Hybrid Time Domain Simulation: Application to Fault Induced Delayed Voltage Recovery (FIDVR)

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Presentation background

- The work presented in this webinar is a part of the work being done in PSERC project S-58 at ASU
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- The graduate student at ASU is Qiuhua Huang and the collaborator is Dr. John Undrill

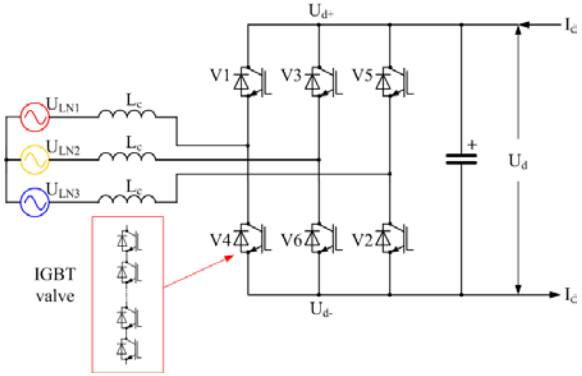
Outline

1. Introduction
2. Part -1: OpenHybridSim: A new hybrid simulation platform
3. Part -2: Application to FIDVR study
4. Conclusions

Introduction: Background

- An increasing demand for simulating a portion of a system in detail with a very small time step and capturing point on wave detail while preserving the effects on the rest of the system
  - Power electronic converter based renewable energy integration
  - HV AC/DC systems
  - Residential air conditioners, variable frequency drive(VFD) and other power electronics based loads
  - Representing other needed detail at the distribution level

PV Farm



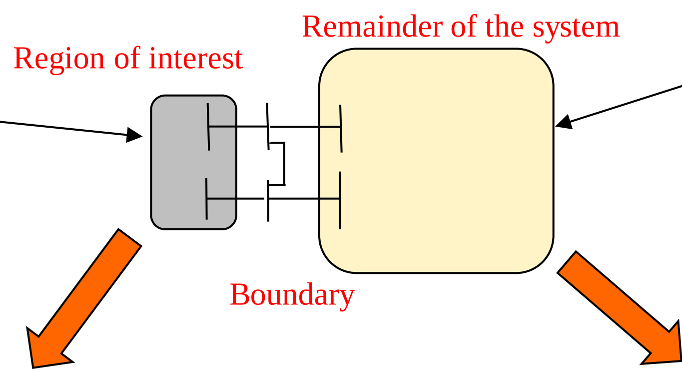
VSC-HVDC

air conditioner

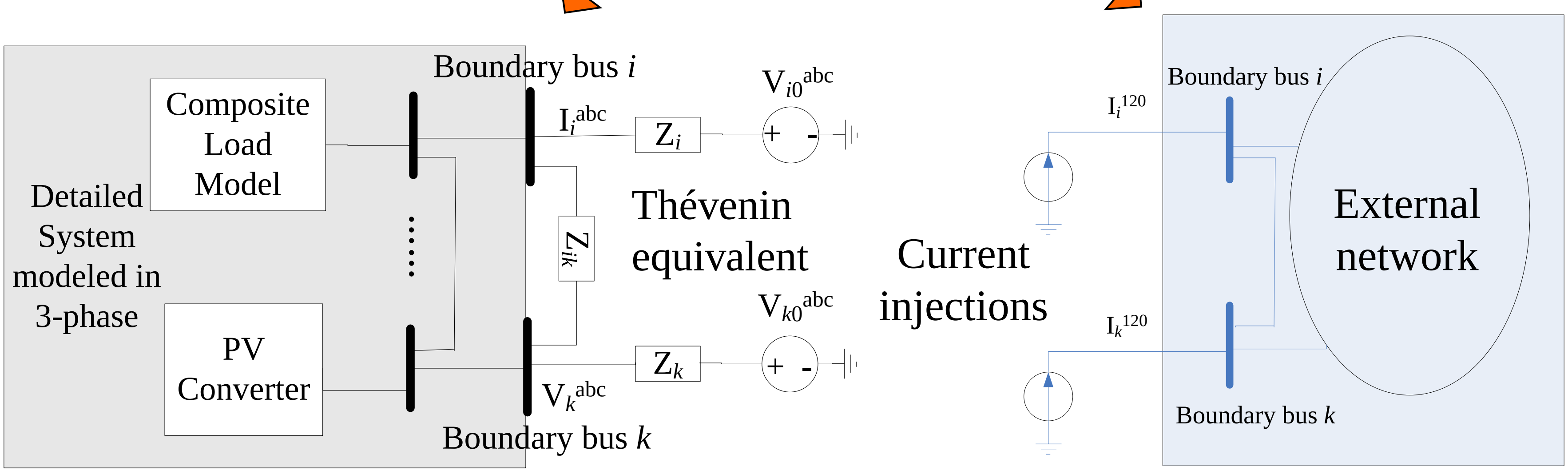
Introduction: Hybrid simulation

Involves electromagnetic transient (EMT)- electro-mechanical transient stability(TS) hybrid simulation

- Instantaneous variable model
- EMT simulator



- Sequence, phasor model
- TS simulator



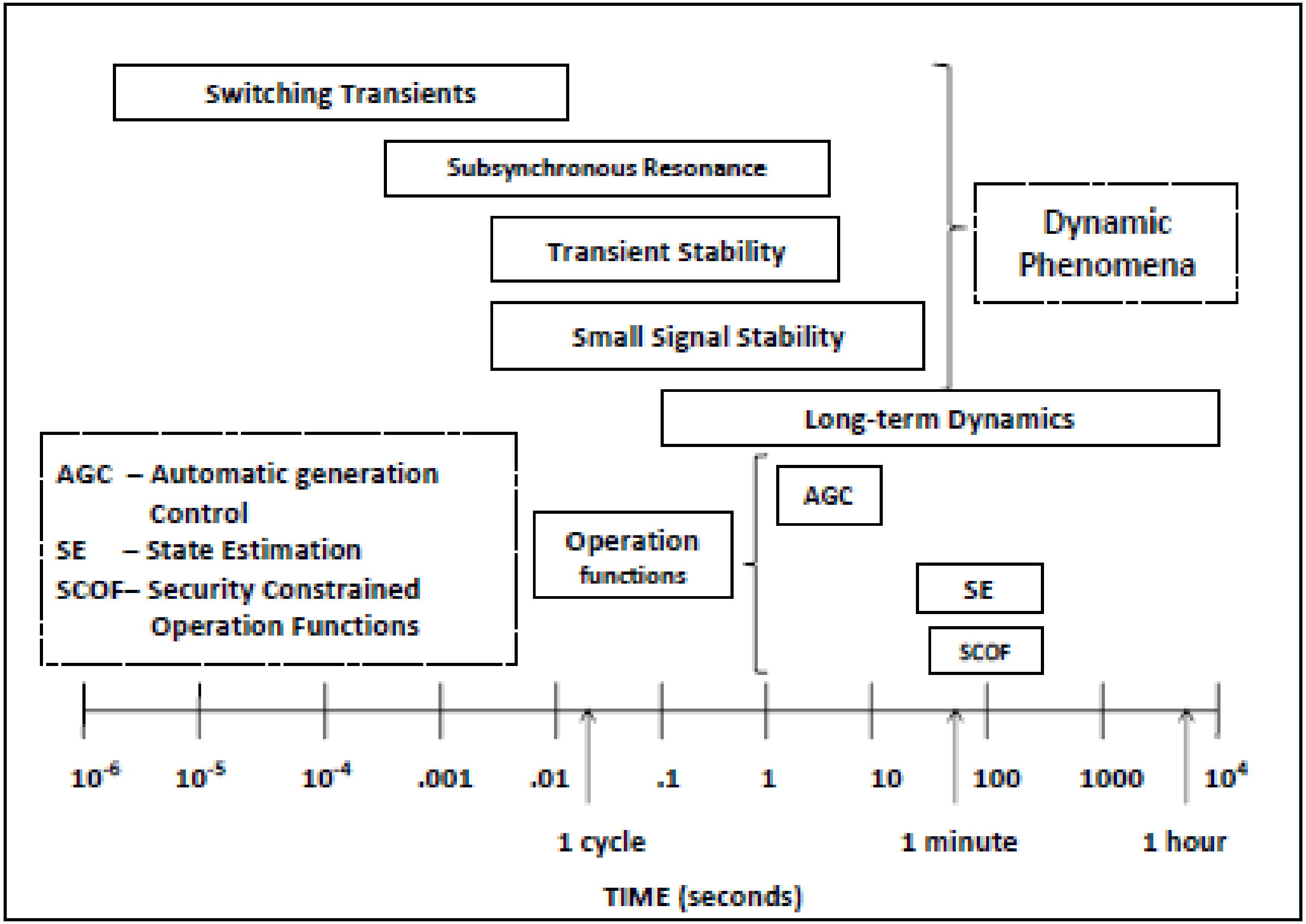
Detailed system modeled in an EMT Simulator

External system modeled in a TS Simulator

Introduction: Hybrid simulation

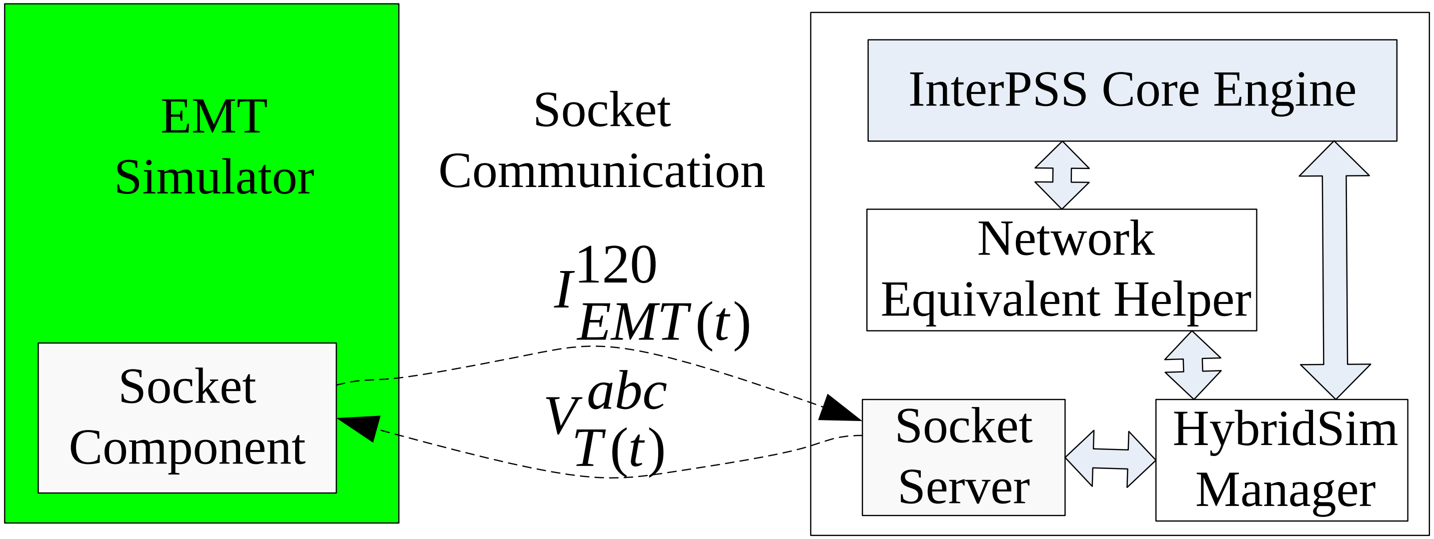
- Key requirements for a successful hybrid simulation platform
  - Architecture : embedded/decoupled
  - Interaction: communication + protocol
  - Equivalent models of both detailed and external system
  - Preparation and initialization of both detailed and external system
- Synopsis of literature review of EMT-TS hybrid simulation
  - Lab research or proof-of-concept type
  - The architecture design is not flexible and the simulators are limited to run on one computer
  - Targeted mainly for three-phase balanced applications
  - No publically available tool for hybrid simulation

Time scale of transient phenomena



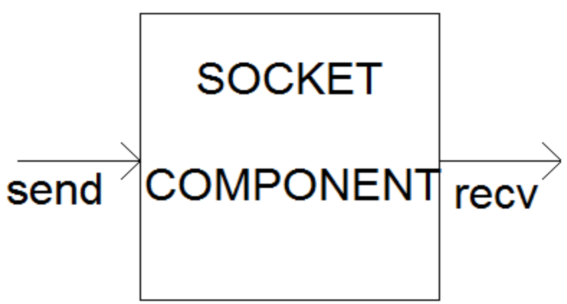
OpenHybridSim: A new hybrid simulation tool

- Overall design
  - **Loosely decoupled** architecture
  - **Socket communication**
  - **InterPSS**, an open source power system simulator
  - A **generic interface** to an EMT simulator, e.g., **PSCAD**, Maltab/SimPowerSystems

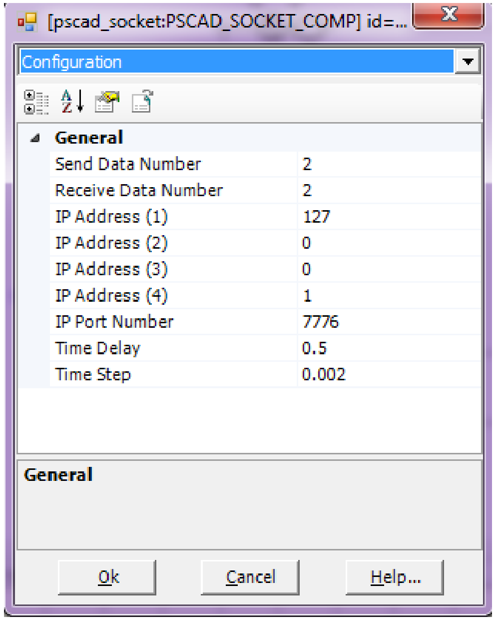


Socket based communication framework

- TCP/IP socket based communication framework
  - Enables decoupling of the EMT and TS simulators
  - Supports application environment
    - Single computer
    - Local area network(LAN)
    - Internet
  - Socket components in PSCAD and Matlab/SimPowerSystems are developed for interfacing



Socket component in PSCAD



External system equivalent for EMT simulation

- Supports both 1-phase and 3-phase equivalents
  - 1-phase: mainly for three-phase balanced applications
  - 3-phase: any type of fault within the detailed system
  - Facilitates simulation of unsymmetrical faults
- 3-phase Thévenin equivalent of external system based on a 3-sequence network model
  - The given base case is modeled using 3-sequences
  - Details are provided on the next slide

Three-phase Thévenin equivalents of the external system

- Step 1: Calculate 3-sequence Norton equivalents

$$I_N^{120} = Y_N^{120} V^{120} - I_{EMT}^{120}$$

- Step 2: 3-sequence to 3-phase transformation for each boundary bus

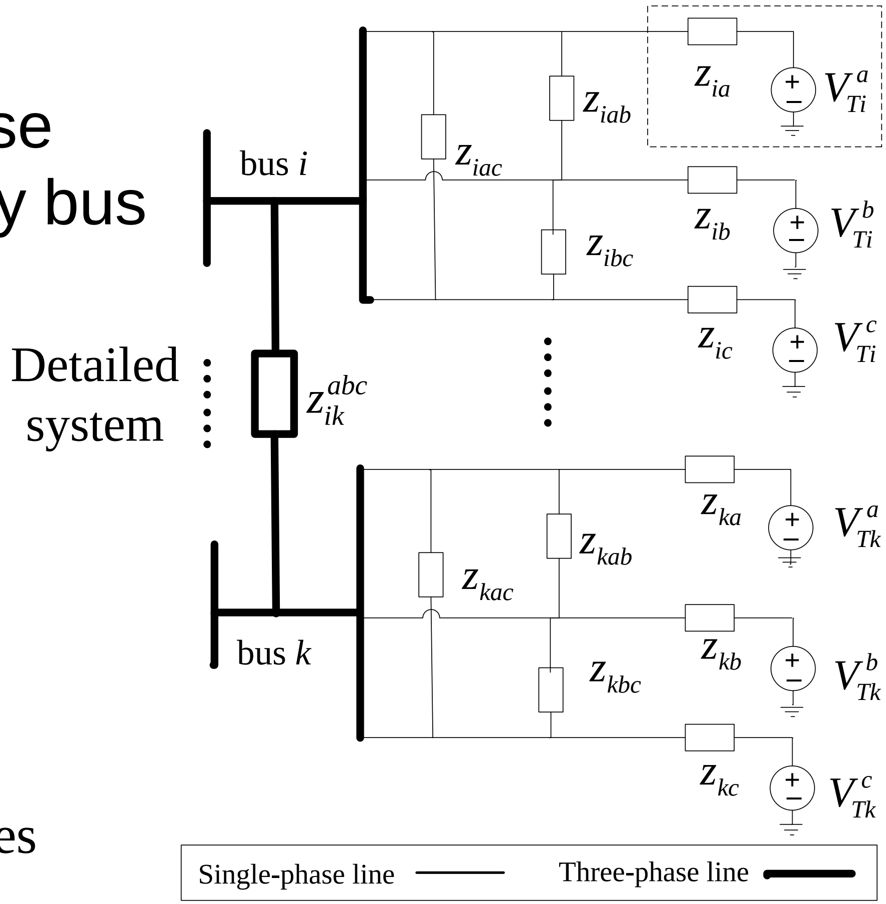
$$I_{Ni}^{abc} = S I_{Ni}^{120} \qquad y_i^{abc} = S y_i^{120} S^{-1}$$

where S is the transformation matrix, y_i^{120} is the bus primitive admittance

- Step 3: 1-phase Norton to Thévenin for each boundary bus

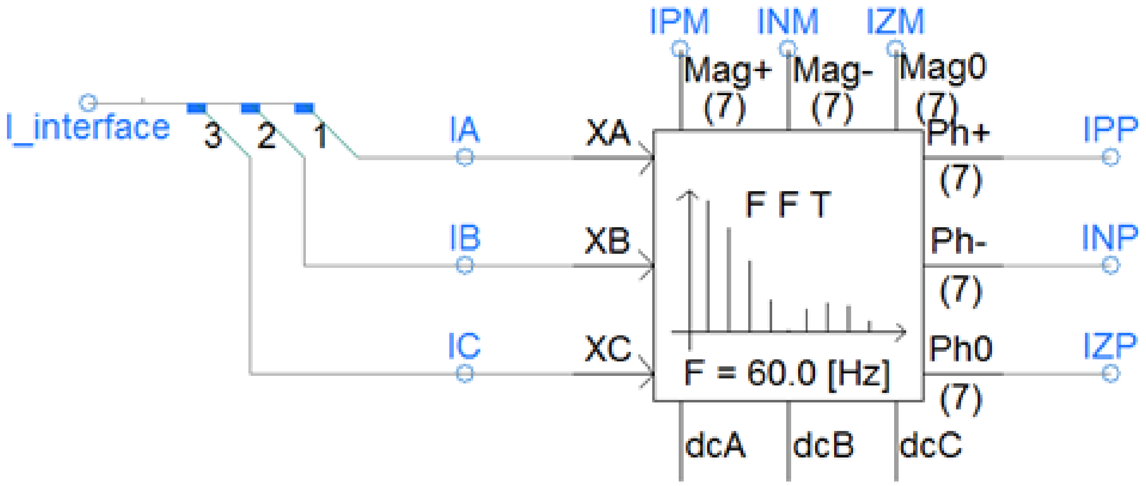
$$V_{Ti}^{p} = I_{Ni}^{p} / y_{ip} \qquad z_{ip} = 1 / y_{ip}$$

where p stands for one of the three phases



Detailed system represented by sequence current sources in TS simulation

- ➢ Need to extract three-sequence, fundamental frequency currents from instantaneous, waveform values
- ➢ Use well-established FFT algorithm
  - PSCAD provides an FFT component
- ➢ Directly used in the network solution (I=YV) in TS simulation



FFT Component in PSCAD

Three-sequence based TS simulation for simulating unsymmetrical faults

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

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

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

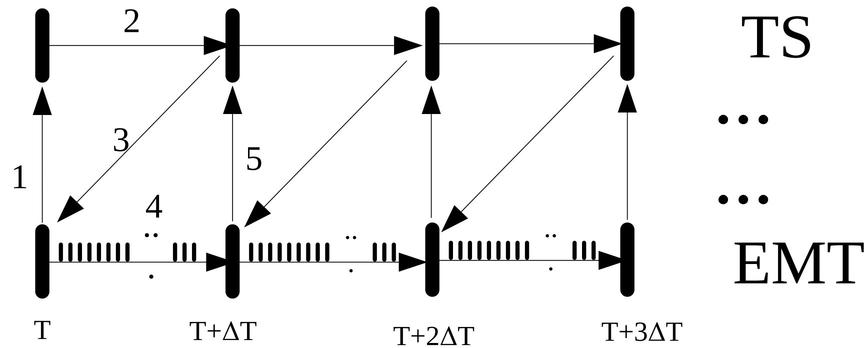
$$0 = g_0(y^{(0)}_{(t+\Delta T)}, I^{(0)}_{EMT(t)})$$

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

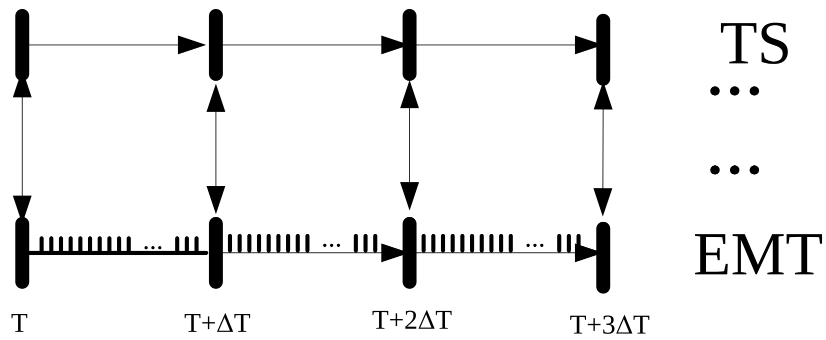
$V^{(0)}_{TS(t+\Delta T)}$

The interaction protocols between two simulators

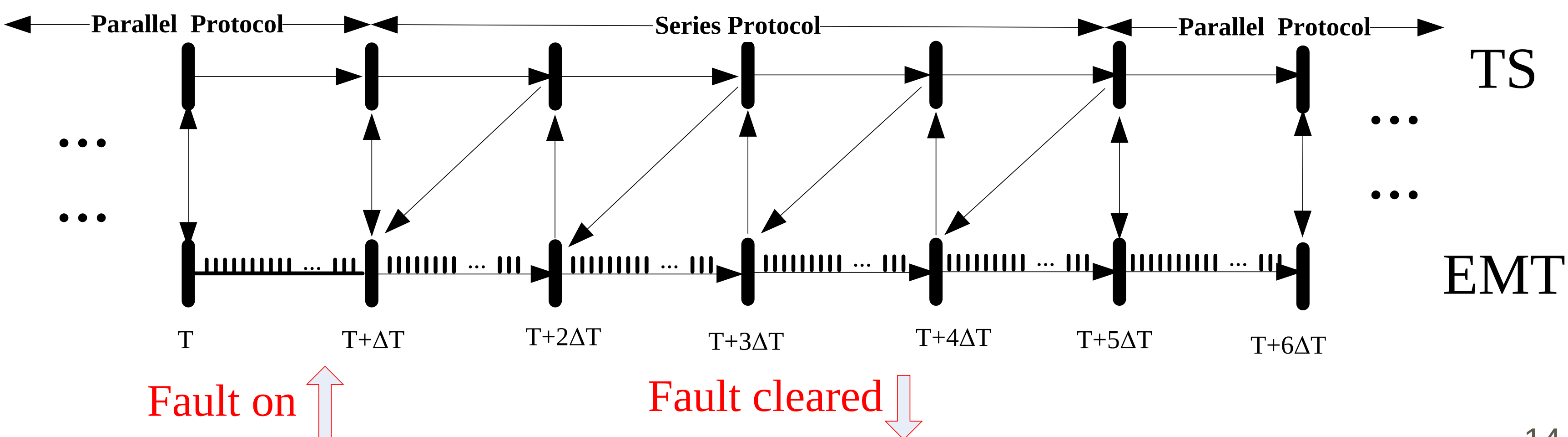
(a) series



(b) parallel

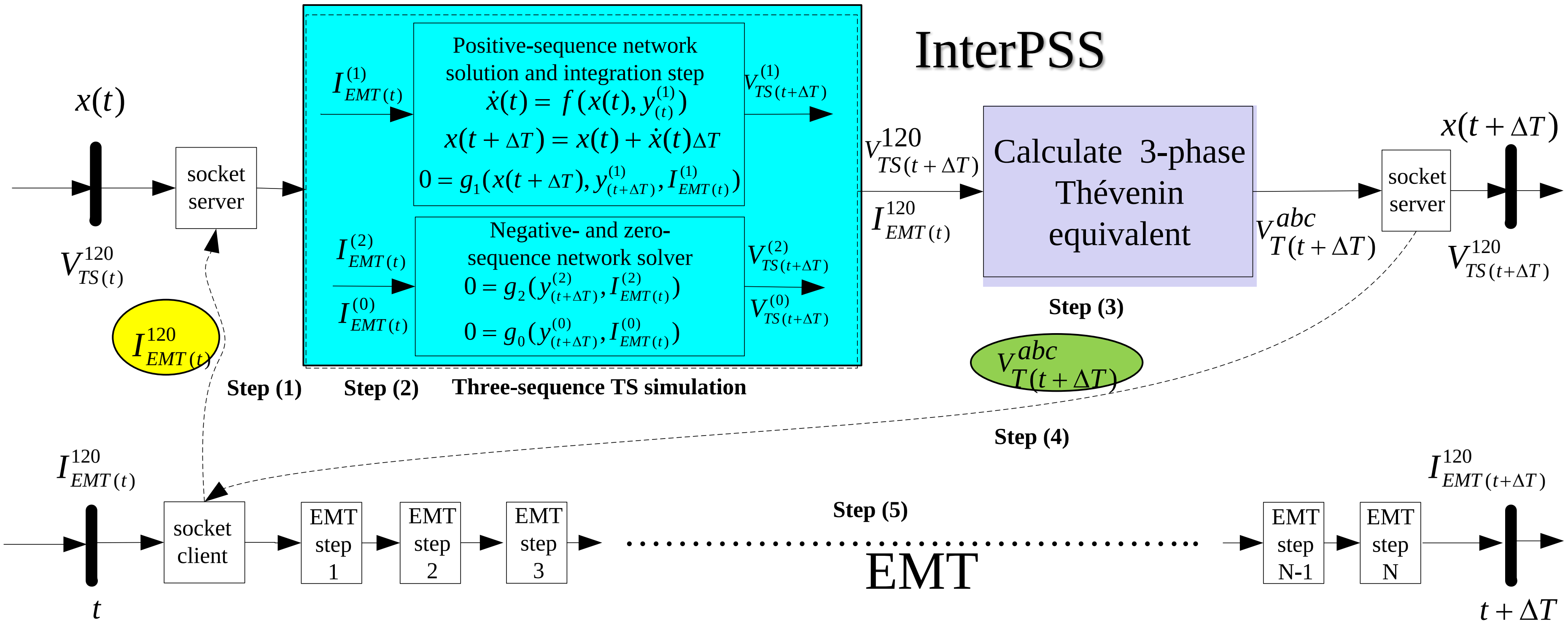


★ (c) combined



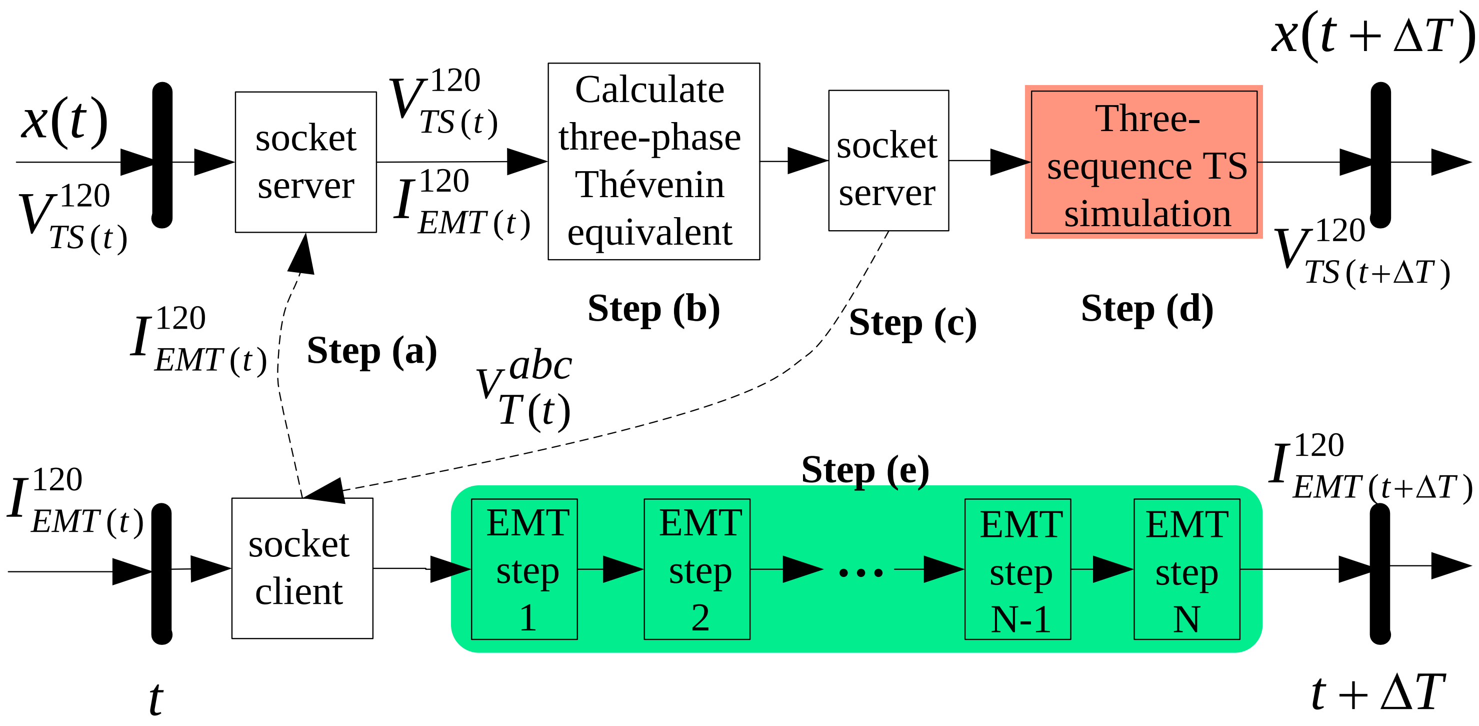
Implementation with the series type protocol

- The series protocol
  - Use the updated equivalent data for simulation with each simulator
  - Performance issue: One simulator has to remain idle when the other is running the simulation



Implementation with the parallel type protocol

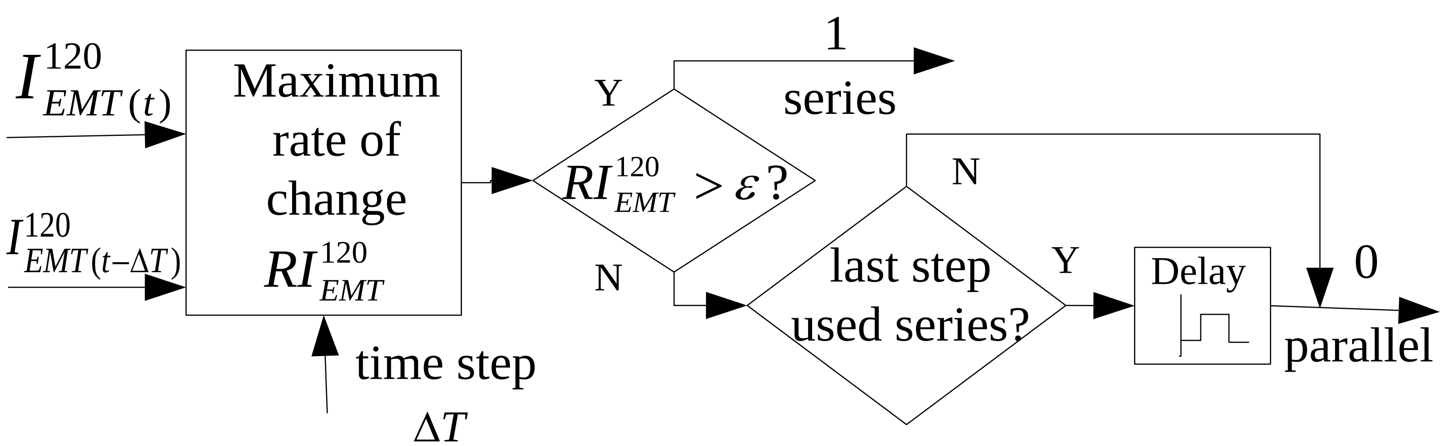
- The parallel interaction protocol
  - Steps (d) and (e) run simultaneously
  - May cause significant interfacing errors under fast transient conditions, as the Thévenin equivalent data is one-step delayed



Automatic protocol switching algorithm

- Automatically switch interaction protocol based on the system conditions, reflected by the maximum rate of change of sequence current injections

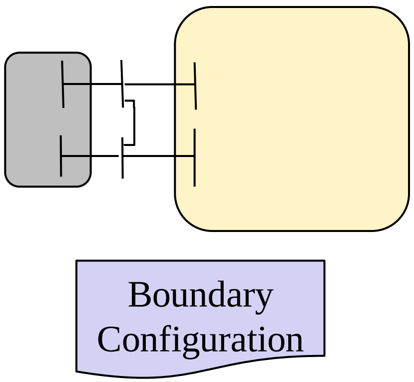
$$RI_{EMT(t)}^{120} = \max_{i}\left(\max_{p\in(1,2,0)}\left(\left|\frac{I_{EMT(i,t)}^{(p)} - I_{EMT(i,t-\Delta T)}^{(p)}}{I_{EMT(i,t-\Delta T)}^{(1)}}\right|\right)\right) / \Delta T$$



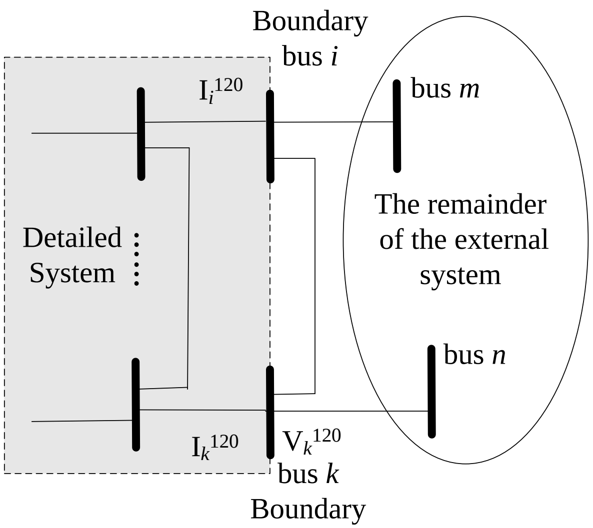
Logic of the protocol switching algorithm

Automatic creation and initialization of the external network

Base case

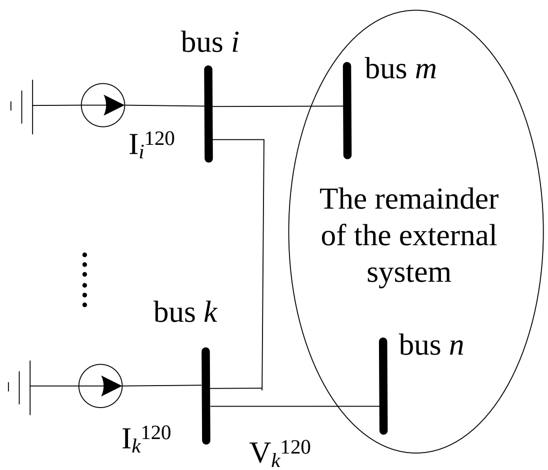


Depth first search(DFS) to identify detailed system



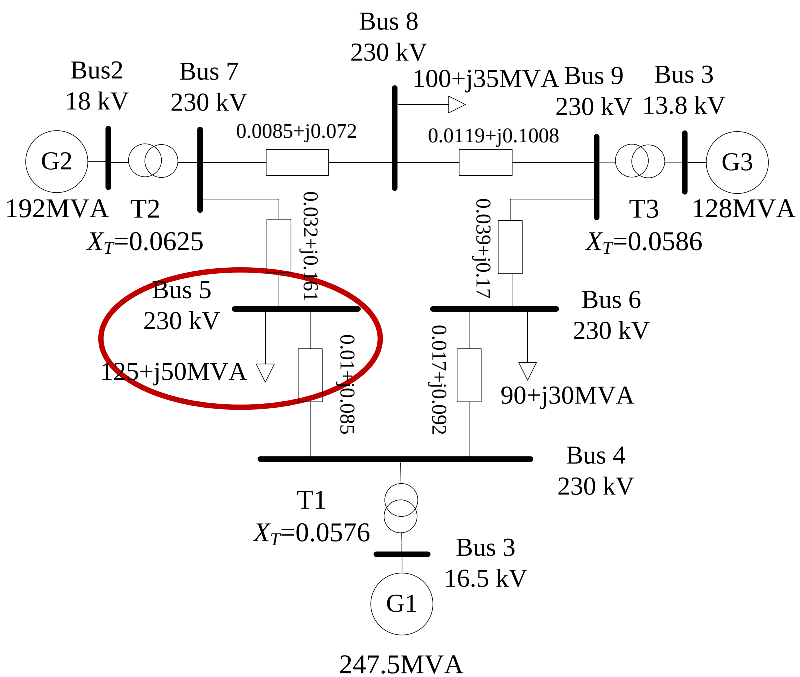
Power flow

1) Set buses and branches within the detailed system out of service
2) initialize the external system



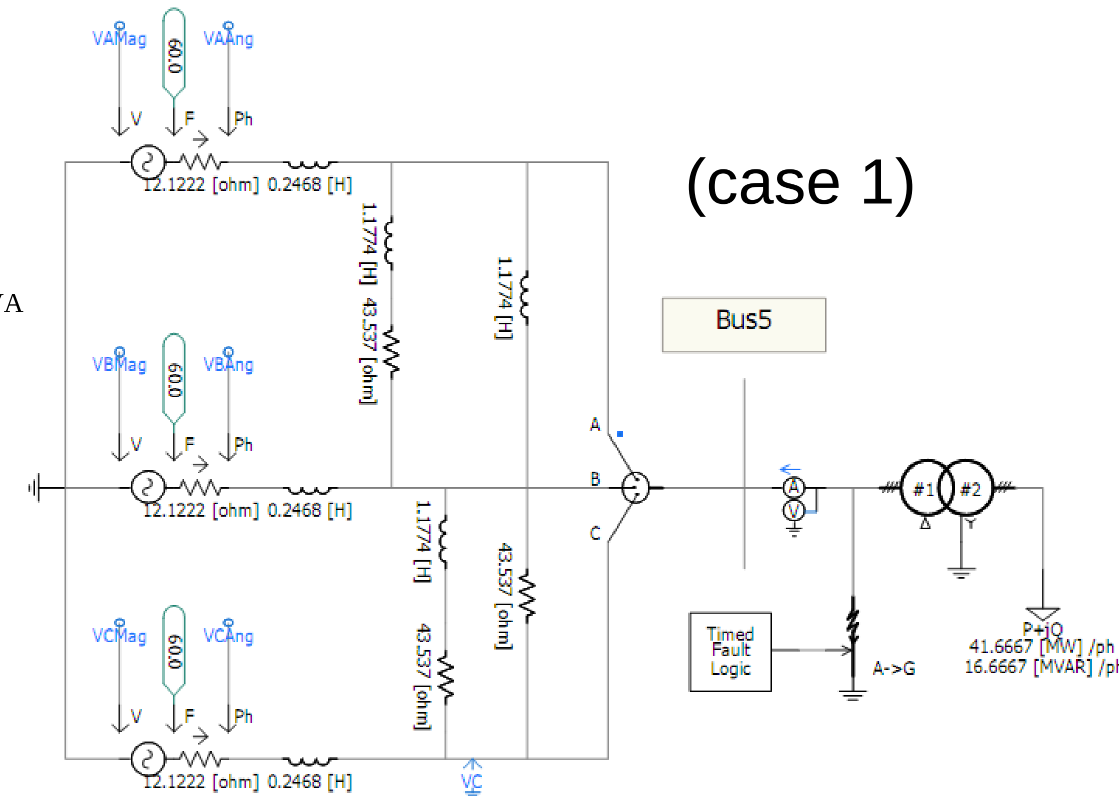
Testing of the developed platform

- Test system



The IEEE 9 Bus system

(case 1)



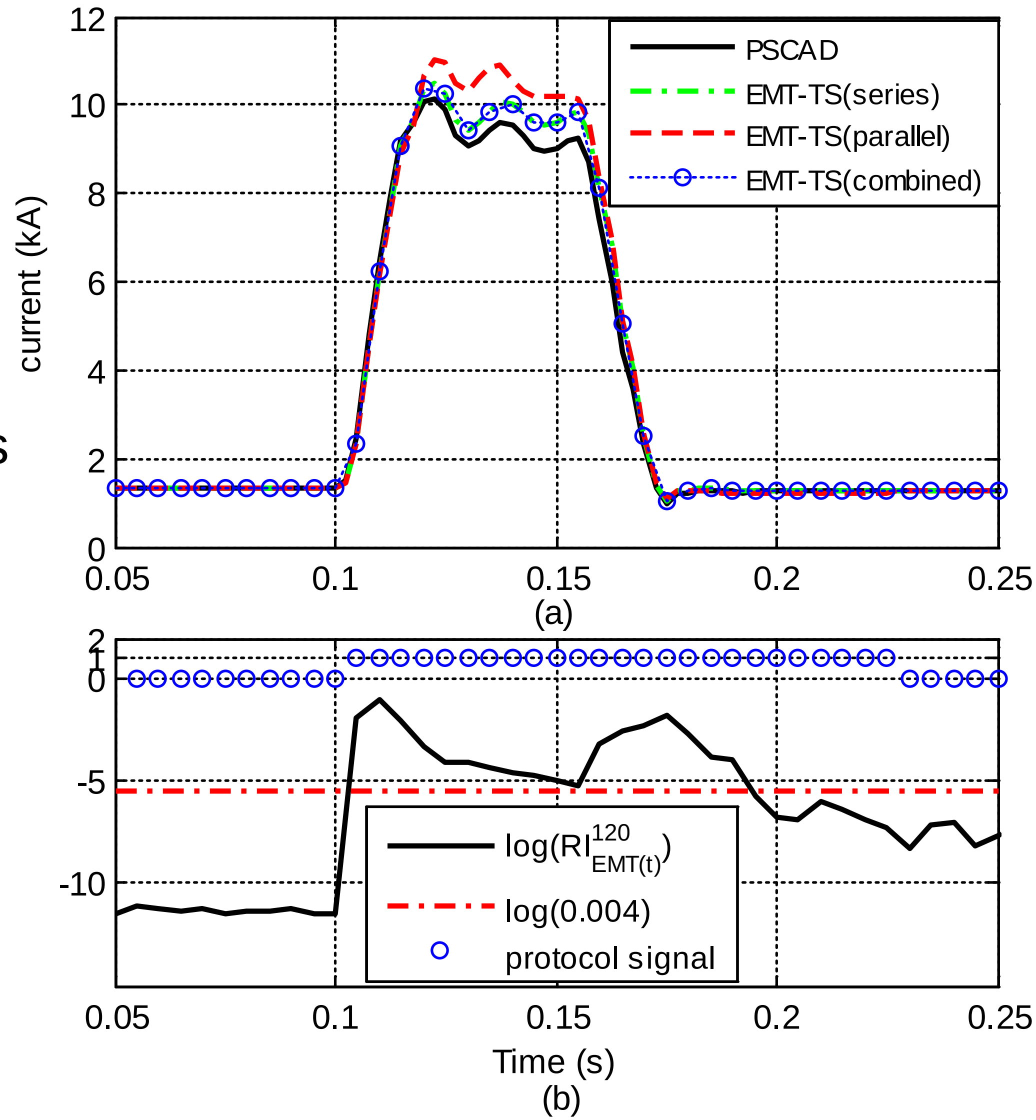
Modeling of Bus 5 and the external network Thévenin equivalents in PSCAD

Case 1: The interaction protocols

- Case 1 setting:
  - \- EMT time step = 50 us
  - -TS time step = 5 ms
- Protocol control setting:
  - -Threshold ε = 0.004
  - \- Delay = 2 cycles
- A three-phase fault at 0.1 s and lasts for 4 cycles
- Plots

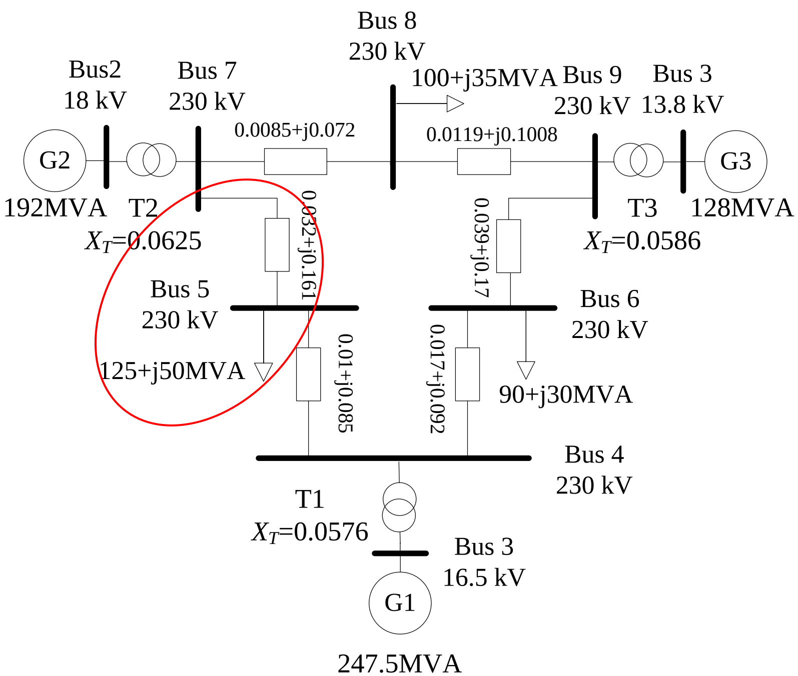
(Top) Positive-sequence current injection at bus 5 into the external network

(Bottom) Protocol switching signal

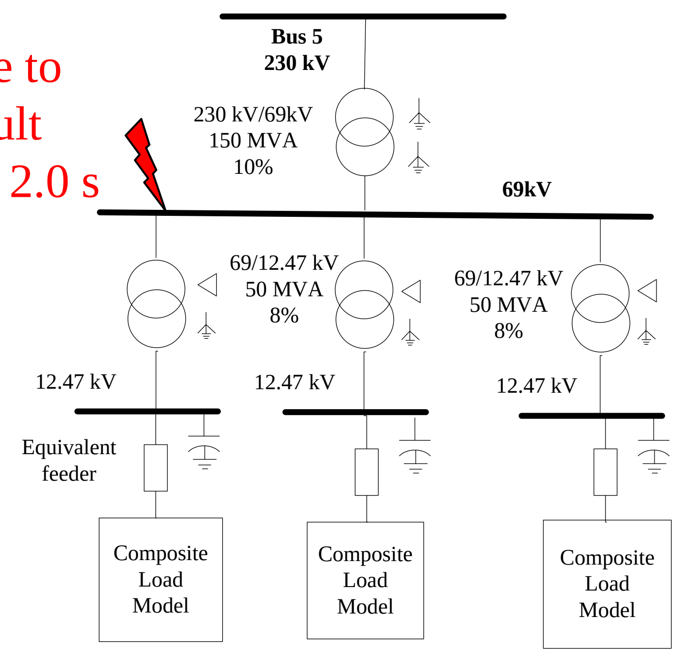


Case 2: Performance of the developed platform under unsymmetrical faults

- Internal network: Bus 5 and branch Bus5-Bus7
- Two-port three-phase Thévenin equivalent
- Detailed modeling of bus 5 using the WECC composite load model, with the 1-p air conditioner compressor motor represented by a EMTP type model developed by Yuan Liu, et al [1]



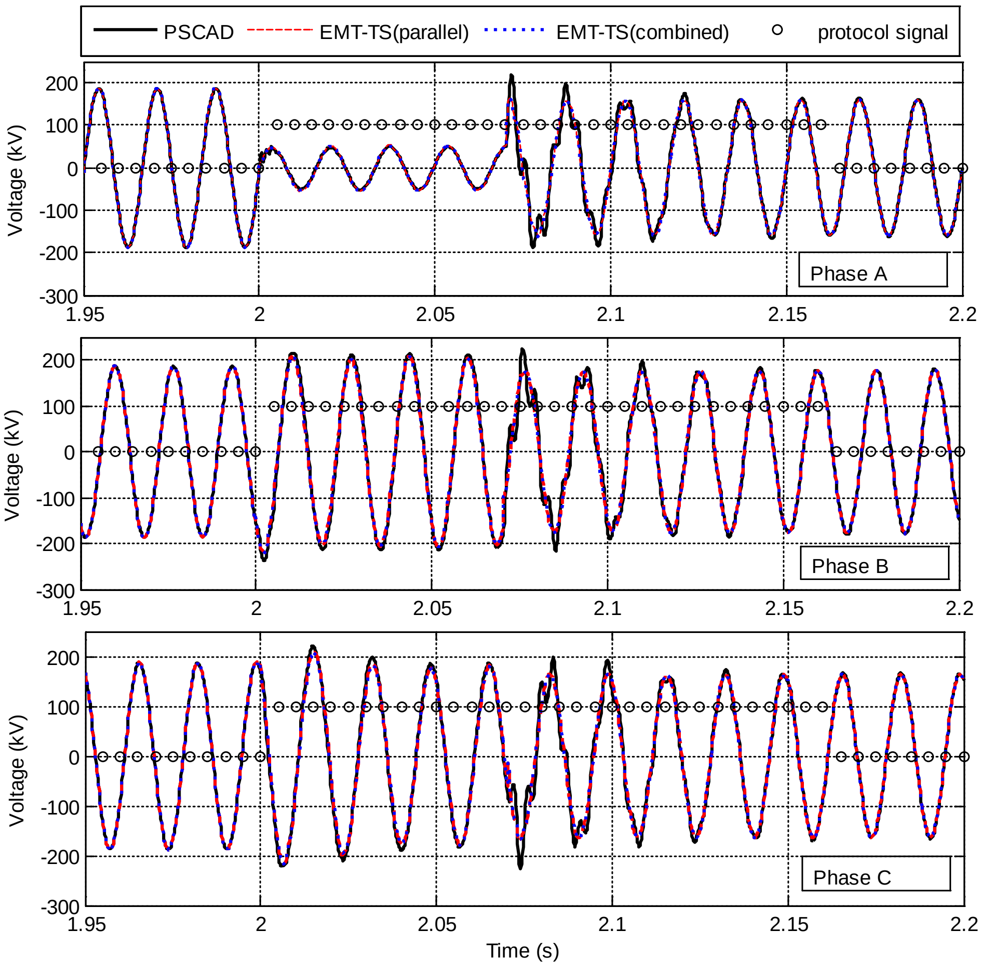
- Single line to ground fault
- starting at 2.0 s
- 4 cycles



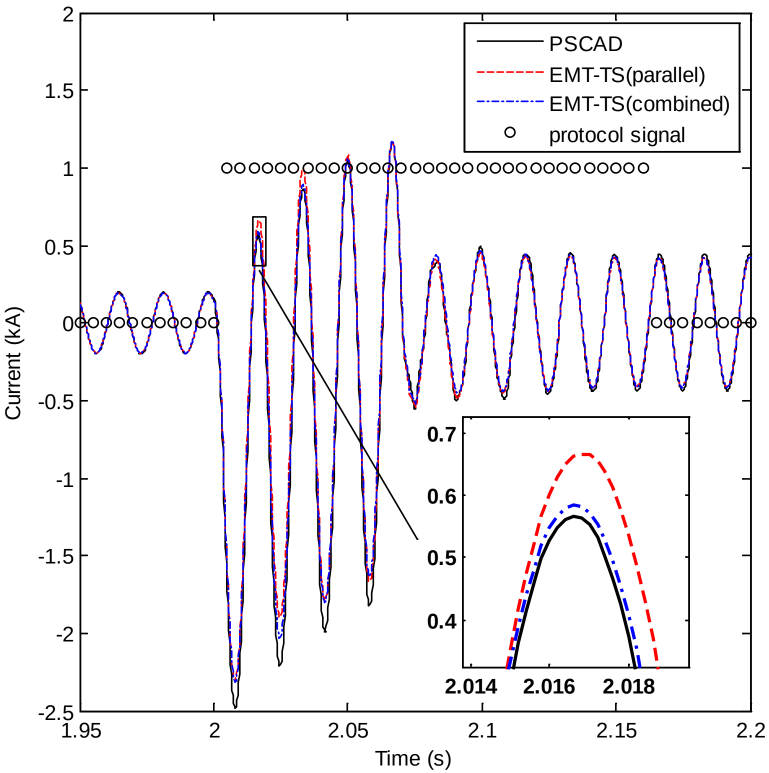
Detailed modeling of Bus 5

[1] 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.

Case 2: Performance of the developed platform under unsymmetrical faults



Three-phase voltage of Bus 5



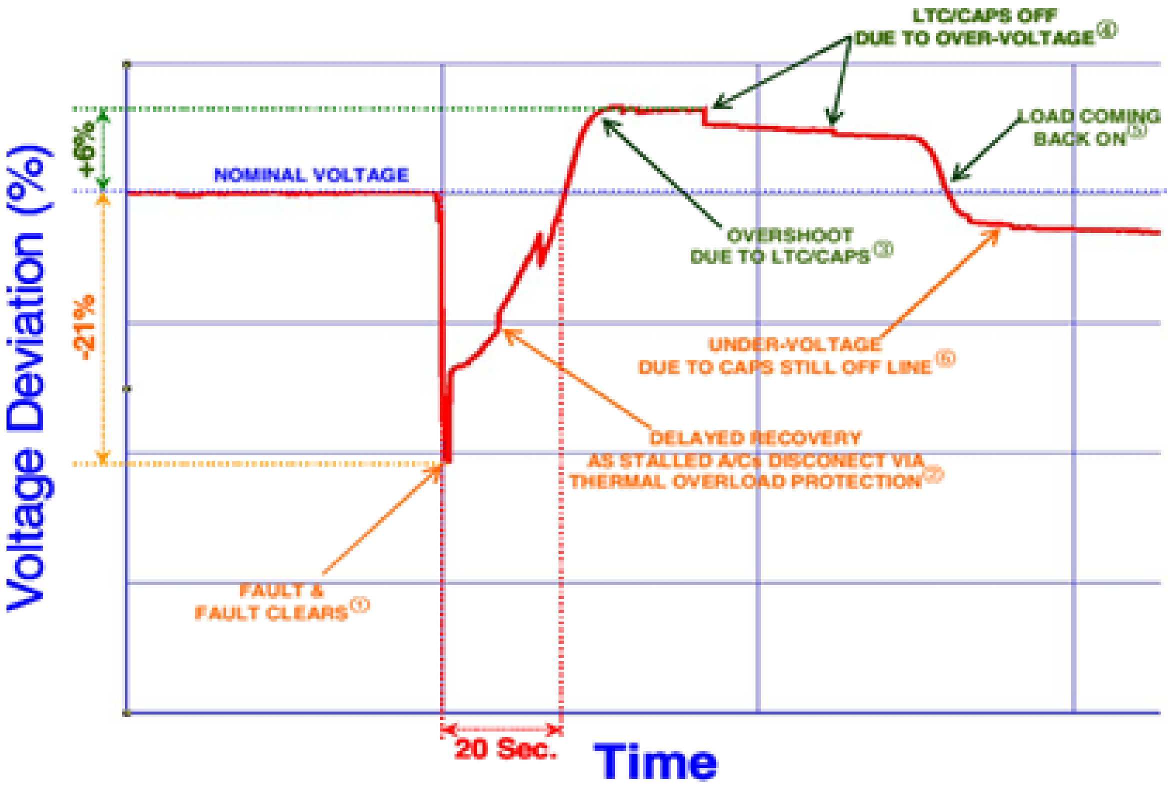
The phase A current injection at Bus 5 into the external network

Takeaways of part-1

1. The combination of the decoupled architecture and socket-based communication facilitates both simulators to be run on either one computer or several computers to achieve more flexibility and a better performance
2. The proposed combined interaction protocol with the auto-switching feature helps improve the hybrid simulation efficiency while a good accuracy is guaranteed
3. Application of the multi-port three-phase Thévenin equivalent enables simulating unbalanced faults within the detailed system, without the constraint of phase balance at the boundary buses

Fault induced delayed voltage recovery (FIDVR)

- Fault
  - distribution, sub-transmission and transmission systems
- Delayed voltage recovery
  - several to tens of seconds
- Root cause of FIDVR
  - air conditioner (A/C) compressor motor stalling and prolonged tripping

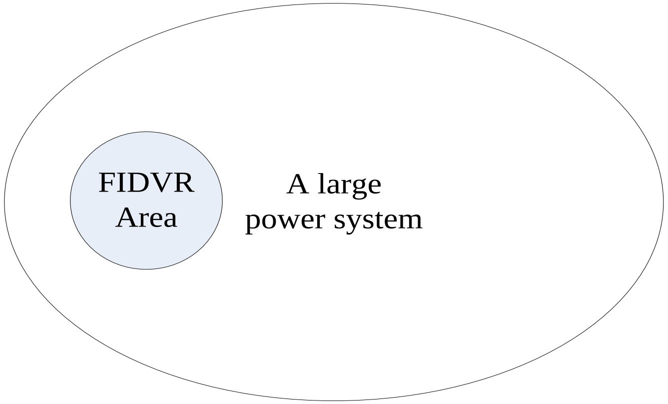


Voltage profile during a typical FIDVR event [2]

[2] D. N. Kosterev, A. Meklin, J. Undrill, B. Lesieutre, W. Price, D. Chassin, et al., "Load modeling in power system studies: WECC progress update," in 2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008, pp. 1-8.

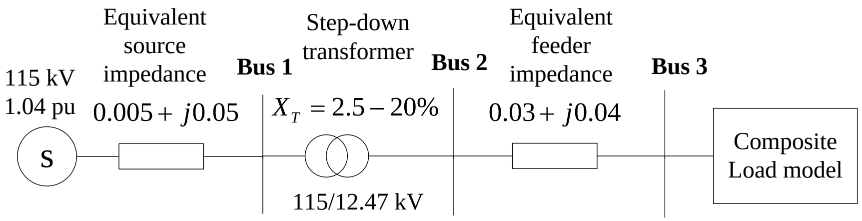
Fault induced delayed voltage recovery (FIDVR)

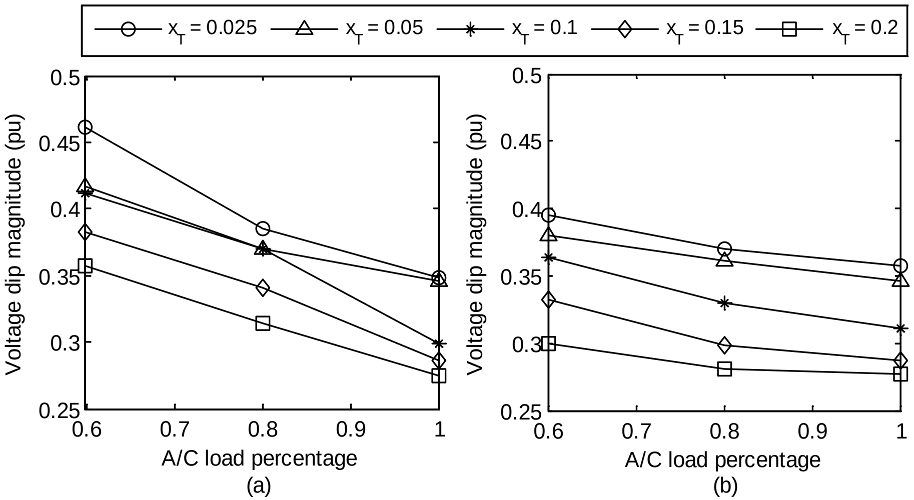
- Accurate FIDVR studies require
  - Detailed A/C modeling
  - Detailed network model down to distribution feeder level
- Limitations of the conventional positive-sequence TS simulator
  - Distribution system configurations
  - Response of single-phase devices when subjected to unsymmetrical faults
- FIDVR events are generally localized
  - Detailed modeling can be limited to a small portion of a large power system



Determination of the boundary of detailed system

- Use a simple yet generic test case to quantify the voltage dip threshold at a transmission bus causing A/C motor stalling
- **<u>Criterion:</u>** A bus is included in the internal system if a single-phase or three-phase fault at that bus causes a phase-to-neutral voltage at buses with a large percentage of A/C motor loads to drop below **0.75 pu**.





Voltage dip magnitude w.r.t. the A/C load percentage and the transformer impedance: (a) A/C power = 4.9 kW (b) A/C power = 6.0 kW

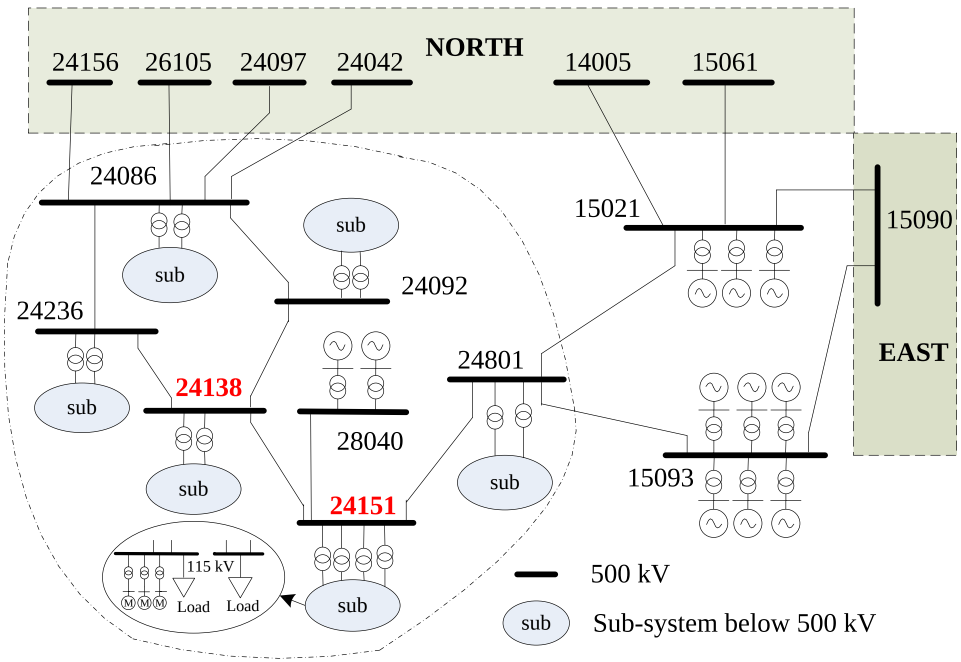
Applied the boundary selection criterion to the WECC system

The WECC system

Buses	Transmission lines	Generators	Loads
15750	13715	3074	7787

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

- Bus 24151
- Bus 24138



One-line diagram of the study region

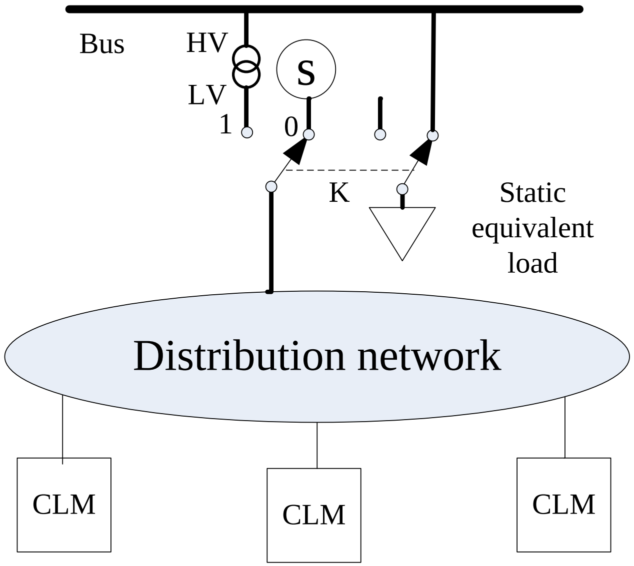
STATISTICS OF THE DETAILED SYSTEM MODEL

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	

Initialization of the detailed system with a large percentage of load as induction motors

- The built-in initialization function of PSCAD fails to initialize the detailed system
- A two-step initialization approach

(1) The switch K is turned to the position 0, and the distribution systems and the CLMs are energized by the fixed voltage sources and initialized independently.
(2) After the CLMs are successfully initialized, the switch K is turned to the position 1 such that distribution systems are connected to the transmission system.

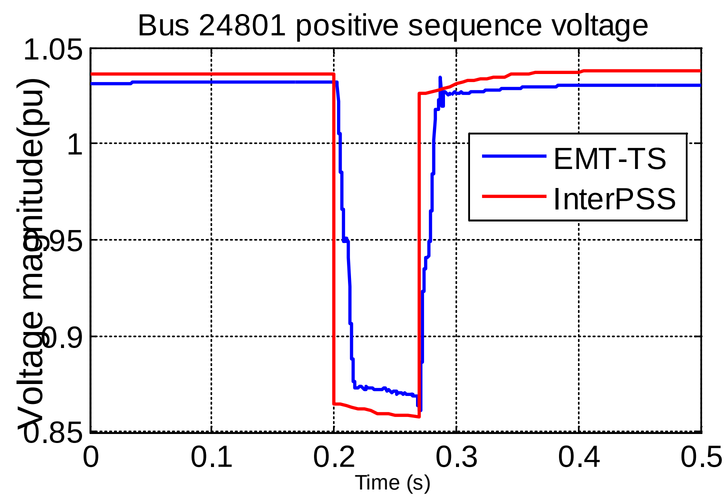


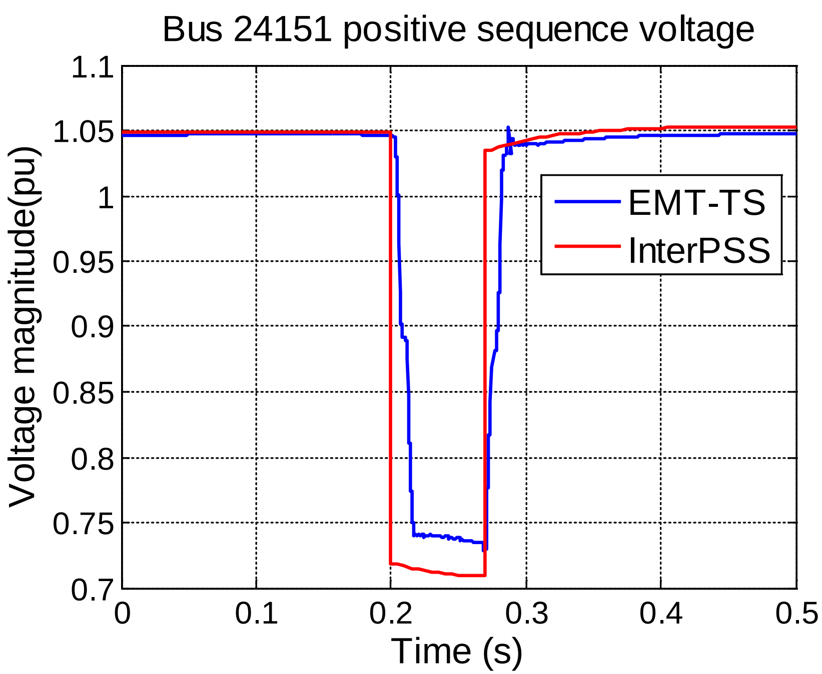
CLM: composite load model

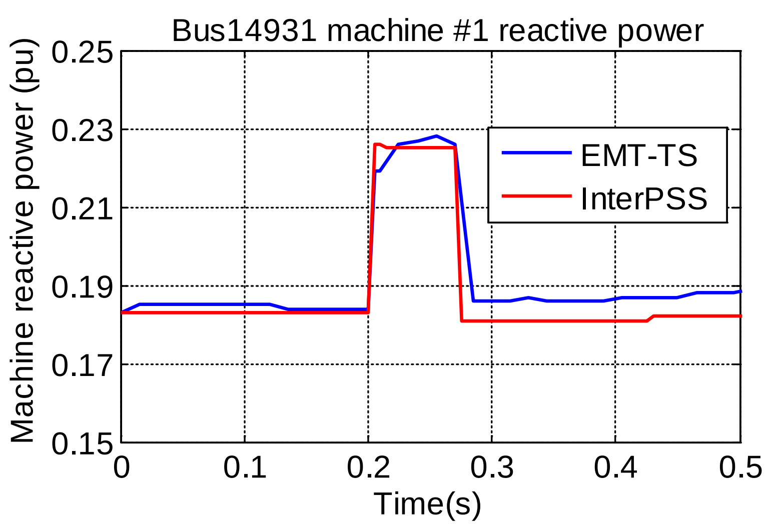
NOTE: The magnitude and phase angle of the fixed voltage source, S, are set based on the power flow solution of the given base case

Benchmarking hybrid simulation against conventional transient stability

- Both use constant impedance load
- A single line to ground (SLG) fault is applied on the phase A of bus 24151 at t = 0.2 s

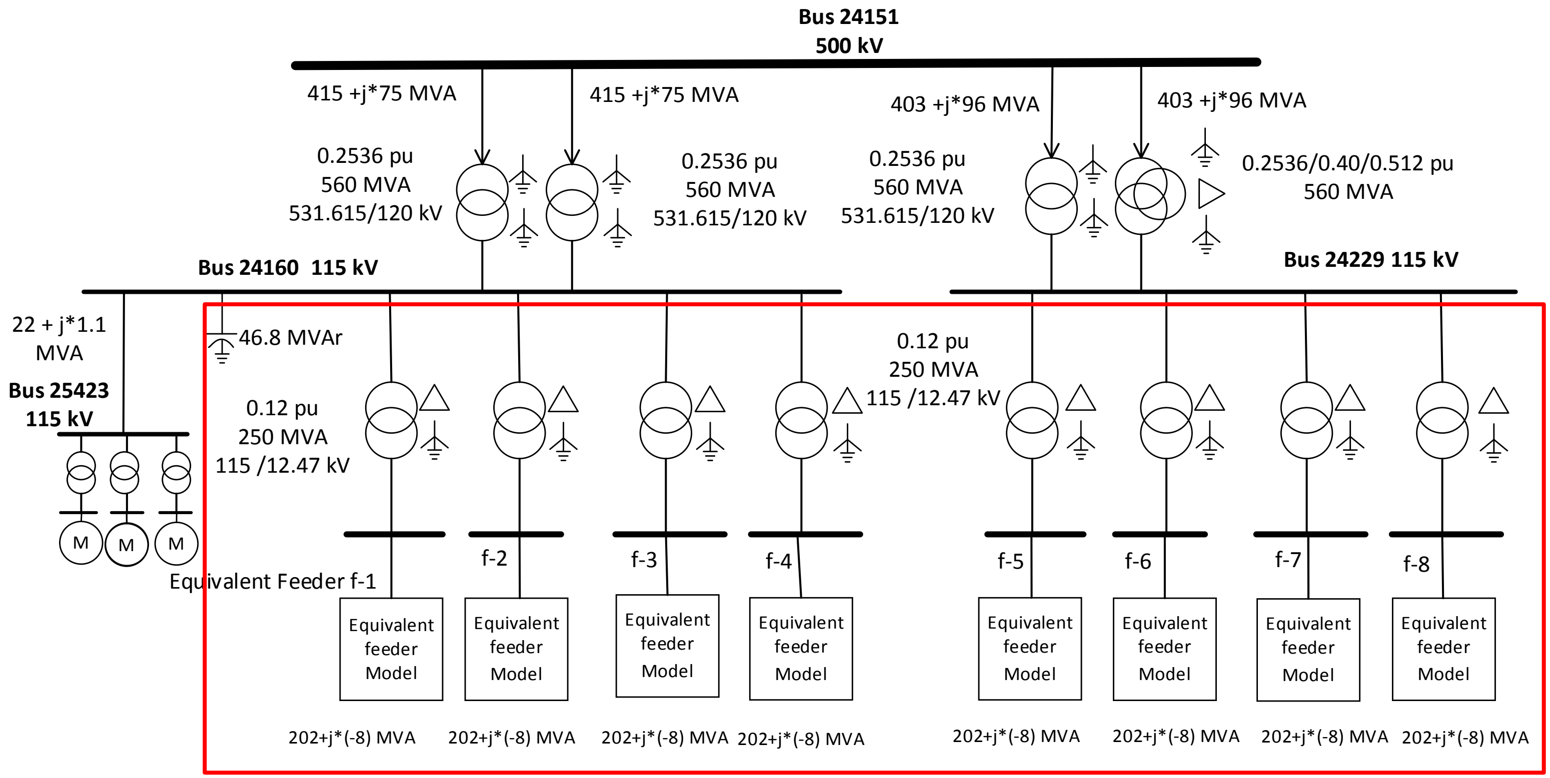




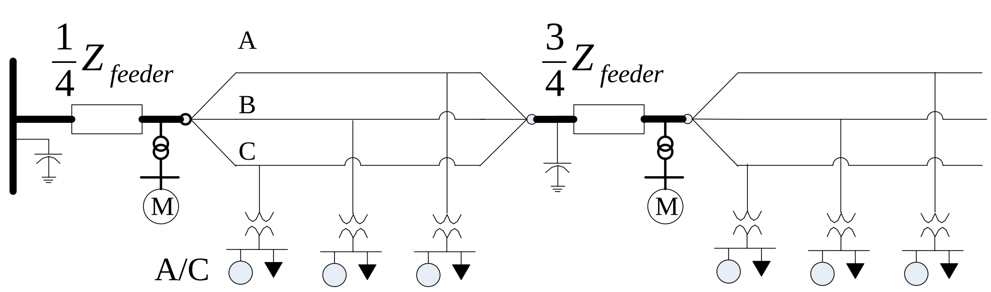


FIDVR event triggered by a SLG fault

- Detailed modeling of the region served by Bus 24151

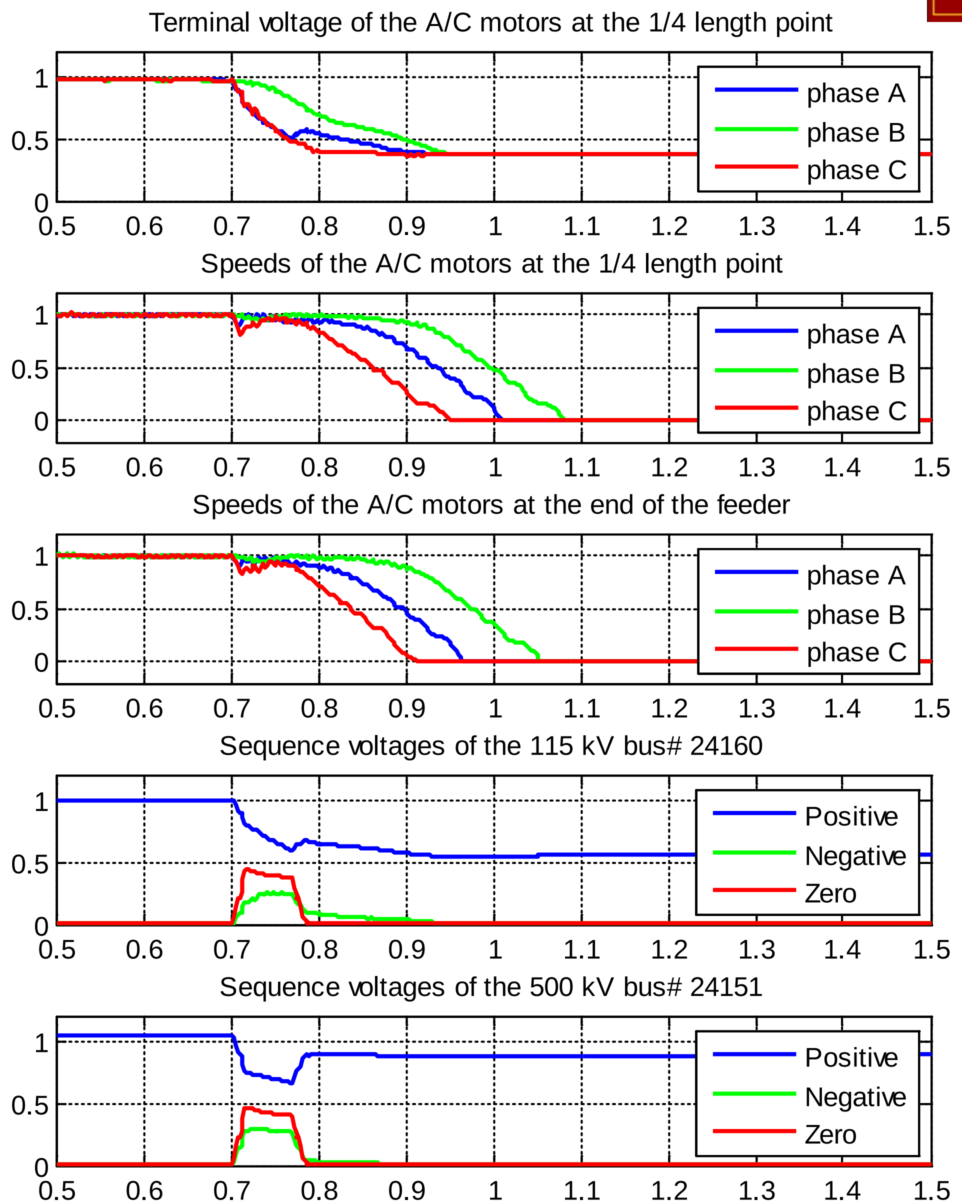


- Feeder modeled in two sections



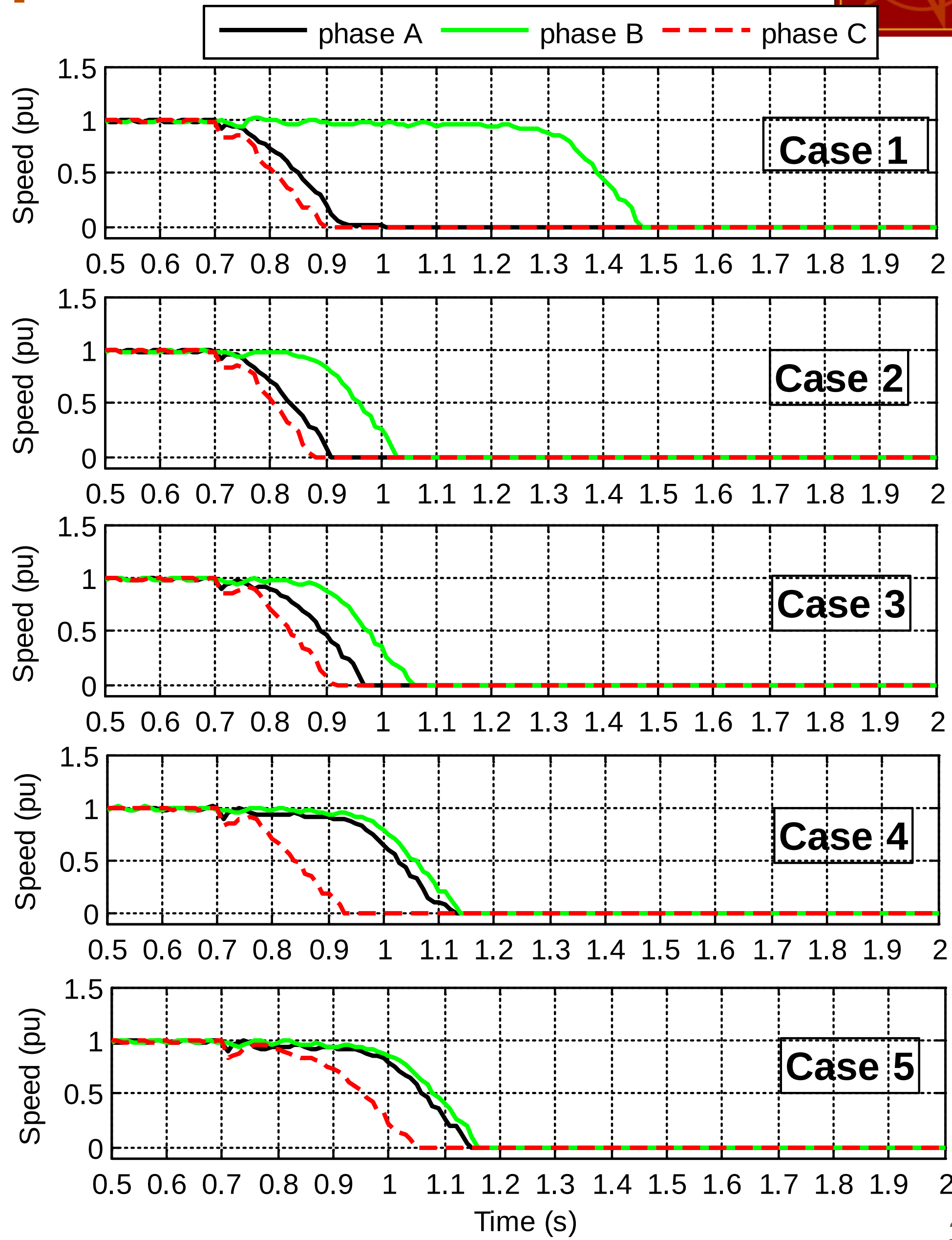
FIDVR event triggered by a SLG fault (cont')

- 70% 1-Φ A/C motor, 15% 3-Φ induction motor, 15% constant impedance
- Phase A and C were directly affected by the SLG fault at Bus 24151
- A/C motor stalling propagated to non-affected phases (phase B in this case)
- Voltages of all three phases were depressed after 0.95 s



Effects of load composition on FIDVR

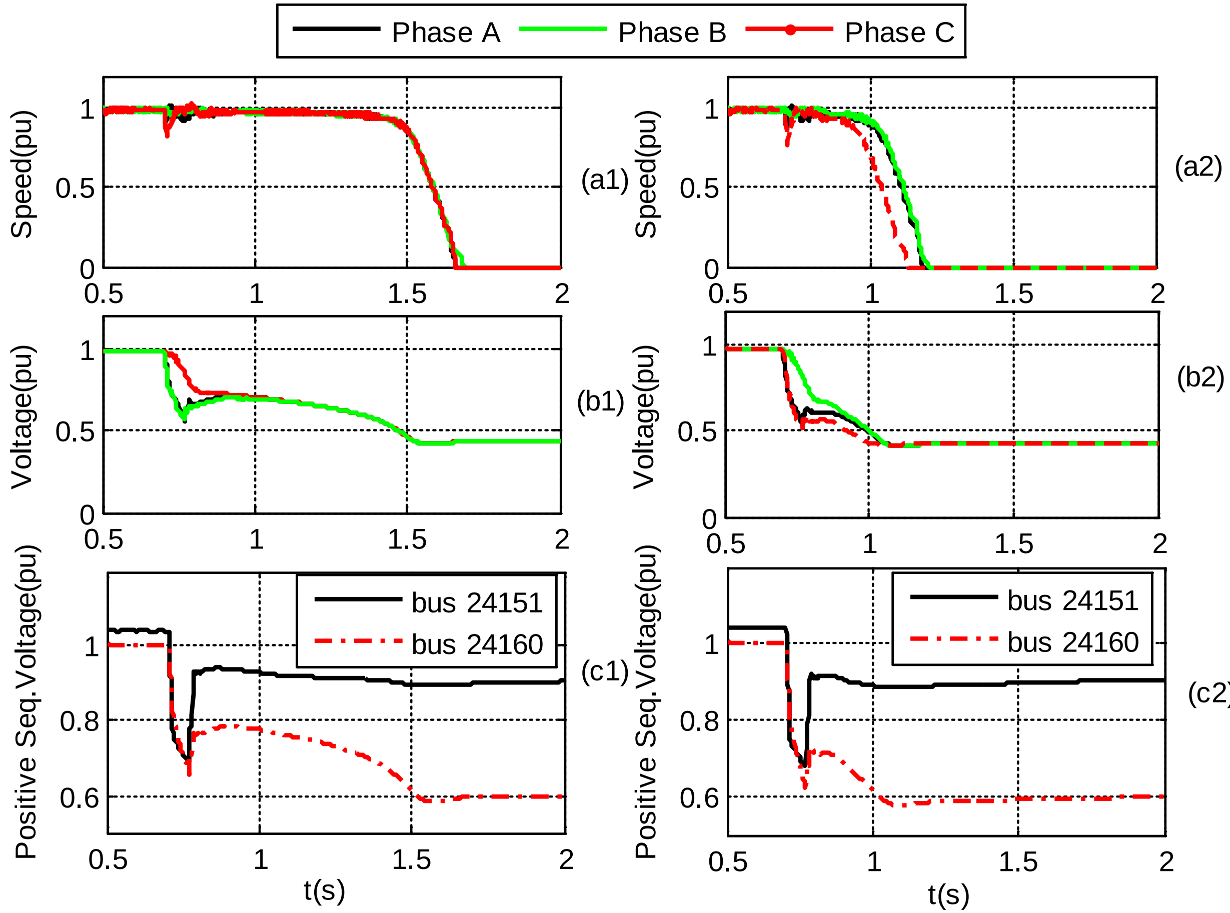
Case #	Load composition
1	75% 1-Φ A/C motor, 25% constant impedance
2	75% 1-Φ A/C motor, 10% 3-Φ NEMA type B induction motor, 15% constant impedance
3	70% 1-Φ A/C motor, 15% 3-Φ NEMA type B induction motor, 15% constant impedance
4	60% 1-Φ A/C motor, 15% 3-Φ NEMA type B induction motor, 25% constant impedance
5	50% 1-Φ A/C motor, 25% 3-Φ NEMA type B induction motor, 25% constant impedance



- Propagation of A/C motor stalling to unfaulted phase is consistent across a substantial range of load compositions
- The impacts of SLG faults close to certain regions of the system with high A/C penetration could be more severe than perceived

Effects of point-on-wave (POW) on FIDVR

- POW effects on the occurrence and evolution of FIDVR are apparent, based on the differences in the response of the A/C motors of bus 24160
- The POW when the fault occurred should be considered for detailed FIDVR study



Case 5A, POW = 45 deg

Case 5, POW = 0 deg

Takeaways of part-2

1. The study shows that a normally cleared, single line to ground fault at a 500 kV bus close to the A/C loads can lead to a FIDVR event. The event begins with A/Cs stalling on two directly-impacted phases, followed by A/C stalling propagating to the unimpacted phase.
2. Further, five study cases with quite different load compositions show similar A/C motor stalling results.
3. The POW when the fault occurs could have a significant impact on the response of the A/C compressor motors.

Conclusions

1. A new EMT-TS hybrid simulation tool is developed, which features 1) decoupling architecture, 2) generic interfacing with an EMT simulator, 3) flexible switching of interaction protocol and 4) support of three-phase equivalent of external system.
2. The hybrid simulation tool has been applied to study the FIDVR phenomenon within a region of WECC system, certain aspects of the evolution of the phenomenon were uncovered for the first time.
3. The developed tool is not limited to FIDVR study, but also applicable to studies that require detailed models and simulation of a part of a large power system, while preserving the slow dynamics of the rest of the system

Thank you!