High-Fidelity Modeling & Simulation of Power Electronics – Approaches and Case Studies

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Panel Session 4: PE Compliant Modeling/Testing

Outline

- About OPAL-RT
- Power Electronics Models for EMT Studies
  - Detailed Switching
  - Ideal Switch
  - Constant Conductance
  - Switching Function
  - Average
- R&D Case Studies

Introduction

About OPAL-RT Technologies

- Founded in 1997 in Montreal, QC, Canada
- 350+ employees, growing sustainably
- 1000+ customers in all industries around the world
- 20% of annual revenue re-invested in R&D
- 40% academic, 60% industries
- 90% revenue from electrical and power electronics sectors
- Markets
  - HIL, RCP, real-time laboratories
  - ...and fast off-line and on-line close-to-real-time (cloud) simulation
  - for education, R&D and all industries: energy, power electronic, automobile, off-highway vehicle, aerospace, ships, trains ...

Strong International Footprint

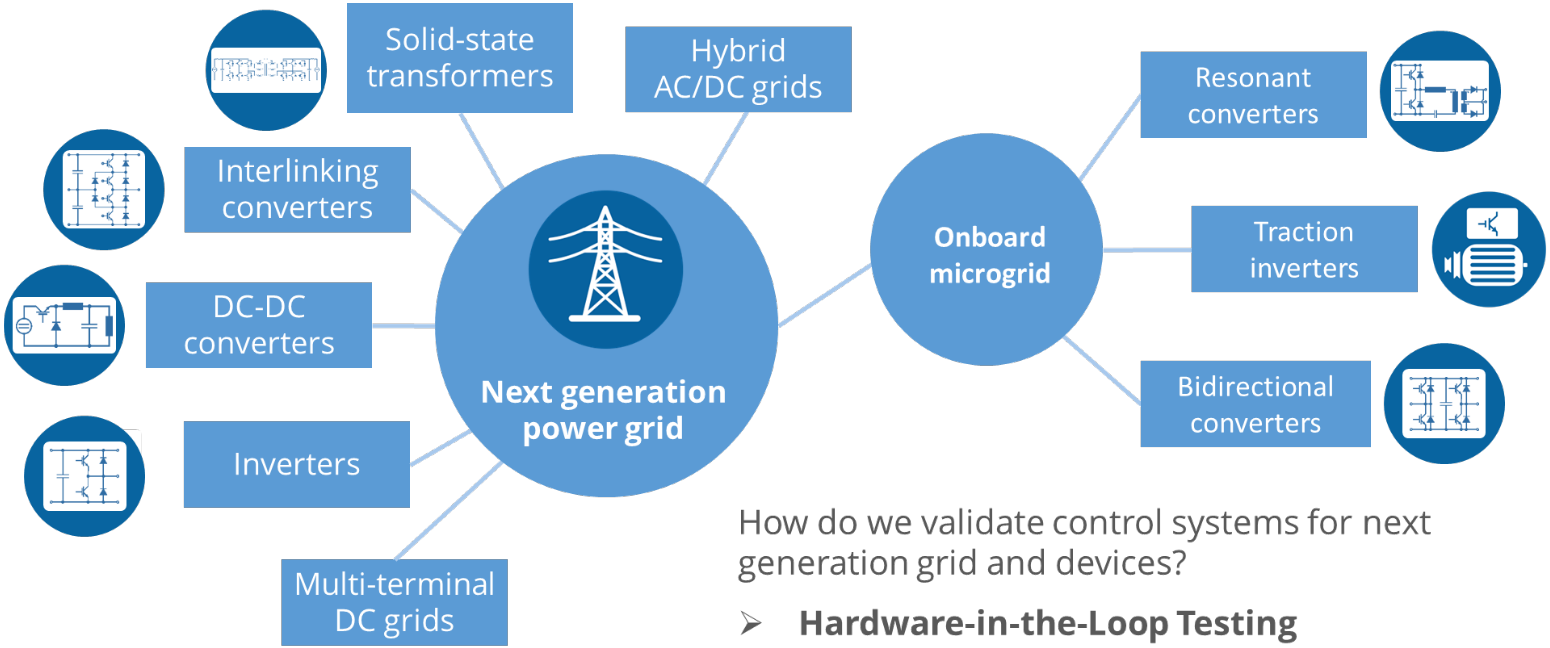
International subsidiaries, offices and Excellence Centers:

- USA (Michigan, Colorado), Germany, France (Paris and Lyon), India, China, Brazil, Australia

Distributors:

- China, Australia, Japan, Korea, Singapore, Israel, Ukraine, Kazakhstan, Oman, Pakistan, Qatar, Turkey, United Arab Emirates , Kingdom of Saudi Arabia

Hardware-In-the-Loop Testing for Power Electronics

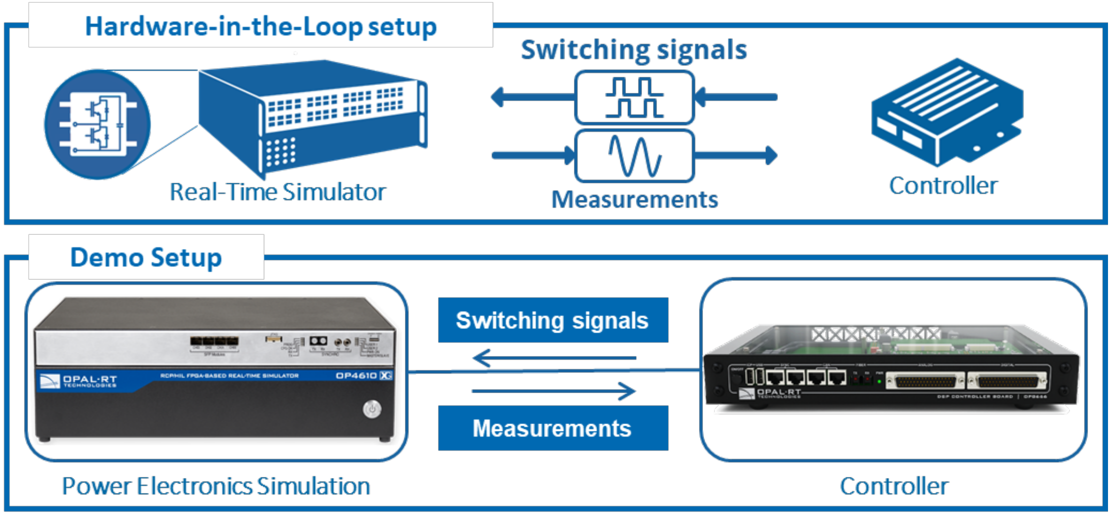


How do we validate control systems for next generation grid and devices?

- **Hardware-in-the-Loop Testing**

HIL Testing of Controllers for Power Electronic Converters

- DuT – controller for a power electronic converter with modulator for generation of switching signals
- Real-Time Simulator – digital simulation of the power electronic converter with switching elements and system surrounding the converter
- Information exchange – analog signals for measurements and digital signals for switching signals



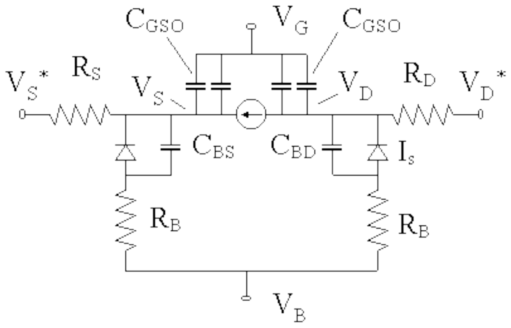
Power Electronics Modeling for EMT Studies

- Power Electronics Modeling Approach
  - Detailed Semiconductor
  - “Ideal” Switching
    - Ideal Switch
    - Constant Conductance
  - Switching Functions
  - Average Models
    - Voltage Source
    - Current Source

Detailed Semiconductor

- Modeled Features
  - Instantaneous turn on/off time representation
  - Conduction and switching losses (Requires good tuning of parameters)
  - Thermal model simulation with high accuracy
  - Ripple representation with high accuracy
  - Device transient characteristics (e.g. MOSFET, IGBT, etc.) can be modeled.

MOSFET SPICE model [1]



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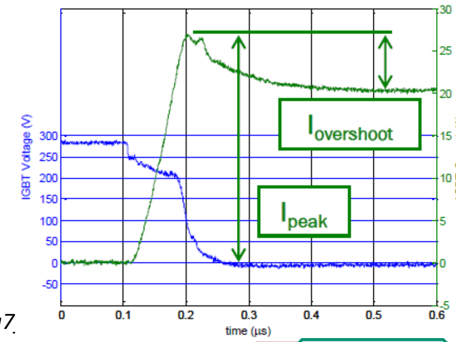

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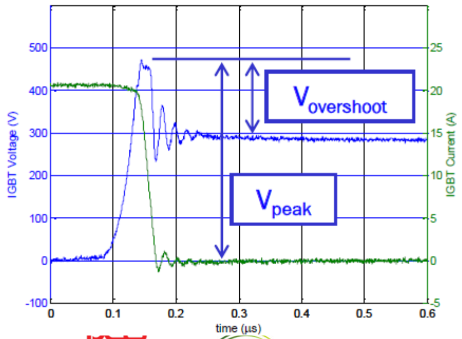


[1] *Source: https://ecee.colorado.edu/~bart/book/book/chapter7/ch7_5.htm#fig7*

[2] *Source: A. Sokolov, "Variable-Speed Power Switch Gate Driver for Switching Loss Reduction in Automotive Inverters."*

Detailed Semiconductor

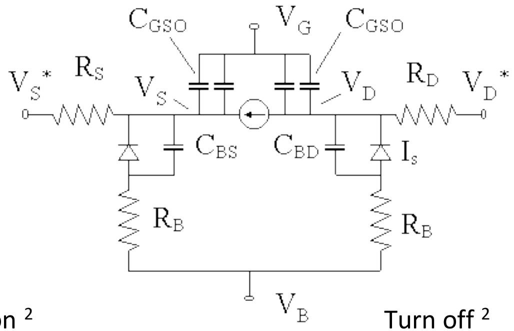
Pros

- Have the highest accuracy in representation of the power electronic converters

Cons

- Computationally intensive, since the switches are modeled with their details
- Requires a very low timestep (~10s of ns) for accurate solution of the discretized non-linear switch models
- Not suitable for real-time simulations

MOSFET SPICE model [1]



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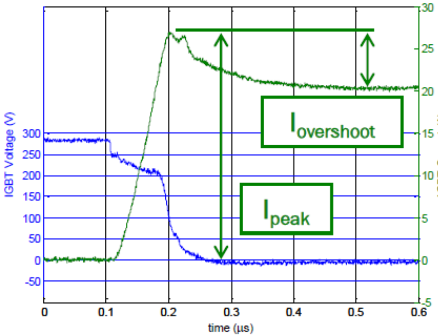

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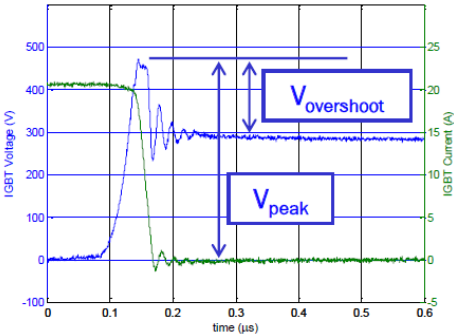

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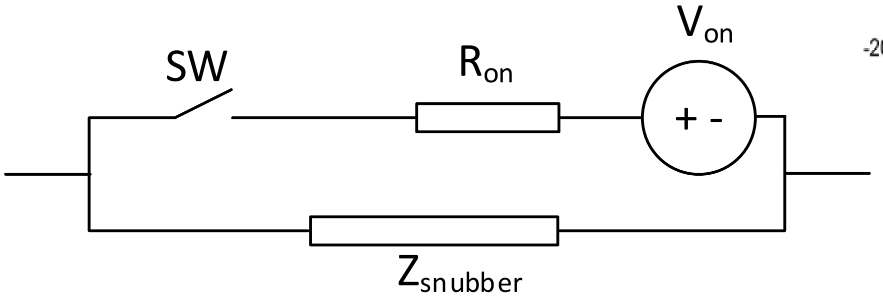
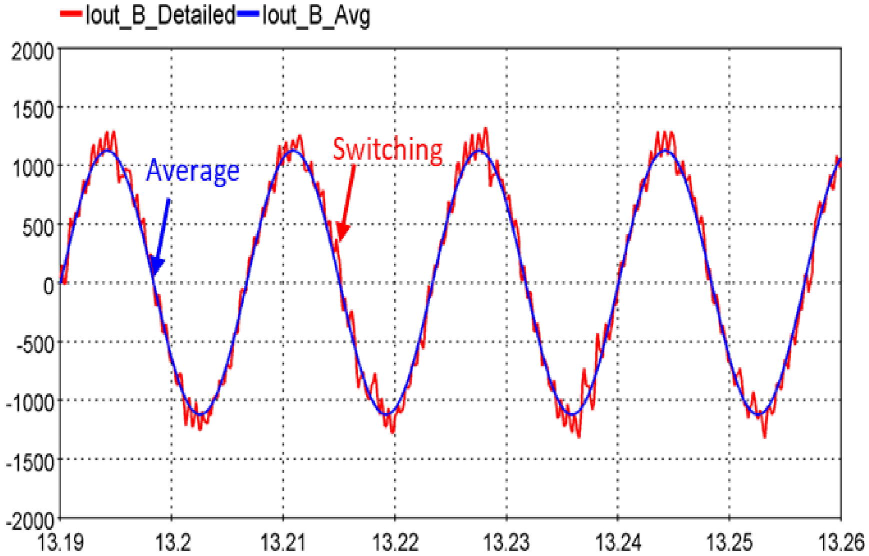
Ideal Switch

- Modeled Features
  - Instantaneous turn on/off time representation
  - Conduction and switching losses (Requires tuning of parameters)
  - Ripple representation with high accuracy





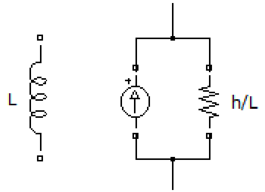
Ideal Switch

- Pros
- The classic EMT-type software model
- Straightforward model which does not require handling particular cases
- Good accuracy for most power electronics CHIL tests with small enough time-step
  - A 10 times smaller timestep than the switching time period $T_{s_{max}} = \frac{1}{10 \times f_{sw}}$ to get a 10% resolution accuracy on the PWM (may result in numerical oscillations)
- Cons
- Computationally intensive and requires matrix pre-calculation or system decoupling for real-time simulation or larger systems
- However, requires increasing memory if pre-calculation if matrices is used
- Requires tuning snubbers with respect to time-step and surrounding model eigenvalues

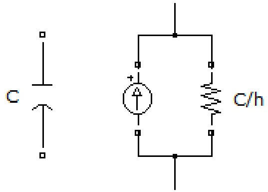
Constant Conductance

Aliases: Pejovic Method | Associate Discrete Circuit

- Modeled Features
  - Instantaneous turn on/off time representation
  - Ripple representation with higher accuracy



Switch closed



Switch opened

$Gs = {}^{h}/_{L} = {}^{C}/_{h}$ where h is the time step used in the circuit

Pejovic, P.; Maksimovic, D.; , "A new algorithm for simulation of power electronic systems using piecewise-linear device models," Power Electronics, IEEE Transactions on , vol.10, no.3, pp.340-348, May 1995.

Constant Conductance

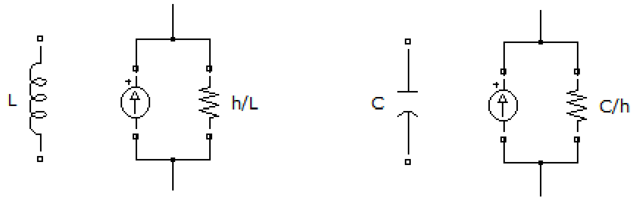
Aliases: Pejovic Method | Associate Discrete Circuit

Pros

- Good accuracy and allows fast simulation for CHIL testing of faster power electronics controls
- Low computational burden allowing very low time-steps when implemented on FPGA

Cons

- Creates virtual power loss (compensated for in the eFPGASIM implementation for standard converter topologies)
- Requires tuning of the Gs parameters (eFPGASIM provides a Gs calculation tool to help tune the Gs parameter)



Switch closed   Switch opened

$Gs = h/L = C/h$ where h is the time step used in the circuit

eFPGASIM

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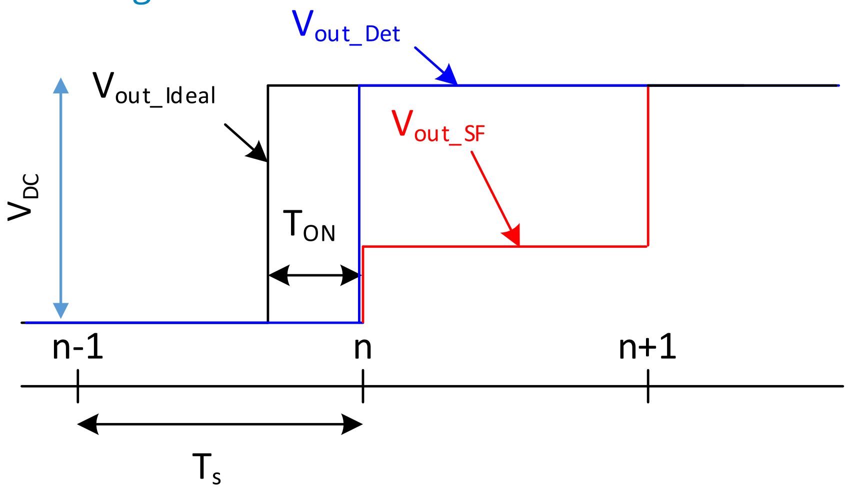
Switching Function

Aliases: Time Stamped Bridge (TSB) | Virtual FPGA Switching

- Model Features
  - Suitable for voltage-source converters modeling
  - Compensates for the adverse effects of pulsing from controllers (CHIL) occurring in between discrete-time steps
  - Accurately represents the voltage harmonic spectrum near the fundamental frequency of operation
  - Allows effective modeling of switch dead-times



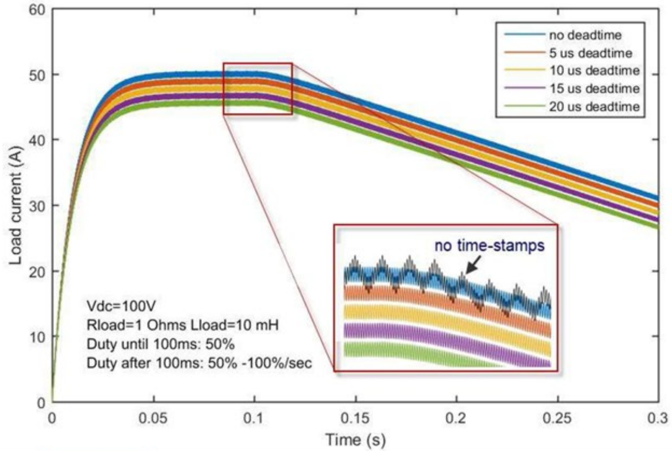
$$V_{out}(n) = \frac{T_{ON}(n-1)}{T_s} \times V_{DC}(n-1)$$

$$V_{out}(n+1) = \underbrace{\frac{T_{ON}(n)}{T_s}}_{=1} \times V_{DC}(n) = V_{DC}$$

Switching Function

Aliases: Time Stamped Bridge (TSB) | Virtual FPGA Switching

- Pros
  - Good accuracy for system level and converter level studies
  - Fast execution time
  - Requires $T_{s_{max}} = \frac{1}{\sim 4 \times f_{sw}}$ for an accuracy of ~2% on the duty cycle
  - Allows study of converters in larger systems without requiring as much decoupling as ideal switch to achieve real-time
  - With computation technology (ex. FPGA) which is very fast, but not enough to simulate very fast power electronics (ex. f_{sw}=100 kHz), switching function remain a very good solution for real-time simulation
- Cons
  - Certain cases may not be possible to simulate (ex. internal faults)



eMEGASIM

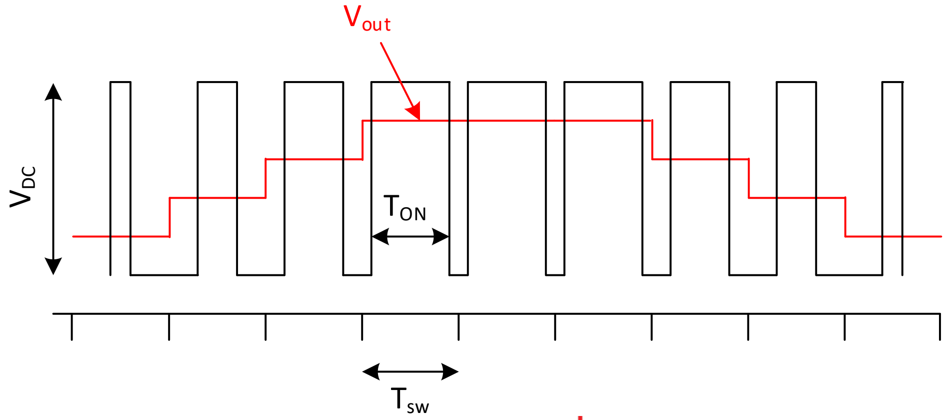
HYPERSIM

Average Models

$$V_{out} = \underbrace{\frac{1}{T_{sw}} \int_{0}^{T_{ON}} S(t)\, dt}_{duty\ cycle} \times V_{dc}$$

S is the switch stat, T_{sw} is the switching period, V_{dc} is the DC link voltage and V_{out} is the output voltage across the switch.

- Model Features
  - Models the average signal produced by the converters
  - Models the near fundamental dynamics of the system
  - Effects of switching are neglected

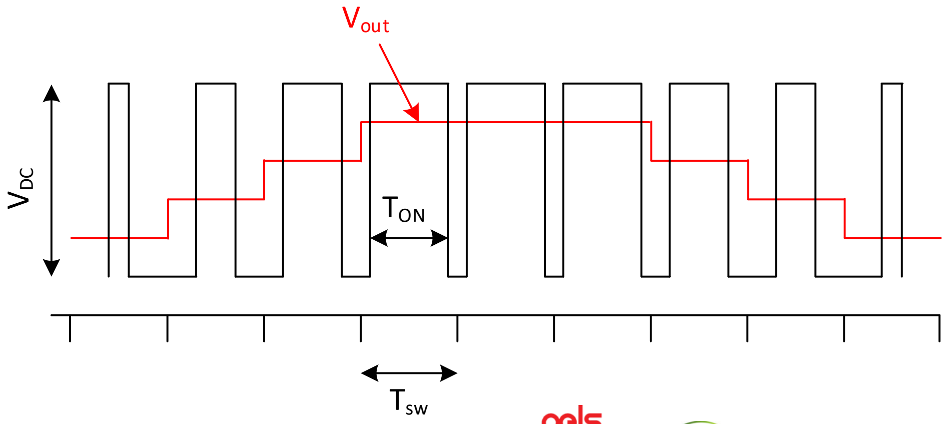


Average Models

$$V_{out} = \underbrace{\frac{1}{T_{sw}} \int_0^{T_{ON}} S(t)\, dt}_{duty\ cycle} \times V_{dc}$$

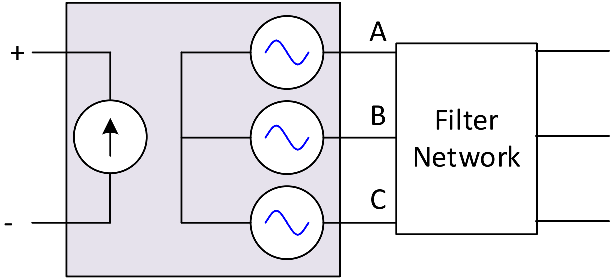
S is the switch stat, T_{sw} is the switching period, V_{dc} is the DC link voltage and V_{out} is the output voltage across the switch.

- Pros
  - Very fast execution
  - Good for large system studies and controller interactions
- Cons
  - Switching frequency and its related phenomena are neglected
  - Does not include low frequency phenomenon due to switching such as non-linearity due to dead-time



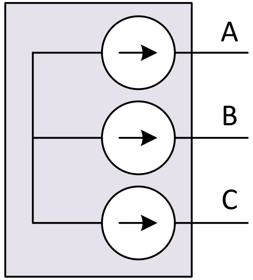
Types Of Average Models

- Voltage Source



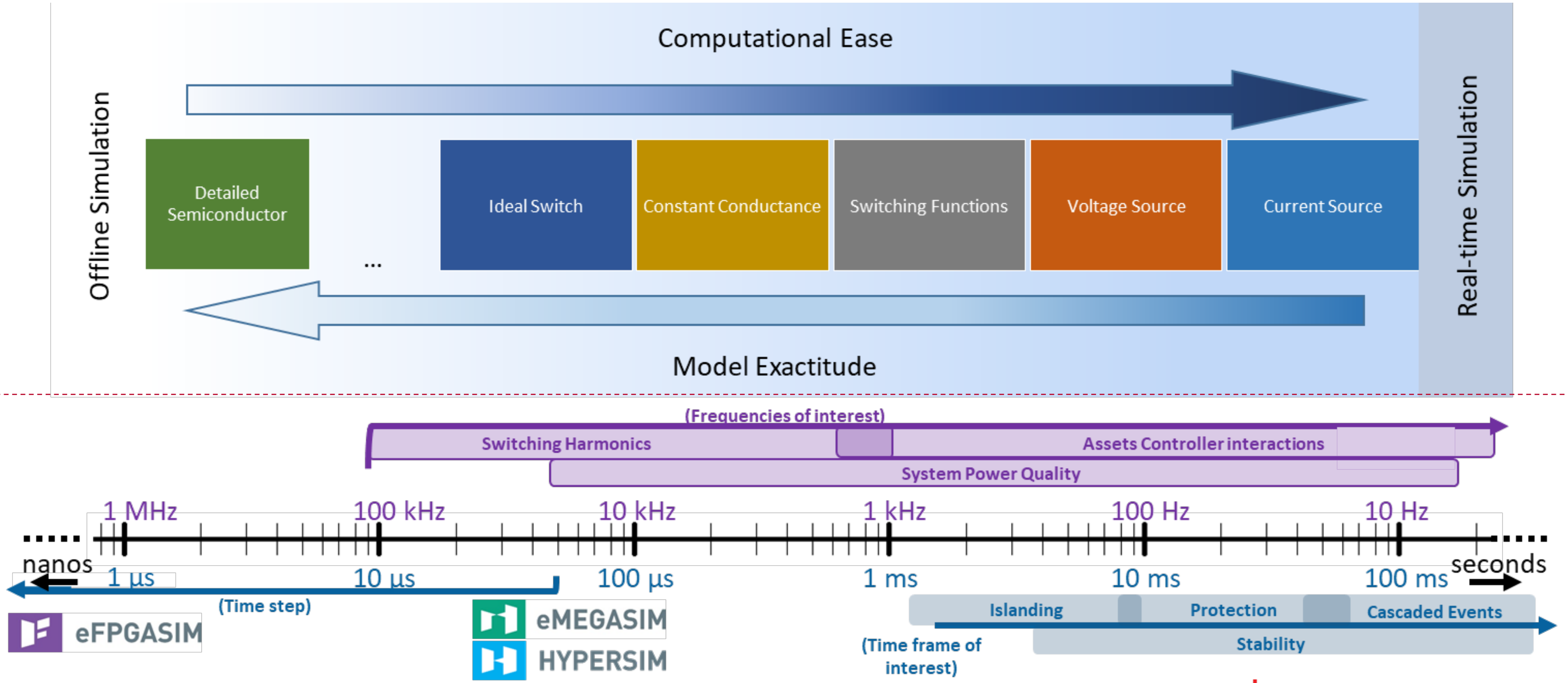
- Implemented with the output filter
- Can include DC side dynamics
- Models the filter related dynamics of the system

- Current Source



- Usually does not include DC side dynamics
- Filter dynamics are also neglected
- System level control dynamics can be modeled

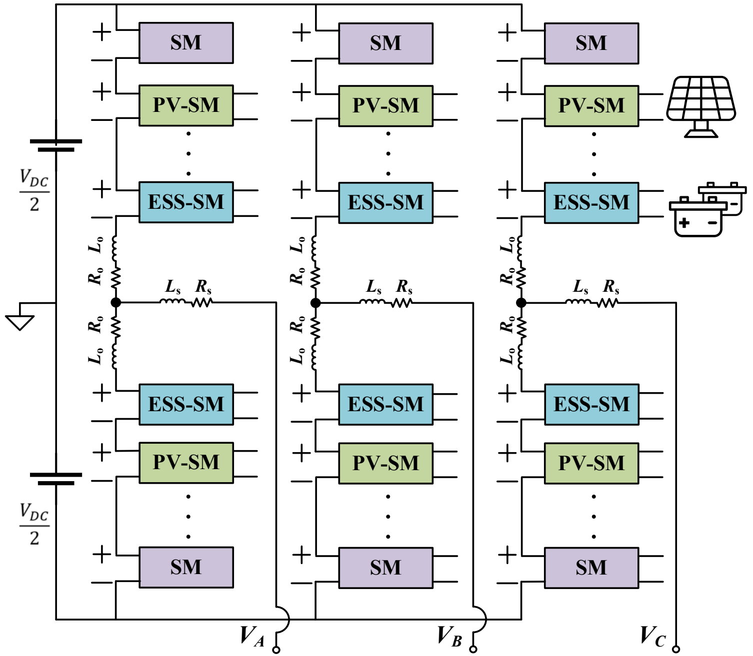
Switching Models for Power Electronics – Summary



Multi-Port Autonomous Reconfigurable Solar power plant (MARS)

- A CHIL simulation platform for Multi-port Autonomous Reconfigurable Solar Power Plant (MARS)
  - Study the integrated power electronics to interface utility-scale solar power, energy storage, dc, and ac systems with advanced grid services
  - Customized FPGA models of front-end converters (sub-μs)
    - OPAL-RT's legacy Time-Stamped Bridges
    - Up to 2400 submodules in the system with independent gating signals
    - Add-on two types of DC/DC converters with PV and ESS
    - Low level control for DC/DC converters with independent gating signals
  - AC grid model (13 buses) running in CPU (60 μs)

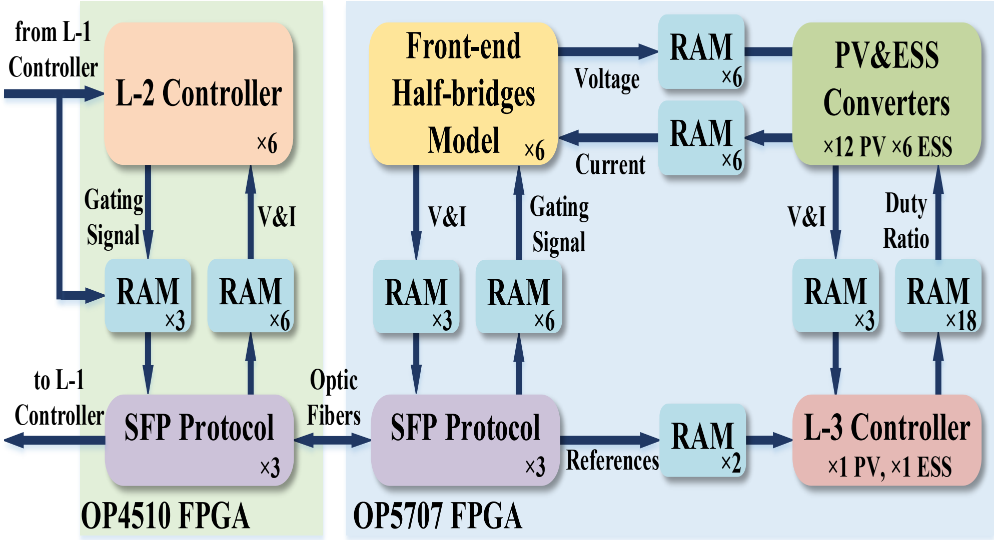
MARS architecture



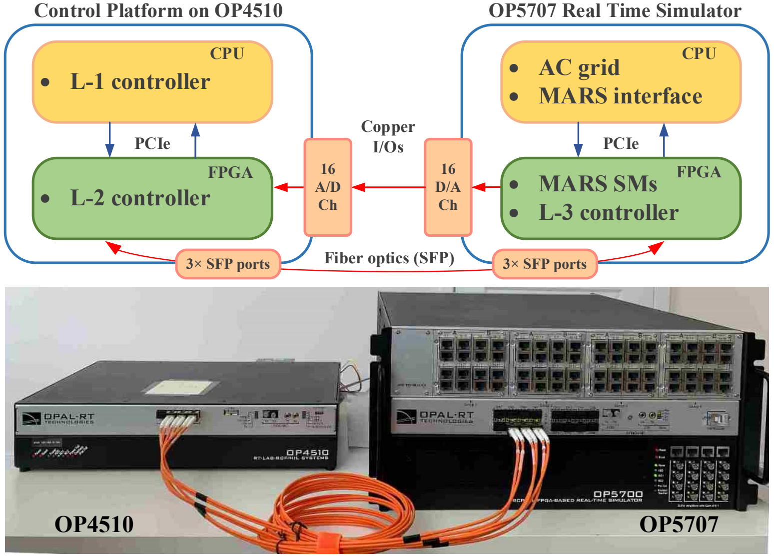
*Z. Dong, S. Debnath, W. Li, Q. Xia, P. R. V. Marthi and S. Chakraborty, "Real-time Simulation Framework for Hardware-in-the-Loop Testing of Multi-port Autonomous Reconfigurable Solar Power Plant (MARS)," 2021 IEEE Energy Conversion Congress and Exposition (ECCE), Vancouver, BC, Canada, 2021, pp. 3160-3167, doi: 10.1109/ECCE47101.2021.9595731.

Multi-Port Autonomous Reconfigurable Solar power plant (MARS)

MARS FPGA model



MARS CHIL system setup



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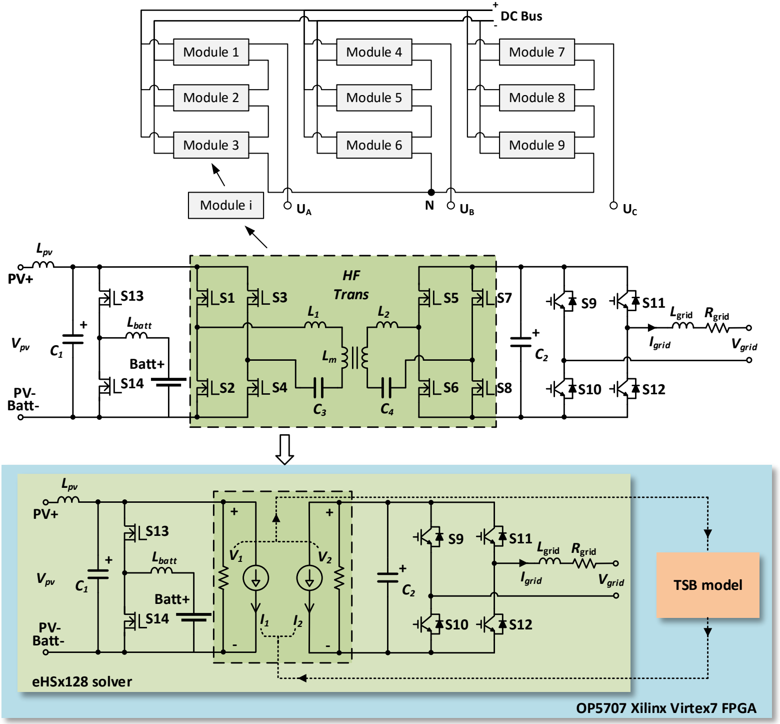
Modular, Multifunction, Multiport and Medium Voltage Utility Scale SiC PV Inverter

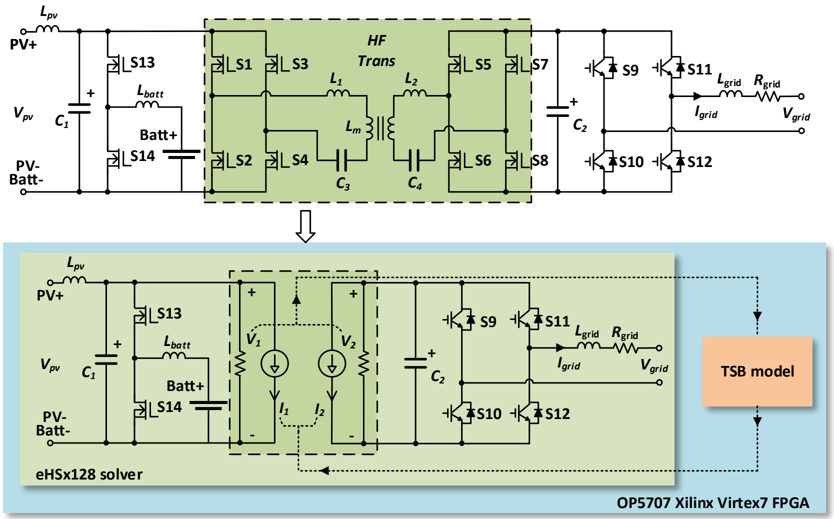
- **Project objective:** Development and demonstration of a Modular, Multi-function, Multiport and Medium Voltage utility scale SiC solar inverter with integrated storage function

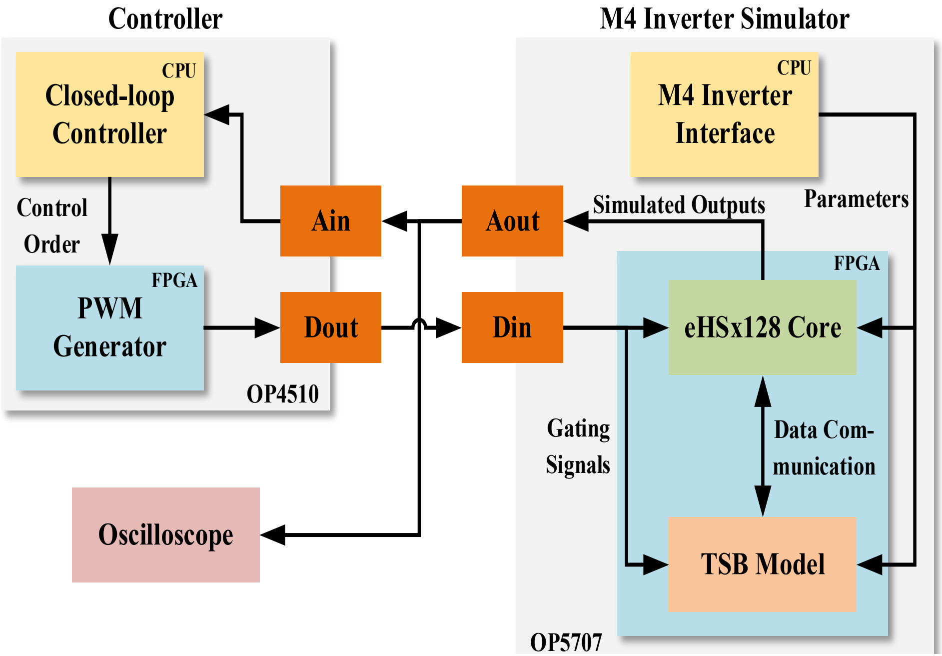
- Real-time model of M4 inverter for CHIL validation (eHS, RT-XSG)

- Input-parallel and output-series converter with **9 modules**
- **72 DAB switches** switching at **max sw. freq.** of **50 kHz**, **2 ESS switches** at sw. freq. **25 kHz** and **36 DC/AC switches** switching at **60 Hz**
- **3 single-phase breakers** between AC grid and M4 inverter
- **DABs with HF transformers** are modeled by **Time-Stamped Bridge (TSB)** and other components are modeled in eHS
- The whole system runs in OP5707 in a single, Xilinx V7 FPGA at **470 ns** time step in TSB, **1 µs** time step in eHS



Modular, Multifunction, Multiport and Medium Voltage Utility Scale SiC PV Inverter





- CHIL simulation platform of M4 inverter
  - OP5707: M4 inverter, OP4510: M4 inverter output current controller
  - Data communication: digital and analog channels

Summary

Hardware-in-the-Loop (HIL) testing and experimentation is essential for validating the behavior of Power Electronics converters accurately.

Accurate models need to be chosen for modeling power electronics-based converters depending on the use cases considered.

While detailing switching models are ideal for accurate HIL testing, in specific cases, the appropriate use of switching function-based models and constant conductance-based models are adequate for HIL testing and scalable real-time simulations.

Thank You!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