Supporting Technology Development and In-Service Operation of Shipboard Power Systems with Fit-For-Purpose Modeling and Simulation

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Acknowledgement

- The models described in this presentation are based on information provided by the Electric Ship Research and Development Consortium (ESRDC) at the following link,

  https://www.esrdc.com/library/documentation-for-a-notional-two-zone-medium-voltage-dc-shipboard-power-system-model-implemented-on-the-rtds/

- While system architecture and physical parameters have been honored as closely as possible, differences in the implementation of certain components and control algorithms is expected.

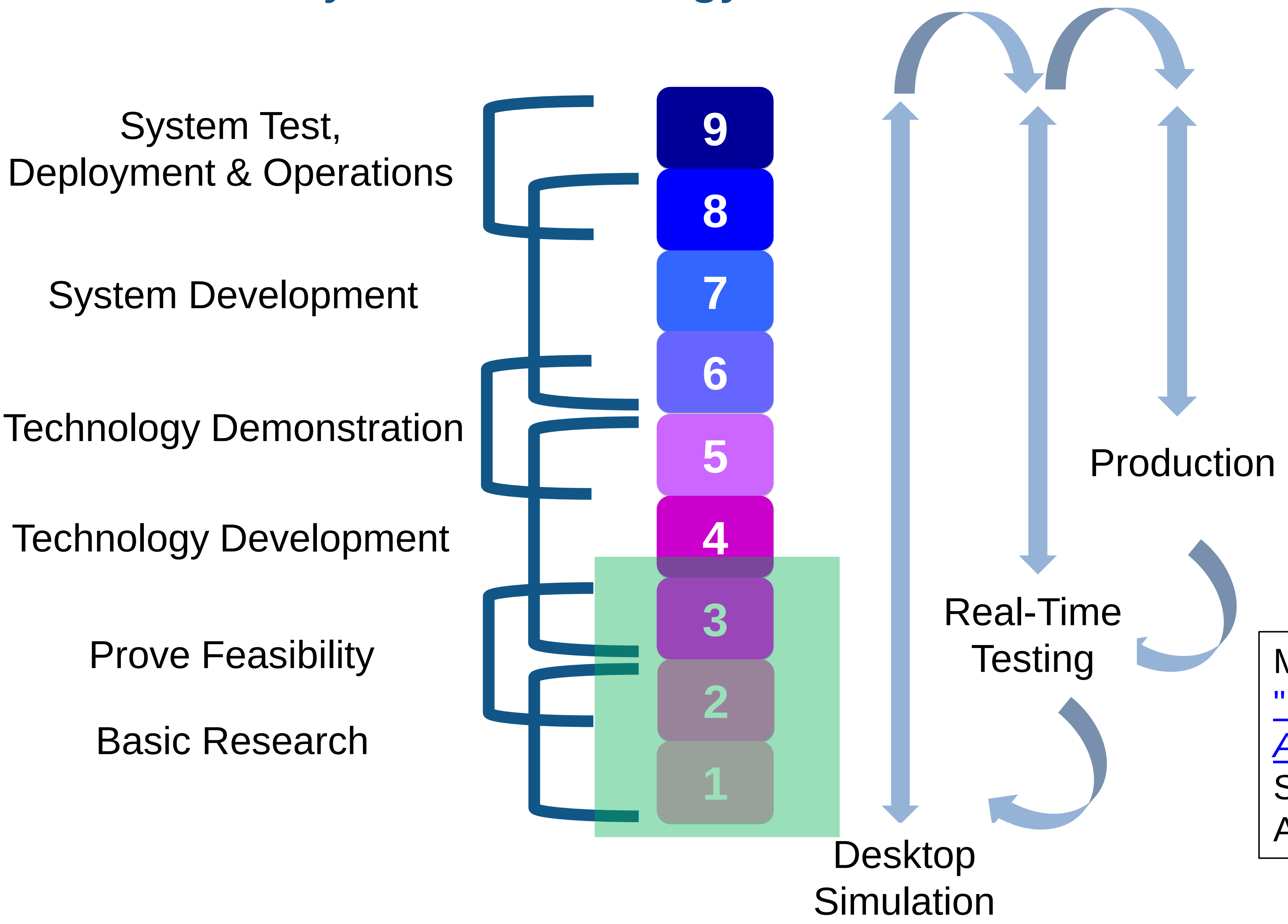
- Simulation results in this presentation should be regarded as being representative, rather than providing an exact engineering match.

Overview

- Model Fidelity and Technology Readiness
- Understanding the Impact of Simulation Solvers on Simulation Speed and Simulation Accuracy
- Configuring a Physical System Simulation to Run at Multiple Sample-Rates
- Two-Zone MVDC Shipboard Power System
  - DC Equivalent
  - Ideal Rectifier
  - Diode and Thyristor Rectifiers
  - Propulsion Motor with Field-Oriented Control
  - Thermal Response and Active Cooling
- Creating and Integrating FMI/FMU Components
- Deploying Models on Real-Time Systems and the Cloud
- Summary

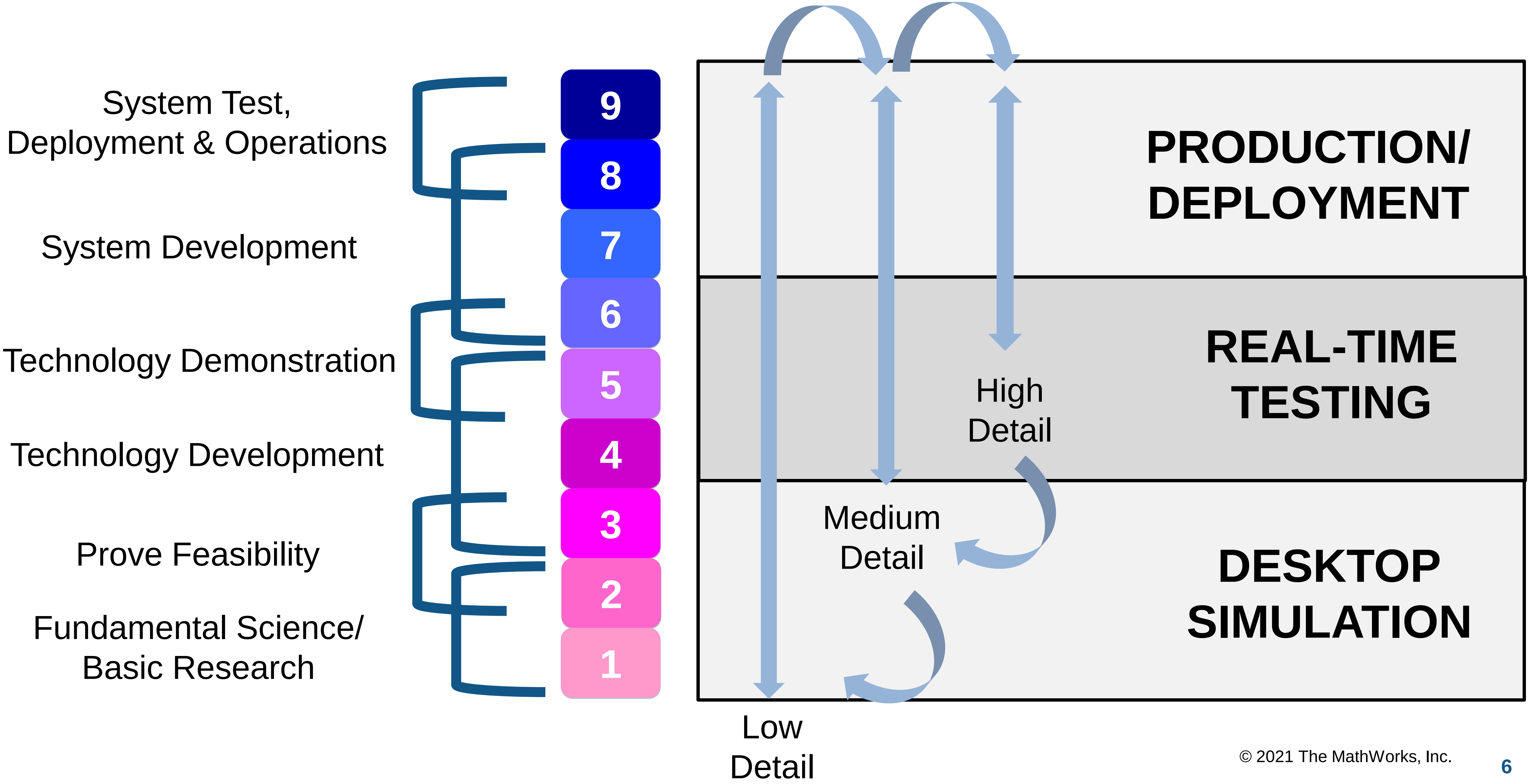
Model Fidelity
and
Technology Readiness

Model Fidelity and Technology Readiness

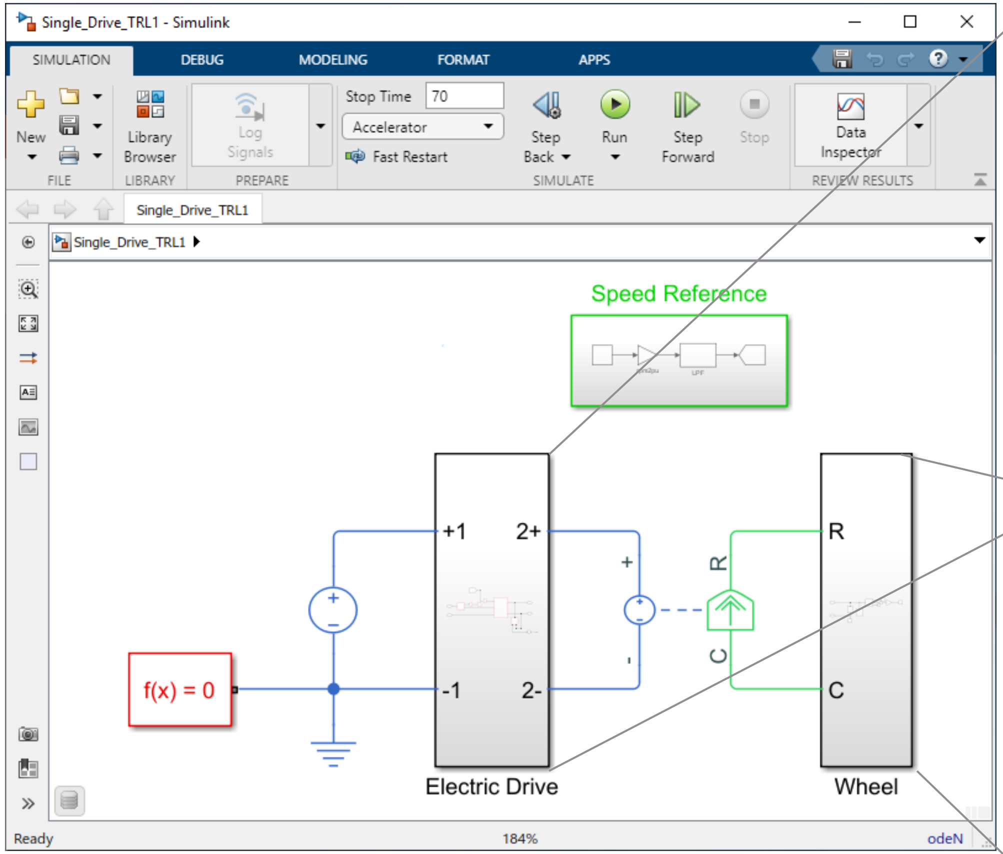


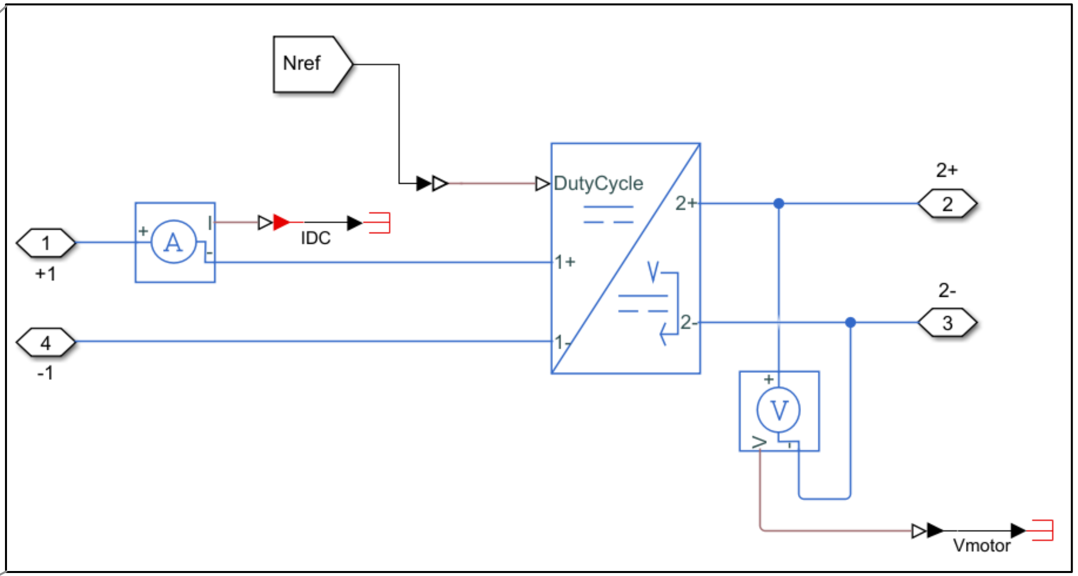
Mankins, John C. (6 April 1995). ["*Technology Readiness Levels: A White Paper*"](). NASA, Office of Space Access and Technology, Advanced Concepts Office.

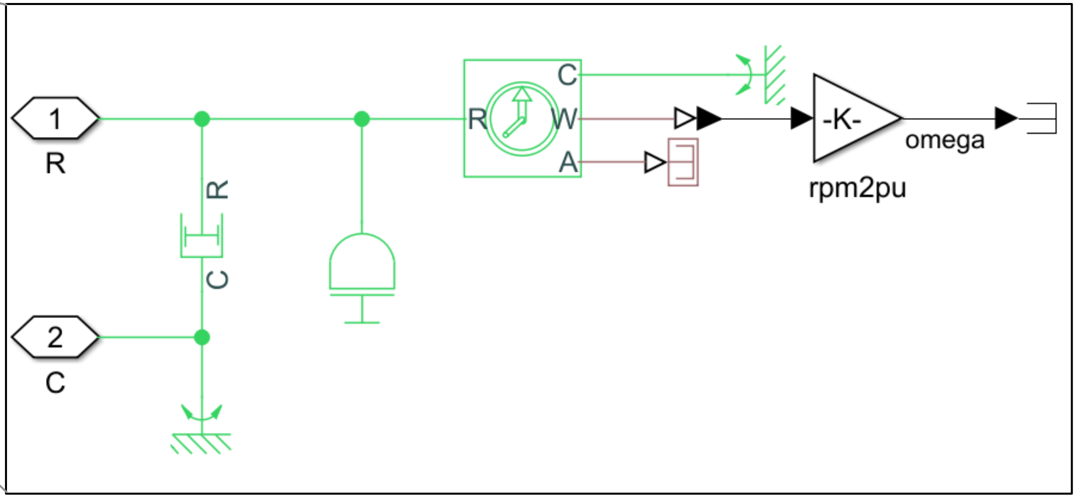
Model-Based Design and Technology Readiness



Ideal Electromechanical Drive



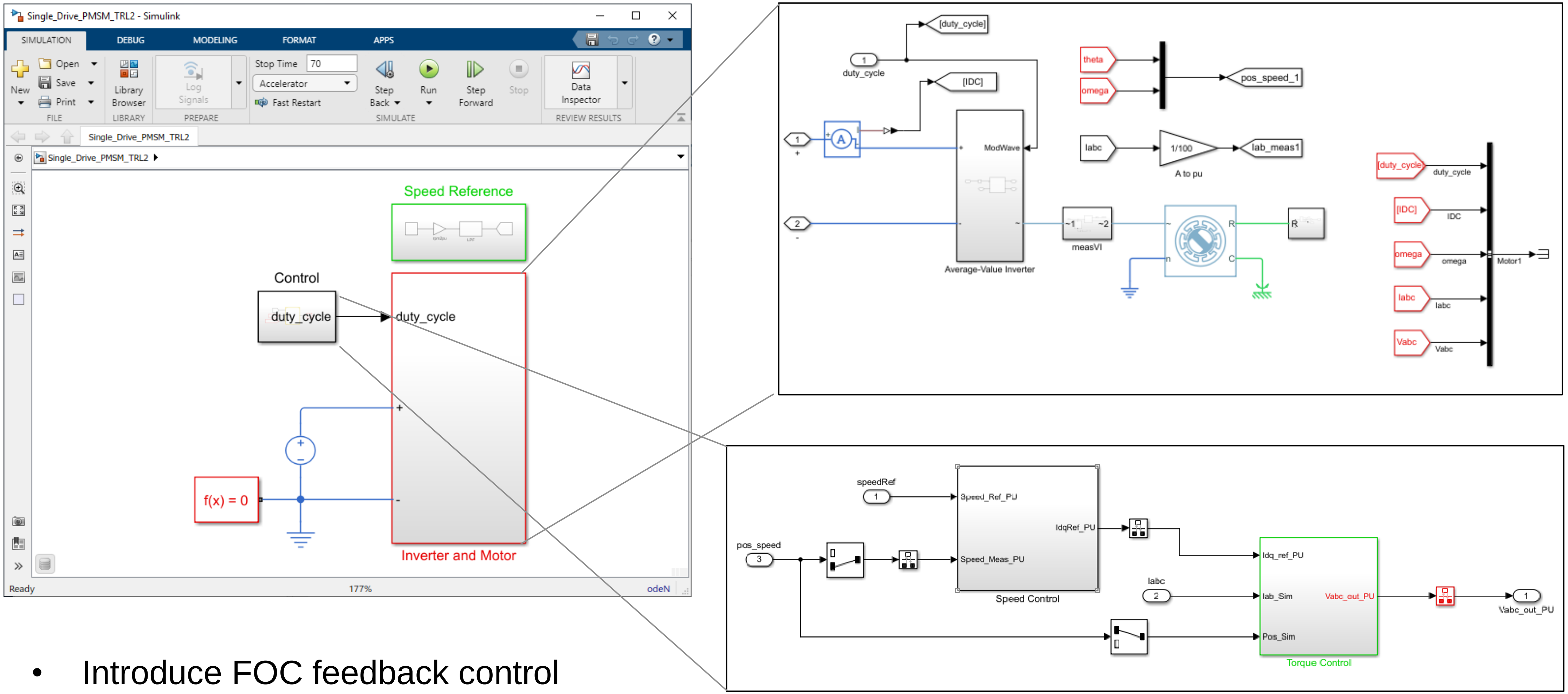




- Lowest fidelity physical system
- No feedback control needed

9 8 7 6 5 4 3 2 1

Linear PMSM with Average-Value Converter



9
8
7
6
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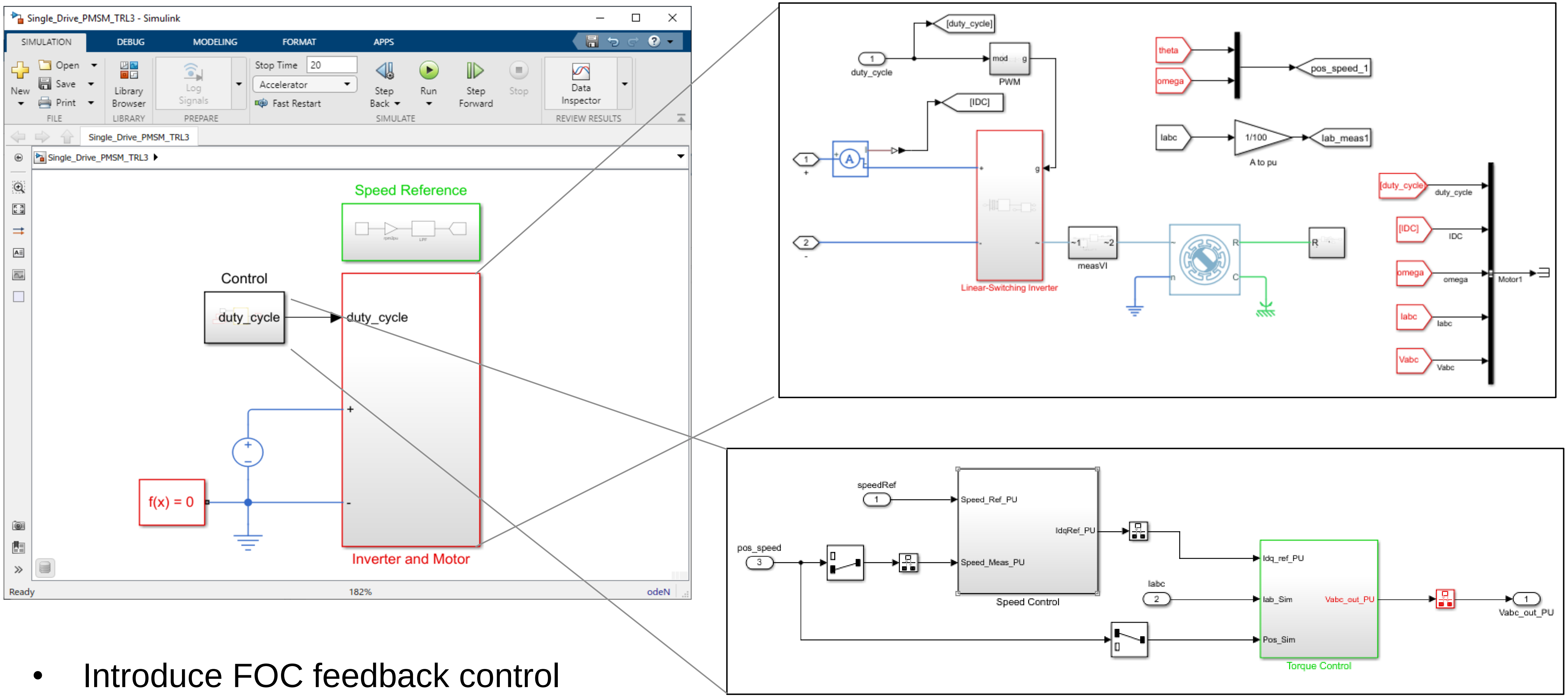
1

- Introduce FOC feedback control
- No switching effects

Linear PMSM with Switched-Linear Converter

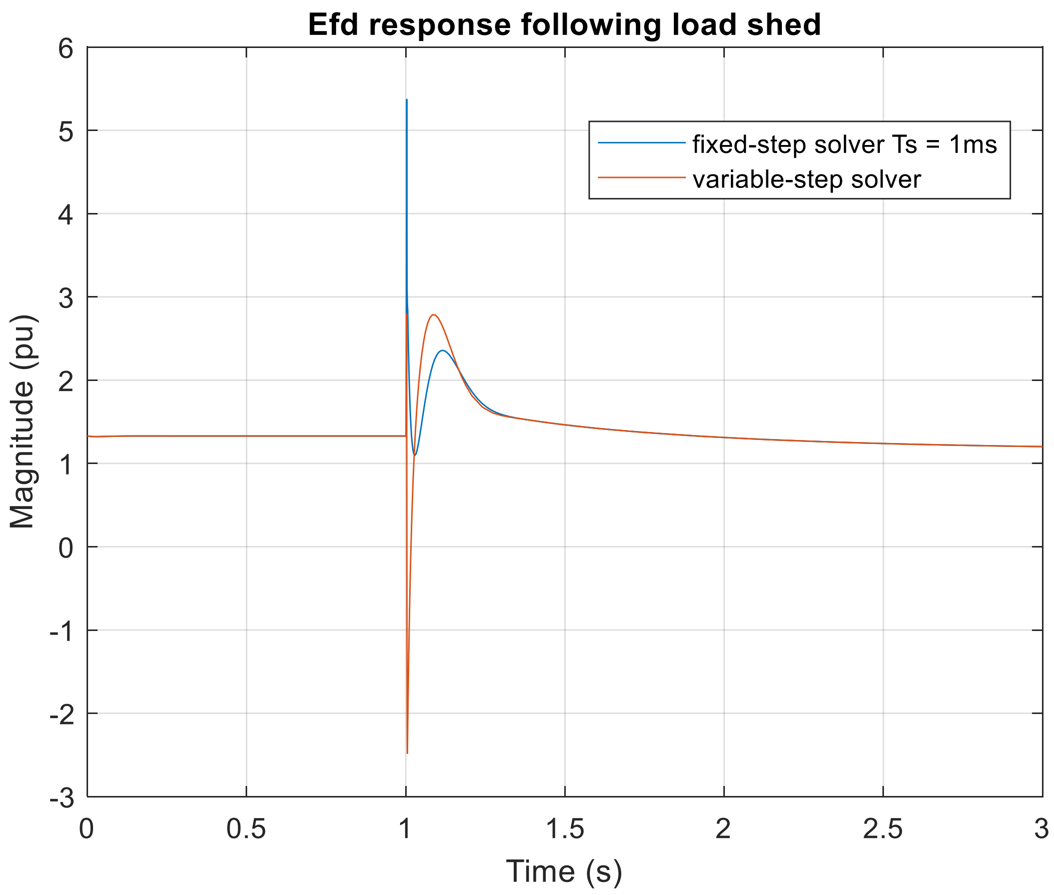


- Introduce FOC feedback control
- Introduce PWM switching

Understanding the Impact of Simulation Solvers on Simulation Speed and Simulation Accuracy

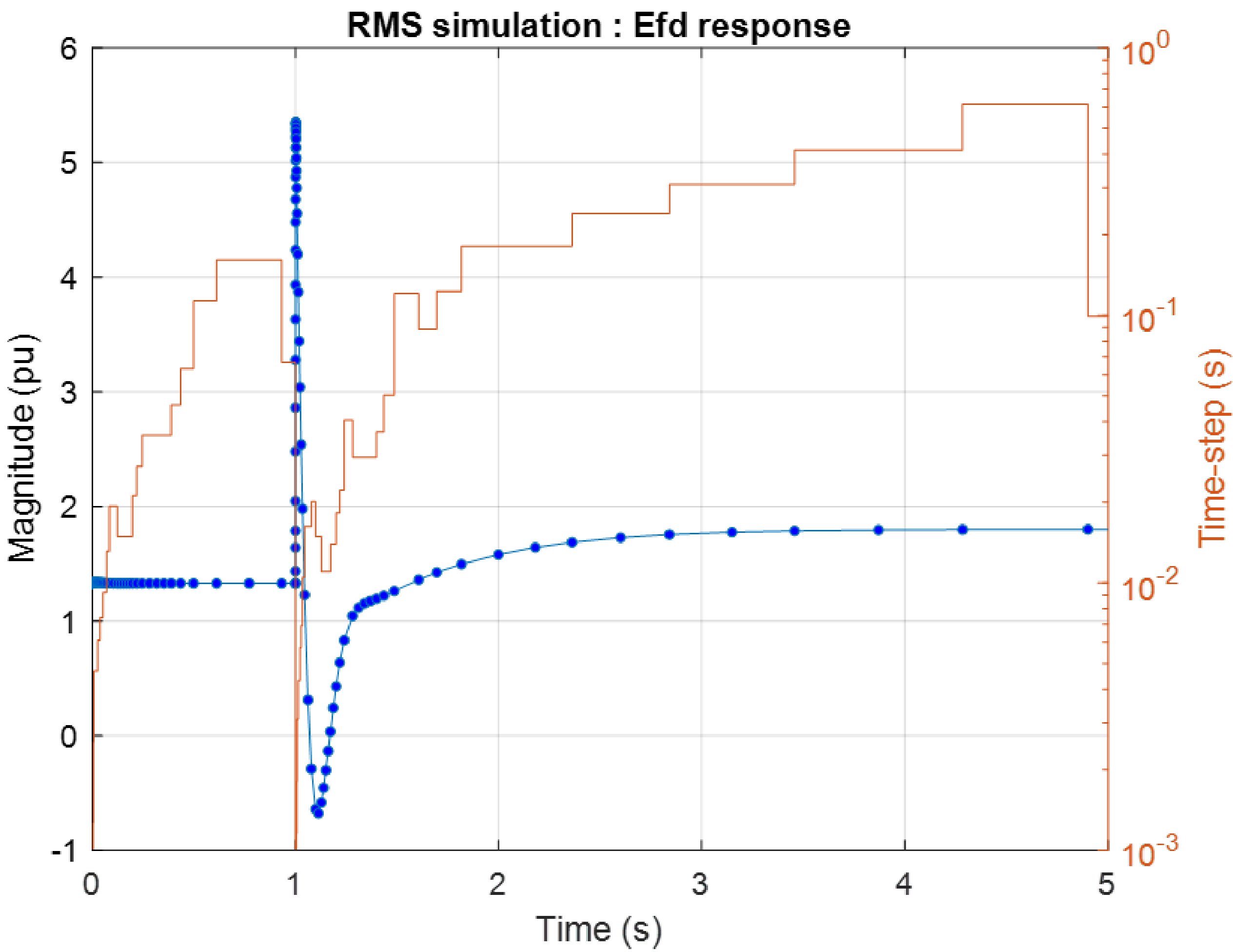
Solvers for RMS Simulation

- The figure shows a comparison of the response of a system when using a fixed-step solver and variable step solver. The fixed-step solver uses a time-step of 1 millisecond. The variable-step solver adapts its time step depending on the rate of change of the response



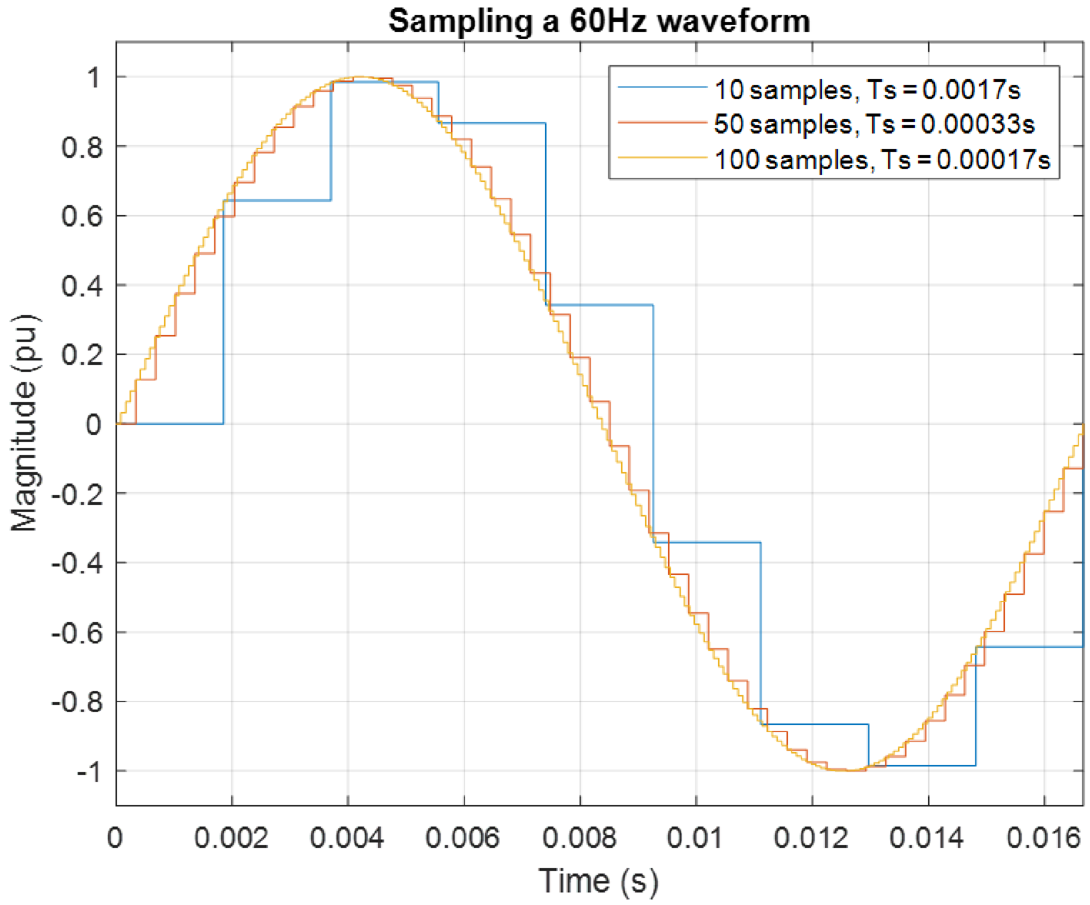
Solvers for RMS Simulation

- The figure shows the variable-step solver time-steps overlaid on the field voltage response. You can see how the time-steps become smaller at the load change event, and larger as the rate of change of the response reduces



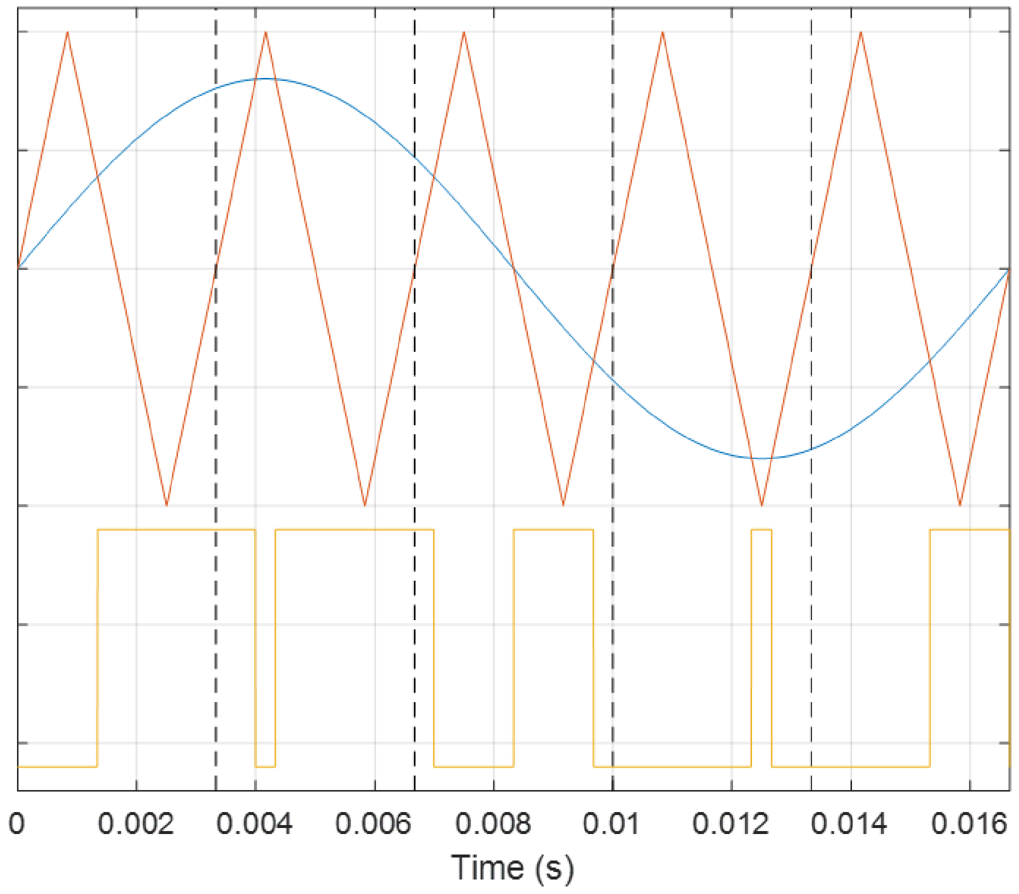
Solver for EMT Simulation

- With EMT simulations, accurate reconstruction of waveforms at the base frequency is a requirement. This requirement puts a limit on the largest step size that can be used to accurately capture EMT effects. The figure shows reconstruction of a 60Hz waveform using 10, 50 and 200 fixed-step samples



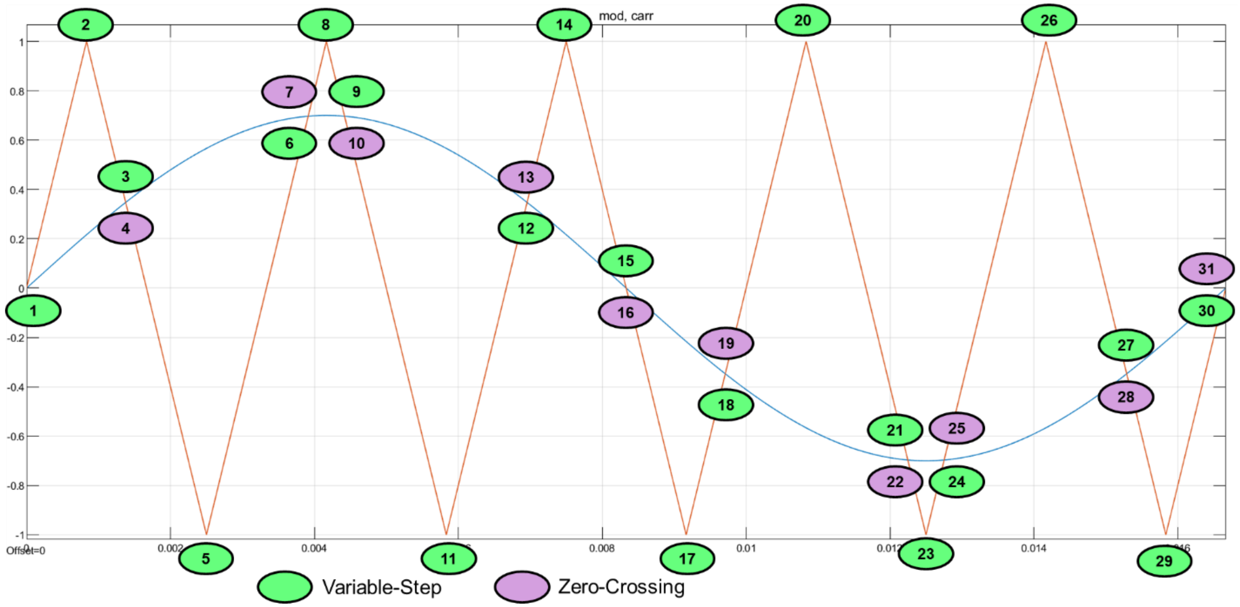
EMT with Power Electronic Switching

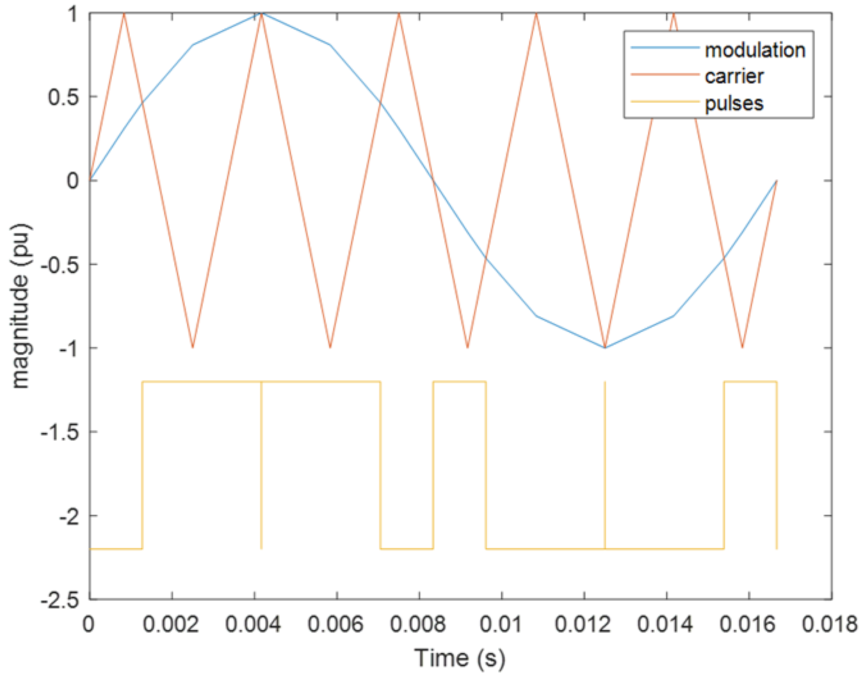
- When accurate simulation of power electronic switching is required, then it is both the switching frequency of the PWM generator and the resolution of the PWM pulse-timing that become limiting factors in the speed and accuracy of a given solver.



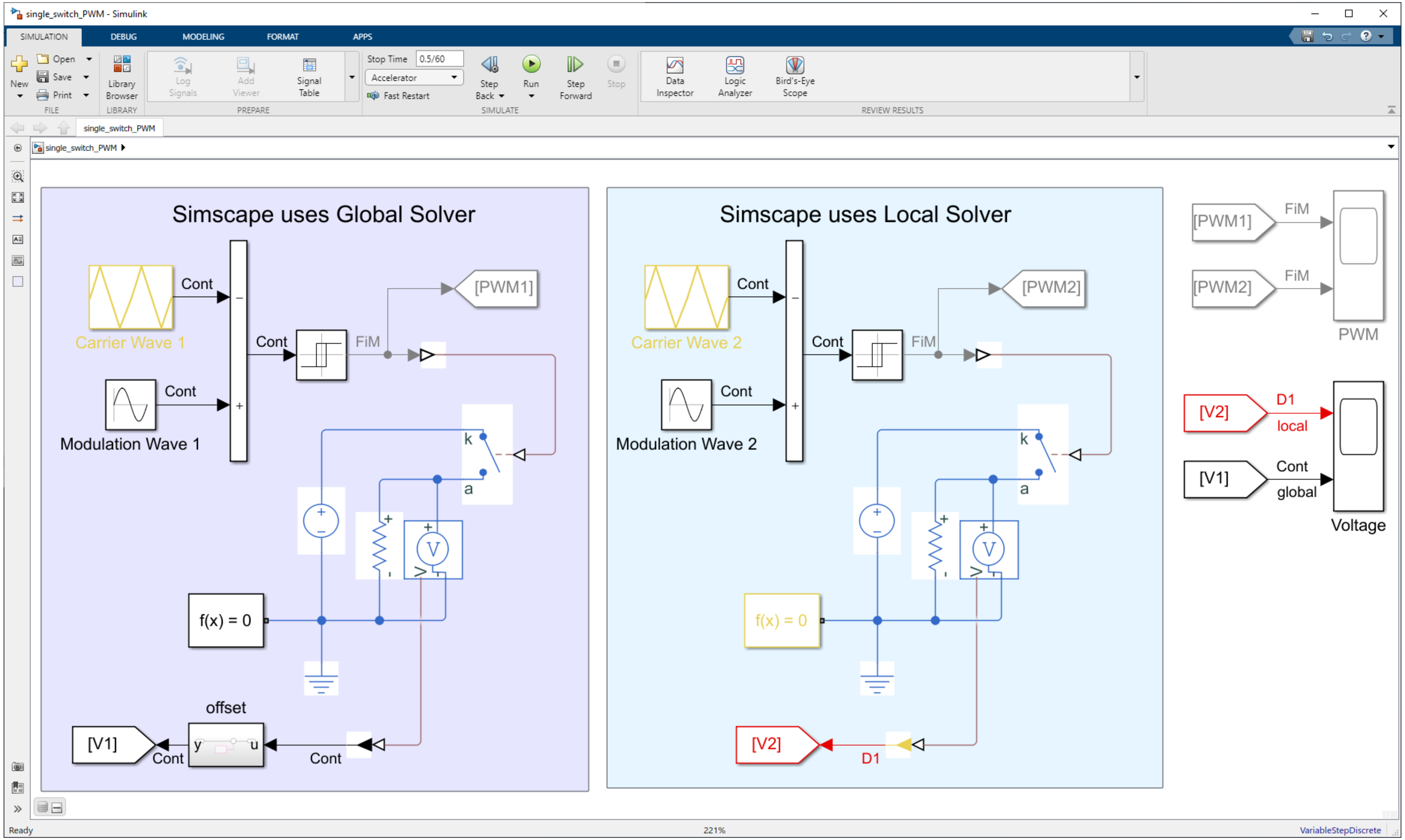
EMT with Power Electronic Switching

- These figures show an example of the minimum number of sample times that are required to accurately capture pulse-timing. The solver used is variable-step with zero-crossing detection. Note the modulation wave is not a ‘clean’ sinusoid.
- For real-time simulation, and for simulation software that supports only fixed-step solvers, then a time-step should be selected that finds a compromise between simulation speed and PWM timing resolution



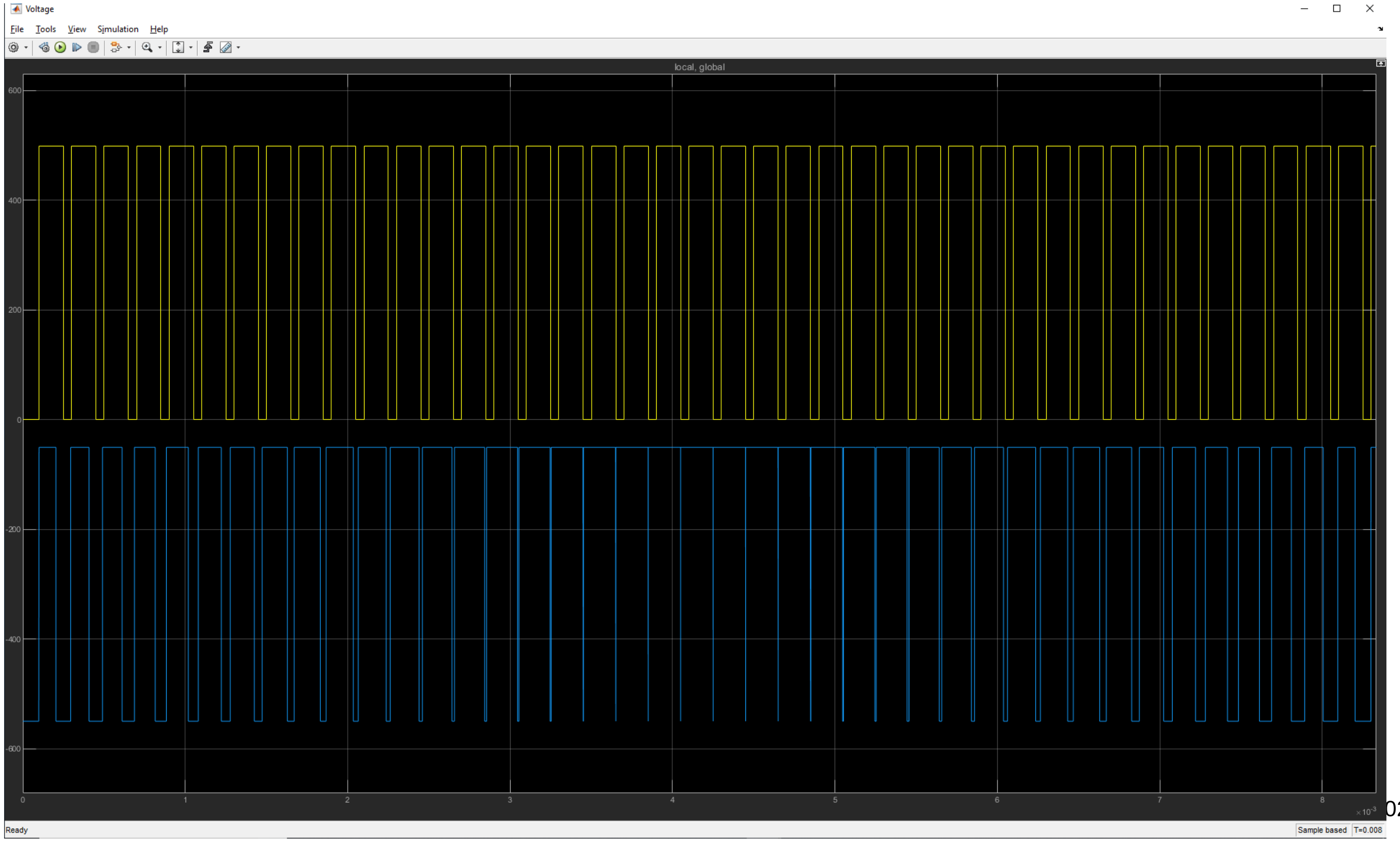


Difference Between Fixed-Step With and Without Zero-Crossing



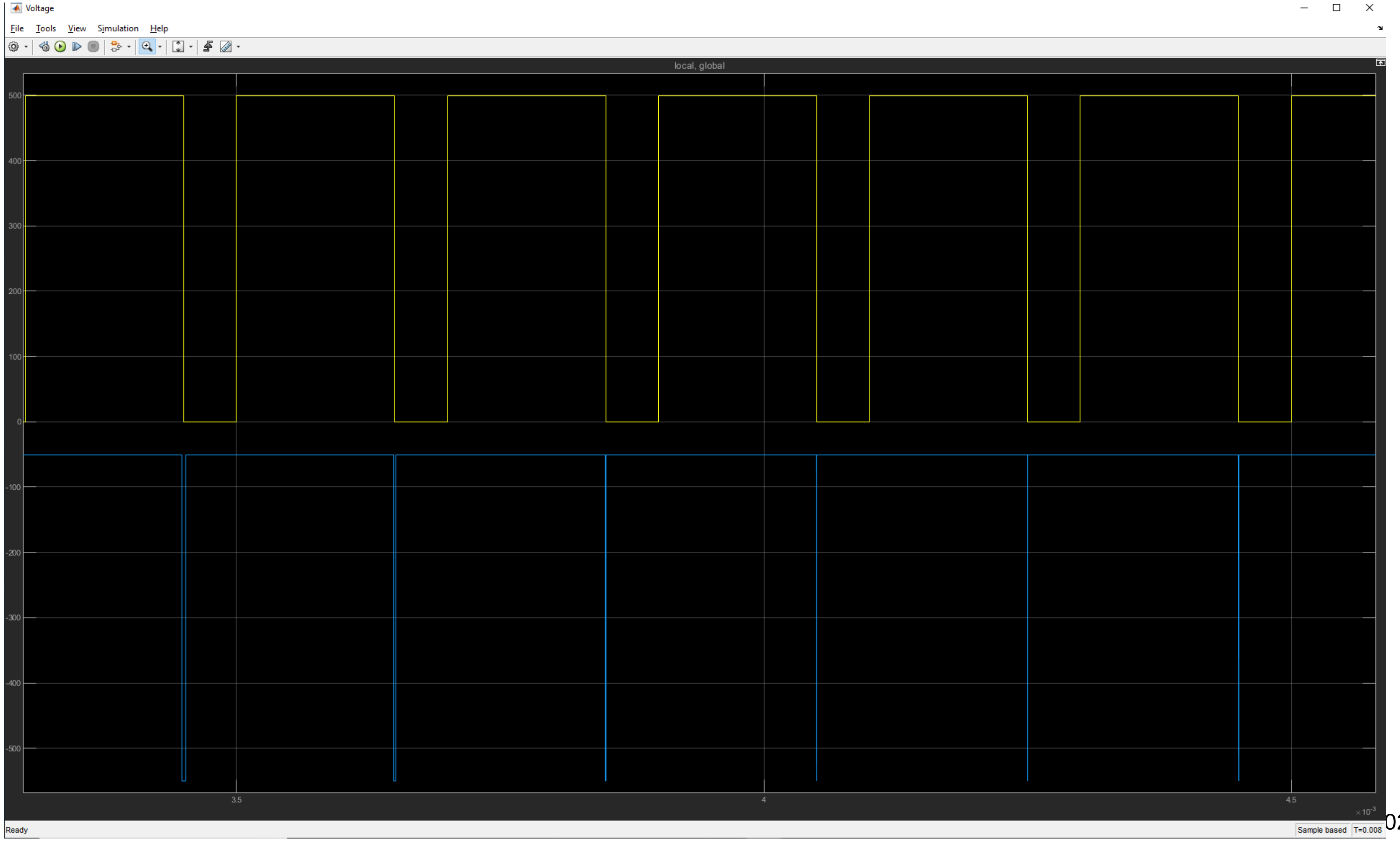
Difference Between Fixed-Step With and Without Zero-Crossing

Without zero-crossing detection, the voltage response pulse-width is limited by the solver time-step.



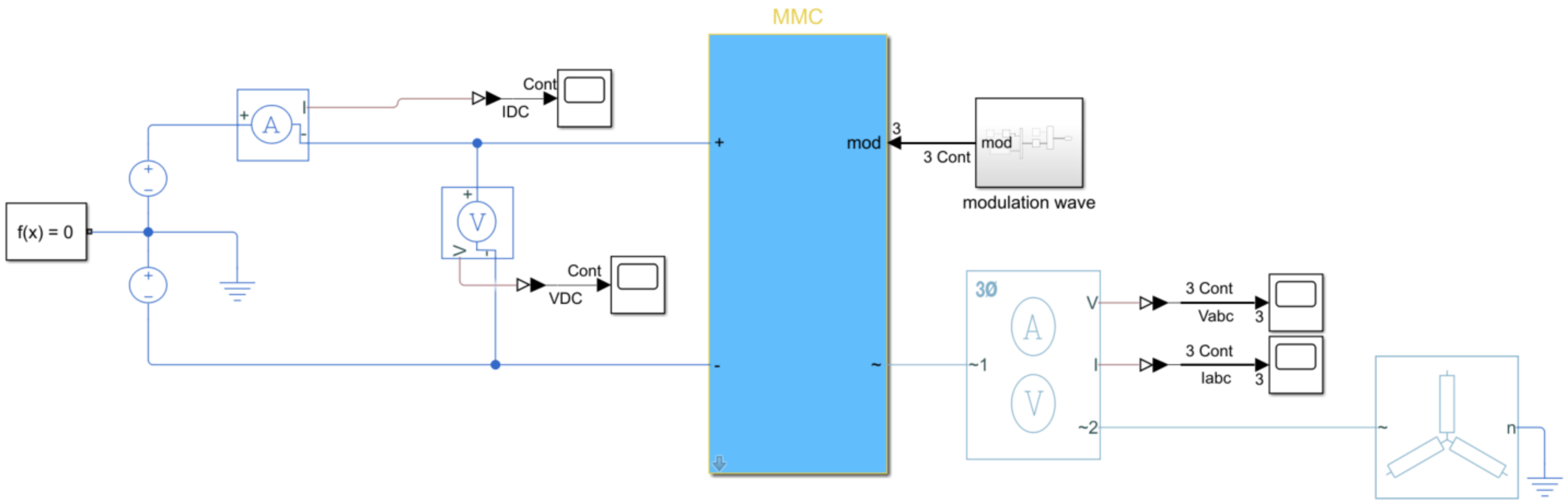
Difference Between Fixed-Step With and Without Zero-Crossing

PWM fidelity is therefore dependent on choosing a suitable fixed time-step.



Desktop Simulation

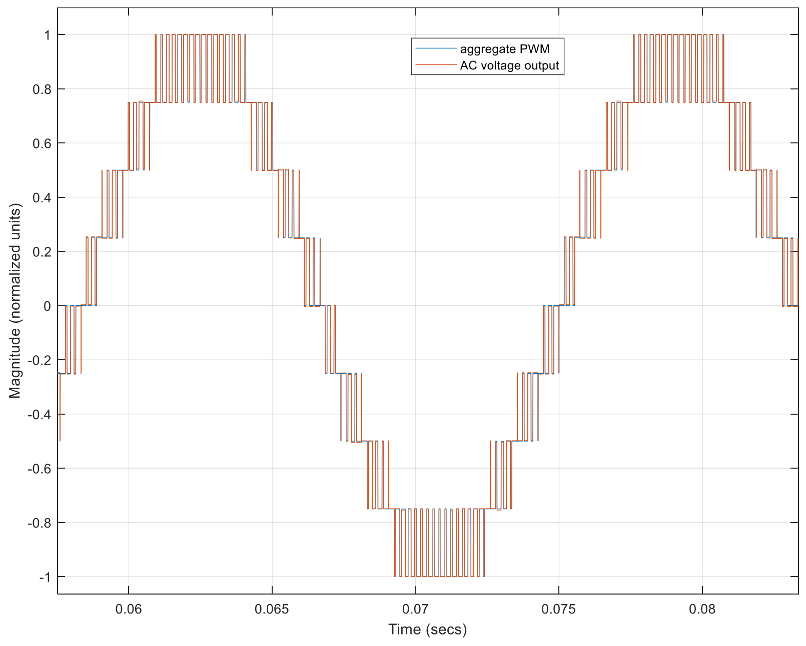
- With simulation on the desktop, we begin by de-risking the power converter architecture and switching algorithm.
- For example, we want to confirm that the voltage profile of the converter is matching the expected response – thereby building our confidence that the PWM generator is implemented correctly and that the PWM signals are being received correctly by the converter.
- To do this, we set up a stylized test-harness, that allows us to focus solely on the switching behavior.



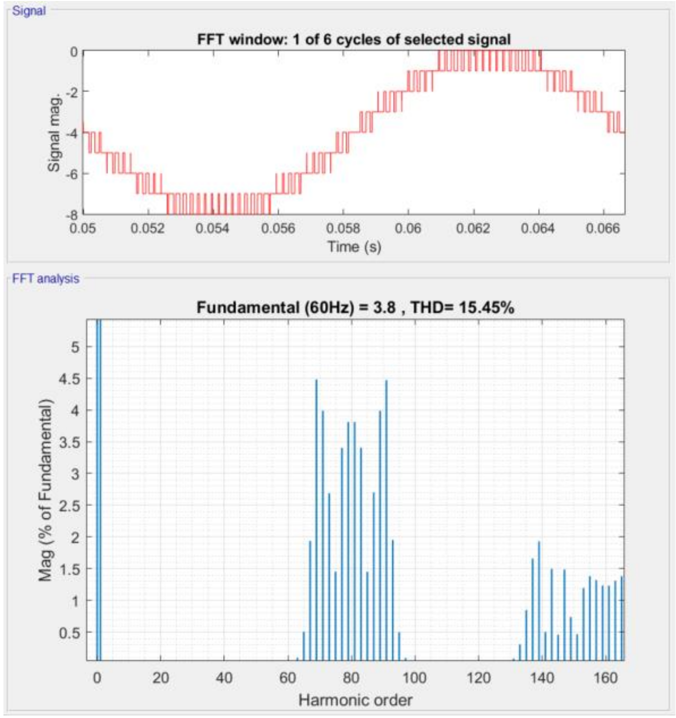
TRL 2

Desktop Simulation

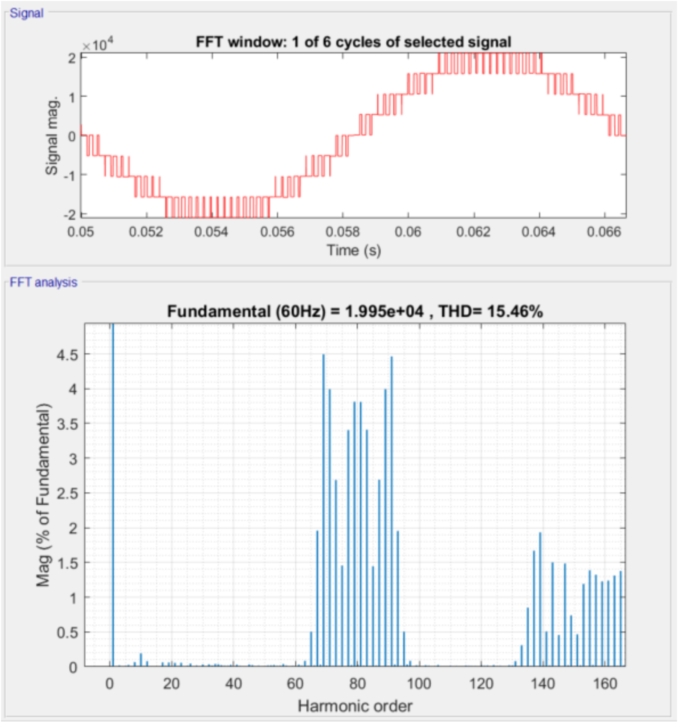
- After running a simulation, we compare the ‘aggregate’ PWM signal and the AC voltage output. A visual comparison is a good step, but a more rigorous evaluation is to compare the harmonics of the signals. With a stylized test-harness, we expect to see ‘clean’ waveforms and ‘clean’ harmonic profiles.



(a) Aggregate PWM and AC voltage output overlaid



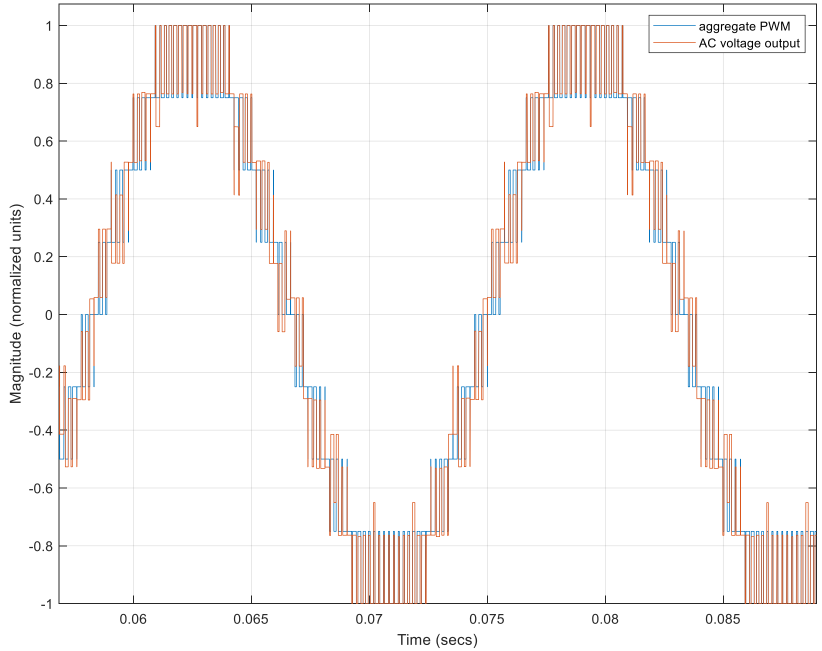
(b) Harmonic analysis of aggregate PWM



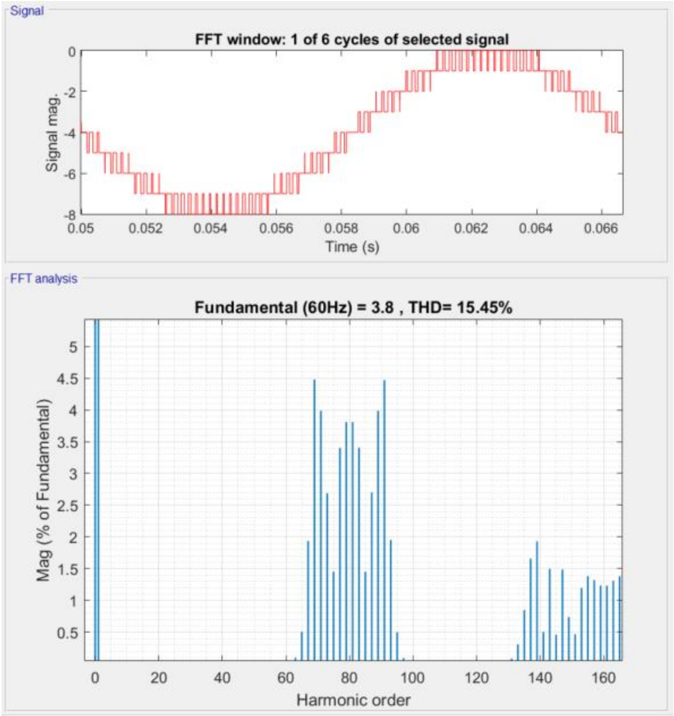
(c) Harmonic analysis of AC voltage output

Desktop Simulation

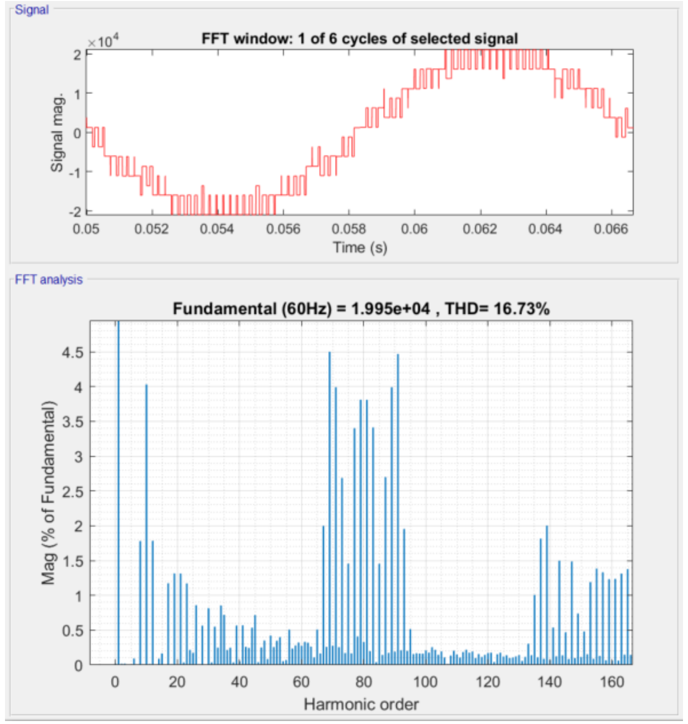
- After running a simulation, we compare the ‘aggregate’ PWM signal and the AC voltage output. A visual comparison is a good step, but a more rigorous evaluation is to compare the harmonics of the signals. With a stylized test-harness, we expect to see ‘clean’ waveforms and ‘clean’ harmonic profiles.



(a) Aggregate PWM and AC voltage output overlaid



(b) Harmonic analysis of aggregate PWM

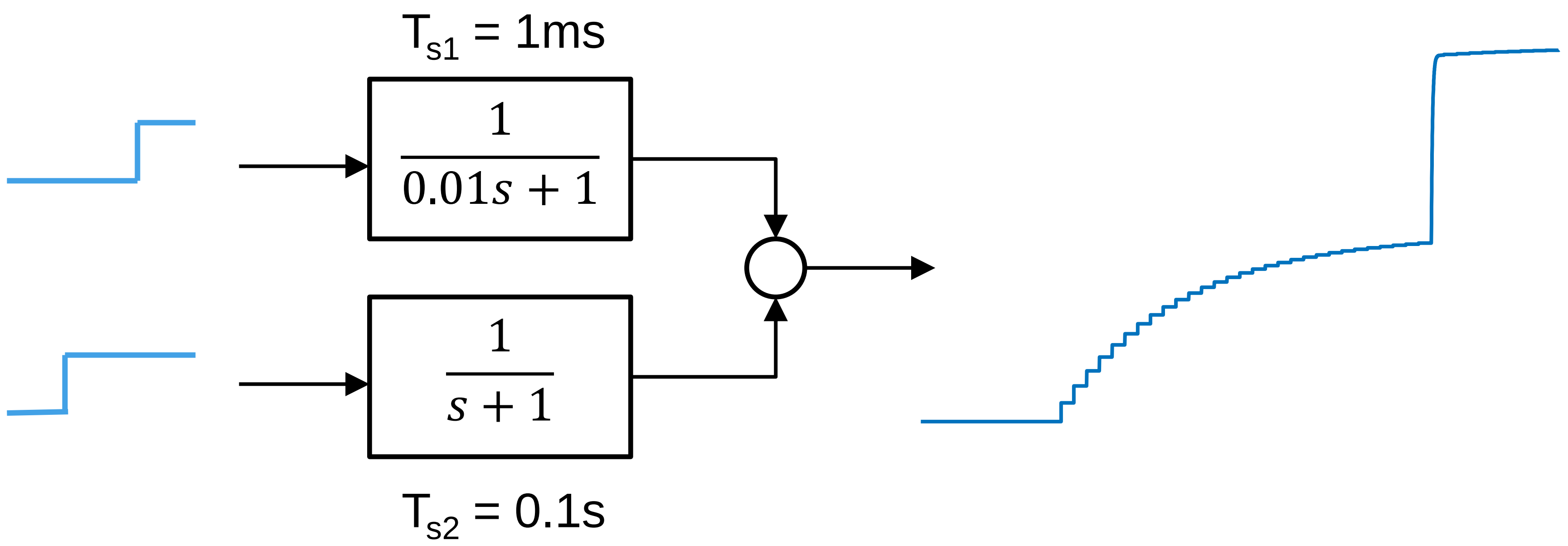


(c) Harmonic analysis of AC voltage output

Configuring a Physical System Simulation to Run at Multiple Sample-Rates

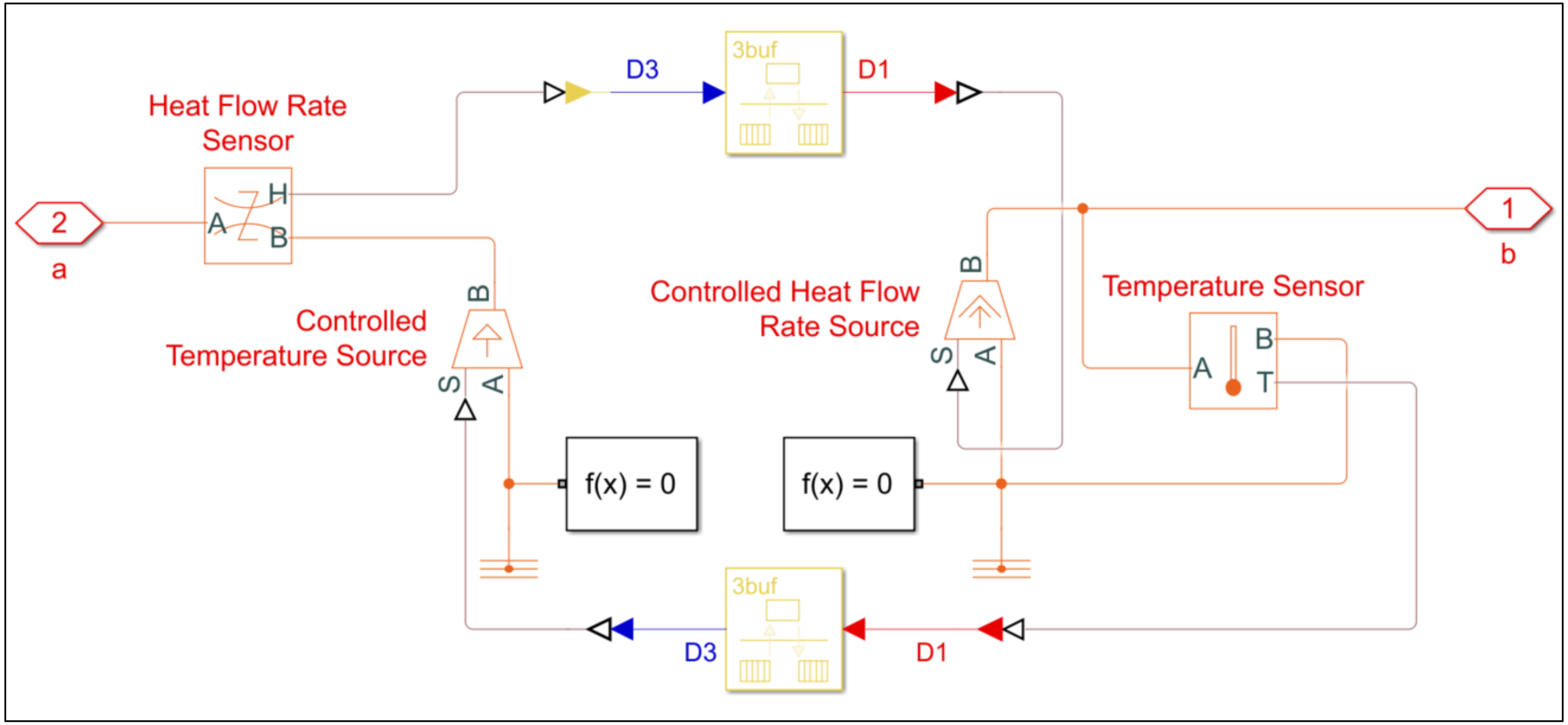
Why Run at Different Sample Rates?

- For physical systems that contain physical domains with different time constants, simulation efficiency can be improved by applying appropriate sample times.



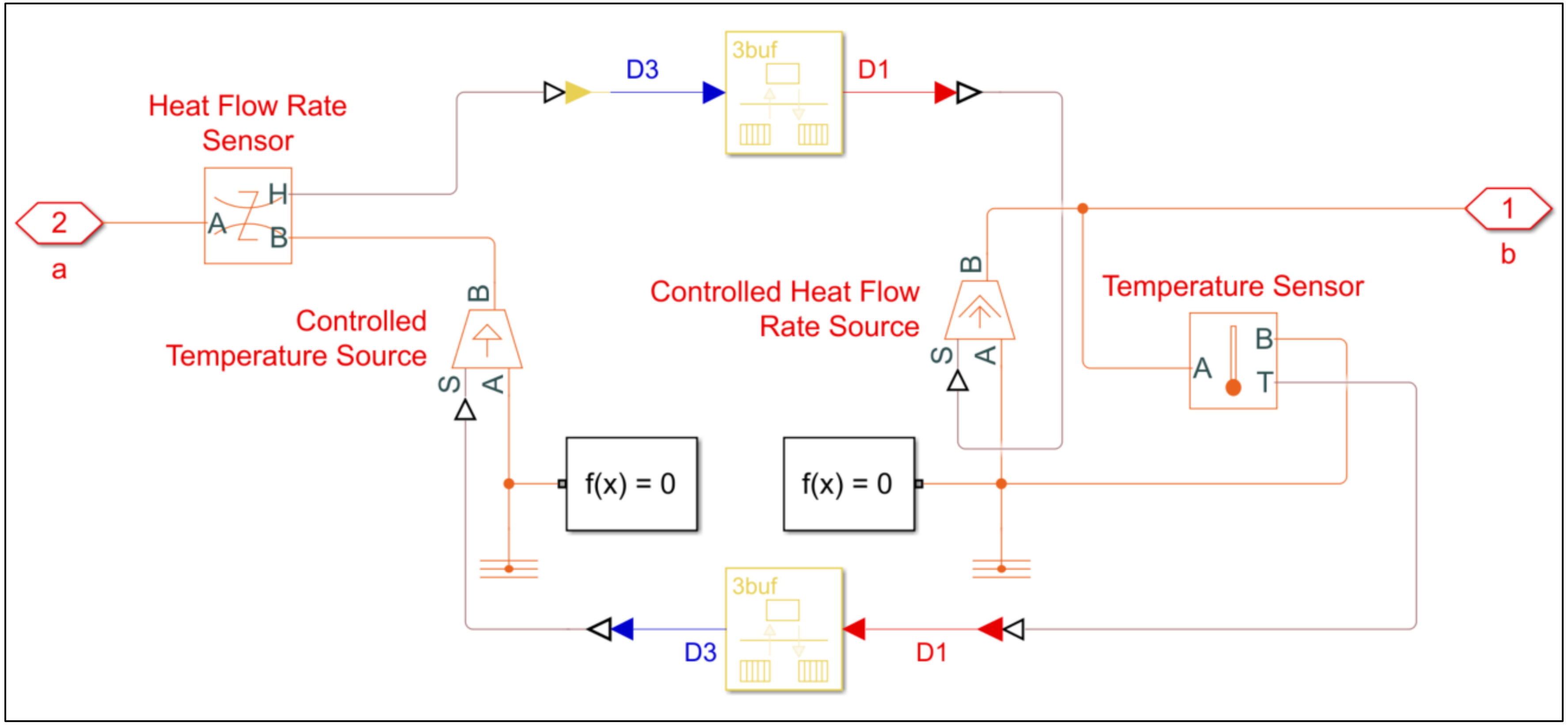
Using Different Sample-Times for Different Networks

- To run different sections of a physical system at different sample times, we need to send physical information between two or more physical networks. As an example, connecting two systems via thermal ports is shown below.



Using Different Sample-Times for Different Networks

- Appropriate sample-times can be set for each physical system. The transfer of data between the two networks must be suitably managed to maintain accuracy.

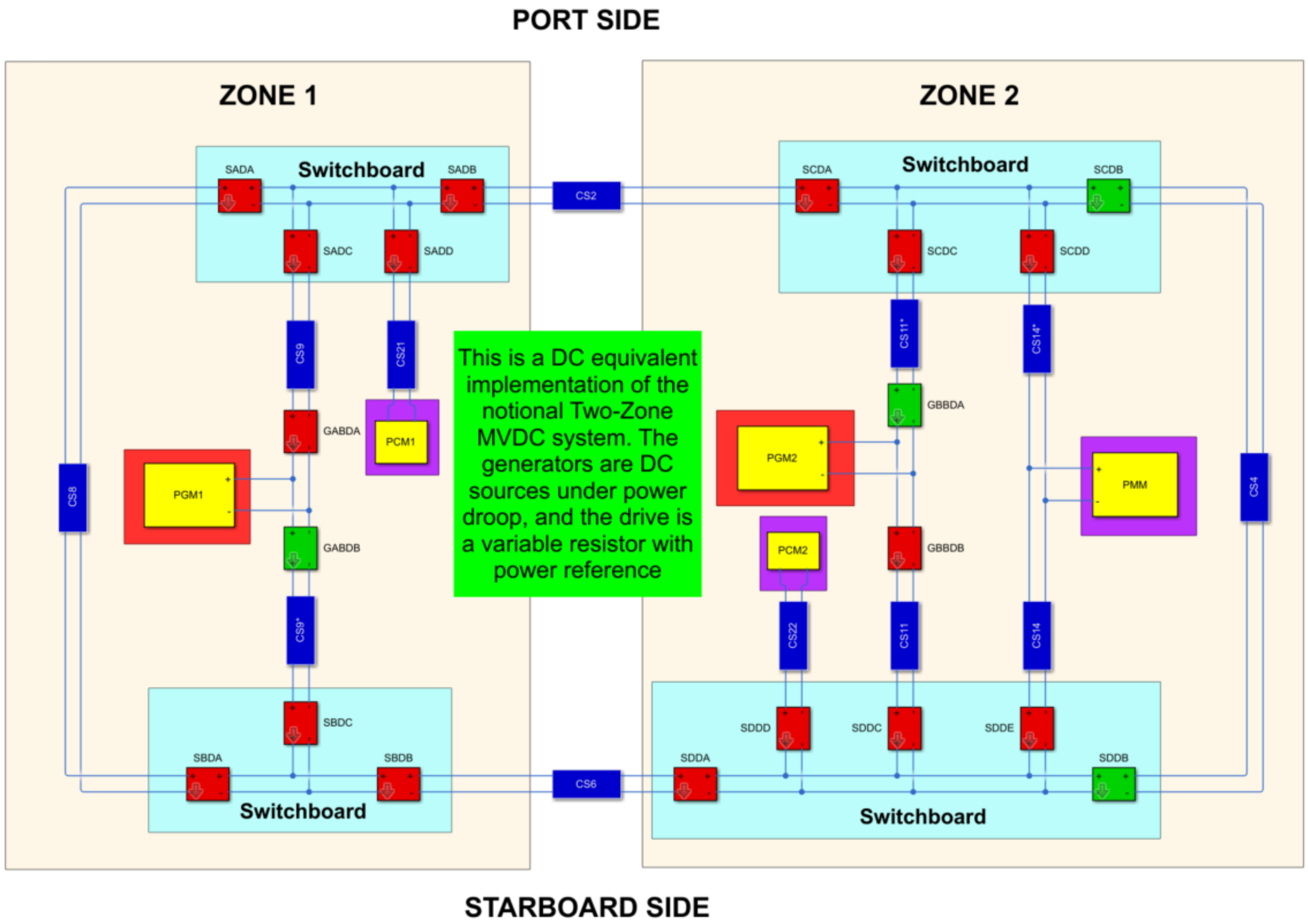


Two-Zone MVDC Shipboard Power System

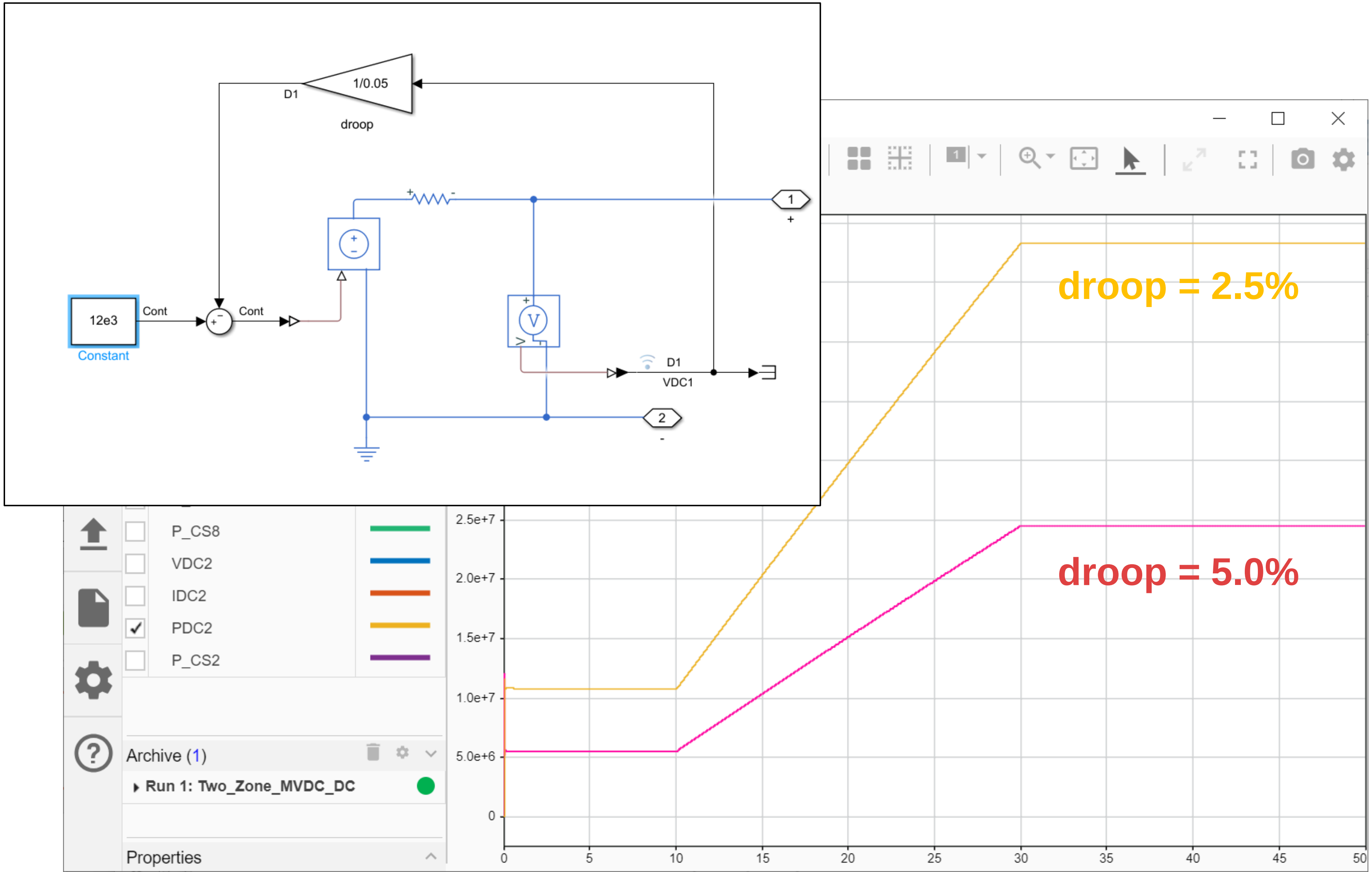
DC Equivalent System Model

DC Equivalent System Model

- Lowest fidelity system level model to assess operational characteristics with rapid simulations



DC Equivalent System Model

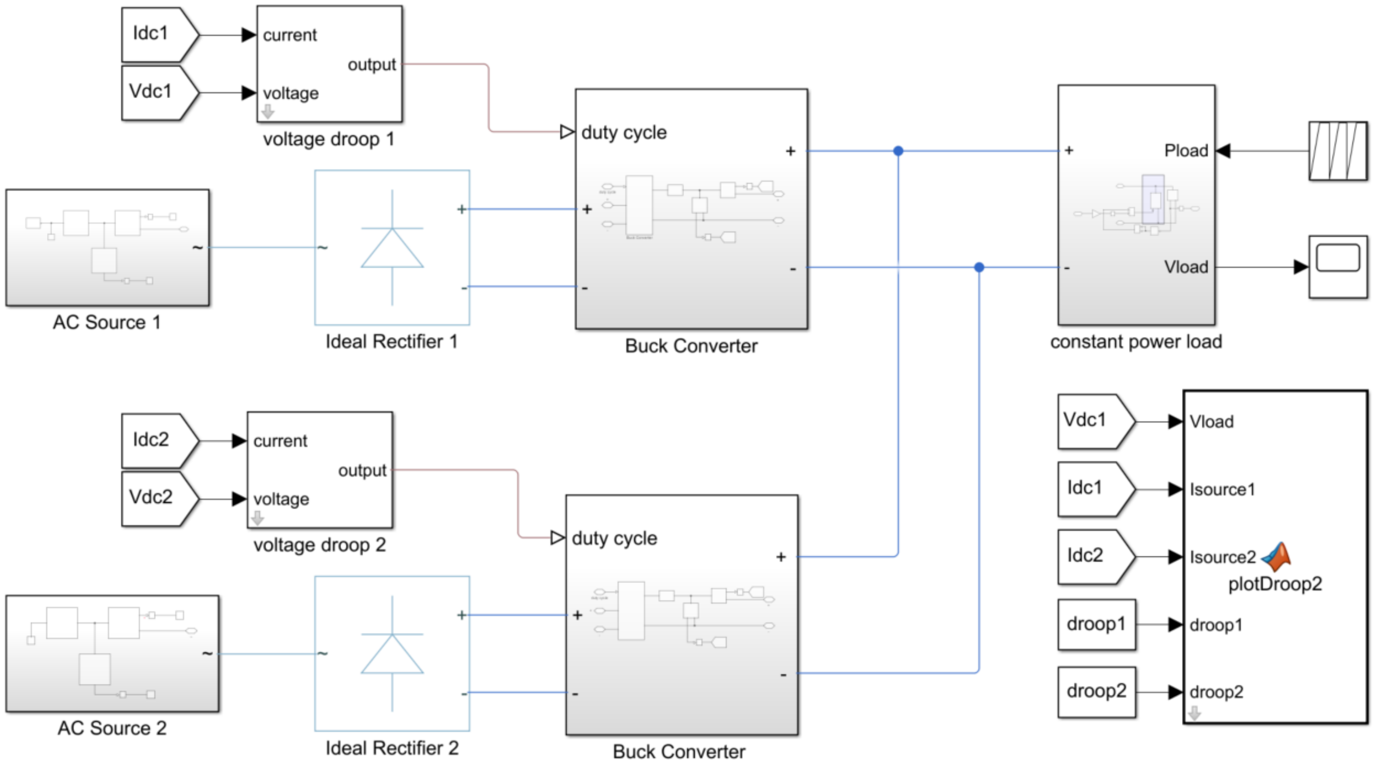


Test voltage droop for power sharing

9 8 7 6 5 4 3 2 1

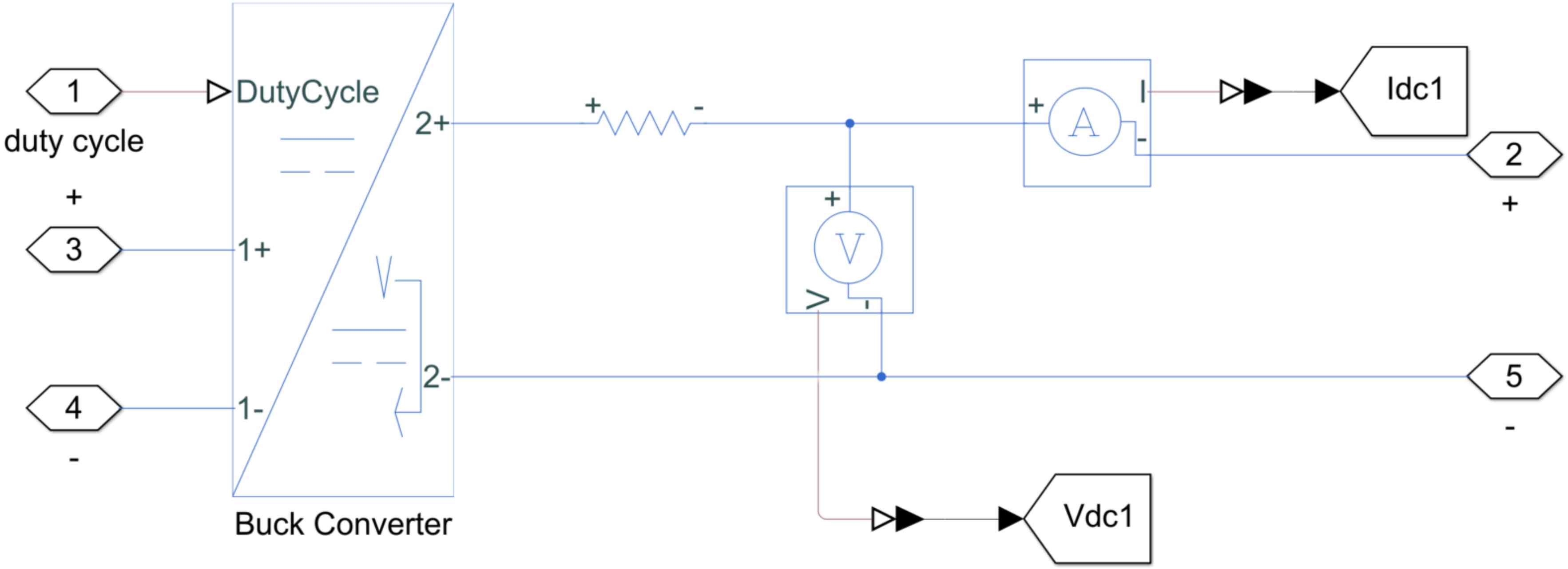
Power Sharing on DC Systems
Rectification and DC/DC Conversion

With AC sources, we need to rectify to DC and also control DC system voltage level. We start with ideal AC/DC conversion that does not include the effect of power electronic switching. This helps us focus on system-level considerations and evaluate the functional correctness of our feedback control systems.



Power Sharing on DC Systems
Rectification and DC/DC Conversion

The feedback control system sends a signal to the buck converter, which changes the system voltage through a duty cycle signal. The duty cycle is the percentage of the system voltage relative to the source voltage.



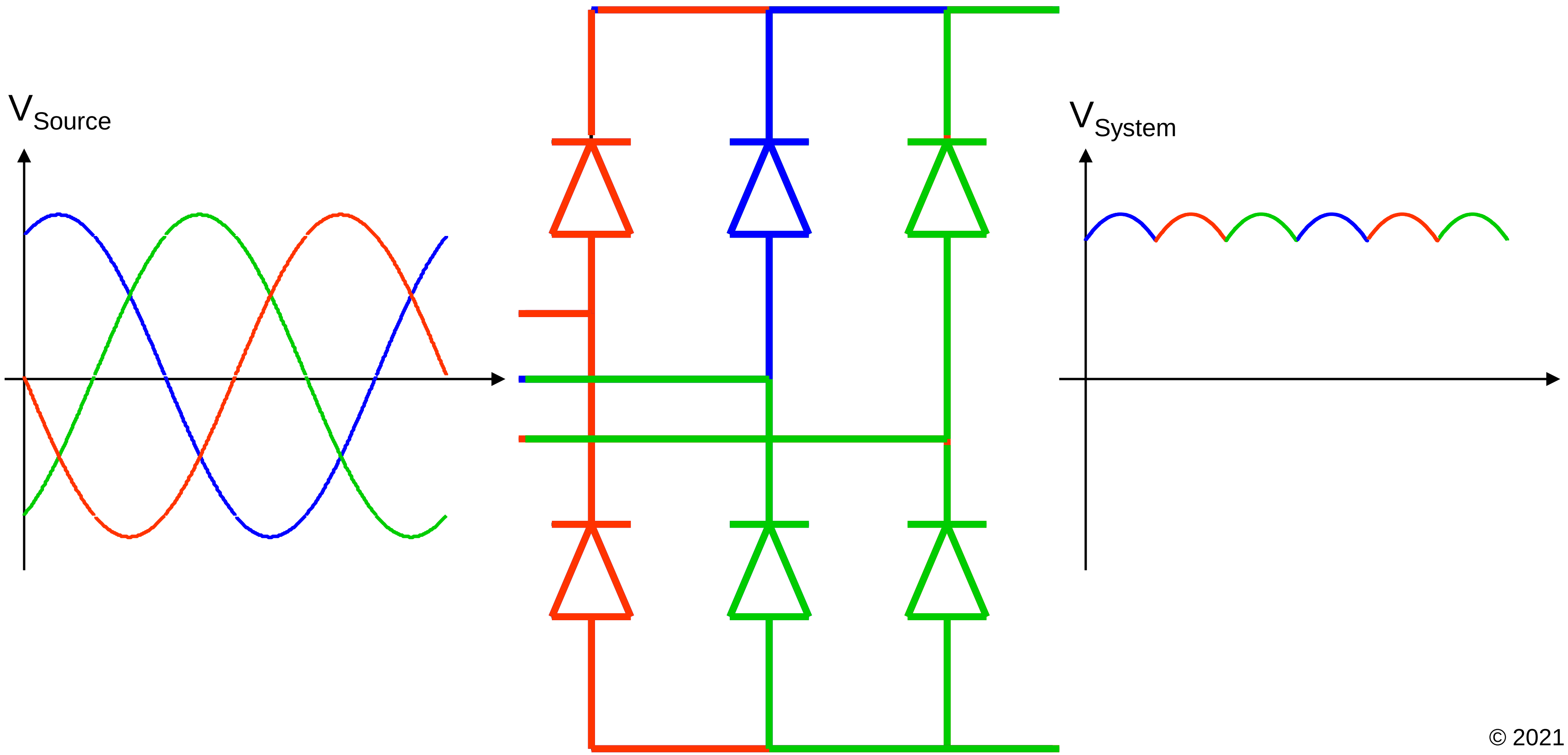
Power Sharing on DC Systems
Rectification and DC/DC Conversion

Once we have confirmed the functional correctness of our droop control system, we can consider including the effect of the rectifier switching devices on the overall system response.

Before we do that, we'll refresh our memories on the operation of diode rectifiers.

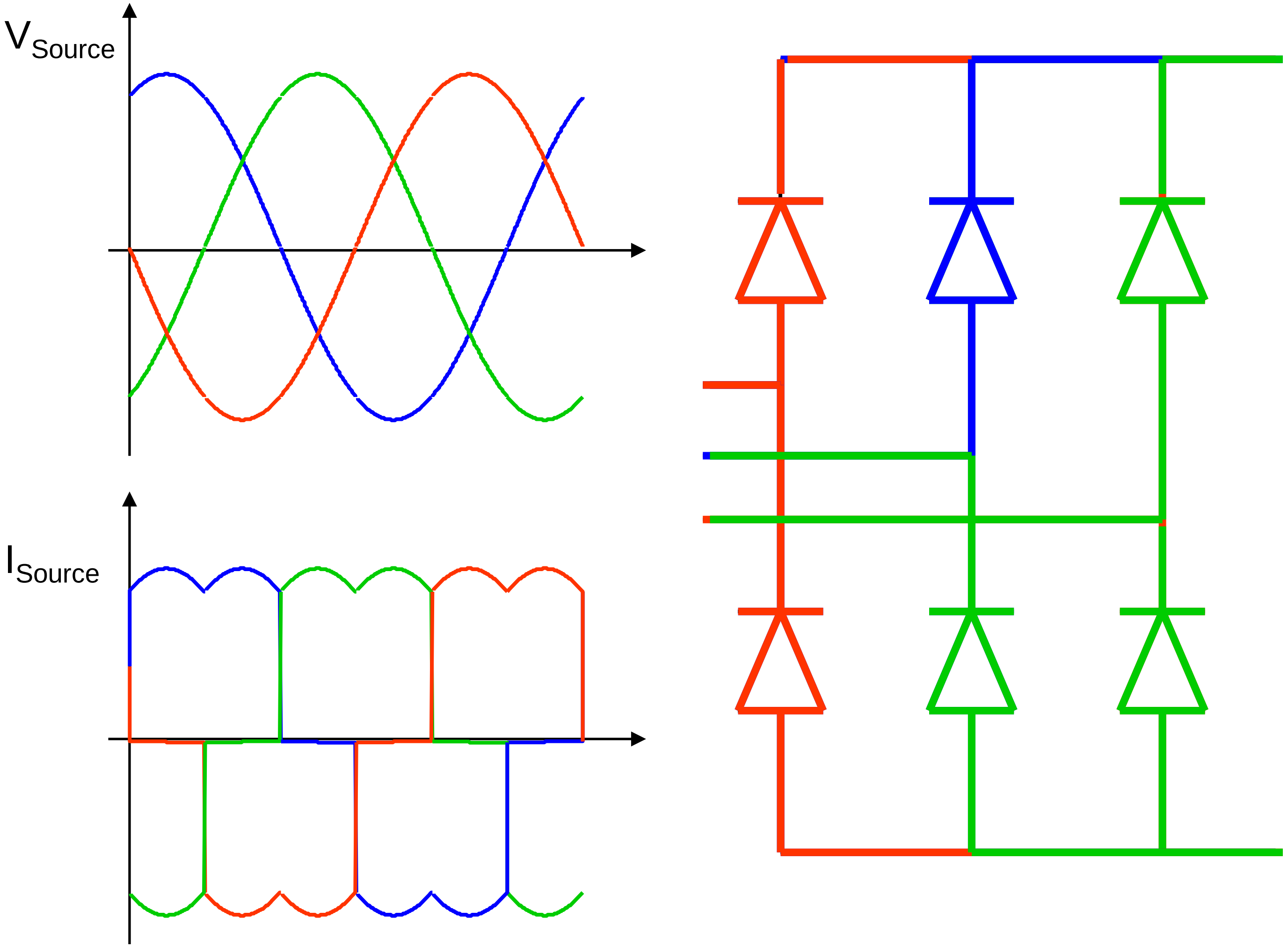
Three-Phase Diode Rectifier (construction of DC voltage)

A diode rectifier is an ‘uncontrolled’ power converter, as it switches (commutates) based on the system conditions, rather than through an active control signal. The example shown is a ‘6-pulse’ rectifier - note the ripple on the system voltage.



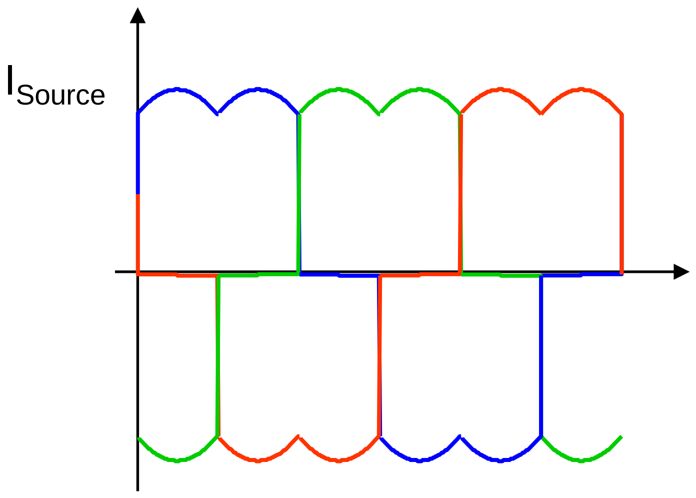
Three-Phase Diode Rectifier (impact on AC current)

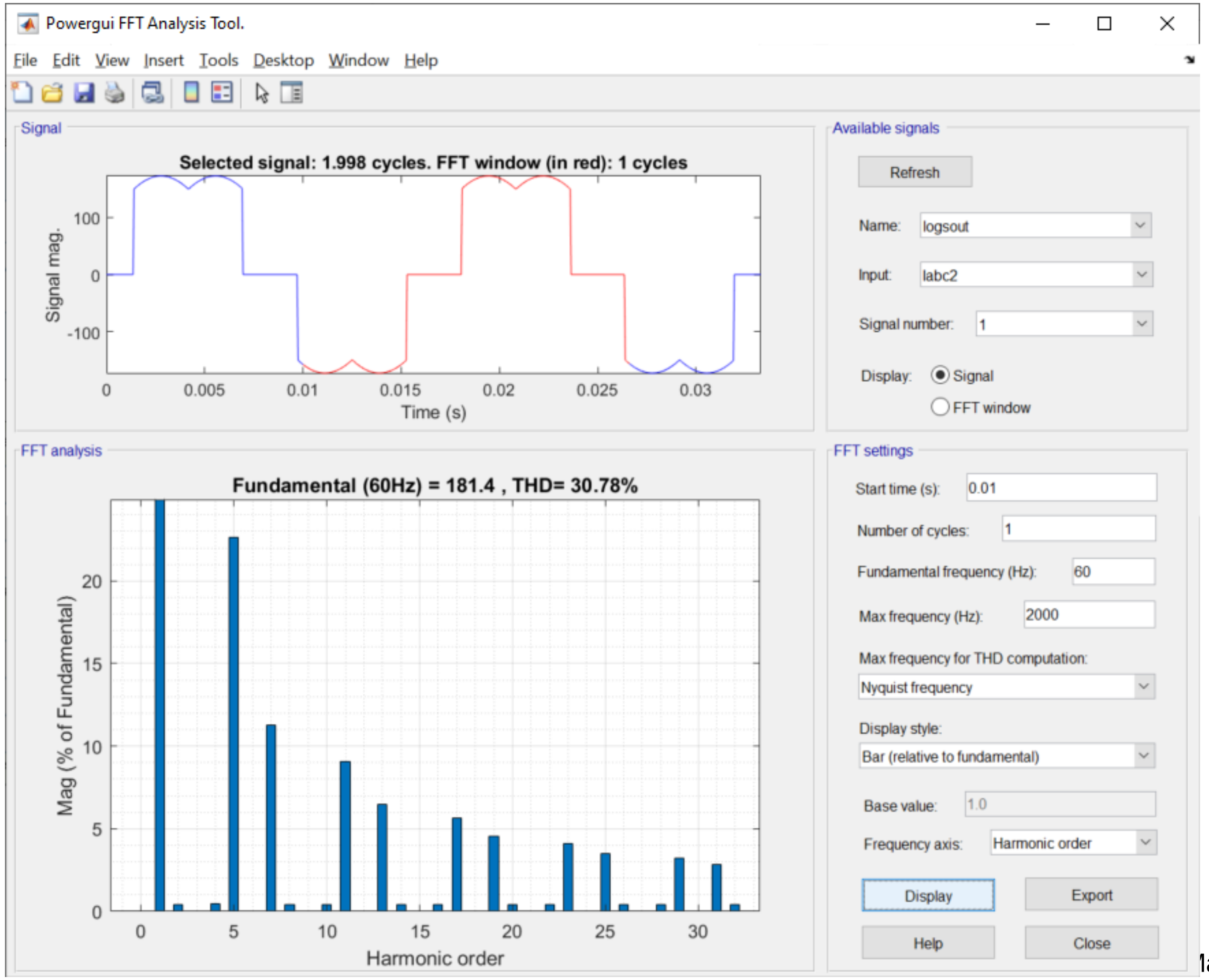
The commutation of the switches causes harmonics to appear on the source current (in reality, both voltage and source are contaminated with harmonics, but we show ideal voltage here for clarity)



Three-Phase Diode Rectifier (impact on AC current)

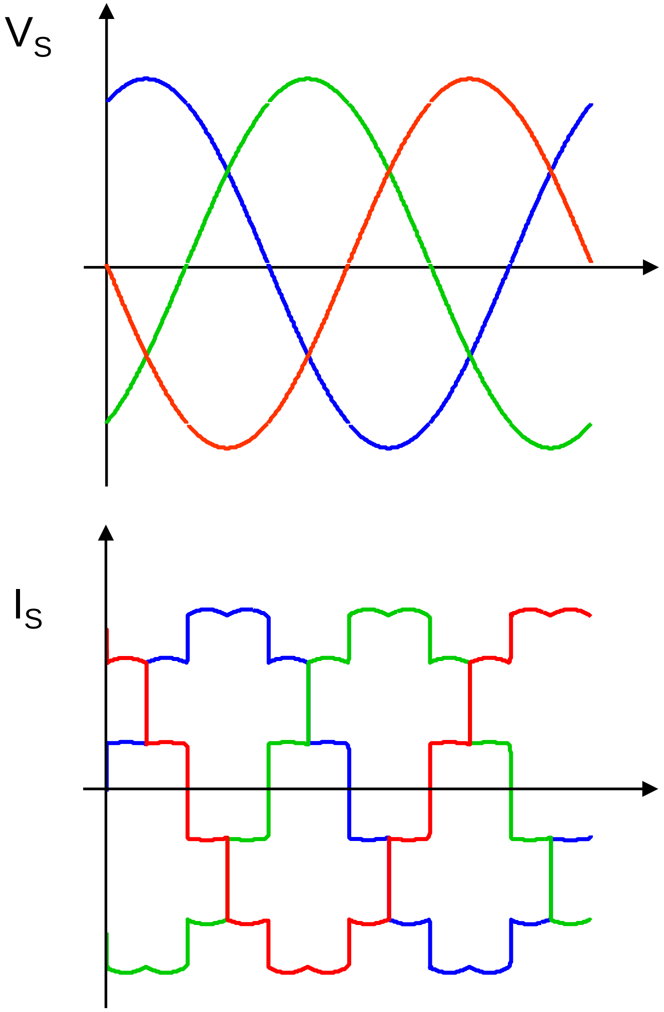
With a 6-pulse device, we expect to see the first significant harmonics on source current showing up on the 5^{th} and 7^{th} harmonics, with additional harmonics showing up at additions of 6 (i.e. 11^{th}-13^{th}, 17^{th}-19^{th} etc).

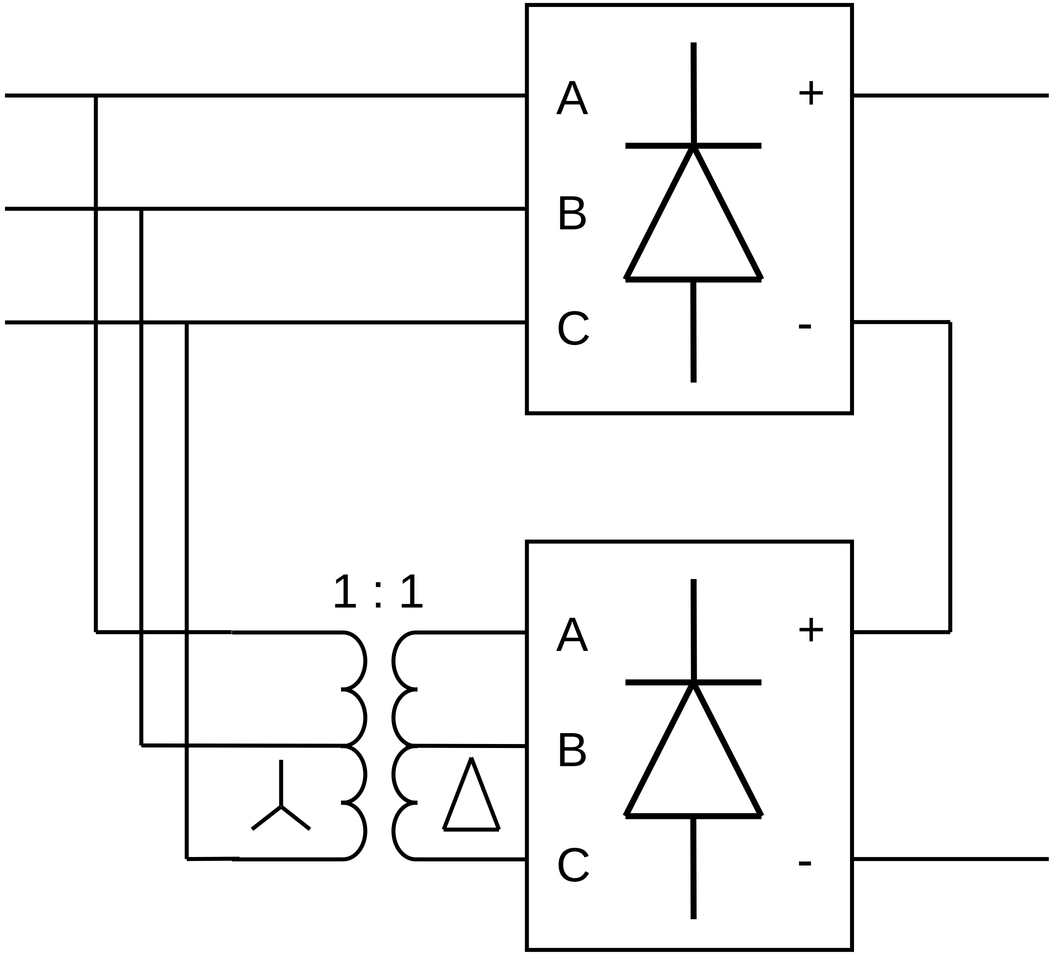




12-Pulse Diode Rectifier

With a 12-pulse device, we connect two 6-pulse devices in parallel and phase shift one of the 6-pulse devices by 30 degrees relative to the other.





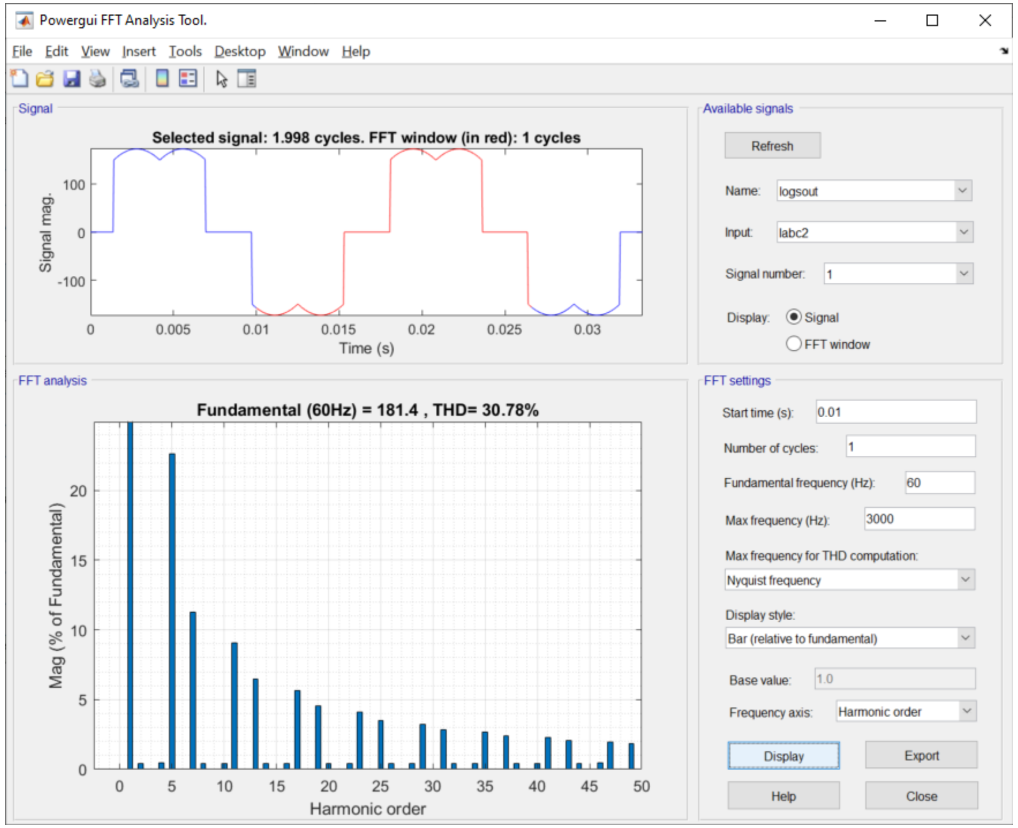
To determine the required phase-shift, simply calculate,

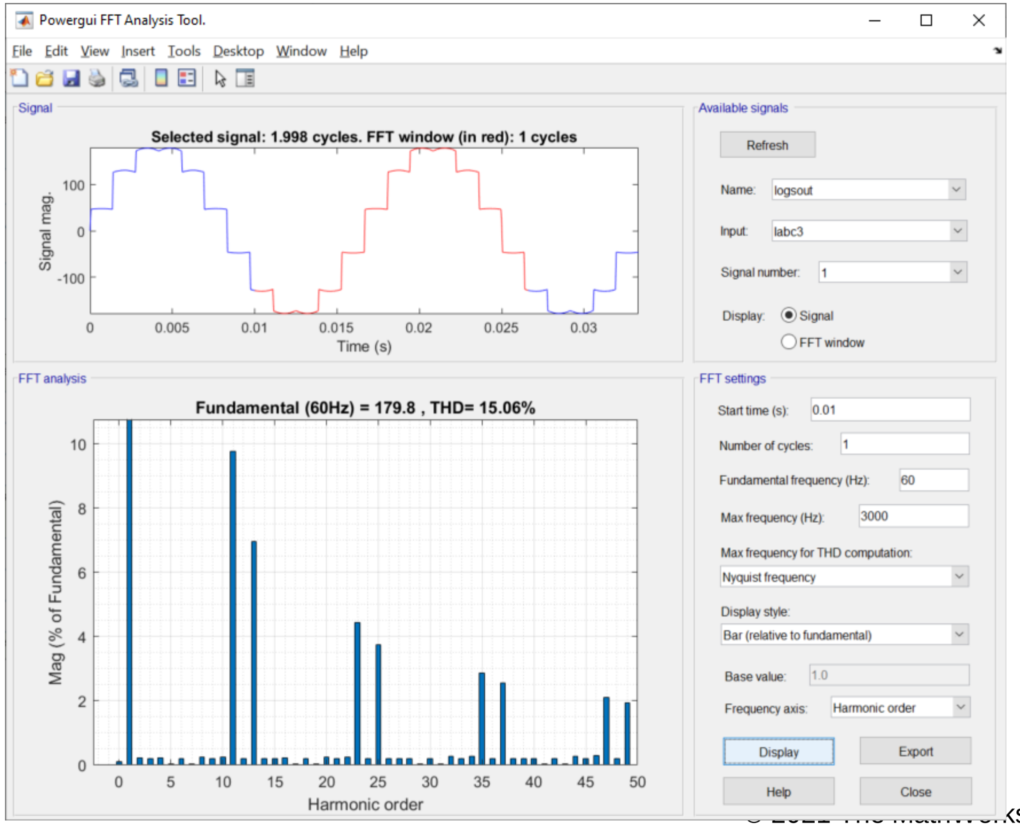
phase shift = 360/p

Where p is the pulse number.

12-pulse Diode Rectifier

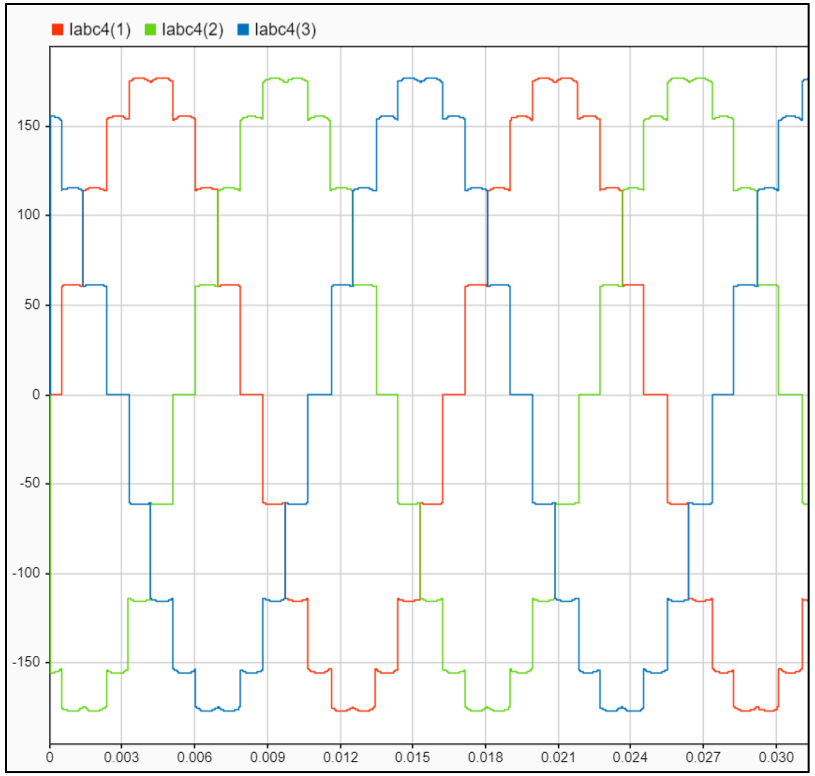
With a 12-pulse device, we expect to see the first significant harmonics on source current showing up on the 11th and 13th harmonics, with additional harmonics showing up at additions of 12 (i.e. 23rd-25th , 35th-37th etc).

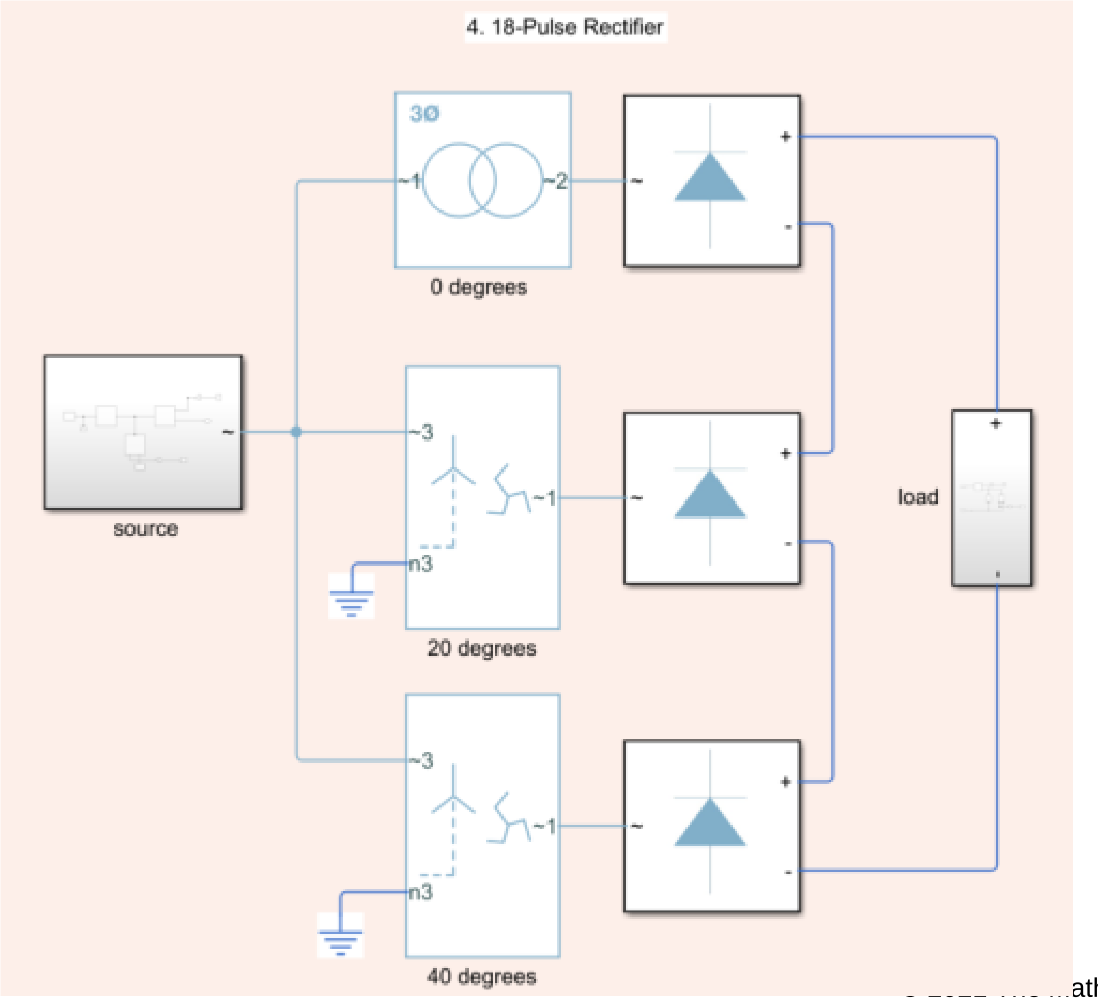




18-Pulse Diode Rectifier

With an 18-pulse device, we connect three 6-pulse devices in parallel and phase shift the devices by 20 degrees relative to each other. phase shift = 360/18 = 20º

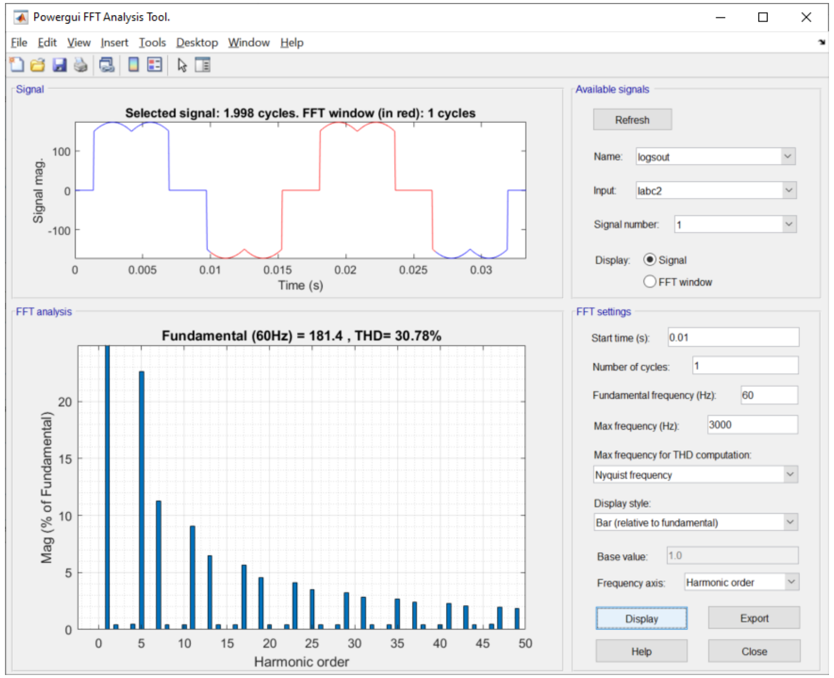


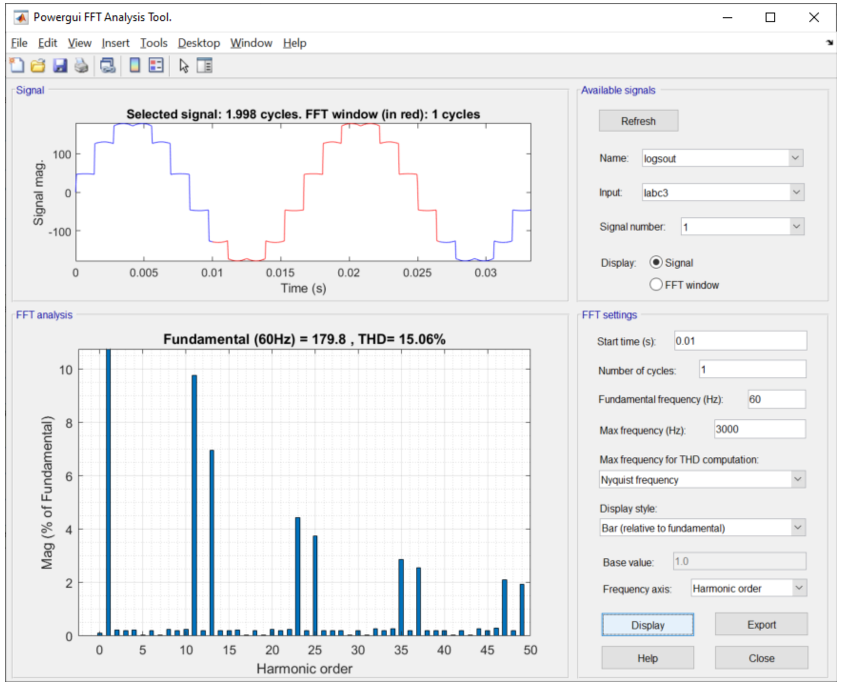


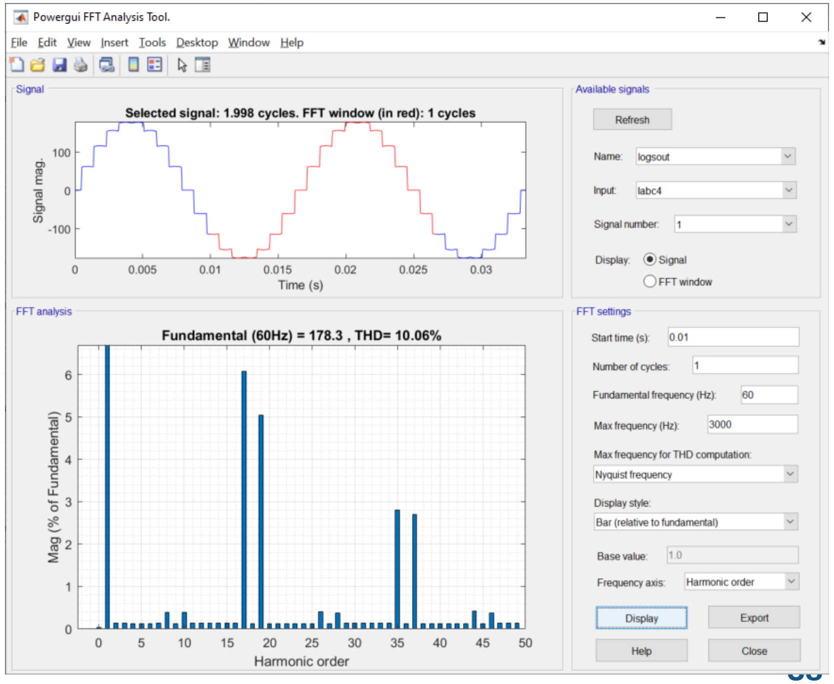
18-pulse Diode Rectifier

With an 18-pulse device, we expect to see the first significant harmonics on source current showing up on the 17^{th} and 19^{th} harmonics, with additional harmonics showing up at additions of 18 (i.e. 35^{th}-37^{th} , 53^{rd}-55^{th} etc).

Notice also the reduction in harmonic distortion as pulse number increases.

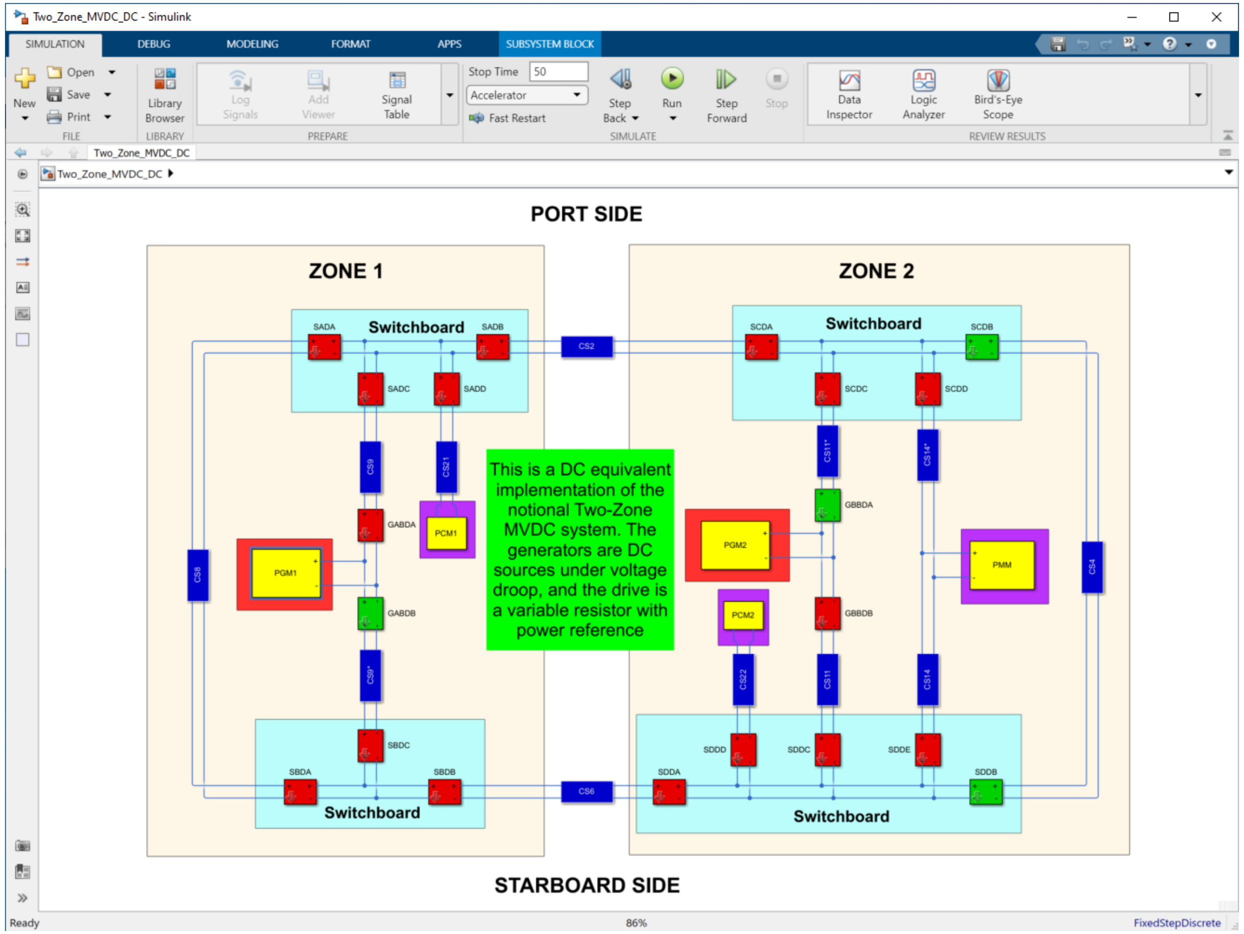






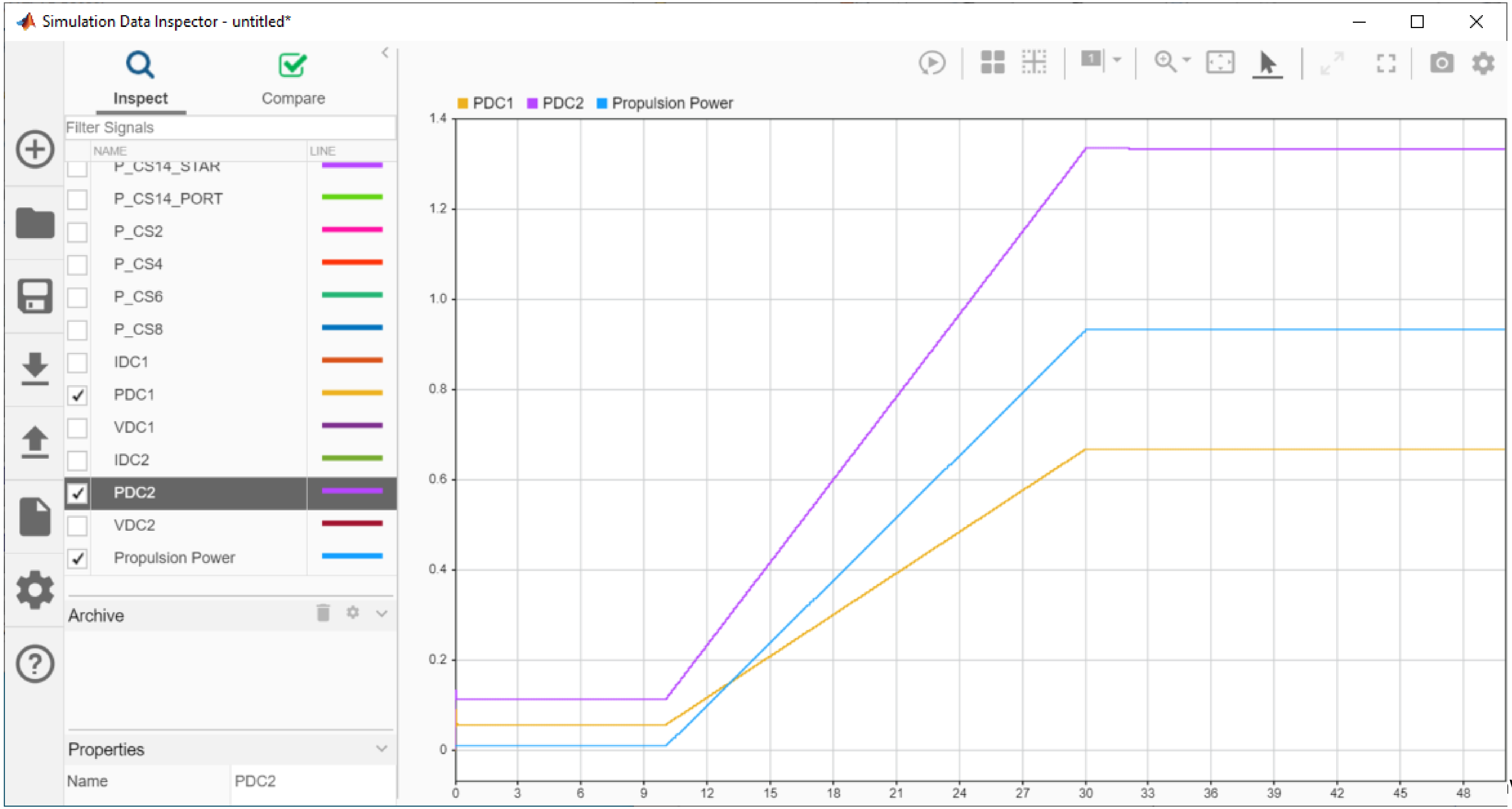
System Analysis

We will now consider some aspects of system analysis, and build up fidelity as we go. We start with a DC equivalent, which has only DC sources and no switching. This allows us to check the functional correctness of the power sharing, and to gain quick insights into voltage and current levels throughout the system.



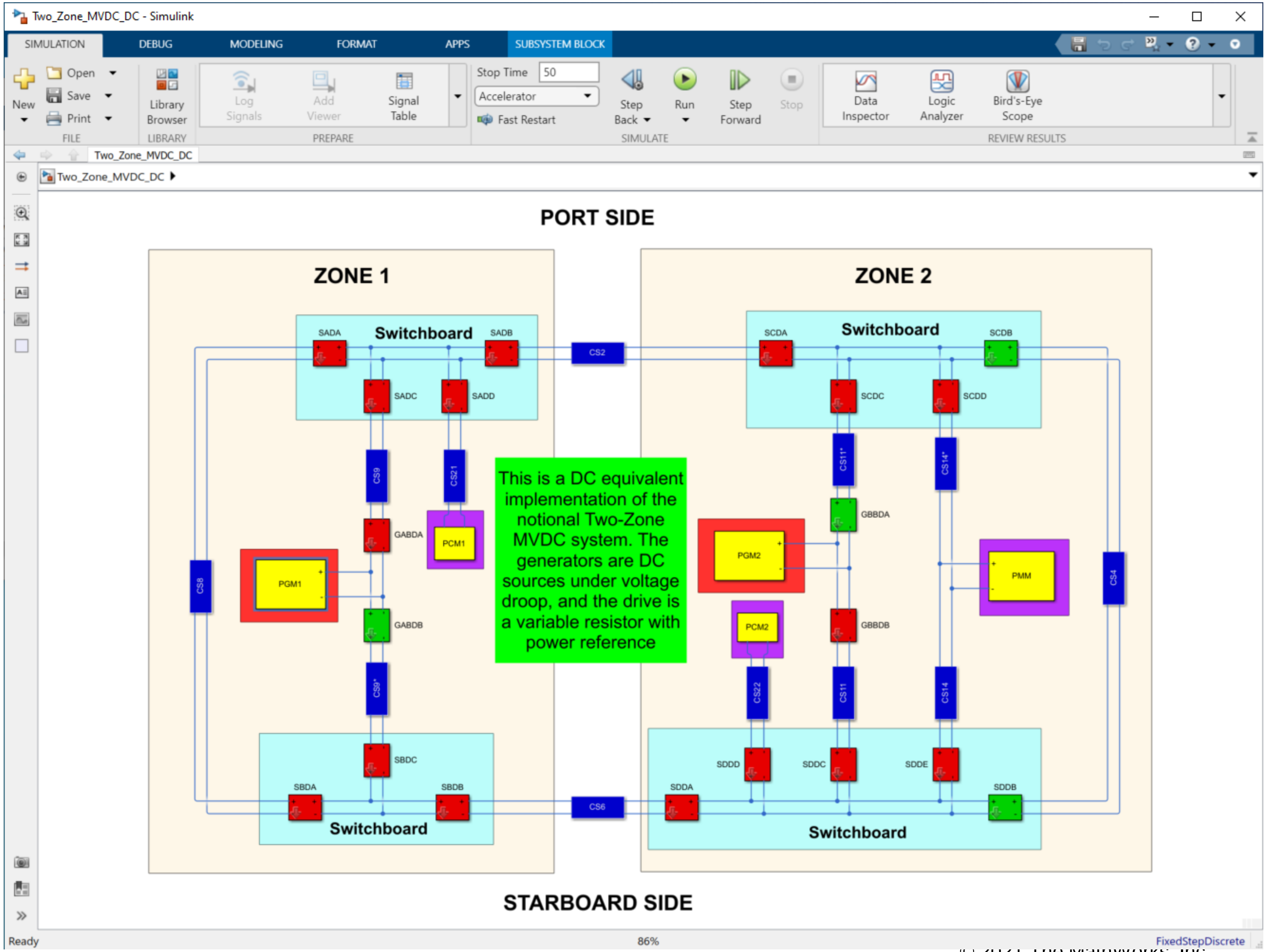
Power Sharing

PGM1 has droop set to 5% and PGM2 has droop set to 2.5%. We expect PGM2 to provide twice the power of PGM1. This is confirmed below.



Cable Loading

Switchboard switches are colored red if they are closed and green if they are open. As GABDB is open, we expect most of the power moving from Zone 1 to Zone 2 to move through CS2 – the port cable, rather than CS6 – the starboard cable.



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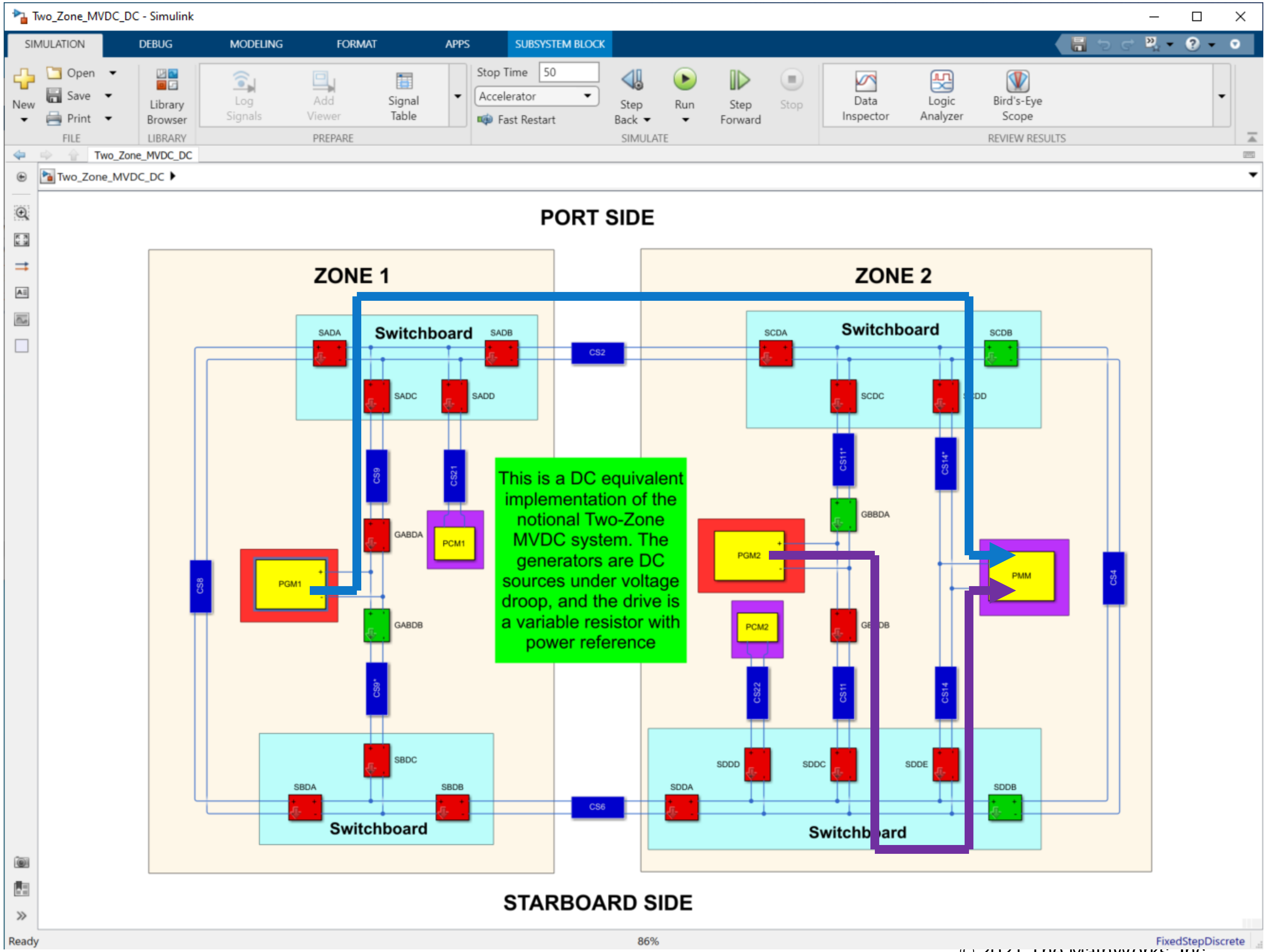

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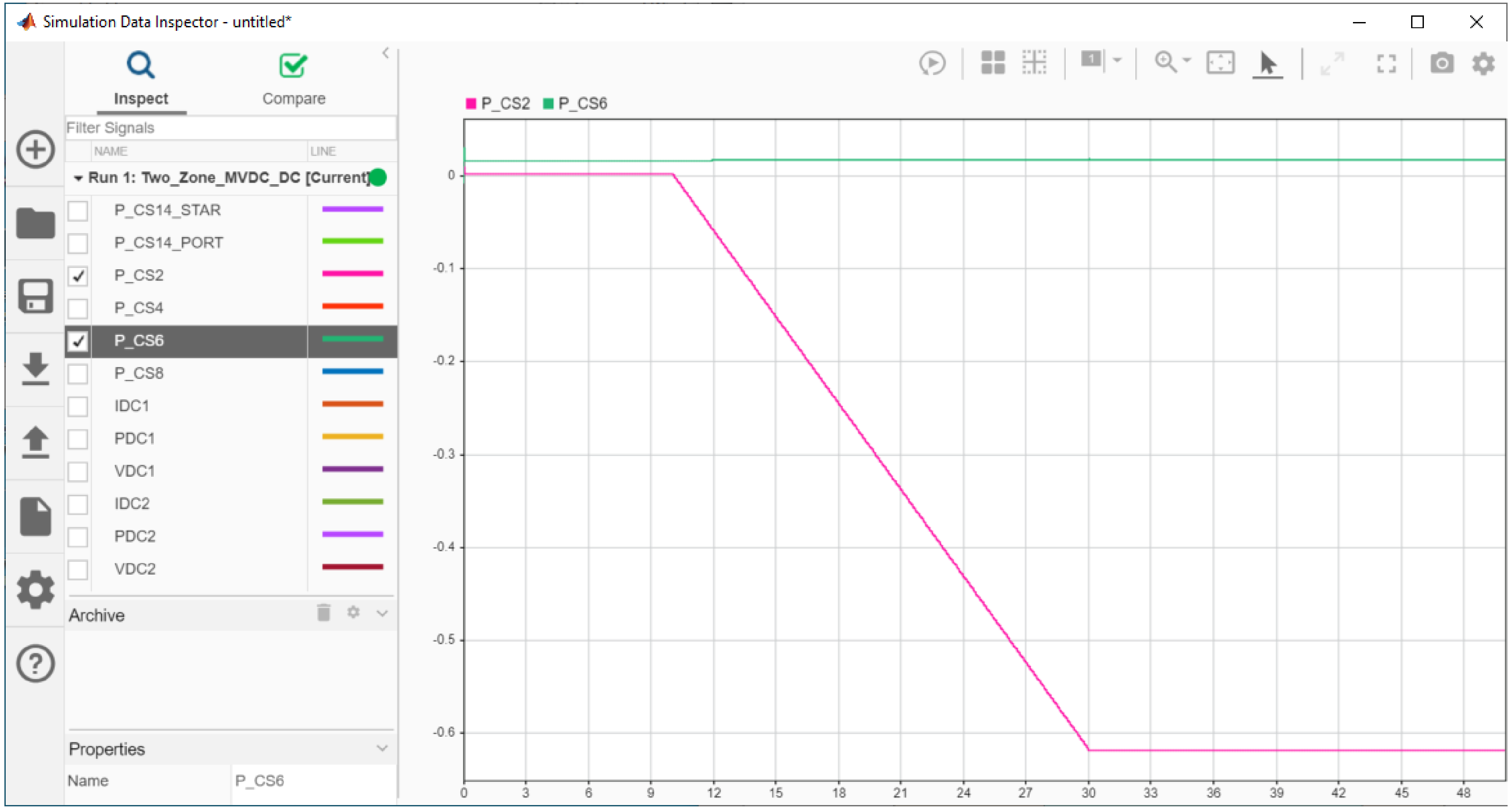
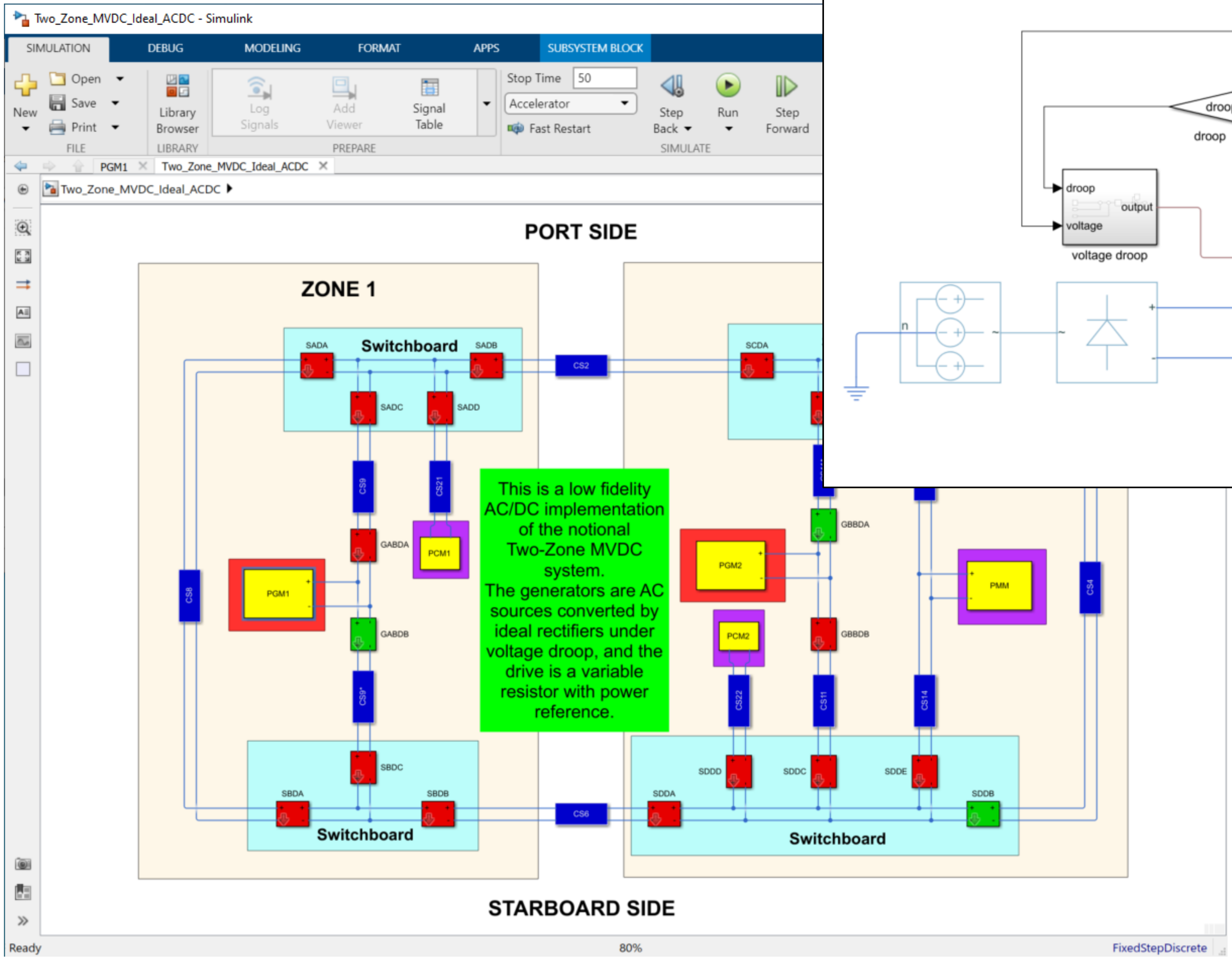
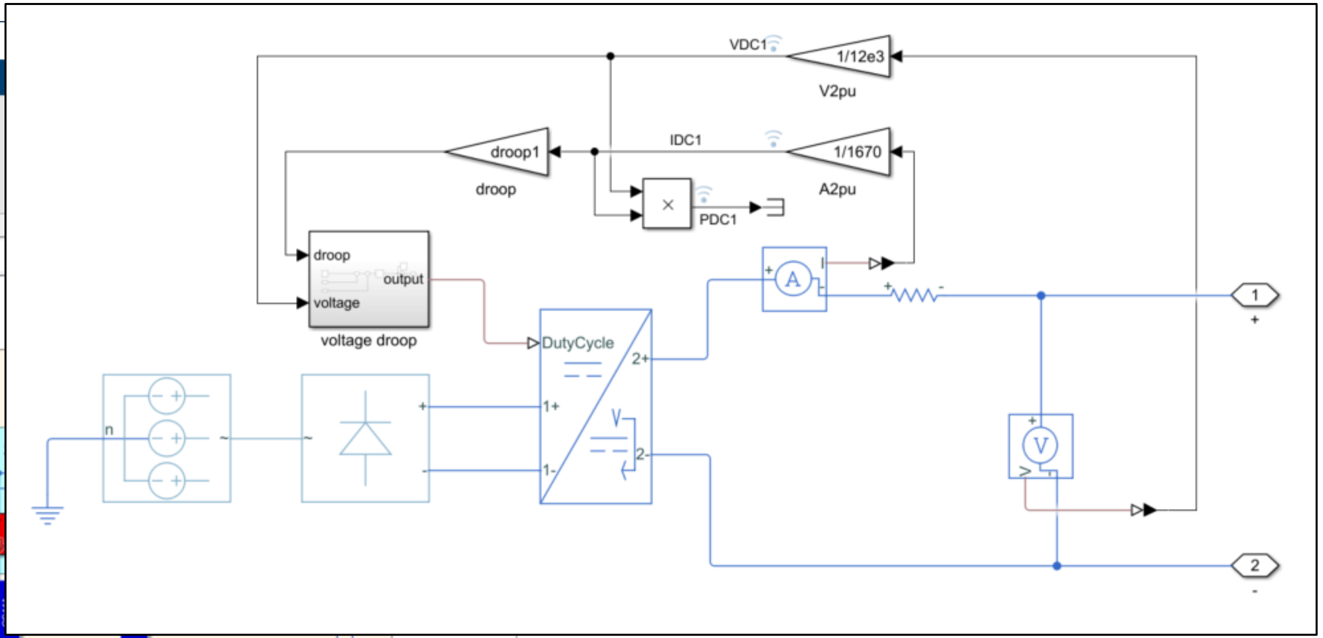


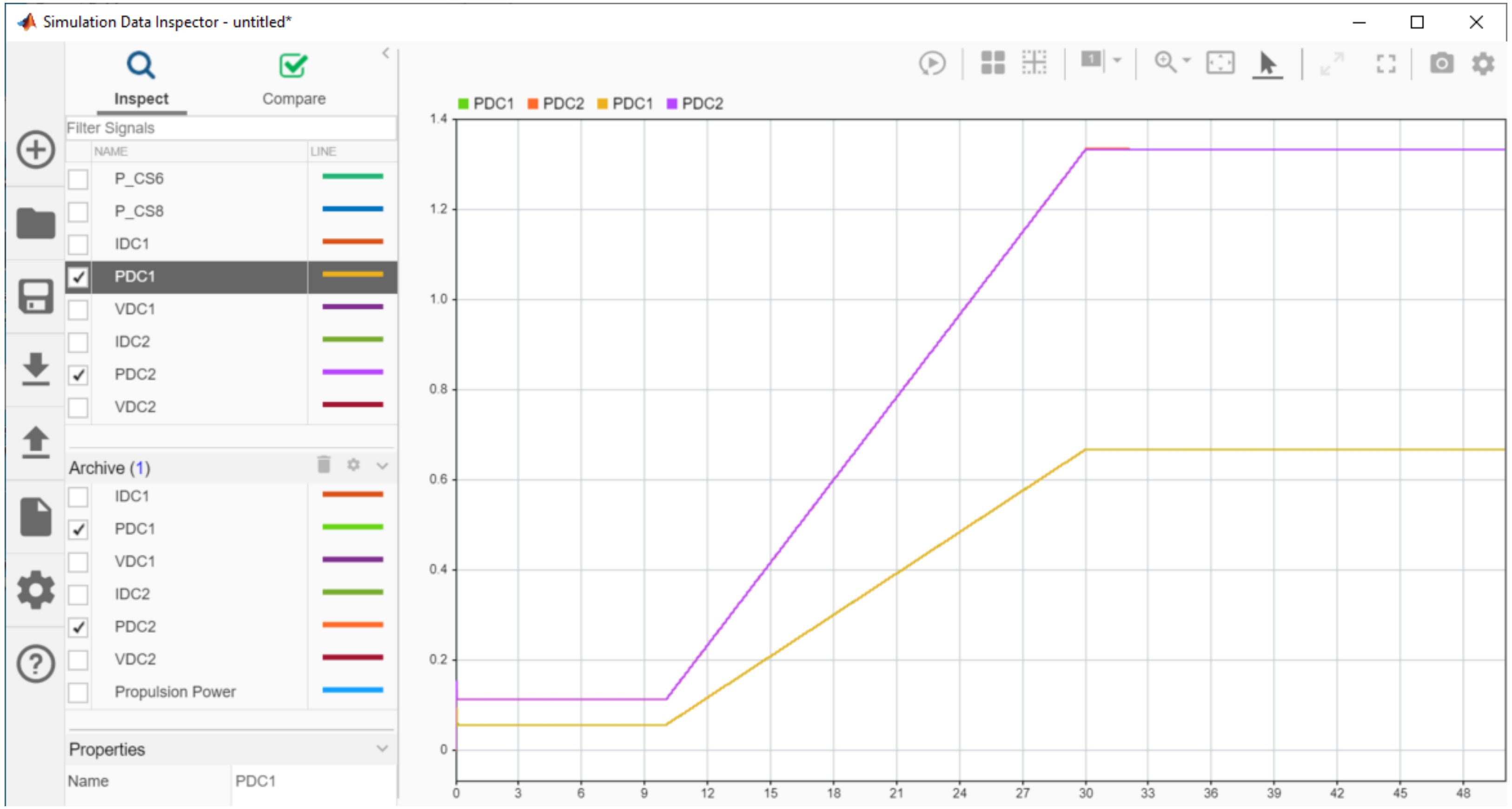
System with Ideal Rectifiers





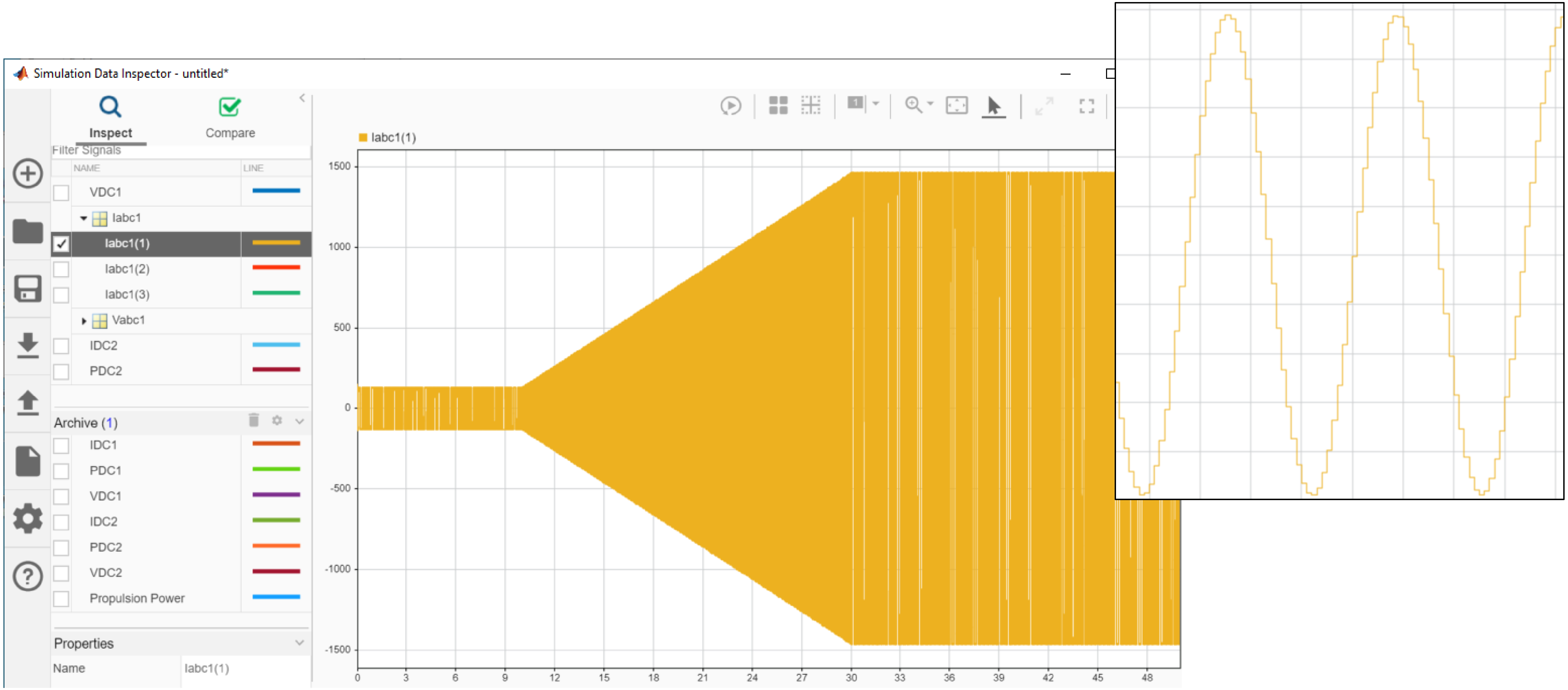
Confirm Operational Equivalence as Fidelity Increases

Changing system fidelity should not result in changes to the broad operational response. We compare responses as we go.

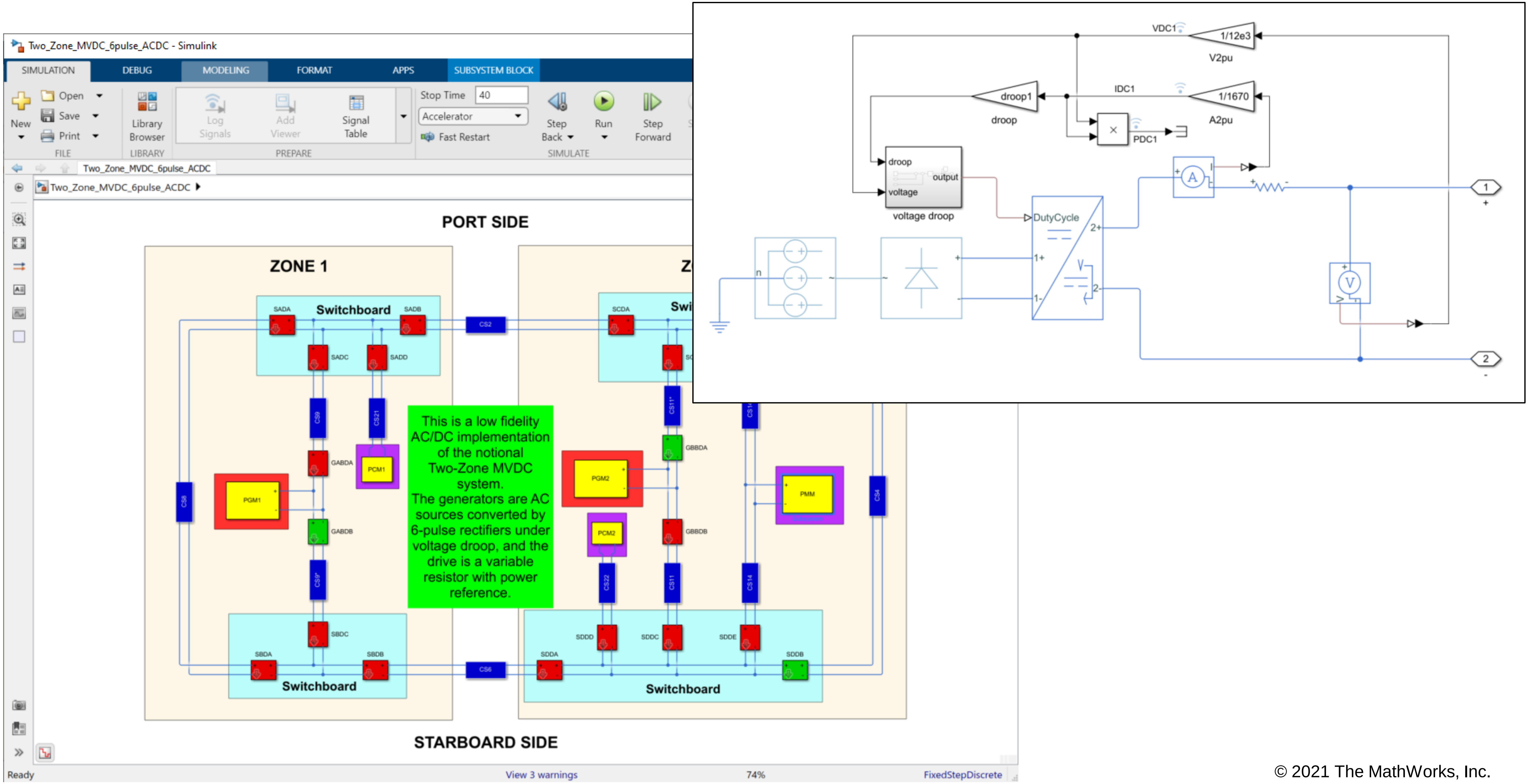


Increased Fidelity Gives More Information

Now we have added ideal rectifiers, we have access to AC voltage and current.

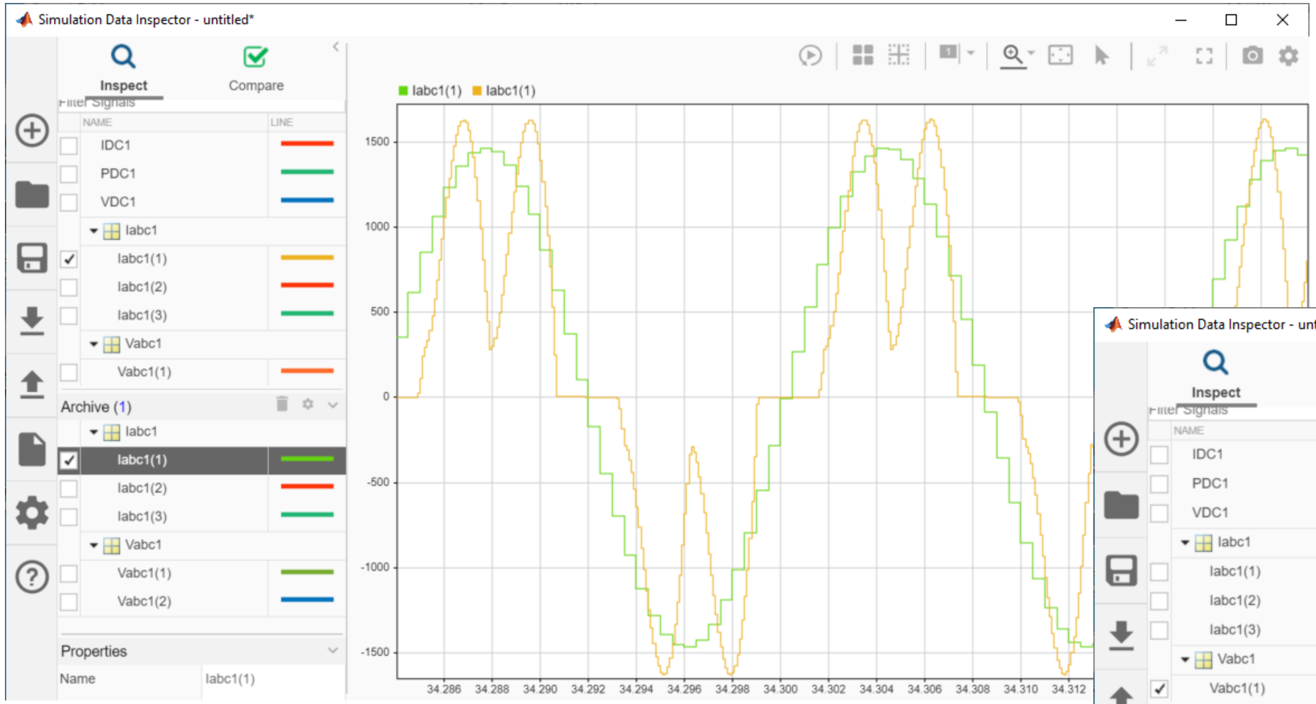


System with 6-Pulse Rectifiers

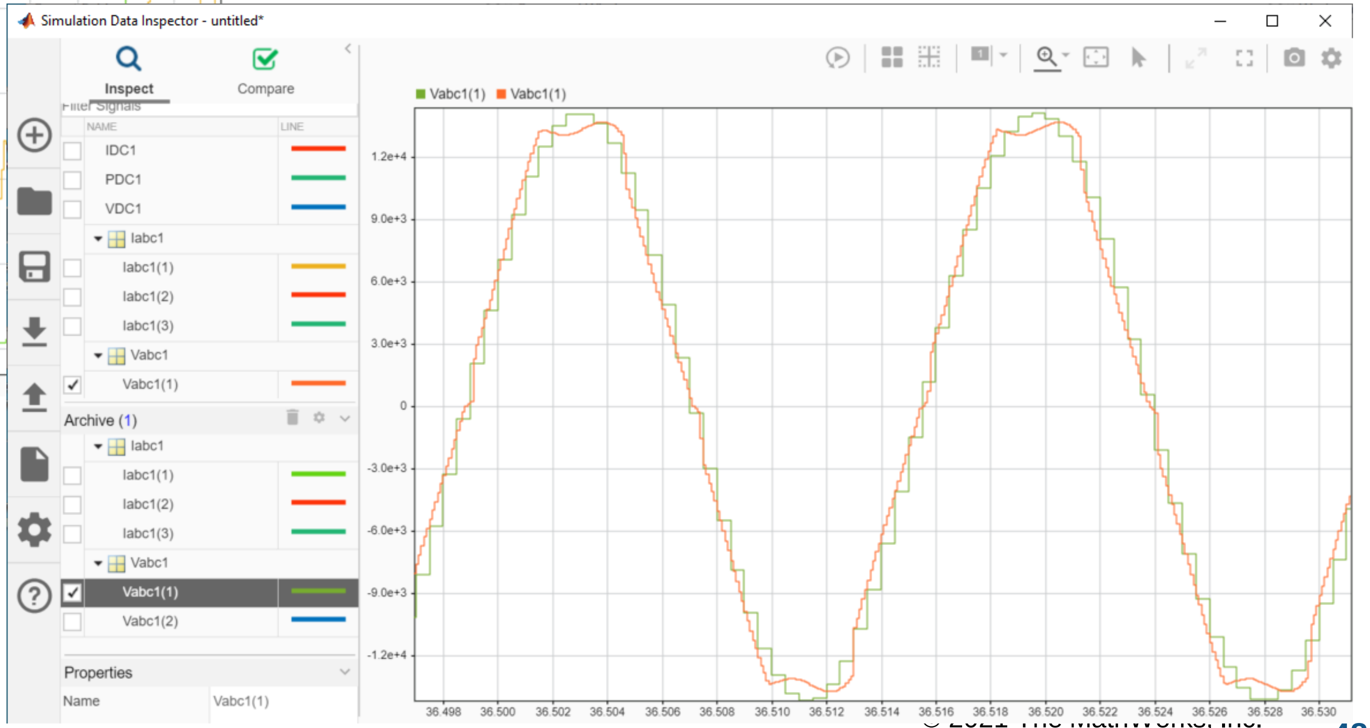


Increased Fidelity Gives More Information

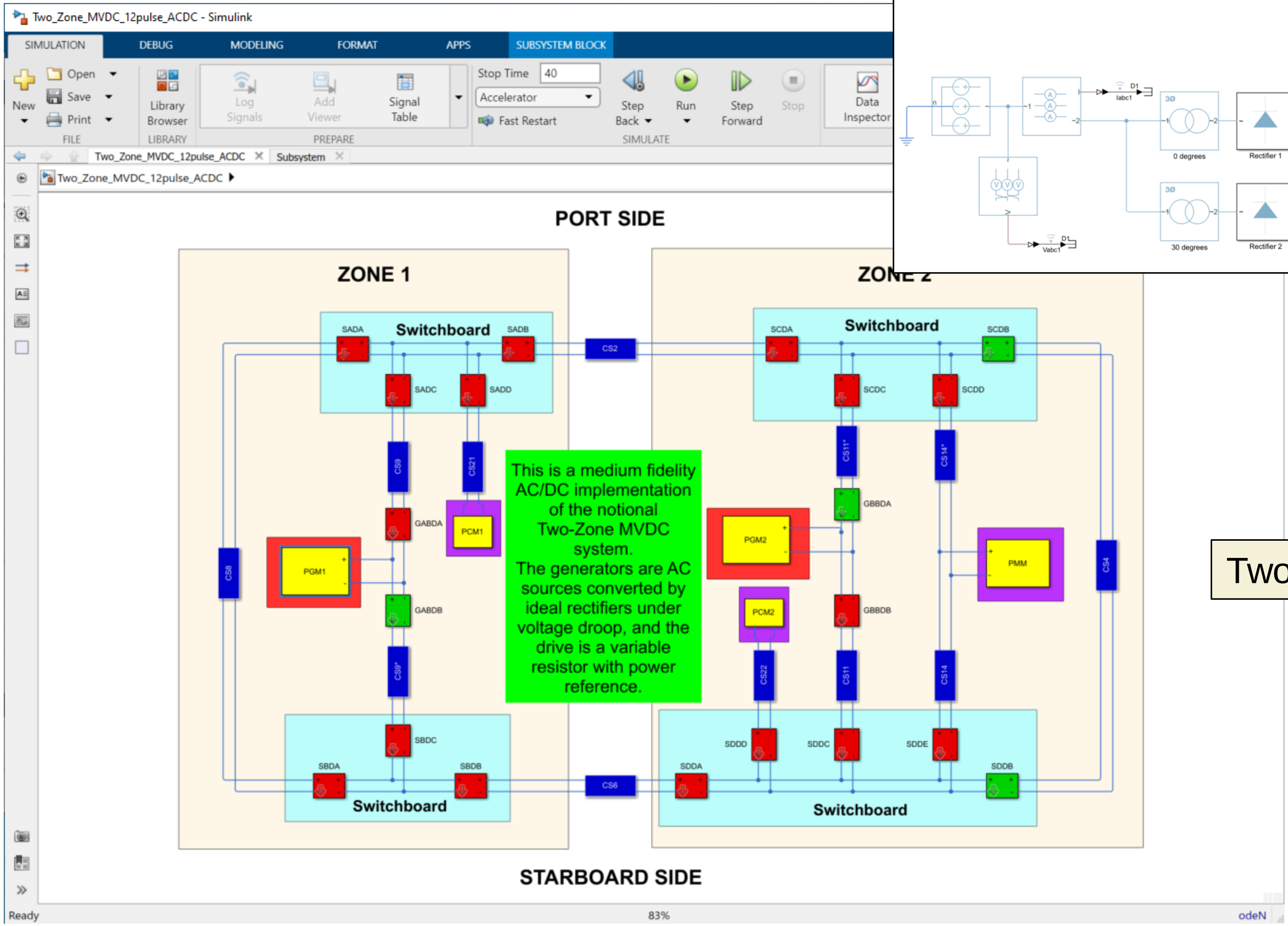
Now we have added 6-pulse rectifiers, we can assess the impact of switching. We can also evaluate whether the droop controllers need modification.

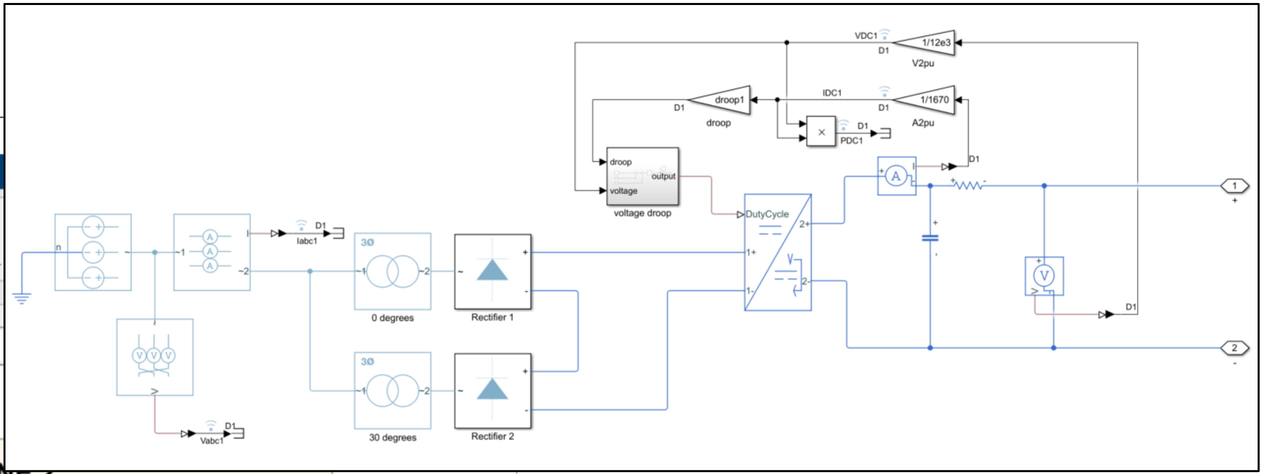


Note that we reduce simulation step-time as fidelity increases.



System with 12-Pulse Rectifiers

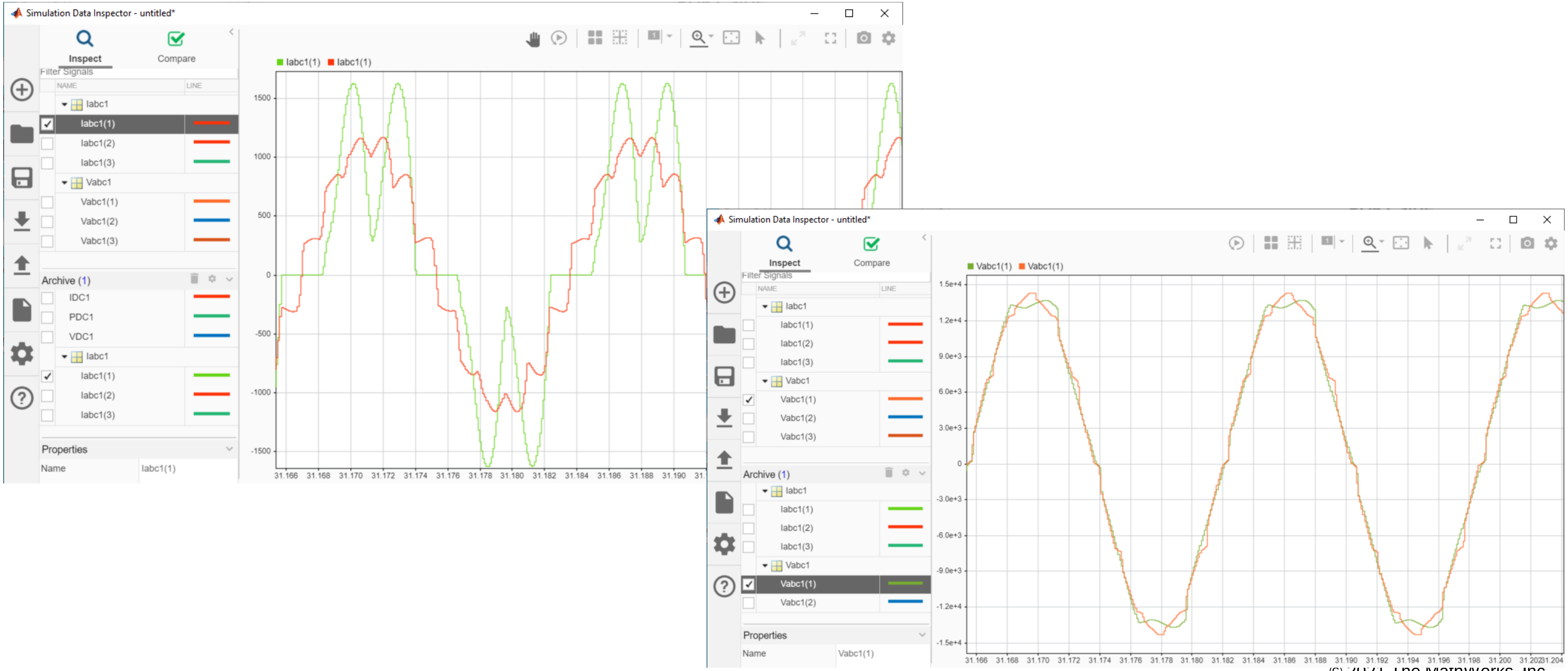




Two_Zone_MVDC_12pulse_ACDC.slx

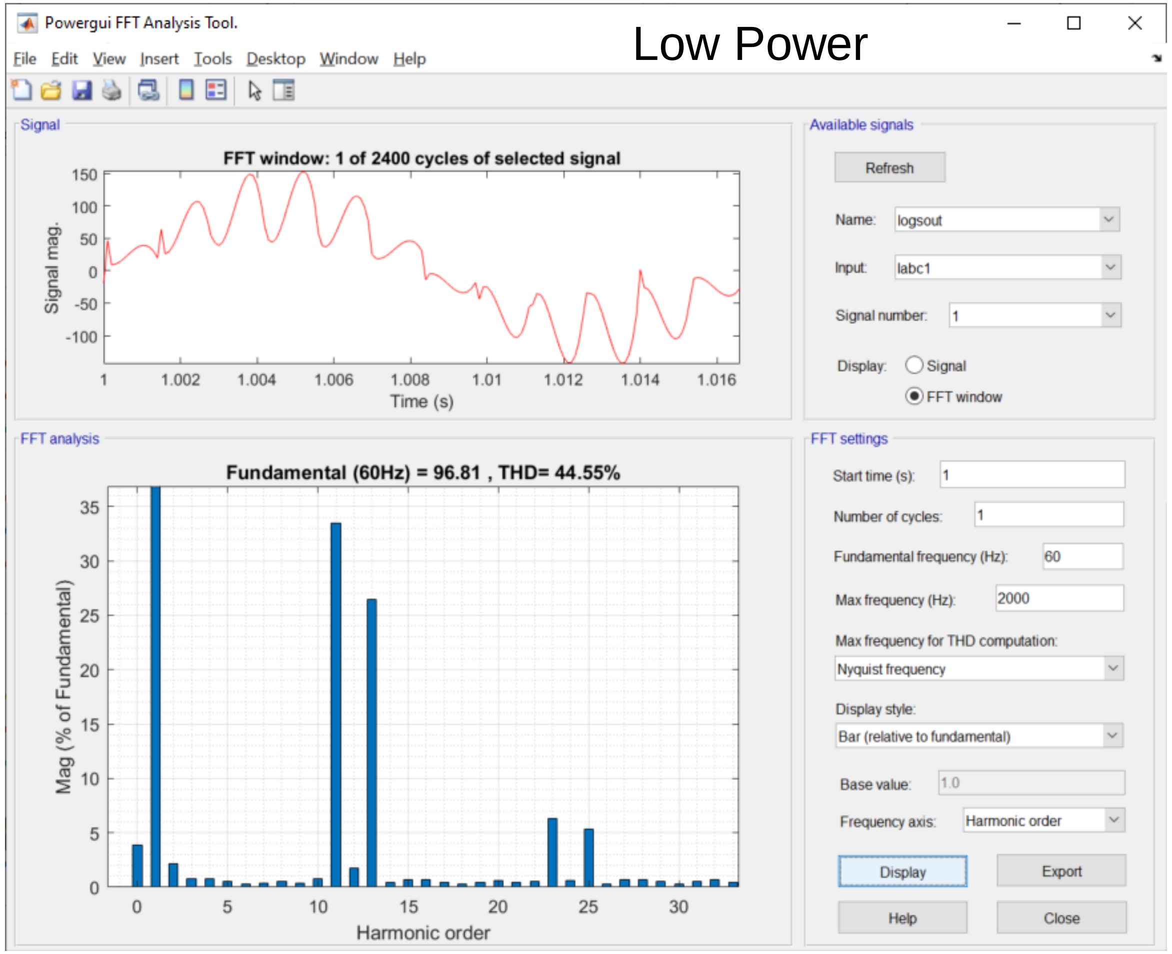
Increased Fidelity Gives More Information

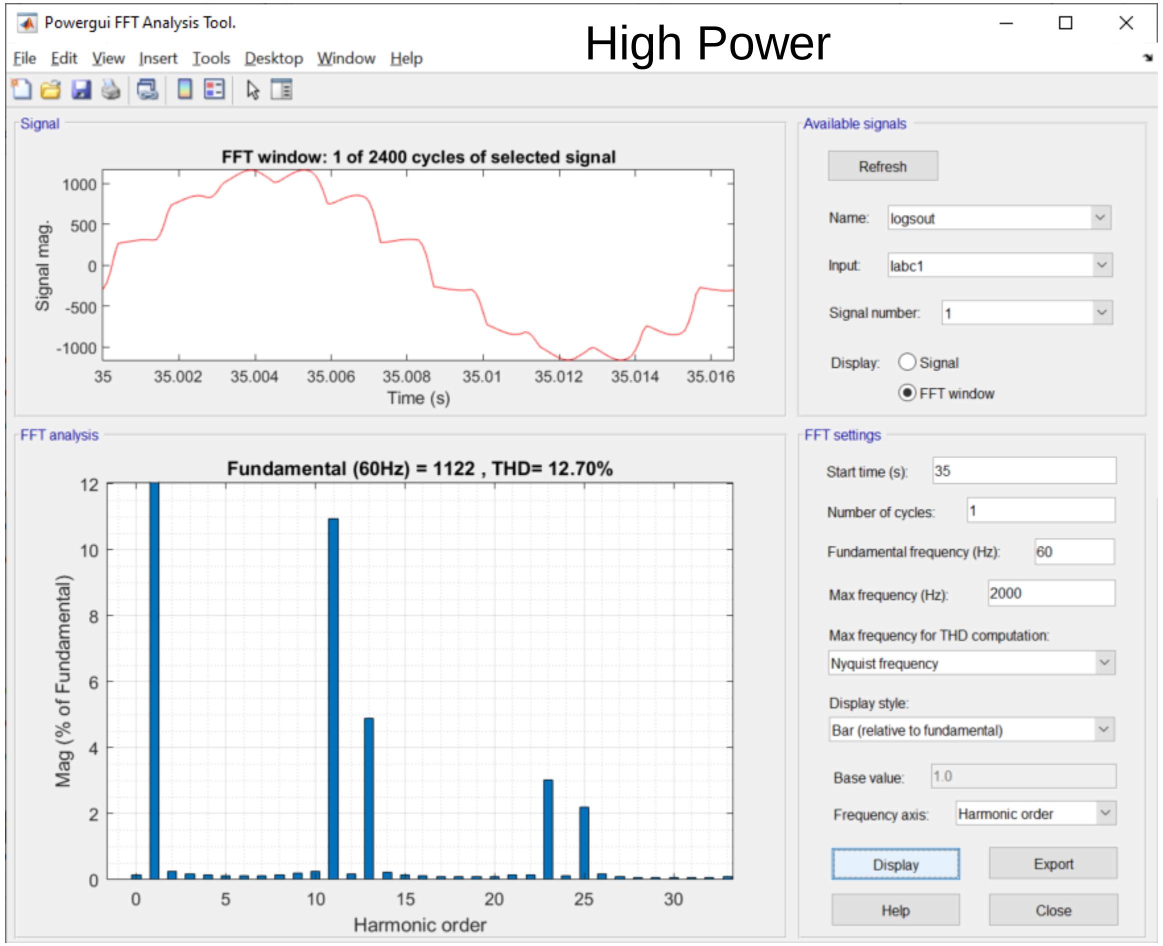
Now we have added 12-pulse rectifiers, we can assess the impact of reducing harmonic distortion.



Harmonic Distortion at Different Power Levels

We can explore the distortion on voltage and current at both low- and high-power levels (or any level we want). In this case, current distortion reduces with increased power, and voltage distortion increases with increased power.





Harmonic Distortion at Different Power Levels

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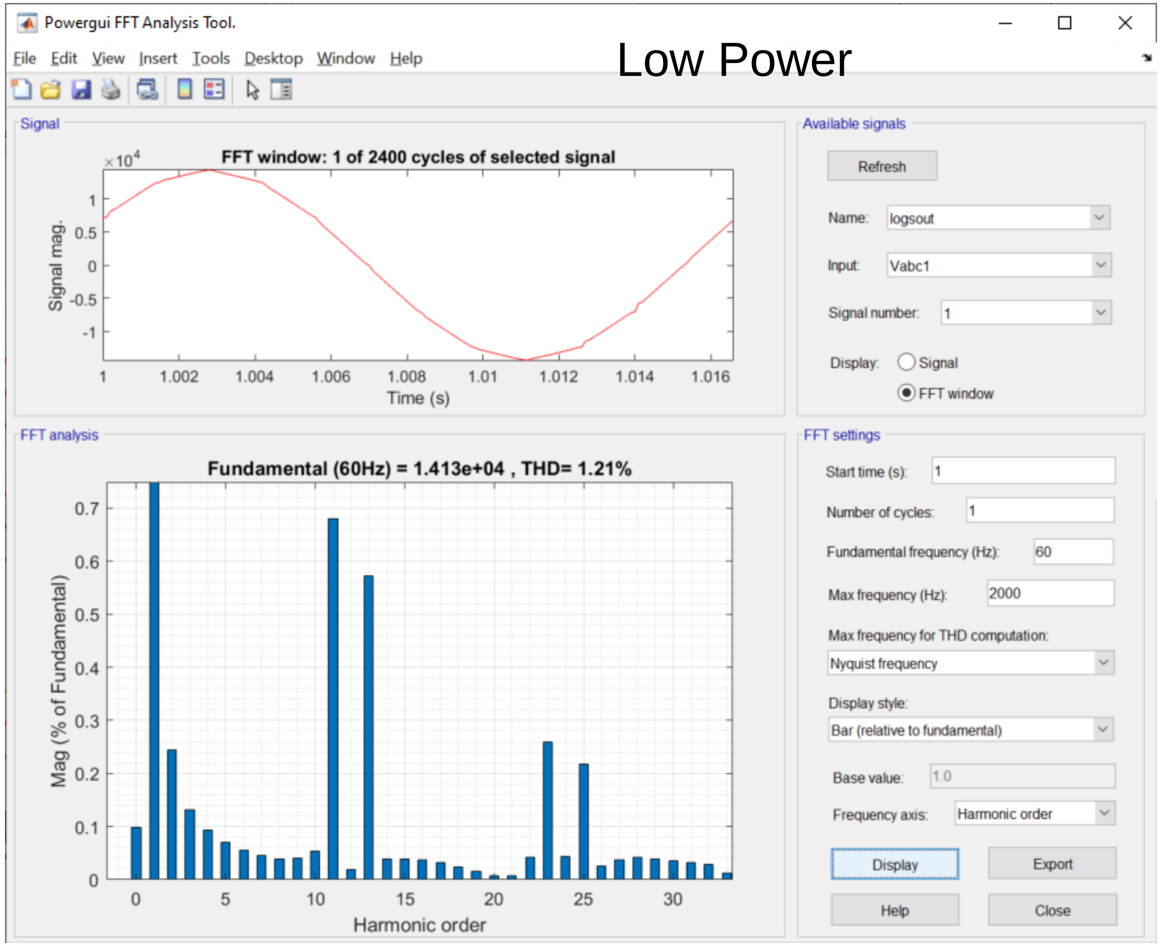
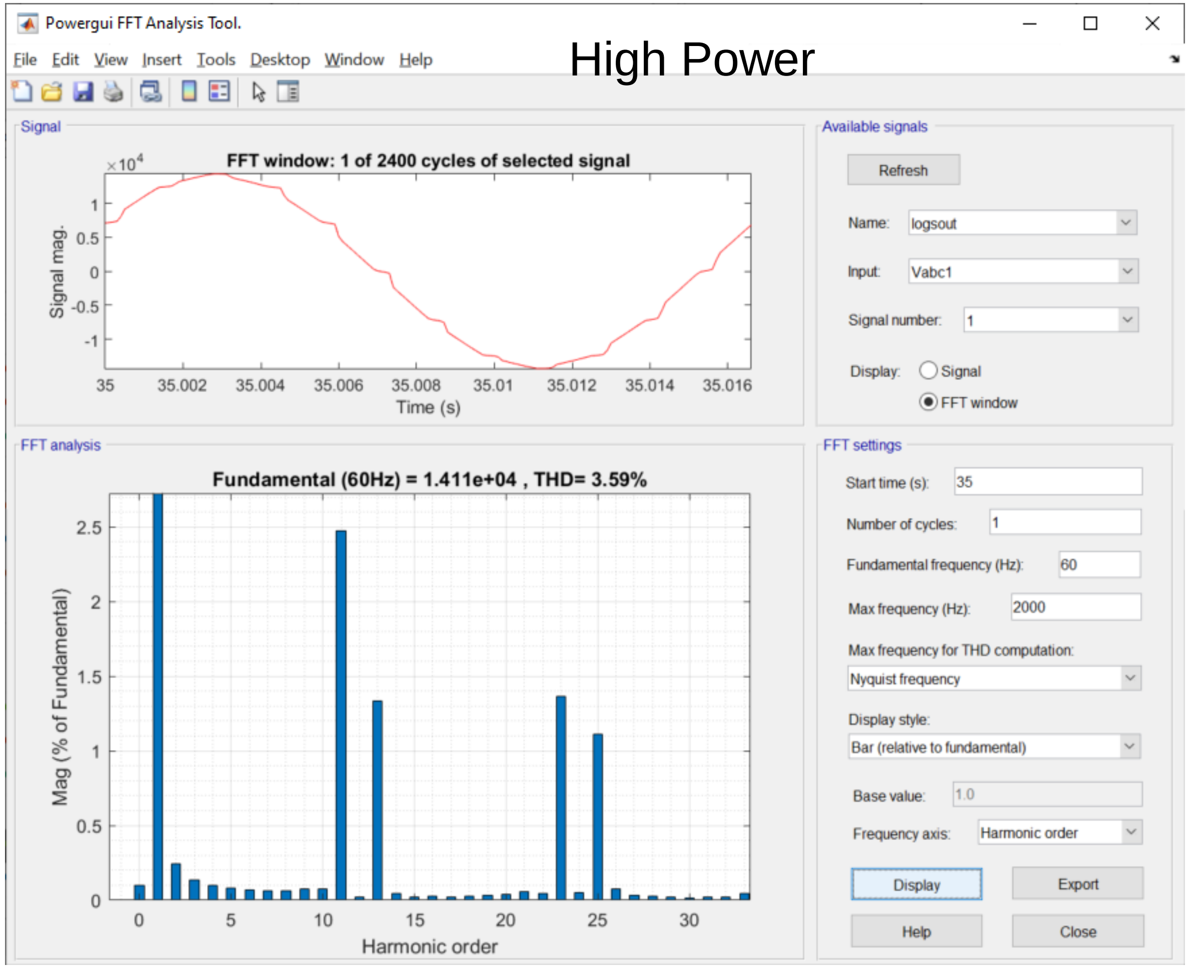
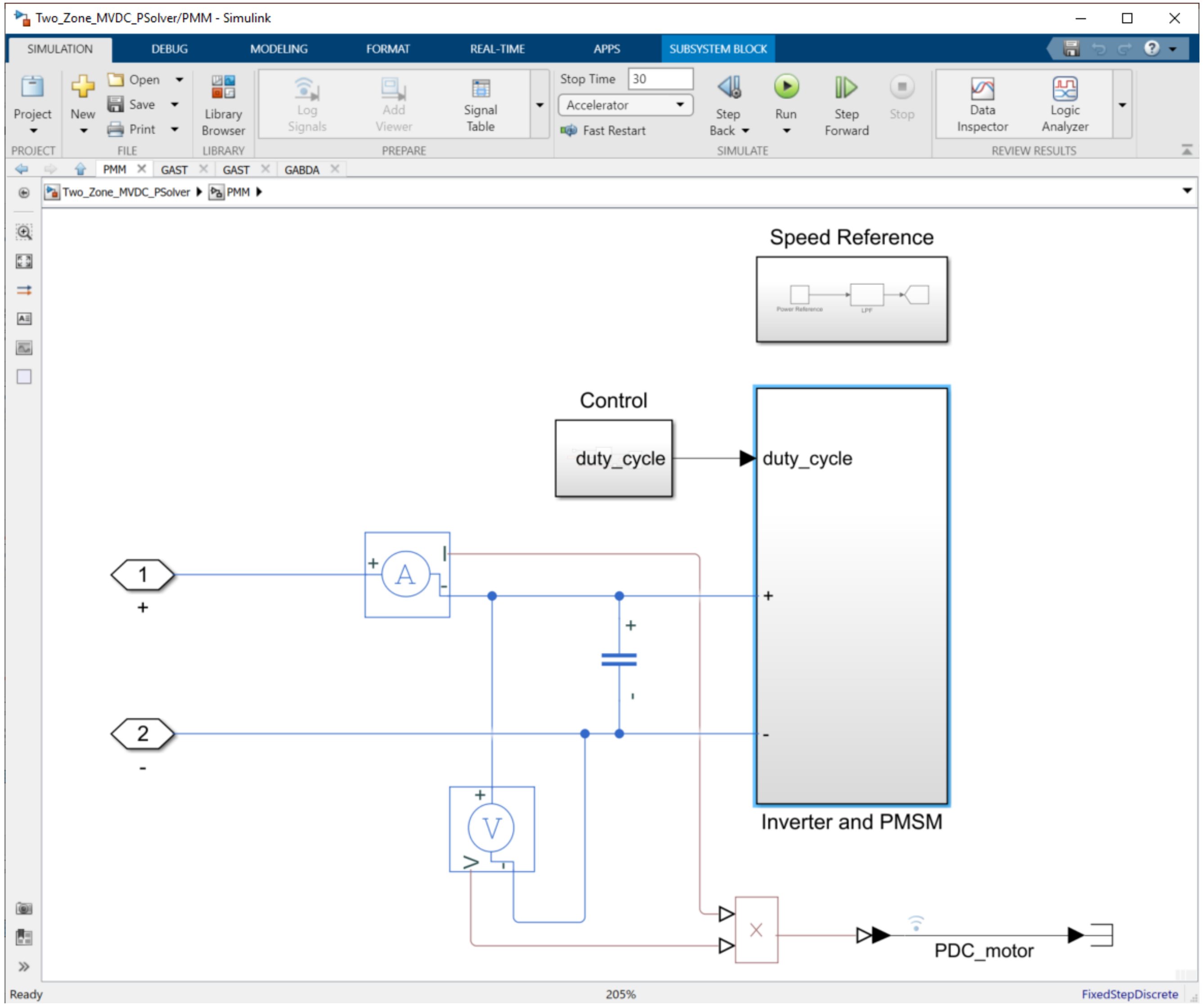




Propulsion Motor
with
Field-Oriented Control

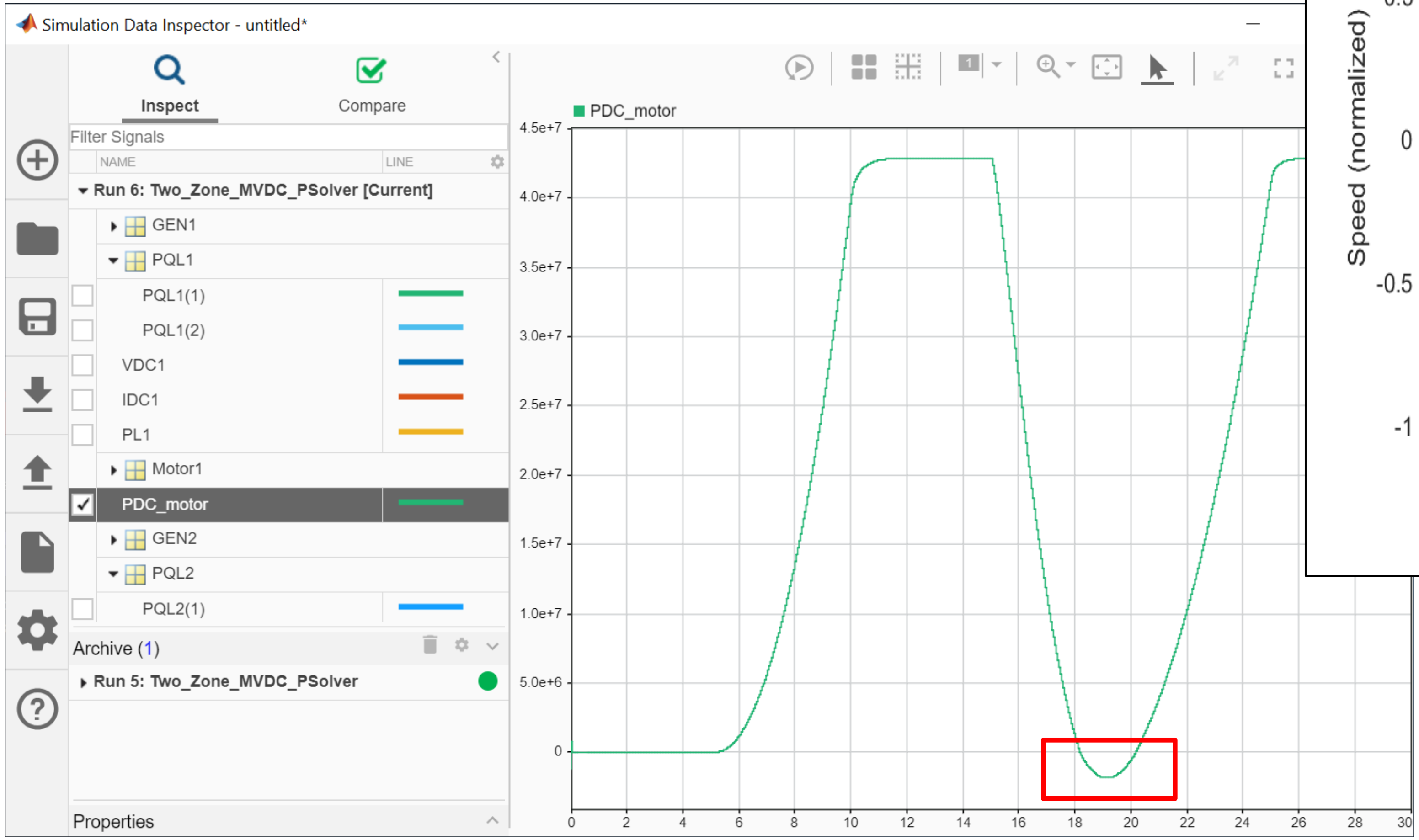
Propulsion Motor with Field-Oriented Control

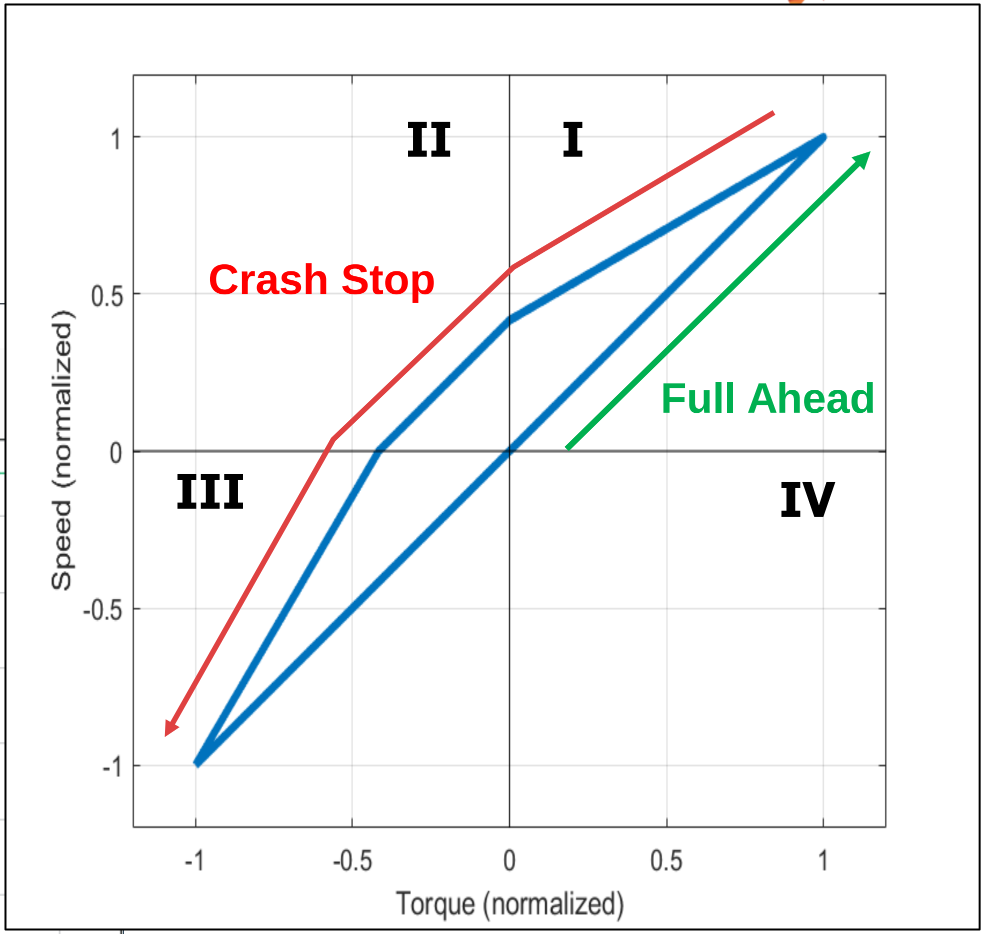


The Propulsion Motor Module (PMM) is implemented as a PMSM with field-oriented control (FOC), connected to the DC system through an average-value converter.

The PMM is configured to simulate a stylized full-ahead crash-stop with Quadrant 2 regeneration.

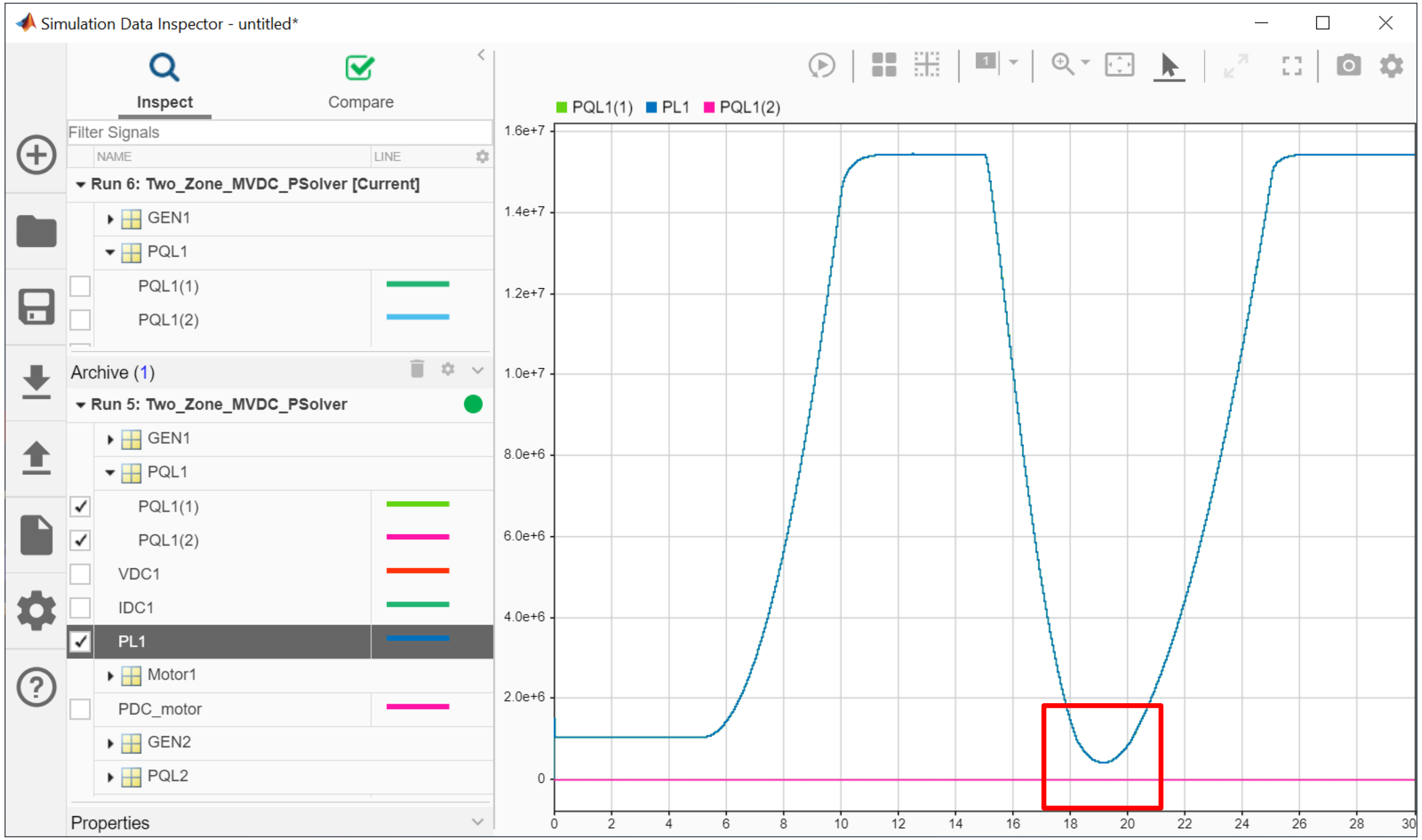
Propulsion Motor with Field-Oriented Control





Note the regenerated power as shaft speed transitions from positive to negative.

Propulsion Motor with Field-Oriented Control



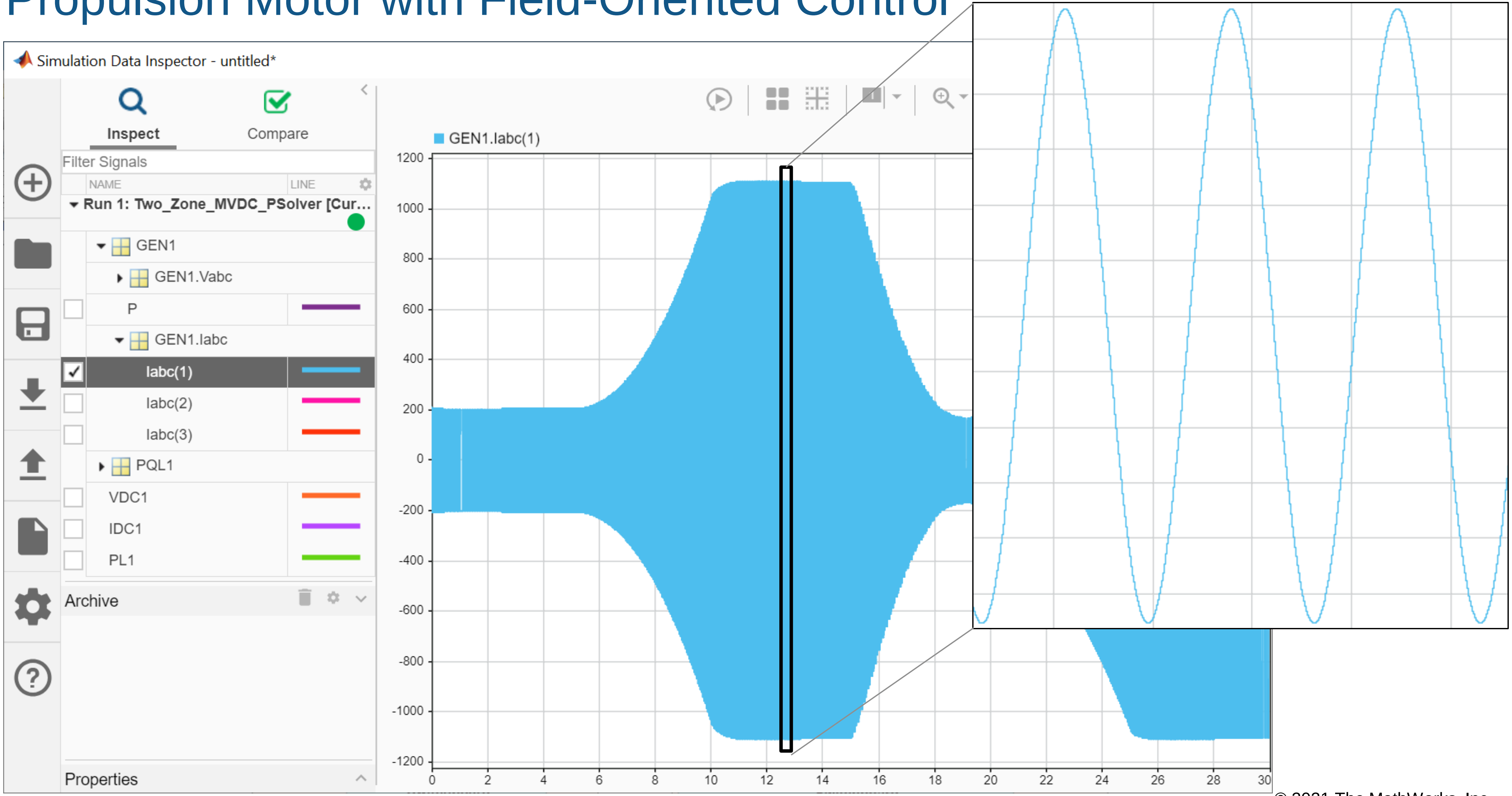
To confirm that power transfer over the AC/DC boundary is honored, and that the AC side operates at unity power factor, select the following signals,

PQL1(1) – PGM1 active power.
PQL1(2) – PGM1 reactive power.
PL1 – PGM1 DC power.

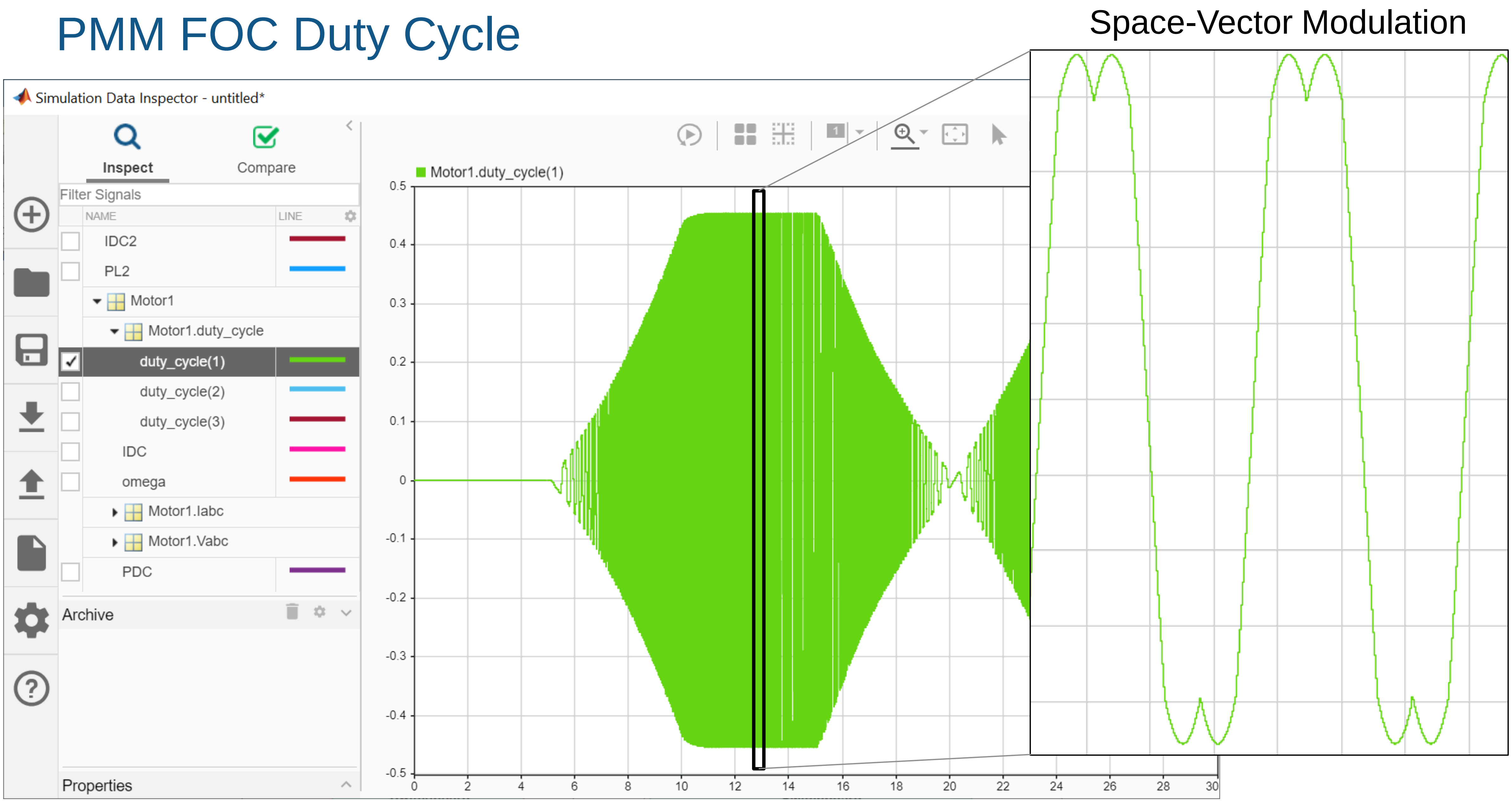
May want to explore energy storage options to keep generator above base load

Propulsion Motor with Field-Oriented Control

No harmonics with ideal converter



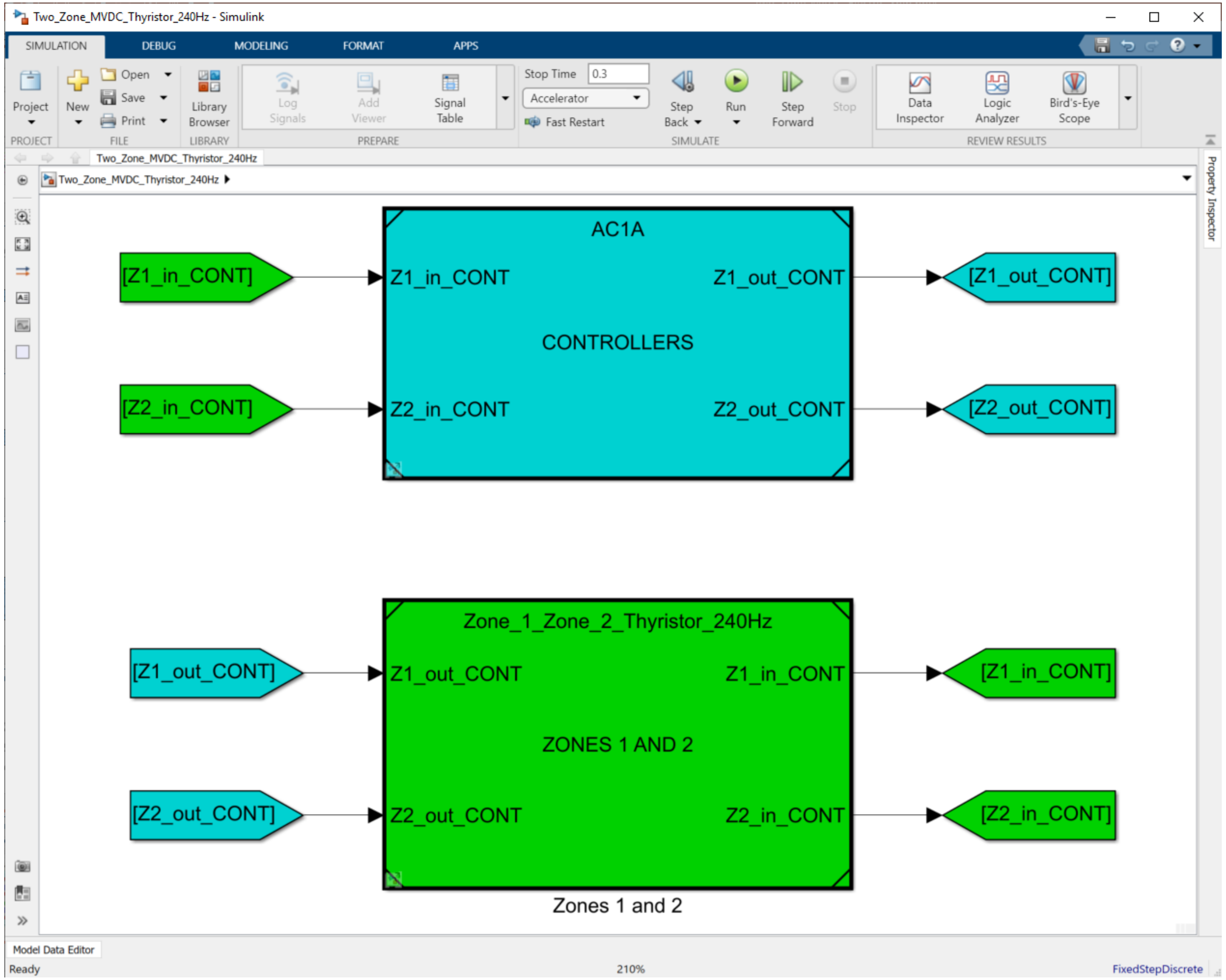
PMM FOC Duty Cycle



Two-Zone MVDC Shipboard Power System

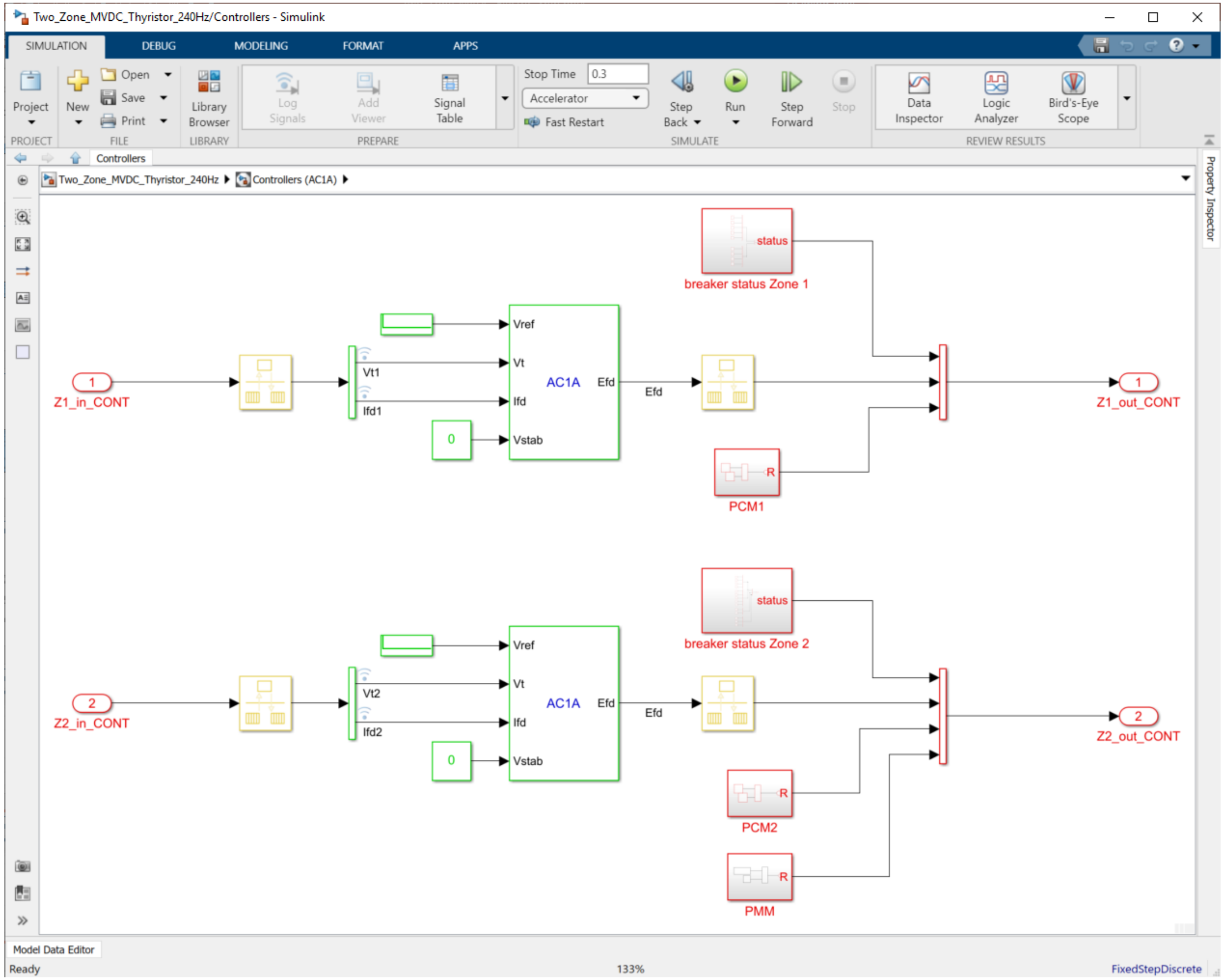
Thyristor Rectifiers

Two-Zone MVDC with Thyristor Rectifiers



Note that the model is constructed as two model-references. This is simply to show how model-reference models may be used in the construction of system levels models.

Two-Zone MVDC with Thyristor Rectifiers

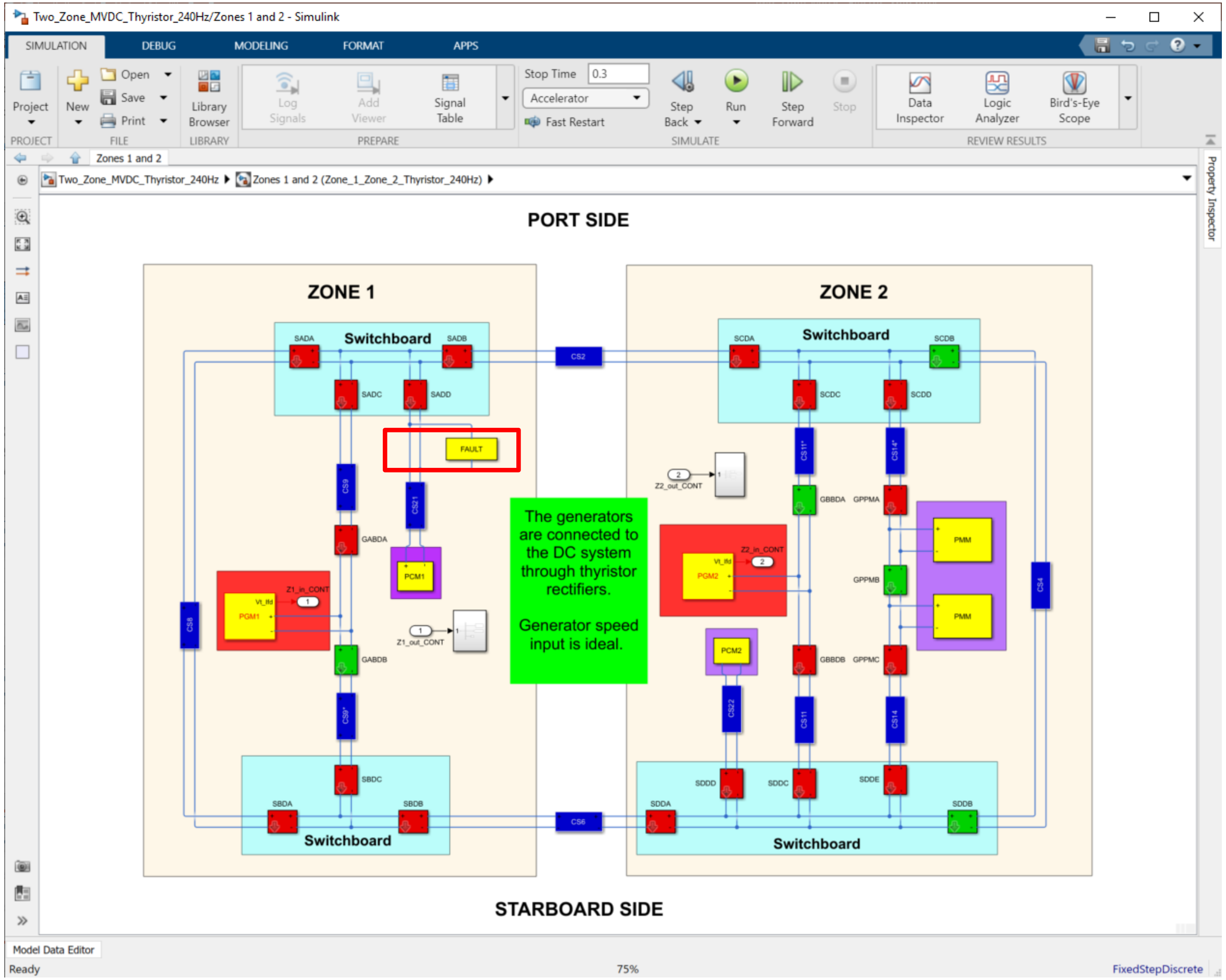


<u>AC1A</u> model reference.

Note that the control systems run at a slower rate than the electrical system.

Breaker status and PMM input is defined in this model reference.

Two-Zone MVDC with Thyristor Rectifiers

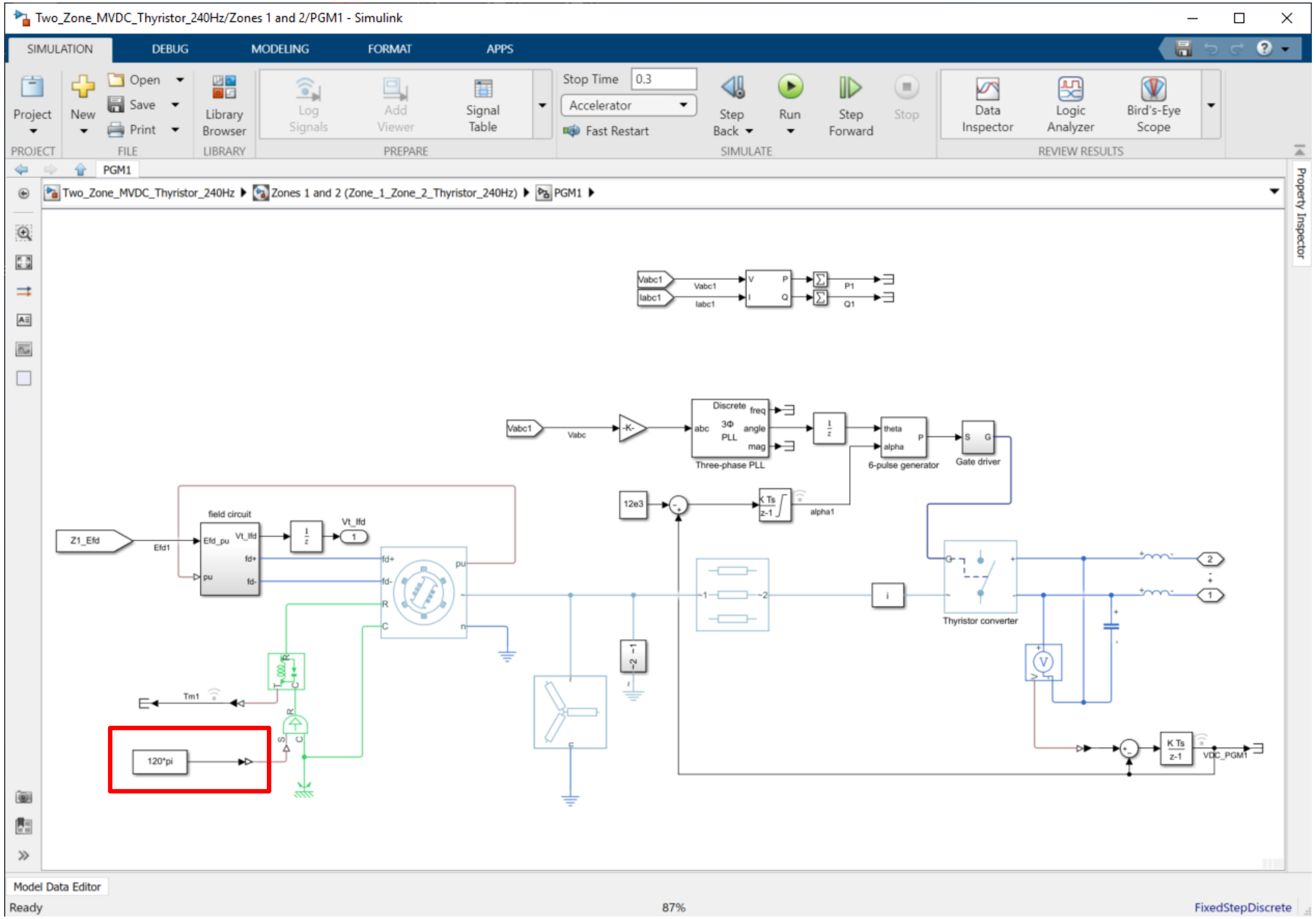


Zone_1_Zone_2_Thyristor_240Hz model reference.

A fault is located just below the SADD breaker. The fault is applied at 0.2s.

The PMMs are modeled as variable resistances.

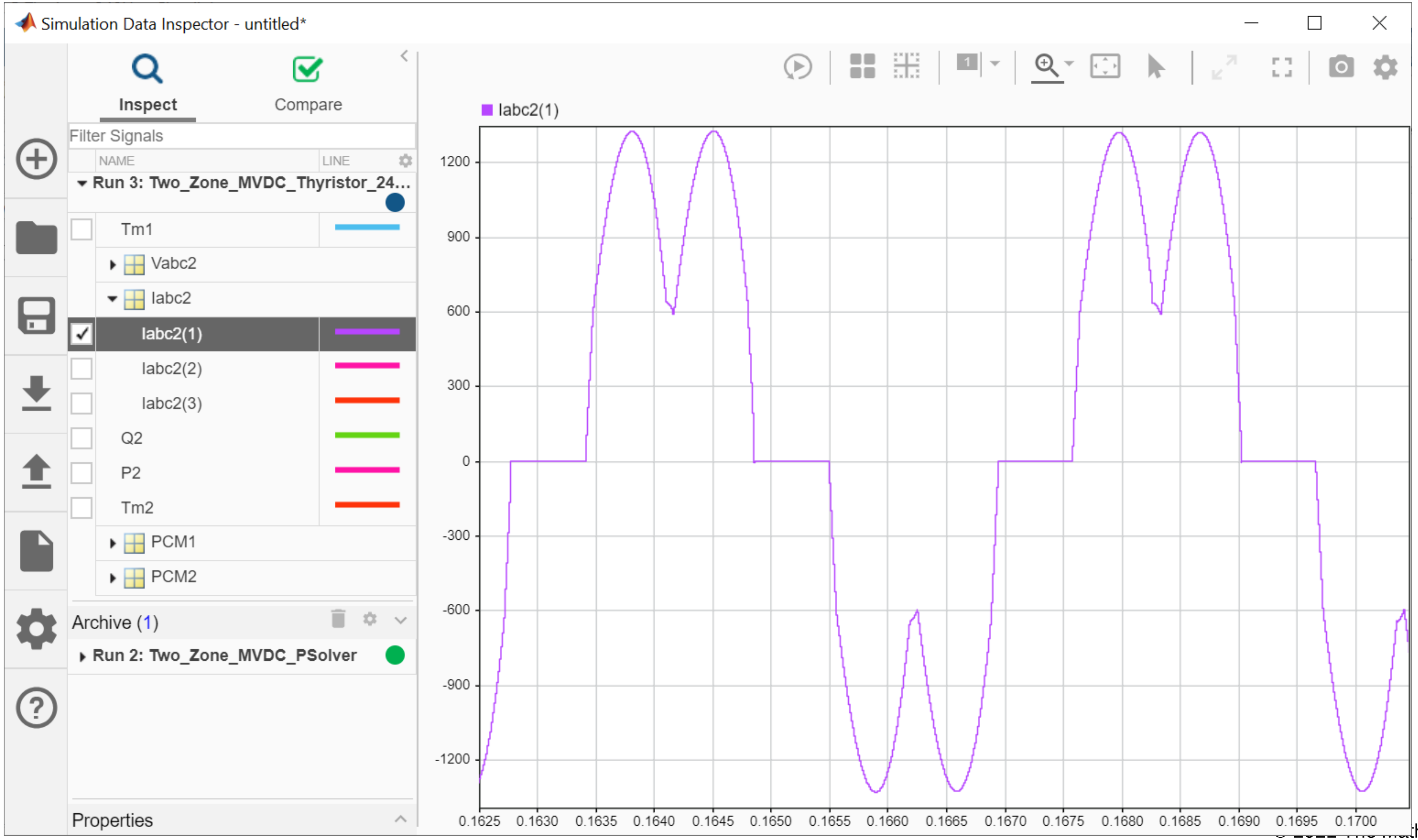
Two-Zone MVDC with Thyristor Rectifiers



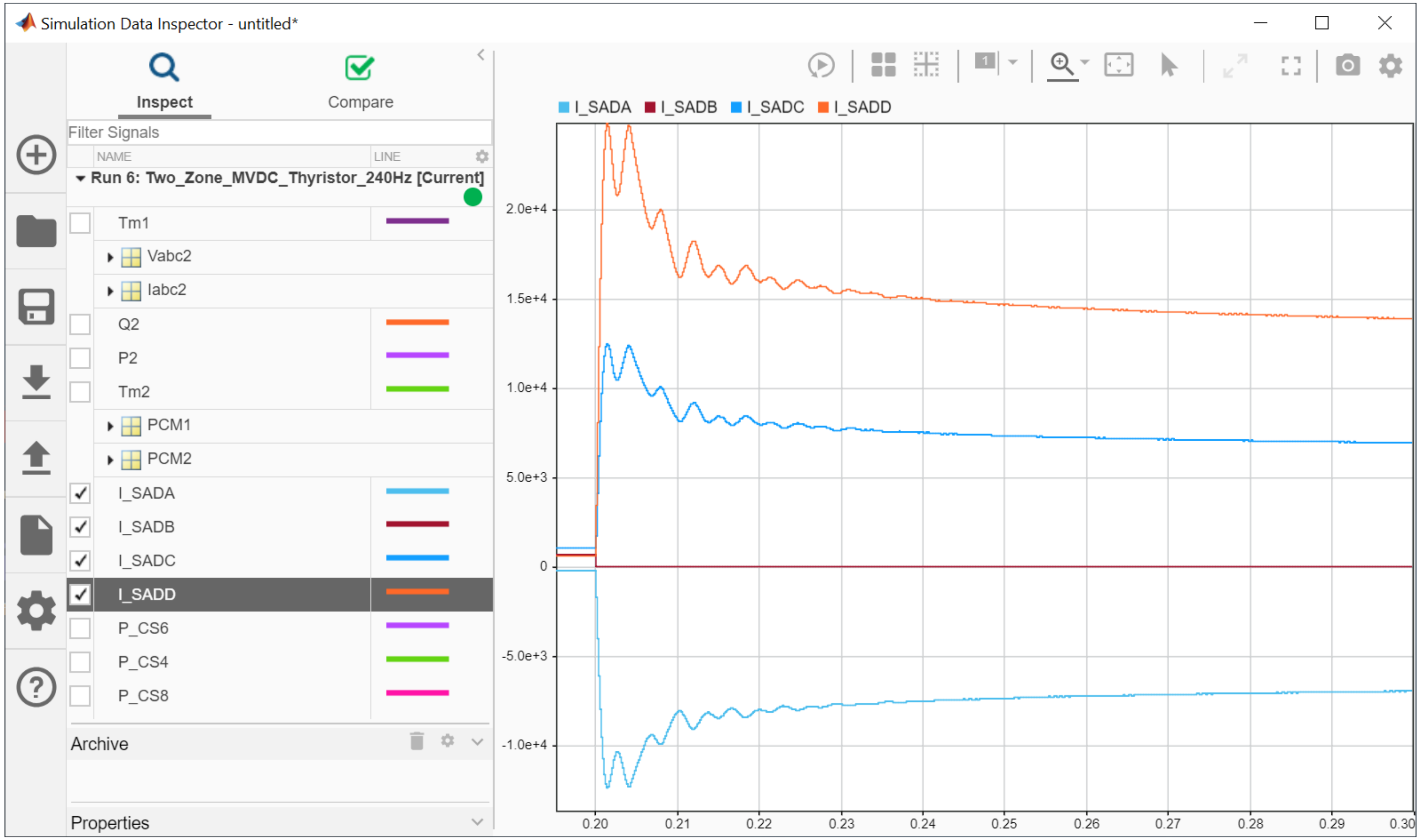
This model runs only for 0.3s, and so the speed reference for the generator is an ideal input.

For longer duration simulations, the GAST models could be included.

Generator 2 Current



Two-Zone MVDC with Thyristor Rectifiers

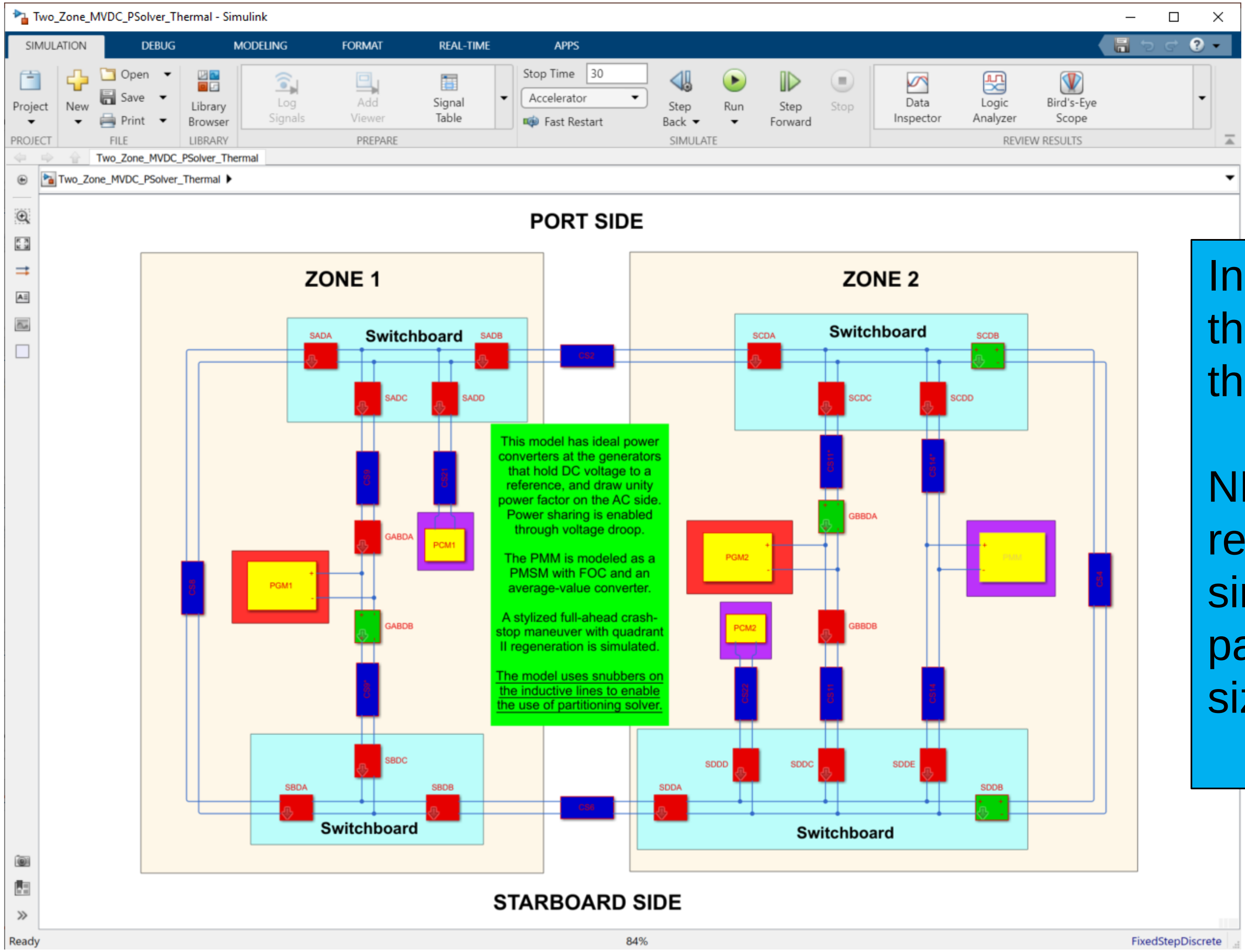


Observe the fault currents through the Zone 1 portside switchboard.

Two-Zone MVDC
Shipboard Power System

Thermal Motor and Active Cooling

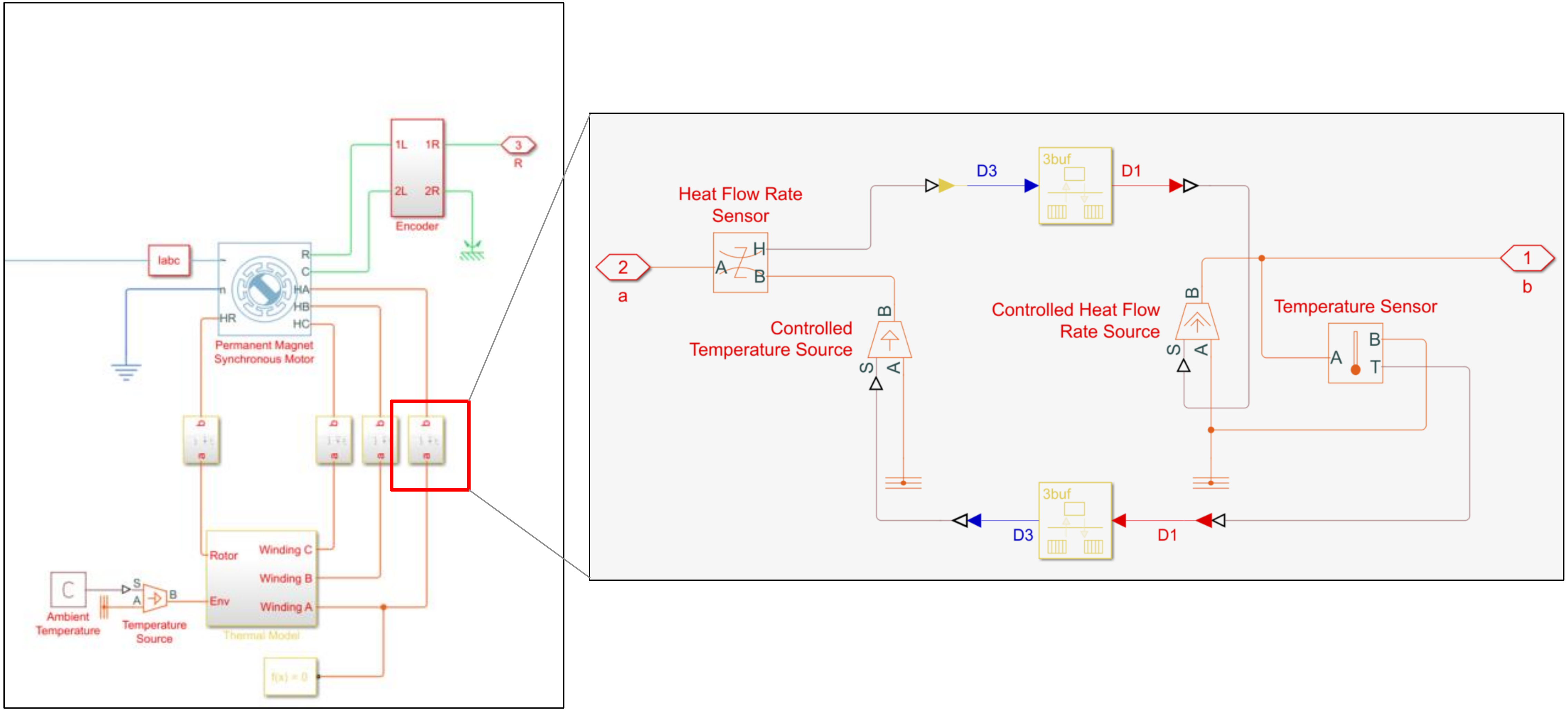
Two-Zone MVDC with Ideal Rectifiers and Thermal PMSM



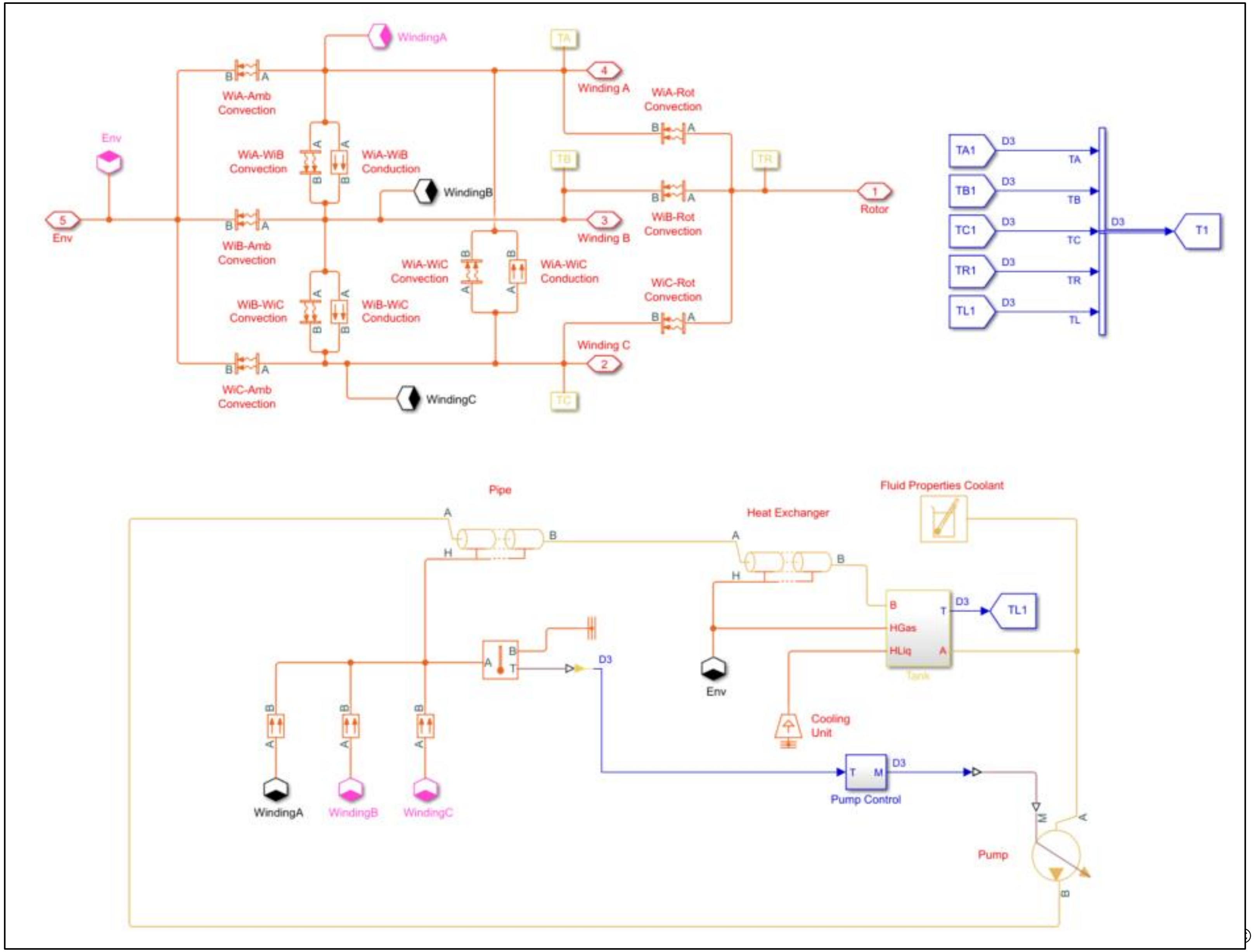
In this example, a thermal circuit and a thermal fluid cooling circuit is added to the PMSM.

NB - The circuits are sized to show a response in a few seconds of simulation, and would need re-parameterized to reflect a properly sized cooling system.

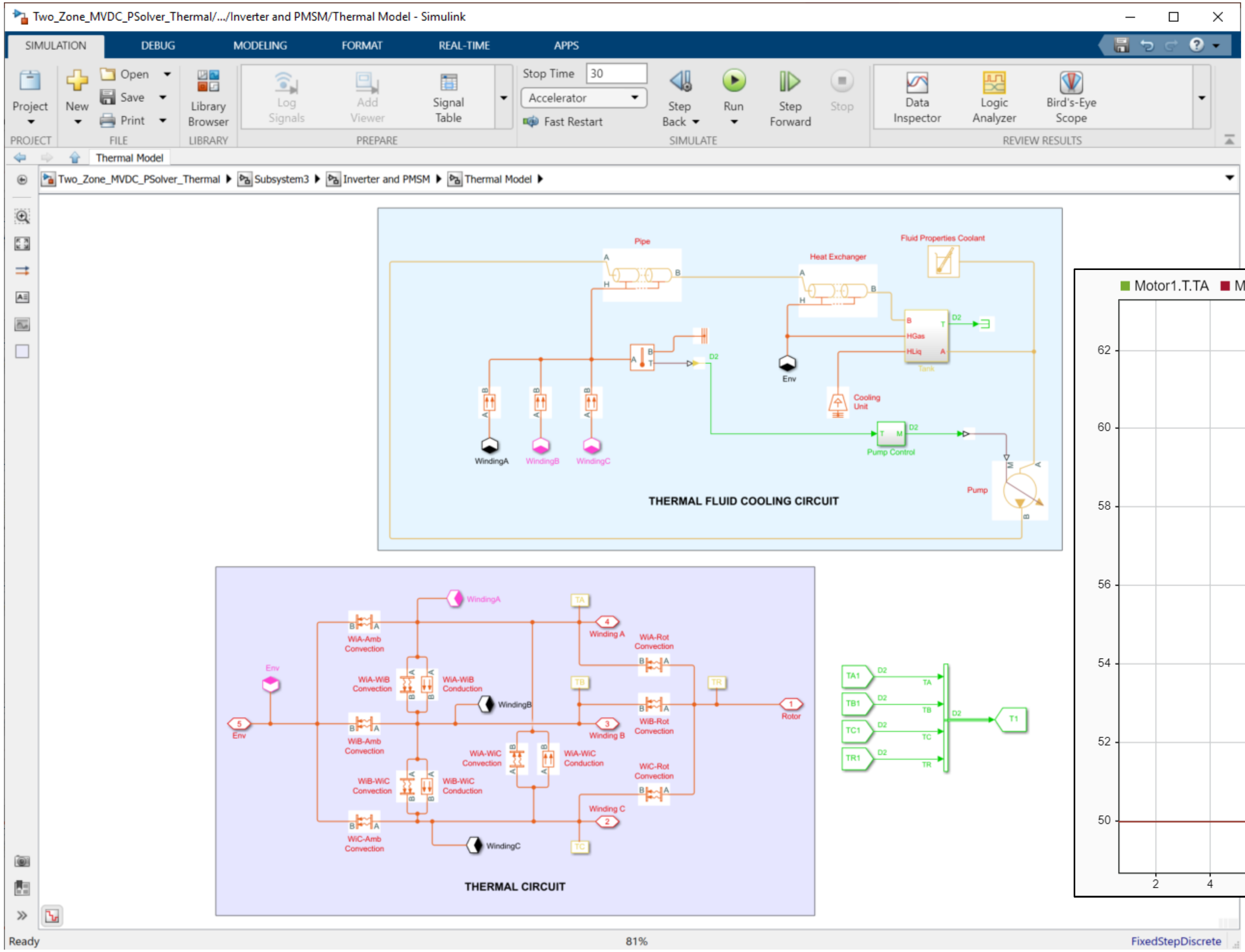
Thermal Modeling



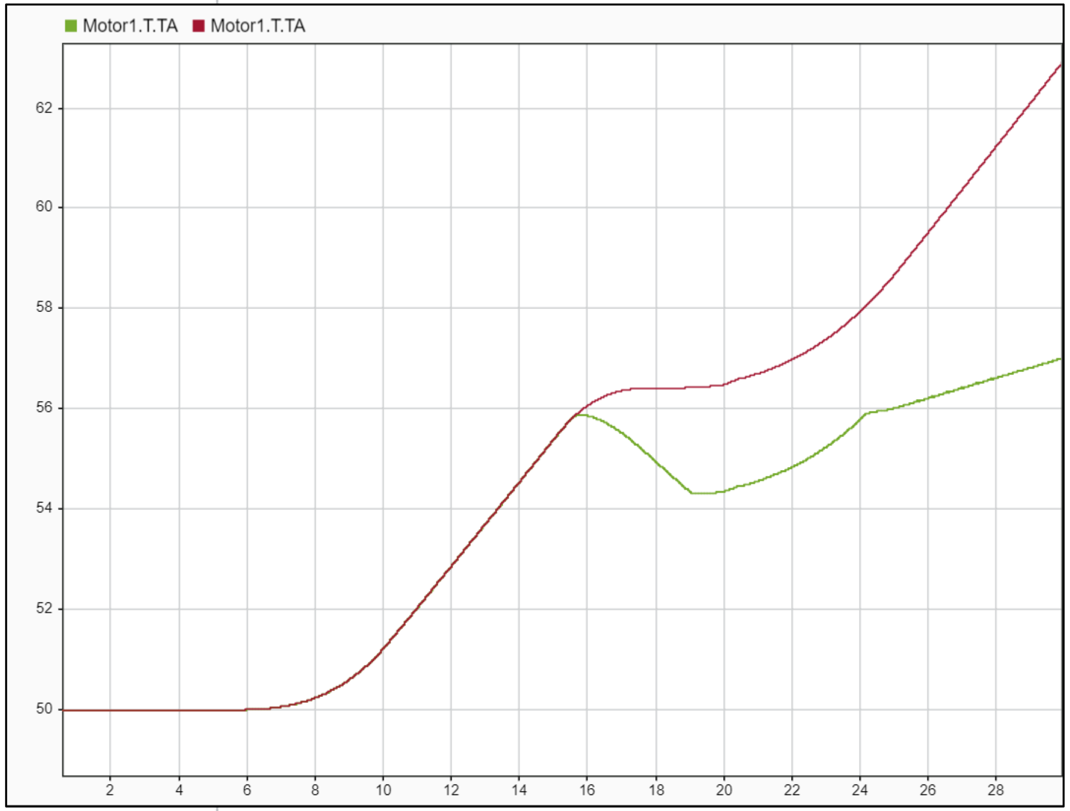
Thermal Modeling



Two-Zone MVDC with Ideal Rectifiers and Thermal PMSM



Compare response with and without active cooling.



Creating an FMU Standalone Component

FMI/FMU

- FMI stands for Functional Mock-up Interface and is an open standard that offers a way to exchange simulation models and interface them into larger simulation environments.

- FMI defines a container and an interface that packages a simulation model using artifacts including XML, binaries and C-code. This container and interface is called a Functional Mock-Up Unit.

- More details can be found at this URL: https://fmi-standard.org/.

FMI/FMU

- There are two types of Functional Mock-Up Unit. Co-Simulation and Model Exchange.

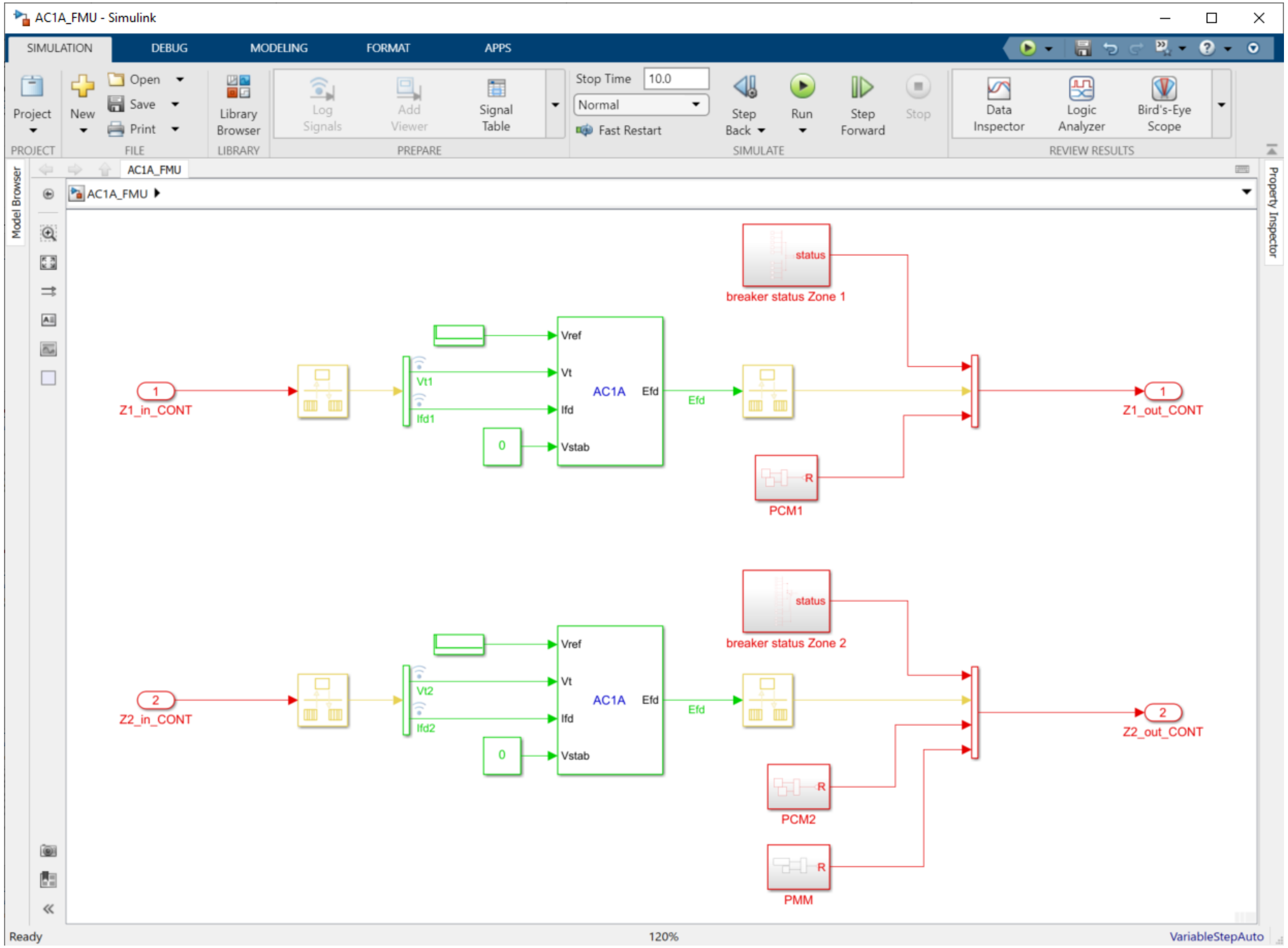
- In a Co-Simulation FMU, the numerical solver is integrated into the FMU. When imported, the importing simulation environment will tell the FMU when to step forward in time, and the FMU will execute its own solver.

- In a Model Exchange FMU, the FMU uses the numerical solver of the importing simulation environment.

- We will consider only the Co-Simulation FMU in this example.

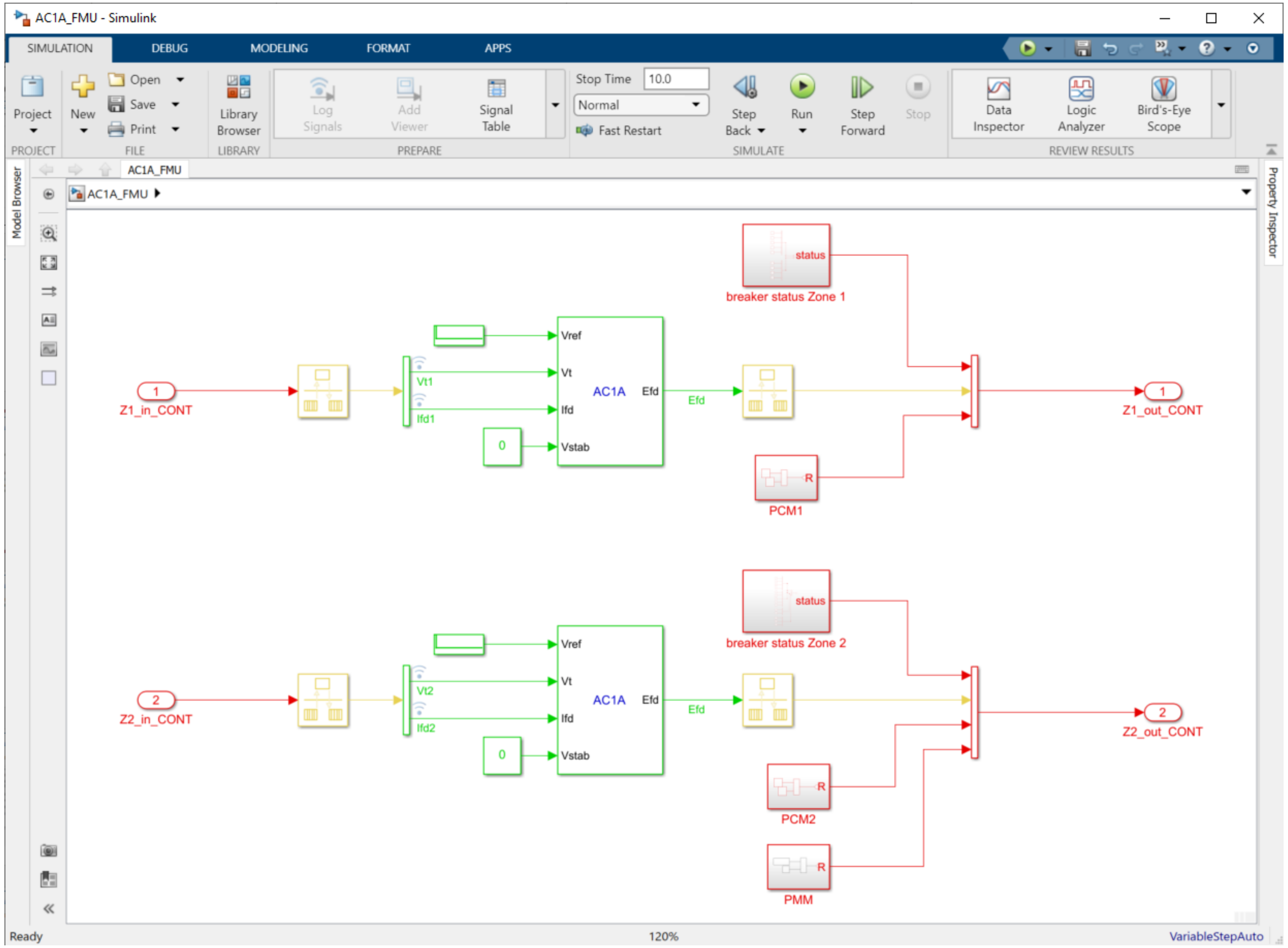
Creating an FMU Standalone model

- First, create a model that contains the system you want to generate an FMU component for. In this case, we reuse the control system model reference.



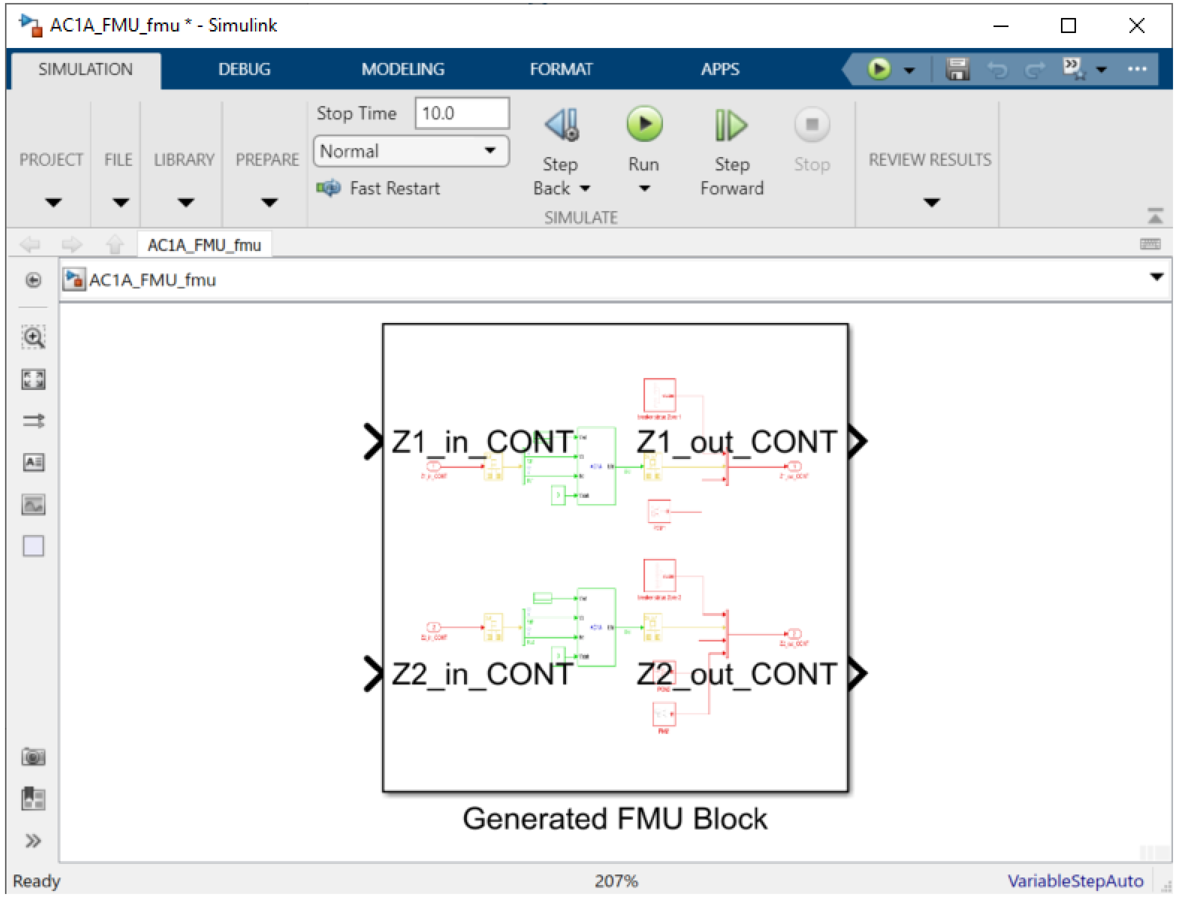
Creating an FMU Standalone model

- We can then create a co-simulation FMU component.
- This is a component which deploys with its own solver.
- The following files are generated,
  - XML
  - DLL
  - Zip file (with .fmu extension) which packages the files.



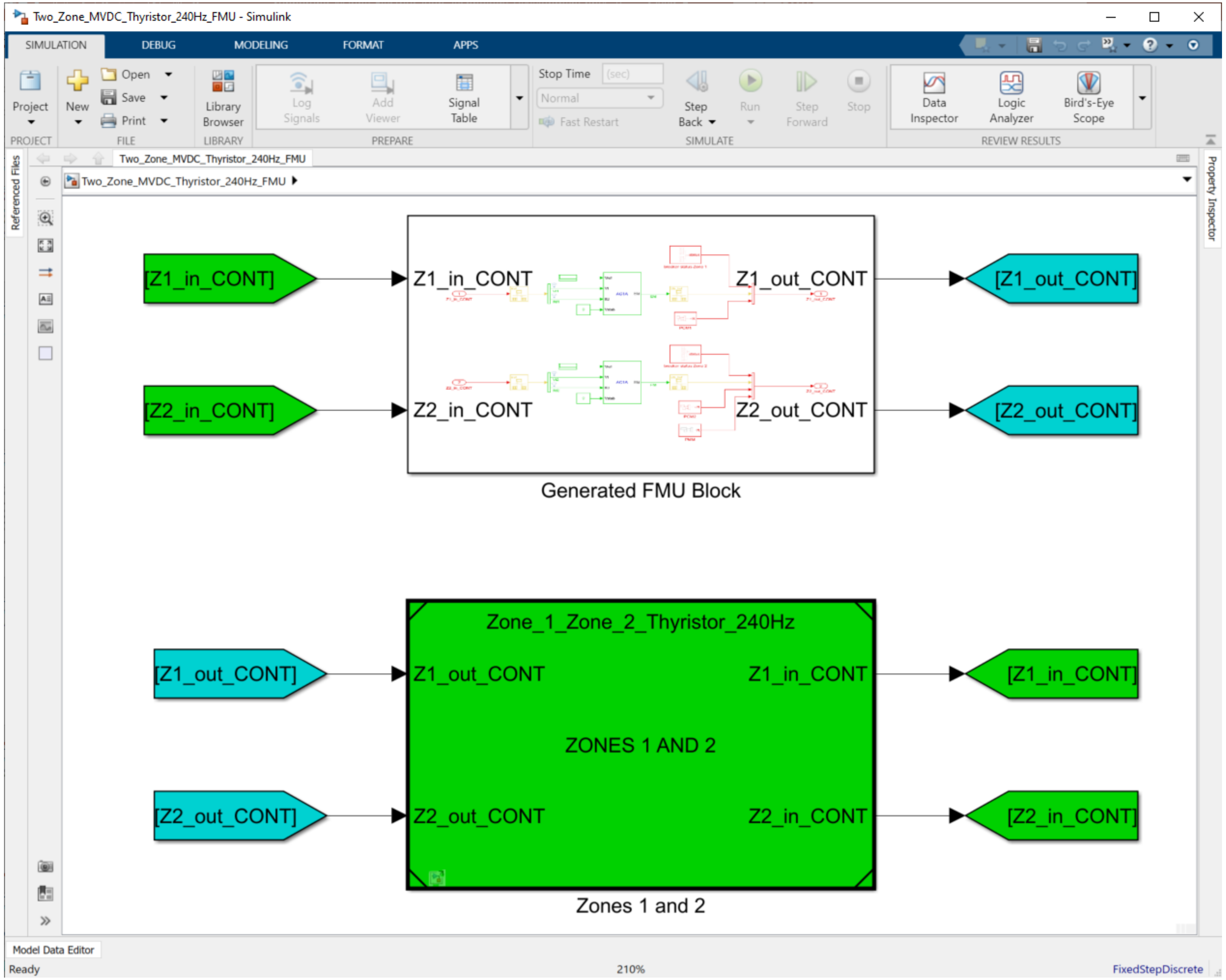
Creating an FMU Standalone model

- Once the FMU component is built, it is presented as a separate component that can be integrated into the simulation environment.



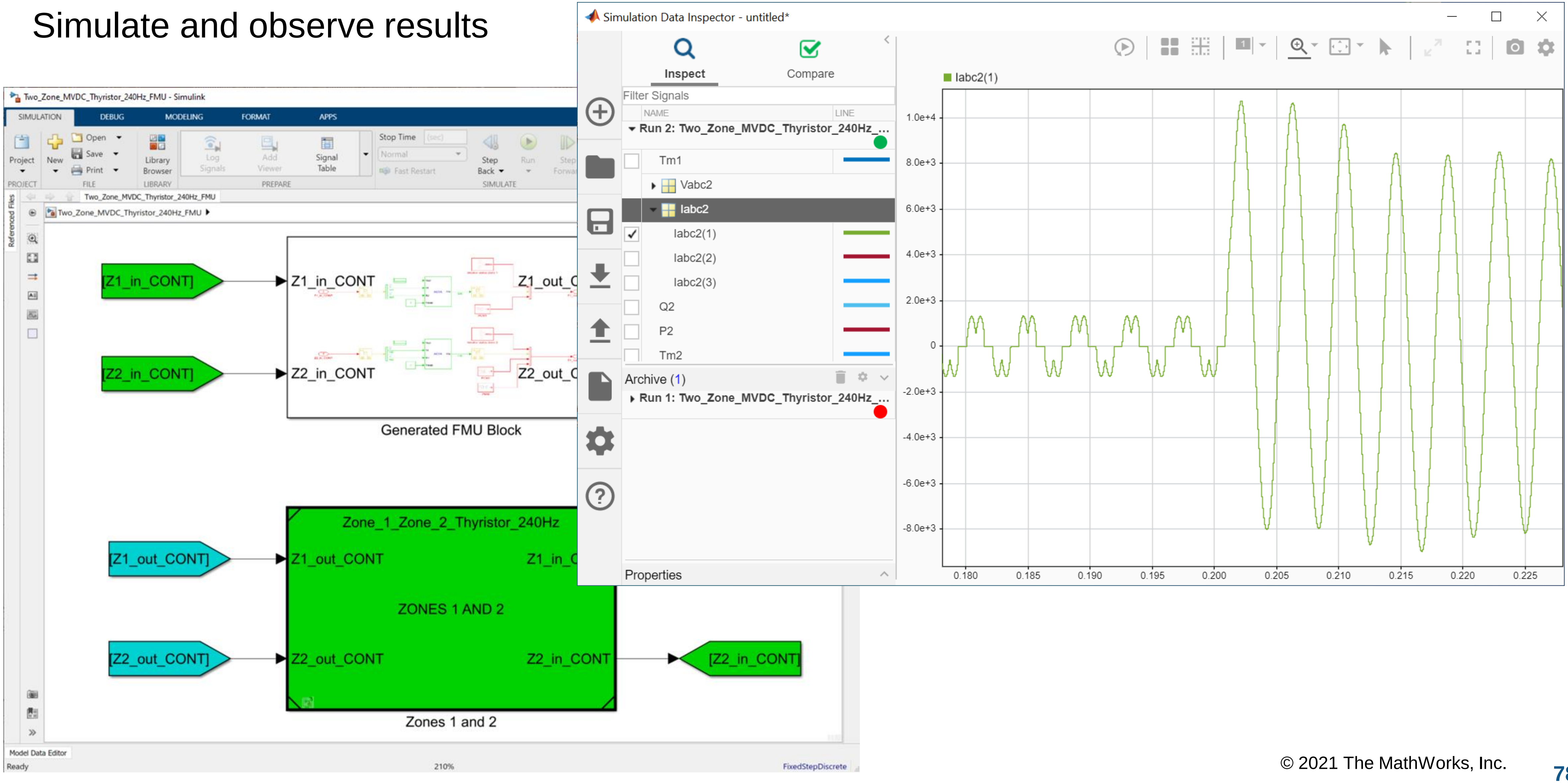
Creating an FMU Standalone model

- Next, place the FMU component in the full system.



Creating an FMU Standalone model

- Simulate and observe results

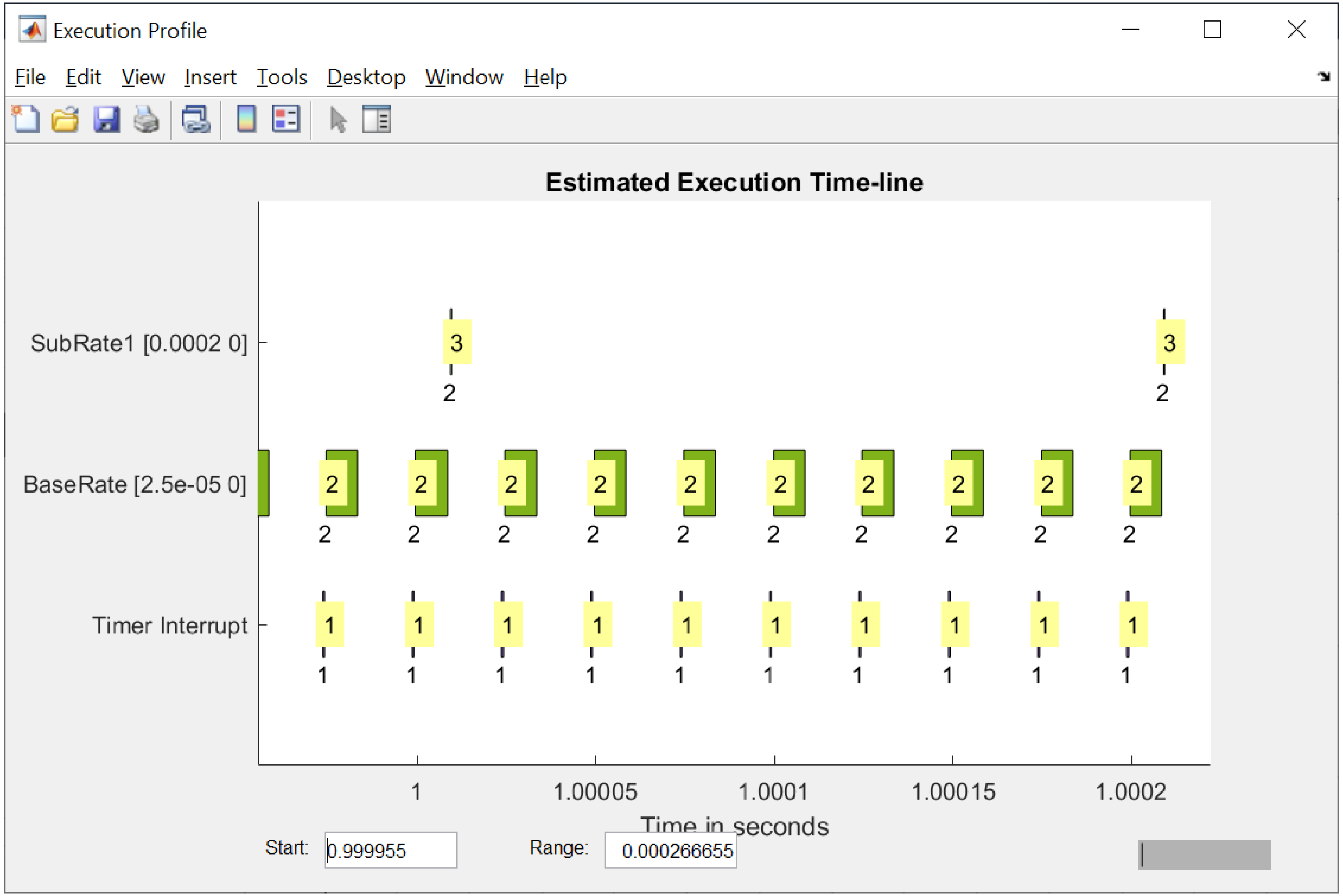


Real-Time Simulation

Two-Zone MVDC with Ideal Rectifiers - Real-Time Simulation

Task-Execution-Time (TET) for the model with ideal converter is approximately 10 microseconds, and the simulation with Ts = 25 microseconds runs comfortably.

Note that the model with Thyristor Rectifier runs with Ts = 1 microsecond and is a desktop-only simulation.

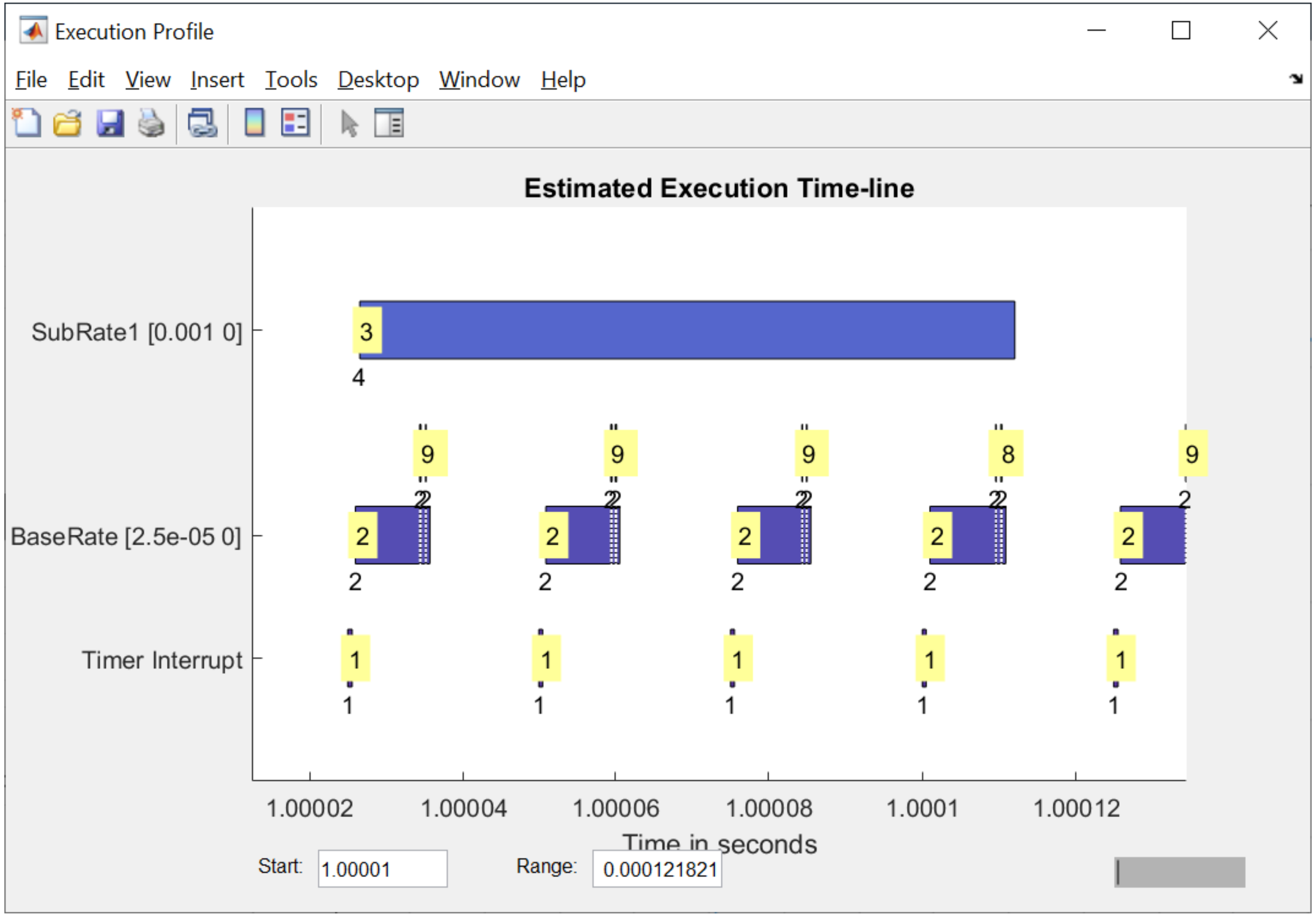


Two-Zone MVDC with Thermal Model - Real-Time Simulation

Note the two rates run on different cores.

Task-Execution-Time (TET) is approximately 10 microseconds for the electrical BaseRate, and the simulation with Ts = 25 microseconds runs comfortably.

Note that while TET for the thermal subrate is larger, it is comfortably within the 1 millisecond rate.

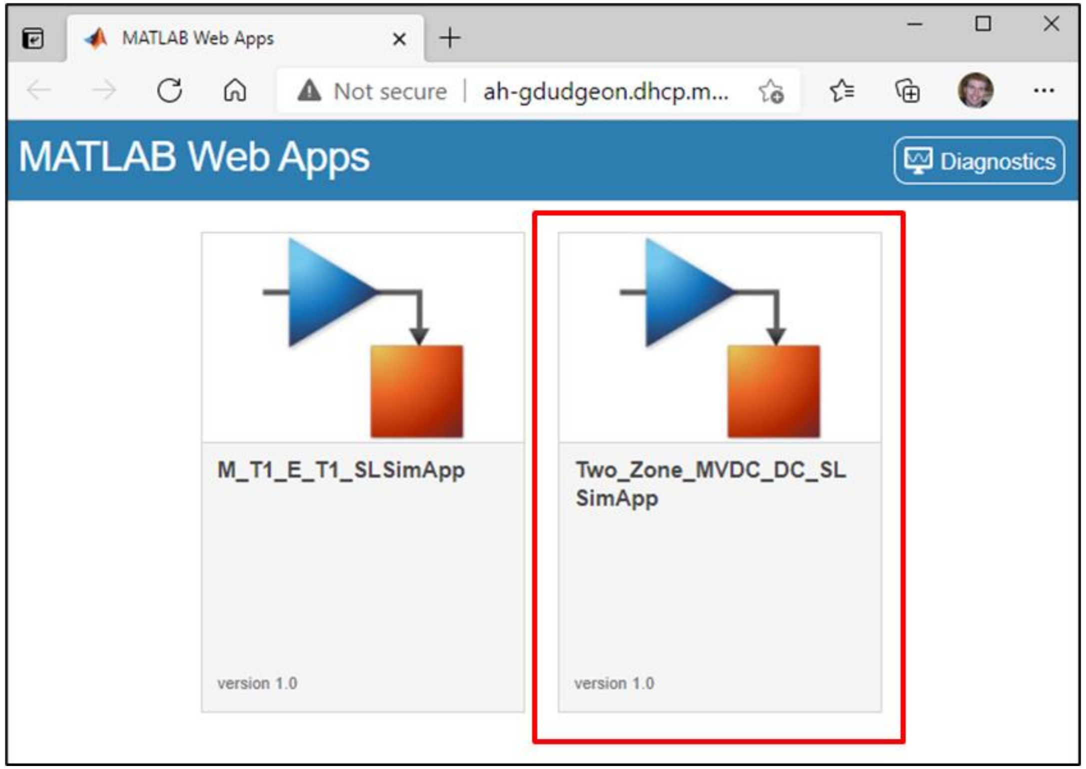


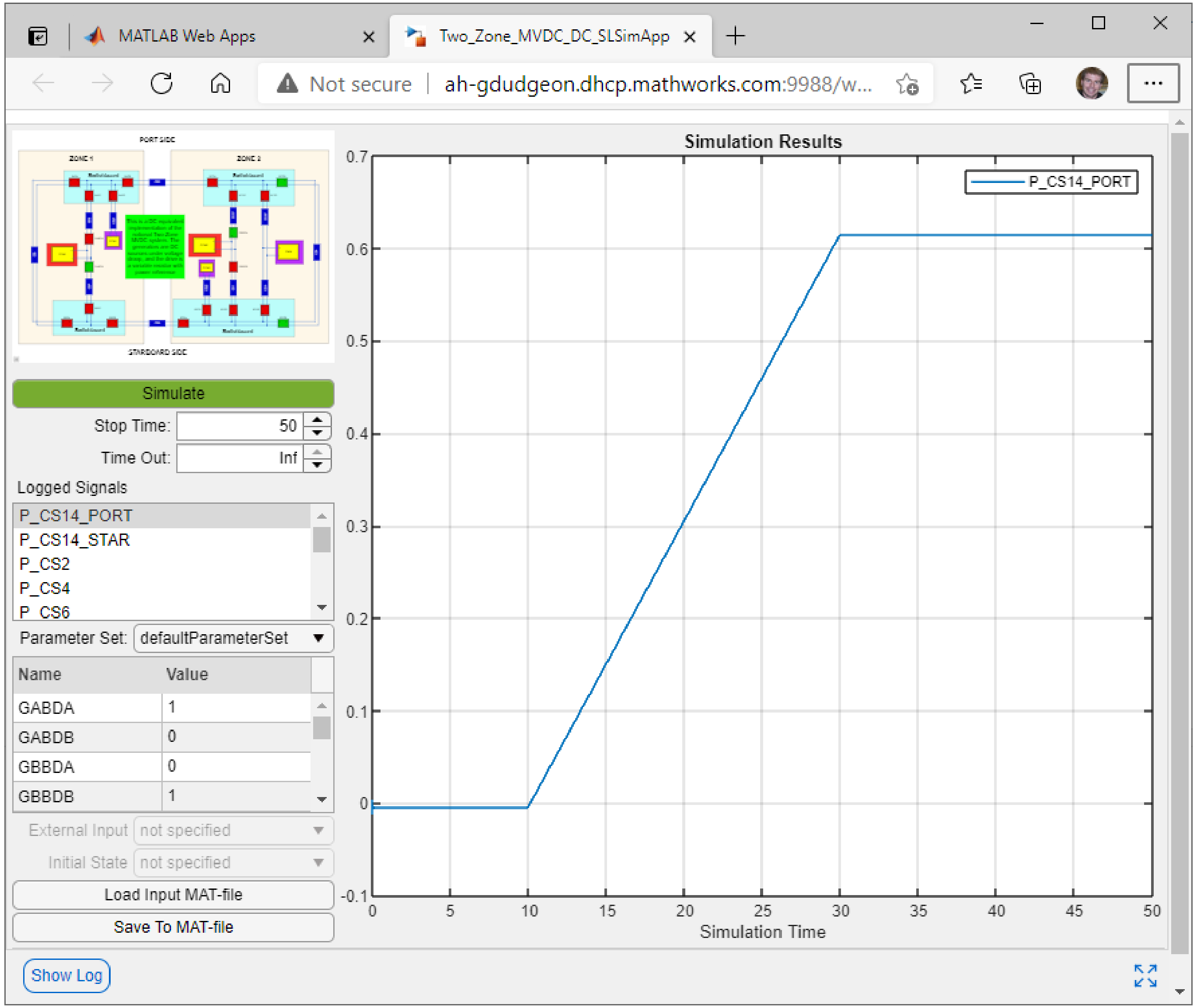
Deploying Models on the Cloud

Creating a Standalone Application for Cloud Deployment

- The objective is to make a simulation model available license-free to a set of users who are looking to gain specific engineering information.
- The simulation structure will be fixed, but input data and parameterization (and hence output data) can change.
- The simulation should be interacted with through a graphical user interface.

Standalone Application on the Web





Summary

Summary

- Model Fidelity and Technology Readiness
- Understanding the Impact of Simulation Solvers on Simulation Speed and Simulation Accuracy
- Configuring a Physical System Simulation to Run at Multiple Sample-Rates
- Two-Zone MVDC Shipboard Power System
  - DC Equivalent
  - Ideal Rectifier
  - Diode and Thyristor Rectifiers
  - Propulsion Motor with Field-Oriented Control
  - Thermal Response and Active Cooling
- Creating and Integrating FMI/FMU Components
- Deploying Models on Real-Time Systems and the Cloud

Resources