Electromagnetic transient and phasor domain hybrid simulation and its application to detailed FIDVR studies

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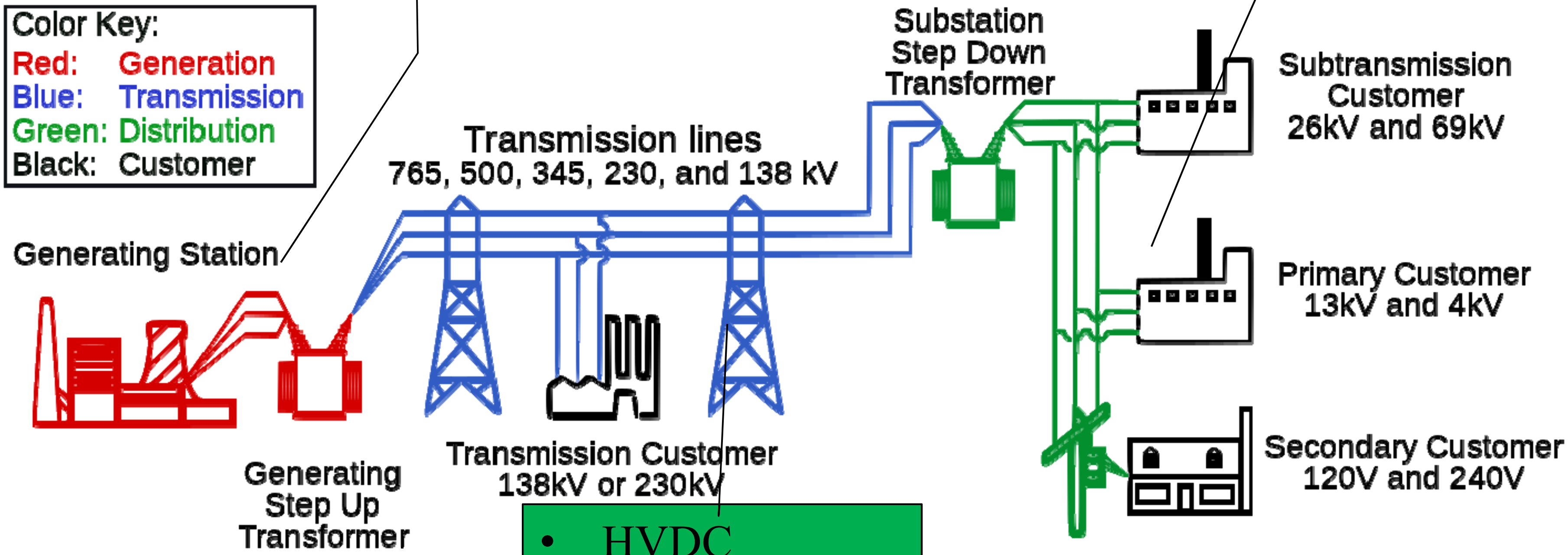
Introduction

- **Significant changes in power systems**
  - Rapid development of renewable generation
  - Shutdown of coal power plants
  - Distributed generation (PV, Wind)
  - More dynamic loads (Air conditioners, VFD motors)

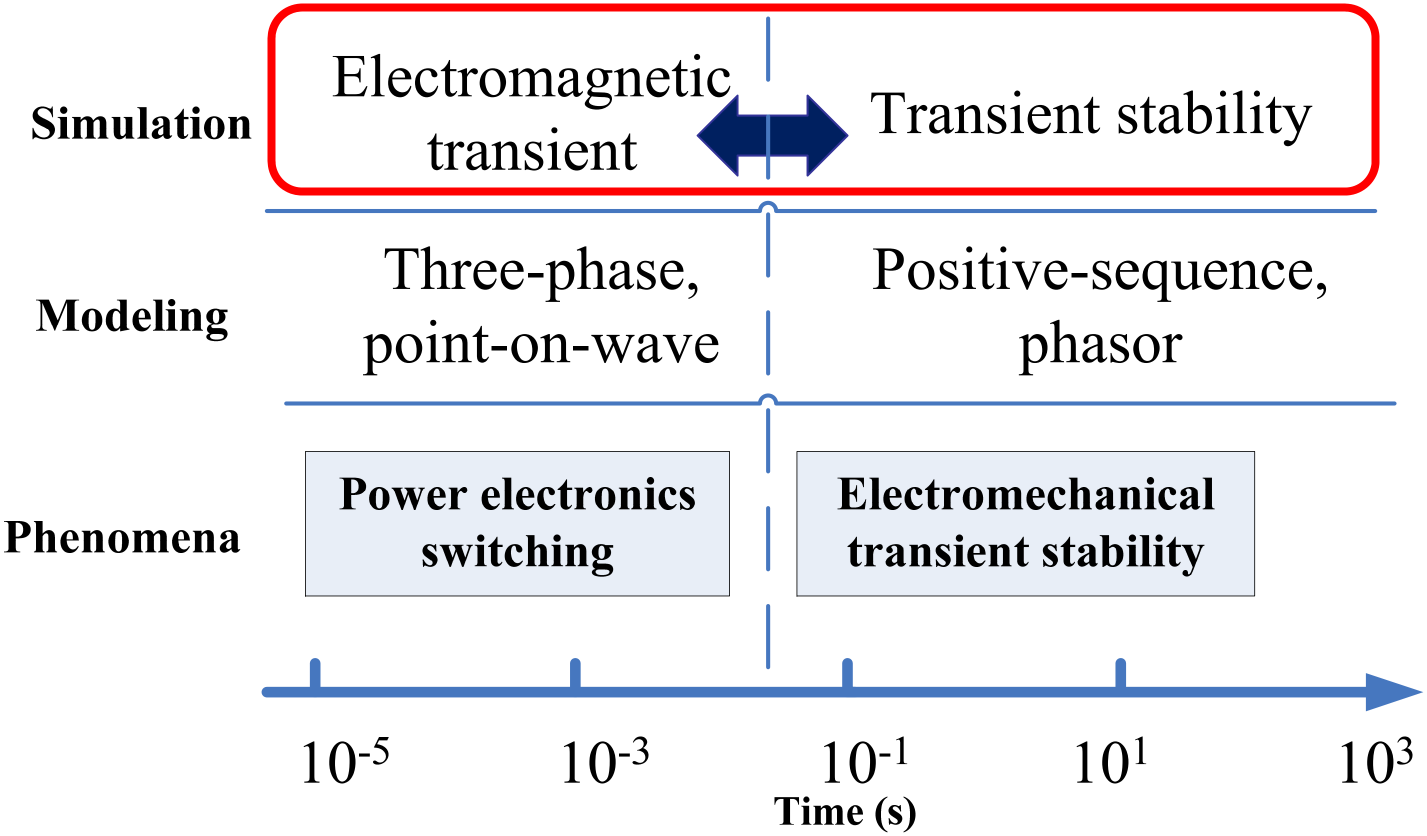


- HVDC
- FACTS

Source: U.S. DOE

Two main challenges in power system dynamic simulation

1. **Modeling and representation of an increasing number of power electronic devices in dynamic simulation**
    - Quasi-steady-state model or performance model in TS simulators
    - Fast switching and control cannot be adequately represented



Simulation	Electromagnetic transient	Transient stability
Modeling	Three-phase, point-on-wave	Positive-sequence, phasor
Phenomena	**Power electronics switching**	**Electromechanical transient stability**

Two main challenges in power system dynamic simulation

2. Representation of distribution systems in power system dynamic simulation

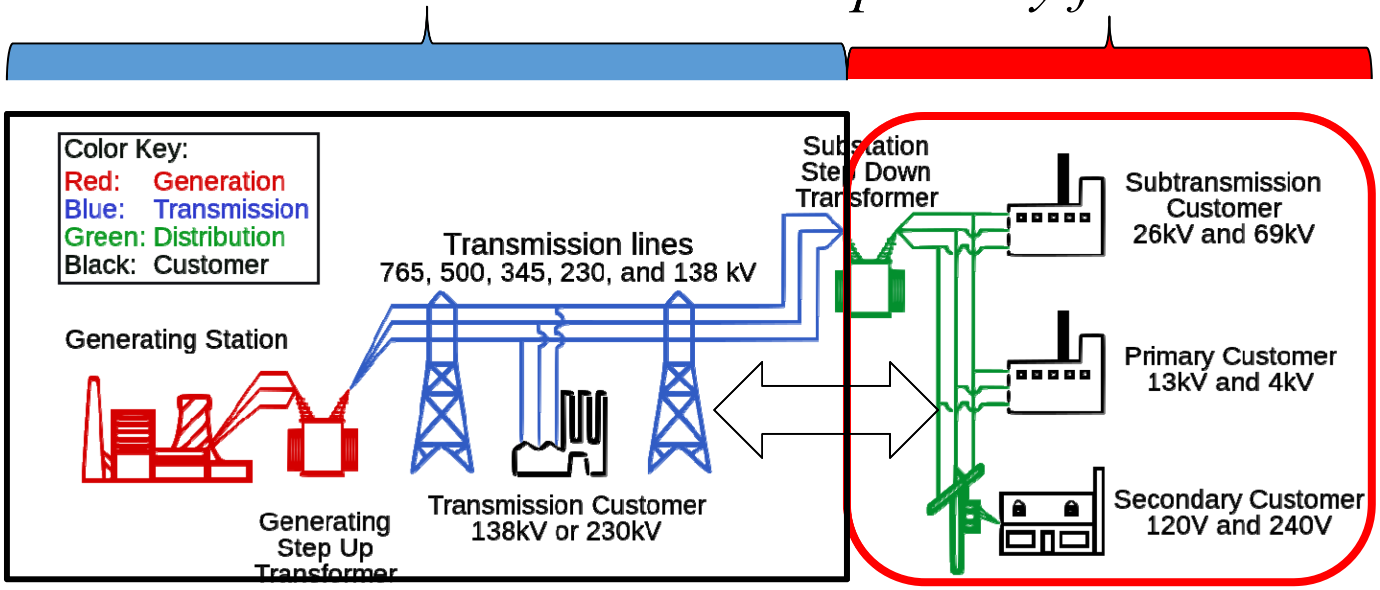
- **Various load models: ZIP, motor + ZIP, CMPLDW 1) computational limitation; 2) availability of distribution system data**
- **Developments of distributed generation, EV and storage significantly change the behavior of distribution systems**
  - Past: the voltage profile gradient along the feeder was small
  - Now the locations matter: A/C stalling, local volt/VAr support of DGs
  - Load modeling → distribution system modeling
- **Integrated transmission and distribution (T&D) systems**
  - EPRI proposed "the integrated grid" framework—for fully realizing the values of distributed and central generation resources
  - To analyze the increased interactions between T&D and to take advantage of them

Two main challenges in power system dynamic simulation

2. Representation of distribution systems in power system dynamic simulation

Three-sequence, phasor models

Detailed 3-phase representation down to primary feeder level



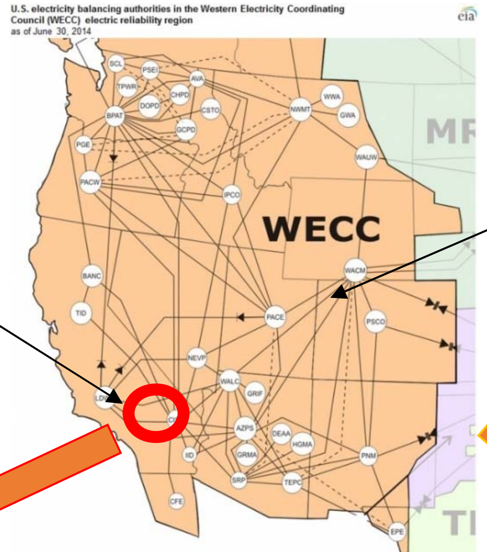
Three-sequence transient stability

EMT or three-phase dynamic simulation

Development of Hybrid Simulation

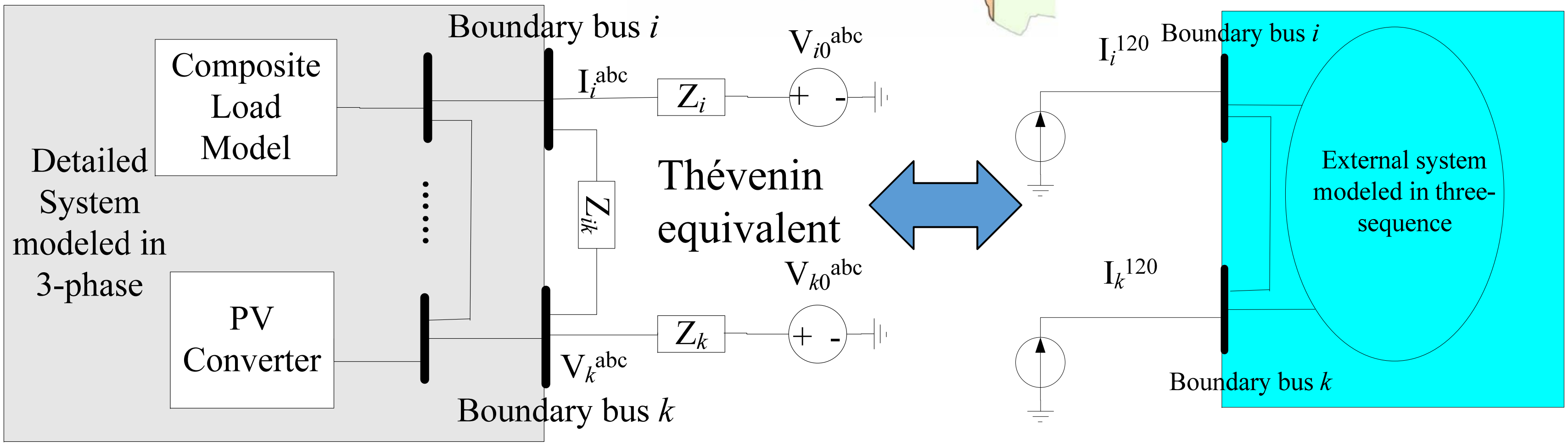
- Three-phase, POW model
- **EMT** simulator

Region of interest
< 300 buses
→ Detailed system



- Sequence, phasor model
- **TS** simulator

Remainder of the system
~15000 buses
→ External system

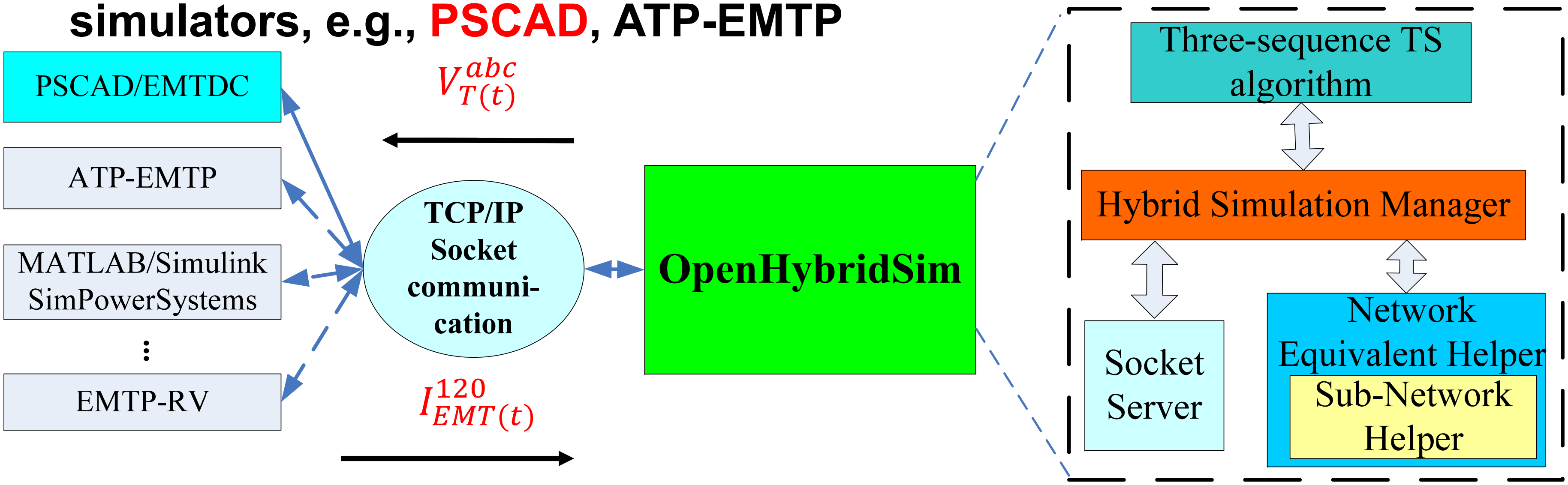


Detailed system modeled in an EMT Simulator

External system modeled in a TS Simulator

OpenHybridSim: A new EMT-TS hybrid simulation tool

- **A decoupled architecture**
- **Three-sequence TS simulation developed based on InterPSS**
- **Network equivalents:**
  - **Three-phase Thévenin equivalent of the external system in EMT simulation**
  - **Three-sequence current source $I_{EMT(t)}^{120}$ as the equivalent of the detailed system in three-sequence TS simulation**
- **TCP/IP socket communication for connecting two simulators**
- **A generic interface framework for integrating with different EMT simulators, e.g., PSCAD, ATP-EMTP**



Equivalent of the external system in EMT simulation: Three-phase Thévenin equivalent

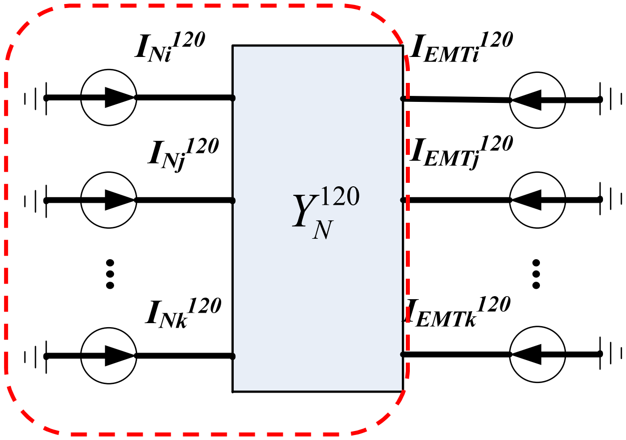
Three-sequence Norton equivalent

120-ABC

Three-phase Norton equivalent

Source transformation

Three-phase Thévenin equivalent



$$\boldsymbol{I}_N^{120} = \boldsymbol{Y}_N^{120} \boldsymbol{V}_{TS}^{120} - \boldsymbol{I}_{EMT}^{120}$$

$$Y_{Nik}^{120} = \begin{bmatrix} Y_{Nik}^{(1)} & 0 & 0 \\ 0 & Y_{Nik}^{(2)} & 0 \\ 0 & 0 & Y_{Nik}^{(0)} \end{bmatrix}$$

$$I_{Ni}^{abc} = \boldsymbol{S} I_{Ni}^{120}$$

$$y_i^{abc} = \boldsymbol{S} y_i^{120} \boldsymbol{S}^{-1}$$

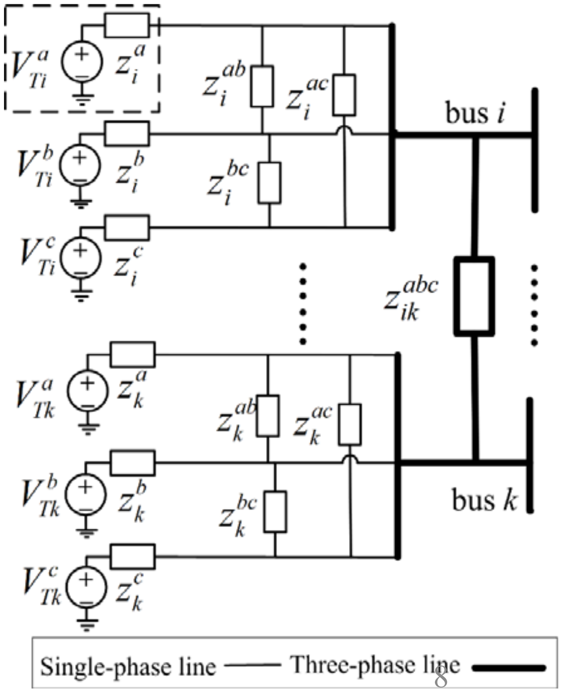
$$y_{ik}^{abc} = \boldsymbol{S} y_{ik}^{120} \boldsymbol{S}^{-1}$$

$$\boldsymbol{S} = \begin{bmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{bmatrix}$$

$$a = \boldsymbol{e}^{j2\pi/3}$$

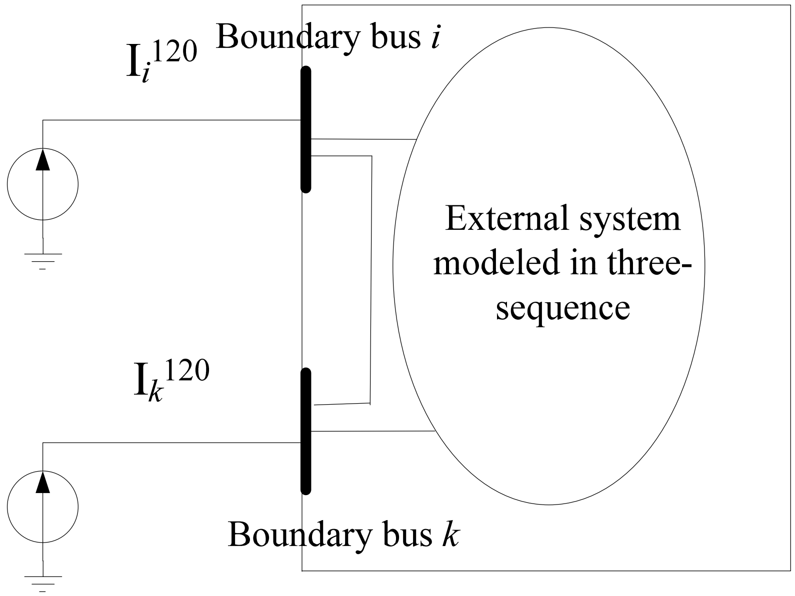
$$V_{Ti}^{\phi} = I_{Ni}^{\phi} / y_i^{\phi}$$

$$z_i^{\phi} = 1/y_i^{\phi}$$

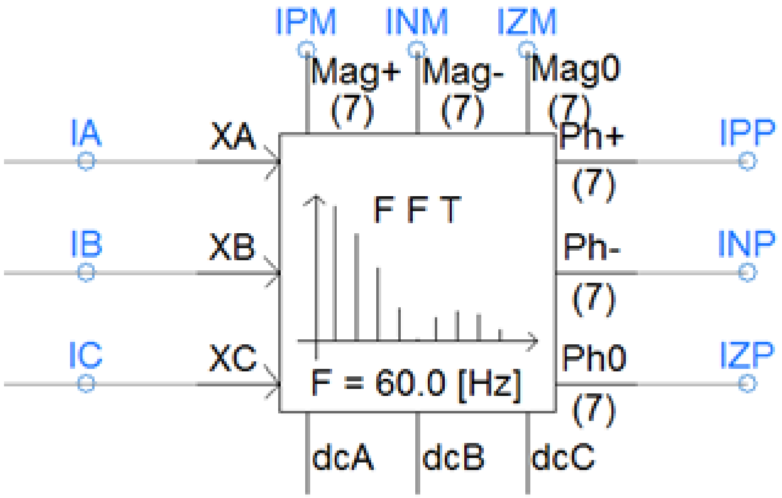


Equivalent of the detailed system in TS simulation: three-sequence current source

- Three-sequence current source
  - Seamlessly integrated into the network solution step of the three-sequence TS simulation
- Obtained from boundary current injection waveforms using FFT and 3-phase to 3-sequence transformation

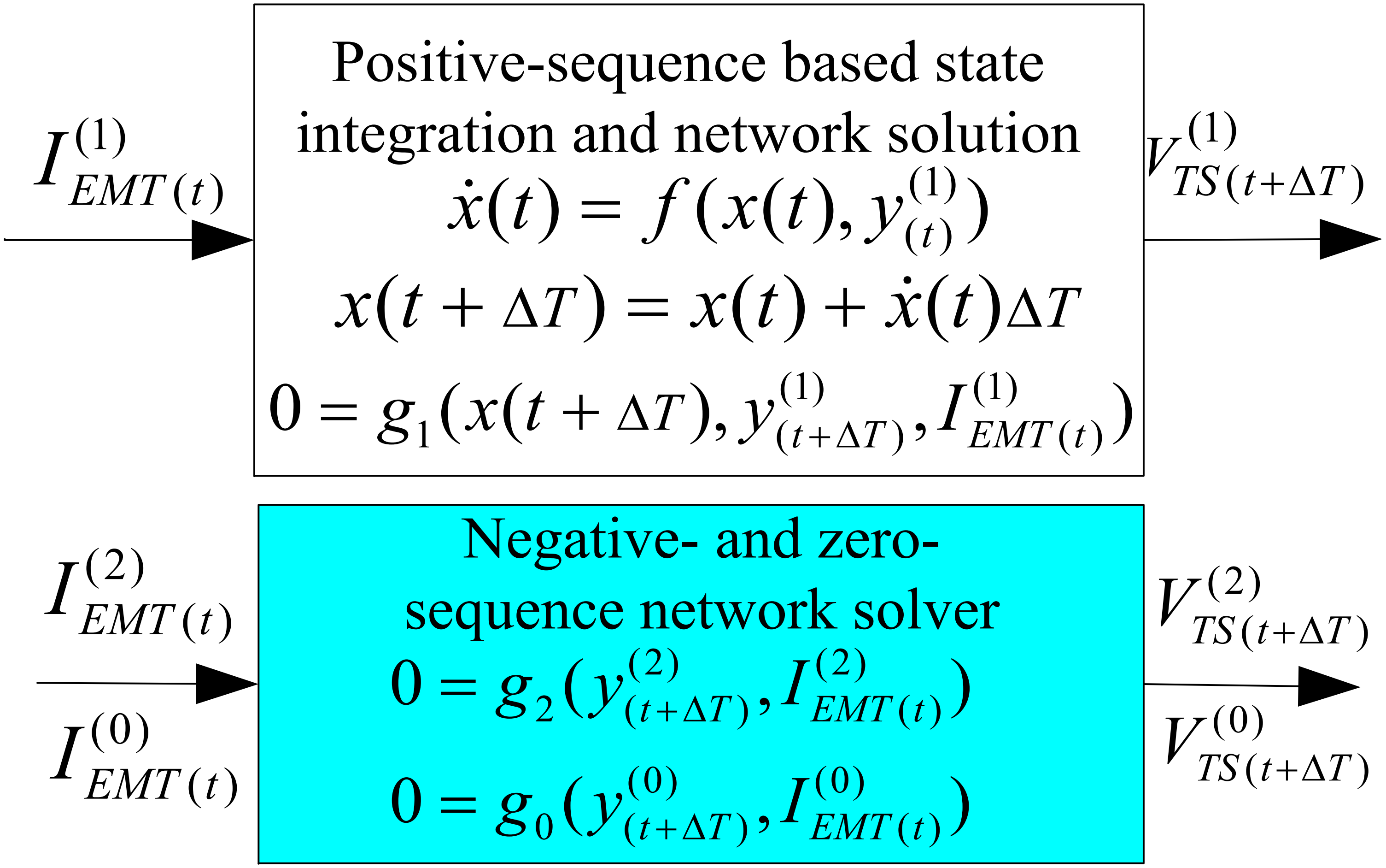


The detailed system is represented by three-sequence current sources in TS simulation



FFT component in PSCAD

Three-sequence TS simulation



$I^{(1)}_{EMT(t)}$

Positive-sequence based state integration and network solution

$$\dot{x}(t) = f(x(t), y^{(1)}_{(t)})$$

$$x(t+\Delta T) = x(t) + \dot{x}(t)\Delta T$$

$$0 = g_1(x(t+\Delta T), y^{(1)}_{(t+\Delta T)}, I^{(1)}_{EMT(t)})$$

$V^{(1)}_{TS(t+\Delta T)}$

$I^{(2)}_{EMT(t)}$

$I^{(0)}_{EMT(t)}$

Negative- and zero-sequence network solver

$$0 = g_2(y^{(2)}_{(t+\Delta T)}, I^{(2)}_{EMT(t)})$$

$$0 = g_0(y^{(0)}_{(t+\Delta T)}, I^{(0)}_{EMT(t)})$$

$V^{(2)}_{TS(t+\Delta T)}$

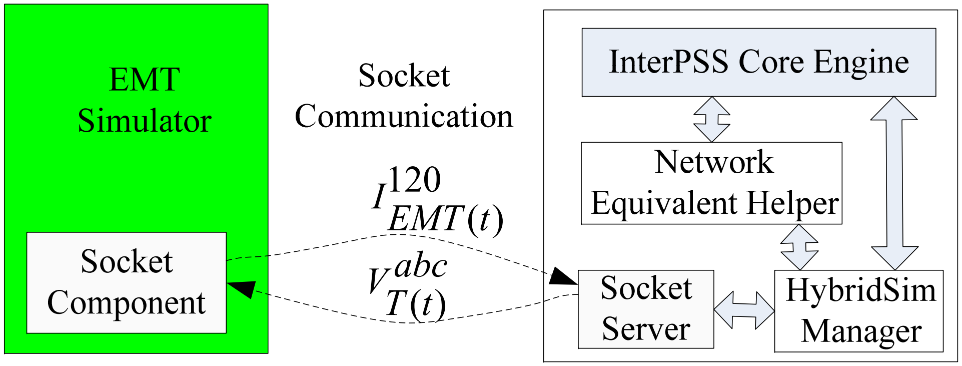
$V^{(0)}_{TS(t+\Delta T)}$

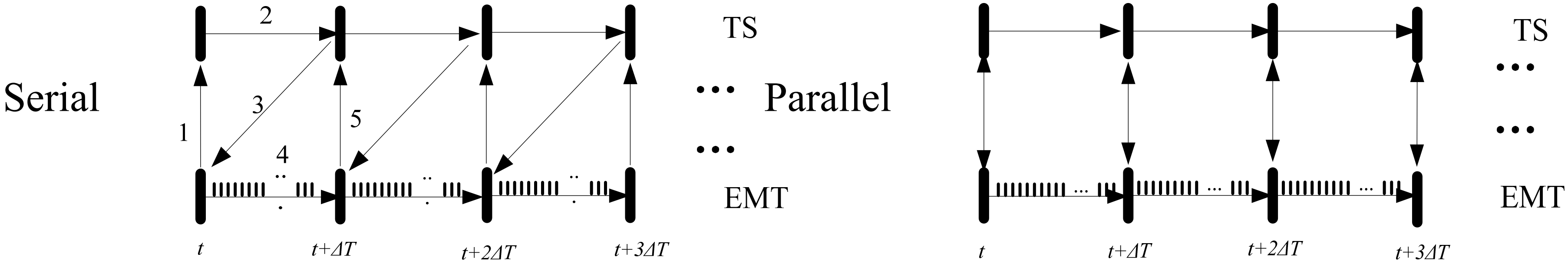
Negative sequence g_2: $\boldsymbol{I}^{(2)}_{ext(t)} - \boldsymbol{Y}^{(2)}_{ext}\boldsymbol{V}^{(2)}_{ext(t)}=0$

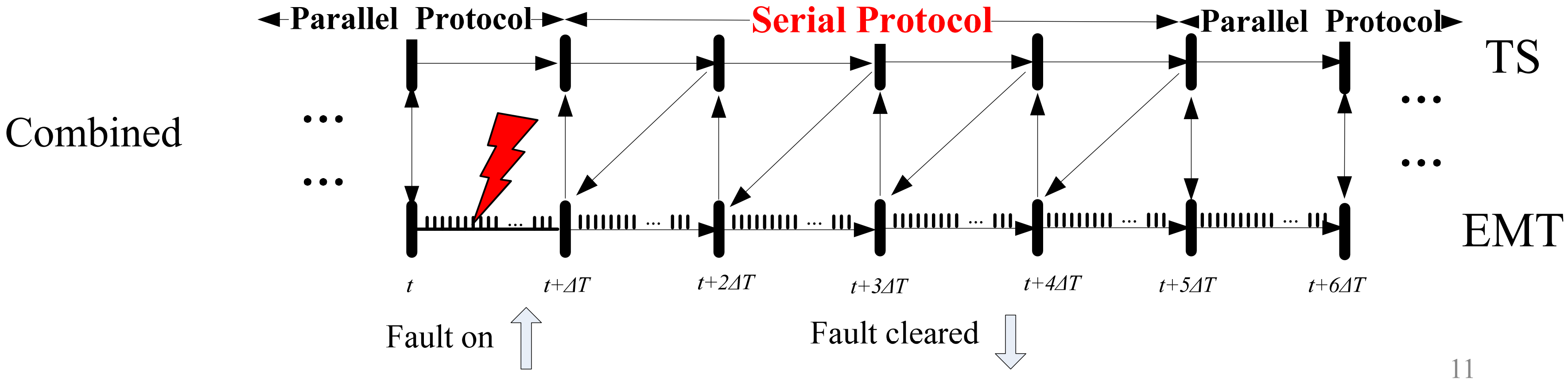
Zero sequence g_0: $\boldsymbol{I}^{(0)}_{ext(t)} - \boldsymbol{Y}^{(0)}_{ext}\boldsymbol{V}^{(0)}_{ext(t)}=0$

Interaction protocol

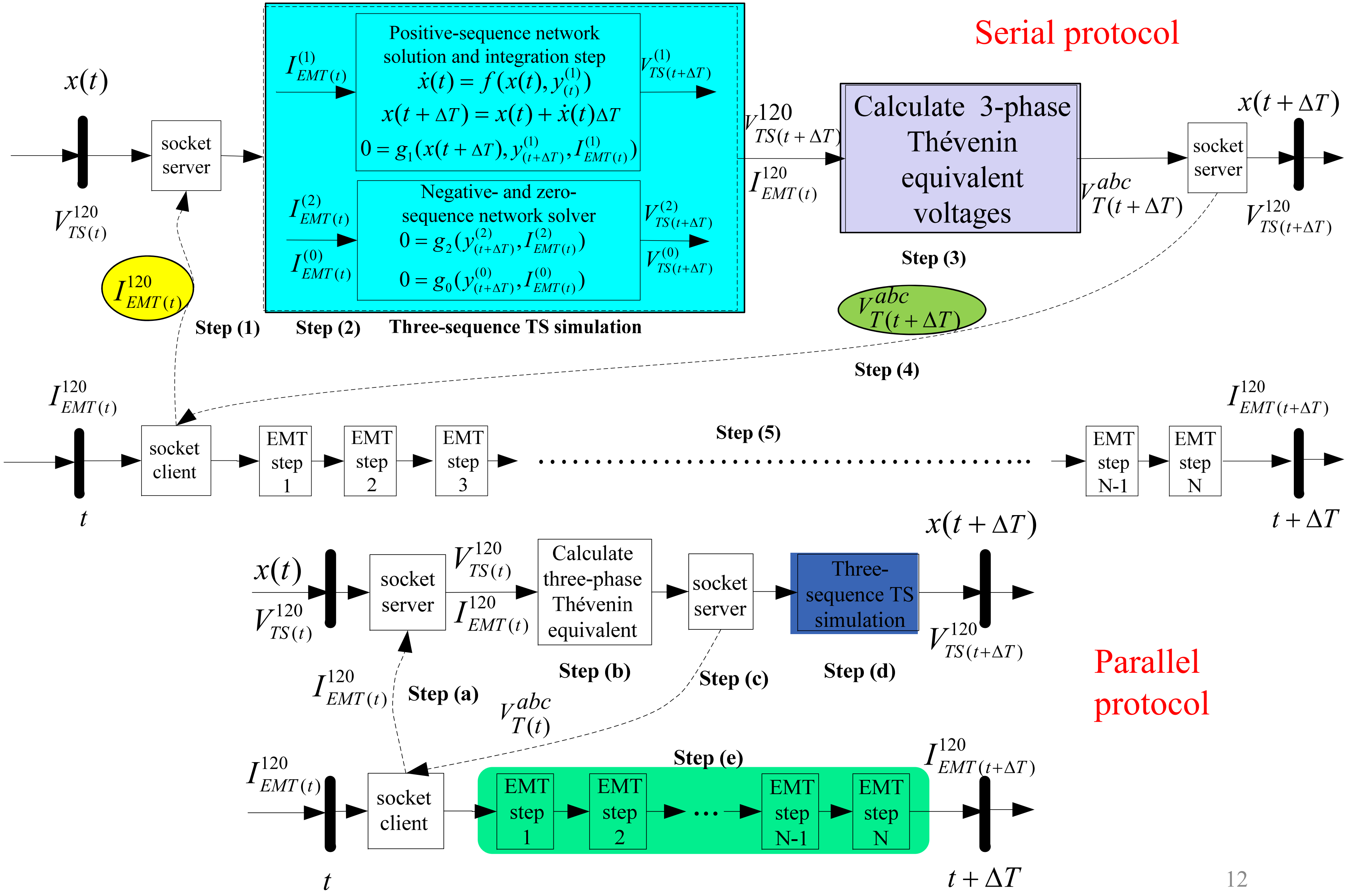
- Interactions between the two simulators







Implementation of the Two Interaction Protocols



Serial protocol

$x(t)$

$V^{120}_{TS(t)}$

socket server

$I^{120}_{EMT(t)}$

Step (1)

$I^{(1)}_{EMT(t)}$

Positive-sequence network solution and integration step

$\dot{x}(t) = f(x(t), y^{(1)}_{(t)})$

$x(t+\Delta T) = x(t) + \dot{x}(t)\Delta T$

$0 = g_1(x(t+\Delta T), y^{(1)}_{(t+\Delta T)}, I^{(1)}_{EMT(t)})$

$V^{(1)}_{TS(t+\Delta T)}$

$I^{(2)}_{EMT(t)}$

$I^{(0)}_{EMT(t)}$

Negative- and zero-sequence network solver

$0 = g_2(y^{(2)}_{(t+\Delta T)}, I^{(2)}_{EMT(t)})$

$0 = g_0(y^{(0)}_{(t+\Delta T)}, I^{(0)}_{EMT(t)})$

$V^{(2)}_{TS(t+\Delta T)}$

$V^{(0)}_{TS(t+\Delta T)}$

Step (2)

Three-sequence TS simulation

$V^{120}_{TS(t+\Delta T)}$

$I^{120}_{EMT(t)}$

Calculate 3-phase Thévenin equivalent voltages

Step (3)

$V^{abc}_{T(t+\Delta T)}$

socket server

$x(t+\Delta T)$

$V^{120}_{TS(t+\Delta T)}$

Step (4)

$I^{120}_{EMT(t)}$

socket client

EMT step 1

EMT step 2

EMT step 3

Step (5)

EMT step N-1

EMT step N

$I^{120}_{EMT(t+\Delta T)}$

t

$t + \Delta T$

Parallel protocol

$x(t)$

$V^{120}_{TS(t)}$

socket server

$V^{120}_{TS(t)}$

$I^{120}_{EMT(t)}$

Calculate three-phase Thévenin equivalent

socket server

Three-sequence TS simulation

$x(t+\Delta T)$

$V^{120}_{TS(t+\Delta T)}$

$I^{120}_{EMT(t)}$

Step (a)

Step (b)

$V^{abc}_{T(t)}$

Step (c)

Step (d)

Step (e)

$I^{120}_{EMT(t)}$

socket client

EMT step 1

EMT step 2

EMT step N-1

EMT step N

$I^{120}_{EMT(t+\Delta T)}$

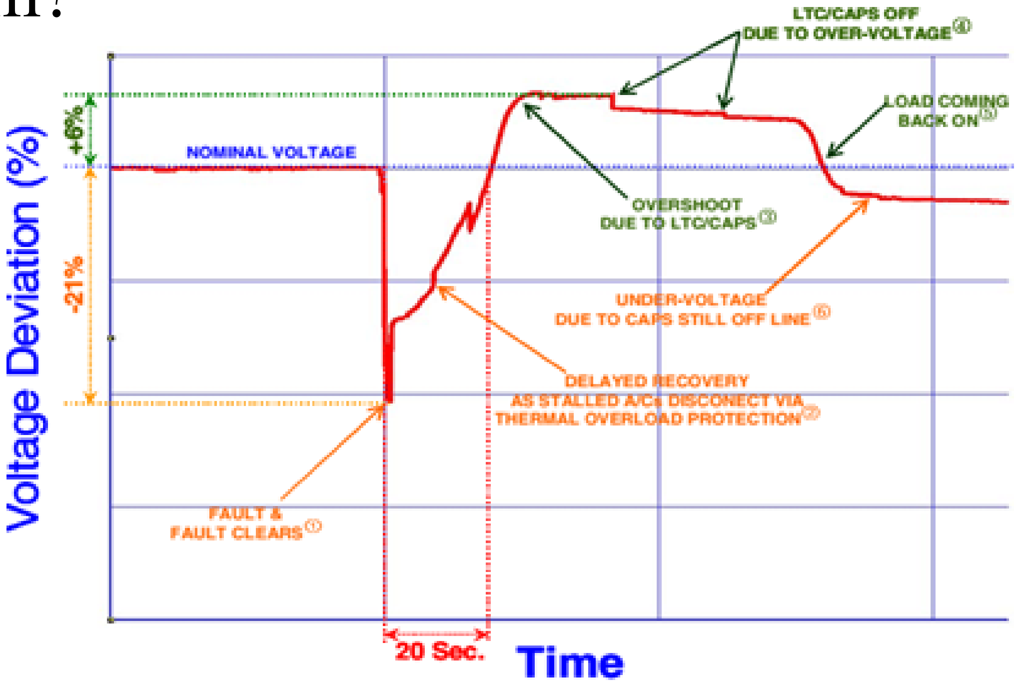
t

$t + \Delta T$

The fault-induced delayed voltage recovery problem

- What is FIDVR problem?

A 230 kV bus voltage profile
during a typical FIDVR event [1]



- Root cause:

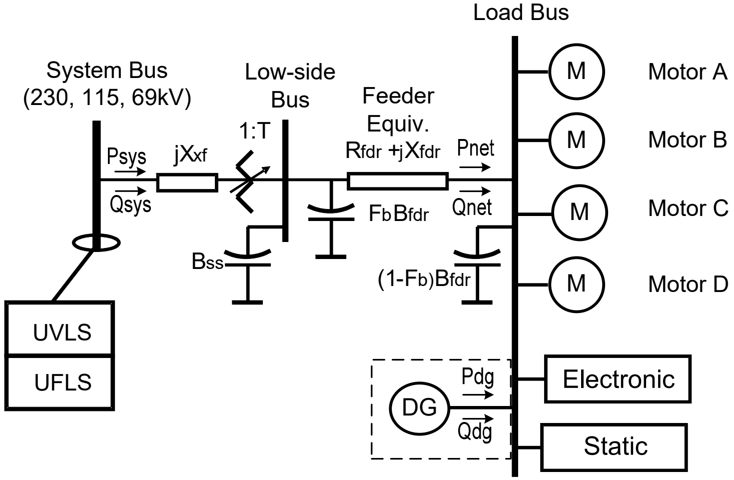
Stalling and prolonged tripping of 1-ϕ residential air conditioner (A/C) compressor motor

- Direct impact of distribution on transmission system

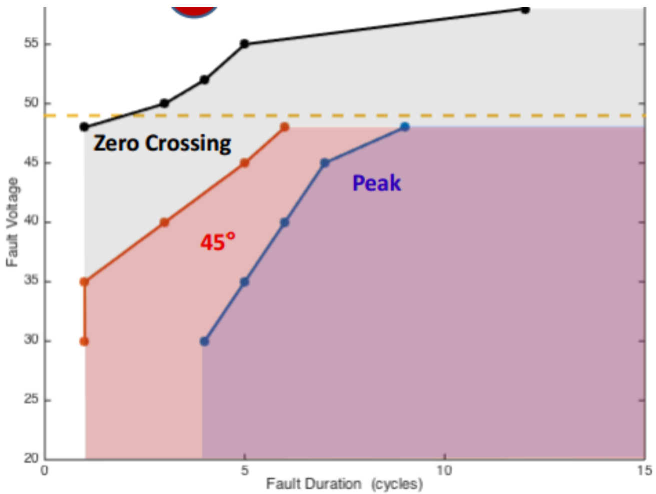
[1] D. N. Kosterev, A. Meklin, J. Undrill, B. Lesieutre, et al., "Load modeling in power system studies: WECC progress update," in 2008 IEEE Power and Energy Society General Meeting, 2008, pp. 1-8.

The FIDVR Problem

- FIDVR has mainly been studied using CMPLDW and positive-sequence TS simulation programs
- Limitations of the CMPLDW model
  - ➢ Limited representation of distribution systems and DGs
  - ➢ Performance-based 1- ϕ A/C compressor motor model
  - ➢ Point-on-wave (POW) effects cannot be considered
  - ➢ Not suitable for cases involving unbalanced conditions
- The issues above can be overcome by hybrid simulation



CMPLDW Model Structure



The point-on-wave effects on A/C stalling

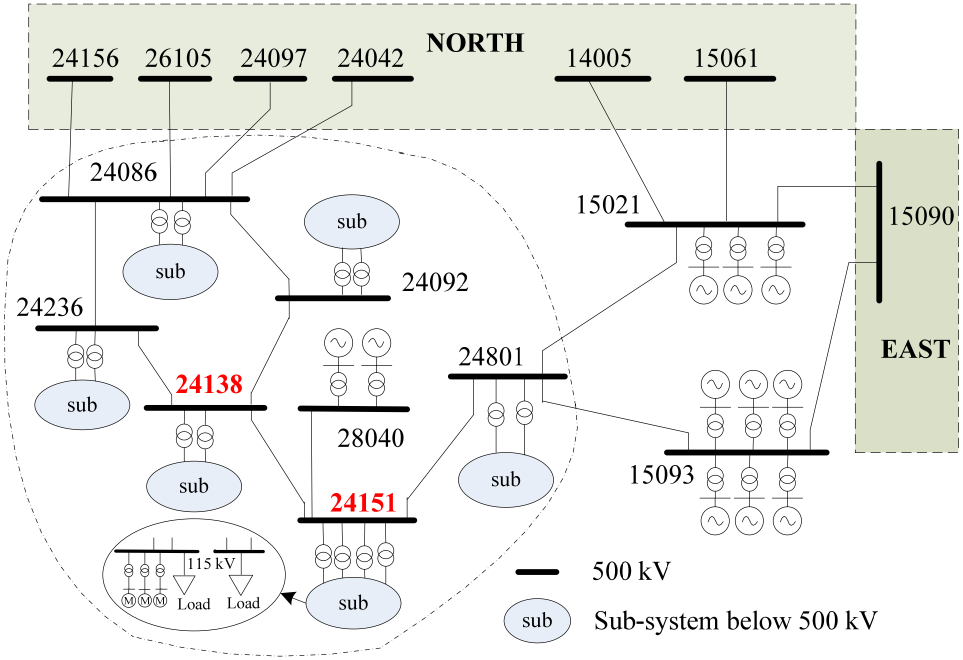
Application of EMT-TS hybrid simulation to FIDVR study on the WECC system

The WECC system

Buses	Transmission lines	Generators	Loads
15750	13715	3074	7787

Buses with a large percentage of 1-Φ A/C load

- Bus 24151
- Bus 24138

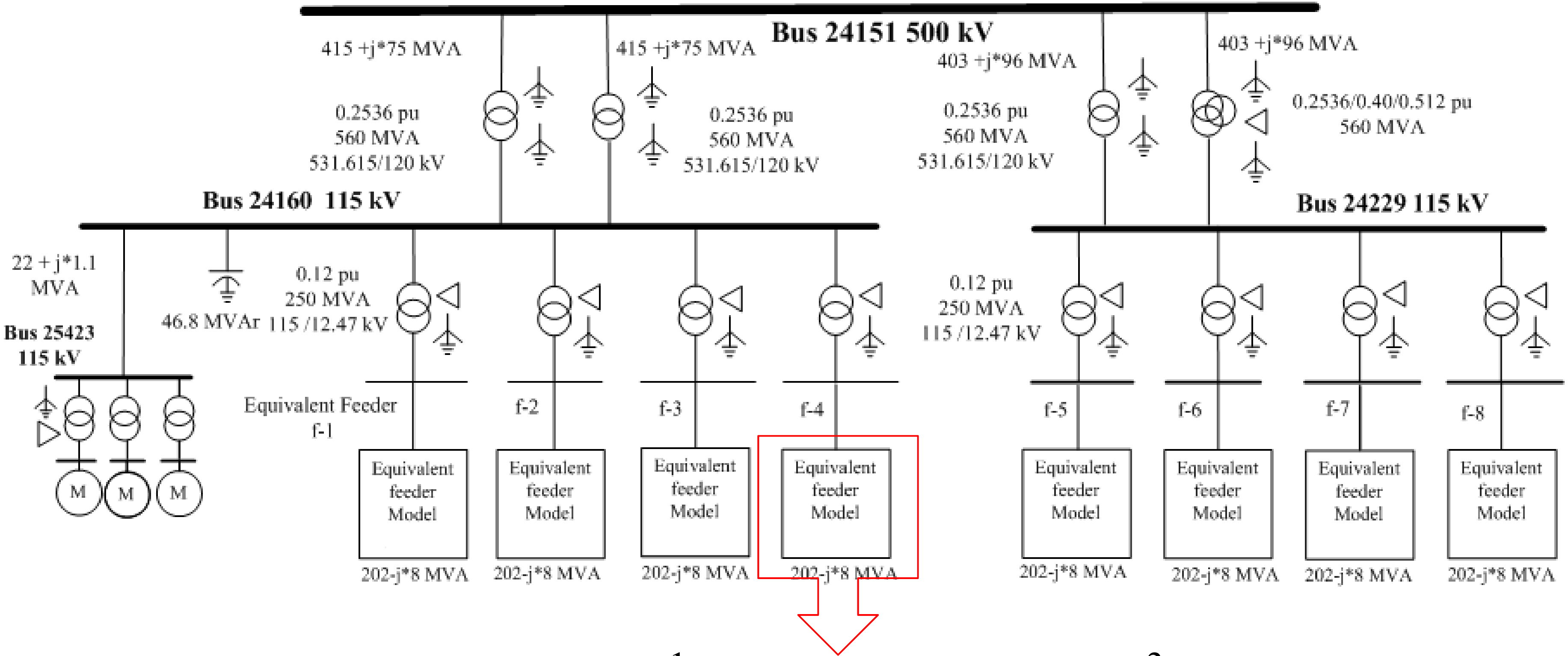


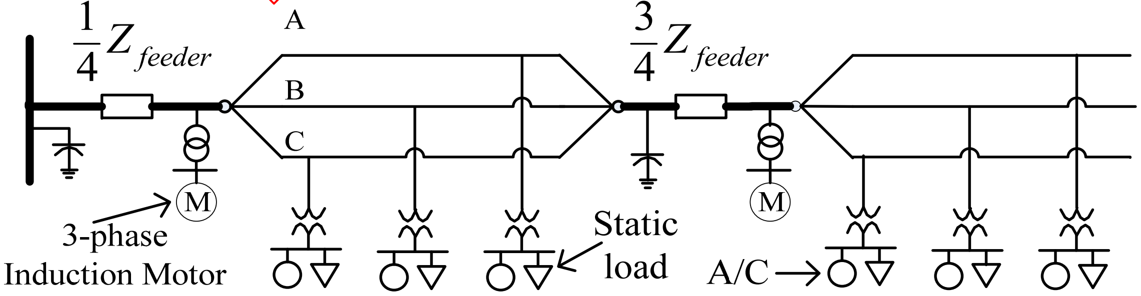
One-line diagram of the study region

Summary of the detailed system

Total number of buses	238	
Number of buses of different voltage levels	500 kV	7
	230 kV	37
	161 kV	3
	115 kV	68
	92 kV	18
	<= 66kV	105
Total Load	11.9 GW	
Interface buses	8	

Set up of the detailed system





50% 1-Φ A/C motor [2]

25% 3-Φ induction motor

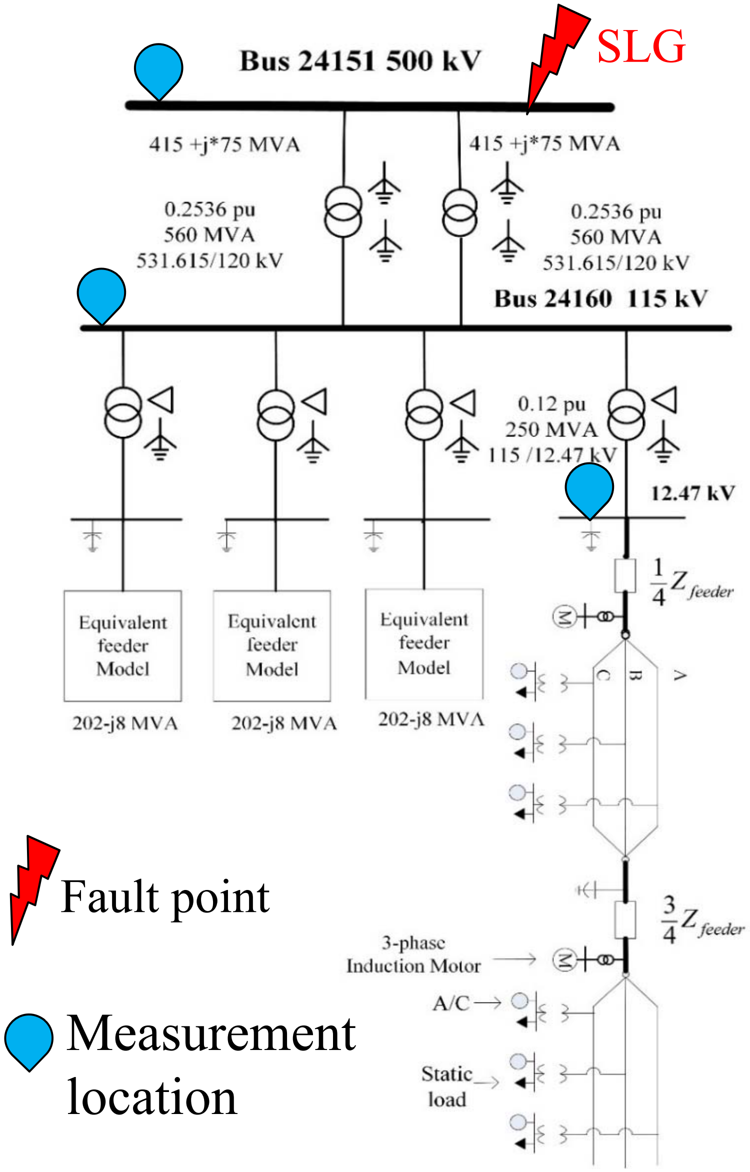
25% constant impedance

Equivalent feeder model[3]

[2] Y. Liu, V. Vittal, J. Undrill, and J. H. Eto, "Transient Model of Air-Conditioner Compressor Single Phase Induction Motor," IEEE Transactions on Power Systems, vol. 28, pp. 4528-4536, 2013.

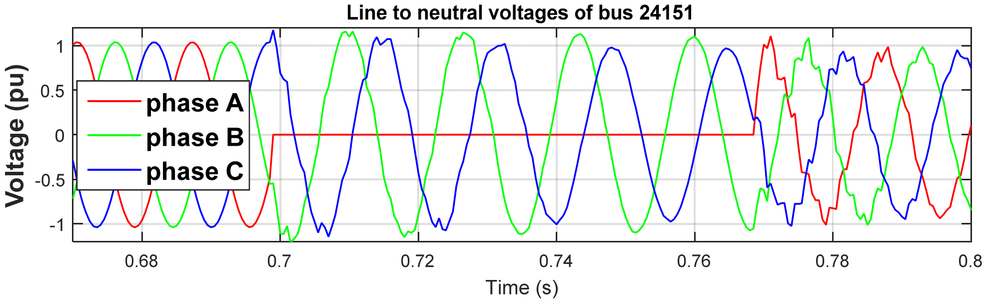
[3] William H. Kersting, Distribution System Modeling and Analysis (Second Edition), CRC Press, 2006, p.52-54

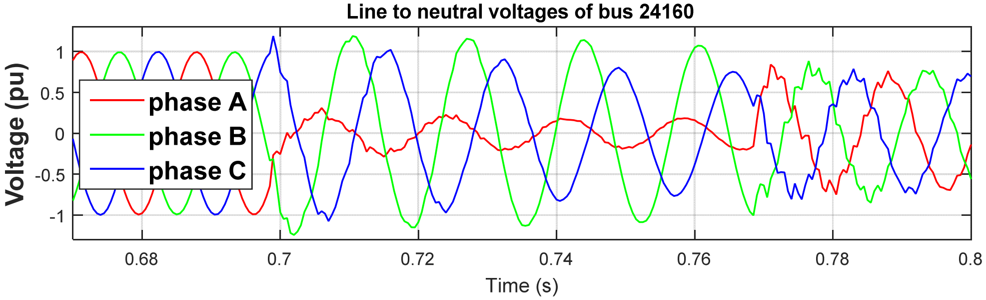
Case A: fault POW at voltage zero crossing

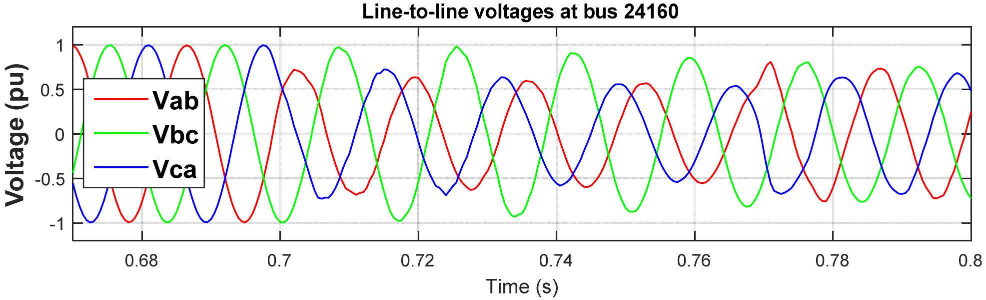


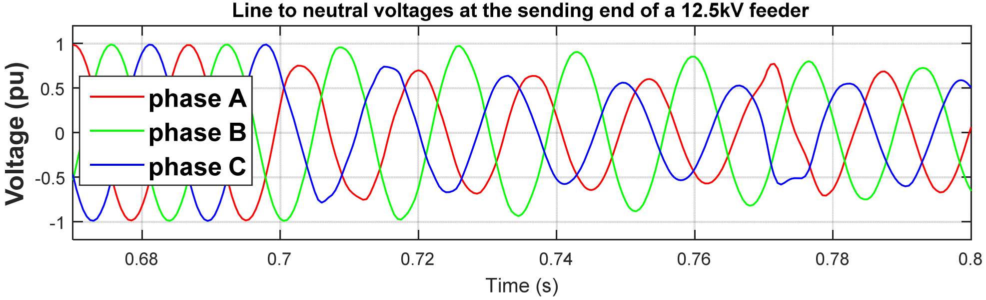
Fault point

Measurement location

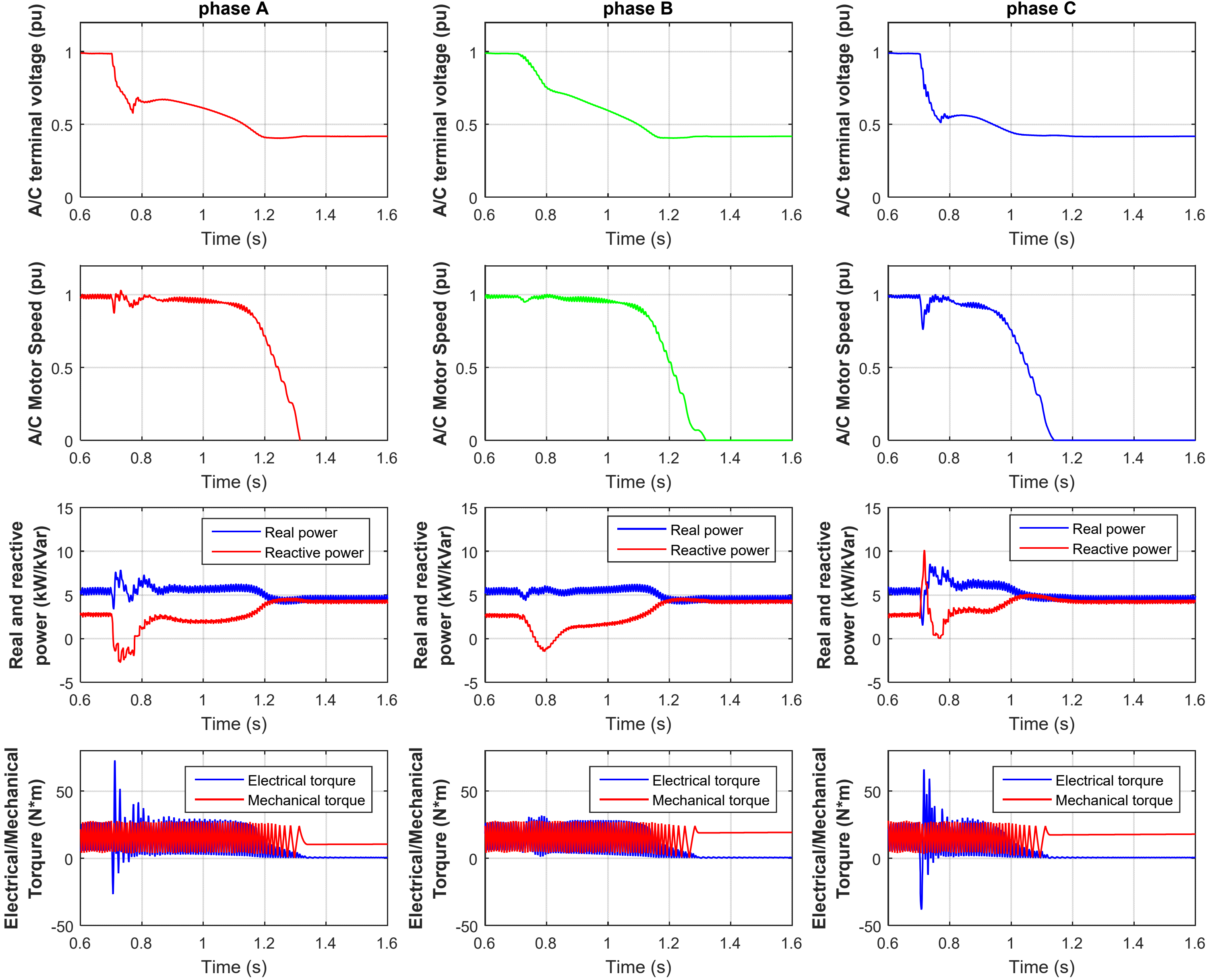

Line to neutral voltages of bus 24151


Line to neutral voltages of bus 24160

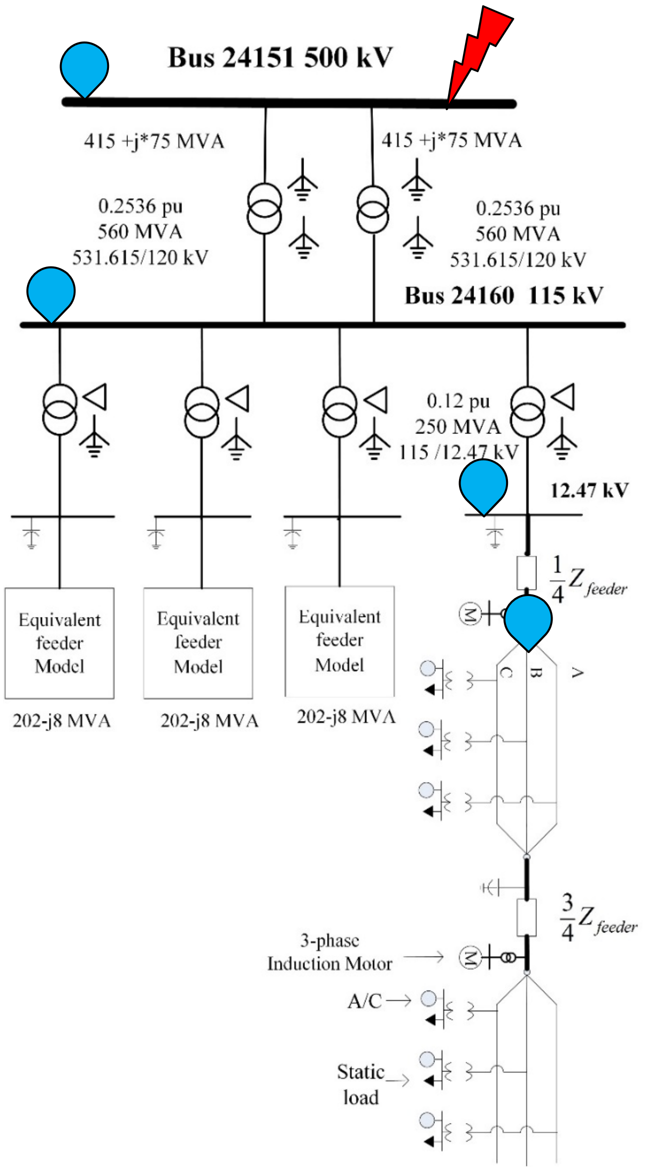

Line-to-line voltages at bus 24160

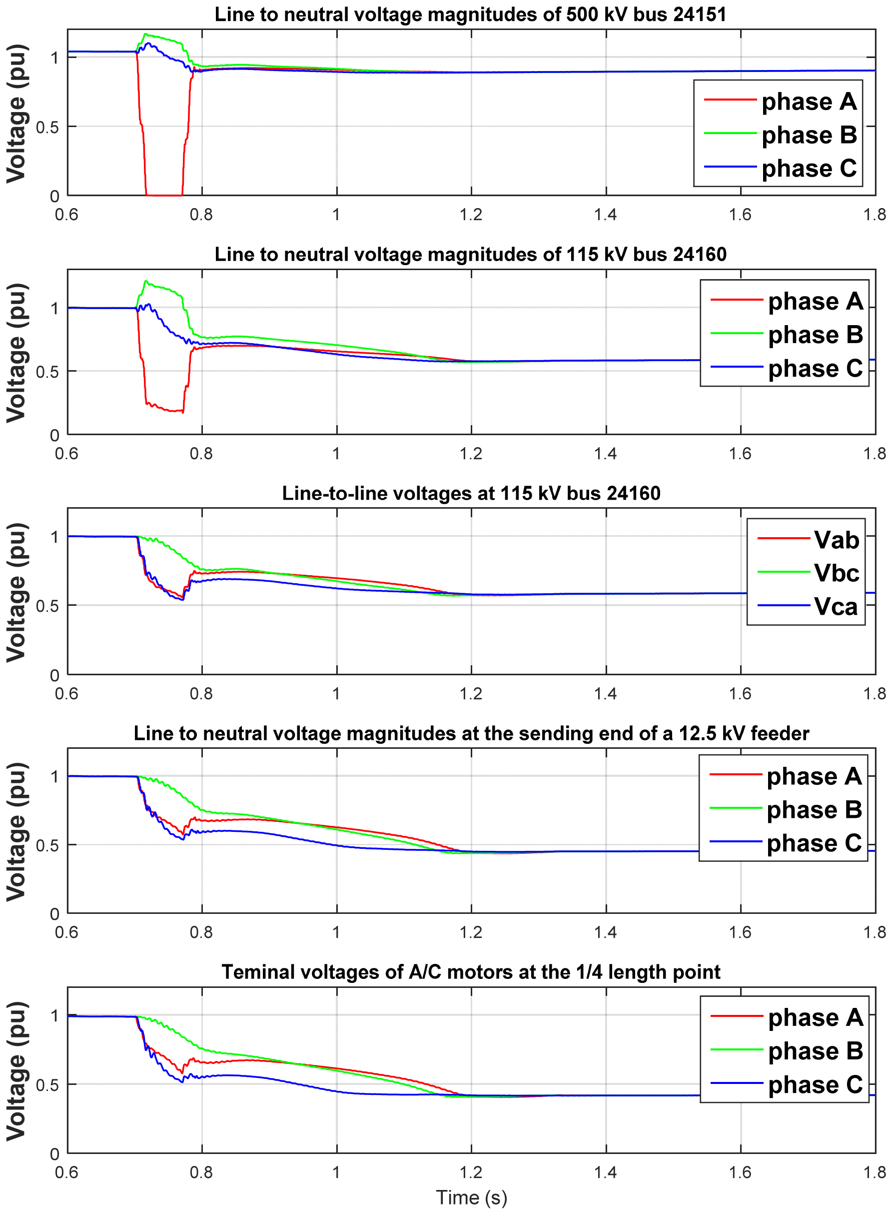

Line to neutral voltages at the sending end of a 12.5kV feeder

Case A: responses of A/C motors



Case A: phasor voltage magnitudes




Line to neutral voltage magnitudes of 500 kV bus 24151

Line to neutral voltage magnitudes of 115 kV bus 24160

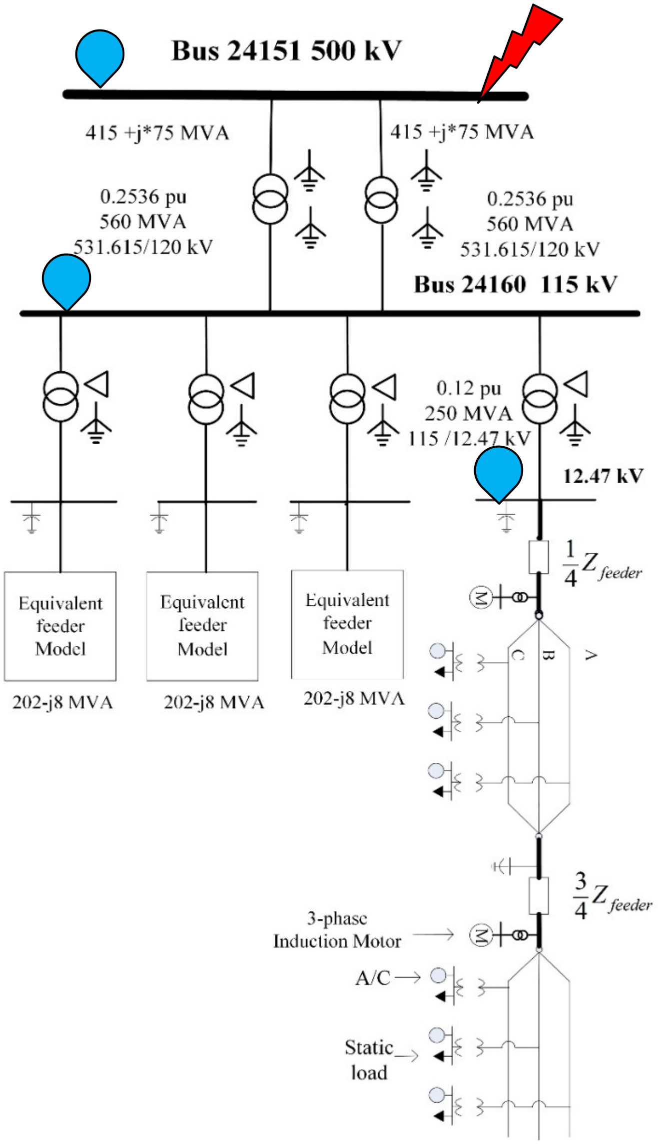
Line-to-line voltages at 115 kV bus 24160

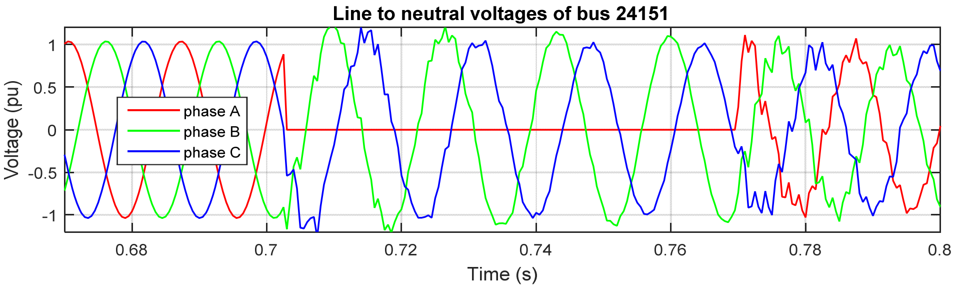
Line to neutral voltage magnitudes at the sending end of a 12.5 kV feeder

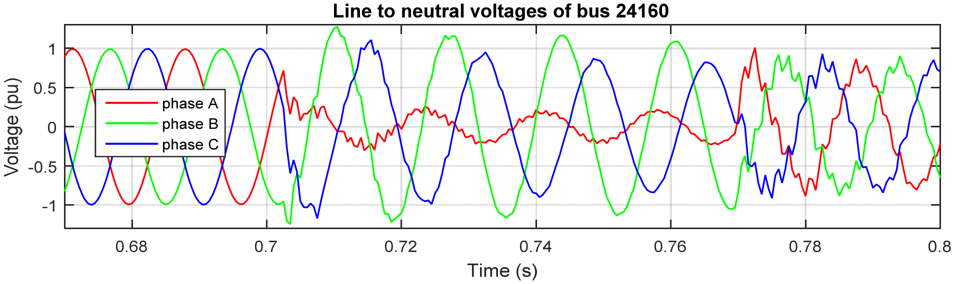
Teminal voltages of A/C motors at the 1/4 length point

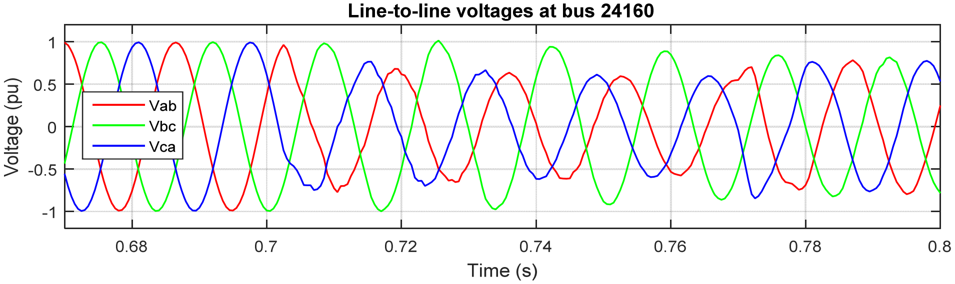
The Point-On-Wave Effects

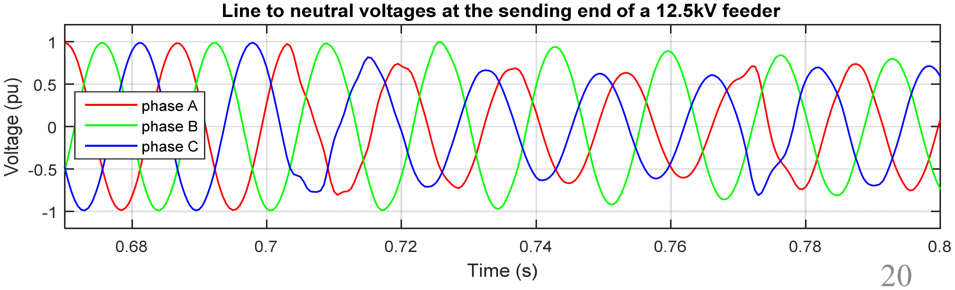
Case B: POW at the peak of phase A voltage waveform (90 degrees)



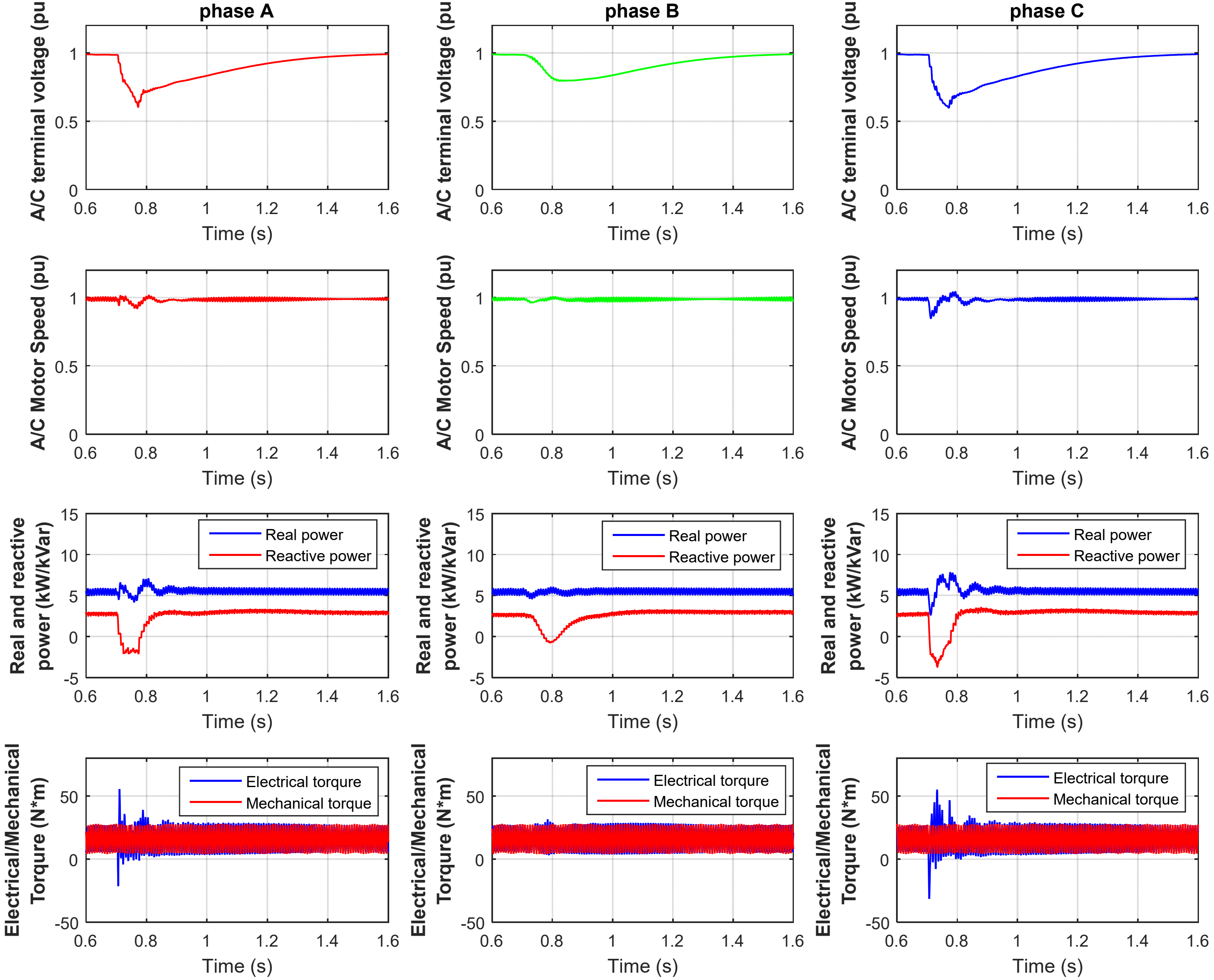




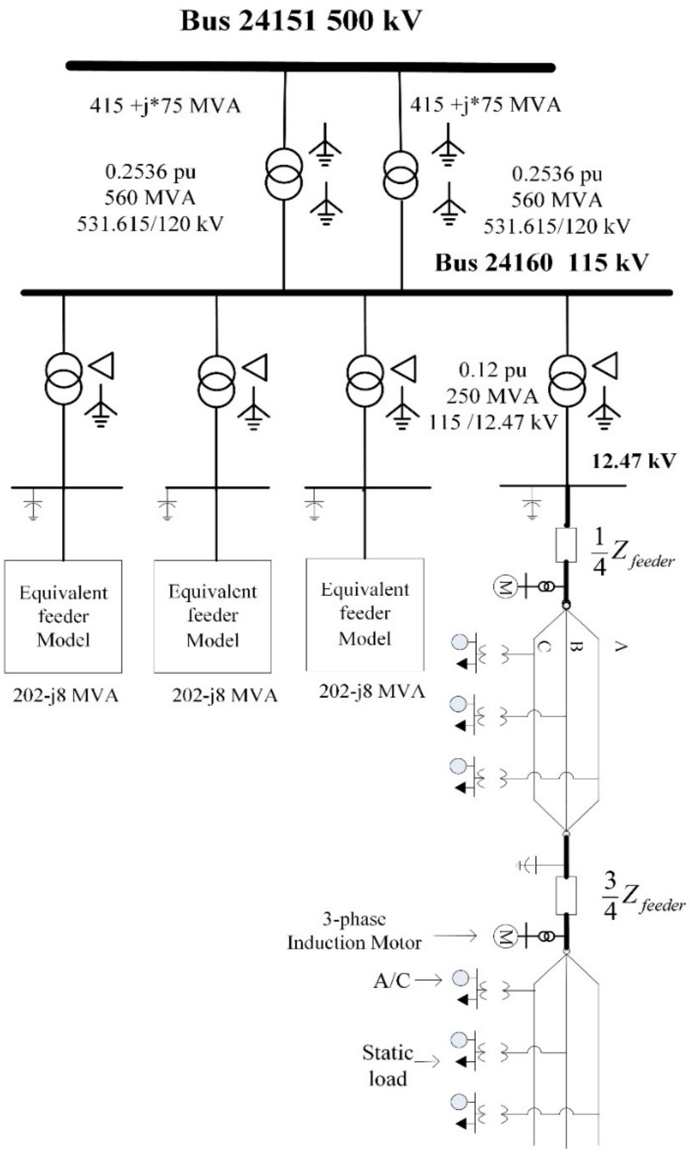


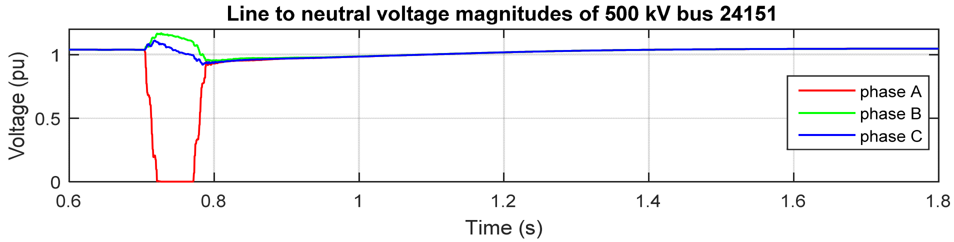


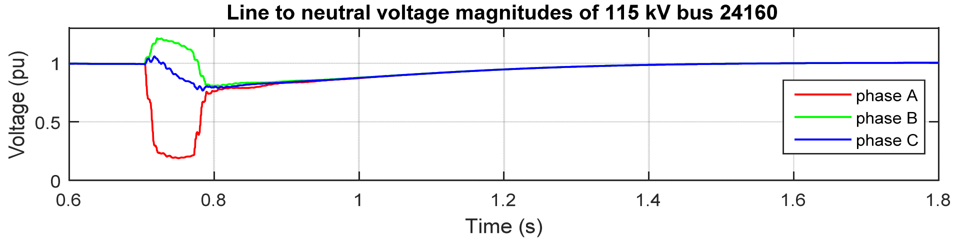
Case B: responses of A/C motors

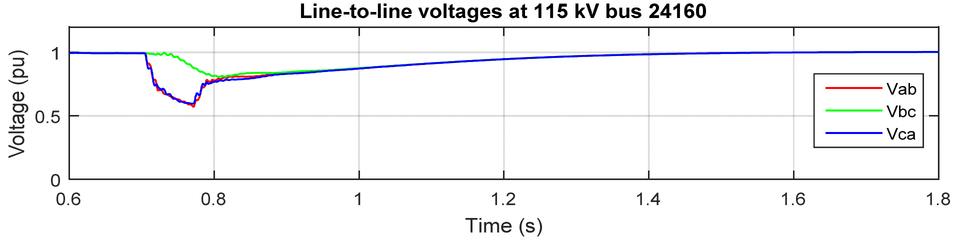


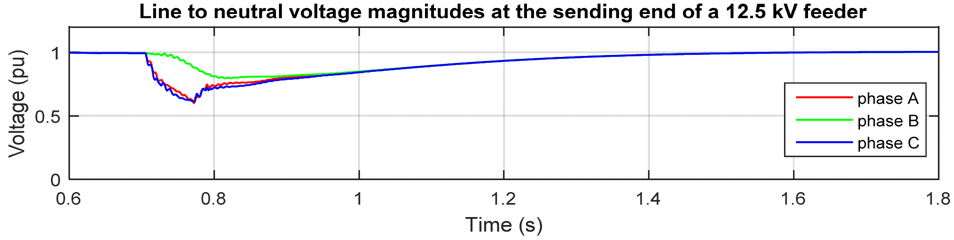
Case B: phasor voltage magnitudes

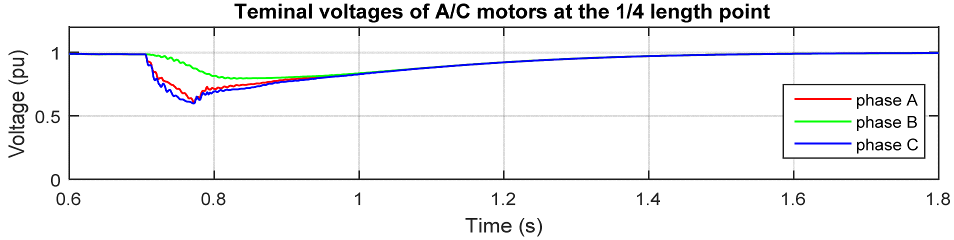



Line to neutral voltage magnitudes of 500 kV bus 24151

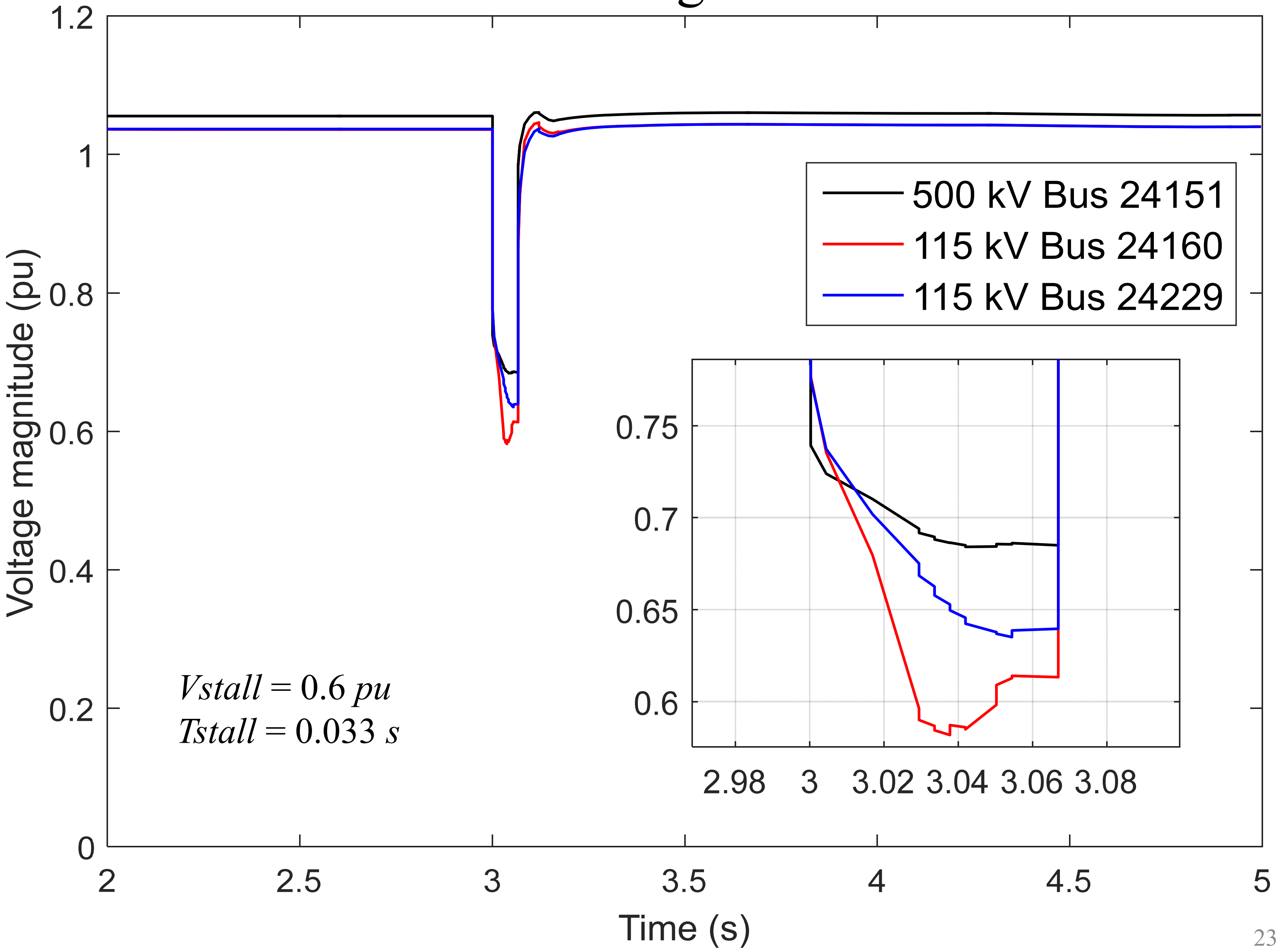

Line to neutral voltage magnitudes of 115 kV bus 24160


Line-to-line voltages at 115 kV bus 24160


Line to neutral voltage magnitudes at the sending end of a 12.5 kV feeder


Teminal voltages of A/C motors at the 1/4 length point

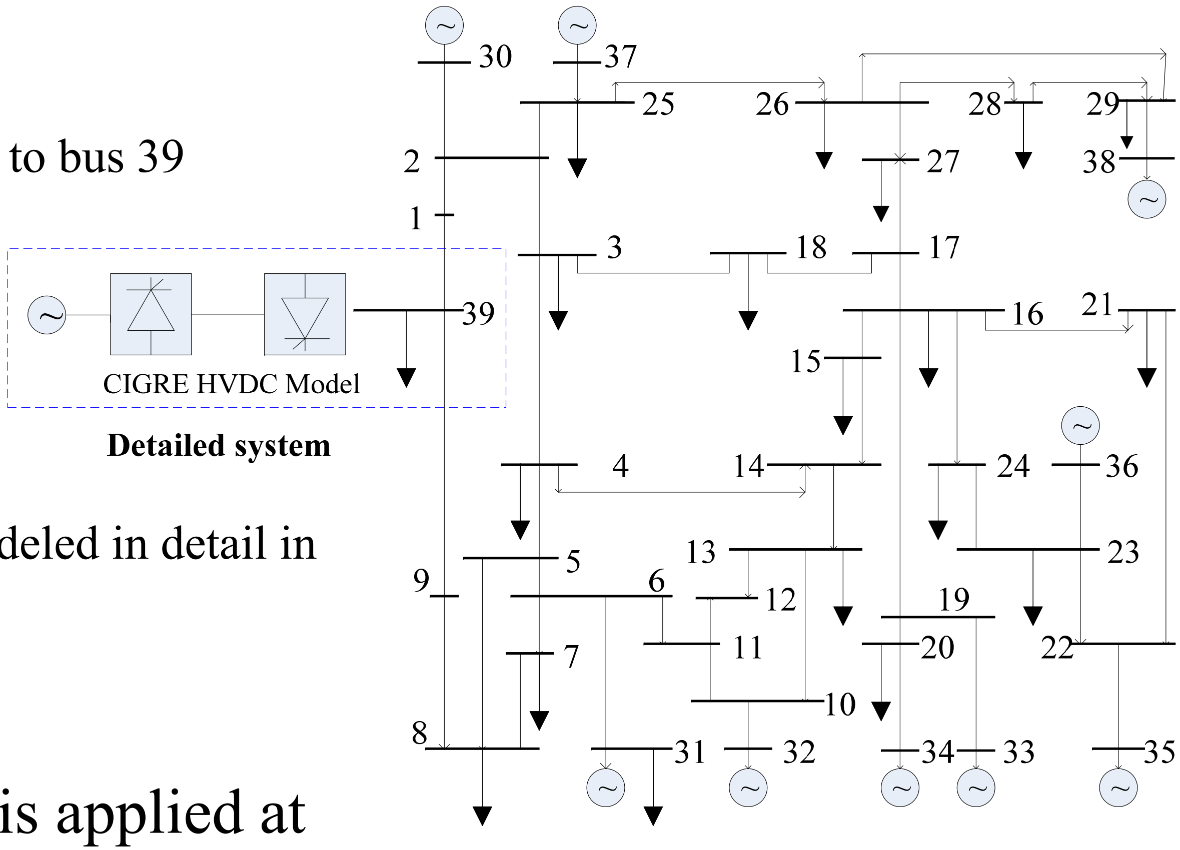
PSLF simulation results using CMPLDW



Application of hybrid simulation to power systems interfaced with a LCC-HVDC system

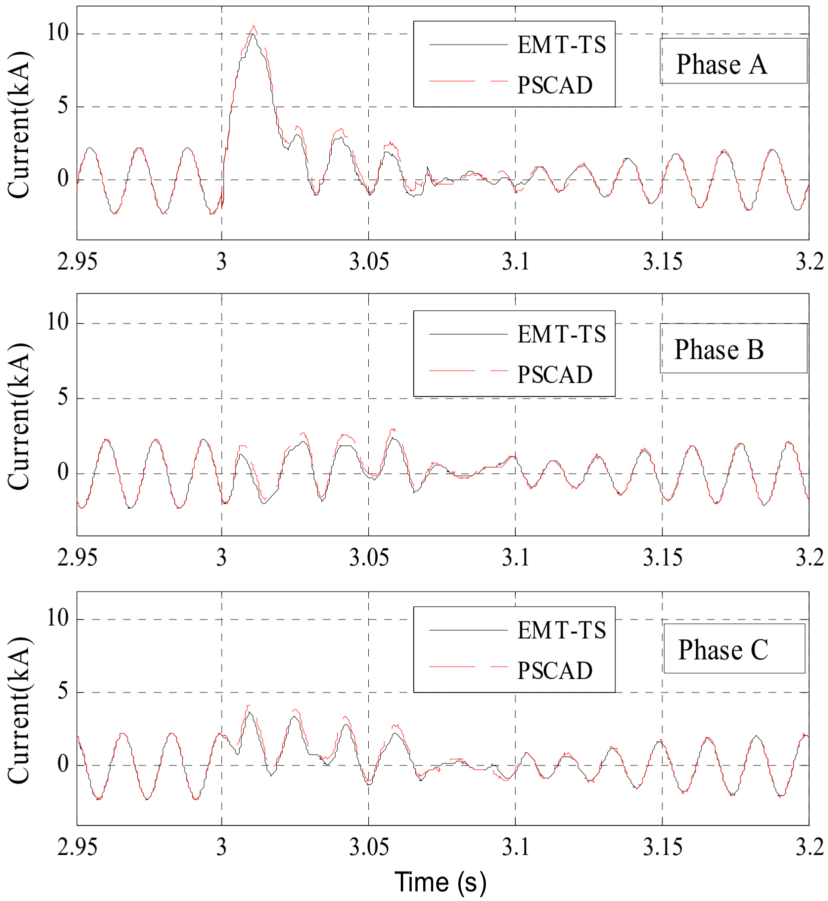
▪ Test case: IEEE 39 Bus system with a LCC HVDC infeed

- HVDC system
  - ➢ CIGRE HVDC model
  - ➢ Rated power: 1000 MW
  - ➢ The inverter is connected to bus 39
- EMT simulation
  - ➢ The whole system time step : 50 μs
- Hybrid simulation
  - ➢ The HVDC system is modeled in detail in PSCAD
  - ➢ EMT time step : 50 μs
  - ➢ TS time step: 5 ms
- Scenario: A SLG fault is applied at bus 39 at 3.0 s, cleared after 4 cycles

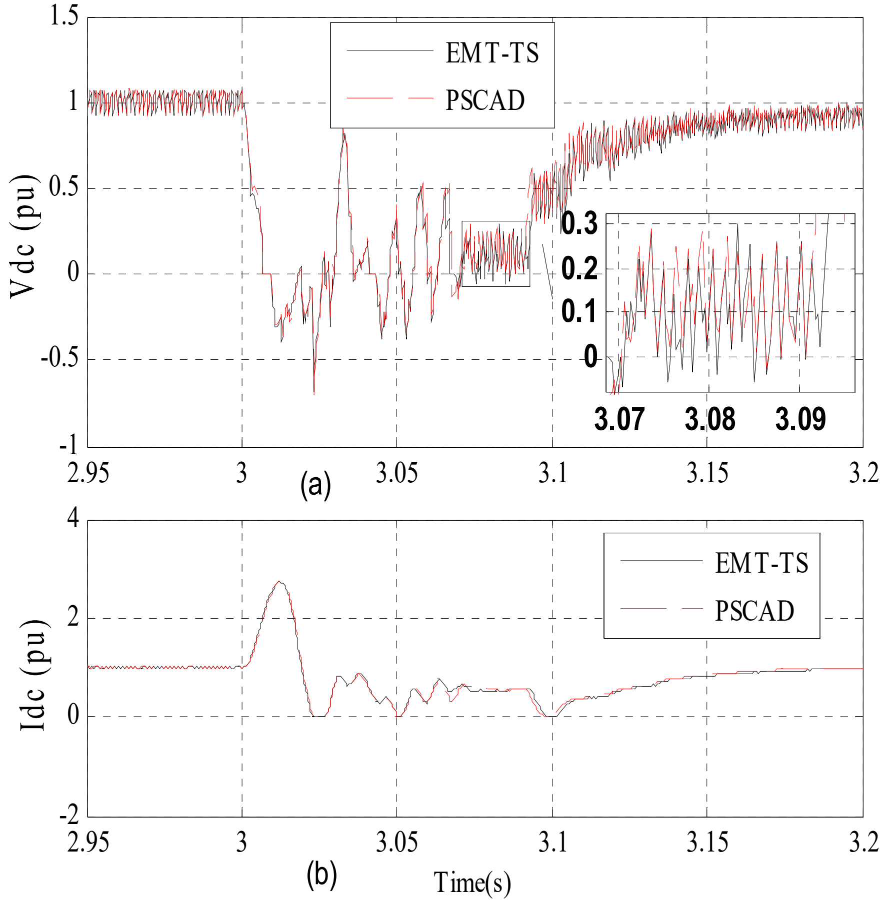


Detailed system

Application of hybrid simulation to power systems interfaced with a LCC-HVDC system

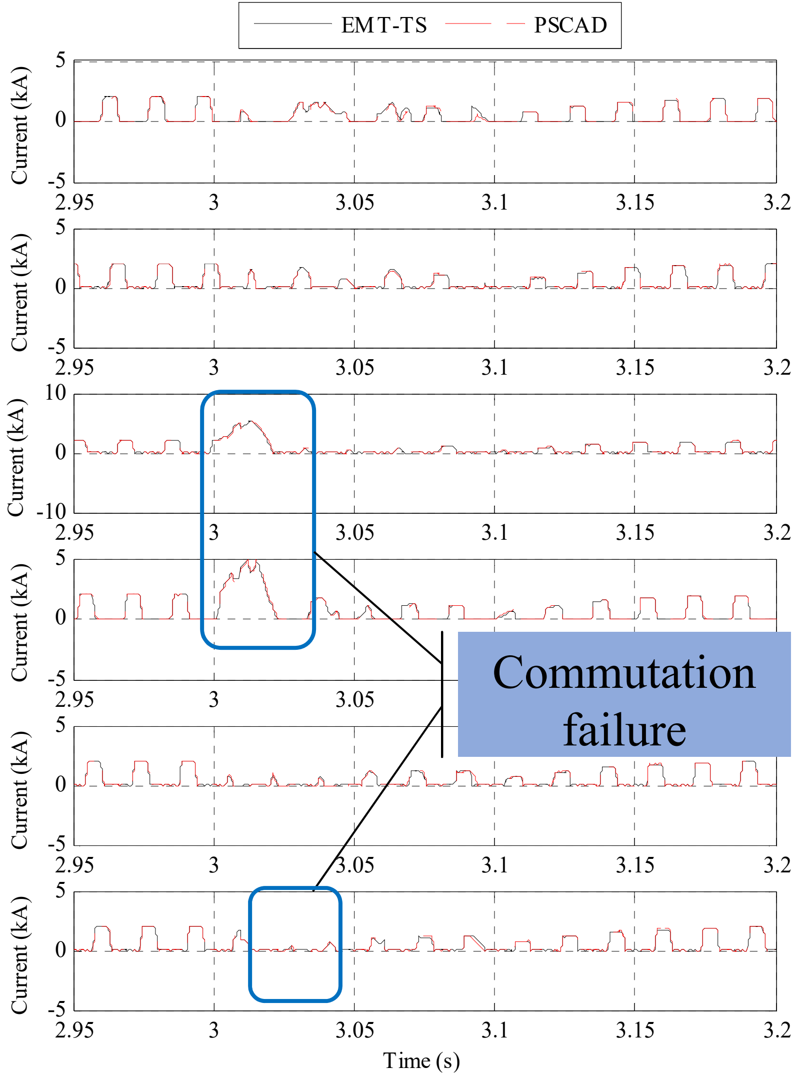


Three phase current flowing into bus 39 from the HVDC inverter



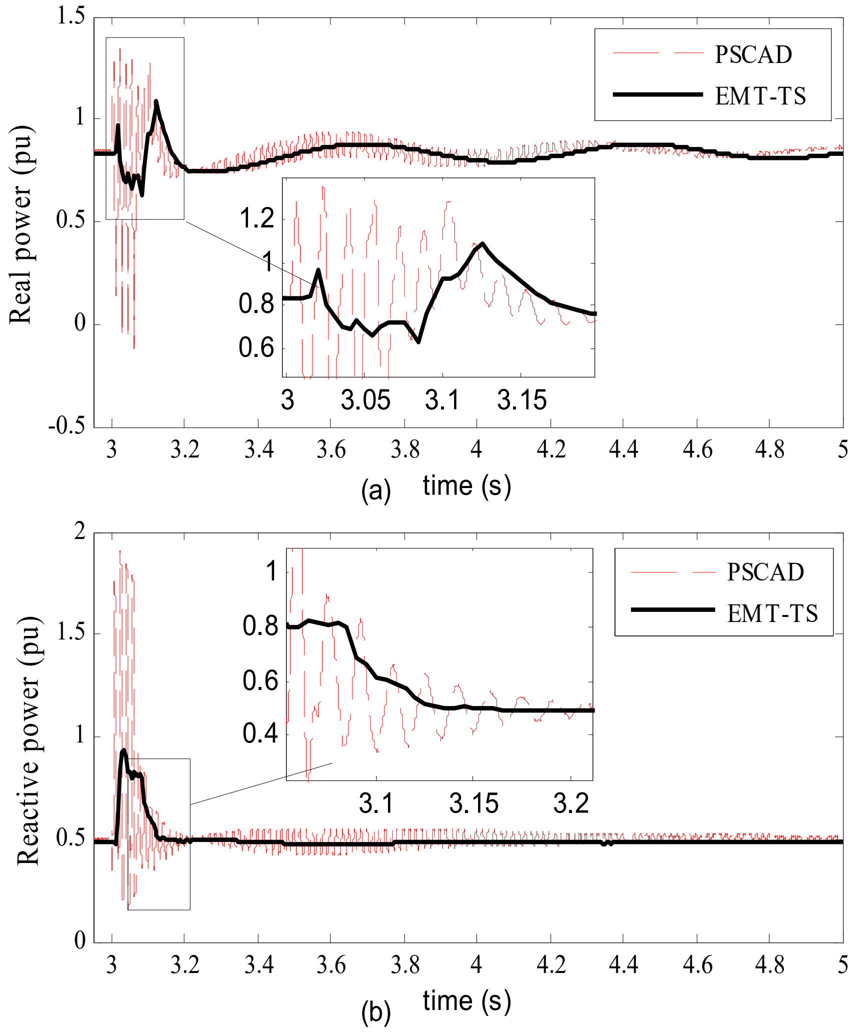
The DC voltage (V_{dc}) and current (I_{dc}) of the HVDC inverter

Application of hybrid simulation to power systems interfaced with a LCC-HVDC system



Commutation failure

The current flows in the 6-pulse bridge of the inverter



Power of the generator at bus 30

Application of hybrid simulation to power systems interfaced with a LCC-HVDC system

Simulation differences with reference to full-blown EMT simulation

Monitored parameters	Average difference/pu	Maximum difference/pu
DC Current of the inverter	0.024	0.224
DC Voltage of the inverter	0.029	0.524
Three phase current into the network at the inverter	0.049	0.351
Three phase voltages of bus 39	0.022	0.155

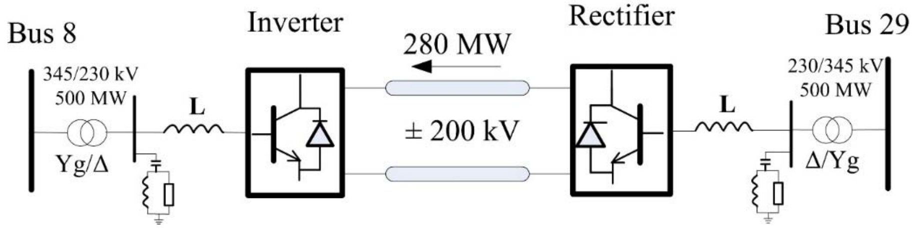
Computational times of hybrid simulation and EMT simulation

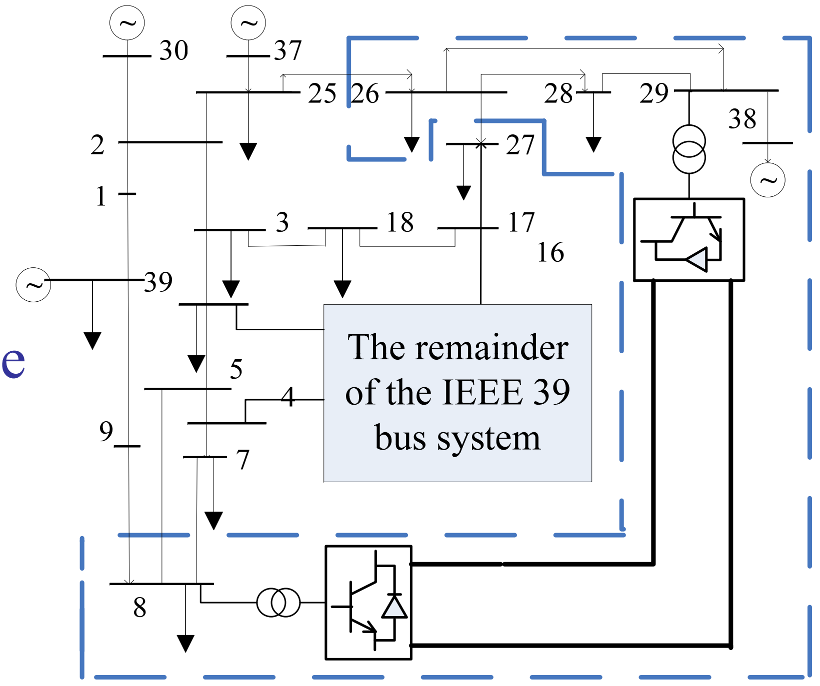
Simulation method	Total computation time*
EMT simulation using PSCAD	352 s
EMT-TS hybrid simulation	81 s

* 5-second simulation

Applied to power systems interfaced with HVDC

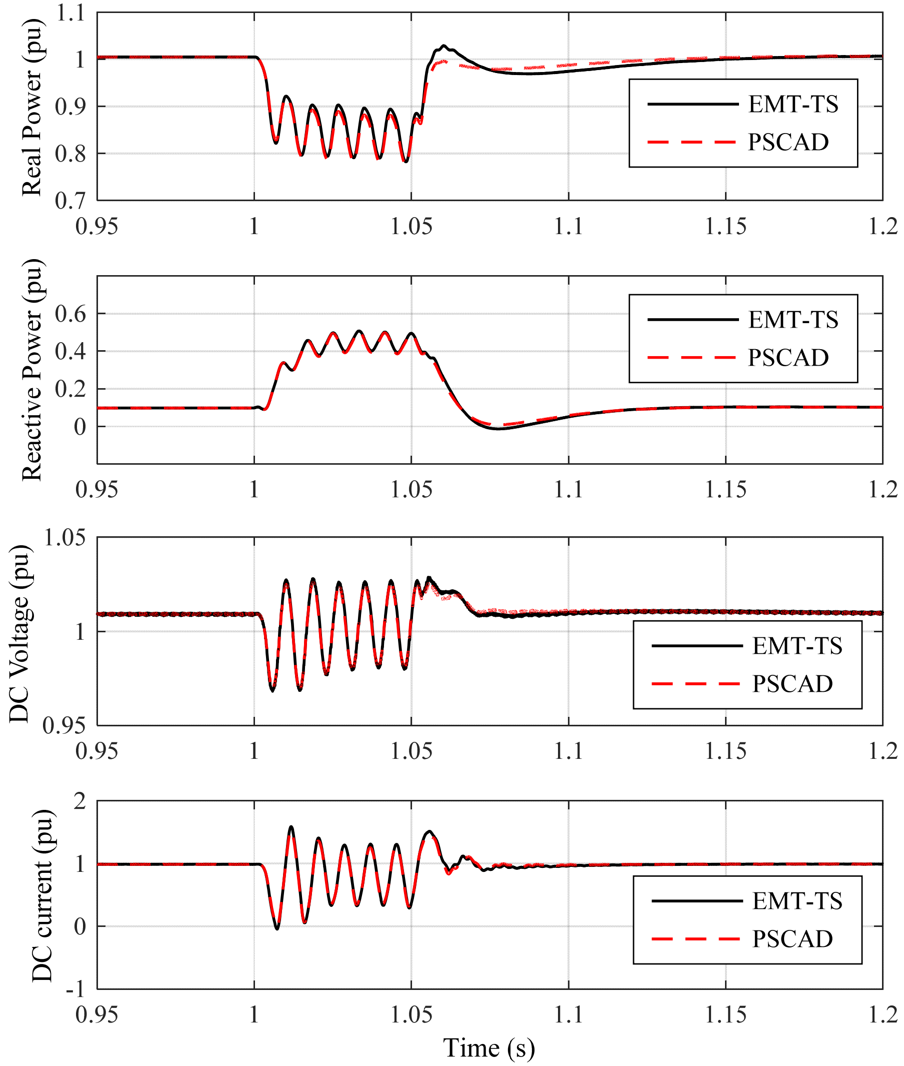
- IEEE 39 bus + VSC-HVDC
- VSC-HVDC
  - Two-level, PWM, decoupled vector control
  - Carrier frequency is 1980 Hz
- EMT simulation using PSCAD
  - The whole system
  - Time step : 5 μs
- Hybrid simulation
  - The part encircled by the dashed line is modeled in detail in PSCAD
  - Boundary buses: Buses 26 and 8
  - EMT time step : 5 μs
  - TS time step: 5 ms





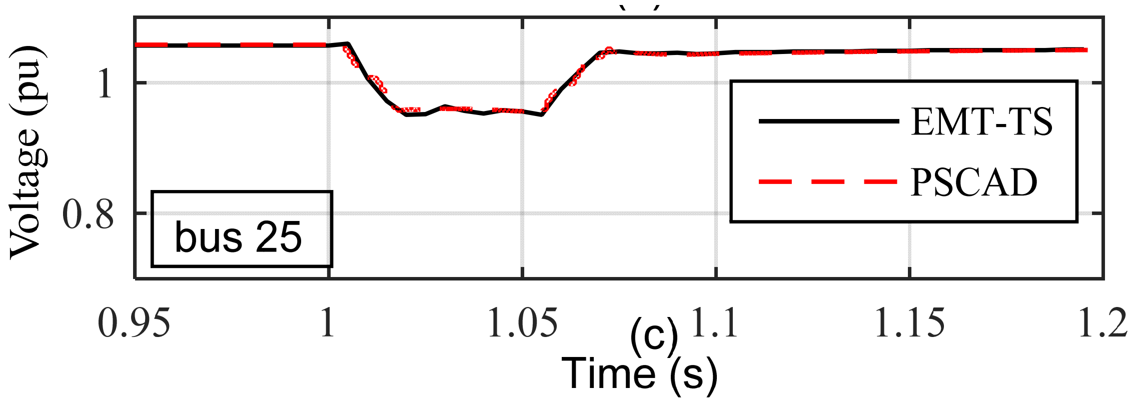
Applied to power systems interfaced with HVDC

- Scenario: a single-line-to-ground(SLG) fault is applied on bus 29 (AC bus of the rectifier) at 1.0 s and cleared after 0.05 s
- Response of VSC-HVDC rectifier to the fault:
  - (a) Real power
  - (b) Reactive power flowing into the rectifier
  - (c) DC voltage
  - (d) DC current



Applied to power systems interfaced with HVDC

- Positive sequence voltage of bus 25 (within the external system)



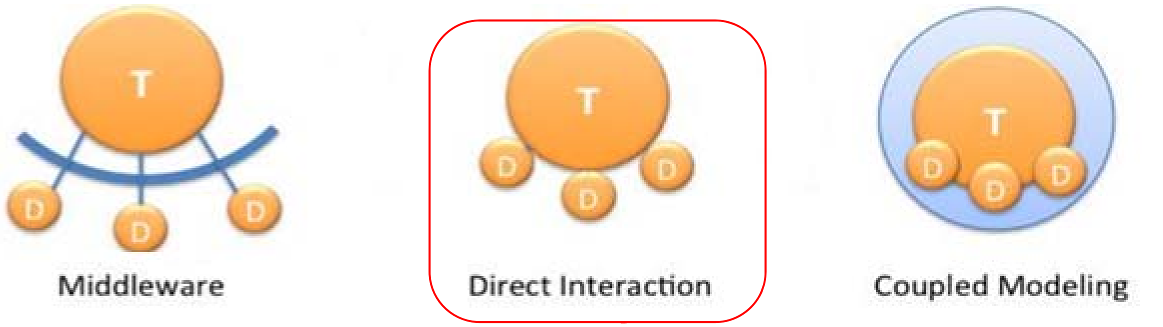
Computation times for a 2-second simulation

Simulation method	Computation time
EMT using PSCAD	1152 s
Hybrid simulation	164 s

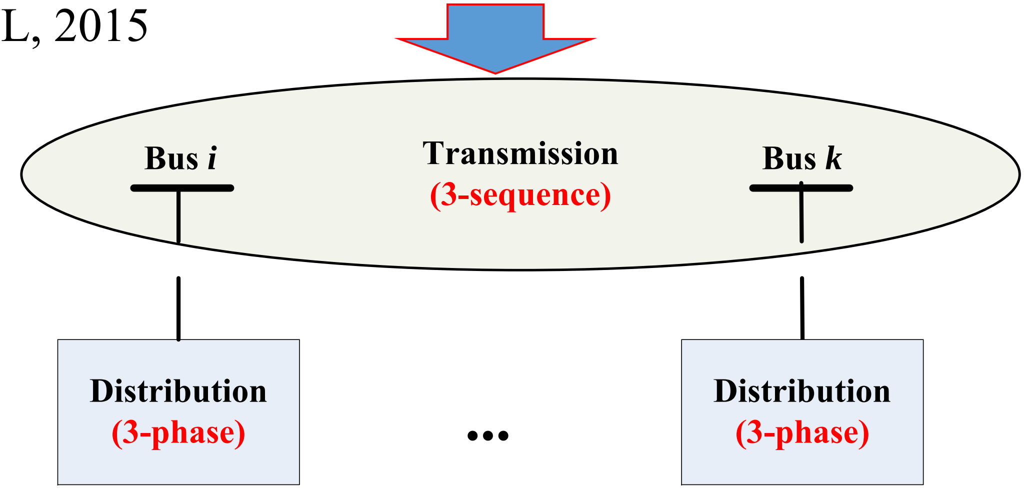
7 times

Integrated T&D system modeling

- Physically:
  - Distribution systems : in general, 3-phase unbalanced
  - Transmission system: 3-phase reasonably balanced
  - Conditions at boundary between T&D: 1) reasonably balanced under normal operating conditions; 2) could be significantly unbalanced during and post contingency
- Modeling



Source: Jason Fuller, PNNL, 2015


Bus *i*

Transmission
(3-sequence)

Bus *k*

Distribution
(3-phase)

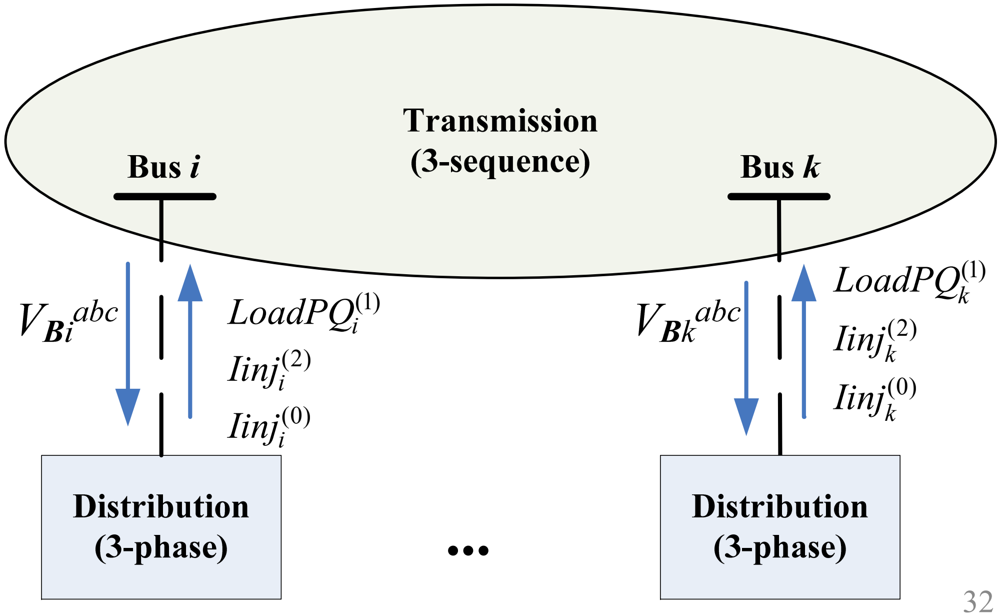
…

Distribution
(3-phase)

Integrated T&D power flow (TDPF)

- **Master-slave splitting method**
  - Iteratively solve power flow for the transmission and the distribution systems
- **Transmission system power flow**
  - Positive sequence: conventional power flow
  - Negative- and zero- sequence: network solution (I=YV)
- **Distribution system power flow**
  - 3-phase power flow: backward/forward sweep algorithm

Boundary data exchange between T&D in TDPF algorithm



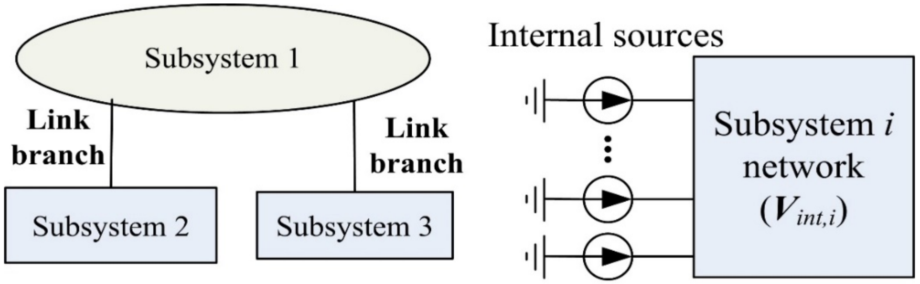
T&D dynamic simulation based on the Multi-Area Thévenin Equivalent (MATE) approach

- Partitioned dynamic simulation method: used in PSS/E and PSLF

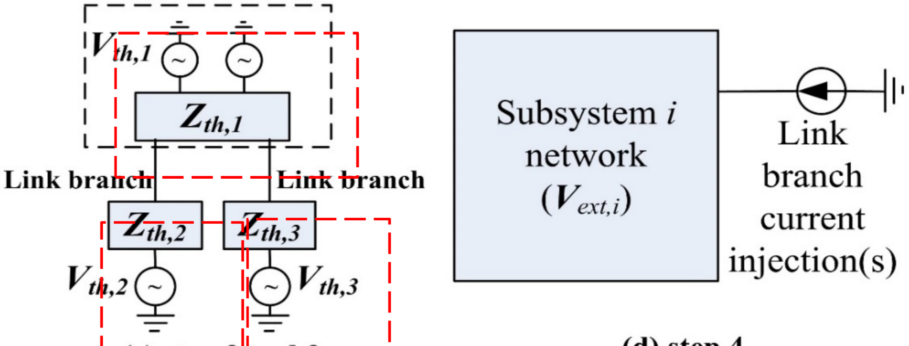
$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{V})$ → Integration step

$\boldsymbol{I}(\boldsymbol{x}, \boldsymbol{V}) = \boldsymbol{YV}$ → Network Solution step

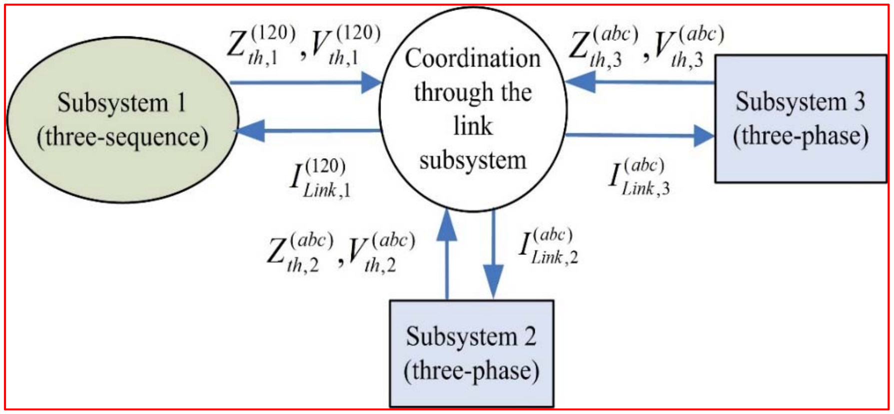
- Main challenges lie in the network solution step
- The MATE [4] approach is employed in the network solution step



(a) A simple integrated T&D system **(b) step 1**



(e) step 2 and 3 **(d) step 4**

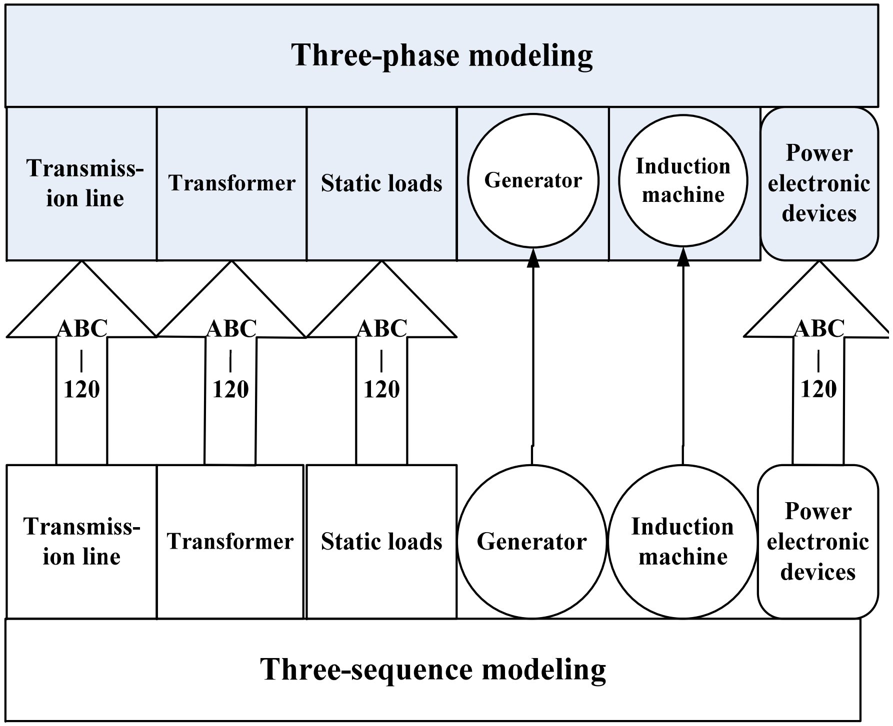


Reconcile the subsystem solution results at the link subsystem level at steps 2 and 3

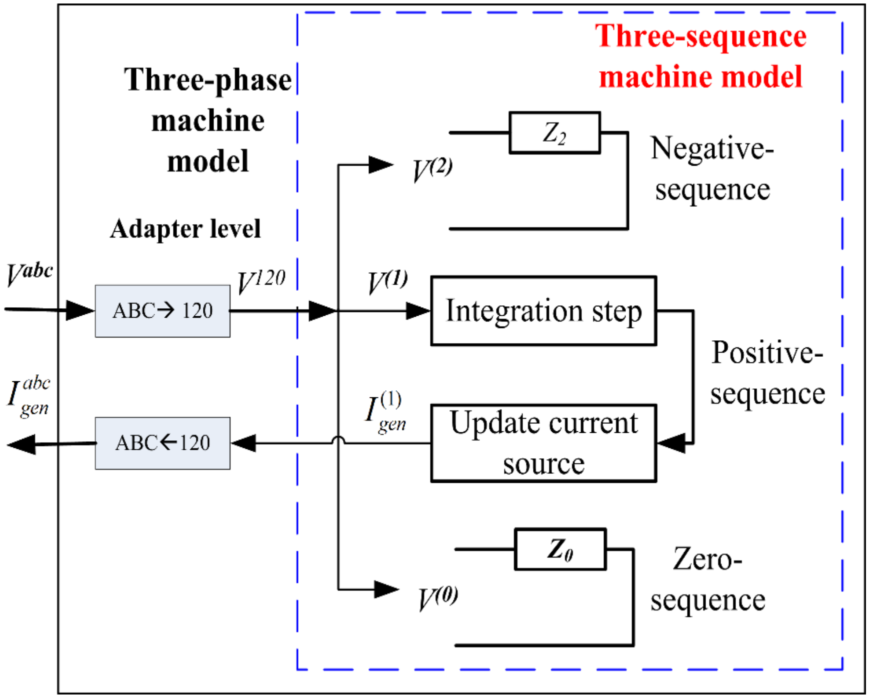
[4] Martí, José R., Luis R. Linares, Jorge A. Hollman, and Fernando A. Moreira. "OVNI: Integrated software/hardware solution for real-time simulation of large power systems." In Proceedings of the PSCC, vol. 2. 2002.

Three-phase dynamic simulation

- Developed by extending existing three-sequence system modeling and TS simulation
  - **Modeling**: Inheritance and the adapter design pattern
  - **Simulation procedure**: the same as the positive-sequence TS except for the three-phase oriented network solution

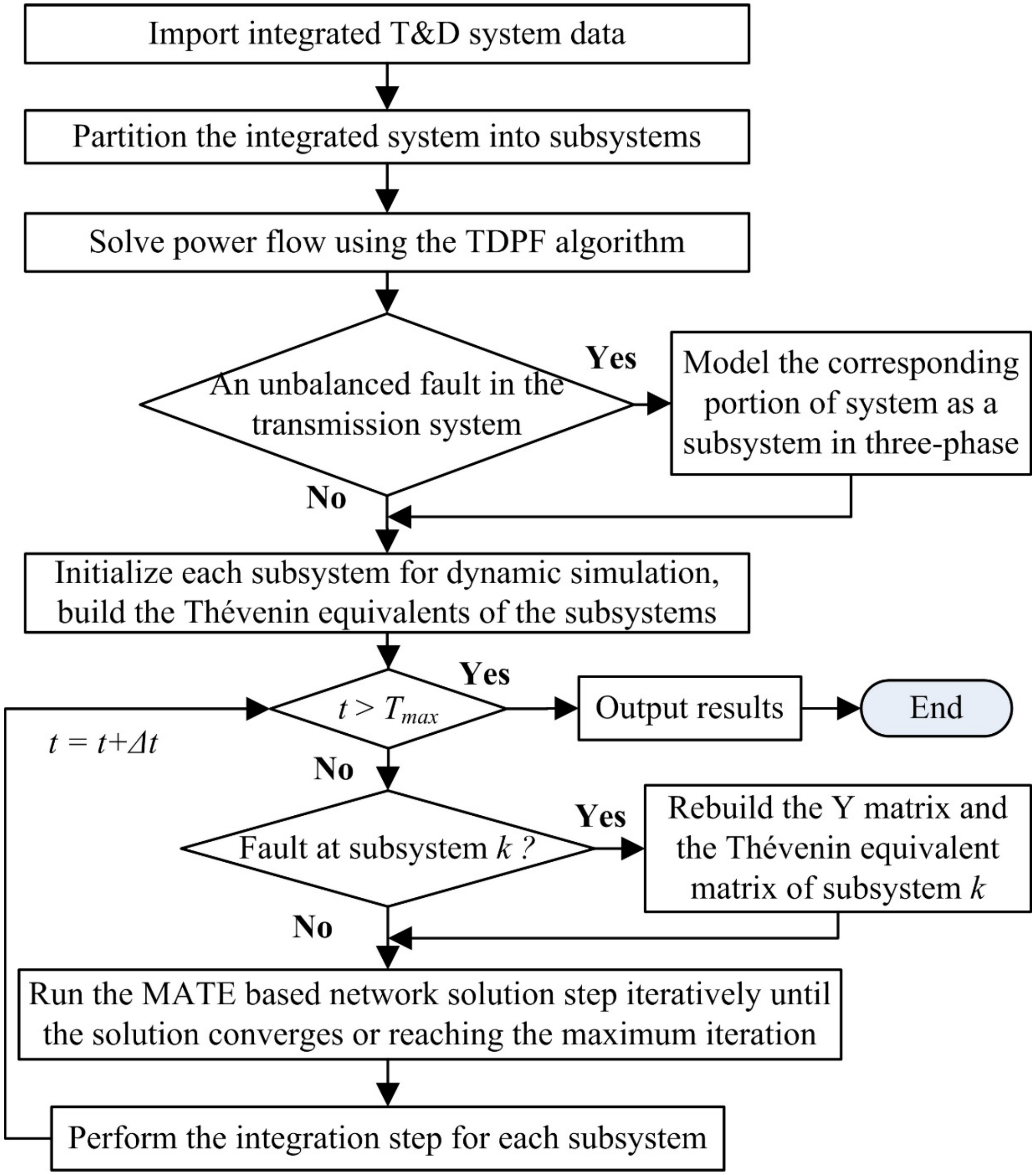


Transformation from three-sequence modeling to three-phase modeling



Development of three-phase machine dynamic model based on the corresponding three-sequence model using the adapter pattern

Flowchart of the integrated T&D dynamic simulation



Import integrated T&D system data

Partition the integrated system into subsystems

Solve power flow using the TDPF algorithm

An unbalanced fault in the transmission system

Yes

Model the corresponding portion of system as a subsystem in three-phase

No

Initialize each subsystem for dynamic simulation, build the Thévenin equivalents of the subsystems

$t > T_{max}$

Yes

Output results

End

$t = t+\Delta t$

No

Fault at subsystem *k* ?

Yes

Rebuild the Y matrix and the Thévenin equivalent matrix of subsystem *k*

No

Run the MATE based network solution step iteratively until the solution converges or reaching the maximum iteration

Perform the integration step for each subsystem

Integrated T&D power flow

Consider unbalanced fault(s) in transmission system

The MATE approach based T&D network solution

Conclusions

- A normally cleared SLG fault could result in A/C motor stalling and propagation to the non-faulted phase, depending on the connection of step-down transformers
- A/C compressor motors could take a much longer time than 2-5 cycles (typical T_{stall} value) to stall when the equivalent impedances between the fault point and A/C motors are large.
- The point-on-wave effects deserve more attention as different POWs could lead to significantly different results in terms of A/C motor stalling.
- OpenHybridSim, the first open-source tool for EMT and phasor domain hybrid simulation, has been developed and is available from: https://github.com/OpenHybridSim
- A modeling framework and power flow and dynamic simulation algorithms for integrated T&D systems have been developed

Publication

Qiuhua Huang, V. Vittal, "Application of Electromagnetic Transient-Transient Stability Hybrid Simulation to FIDVR Study," IEEE Transactions on Power Systems, Vol. 31, No. 4, pp. 2634-2646, July 2016.

Questions?

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