - 1 \right]$$

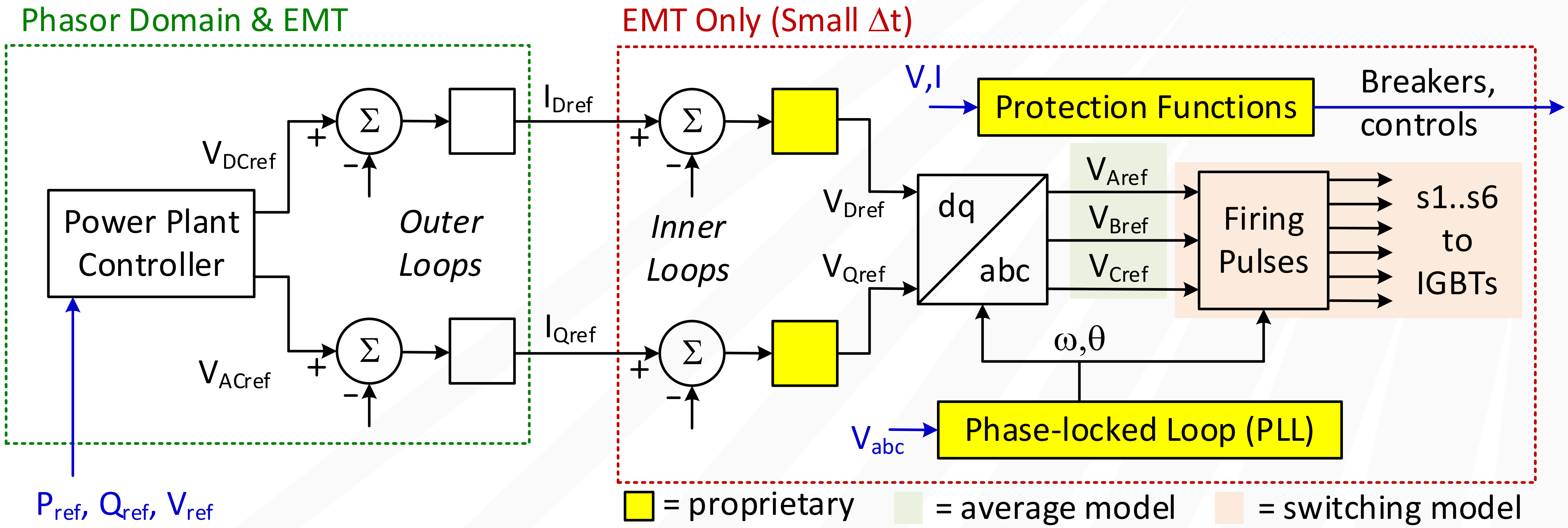
$$\tau = \frac{Q_{rr}}{I_{fm}}$$

$$T_M = \frac{\tau T_{rr}}{T_{rr} - \tau}$$

Results are from Simplorer, which is a SPICE-like simulator with variable time step.

Suggested references: https://doi.org/10.1109/TPWRD.2005.848764 and https://doi.org/10.1109/63.575666

An EMT IBR model adds fast control loops, protection functions, and vendor-proprietary code to the phasor-domain model.

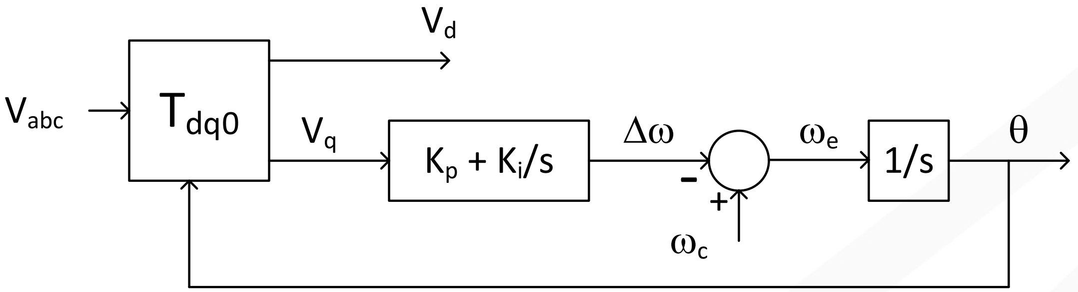


Source: Andrew L. Isaacs, "EMT Model Intake and Quality Assurance", ESIG Webinar, 5/18/2023. Adapted with permission.

Suggested references: https://www.nerc.com/comm/RSTC_Reliability_Guidelines/Reliability_Guideline-EMT_Modeling_and_Simulations.pdf and https://www.epri.com/research/products/3002014083 for architecture of generic models.

There are <u>many</u> phase-locked loop implementations; their performance matters to simulation and in the real world.

A simple Synchronous Reference Frame (SRF) PLL works by driving V_q to zero.



$$K_p = \omega_{bw} / V_{pk}$$

$$K_i = K_p T_s \omega_{bw}^2$$

- Choose θ_{bw}=188.5 and T_s=20ms
- Choose V_{pk}=1 in per-unit system
- K_p=188.5 and K_i=134e3

Second-Order Generalized Integrator (SOGI) Frequency-Locked Loop (FLL) is more robust.

1. Transform V_{abc} to V_α and V_β
2. Pass V_α and V_β through separate quadrature signal generator (QSG)s, each using two integrators
   - These require an estimate of ω from the FLL
3. Algebraically separate the positive and negative sequence components of V_α and V_β
   - Those 4 sequence components feed a gain-normalized FLL, which uses 1 integrator in estimating ω for step 2
   - Integrating ω to estimate θ
   - They also establish V_1 and V_2 if needed
4. Comparable to the possibly more popular DDSRF:
   - No trig function evaluations
   - Smoother response has been observed

Suggested references: ISBN https://doi.org/10.1109/OJIA.2020.3020392 and https://doi.org/10.1109/TIE.2010.2042420

Simulation time and time step selection guidelines.

Factor	Shortest Tmax	Typical Δt
Natural frequency	2 – 10 cycles	20 per cycle
Line travel time	1 – 4 travel times	1-20 per travel time
Lightning surges	100 – 200 μs	0.1 – 1 μs
Cable switching surges	0.2 – 1 ms	1 – 20 μs
Capacitor switching	1 – 100 ms	10 – 100 μs
Short circuits	0.1 – 1 s	10 – 200 μs
Machine dynamics	0.5 – 5 s	100 – 1000 μs
Ferroresonance	0.1 – 1 s	10 – 50 μs
Steady state / Harmonics	50 – 500 ms	50 μs
Inverter-based resources	0.5 – 45 s	1 – 200 μs

EMT References

Theory

1. Juan A. Martinez-Velasco (ed.), *Transient Analysis of Power Systems: Solution Techniques, Tools and Applications*, IEEE Press, 2014.
2. Watson & Arrillaga, *Power Systems Electromagnetic Transients Simulation (2nd ed.)*, IET, 2018.

IBR Behaviors

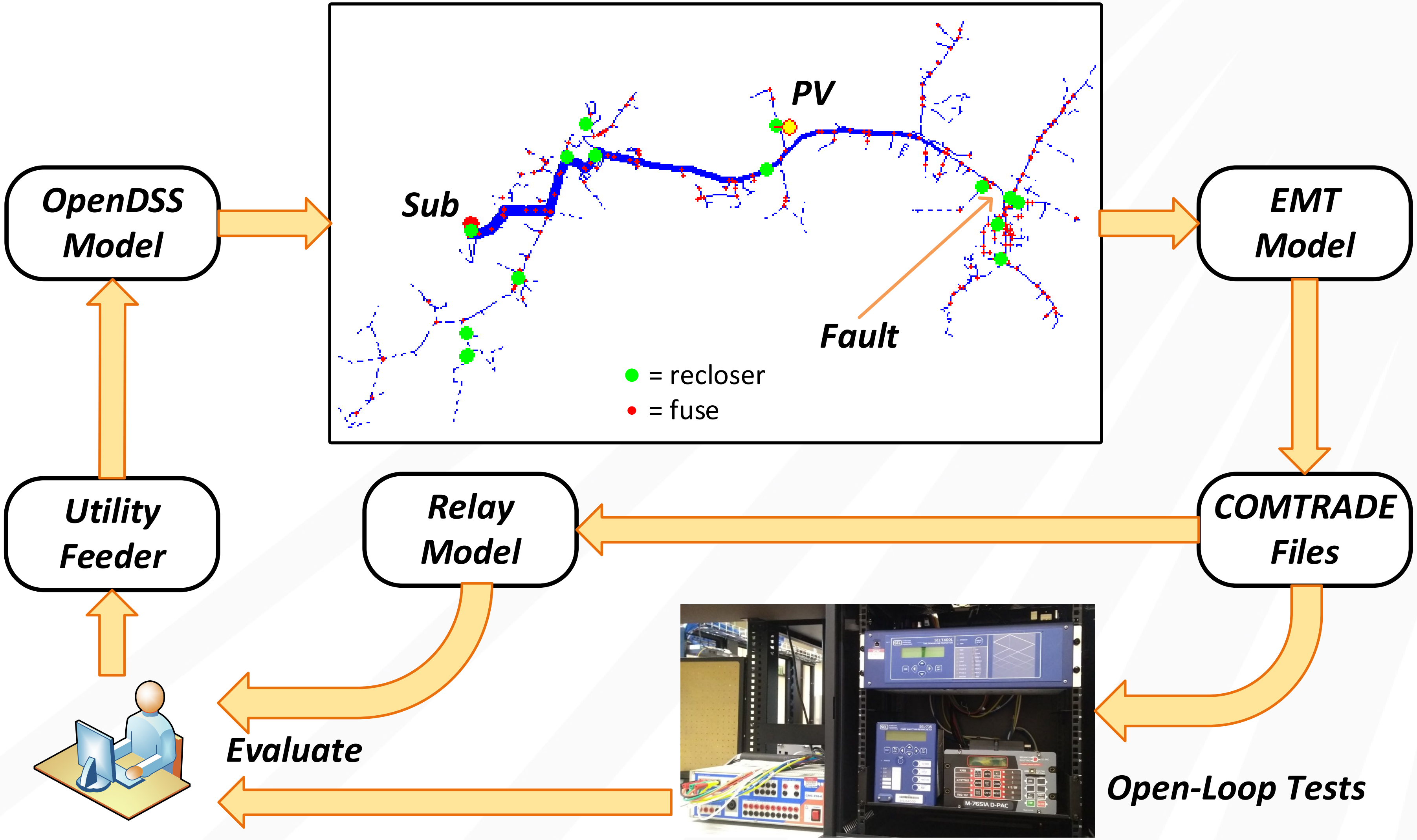
1. Yazdani & Iravani, *Voltage-Sourced Converters in Power Systems: Modeling, Control, and Applications*, IEEE Press, 2010.
2. Blaabjerg, *Control of Power Electronic Converters and Systems*, v1-3, Academic Press, 2018-2021.

Industry Reports

1. PES-TR77, "Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies", PSDPC, April 2020.
2. PES-TR106, "Trends in microgrid modeling for stability analysis", PSDPC, November 2022.
3. CIGRE TB 727, "Modeling of Inverter-Based Generation for Power System Dynamic Studies", 2018.
4. CIGRE TB 736, "Power system test cases for EMT-type simulation studies", 2018.
5. CIGRE TB 766, "Network Modelling for Harmonic Studies", 2019.
6. CIGRE TB 832, "Guide for electromagnetic transient studies involving VSC converters", 2021.

International Conference on Power System Transients: https://www.ipstconf.org/

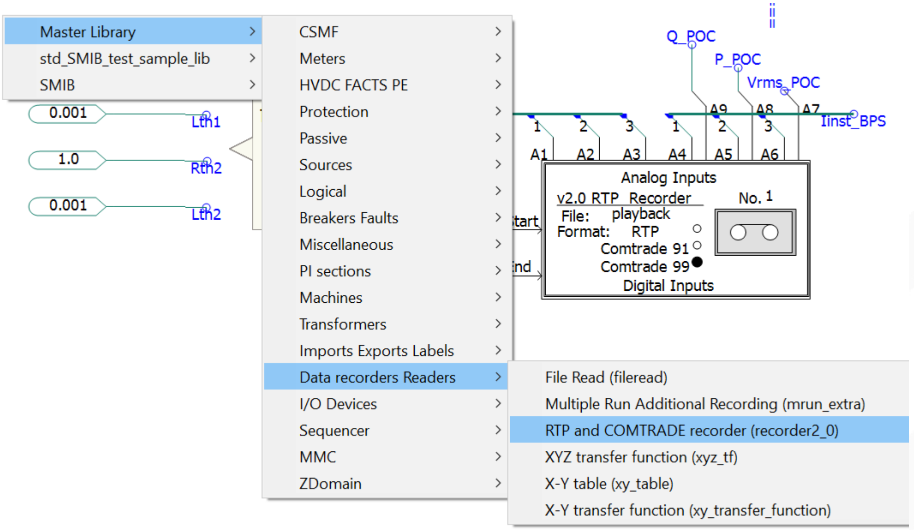
Platform and tool-independent post-processing with COMTRADE and Python.



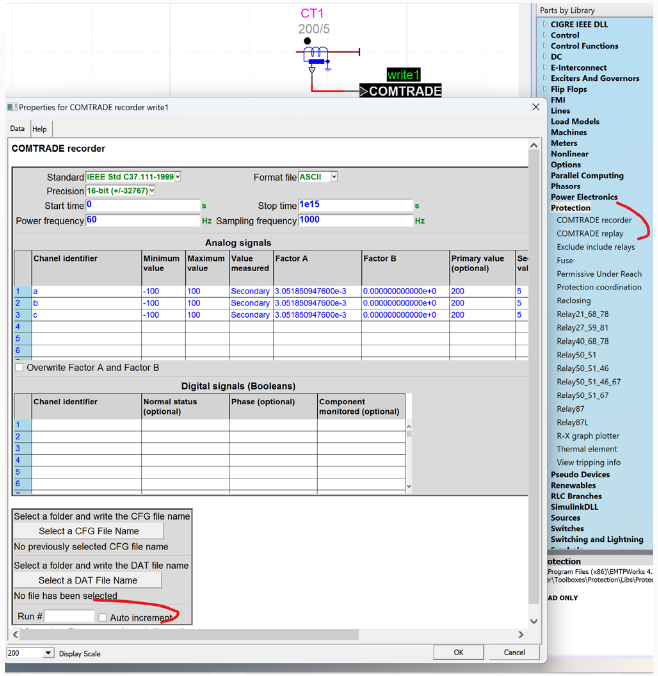
Suggested reference: https://doi.org/10.1109/EPC.2008.4763331

Producing and using COMTRADE files from two EMT tools.

- In PSCAD, the recorder is under "Data recorders Readers"



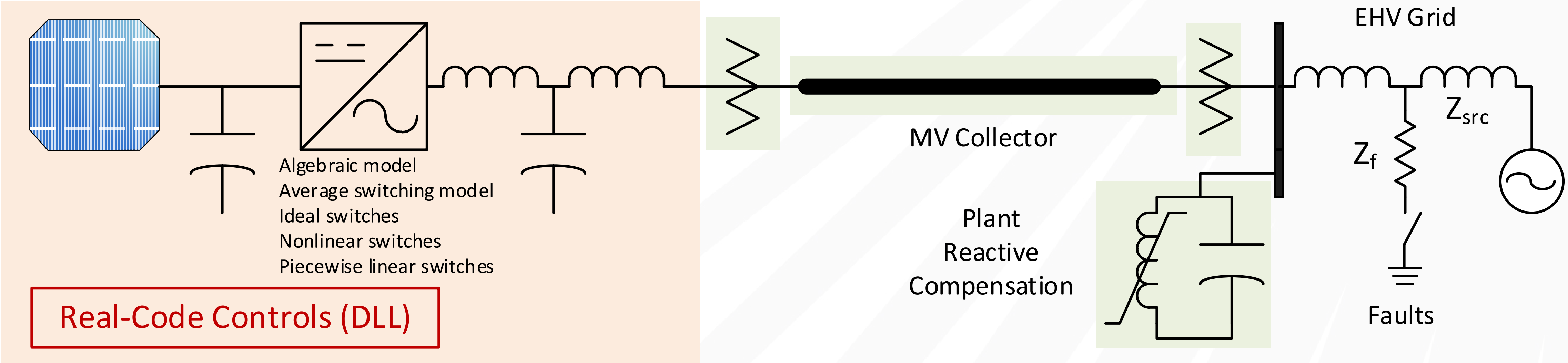
- In EMTP, the recorder is under "Protection"



- COMTRADE processing options:
  - Bootcamp examples using https://github.com/dparrini/python-comtrade
  - Plotting tool in your EMT simulator probably reads COMTRADE
  - Relay vendors and other "COMTRADE viewers" you might Google
  - https://www.mathworks.com/matlabcentral/fileexchange/15619-comtrade-reader

Suggested reference: https://doi.org/10.1109/IEEESTD.2013.6512503

Framework of the bootcamp’s plant-level model and basic tests.



From P2800.2/D0.3 SG3

1. 10-s initialize; then 10-s flat run; $P=P_{min}$ and ICR*; Q=0, ± 0.3287 ICR
2. UV ride-through: 3ϕg fault; 0.16-s; $Z_f = 0$ and Z_s; P=ICR; Q=0, ± 0.3287 ICR
   A. Repeat for 2ϕg, 2ϕ and 1ϕg; $Z_f = 0$ only
3. OV ride-through: 1.2 V for 1-s; P=ICR; Q=0, ± 0.3287 ICR

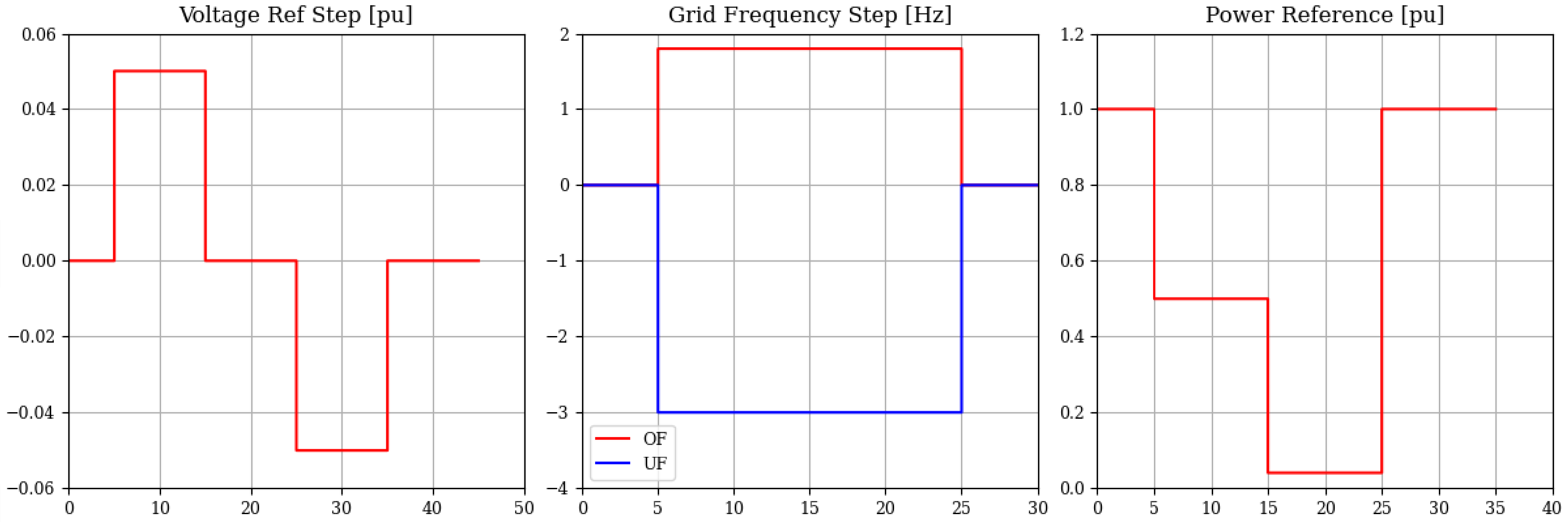
** IBR continuous rating*

Suggested reference: https://sagroups.ieee.org/2800-2/

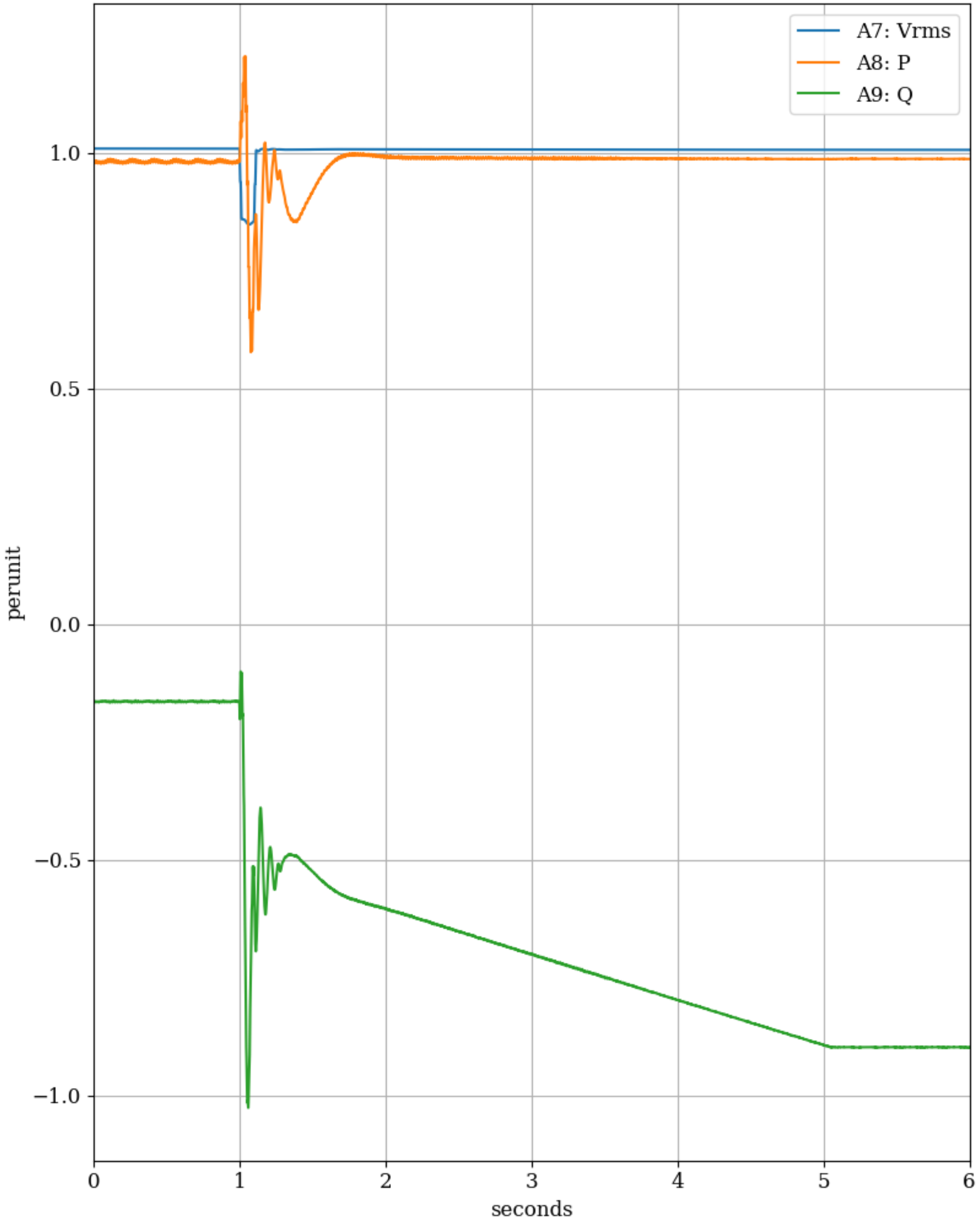
More plant-level control and response tests (P2800.2/D0.3_SG3).

1. V_{ref}, Q_{ref}, or pf_{ref} change at ICR; +0.05 pu 5-15s; -0.05 pu 25-35s; run 45s
2. P_{ref} change at ICR; 1 pu 0-5s; 0.5 pu 5-15s; *0.04* pu 15-25s; 1 pu 35-35s
3. Frequency RT at P_{min} and ICR, Q=0; +1.8 or -3.0 Hz from 5-25s; run 35s
4. Grid angle ride-through: ± 25°; P=P_{min} and ICR; Q=0
5. Short-circuit ratio (SCR) ramp-down (informational); P=ICR; 3ϕg fault with Z_f = 0 every 5s; stable operation expected until SCR approaches 2.5

Range [s]	SCR
0-5	20
5-10	10
10-15	5
15-20	4
20-25	3
25-30	2.5
30-35	2
35-40	1.5
40-45	1



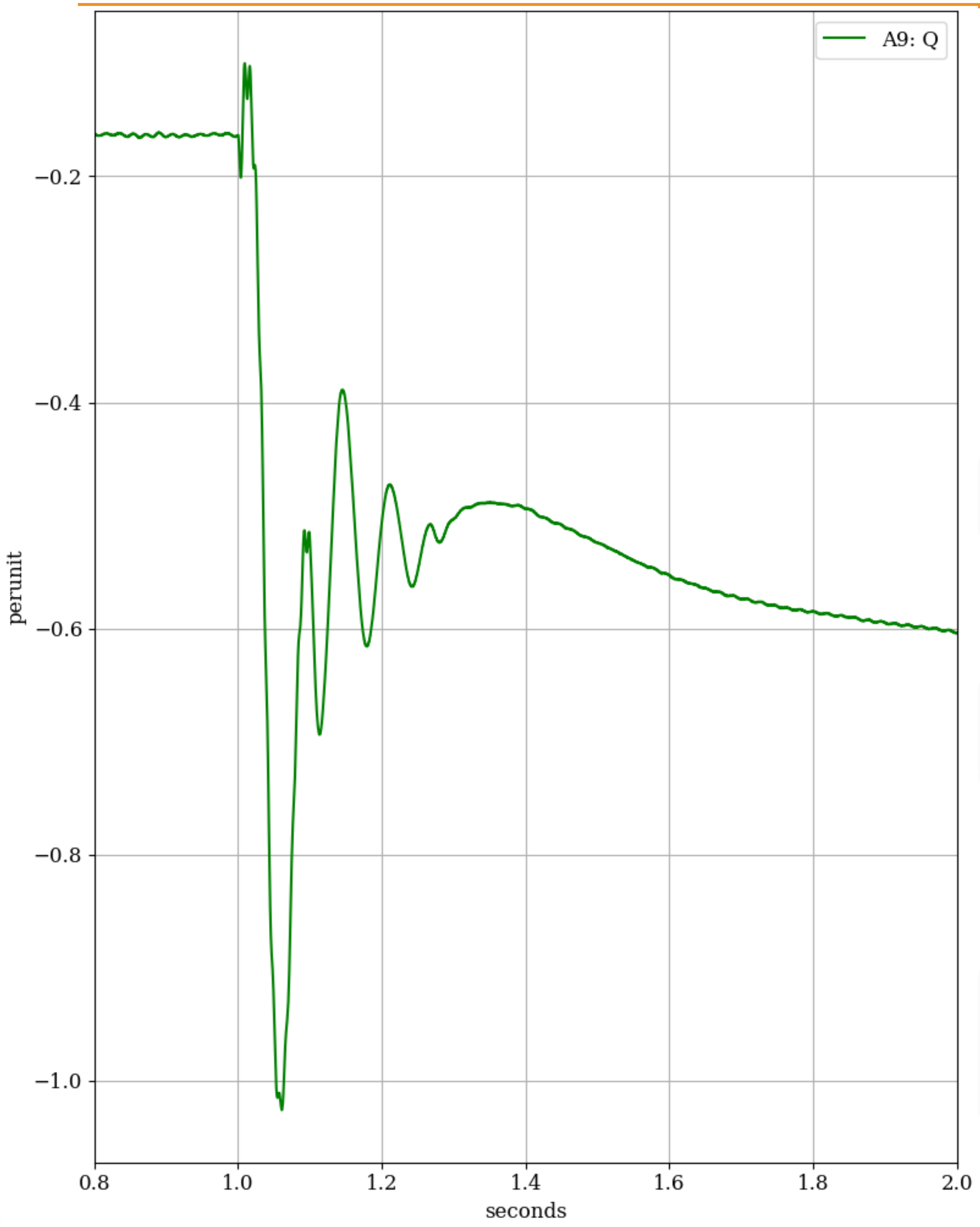
Some important figures of merit expected from post-processing.



- Reaction time: duration from step input to changed output at same location
- Rise time: duration from 10% to 90% of the final settled output level
- Settling time: duration from step change to output stays within a settling band around final output level
- Overshoot: normalized amount by which the peak output exceeds final settled output level
- *RMS Error*: point-by-point root mean square difference from expected output (measurement, spec, another model)

Suggested reference: https://doi.org/10.1109/IEEESTD.2022.9762253, especially the definitions.

Damping ratio estimates: by overshoot or by log decrement.



By per-unit overshoot (O):

$$\zeta = \frac{-\ln(O)}{\sqrt{\pi^2 + \ln^2(O)}}$$

By log decrement:

$$\sigma = \frac{1}{n}\ln\left(\frac{Q_{peak-1}}{Q_{peak-n}}\right)$$

$$\zeta = \frac{1}{\sqrt{1+\left(\frac{2\pi}{\sigma}\right)^2}}$$

ζ	Behavior
0	Purely oscillatory
< 1	Damped oscillations
1	Critically damped, i.e., no overshoot
> 1	Sluggish

Suggested reference: https://doi.org/10.1109/IEEESTD.2022.9762253, Annex L.

Important Links and Instructions

- Instructions, models, slides, videos, and other material: https://github.com/pnnl/i2x/tree/develop/emt-bootcamp
- Direct questions about software operation to your tool vendor
- Post questions about the bootcamp materials here:
  - https://github.com/pnnl/i2x/issues/16
  - You may benefit from the experience of others this way
- Upcoming video and exercise releases (separate for each tool):
  - August 10: Comparing rotating machine and IBR behaviors in EMT
  - August 17: Comparing switching and average models
  - August 24: Automation of faults
  - August 31: Automation of IEEE P2800.2 type tests
  - September 7: Automation of waveform evaluations
- September 14, 2-4 p.m. Eastern time: System-level Emphasis