

MATLAB EXPO

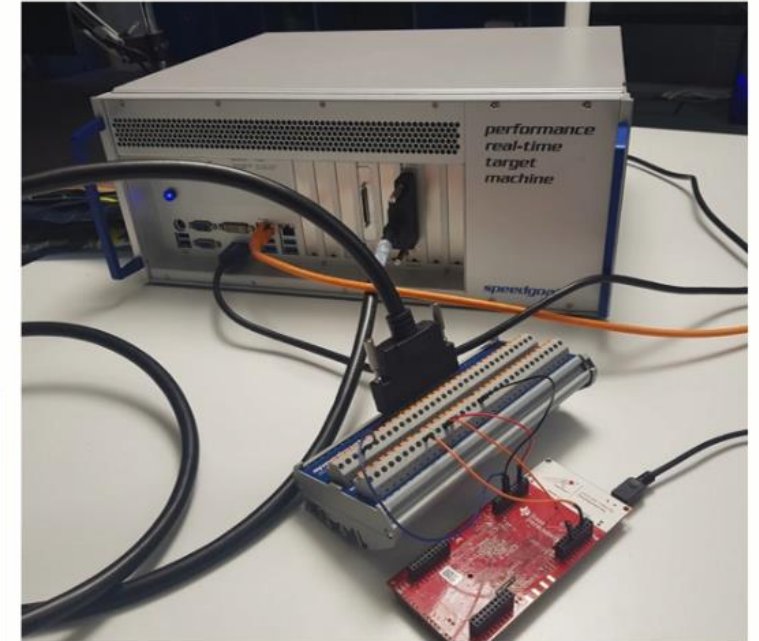
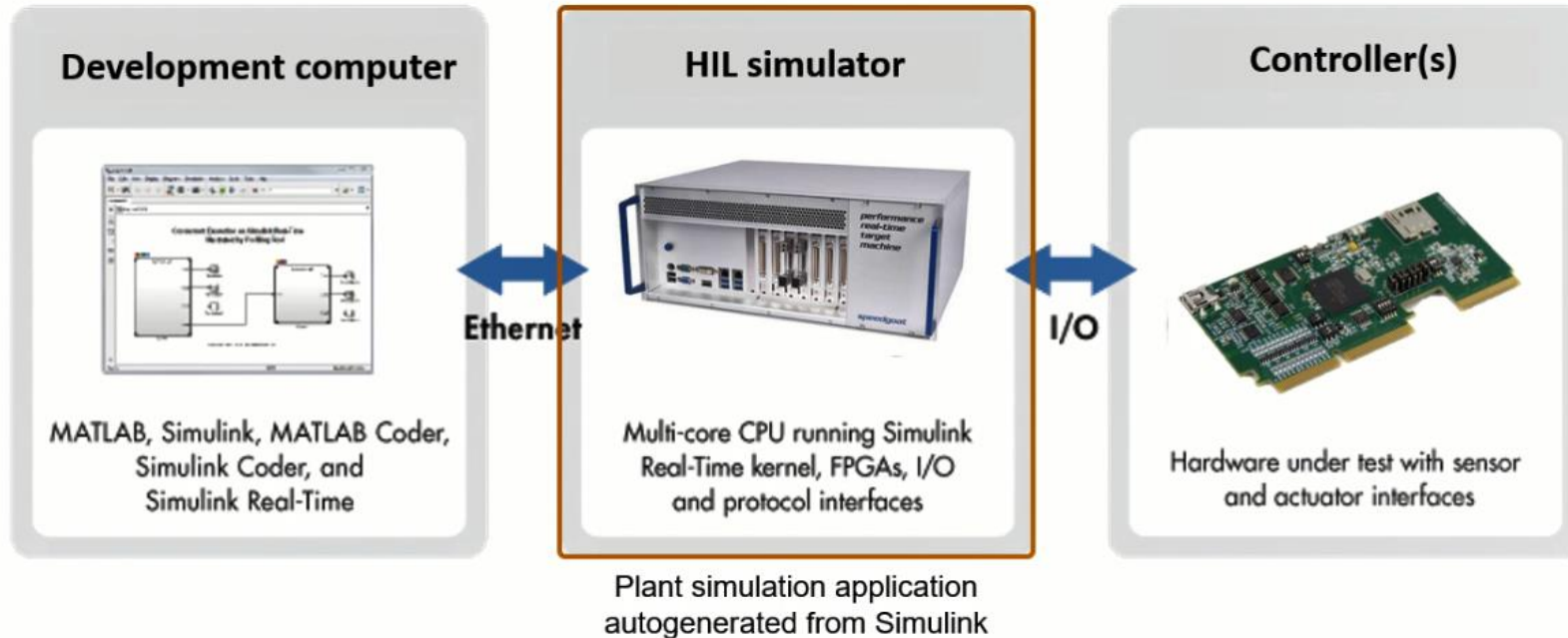
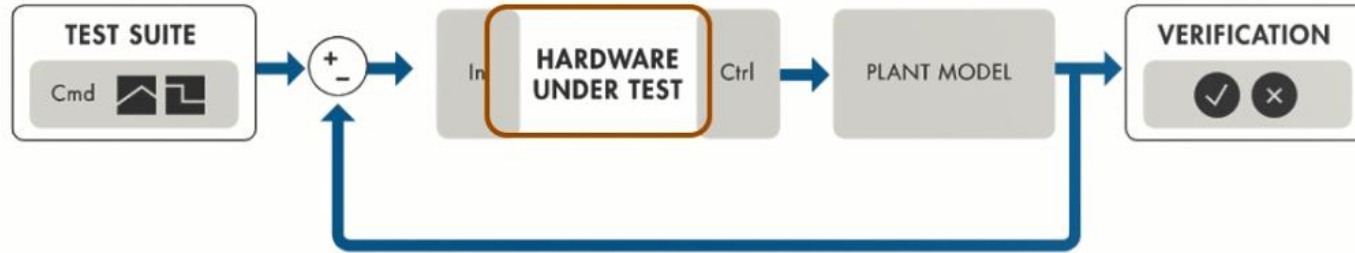
2021

Hardware-in-the-Loop Testing of Control Algorithms for Modular Multi-Level Converters

Mohsen Aleenejad and Manuel Fedou



Where Our Journey Today Will Take Us



Key Takeaways

- MathWorks tools support all stages of technology readiness.
- Complex power converter architectures can be built automatically in Simulink.
- Complex power converter architectures and their control systems can be effectively simulated using both desktop and real-time simulation.
- Variable-step solvers provide accurate PWM timing on desktop and online simulation.
- Functional correctness of control configurations can be rapidly assessed, and hardware implementation can be de-risked using automatic code generation and HIL testing.

About Speedgoat

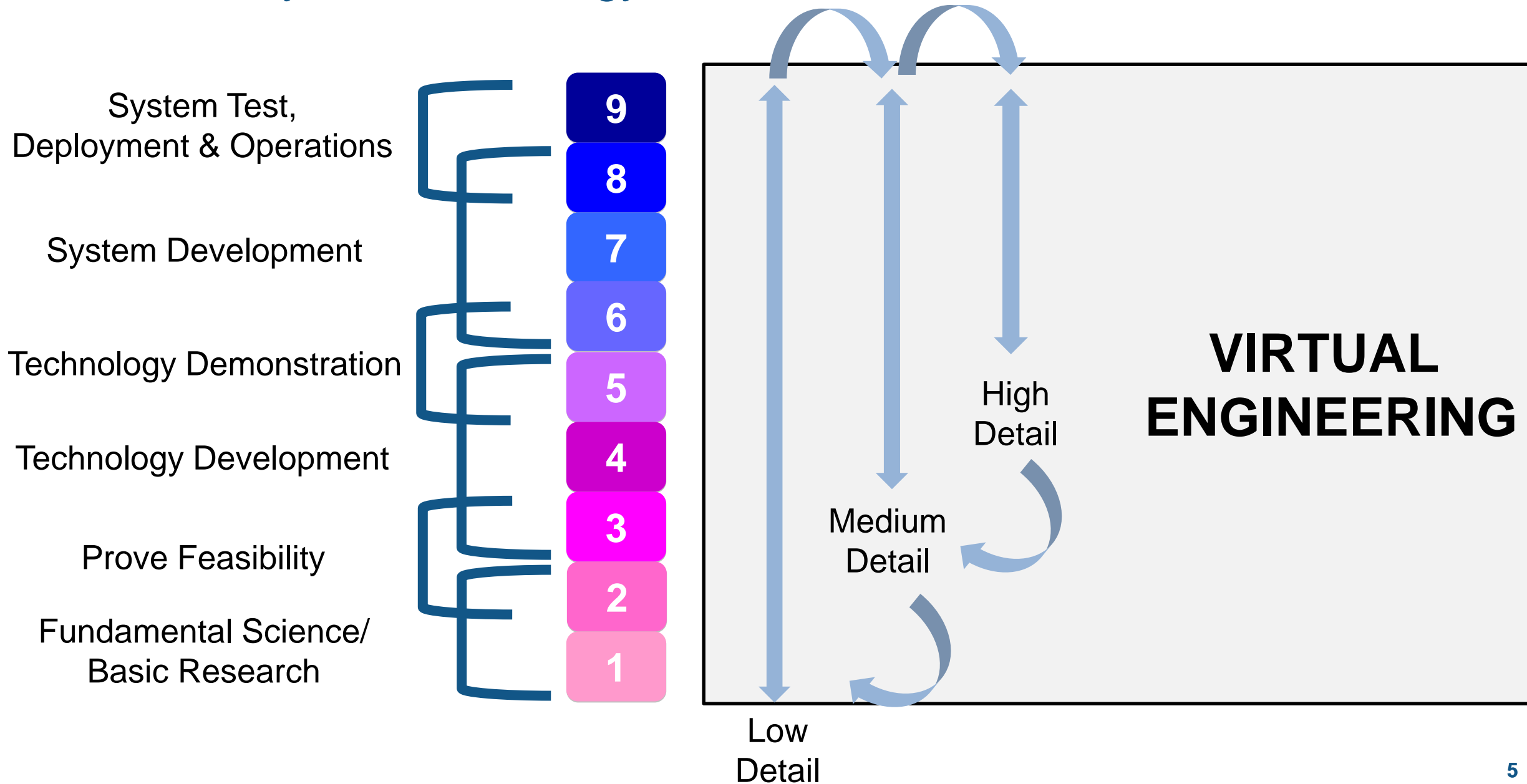
- A MathWorks associate company, incorporated in 2006 by former MathWorks employees. Headquarters in Switzerland, with subsidiaries in the USA and Germany
- Provider of real-time target computers, expressly designed for use with Simulink
- Real-time core team of around 200 people within MathWorks and Speedgoat. Closely working with the entire MathWorks organization employing around 5,000 people worldwide



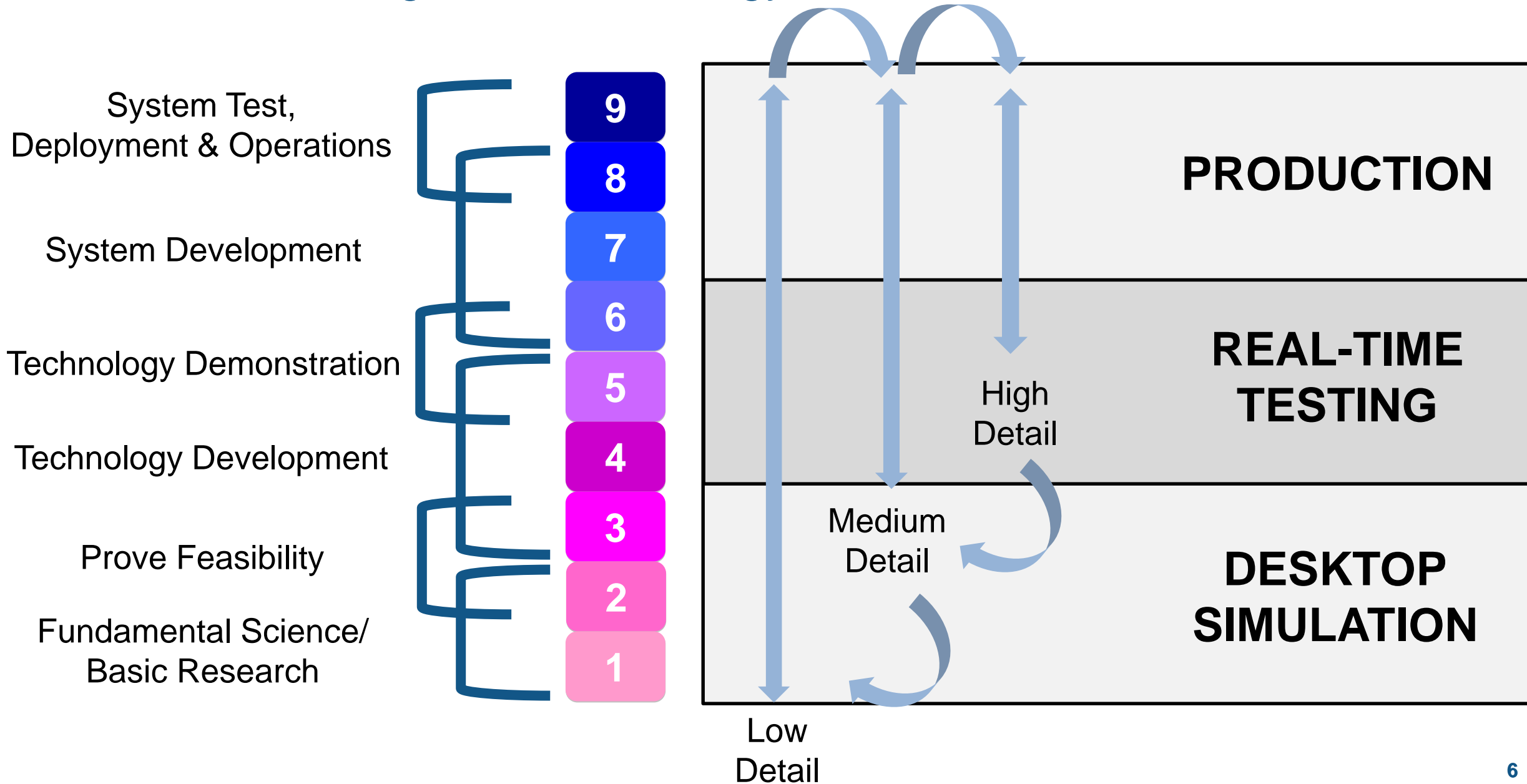
Problem Statement

- There is a persistent need to reduce harmonics and improve fault tolerance of power converters.
- Harmonics can be reduced by increasing switching frequency and/or increasing the number of power electronic devices. Fault tolerance is improved by increasing the number of devices.
- It can be challenging to evaluate a broad range of configurations and move models seamlessly from desktop to real-time systems at early stages of technology development.

Model Fidelity and Technology Readiness



Model-Based Design and Technology Readiness



Alstom Grid Develops High-Voltage Direct Current Transmission Control System Using Model-Based Design

Challenge

Accelerate control system development for high-voltage direct current voltage source converters

Solution

Use Model-Based Design to model, simulate, verify, and generate code and documentation for the control and protection systems

Results

- Quantifiable process improvements
- Rapid integration with power system simulation software
- Protection systems implemented in one week



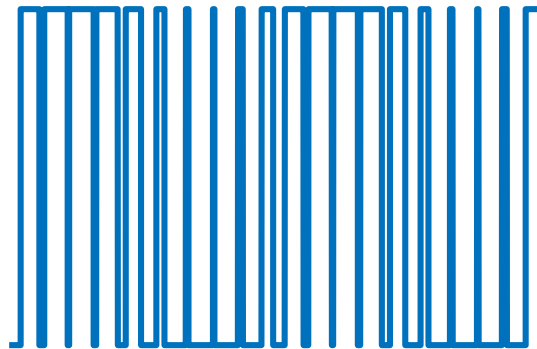
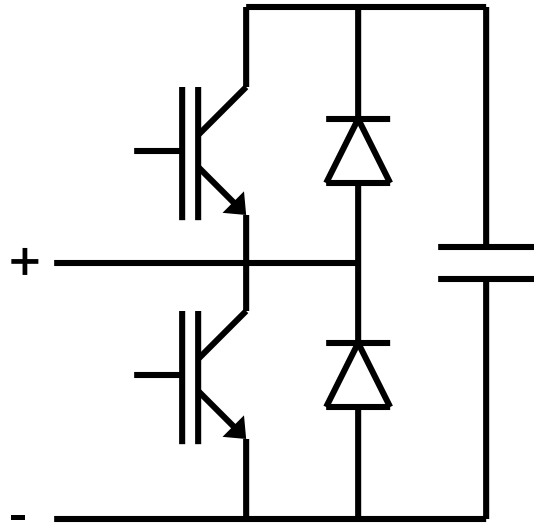
Alstom Grid's HVDC demonstrator system with power converter modules. The improved controllability of the VSC in this system makes it well-suited for smart grid applications.

“Using Model-Based Design we developed a complex control system in significantly less time than our traditional process would have required. We eliminated months of hand-coding by generating code from our models, and we used simulations to enable early design verification.”

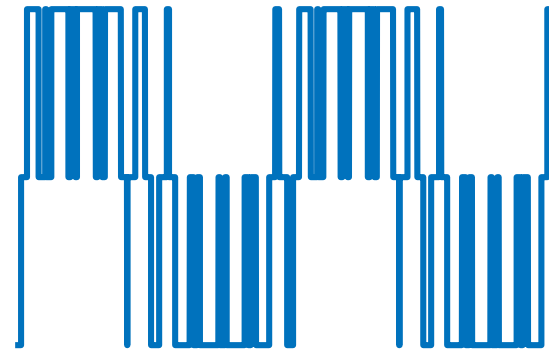
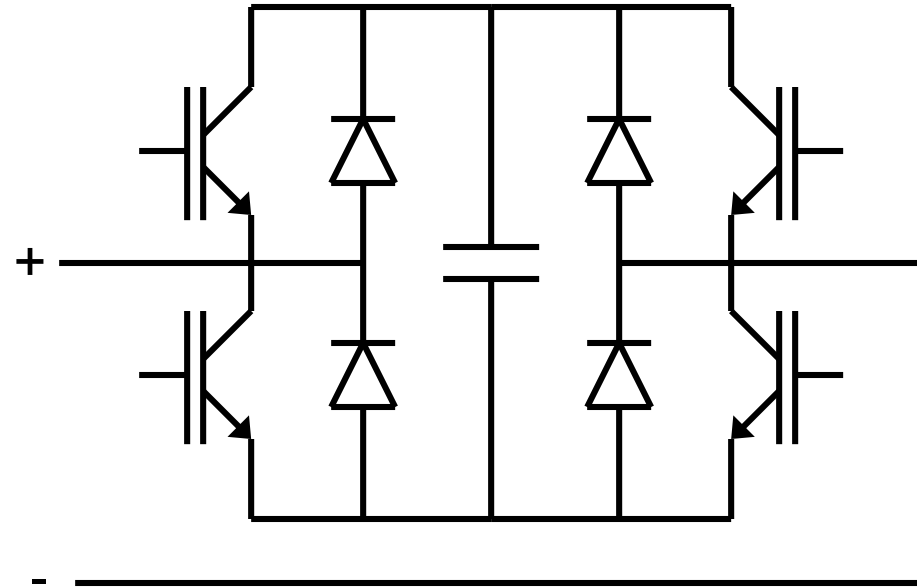
- Anthony Totterdell, Alstom Grid

Converter Submodules (SM)

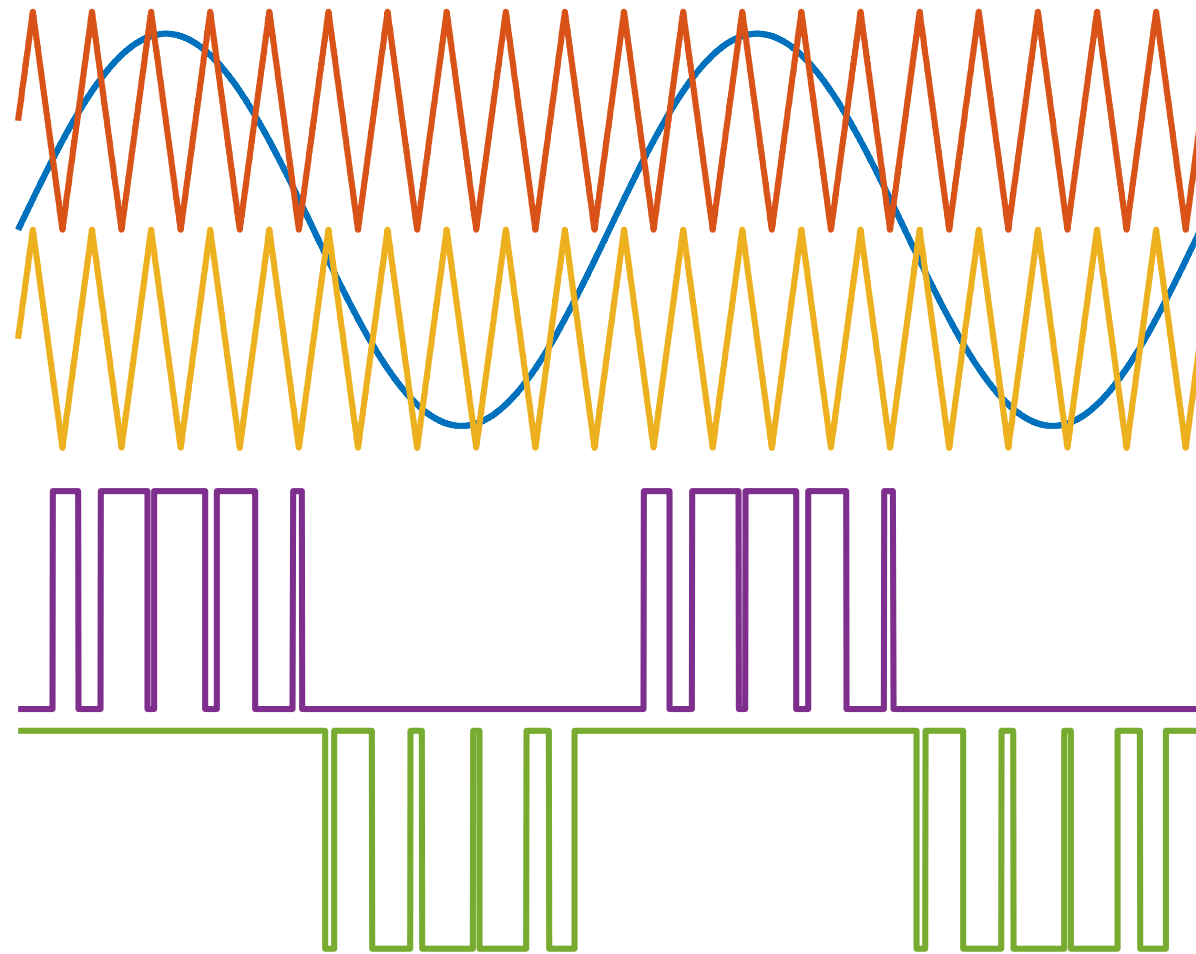
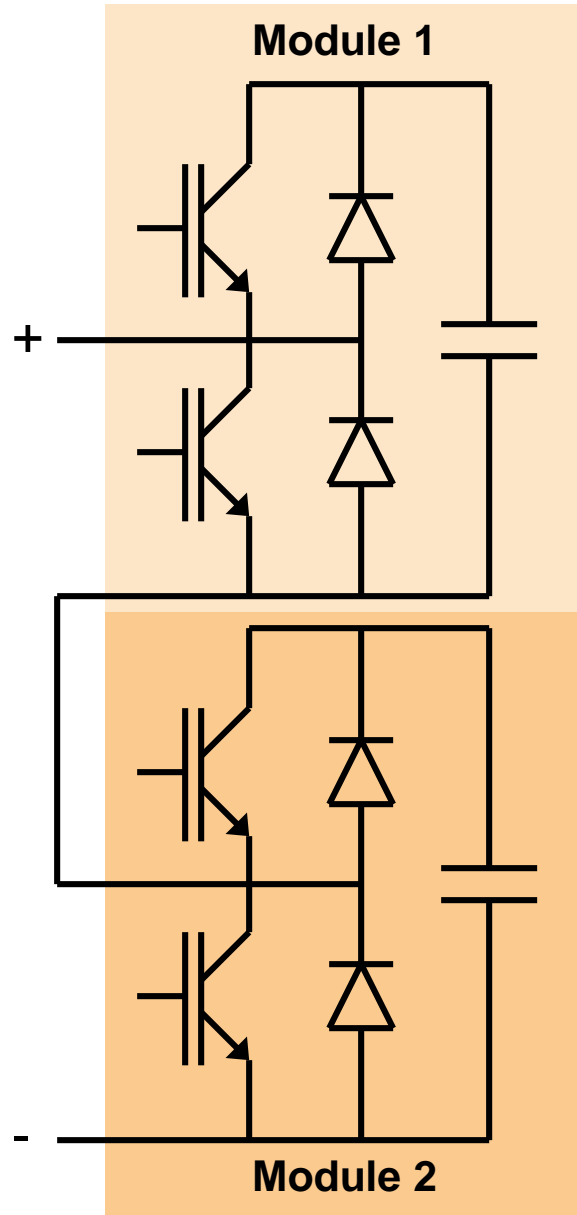
Half-Bridge



Full-Bridge



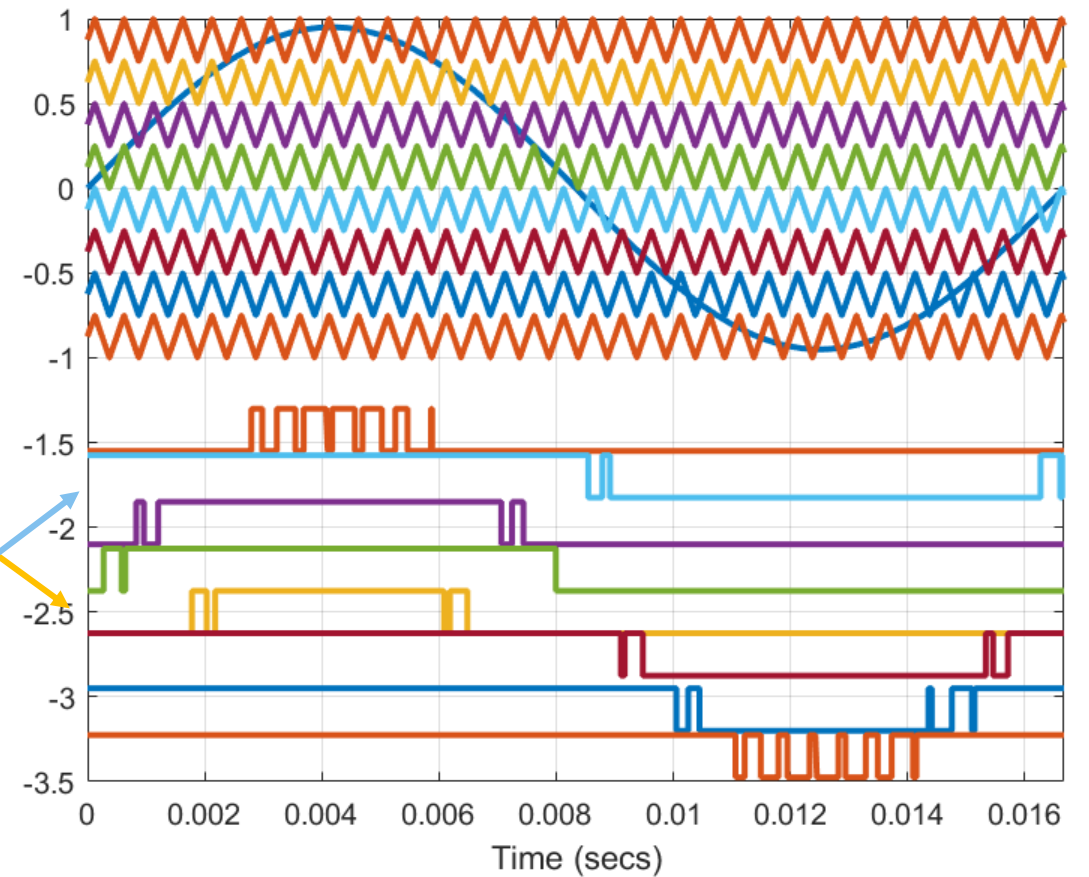
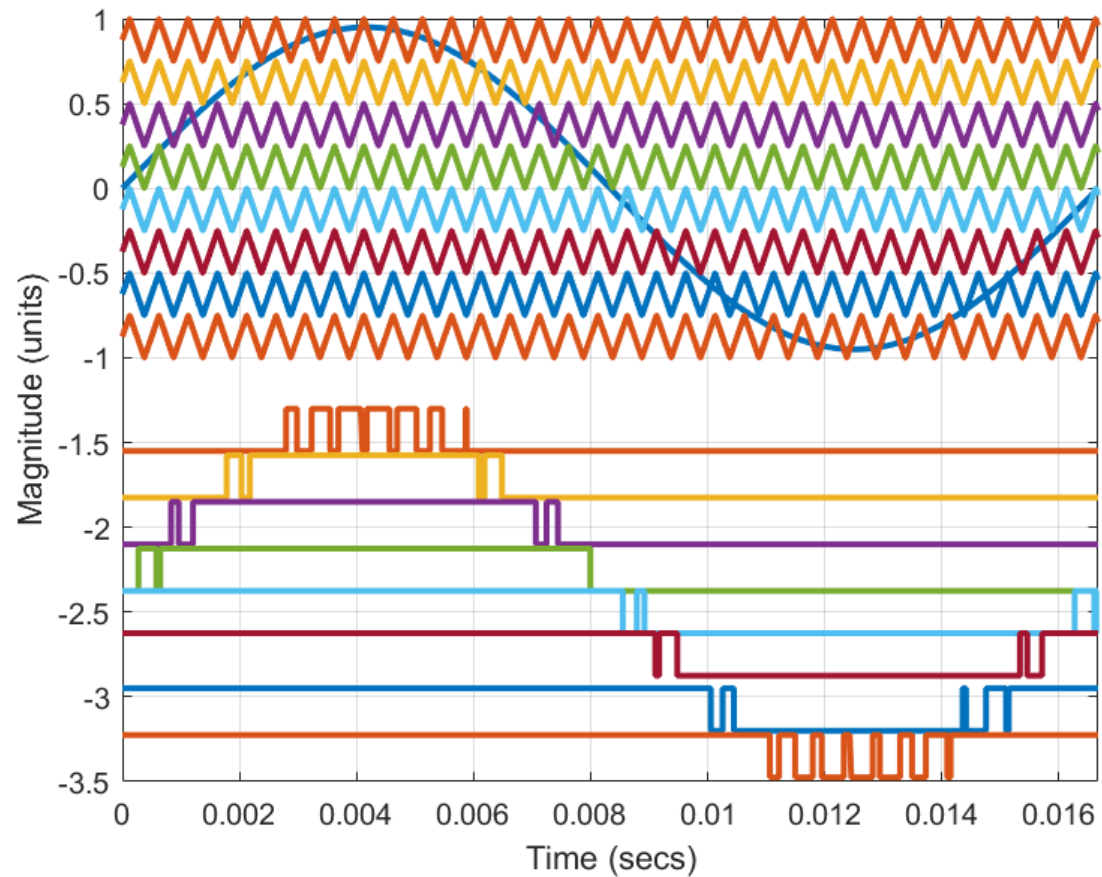
Modular Topology



Sorting and Signal Disposition

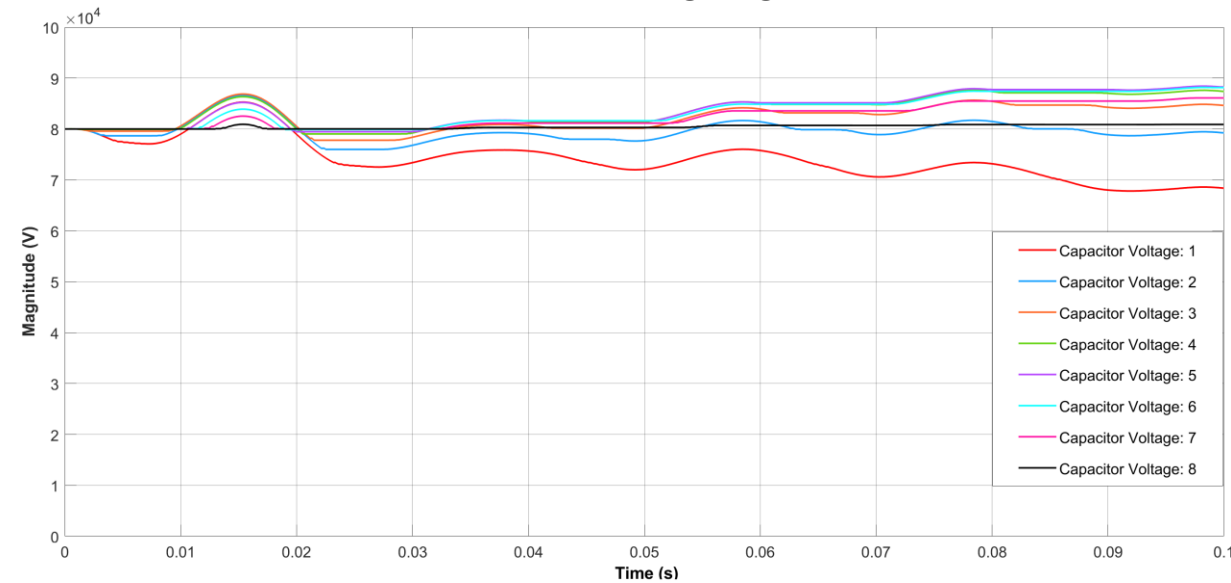
For the entire fundamental cycle assume:

$$V_{c1} < V_{c5} < V_{c3} < V_{c4} < V_{c2} < V_{c6} < V_{c7} < V_{c8}$$

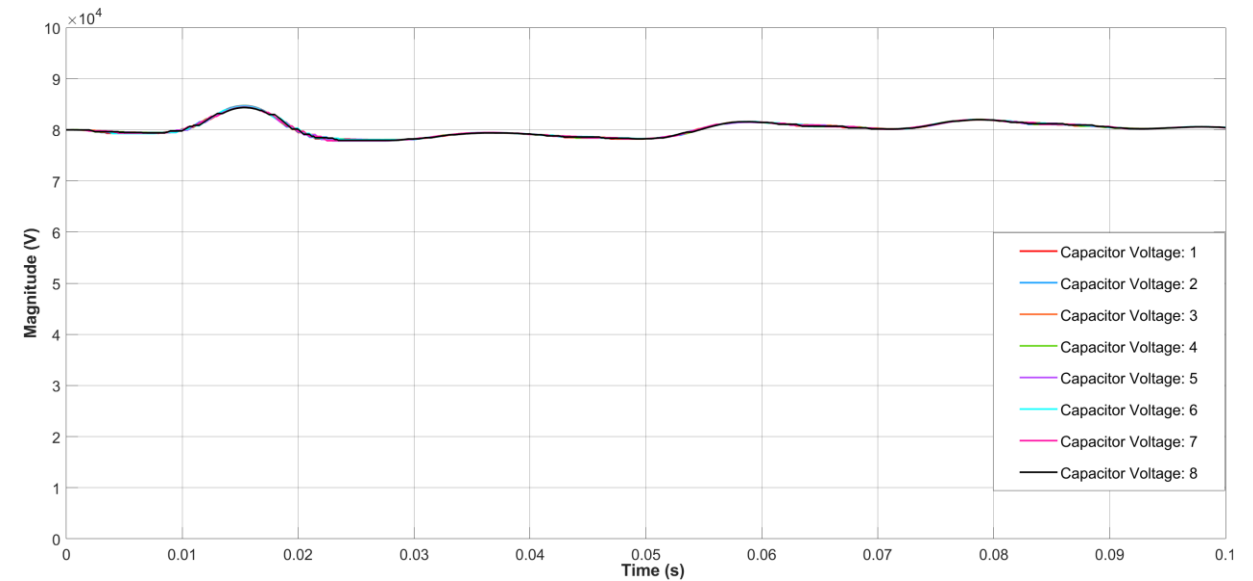


Sorting and Signal Disposition

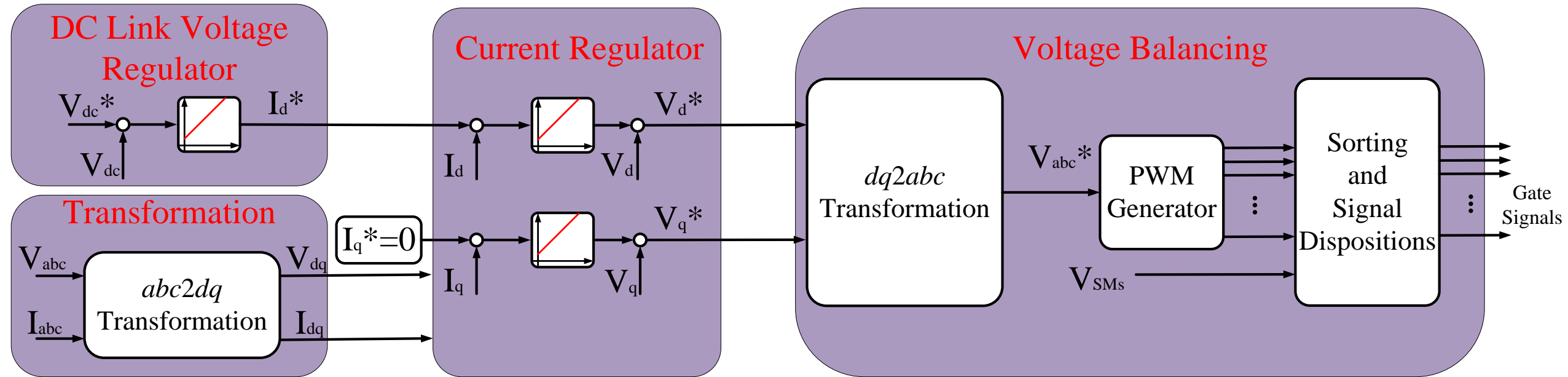
Capacitor Voltages for one arm of the converter
before sorting algorithm



Capacitor Voltages for one arm of the converter
after sorting algorithm

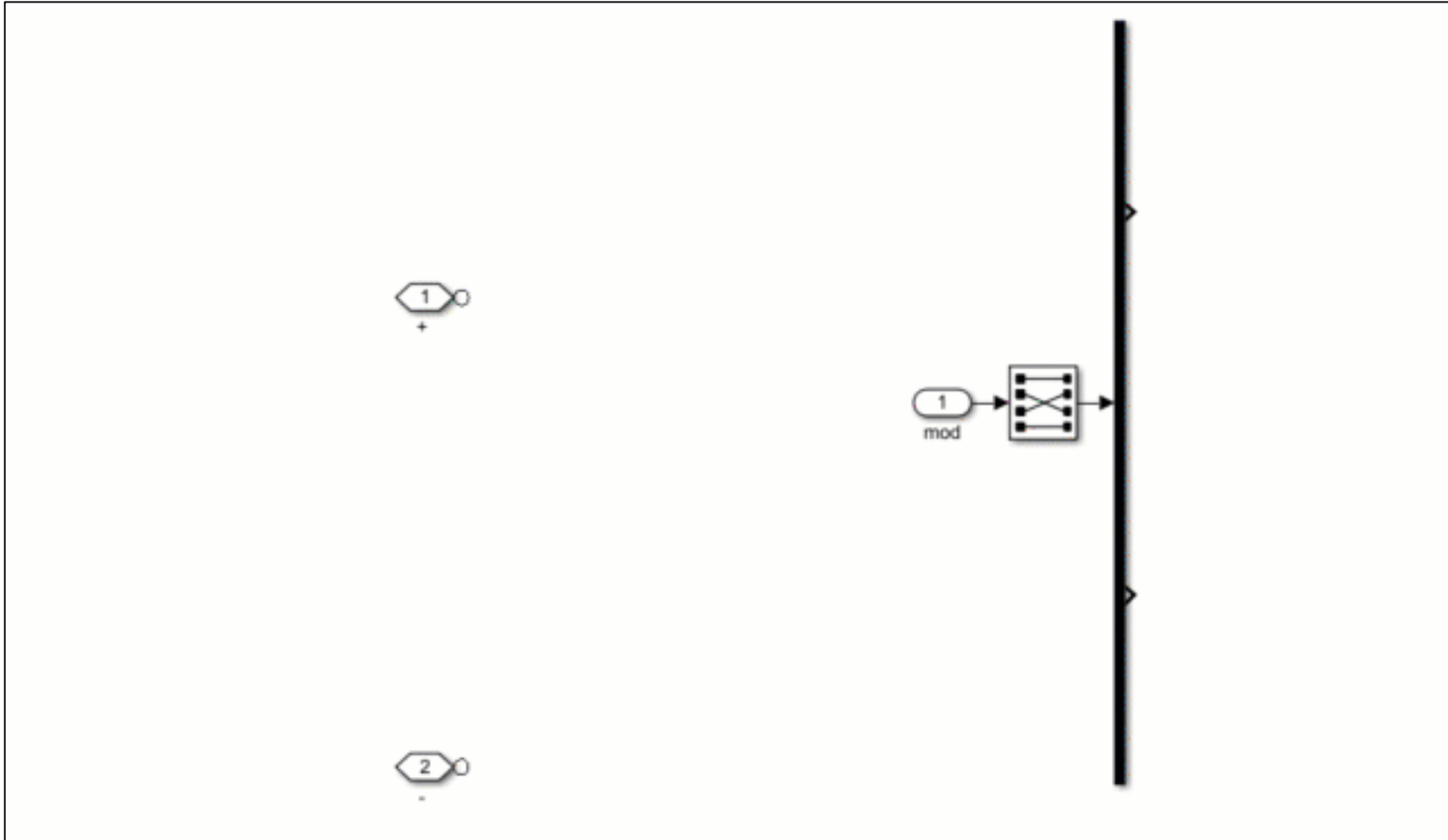


Control Algorithm

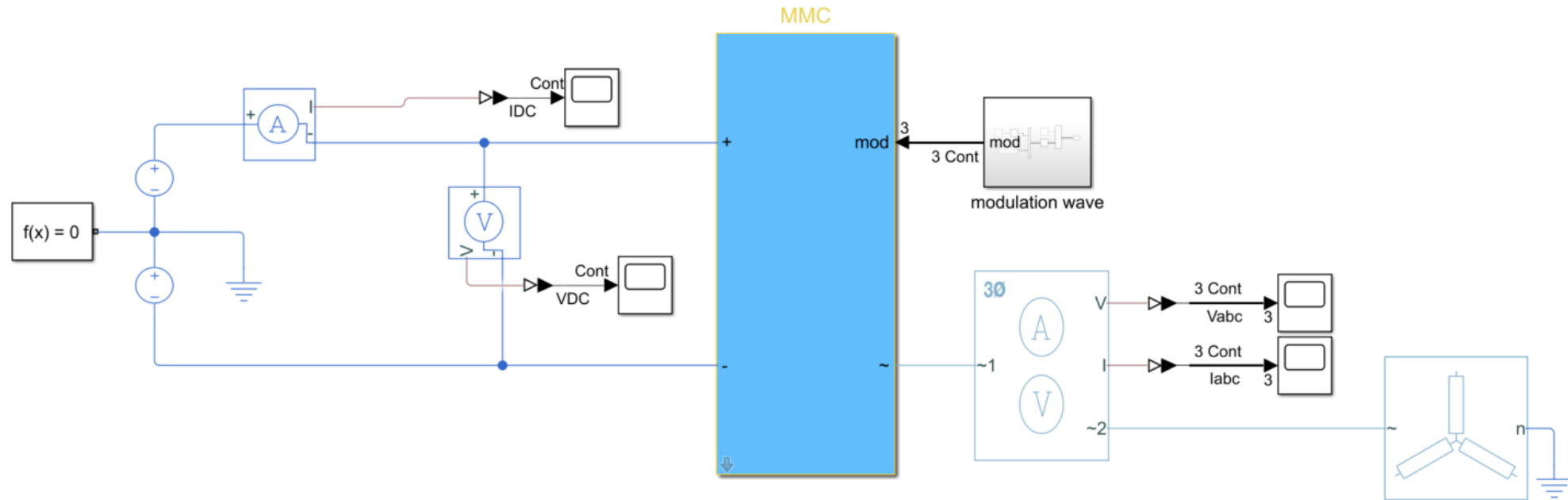


Build MMCs Programmatically

- With MATLAB, we can use the Simulink API to build programmatically more complex power converter architectures.

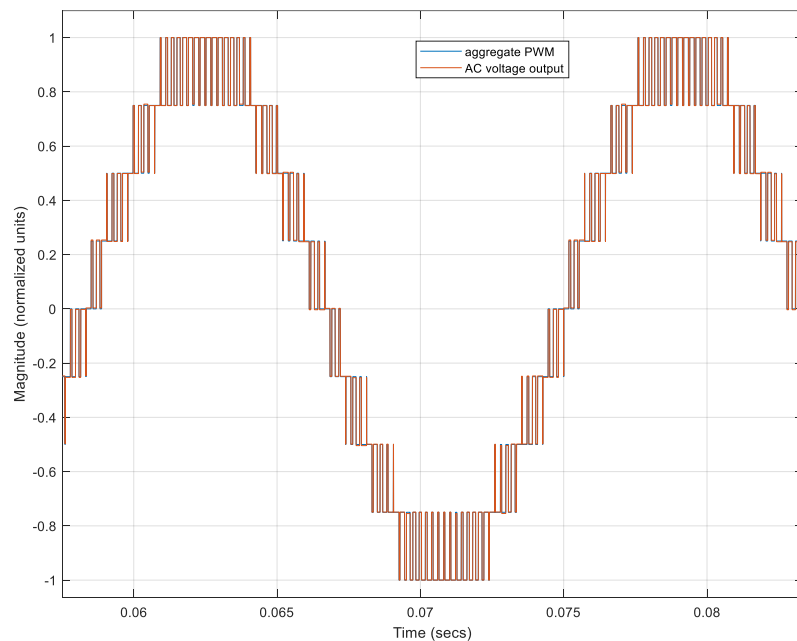


Desktop Simulation and Simulink Online

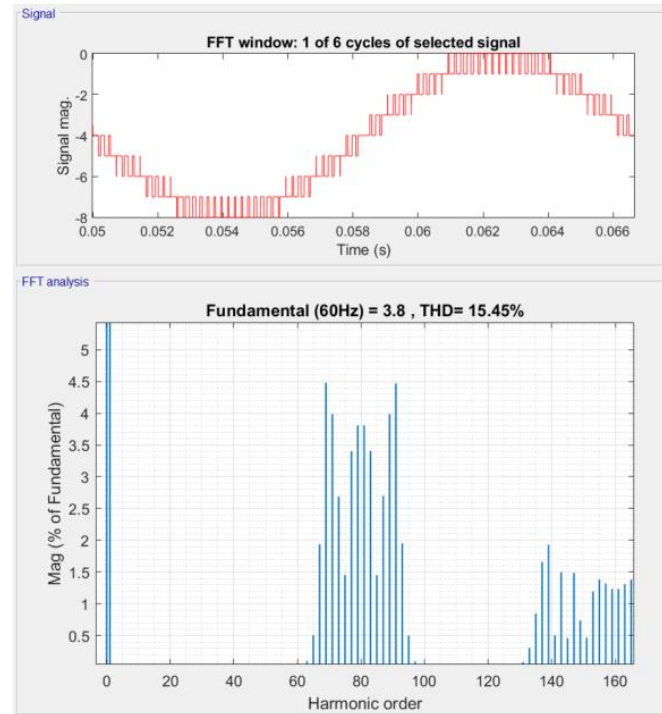


Desktop Simulation and Simulink Online

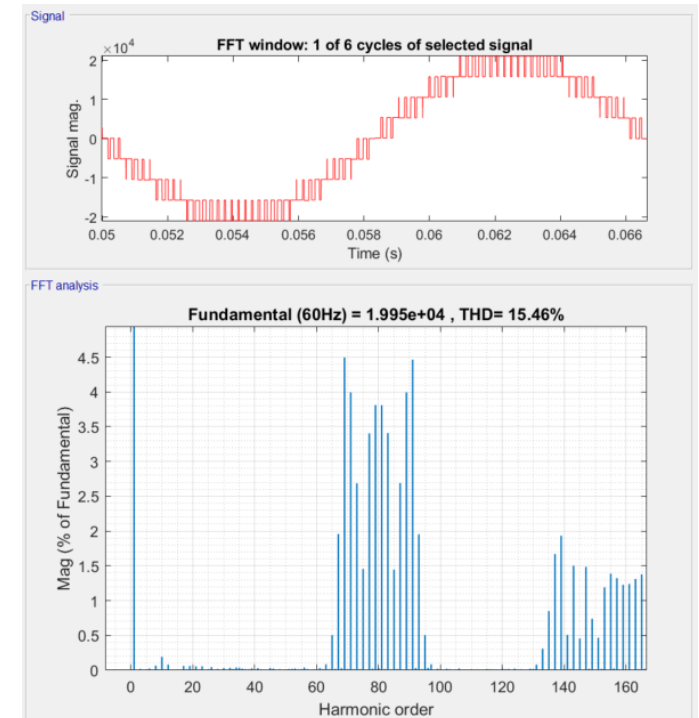
- After running a simulation, we compare the 'aggregate' PWM signal and the AC voltage output. A visual comparison is a good step, but a more rigorous evaluation is to compare the harmonics of the signals. With a stylized test-harness, we expect to see 'clean' waveforms and 'clean' harmonic profiles.



(a) Aggregate PWM and AC voltage output overlaid



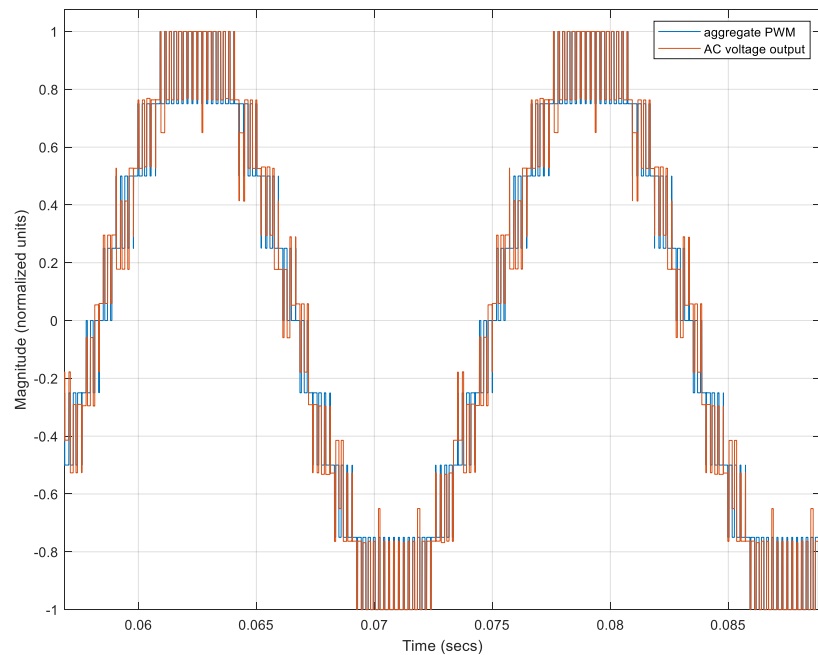
(b) Harmonic analysis of aggregate PWM



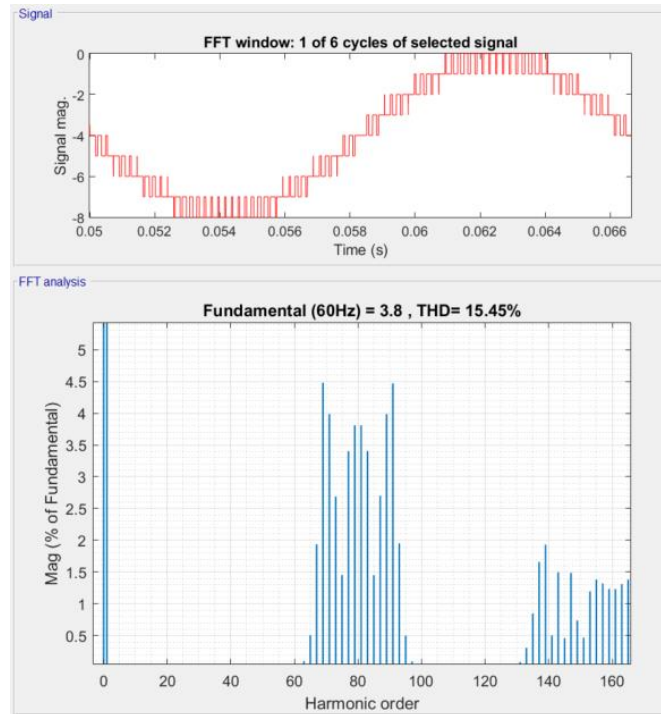
(c) Harmonic analysis of AC voltage output

Desktop Simulation and Simulink Online

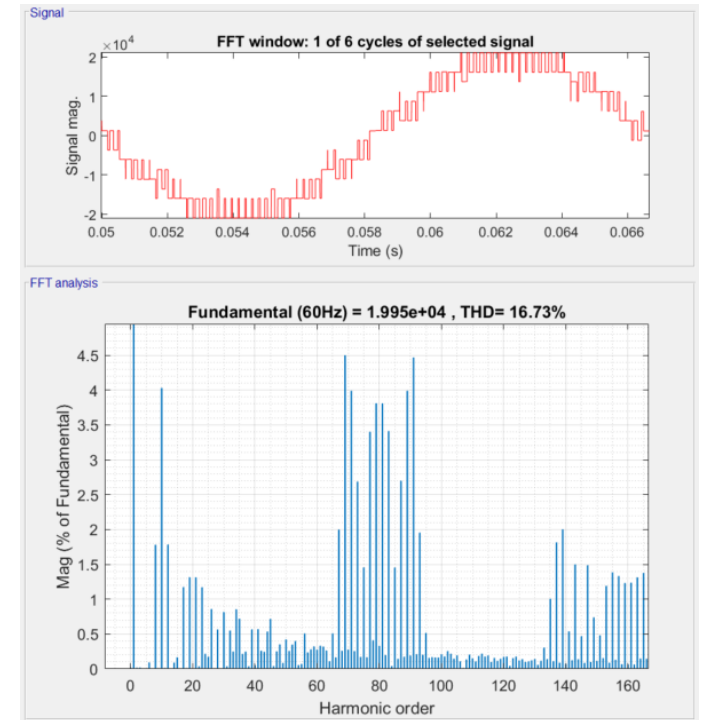
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(a) Aggregate PWM and AC voltage output overlaid



(b) Harmonic analysis of aggregate PWM



(c) Harmonic analysis of AC voltage output

Desktop Simulation and Simulink Online

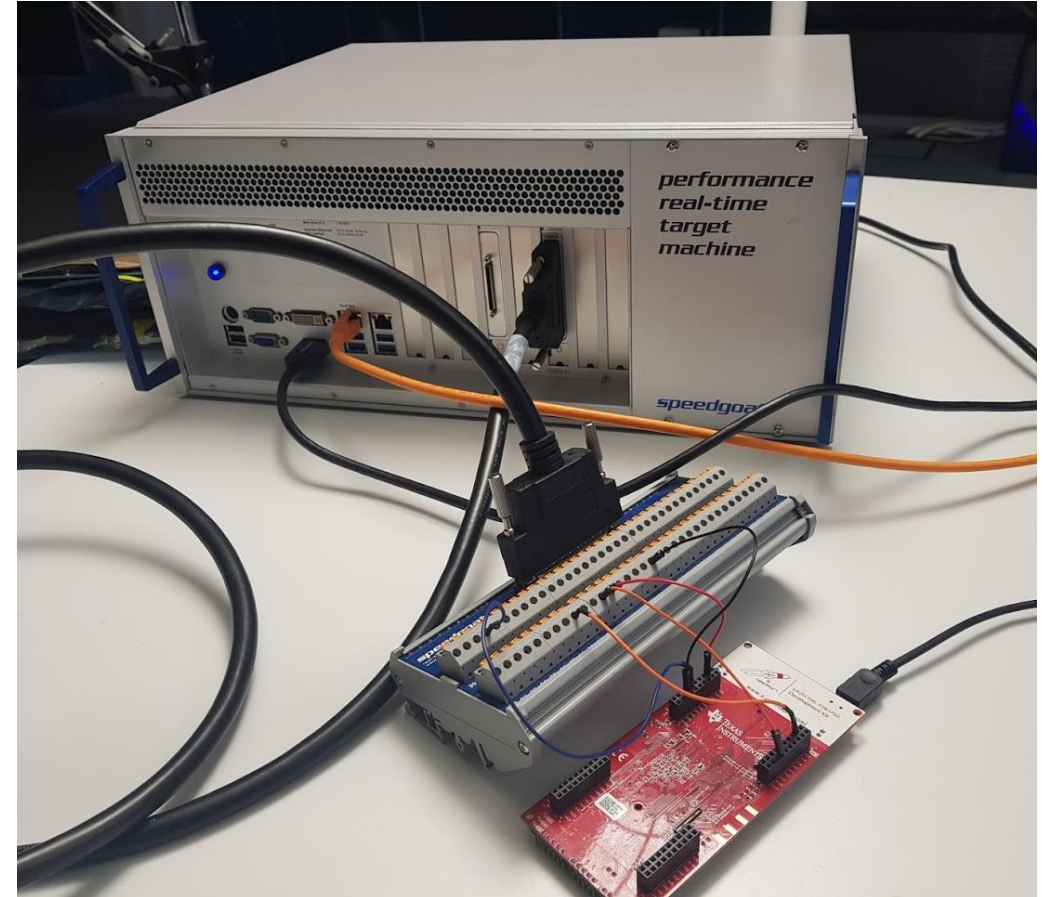
The screenshot displays the MATLAB Online R2021a environment. The browser window shows the URL `matlab.mathworks.com`. The main interface is divided into several sections:

- File Explorer:** Shows the current folder structure with files like `initParams.mat`, `MMC_8_PSPWM_test.slx`, and `MMC_8_PSPWM_test.sxc`.
- Workspace:** Contains variables `Ts` (value: $5.0000e-05$) and `Vdc` (value: 41000).
- Simulink Model:** Titled `MMC_8_PSPWM_test - Simulink`. The model includes:
 - A current source `f(x) = 0` connected to an ammeter `A` measuring `idc`.
 - A voltage source `V` connected to a voltmeter `V` measuring `vdc`.
 - A central `MMC` block with a `mod` input and a `modulation` output.
 - A three-phase current source block with values `30`, `-1`, and `-2`, connected to a three-phase load block.
 - Output signals `vabc` and `iabc` are measured at the load.

The status bar at the bottom indicates the model is `Ready` and the simulation is at `100%` completion.

Real-Time Testing with Simulink Real-Time and Speedgoat

- Prepare the model to run on Speedgoat hardware and run model in real-time at 50us sample rate
- Deploy the controls to a microcontroller and perform PIL testing
- Prepare the Simulink model for HIL, run HIL and compare results



Configure and run model in real-time on Speedgoat

The screenshot displays the Simulink environment for a real-time control system. The main workspace shows a block diagram with the following components:

- Current Controller:** A blue block that receives a reference signal and outputs a control signal.
- Multilevel PWM:** A yellow block that generates a multilevel PWM signal based on the control signal.
- Electrical Model:** A large green block representing the motor drive system, containing:
 - Upper Arm:** A series of switching devices (IGBTs) and diodes.
 - Lower Arm:** A series of switching devices (IGBTs) and diodes.
 - SM (Switching Modulator):** A central block that coordinates the switching of the arms.
 - Grid:** A block representing the AC grid connected to the motor.
 - Inductor (L) and Capacitor (C):** Passive components in the circuit.

The interface includes a top toolbar with tabs for SIMULATION, DEBUG, MODELING, FORMAT, REAL-TIME, APPS, and BLOCK. The 'REAL-TIME' tab is active, showing options like 'Run on Target' and 'Data Inspector'. On the right, the 'Property Inspector' shows the 'Current Controller' block with parameters for 'SLRT Closed-Loop'. At the bottom, a 'Timing Legend' indicates the execution of continuous and discrete blocks.

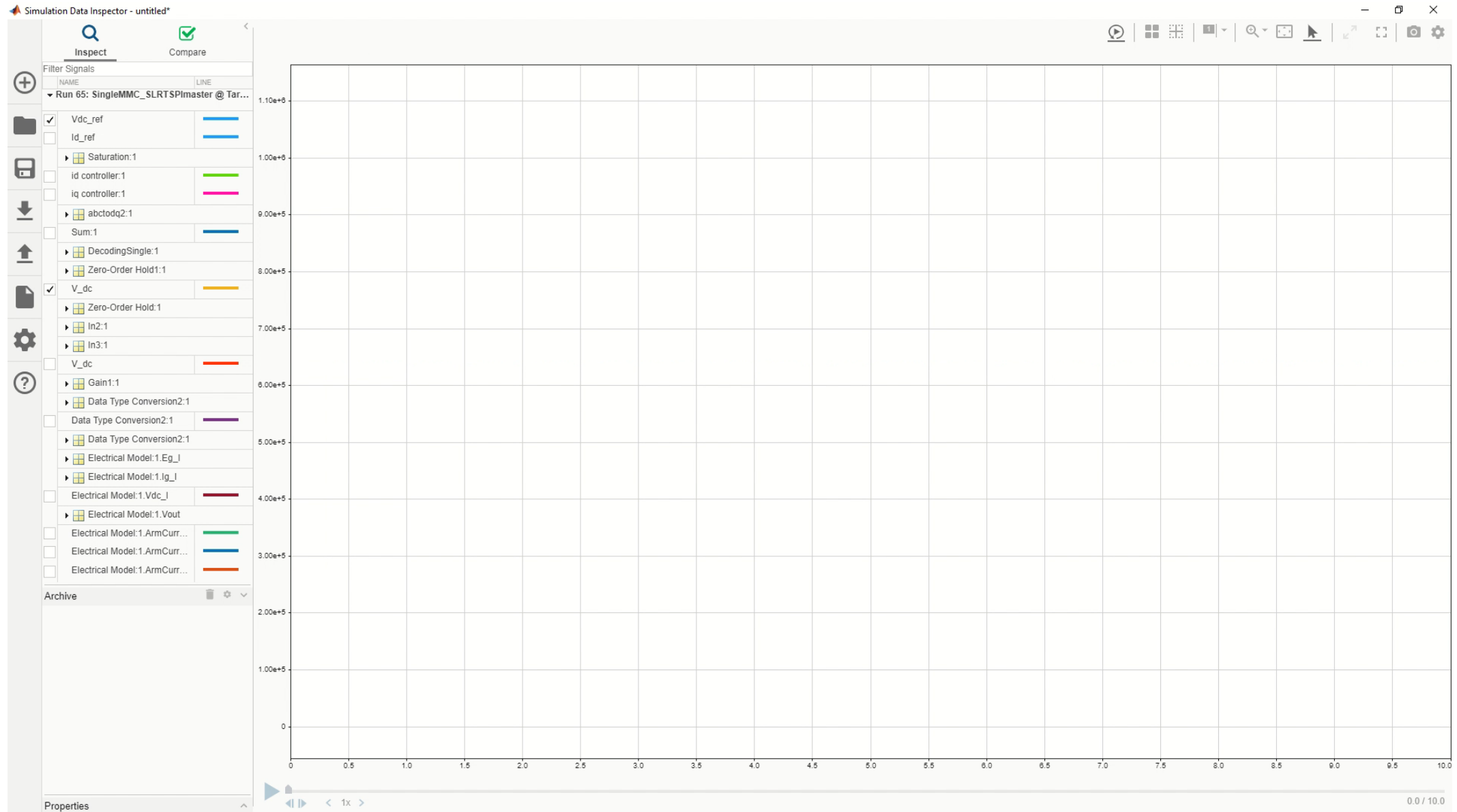
Configure and run model in real-time on Speedgoat

The screenshot displays the MATLAB R2020b environment with the following components:

- Top Bar:** MATLAB R2020b - sponsored third party support use. Includes navigation icons and a search bar.
- Toolbars:**
 - FILE:** New, Open, Share.
 - TOOLS:** Dependency Analyzer, Model Testing Dashboard, Search, Custom Tasks, Run Checks.
 - ENVIRONMENT:** References, Project Path, Startup Shutdown.
 - SOURCE CONTROL:** Git Details, Refresh, Commit, Fetch, Push, Pull, Remote, Branches, Stashes, Submodules.
- Current Folder:** Shows the project structure under 'C:\Work\Projects\MMC\V2\20200202_MMCProject\20200202_MMCProject\SimulinkModels'. Files include 'SingleMMC_SLRTSPImaster.slx', 'SingleMMC_SLRT.slx', 'SingleMMC.slx', 'runmdl.m', 'repro.zip', 'ControlSlave.slx', 'controllerinputs.mat', 'Control_MMC_C2000.slx', 'control_algorithm_Testbench.slx', 'control_algorithm_single.slx', '.keep', 'work', 'SwitchingSignalGeneration', 'SPITests', 'repro', 'old', 'ElectricalSystem', and 'controlmodels'.
- Live Editor:** 'initparams_MMCWC.mlx'. Shows a file browser with folders like 'Data', 'Documentation', 'helpers', 'Scripts', and 'SimulinkModels'. A 'Classification' pane is visible. Git status shows 'Current branch: master', 'Branch status: Normal', and 'Coincident with /origin/master'.
- Command Window:** Shows the MATLAB prompt 'fx >>' with a cursor.
- Workspace:** A table of variables and their values.

| Name | Value |
|----------------------|-----------------------------|
| alpha_f | 100 |
| C | 0.0200 |
| C_sm | 0.0200 |
| C_sm_vector | [0.0200,0.0200,0.0200,... |
| CapacitorVoltages... | 1x1 Bus |
| carrier_max | [0.1250,0.2500,0.3750,... |
| carrier_min | [0.0,0.1250,0.2500,0.375... |
| cf | 300 |
| Co | 0.0100 |
| f_g | 50 |
| f_sw | 2000 |
| I_f_max | 10000 |
| ind1 | [1,2,3,4,5,6,7,8] |
| ind2 | [9,10,11,12,13,14,15,16] |
| ind_reshape | 1x16 double |
| K_gc_id | 65 |
| K_gc_iq | 65 |
| K_gc_iW | 25 |
| K_gc_pd | 0.6500 |
| K_gc_pq | 0.6500 |
| K_gc_pW | 1 |
| L | 1.0000e-04 |
| L_arm | 0.0030 |
| L_f | 0.0065 |
| L_g | 0.0050 |
| LegCurrentsBus | 1x1 Bus |
| logout | 1x1 struct |
| mdl | 'SingleMMC_SLRTSPIm... |
| num_sm | 8 |
| R | 5 |
| R_arm | 0.1000 |
| R_f | 0.1500 |
| R_g | 0.1000 |
| R_gc_a | 0.5000 |
| R_res_a | 1.0000e-03 |
| Ro | 2048 |
| SwitchingSignalsB... | 1x1 Bus |
| T_HIL | 5.0000e-06 |
| tg | 1x1 Target |
| Ts | 5.0000e-05 |
| Ts_CurrentControl | 1.0000e-04 |
| V_dc | 640000 |
| V_ggrms | 110000 |
| V_gpeak | 8.9815e+04 |
| V_sm | 80000 |
| V_sm_vector | [80000,80000,80000,8... |
| VabcBus | 1x1 Bus |
| vdc | 640000 |

Configure and run model in real-time on Speedgoat



Generate Embedded Application on TI C2000 Microcontroller

The screenshot displays the Simulink Hardware Support Package interface for a TI C2000 microcontroller. The main workspace shows a block diagram with the following components and connections:

- SPI outputs**: A block on the left that receives a signal of width 5 and outputs three signals: *Vdc* (width 1), *Vab* (width 2), and *lab* (width 2).
- control algorithm single**: A large central block that receives *Vdc*, *Vab*, and *lab* as inputs. It contains a detailed control algorithm model and outputs a *Controls* signal of width 5.
- SPI**: A block on the right that receives the *Controls* signal and outputs a signal of width 5.

The interface includes a top toolbar with tabs for SIMULATION, DEBUG, MODELING, FORMAT, HARDWARE, APPS, and SUBSYSTEM BLOCK. The HARDWARE tab is active, showing the hardware board as TI Delfino F28379D LaunchPad. A Timing Legend on the right side of the interface lists various signal types and their periods:

| Discrete | Period |
|----------|----------------|
| Red | 100.0000e-006 |
| Event | Asynchronous 1 |
| Other | Constant |
| | Multirate |

At the bottom of the window, the status bar shows "Ready", "View 14 warnings", "243%", and "FixedStepDiscrete".

Generate Embedded Application on TI C2000 Microcontroller

The screenshot displays the MATLAB Simulink Hardware Support Package interface. The main window is titled "Configuration Parameters: Control_MMC_C2000/Configuration (Active)". The interface includes a top menu bar with tabs for SIMULATION, DEBUG, MODELING, FORMAT, HARDWARE, and APPS. Below the menu bar, there are several toolbars and panels:

- Hardware Board:** TI Delfino F28379D LaunchPad
- Hardware Settings:** Hardware Settings, Test Point, Control Panel
- Stop Time:** 8
- Monitor & Tune:** Monitor & Tune
- MATLAB Workspace:** MATLAB Workspace
- Build, Deploy & Start:** Build, Deploy & Start

The main workspace area is currently empty, showing a loading spinner. A "Timing Legend" panel is visible on the right side, displaying the following information:

| Discrete | Period |
|--------------|----------------|
| | 100.0000e-006 |
| Event | |
| | Asynchronous 1 |
| Other | |
| | Constant |
| | Multirate |

At the bottom of the window, there are buttons for "OK", "Cancel", "Help", and "Apply". The status bar at the bottom indicates "Ready", "View 14 warnings", "157%", and "FixedStepDiscrete".

Generate Embedded Application on TI C2000 Microcontroller

The screenshot displays the MATLAB/Simulink environment with a diagnostic viewer window open, showing the build process for the Control_MMC_C2000 project. The diagnostic viewer contains the following text:

```

*** Terminating debug session...

*** LOAD & RUN DONE.
## Invoking custom build hook: CodeGenAfterMake
## Successful completion of build procedure for: Control_MMC_C2000
## Invoking custom build hook: CodeGenExit
## Simulink cache artifacts for 'Control_MMC_C2000' were created in
'C:\Work\Projects\MMC\V2\20200202_MMCProject\20200202_MMCProject\work\SimulationCache\Control_M
MC_C2000.slxc'.

Build process completed successfully

Build Summary 1
Elapsed: 0.11 sec

Top model targets built:

Model      Action      Rebuild Reason
-----
Control_MMC_C2000  Code generated and compiled  Generated code was out of date.

1 of 1 models built (0 models already up to date)
Build duration: 0h 1m 27.515s
    
```

The background shows a Simulink block diagram titled "SPI Master Transfer". The diagram includes the following blocks and connections:

- An input port labeled "1" with data type "int16 (5)" connects to a "Byte Pack" block.
- The "Byte Pack" block outputs "uint16 (5)" to an "SPI Transmit" block.
- The "SPI Transmit" block (Slave select: SPISTE) outputs "uint16" to a bus.
- The bus connects to an "SPI Receive" block (Slave select: SPISTE).
- The "SPI Receive" block outputs "uint16 [5x1]" to a "Byte Unpack" block.
- The "Byte Unpack" block outputs "int16 (5)" to an output port labeled "1".

On the right side of the interface, a "Timing Legend" is visible, showing various signal types and their periods:

| Discrete | Period |
|----------|----------------|
| Red | 100.0000e-006 |
| Event | |
| Purple | Asynchronous 1 |
| Other | |
| Pink | Constant |
| Yellow | Multirate |

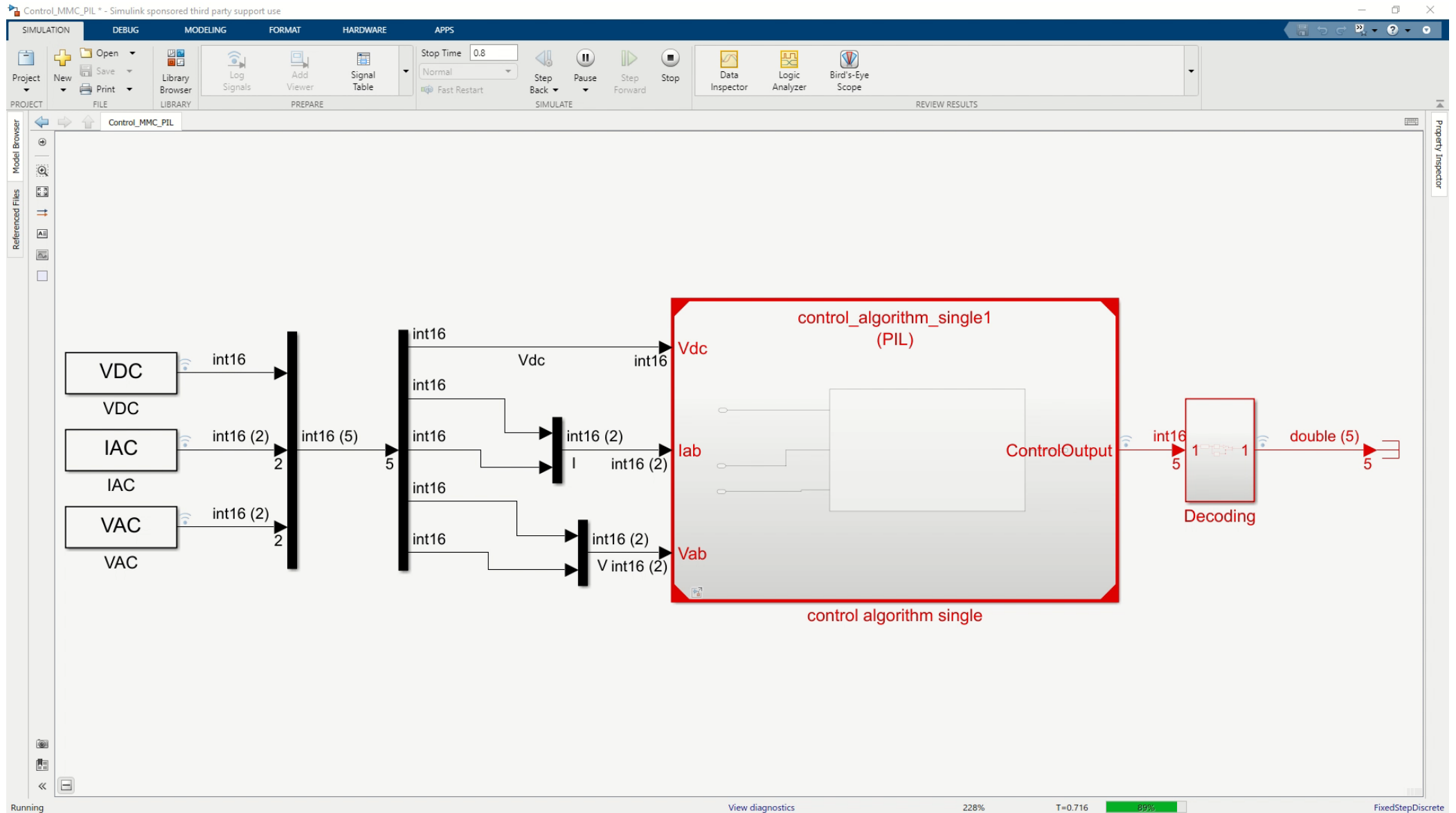
Processor-In-the-Loop (PIL) Testing

The screenshot displays the Simulink environment for a project named "Control_MMC_PIL". The interface includes a top toolbar with tabs for SIMULATION, DEBUG, MODELING, FORMAT, HARDWARE, APPS, and MODEL BLOCK. The MODEL BLOCK tab is active, showing a block diagram with the following components:

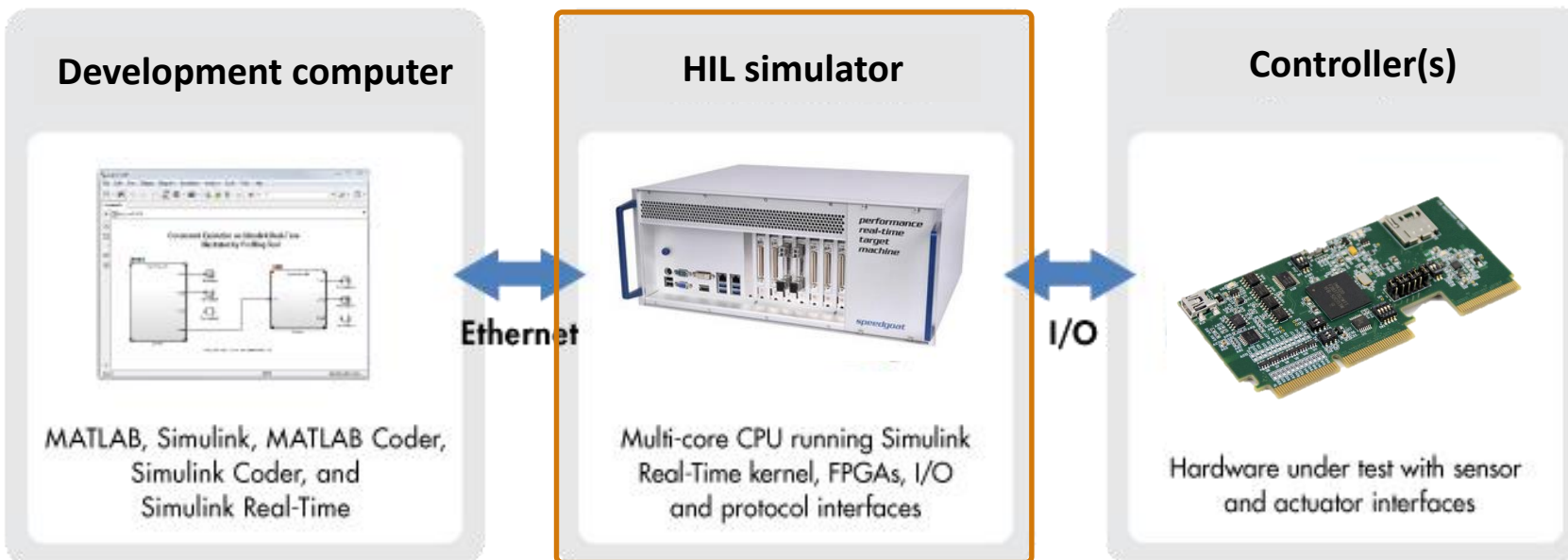
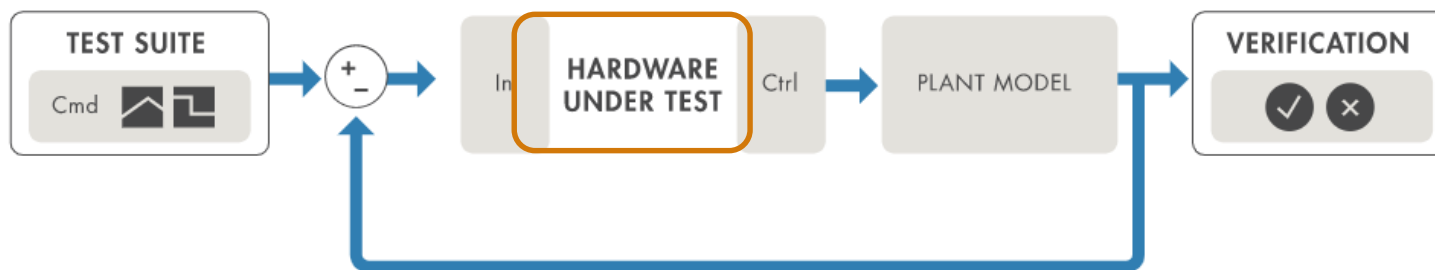
- Three input blocks: VDC, IAC, and VAC, each with a "V" icon.
- Each input block has two "int16 (2)" outputs.
- These outputs are combined into a "int16 (5)" bus.
- The bus feeds into a larger block with three outputs: "Vdc", "lab", and "Vab", each with a "V" icon.
- A "Decoding" block (1-to-1) receives "int16 (5)" and outputs "double (5)".

A context menu is open over the "lab" output block, listing various actions such as "Explore", "Copy", "Paste", "Delete", and "Block Parameters (ModelReference)". The "Block Parameters (ModelReference)" option is highlighted.

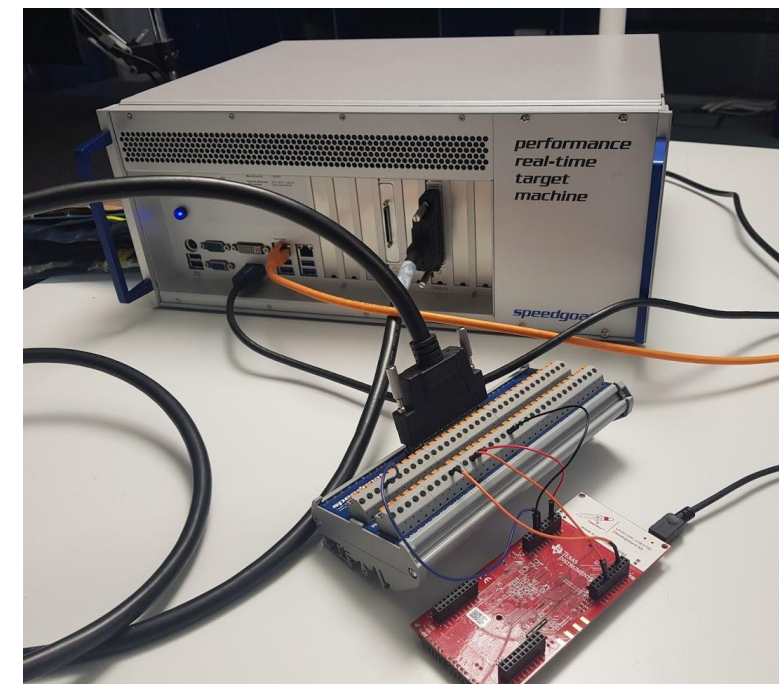
Processor-In-the-Loop (PIL) Testing



Hardware-in-the-Loop Simulation



Plant simulation application autogenerated from Simulink

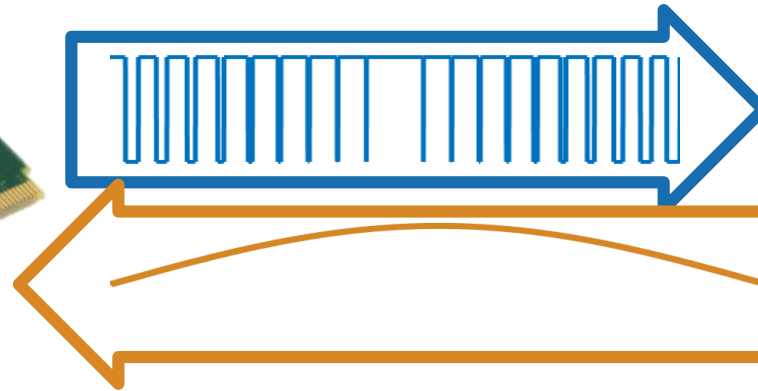


Advantages of Hardware in the Loop (HIL) Testing

- Can replace prototypes or production hardware with a real-time system
- Easier to automate testing
- Safer than most power electronics hardware
- Start many design/test tasks earlier



Controller



**Virtual Simulation
(Plant)**

Hardware-in-the-Loop Simulation

SingleMMC_SLRTSPImaster - Simulink sponsored third party support use

TargetIO333
Disconnected

CONNECT TO TARGET COMPUTER PREPARE RUN ON TARGET

Hardware Settings Log Signals Add Viewer Run on Target Data Inspector Logic Analyzer TET Monitor REVIEW RESULTS

control algorithm single SingleMMC_SLRTSPImaster

Discrete 5e-05 s.

Multilevel PWM

Electrical Model

Upper Arm Lower Arm SM Grid

Property Inspector

Current Controller

Parameters Properties Info Execution

HIL

Script Reference

Timing Legend

Highlight None $\frac{1}{p}$

| Continuous | |
|------------|------------|
| Cont. | Continuous |

| Discrete | |
|----------|---------------|
| Block | Period |
| D1 | 50.0000e-006 |
| D2 | 100.0000e-006 |
| D3 | 500.0000e-006 |

Ready View 3 warnings 74% FixedStepDiscrete

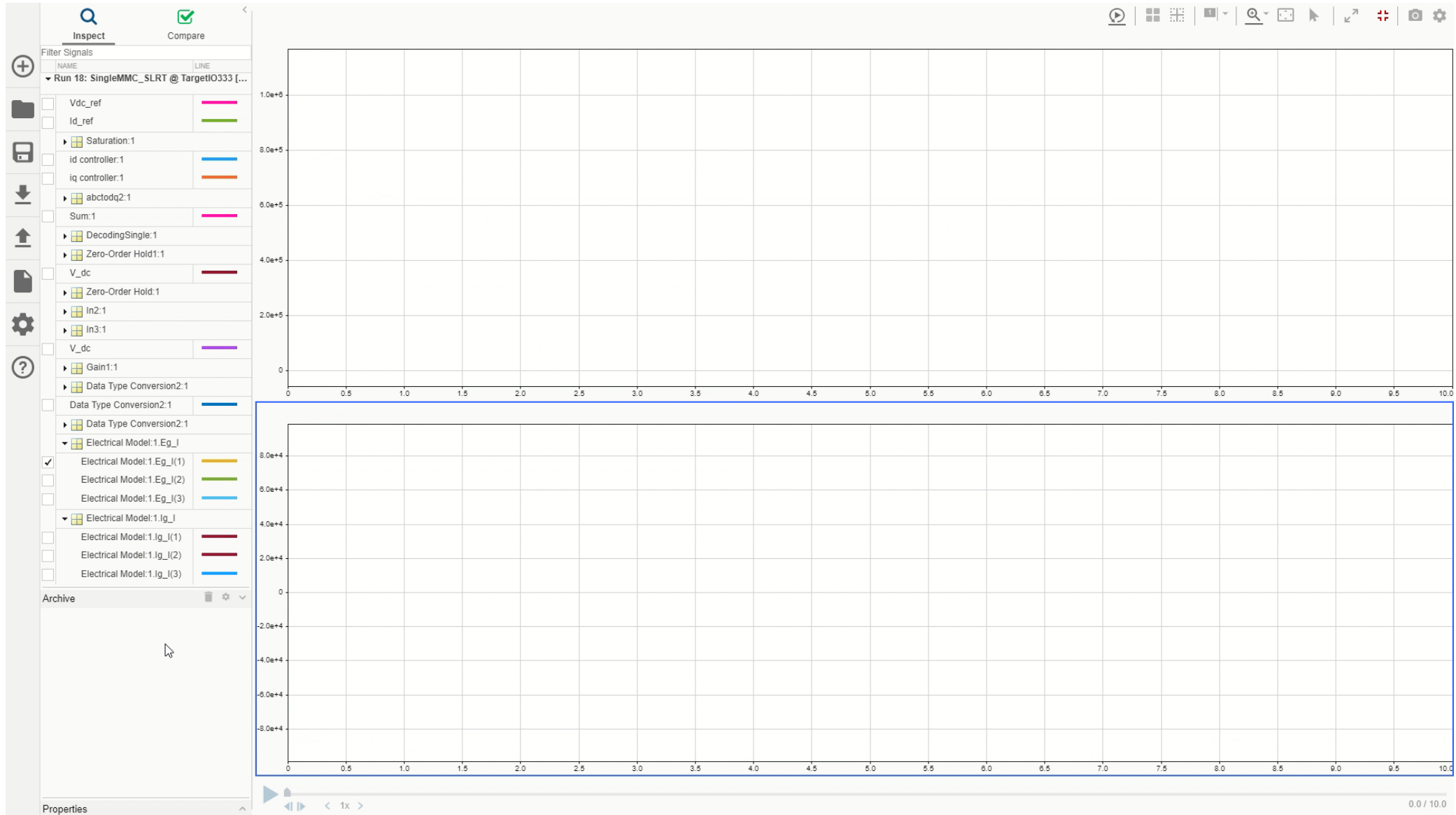
Hardware-in-the-Loop Simulation

The screenshot displays the MATLAB R2020b interface with the following components:

- Top Bar:** MATLAB R2020b - sponsored third party support use. Includes search and manual options.
- Toolbox:** HOME, PLOTS, APPS, PROJECT, PROJECT SHORTCUTS. Includes icons for New, Open, Share, Dependency Analyzer, Model Testing Dashboard, Search, Custom Tasks, Run Checks, References, Project Path, Startup/Shutdown, Git, Refresh, Commit, Fetch, Remote, Submodules, Push, Pull, Branches, Stashes.
- Current Folder:** C:\Work\Projects\MMC\V2\20200202_MMCProject\20200202_MMCProject\SimulinkModels
- Workspace:**

| Name | Value |
|----------------------|---------------------------|
| alpha_f | 100 |
| C | 0.0200 |
| C_sm | 0.0200 |
| C_sm_vector | [0.0200,0.0200,0.0200,... |
| CapacitorVoltages... | 1x1 Bus |
| carrier_max | [0.1250,0.2500,0.3750,... |
| carrier_min | [0,0.1250,0.2500,0.375... |
| cf | 300 |
| Co | 0.0100 |
| dataType | 'single' |
| f_g | 50 |
| f_sw | 2000 |
| I_f_max | 10000 |
| ind1 | [1,2,3,4,5,6,7,8] |
| ind2 | [9,10,11,12,13,14,15,16] |
| ind_reshape | 1x16 double |
| inverter | 1x1 struct |
| K_gc_id | 65 |
| K_gc_iq | 65 |
| K_gc_iW | 25 |
| K_gc_pd | 0.6500 |
| K_gc_pq | 0.6500 |
| K_gc_pW | 1 |
| L | 1.0000e-04 |
| L_arm | 0.0030 |
| L_f | 0.0065 |
| L_g | 0.0050 |
| LegCurrentsBus | 1x1 Bus |
| logout | 1x1 struct |
| mdl | 'SingleMMC_SLRT' |
| num_sm | 8 |
| PI_params | 1x1 struct |
| pmsm | 1x1 struct |
| PWM_frequency | 20000 |
| R | 5 |
| R_arm | 0.1000 |
| R_f | 0.1500 |
| R_g | 0.1000 |
| R_gc_a | 0.5000 |
| R_res_a | 1.0000e-03 |
| Ro | 2048 |
| SI_System | 1x1 struct |
| SwitchingSignalsB... | 1x1 Bus |
| T_HIL | 5.0000e-06 |
| T_pwm | 5.0000e-05 |
| target | 1x1 struct |
| tg | 1x1 Target |
| Ts | 5.0000e-05 |
| Ts_CurrentControl | 1.0000e-04 |
- Views:** Files, Dependency Analyzer. Shows a tree view of the project structure with folders like Data, Documentation, helpers, Scripts, SimulinkModels, and work.
- Labels:** Git, Current branch: master, Branch status: Normal, Coincident with /origin/master.
- Command Window:** Shows a prompt `fz >>` with a cursor.
- Status Bar:** SingleMMC_SLRT.slx (Simulink Model)

Hardware-in-the-Loop Simulation



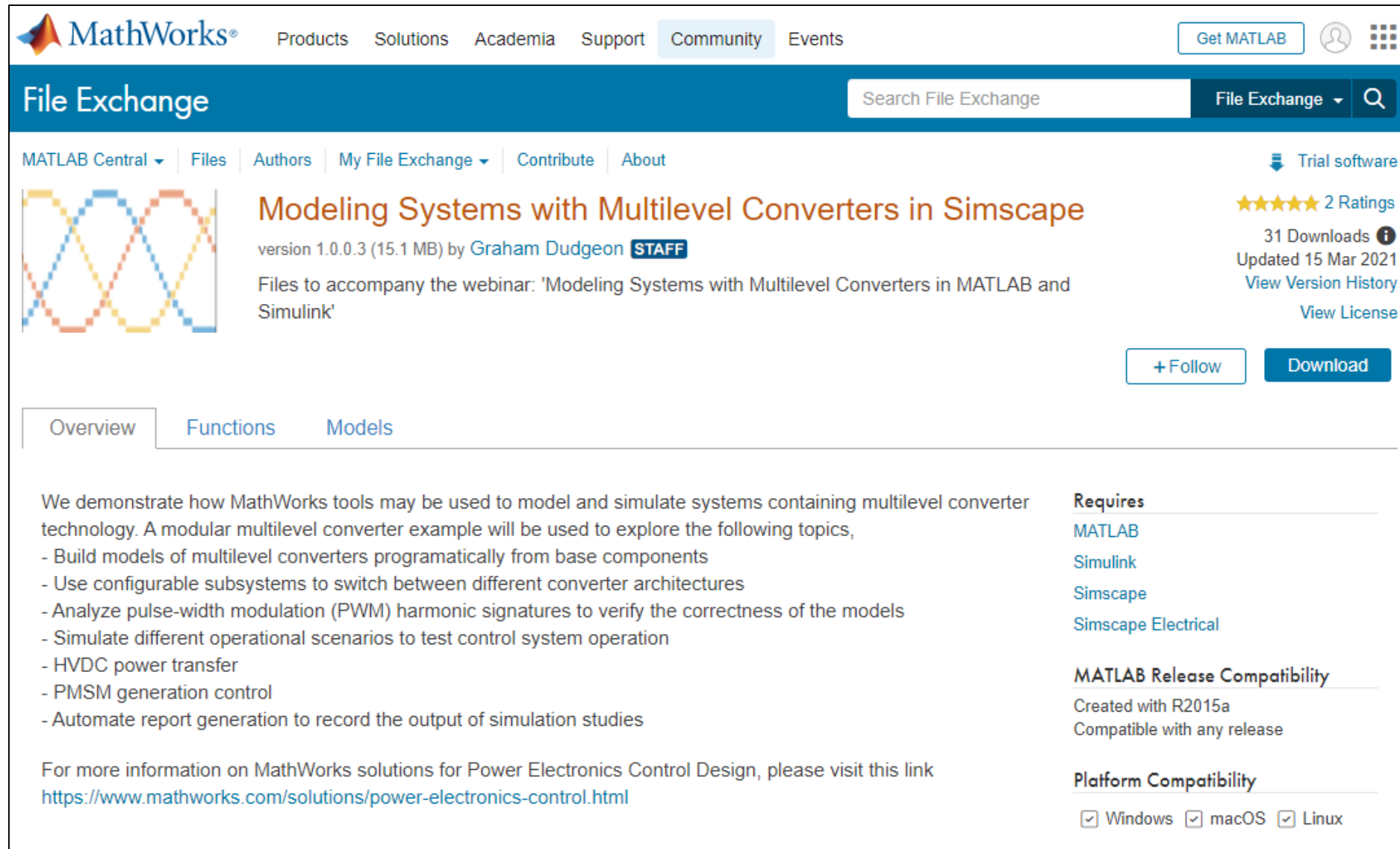
Hardware-in-the-Loop Simulation



Conclusion

- MathWorks tools support all stages of technology readiness.
- Complex power converter architectures can be built automatically in Simulink.
- Complex power converter architectures and their control systems can be effectively simulated using both desktop and real-time simulation.
- Variable-step solvers provide accurate PWM timing on desktop and online simulation.
- Functional correctness of control configurations can be rapidly assessed, and hardware implementation can be de-risked using automatic code generation and HIL testing.

Learn More



The screenshot shows the MathWorks File Exchange interface. At the top, there is a navigation bar with the MathWorks logo and links for Products, Solutions, Academia, Support, Community, and Events. A 'Get MATLAB' button and user profile icons are also present. Below the navigation bar is a search bar labeled 'Search File Exchange' and a 'File Exchange' dropdown menu. The main content area features a header for 'MATLAB Central' with sub-links for Files, Authors, My File Exchange, Contribute, and About. A 'Trial software' icon is visible in the top right corner of the content area.

The featured item is titled 'Modeling Systems with Multilevel Converters in Simscape', version 1.0.0.3 (15.1 MB) by Graham Dudgeon (STAFF). It includes a thumbnail image of a waveform plot. The description states: 'Files to accompany the webinar: 'Modeling Systems with Multilevel Converters in MATLAB and Simulink''. The item has 2 ratings (represented by five stars), 31 downloads, and was updated on 15 Mar 2021. There are links for 'View Version History' and 'View License'. Action buttons for '+ Follow' and 'Download' are located at the bottom right of the item details.

Below the item details, there are tabs for 'Overview', 'Functions', and 'Models'. The 'Overview' tab is active, displaying the following text:

We demonstrate how MathWorks tools may be used to model and simulate systems containing multilevel converter technology. A modular multilevel converter example will be used to explore the following topics,

- Build models of multilevel converters programatically from base components
- Use configurable subsystems to switch between different converter architectures
- Analyze pulse-width modulation (PWM) harmonic signatures to verify the correctness of the models
- Simulate different operational scenarios to test control system operation
- HVDC power transfer
- PMSM generation control
- Automate report generation to record the output of simulation studies

For more information on MathWorks solutions for Power Electronics Control Design, please visit this link <https://www.mathworks.com/solutions/power-electronics-control.html>

On the right side of the overview, there are sections for 'Requires' (MATLAB, Simulink, Simscape, Simscape Electrical), 'MATLAB Release Compatibility' (Created with R2015a, Compatible with any release), and 'Platform Compatibility' (Windows, macOS, Linux).

<https://www.mathworks.com/matlabcentral/fileexchange/51198-modeling-systems-with-multilevel-converters-in-simscape>

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Thank you



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