Integrated Systems/Subsystems Modeling for Aerospace Applications

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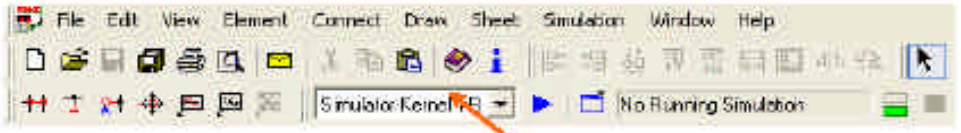
Introduction

- Boeing is currently using Simplorer for the electrical system modeling and simulation in research & technology projects and the modeling and design and analysis for Aircraft, Spacecraft and Ground Vehicles
  - Fuel Cells Electrical System Integration
  - International Space Station
  - Commercial Aircraft and Derivatives
  - Future Combat System Ground Vehicles
- Generic Models are illustrated

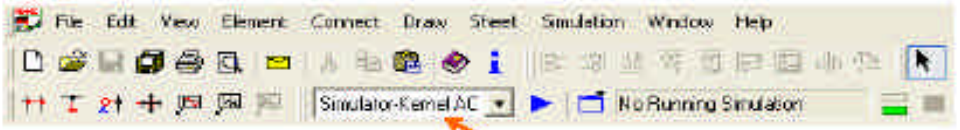
Simplorer Modeling and Analysis

- Model Development
  - Block Diagram – Algebraic, Differential and Difference Equations
  - Circuit Schematics – Electrical and Electronic Components
- Analysis
  - **Time Domain** - transient analysis or TR simulation



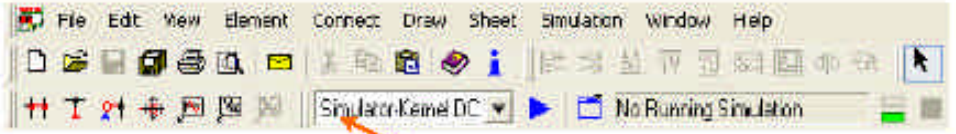
Transient Domain

  - **Frequency Domain** - harmonic analysis or AC simulation



Frequency Domain

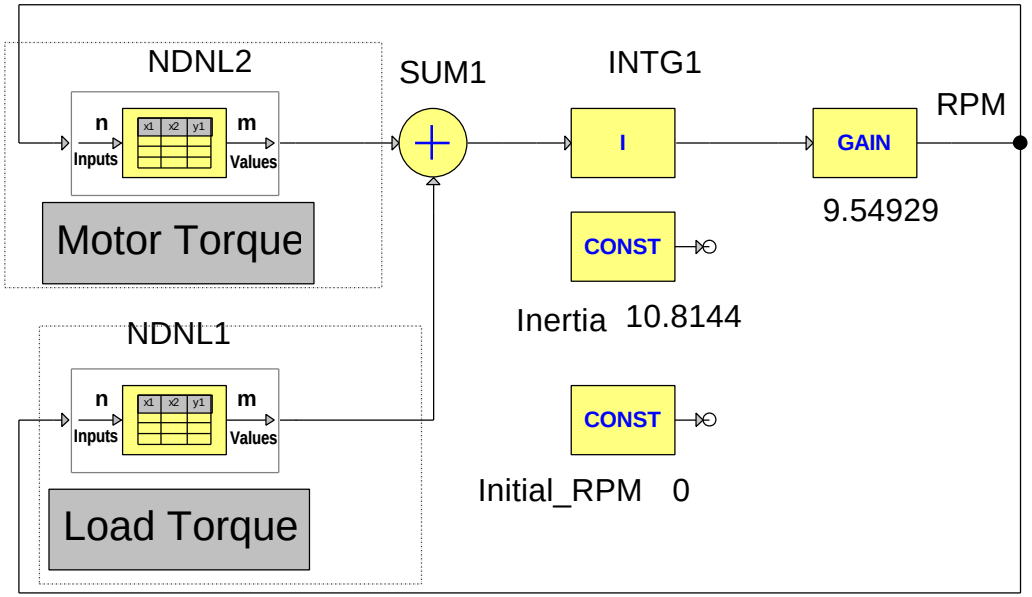
  - **Quiescent Domain** - DC operating point analysis or DC simulation

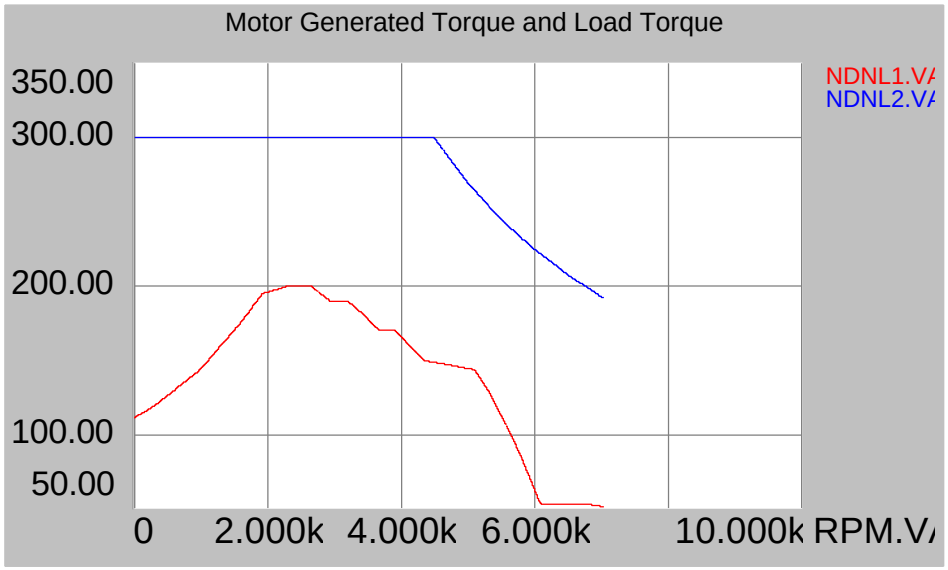


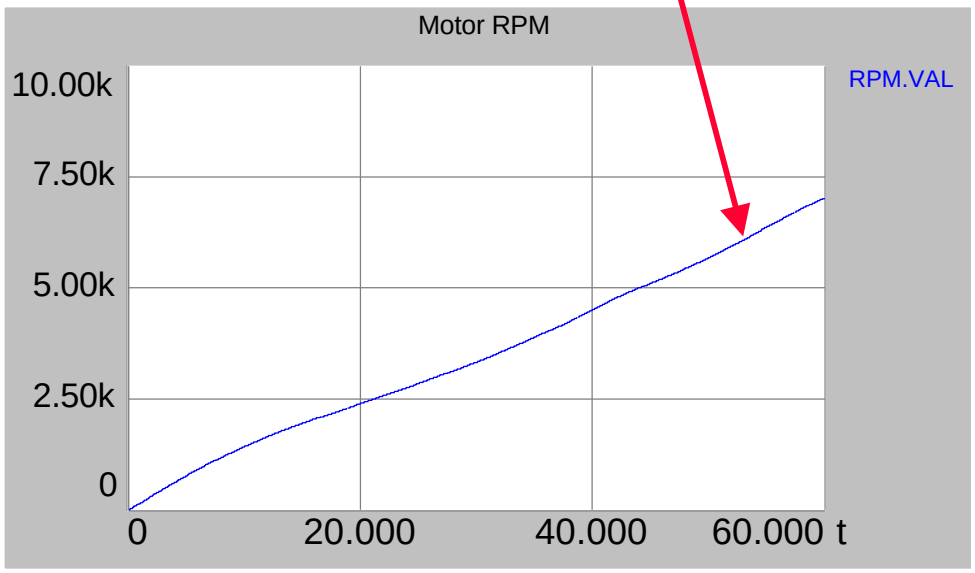
Quiescent Domain

Block Diagram Simulation

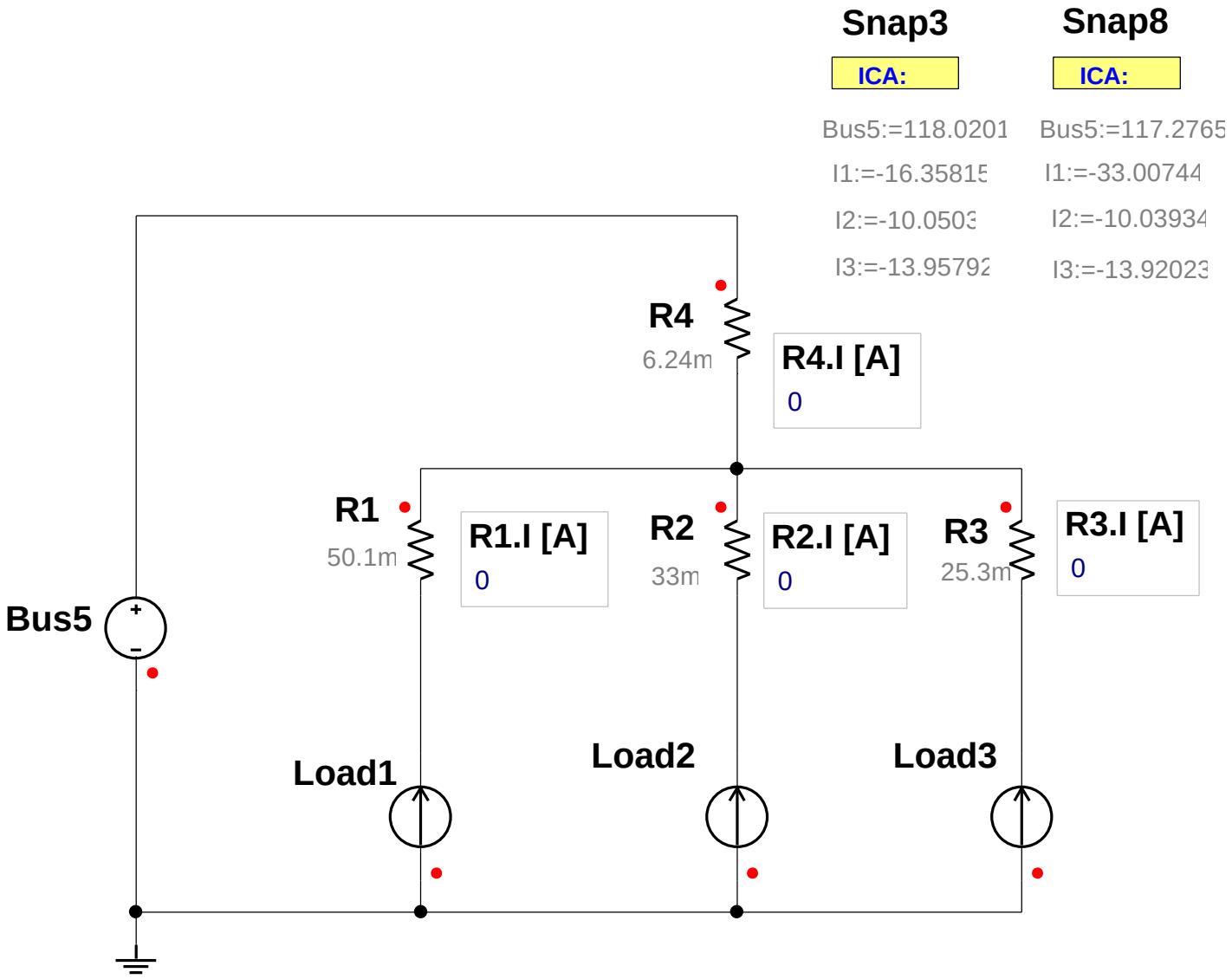
Generic Motor Starting to 6000 RPM



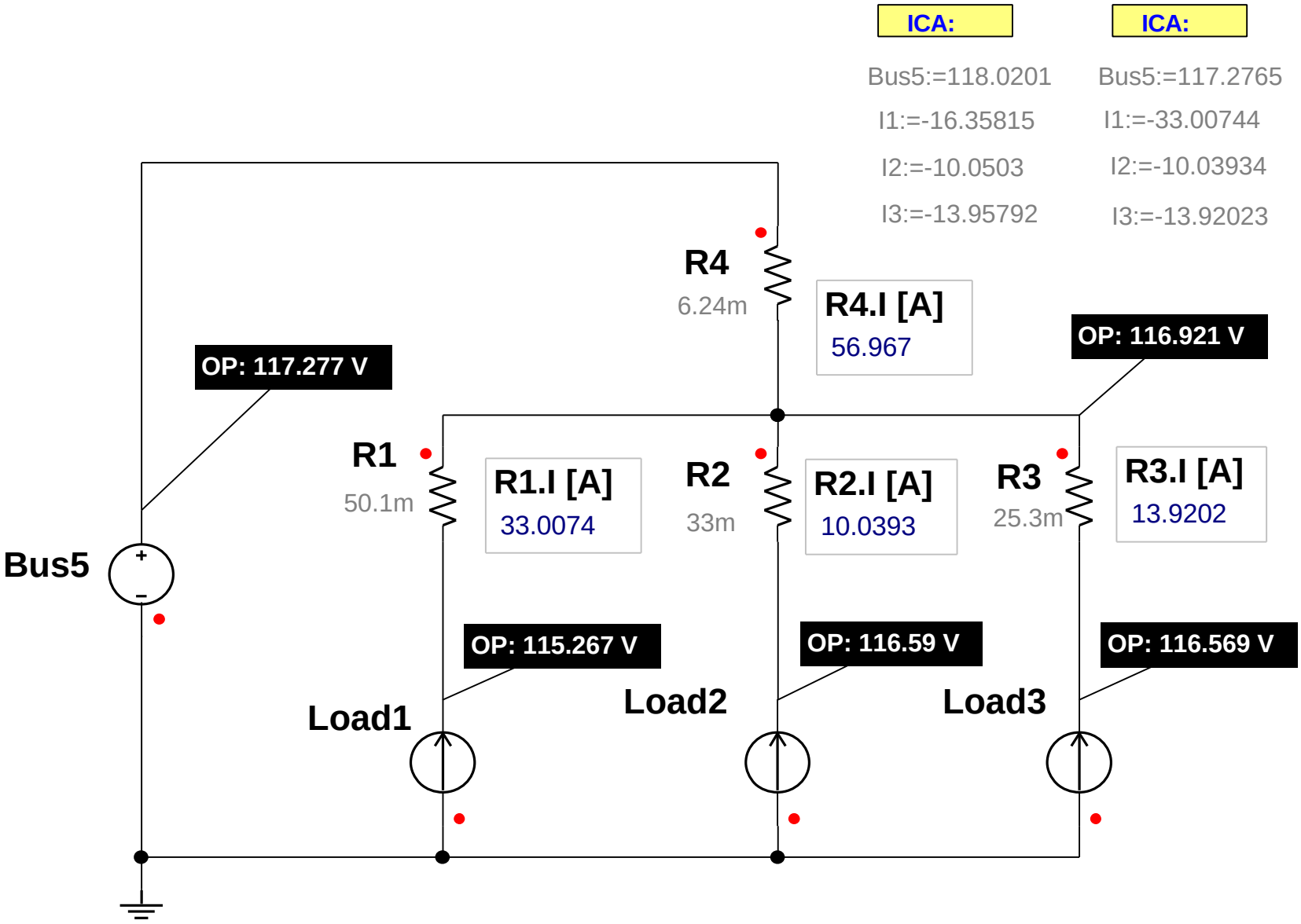




Generic Low-Order DC Models



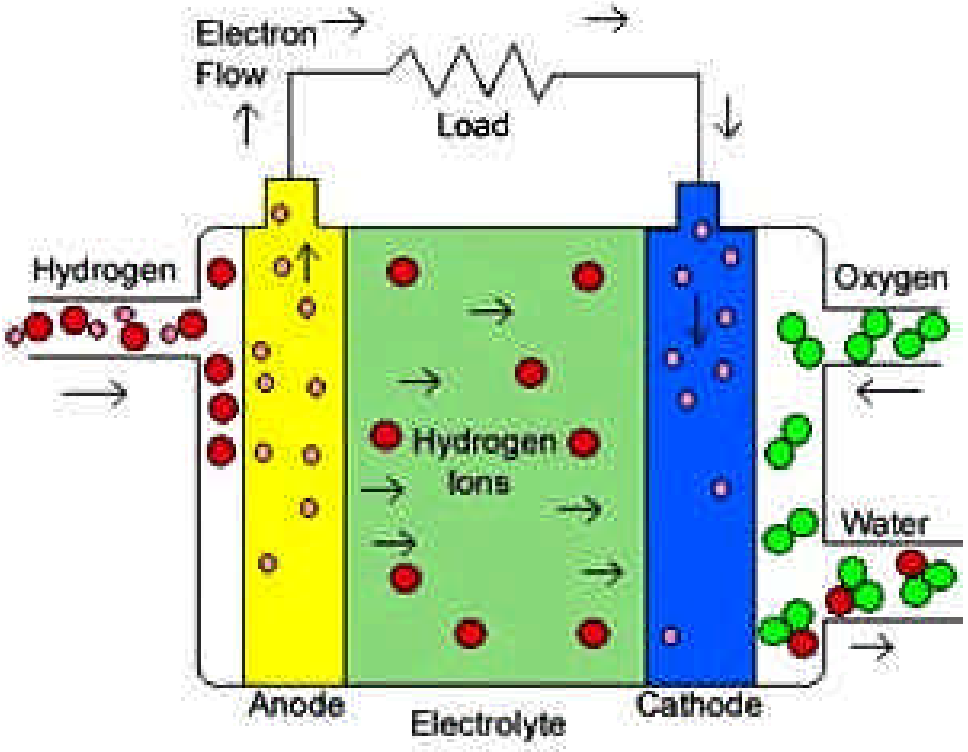
DC Load Flow Analysis Results



DC Power Applications

- Fuel Cells
- Batteries
- Ultra Capacitor

Proton Exchange Membrane Fuel Cell Model & Parameters



- Cathode mode: Oxygen or Air
- Temperature
- Membrane area
- Membrane thickness
- Membrane water content ?
- Electronic resistance

Simplorer PEM Fuel Cell Model

Generalized Steady-State Electrochemical Model

$V_{cell} = E_{nernst} + ?_{act,a} + ?_{act,c} + ?_{ohmic}$

- Thermodynamic Potential

  $E_{nernst} = f(T, p^*_{H2}, p^*_{O2})$

- Activation Voltage Loss

  $?_{act} = ?_{act,a} + ?_{act,c} = ?_1 + ?_2 T + ?_3 T \ln(c^*_{O2}) + ?_4 \ln(i)$

- Ohmic Voltage Loss

  $?_{ohmic} = -i \cdot (R_{electronic} + R_{proton})$

  $R_{proton} = l / A * r_M(?)$

i : Cell Current

T: Cell Temperature

p^*_{H2}, p^*_{O2}; Hydrogen and oxygen pressures at the electrode-electrolyte interface

$?_1, ?_2, ?_3, ?_4$: Empirical coefficients

c^*_{O2}: Oxygen concentration

l: Membrane thickness

A: Cell Area

?: Water content

$r_{M:}$ Membrane specific resistivity

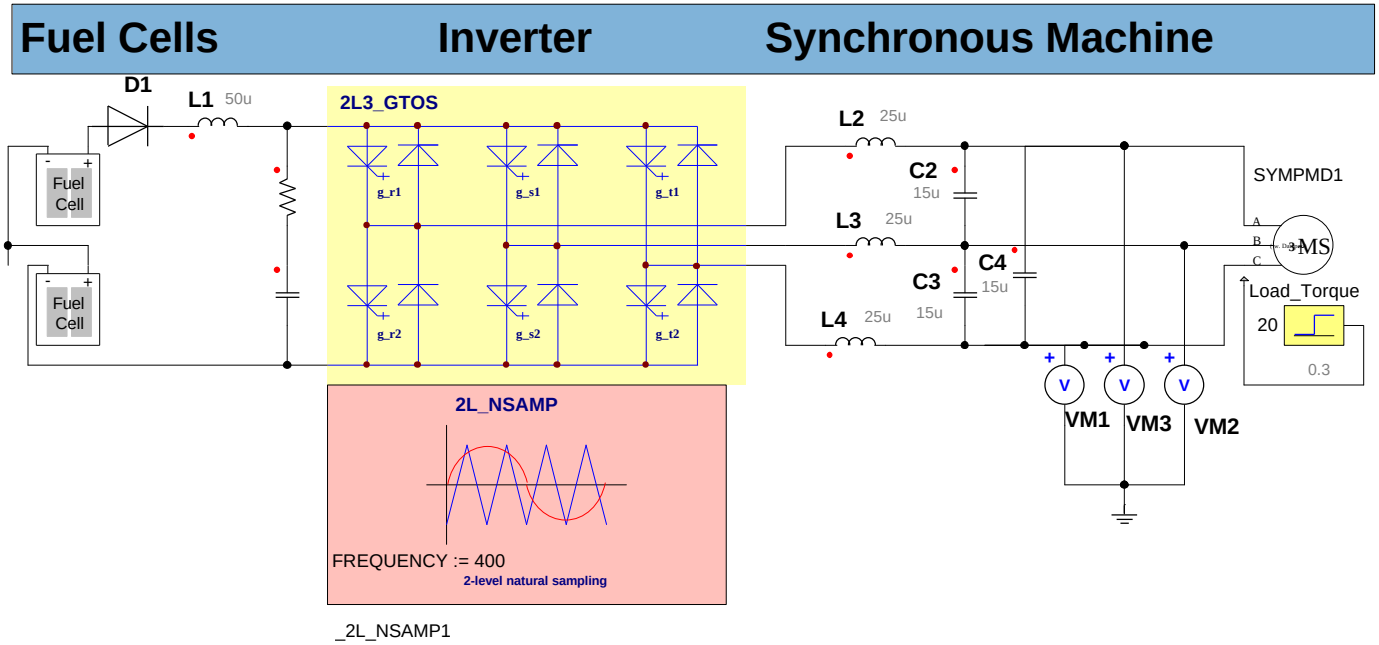
Electrical Power Systems Integration

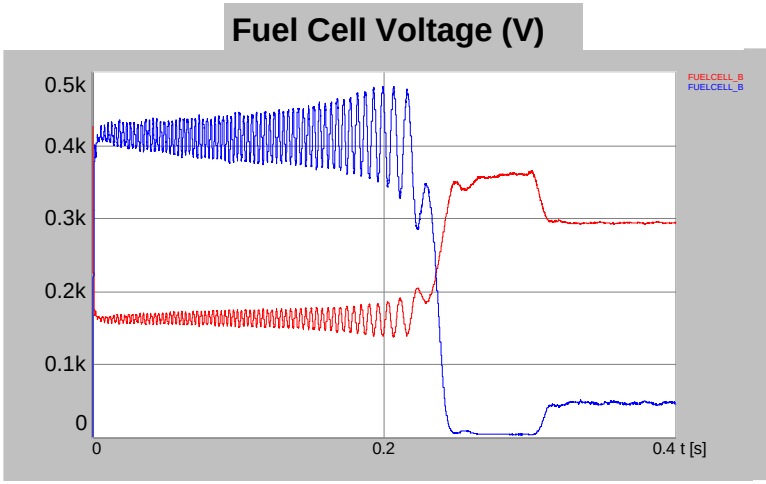
- Detailed analysis of fuel cells integrated in electrical power system is required for the understanding of the design integration in commercial airplane configuration

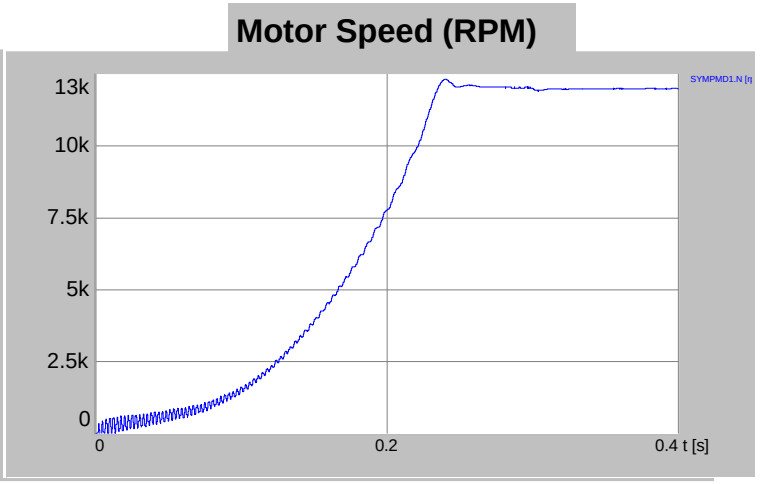
- Fundamental framework and toolset for Fuel Cell Power System Model are developed
  - 270 V Fuel Cell System powering an inverter and a motor
  - 120 V Fuel Cell System powering low-voltage electronic loads
  - Battery and Ultracapacitor Models
  - Paralleled Battery and Fuel Cell Power Source

Generic Fuel Cell Power System and Load

270VDC Fuel Cell Power System Model

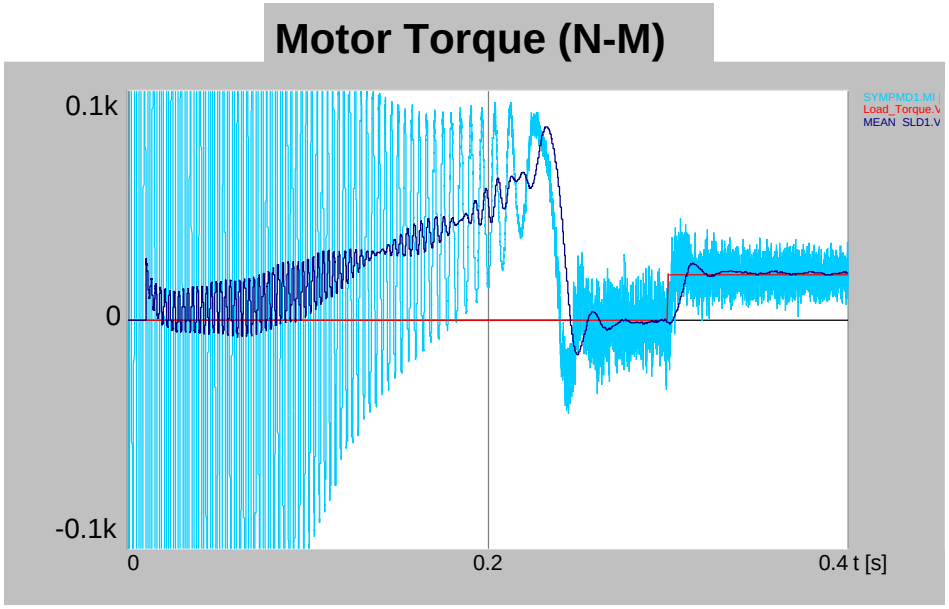


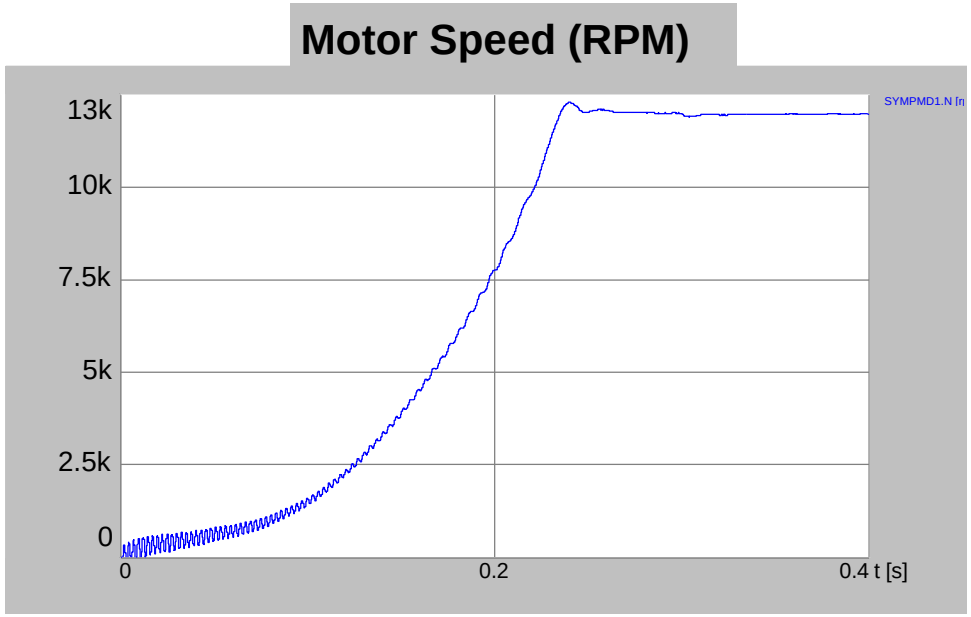




Synchronous Motor Start and Load Variation

Simplorer Model

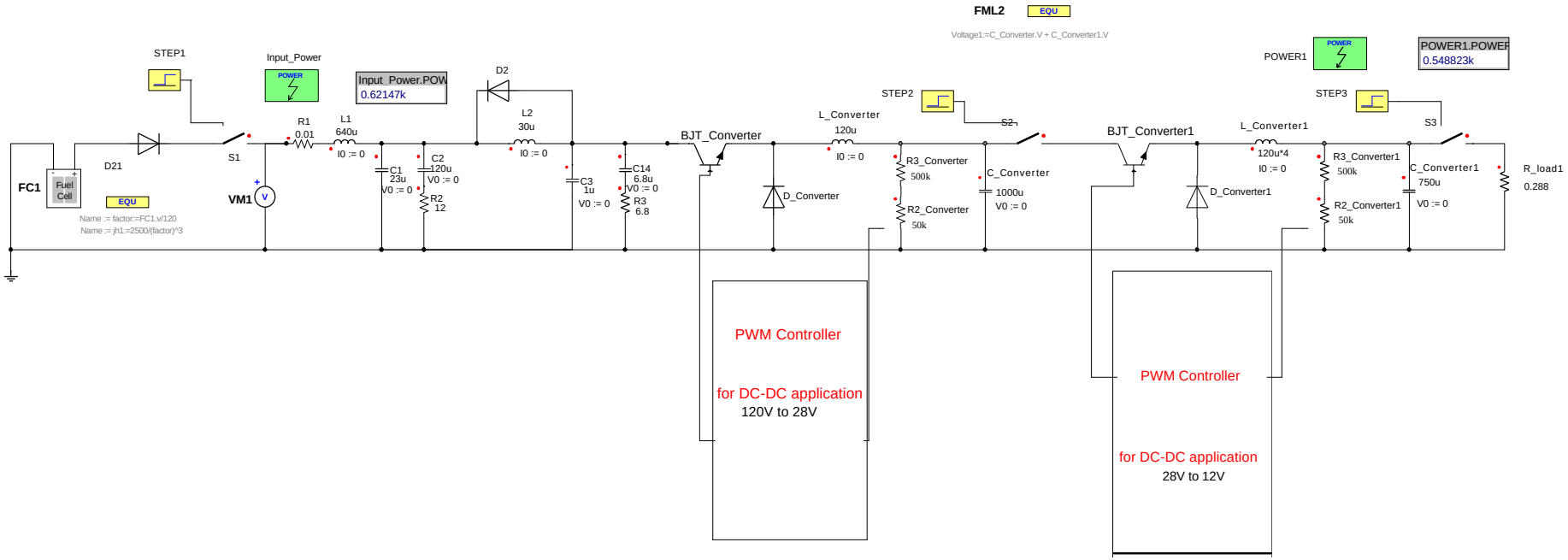




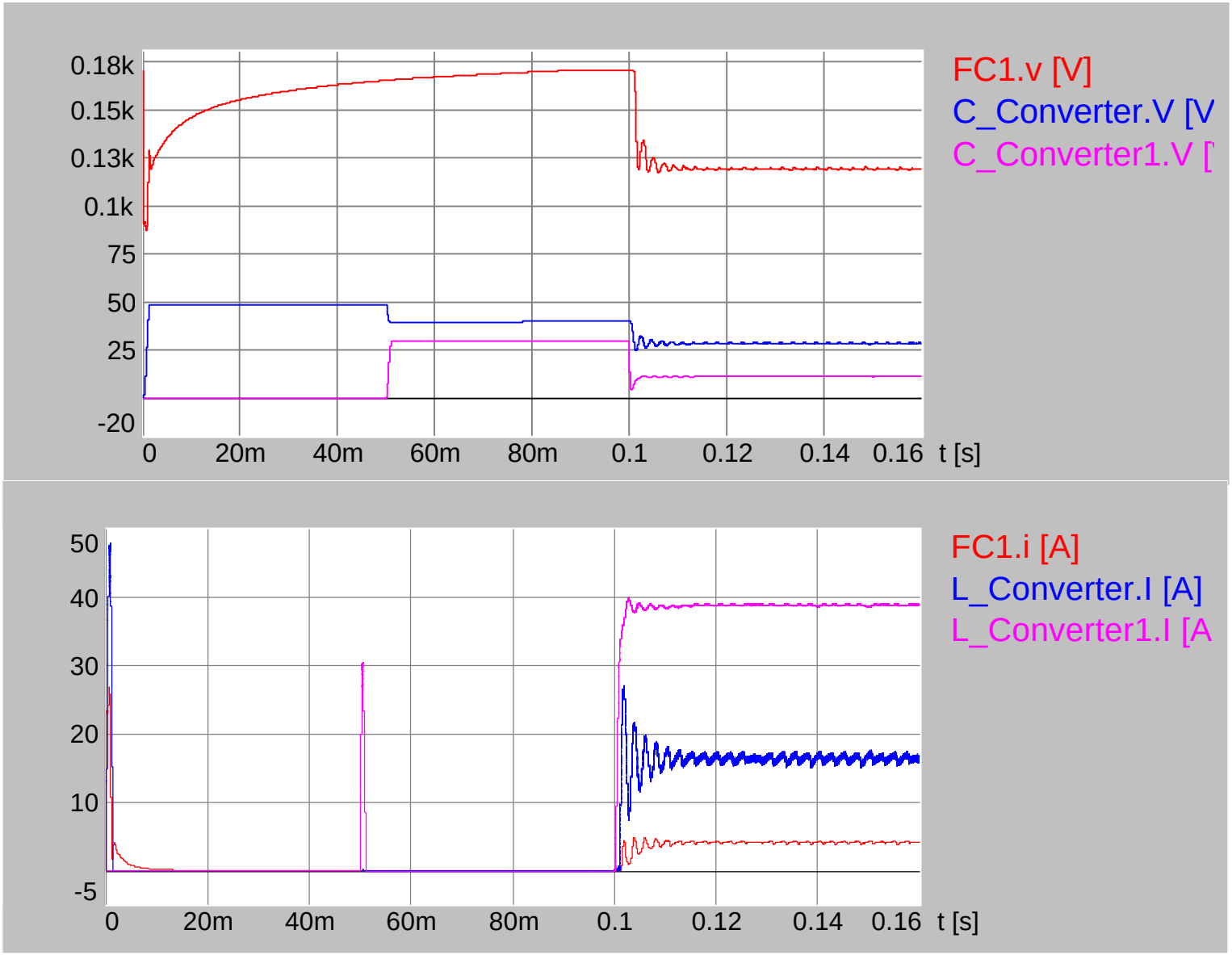
Generic Fuel Cell Power System and Load

120VDC Fuel Cells Powering Low-Voltage Electronic Loads

Fuel Cells	Filter	120/28VDC Conv	28/12VDC Conv

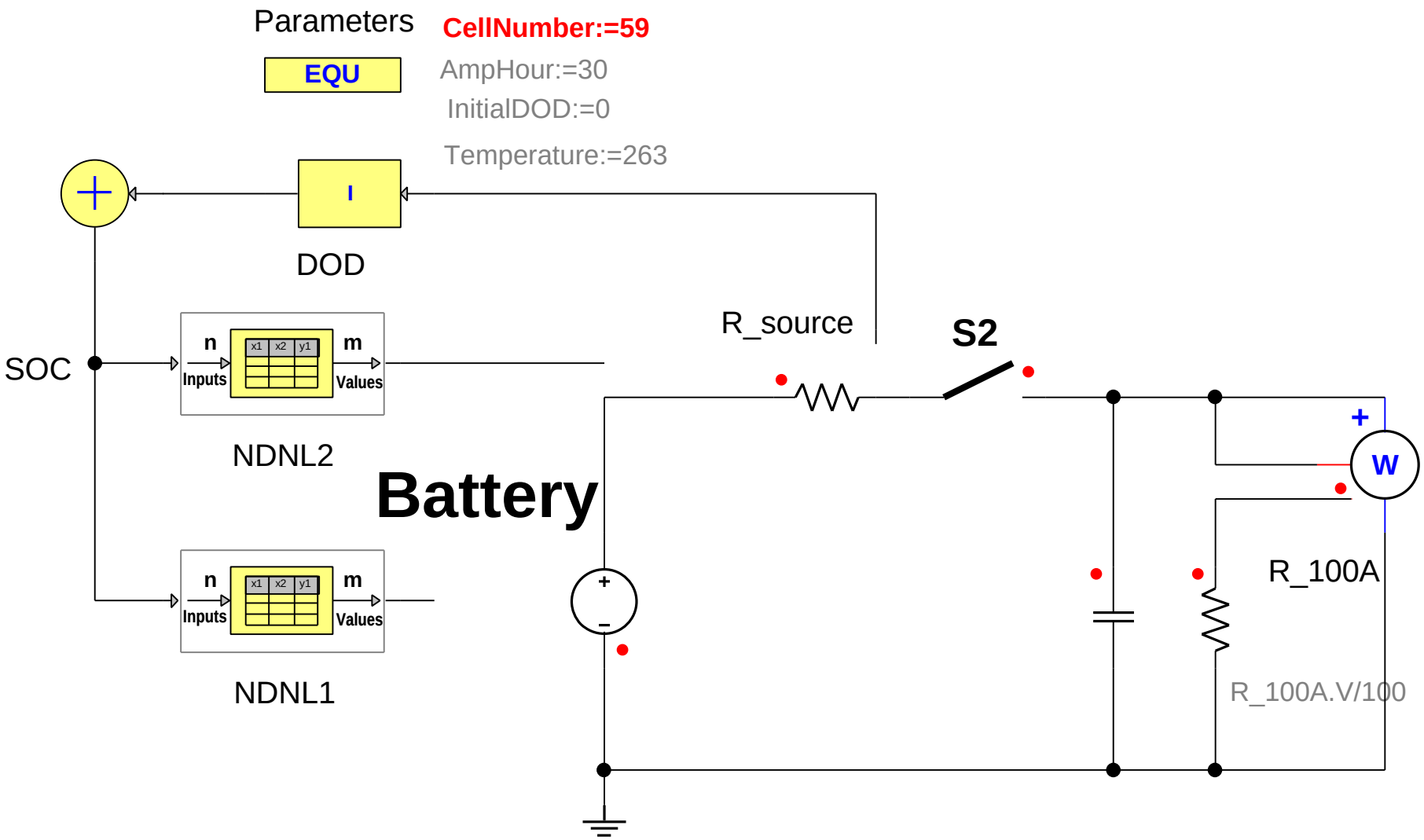


Voltage and Current Responses



Battery and Fuel Cells in Parallel

Lithium-Ion Battery
Equivalent Circuit Model

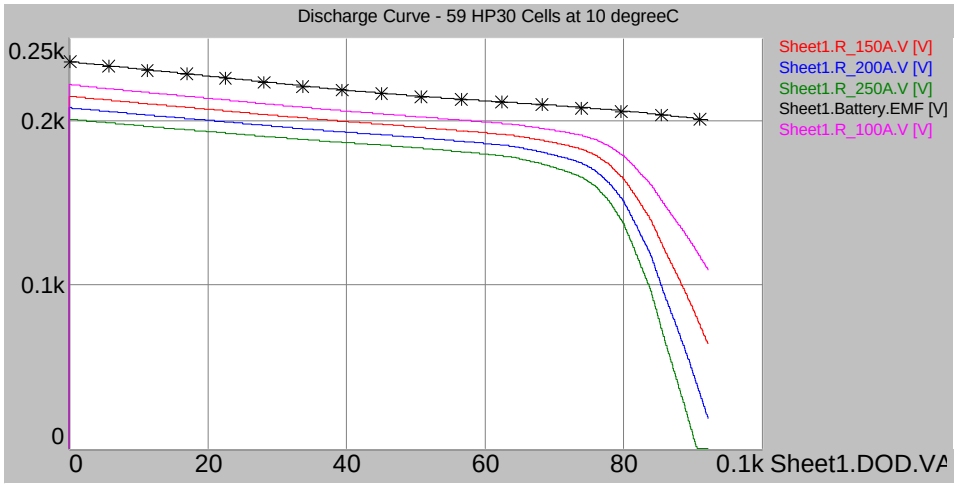


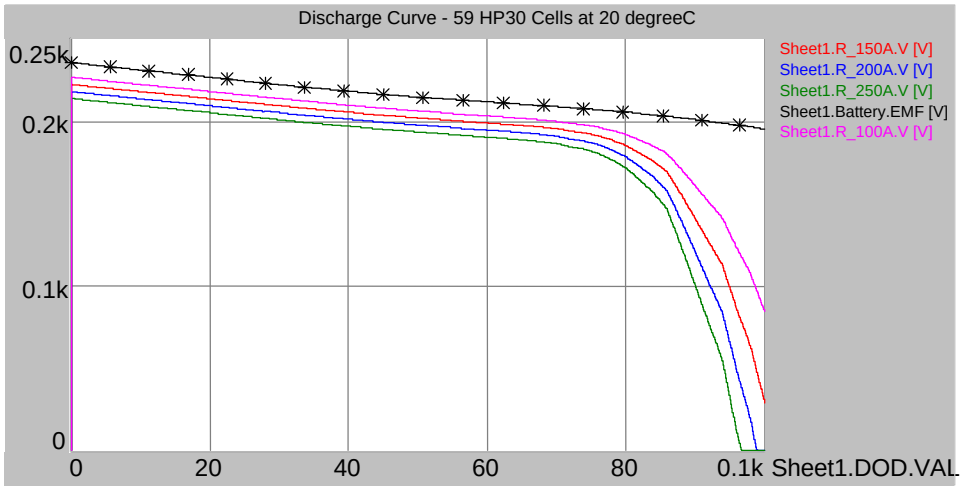
Lithium-Ion Battery Model

Discharge Curves for 59-Cell Battery

Battery Terminal Voltage (volts) v.s. Depth-of-Discharge (percent)

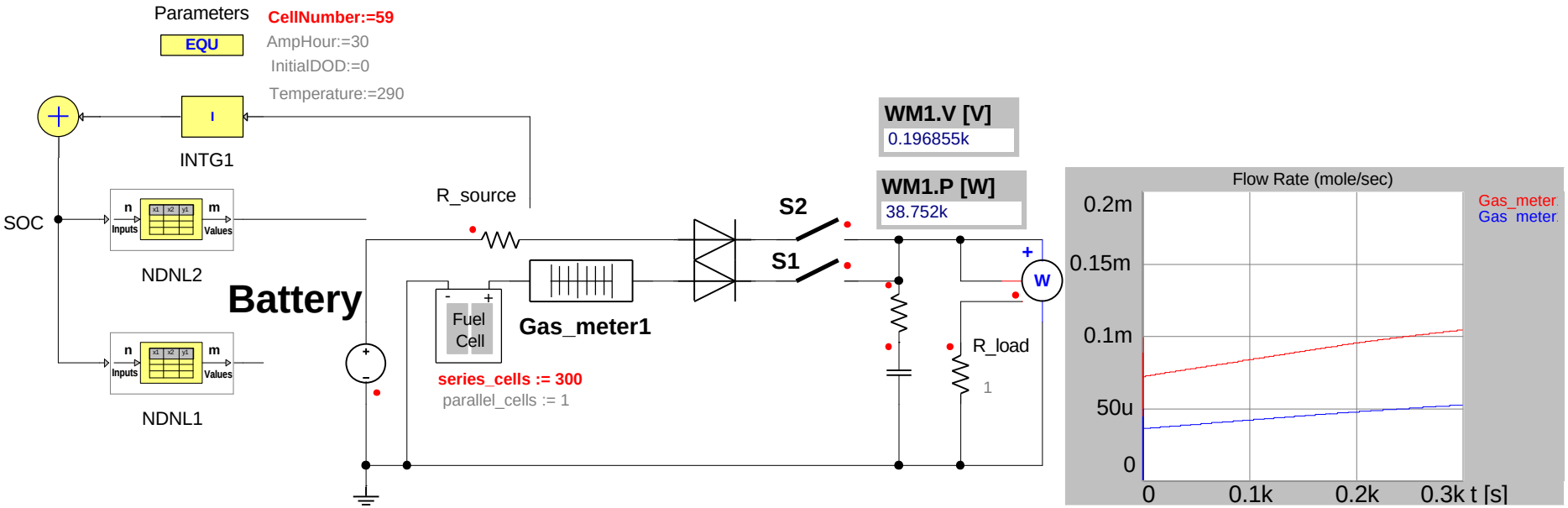
Discharge Current (Amps) – No Load, 100A, 150A, 200A and 250A

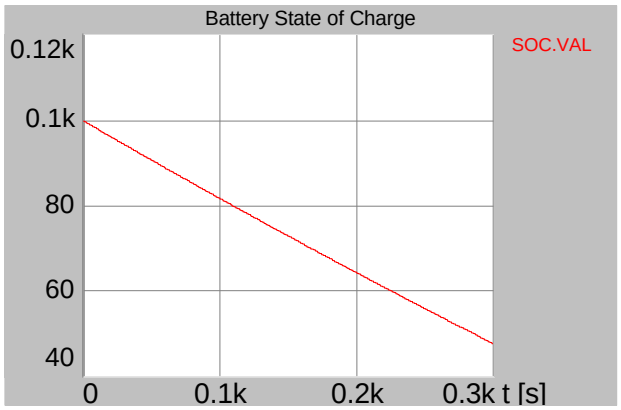


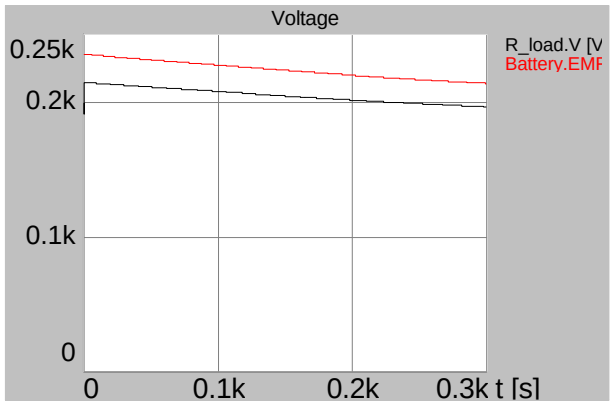


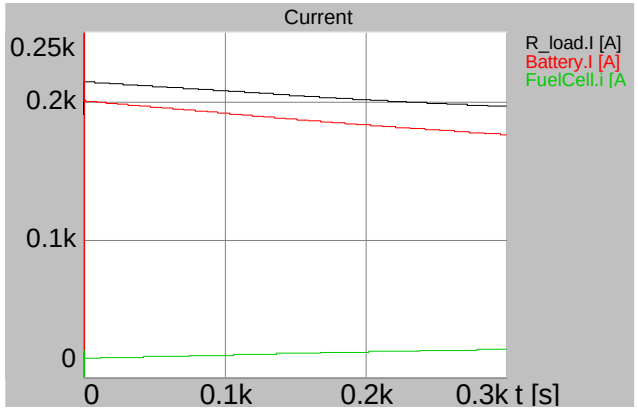
Paralleled DC Sources

Fuel Cells and Lithium-Ion Battery





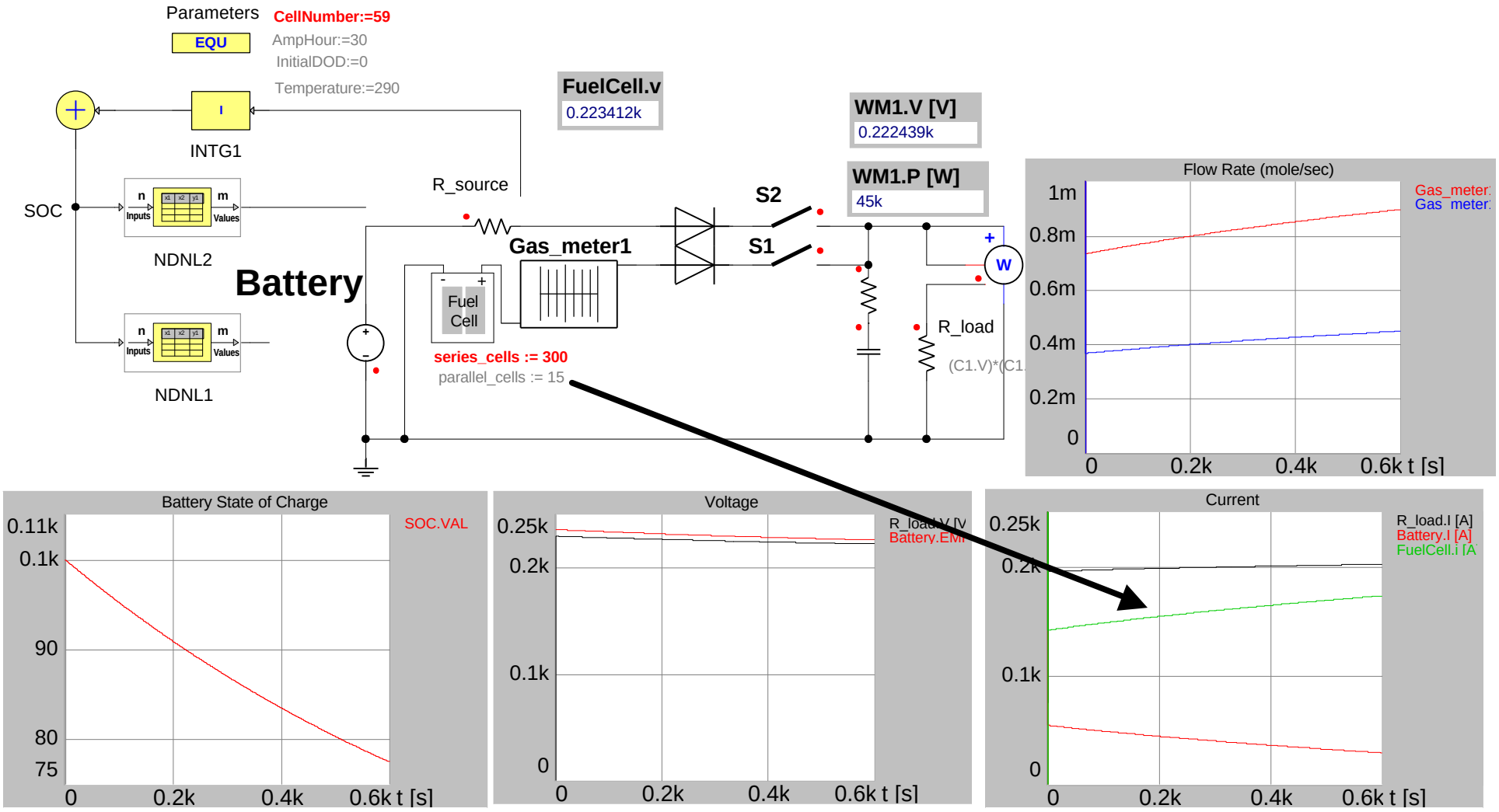




Paralleled DC Sources

Fuel Cells and Lithium-Ion Battery

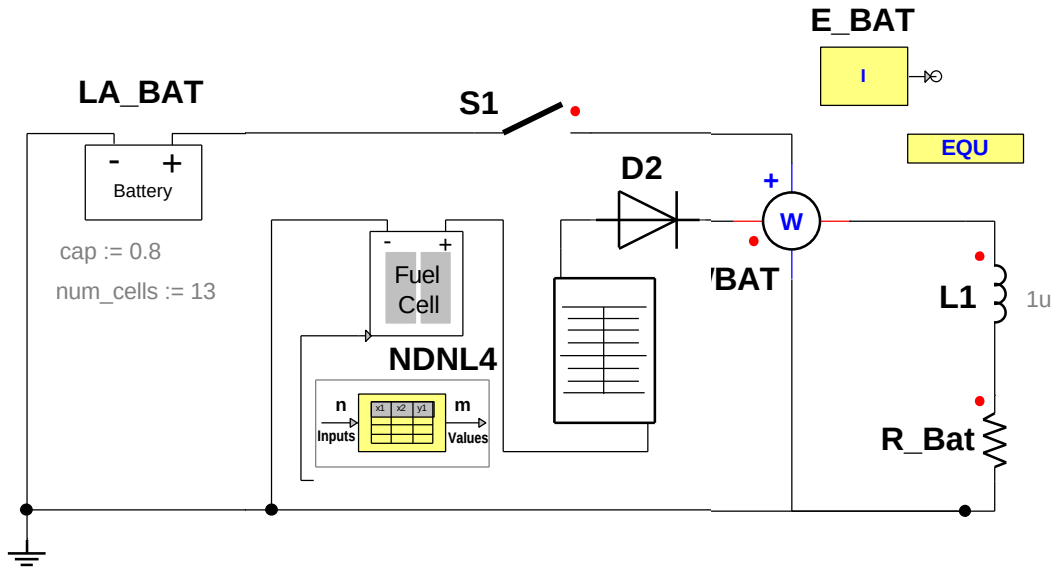
Fuel cell current increases with size

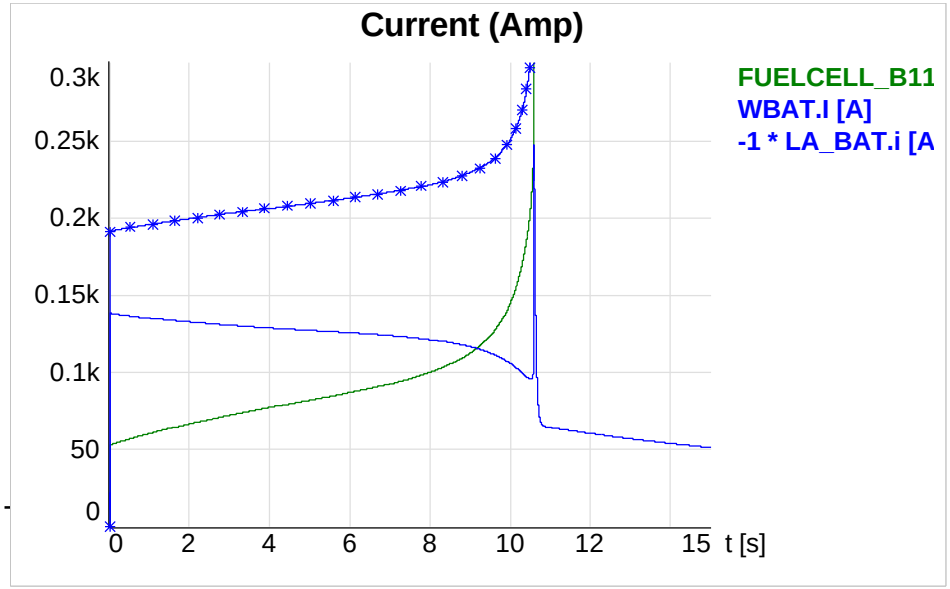


Paralleled DC Sources

Fuel Cells and Lead-Acid Battery

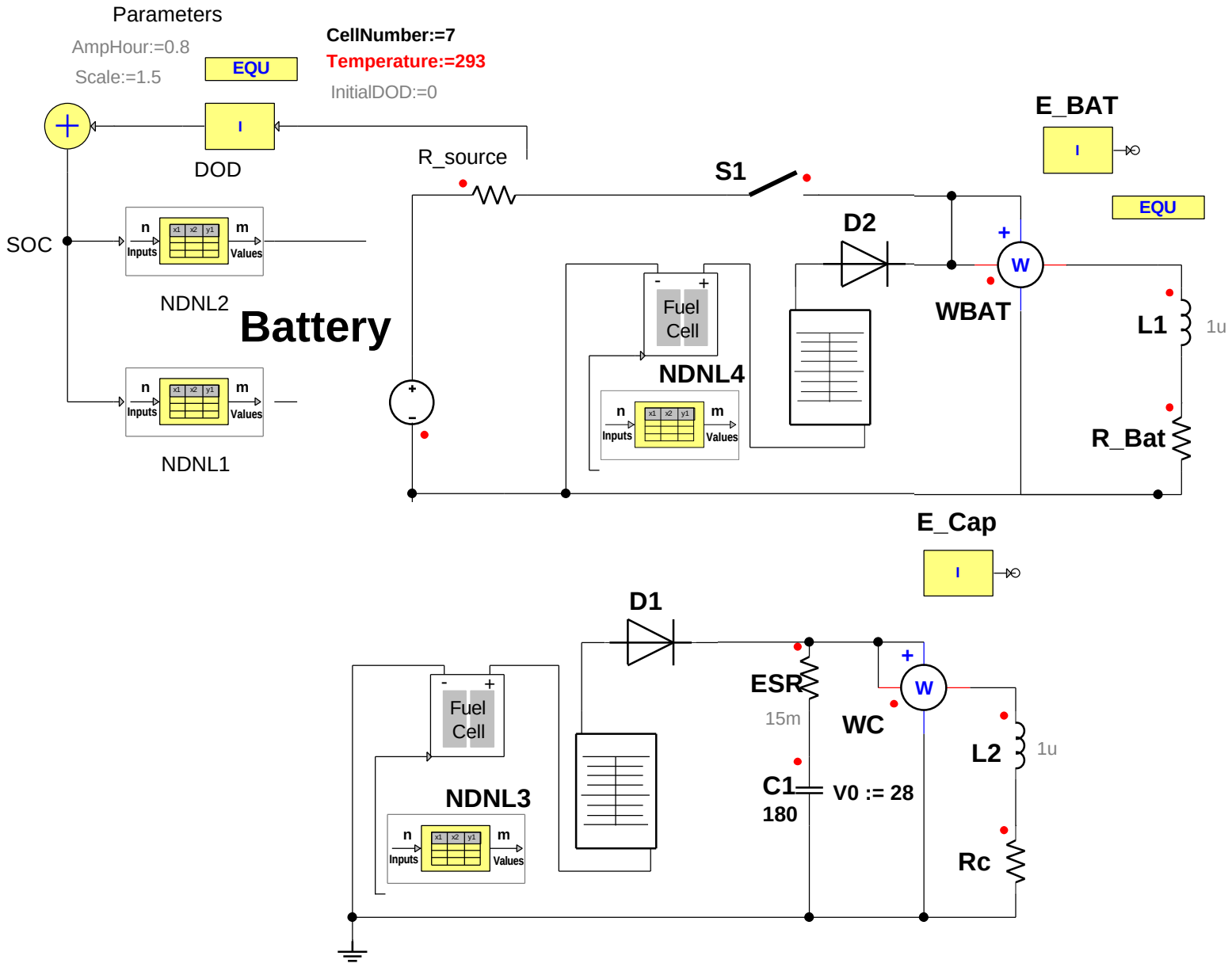
Lead Acid Battery





Battery and Ultra Cap Discharge

In Parallel with Fuel Cells

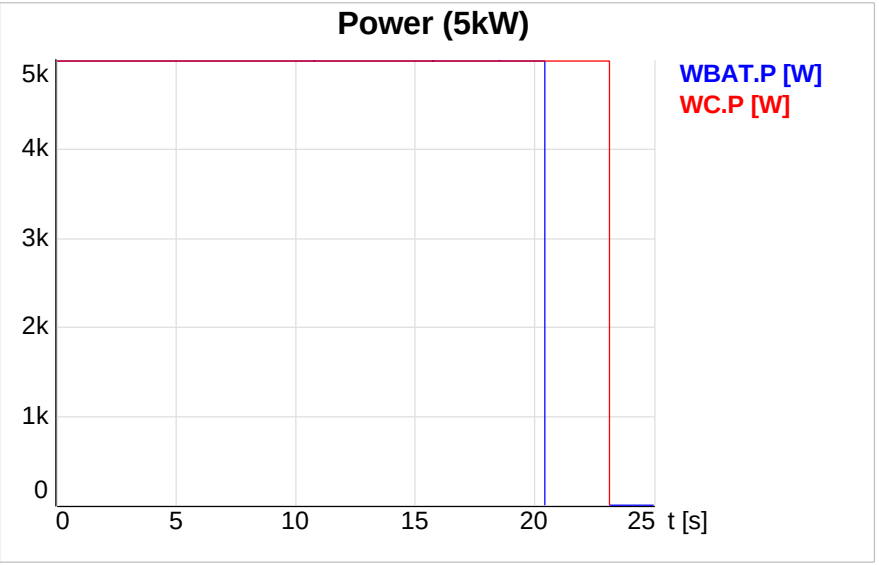


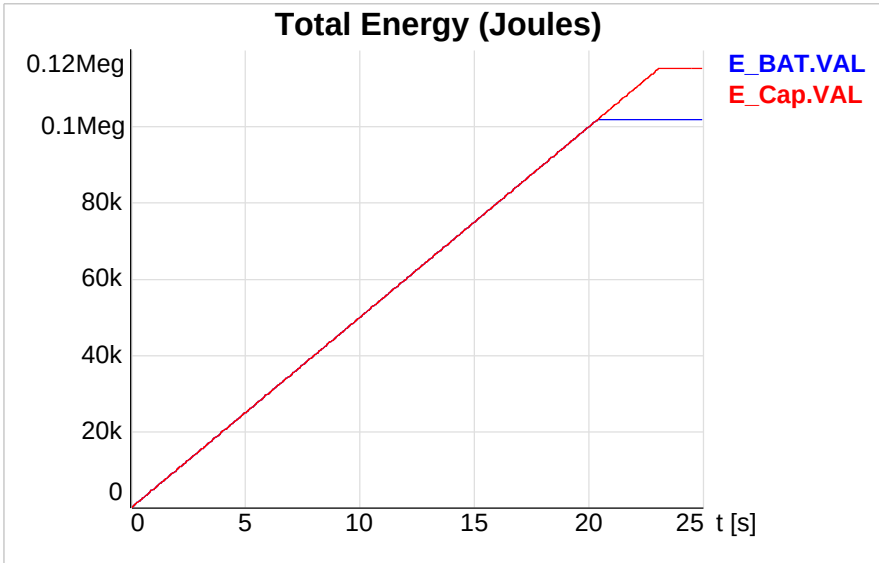
Battery and Ultra Cap Discharge

5 kW Constant Load

Fuel cells in Parallel with Battery

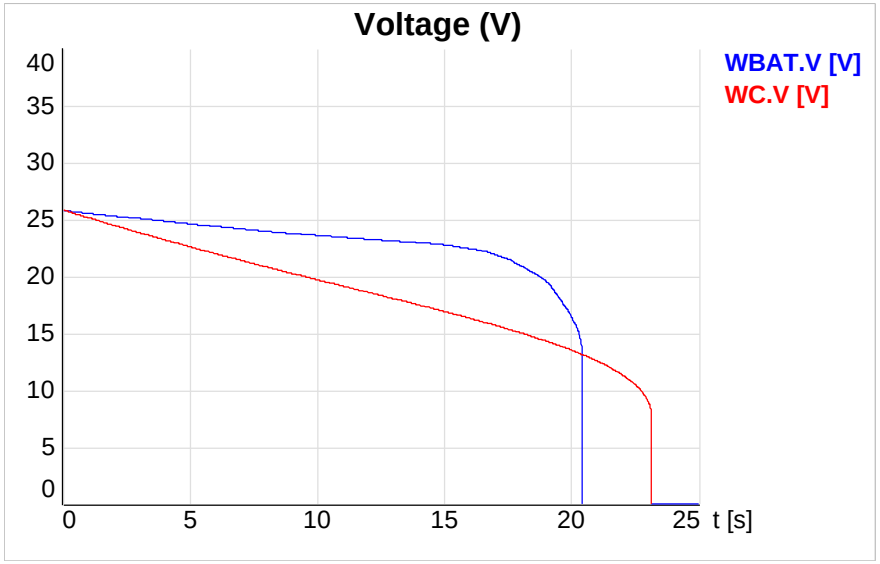
Fuel cells in Parallel with Ultracapacitor





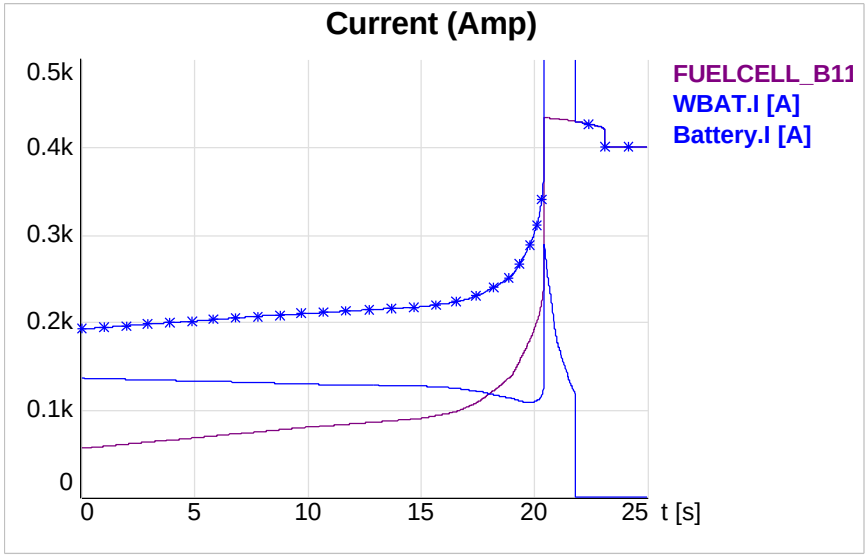
Battery and Ultra Cap Discharge

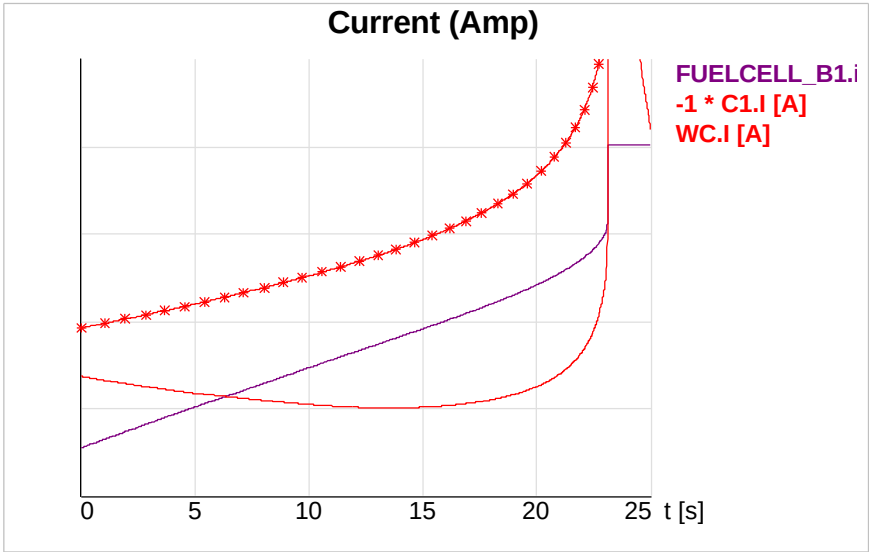
5 kW Constant Load



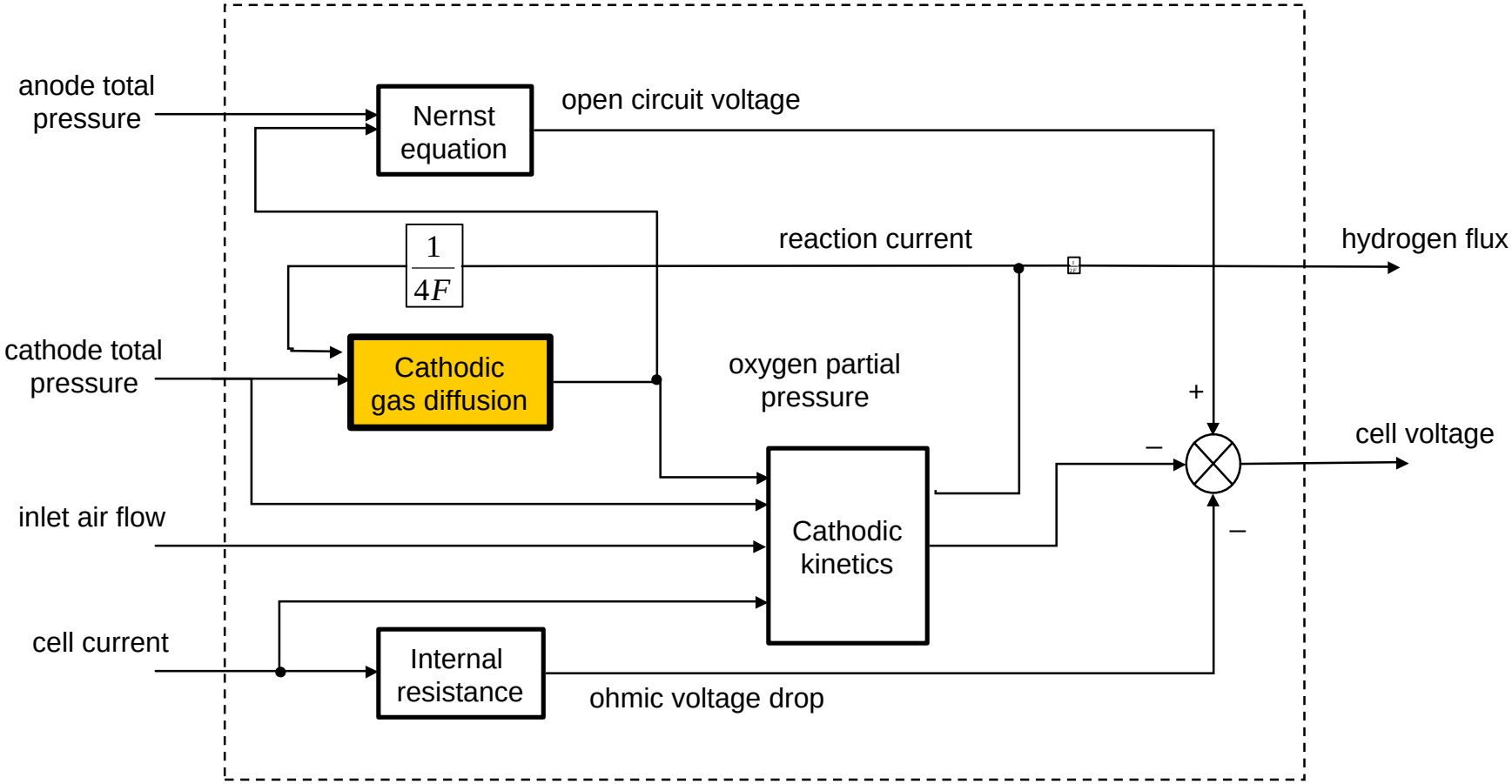
Fuel cells in Parallel with Battery

Fuel cells in Parallel with Ultracapacitor





Dynamic PEM Fuel Cell Model
Under Development with ANSOFT Corp.



Dynamic PEM Fuel Cell Model
Under Development with ANSOFT Corp.

Dynamics introduced by considering

1. Cathodic gas diffusion: $\frac{\partial p}{\partial t} = w \frac{\partial^2 p}{\partial x^2} - y \frac{i_r}{4F} \frac{\partial p}{\partial x}$, where *?* is a spatial coordinate, i_r is the reaction current, *?* and *?* are parameters calculated from geometrical properties and diffusion constants of the gases O_2, H_2 and H_2O. $p = p(t,?)$ is the oxygen partial pressure ^{i}

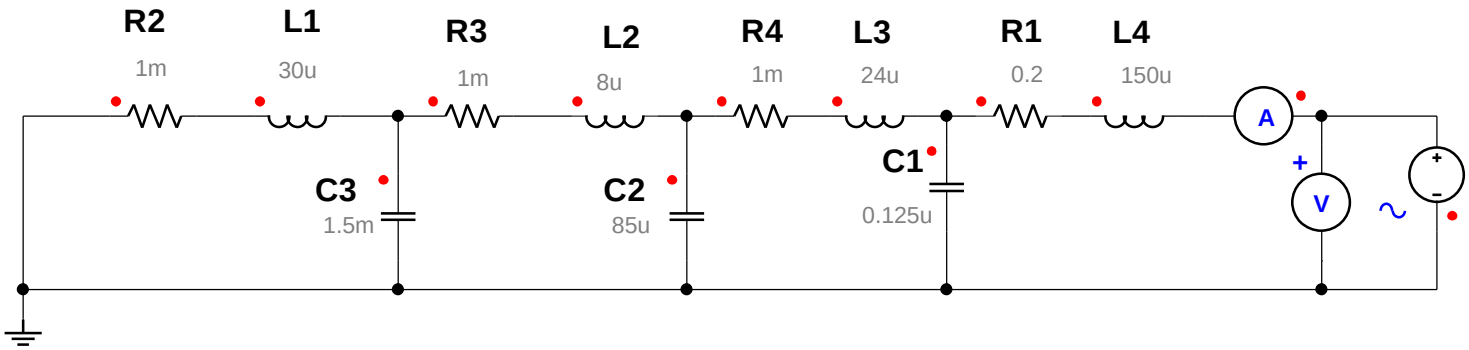
2. Double layer capacity: $i = i_r + C_{dl} \frac{\partial h}{\partial t}$, where *i* is the cell current, ? the cathodic overvoltage and C_{dl} the double layer capacity

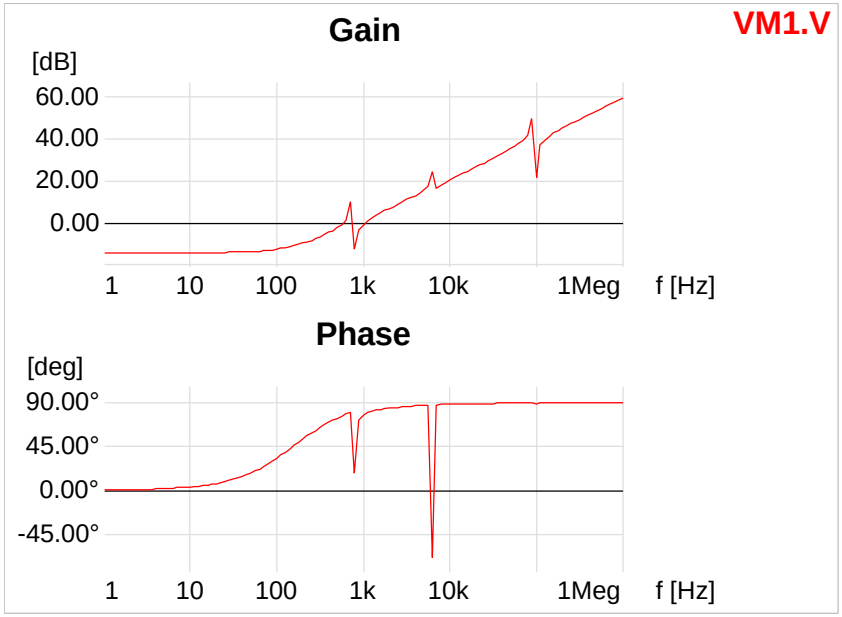
AC Analysis

- International Space Station Payload Ground Processing

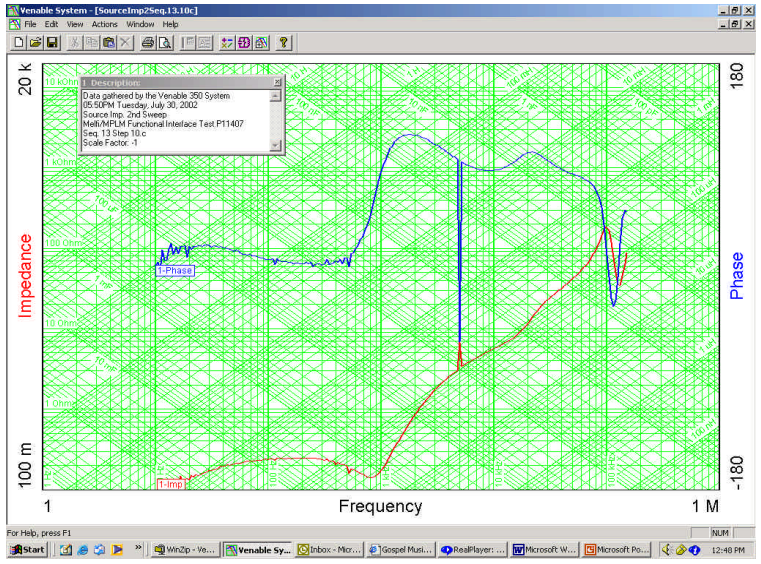
- Synchronous Generator

Model for Power Supply Output Impedance



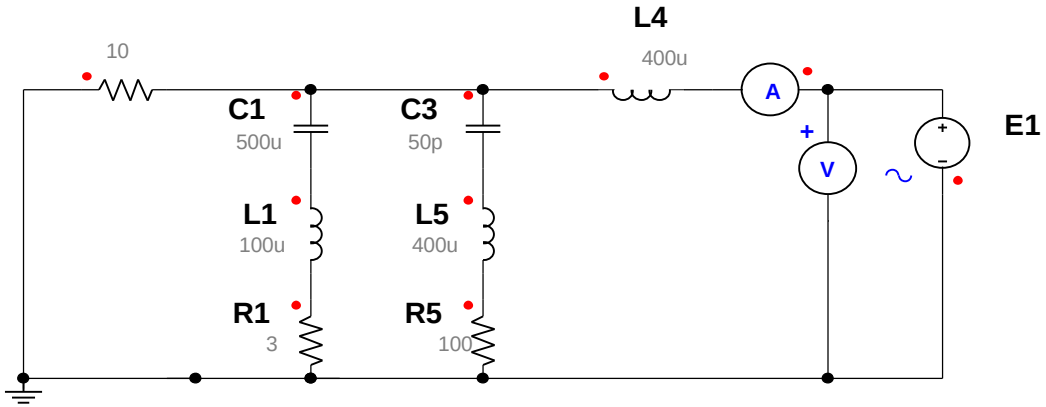


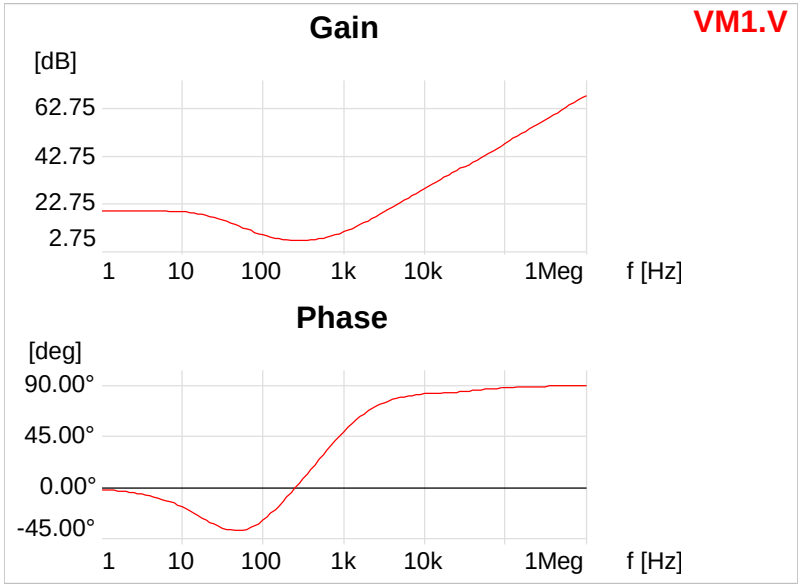
Model



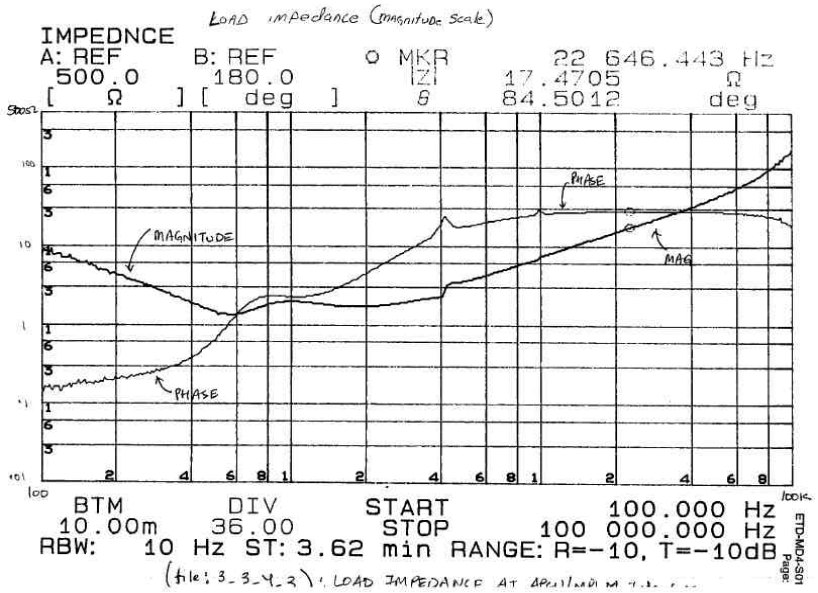
Test Data

Model for Logistics Module
Input Impedance



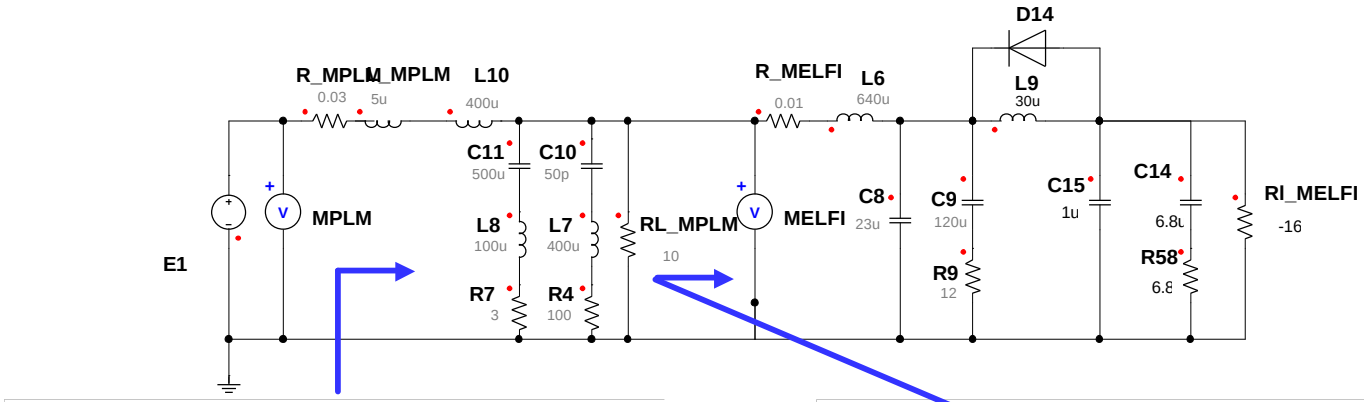


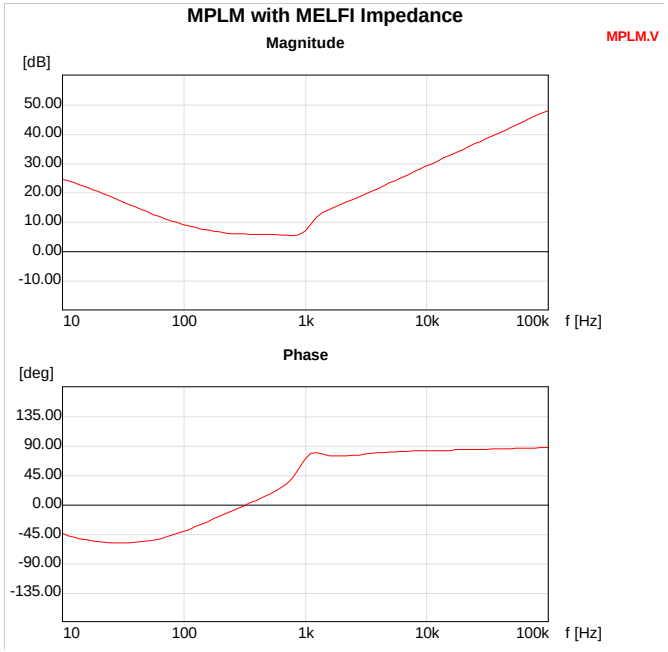
Model

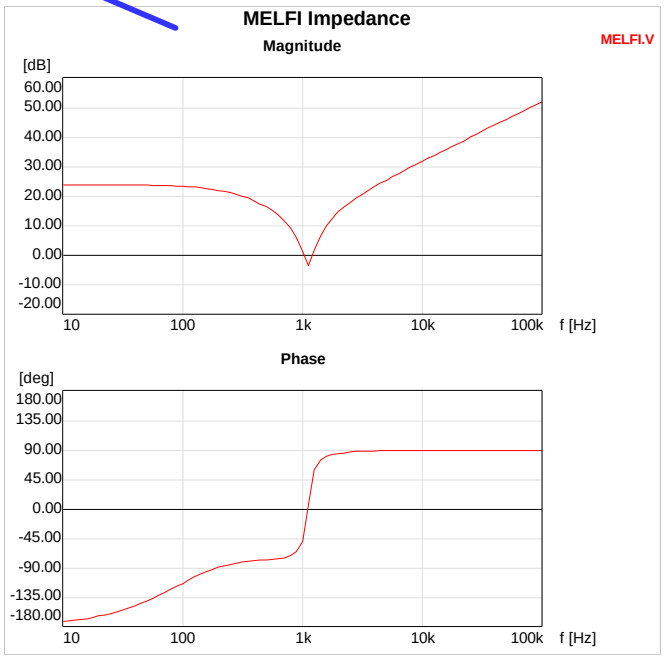


Test Data

Logistics Module (MPLM) & Payload (MELFI) Input Impedance

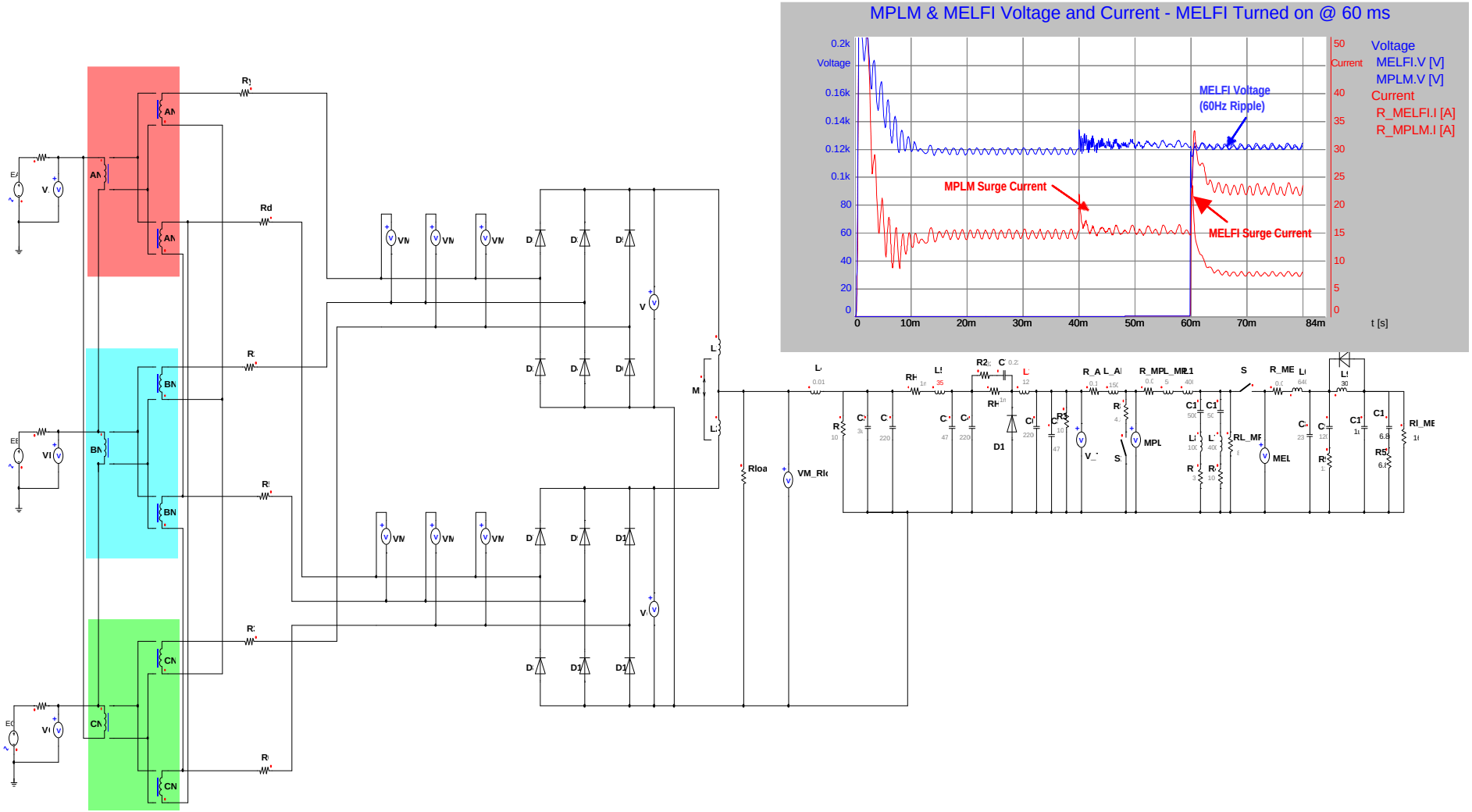






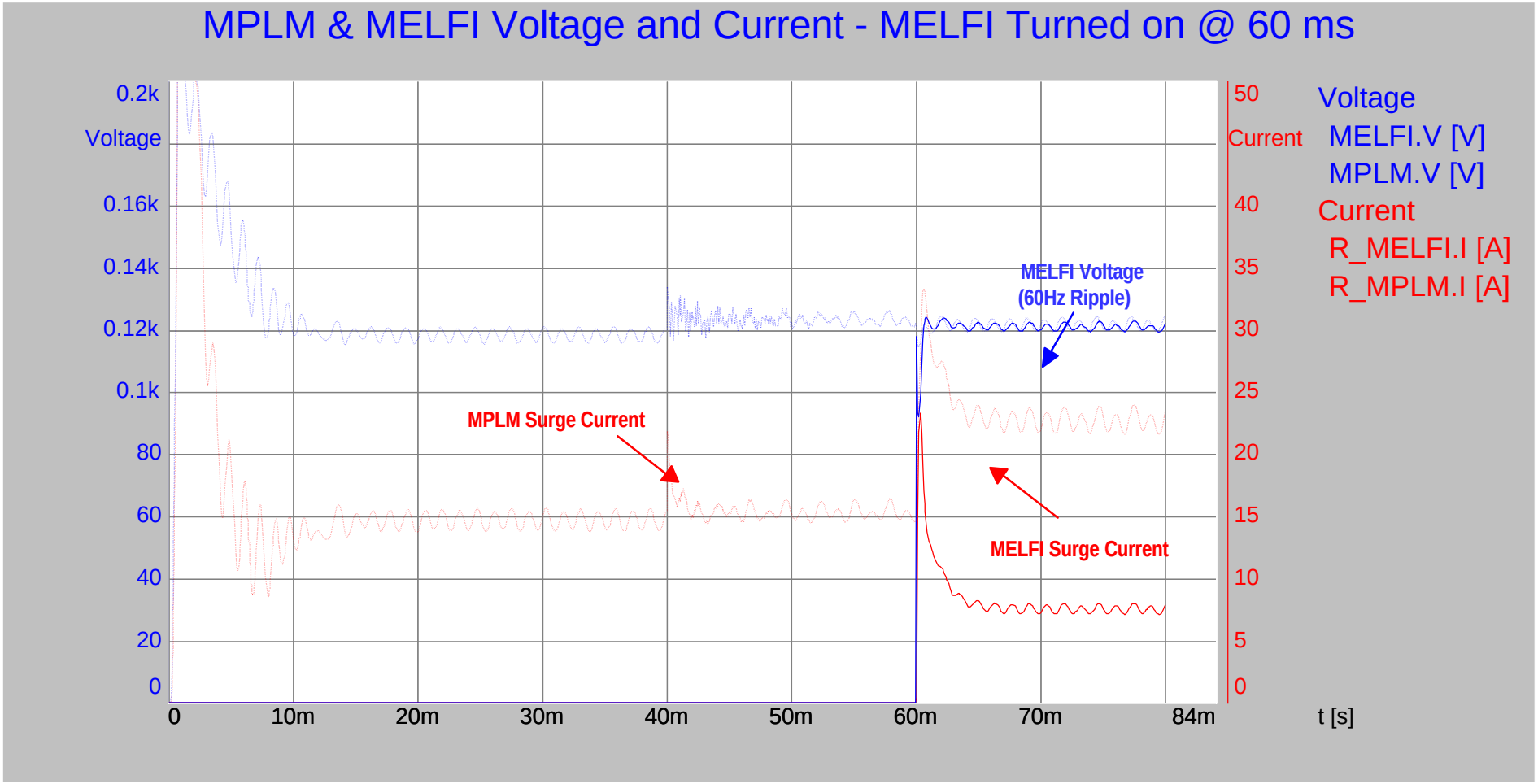
Integrated Power System Model

Power Supply/Anaconda Cable/MPLM/MELFI

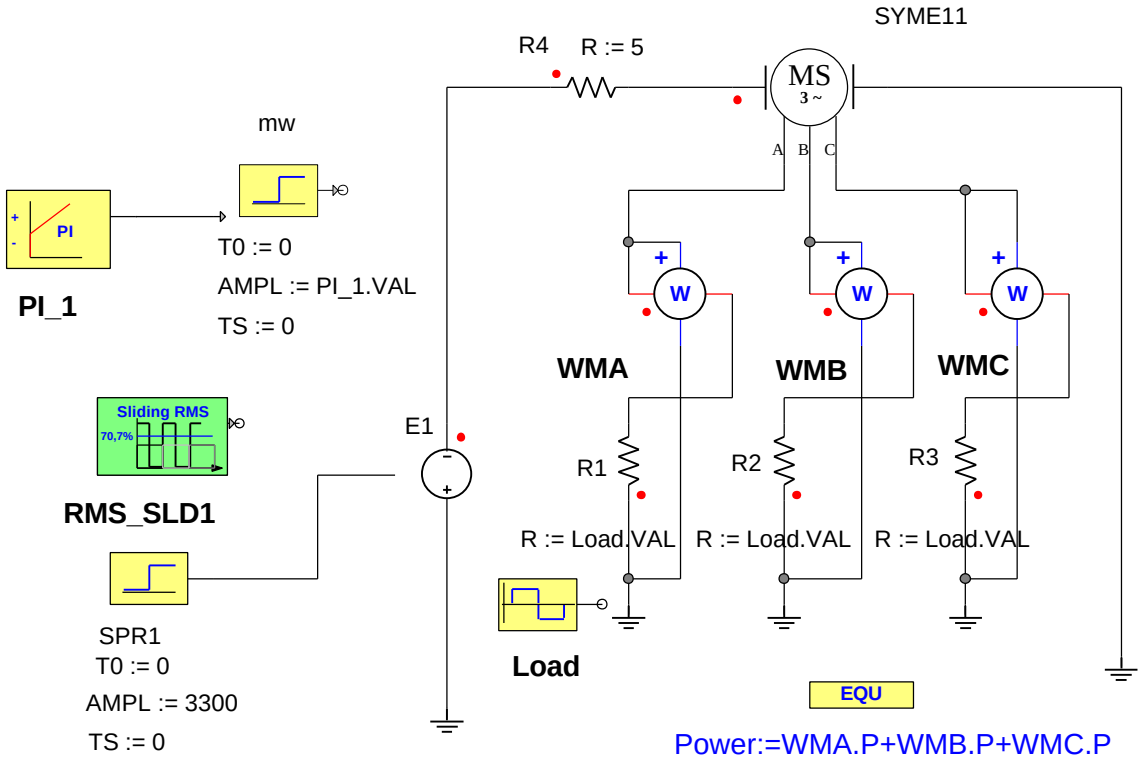


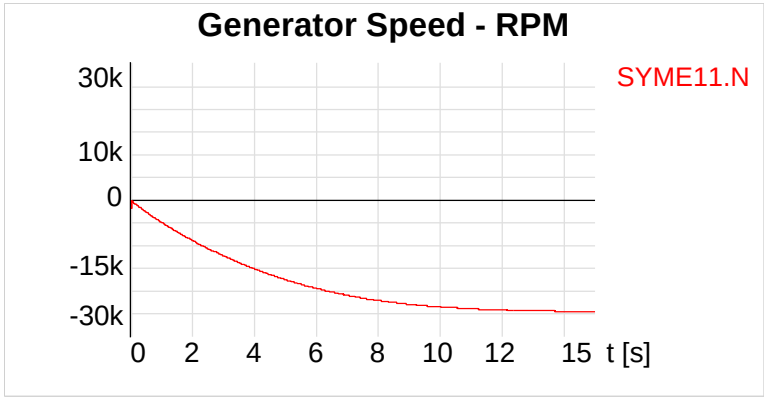
Integrated Power Model

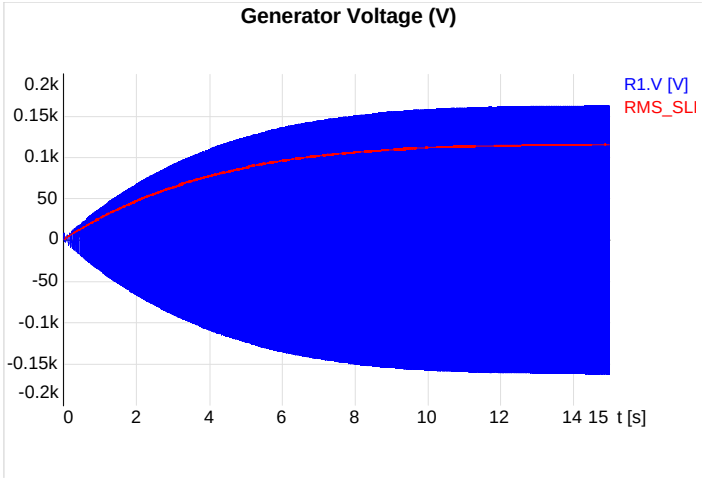
Power Supply/Anaconda Cable/MPLM/MELFI

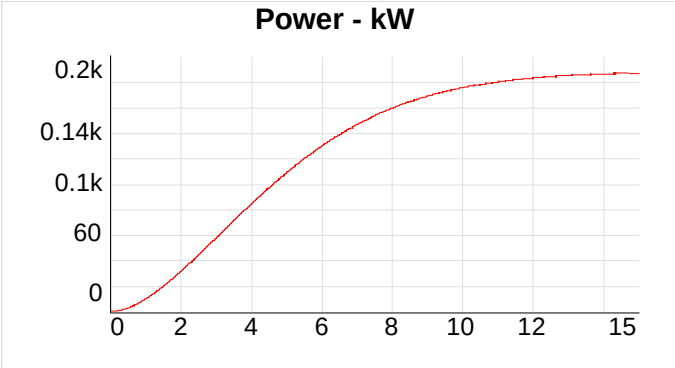


Generic Generator Model

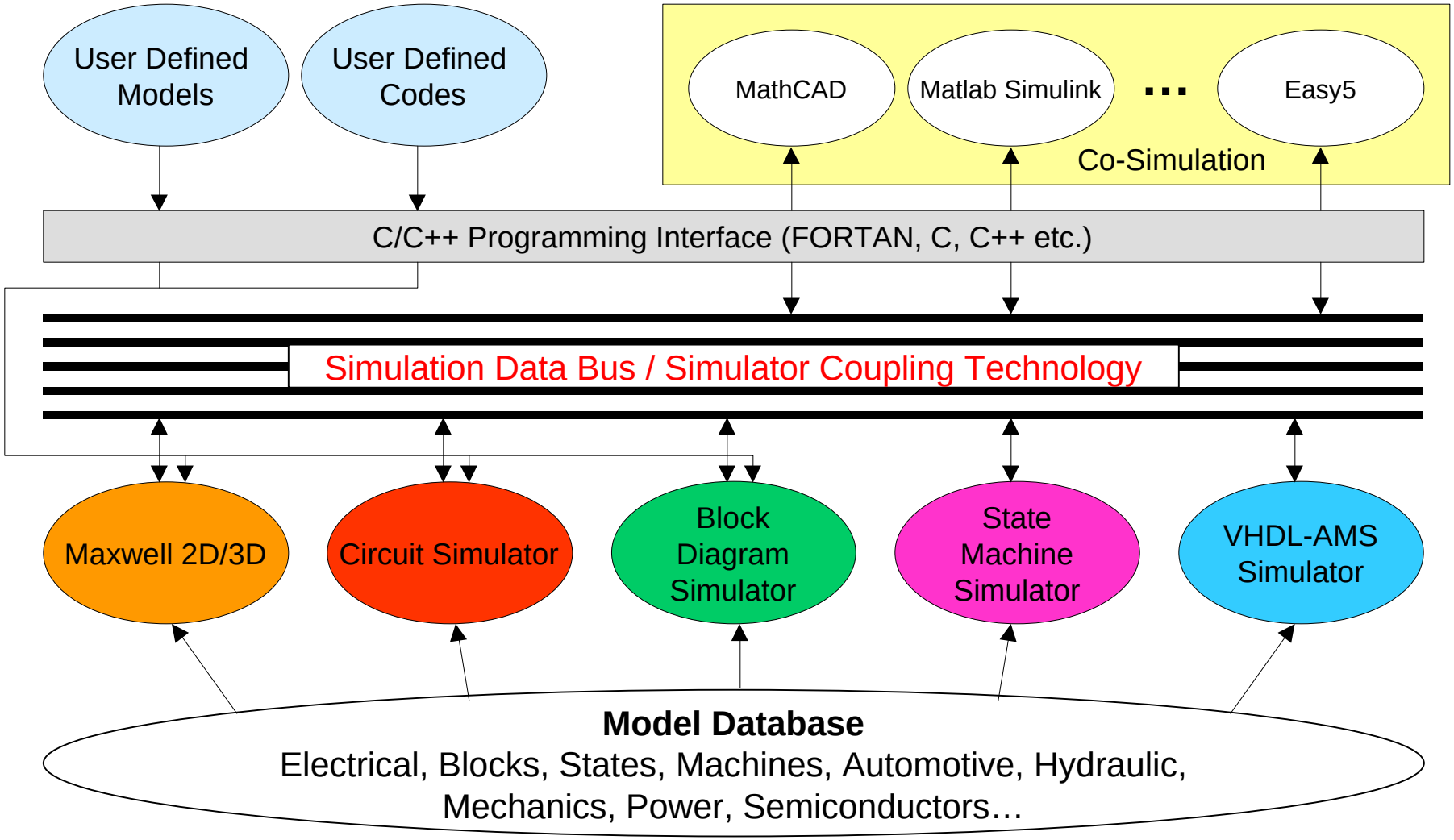








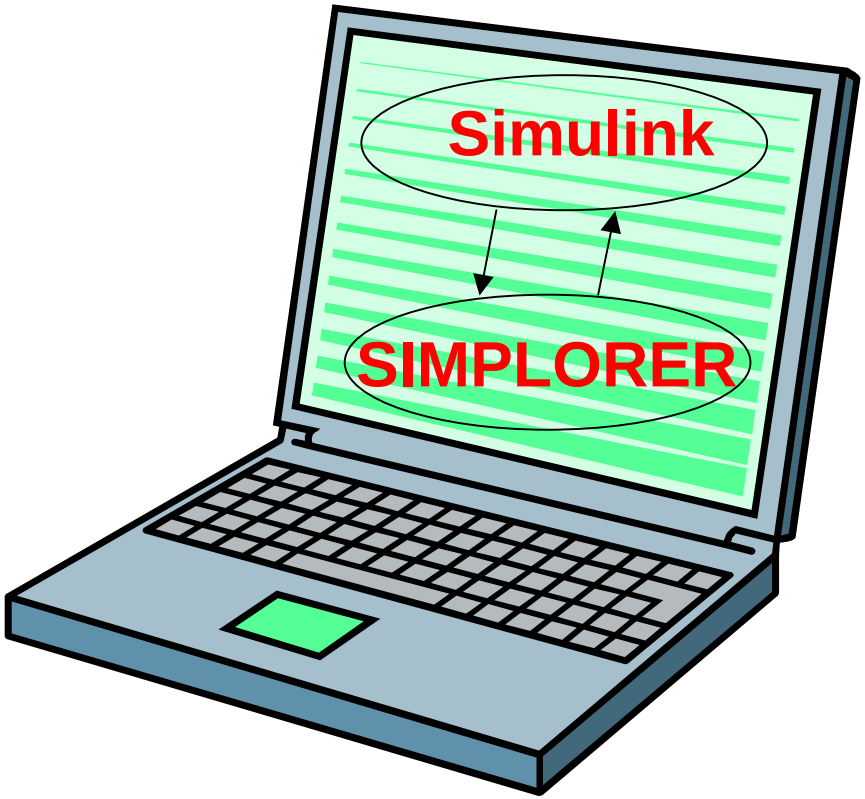
Ansoft Design Environment with External Modeling Interface



SIMPLORER/Simulink Co-Simulation

SIM2SIM – Simplorer60 interface

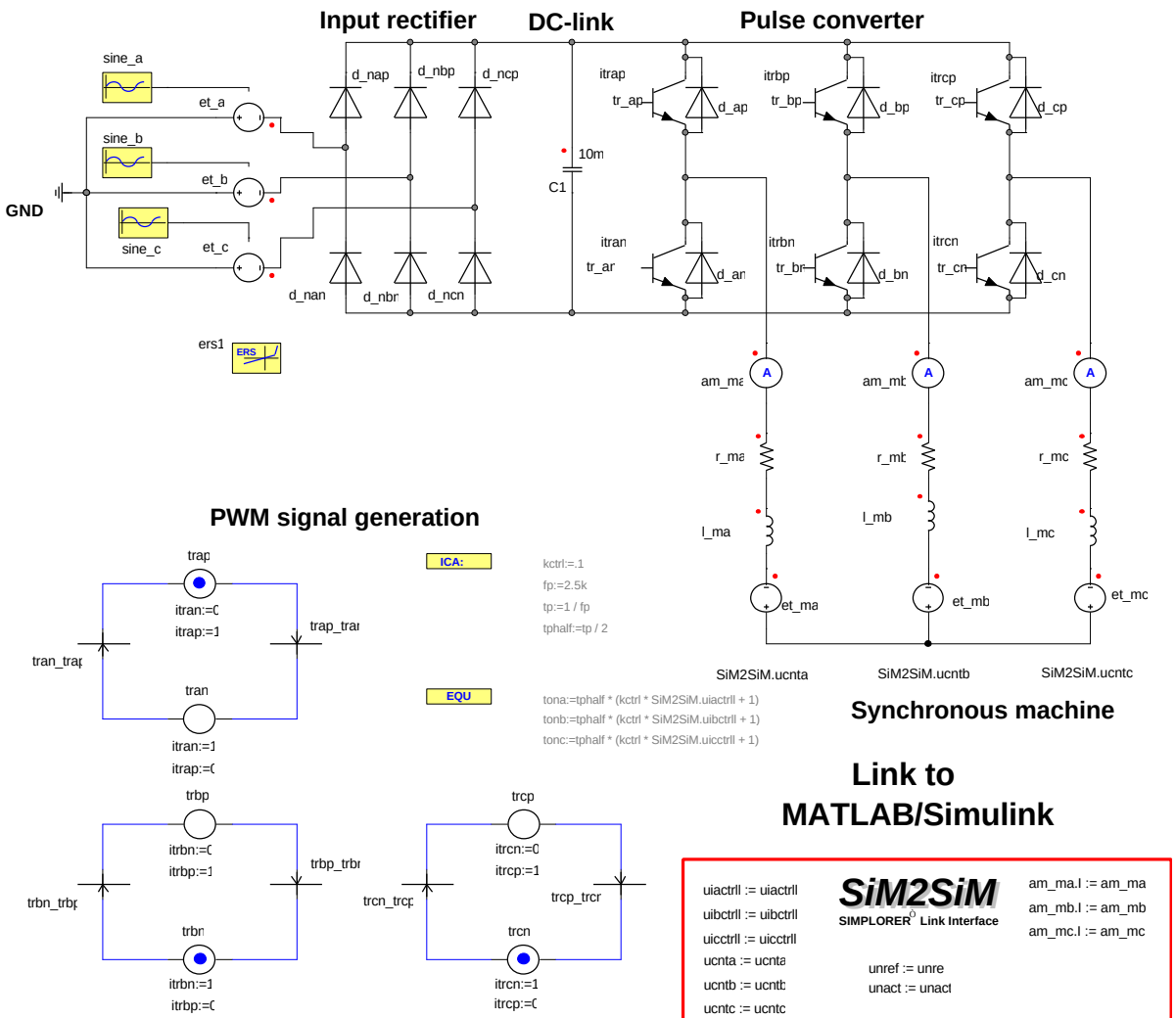
- Co-Simulation Interface is an open API that can be used for other simulation packages
  - – Linking models in both packages
  - – Using SIMPLORER's external simulator integration interface and S-function in Matlab



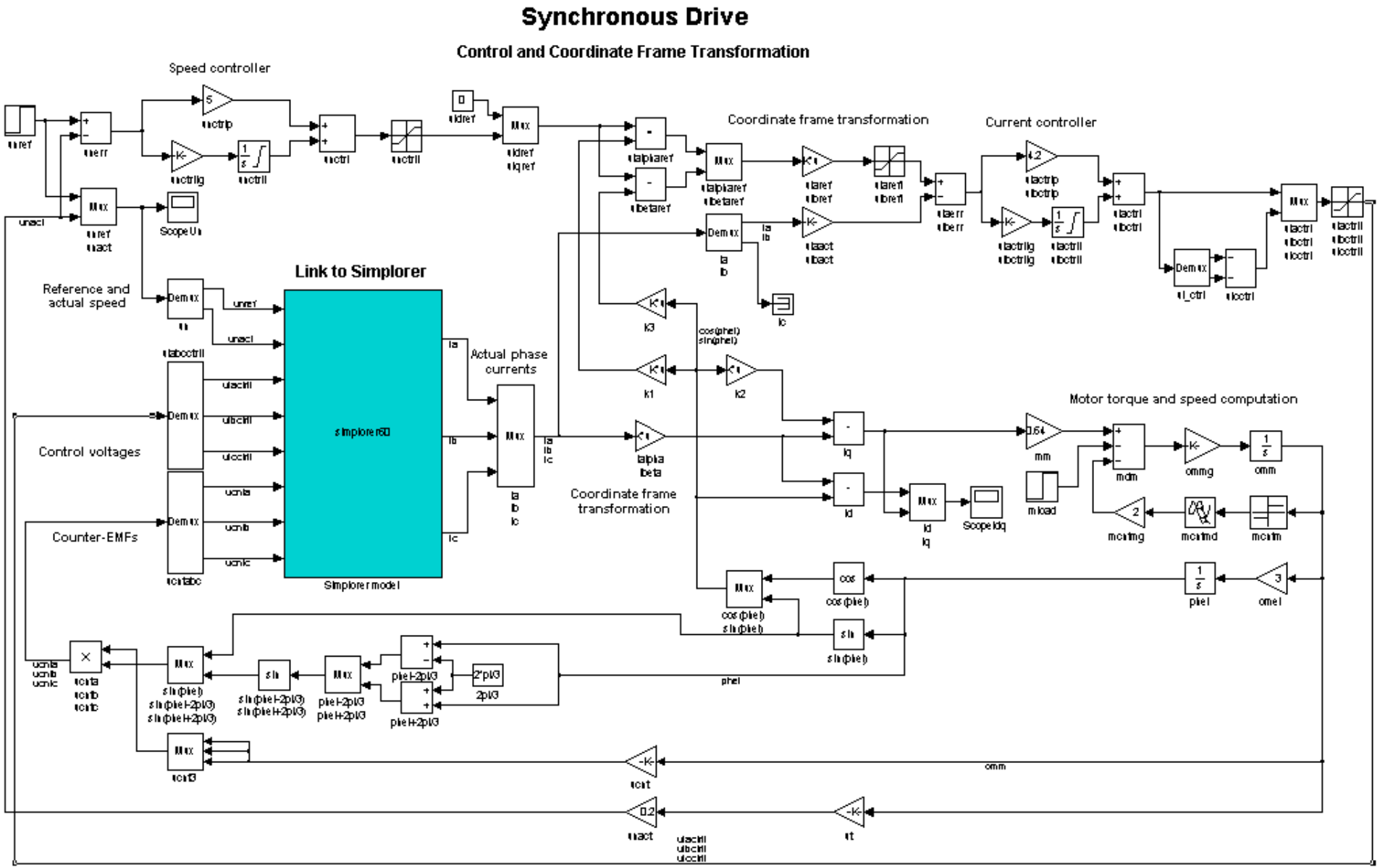
Simulink Power System and Motor Drive Model

Synchronous Drive

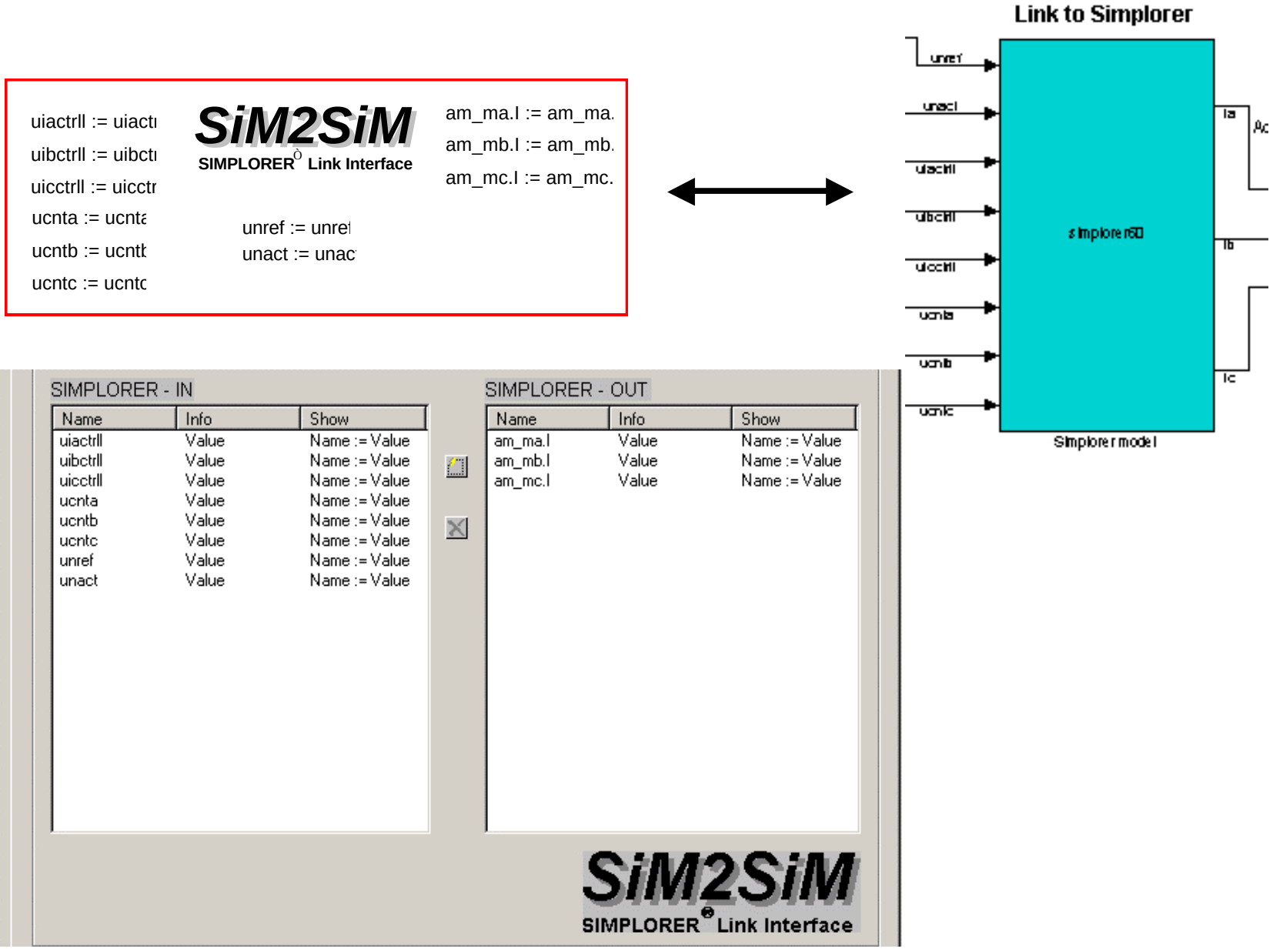
Electric Circuit and PWM Signal Generation



Simulink Motor and Controller Model



Simplorer/Simulink Model Interface



Conclusion

- Conventional Analysis Tools are often limited to single technical domain and single software package

- Simplorer provides the system integrator with the flexibility to use models developed in multiple simulation software, such as PSPICE, Simulink, MathCad, EASY5, and Saber (via VHDL-AMS).
  - Component and subsystem models developed in different simulation tools can be integrated in ANSOFT Simplorer Environment
  - Multi-domain, cross-language modeling and simulation provides an efficient common design environment to realize the synergistic benefits of multiple simulation/analysis tools, and facilitates a decentralized configuration control and parallel effort for model development and design parameter management