

MATLAB EXPO

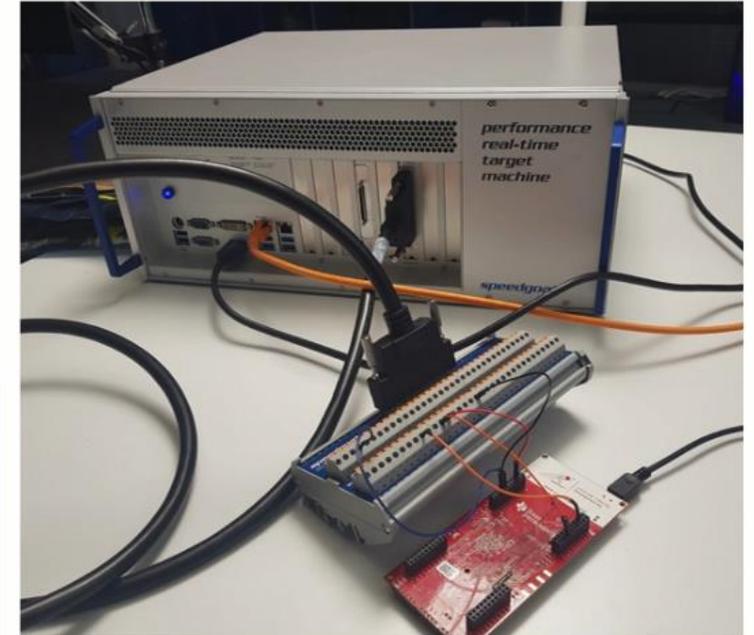
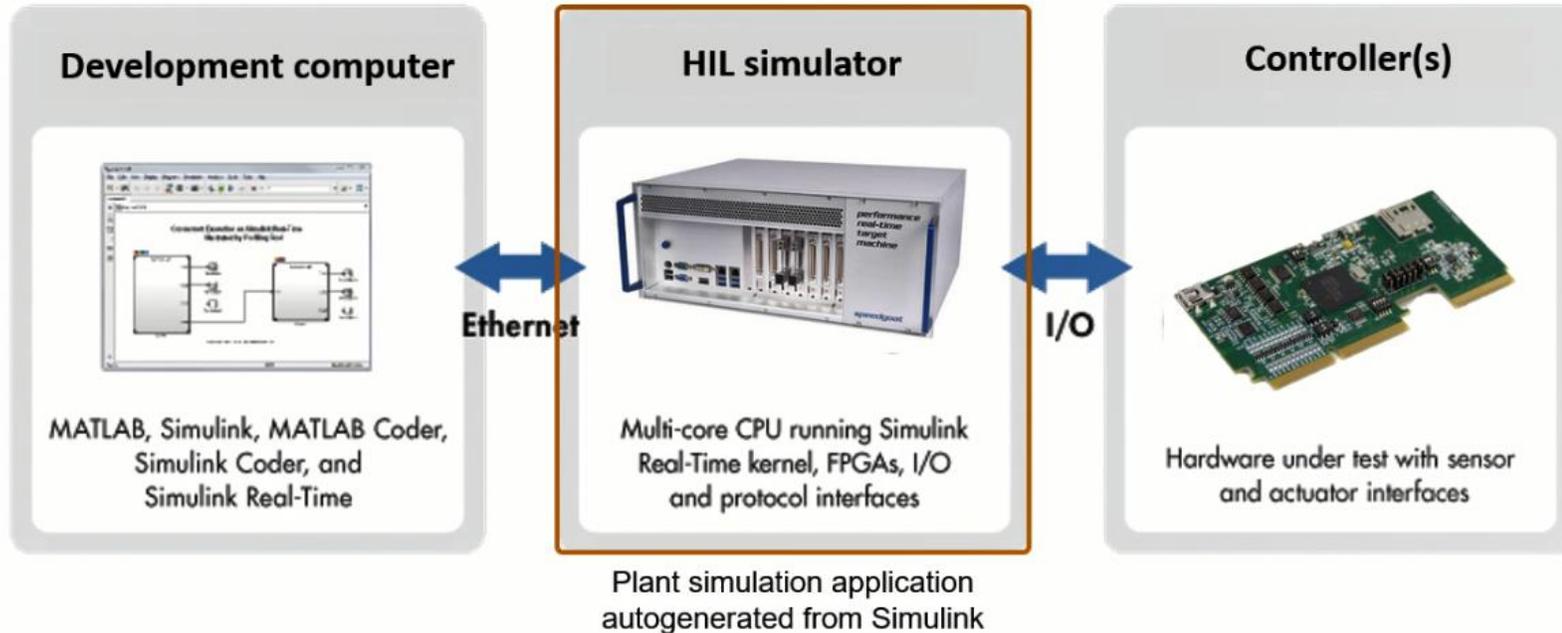
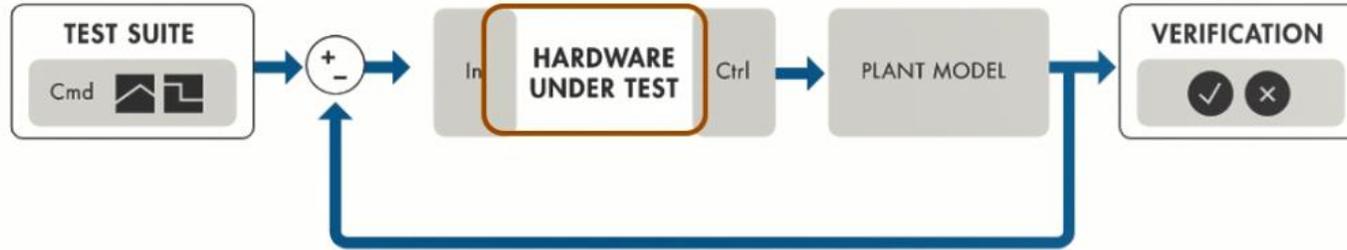
2021

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

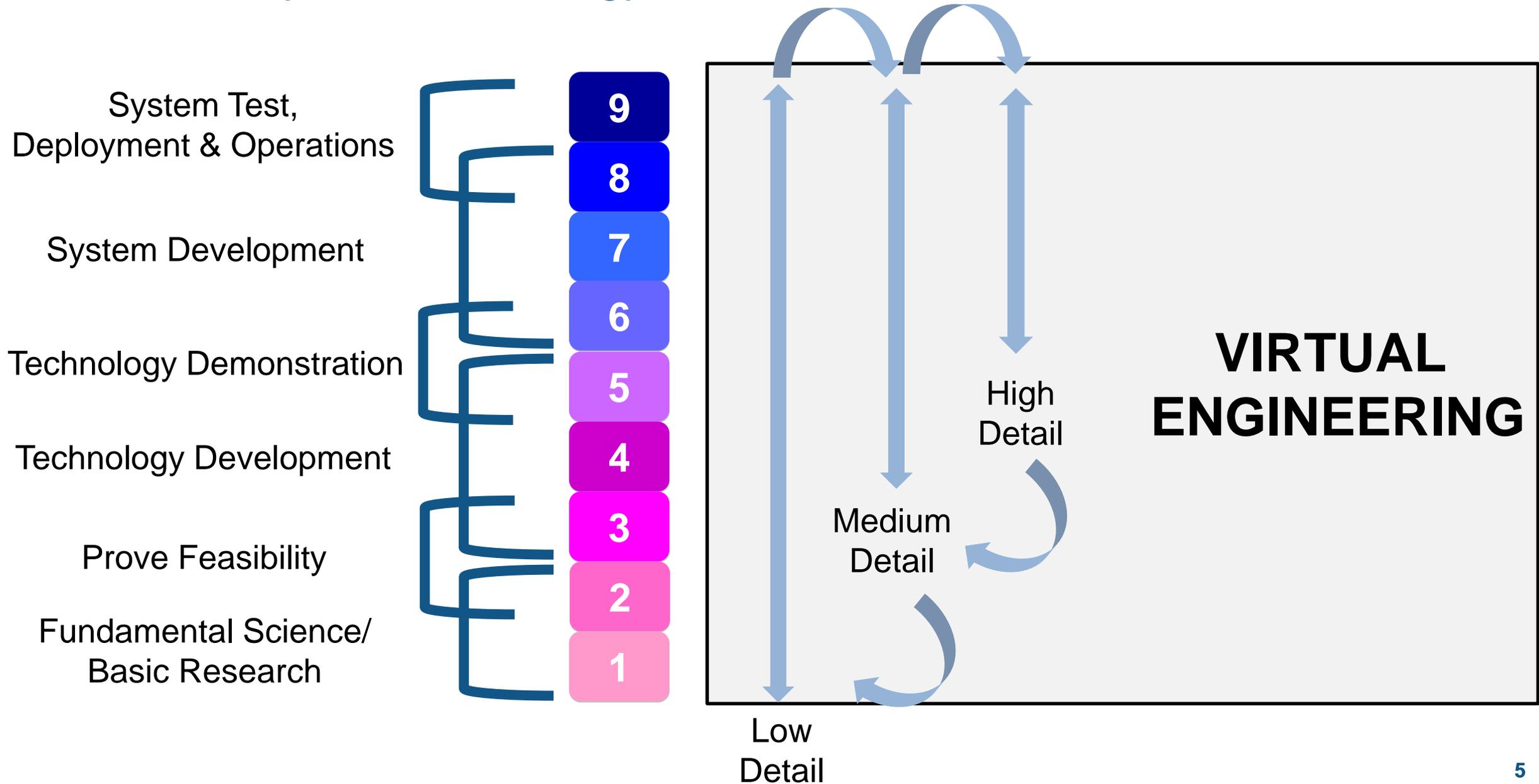
- A MathWorks associate company, incorporated in 2006 by former MathWorks employees. Headquarters in Switzerland, with subsidiaries in the USA and Germany
- Provider of real-time target computers, expressly designed for use with Simulink
- Real-time core team of around 200 people within MathWorks and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



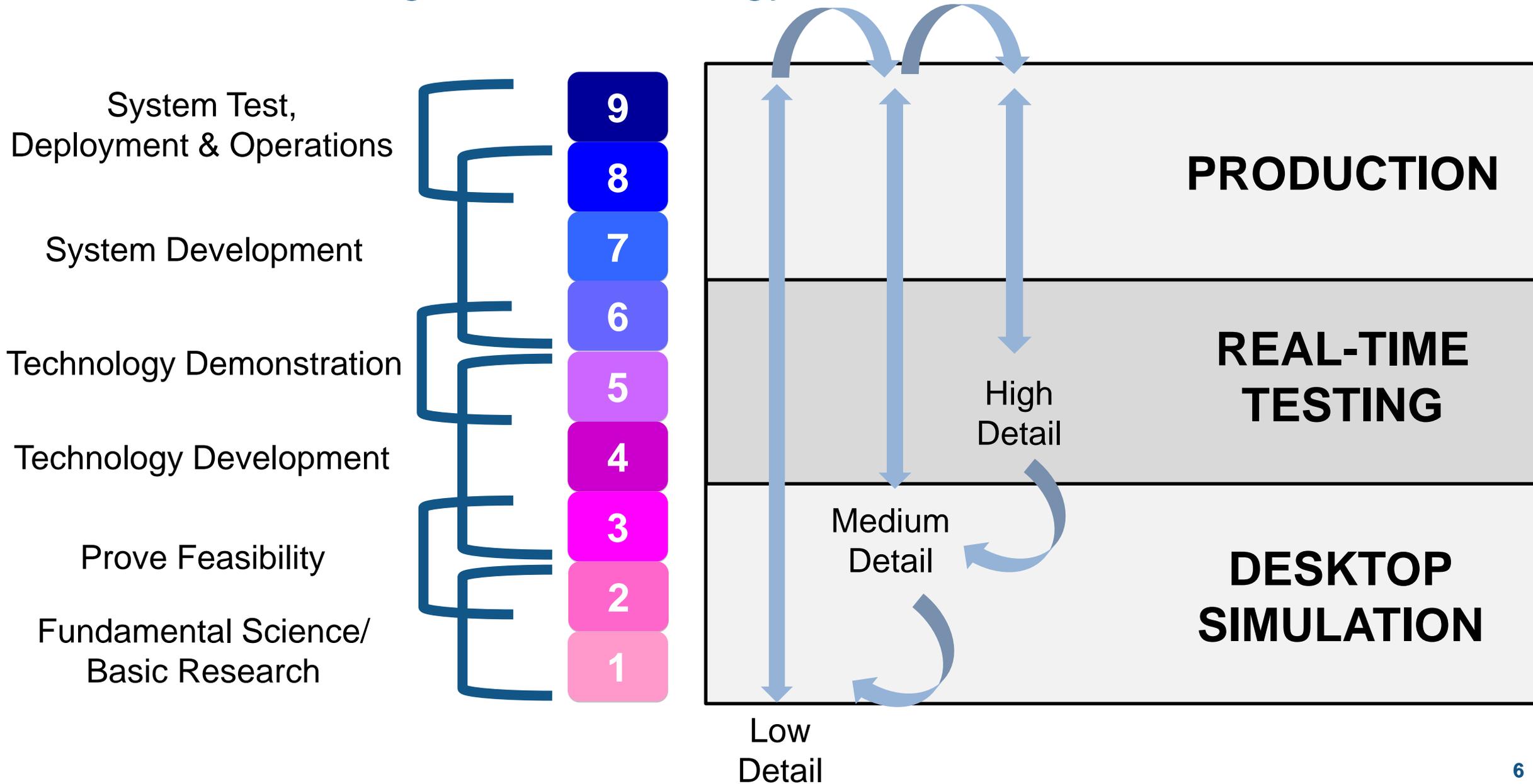
Problem Statement

- 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



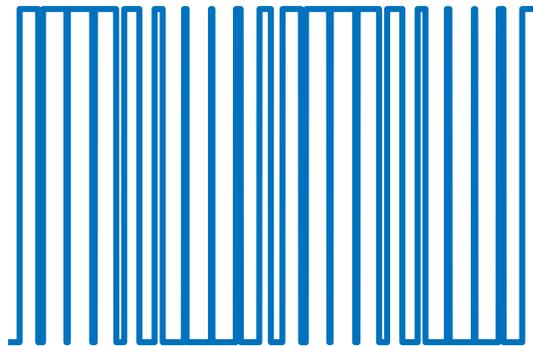
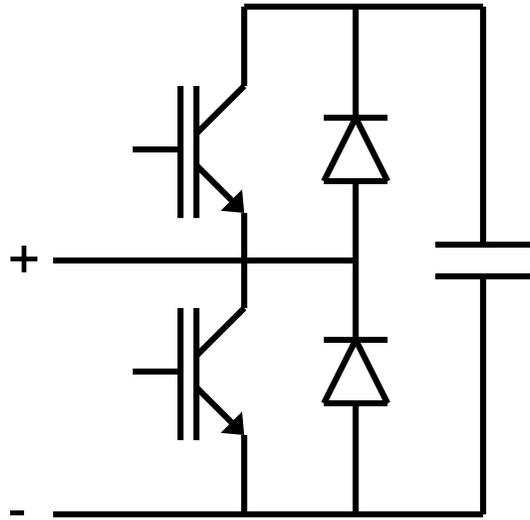
Alstom Grid's HVDC demonstrator system with power converter modules. The improved controllability of the VSC in this system makes it well-suited for smart grid applications.

“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.”

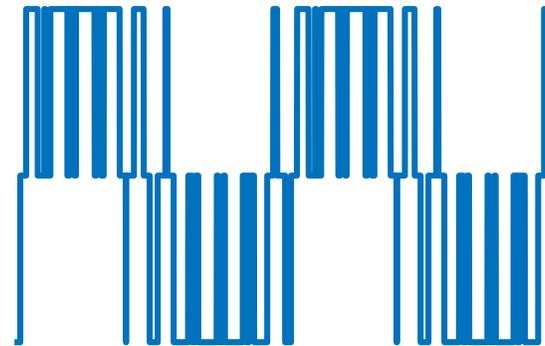
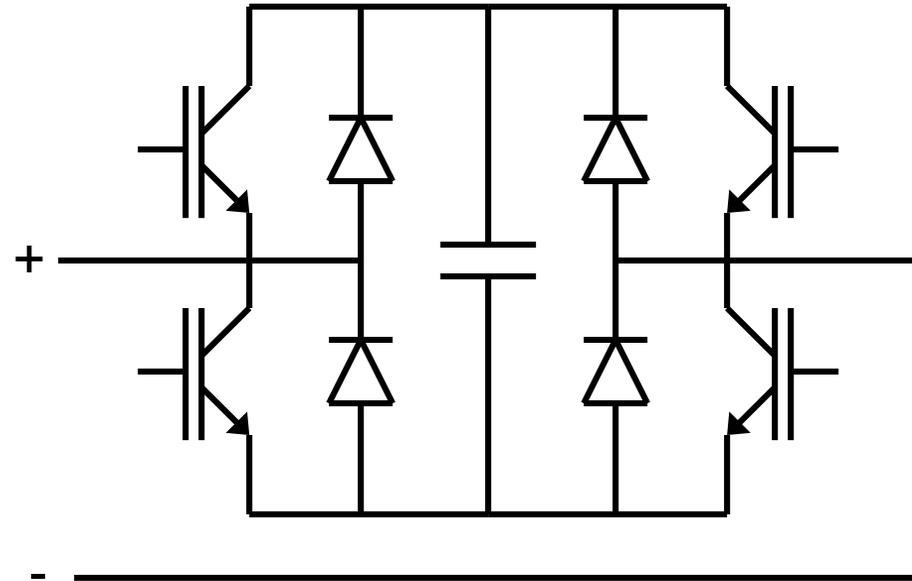
- Anthony Totterdell, Alstom Grid

Converter Submodules (SM)

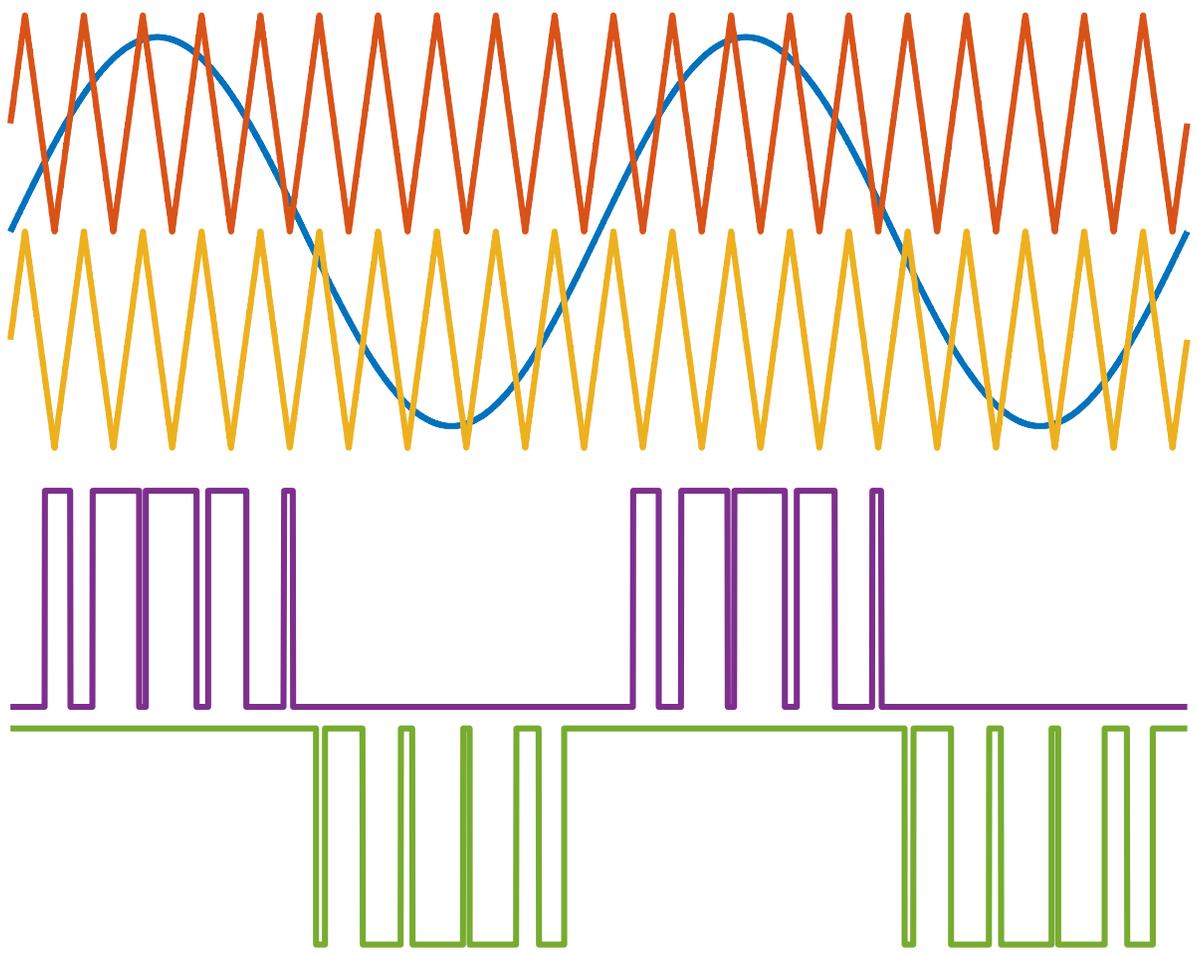
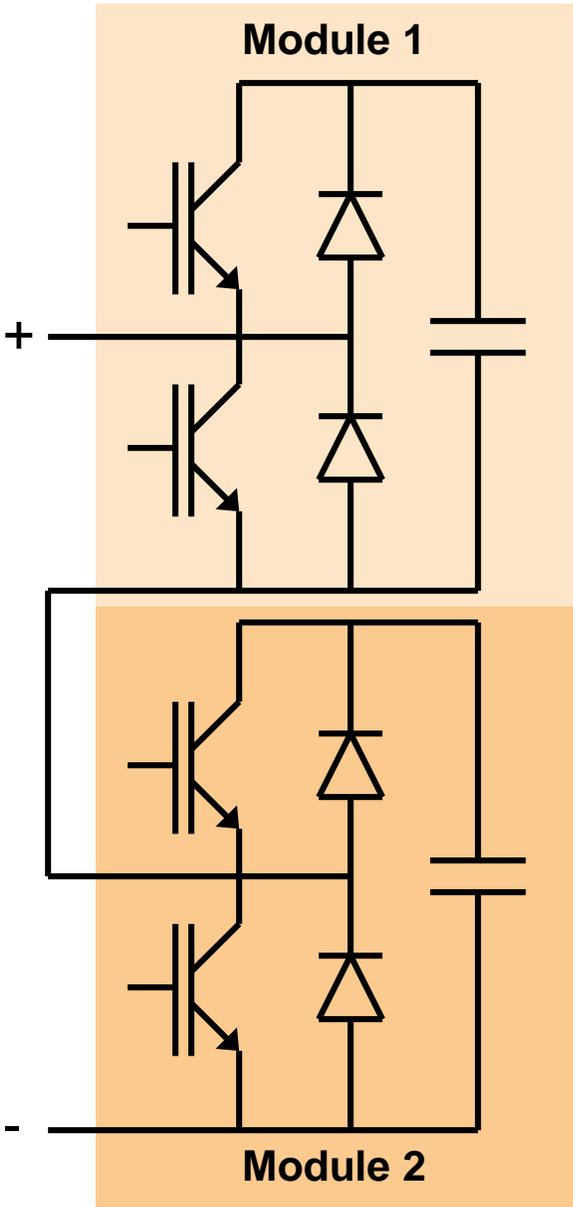
Half-Bridge



Full-Bridge



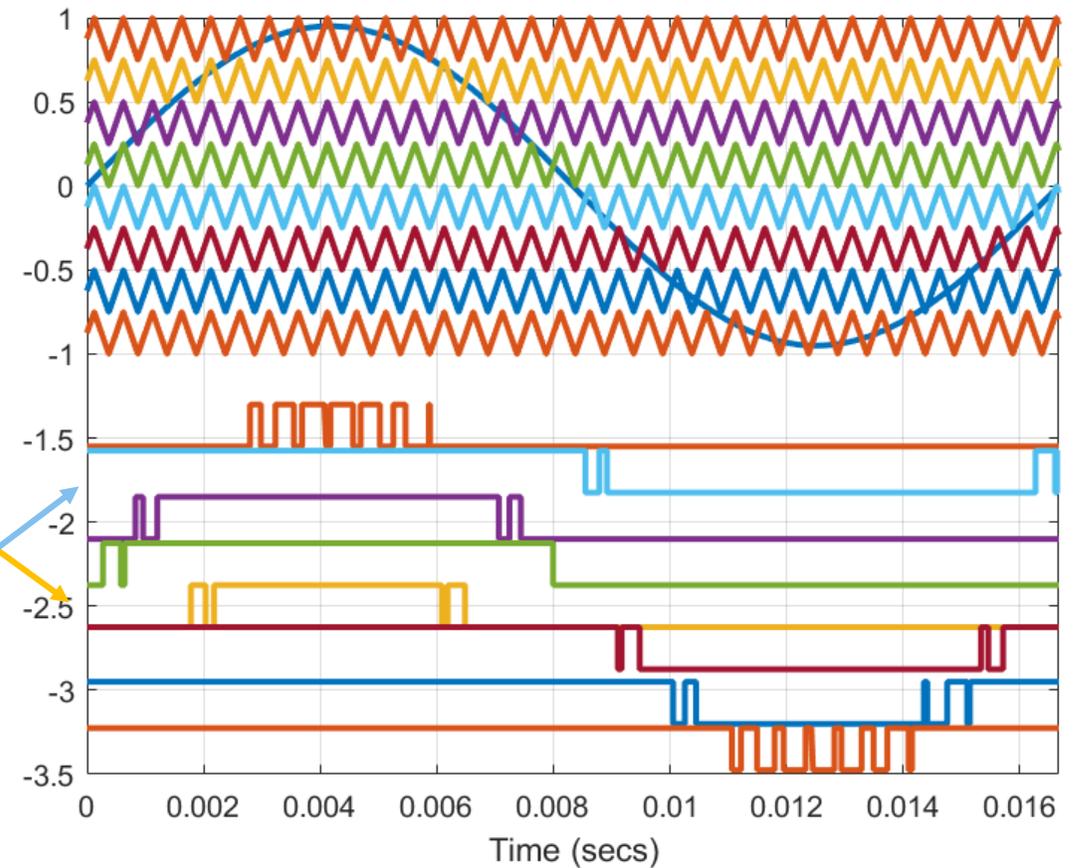
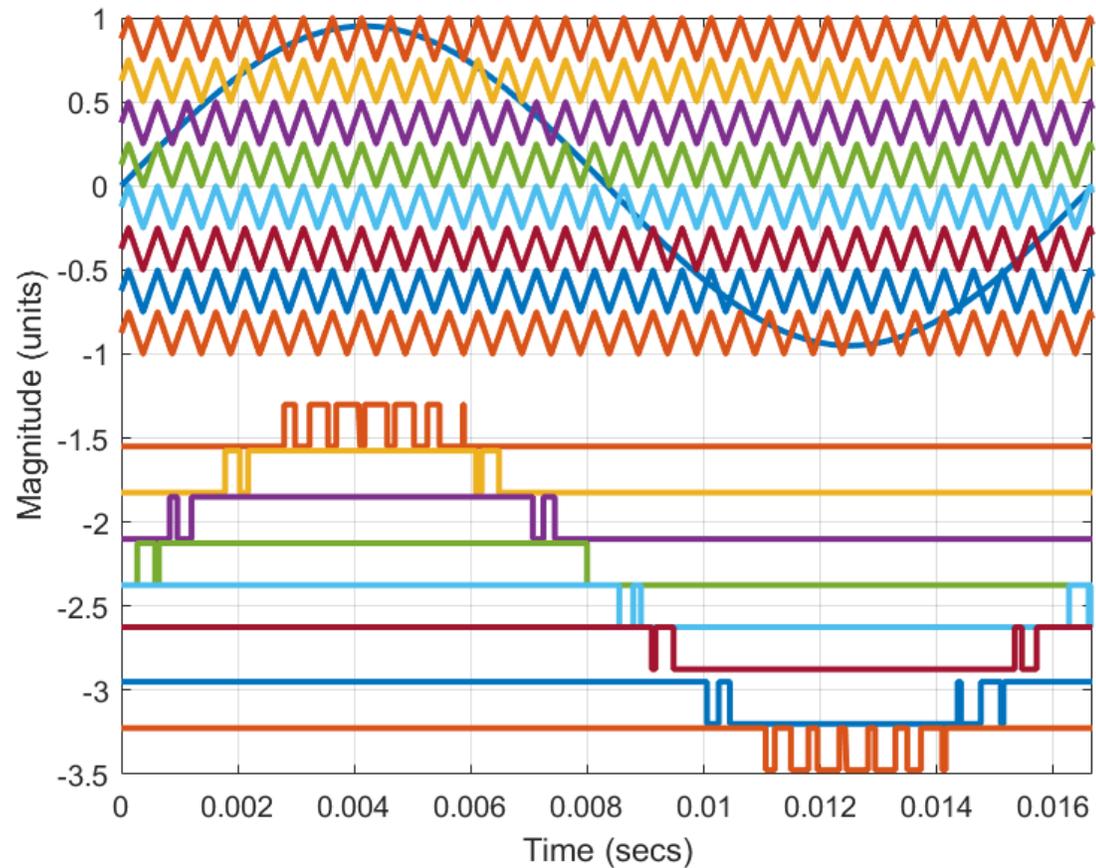
Modular Topology



Sorting and Signal Disposition

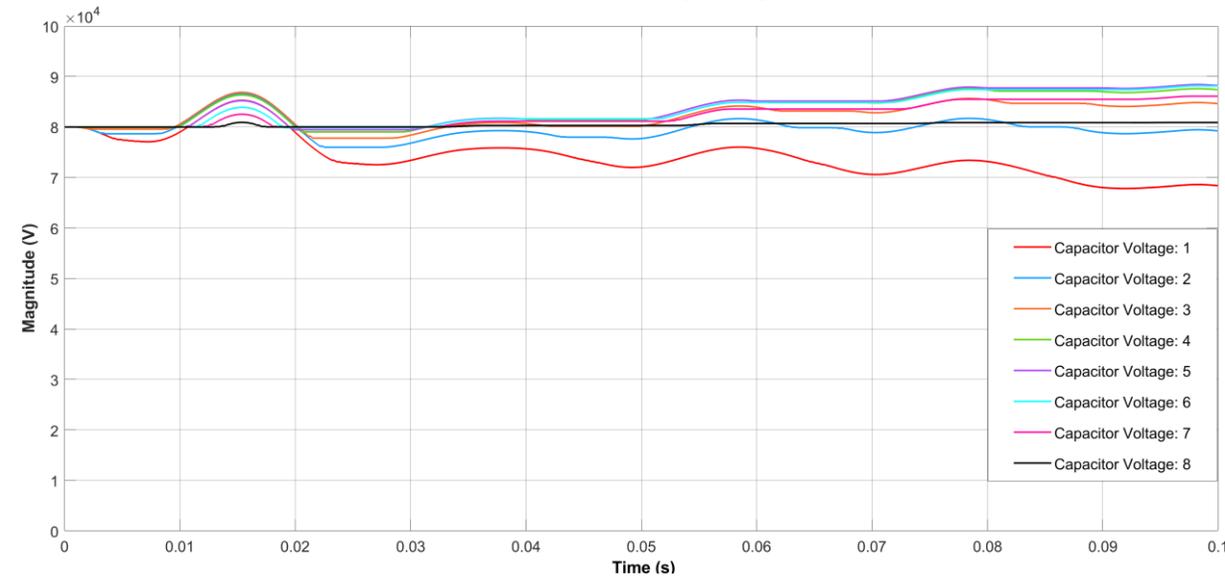
For the entire fundamental cycle assume:

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

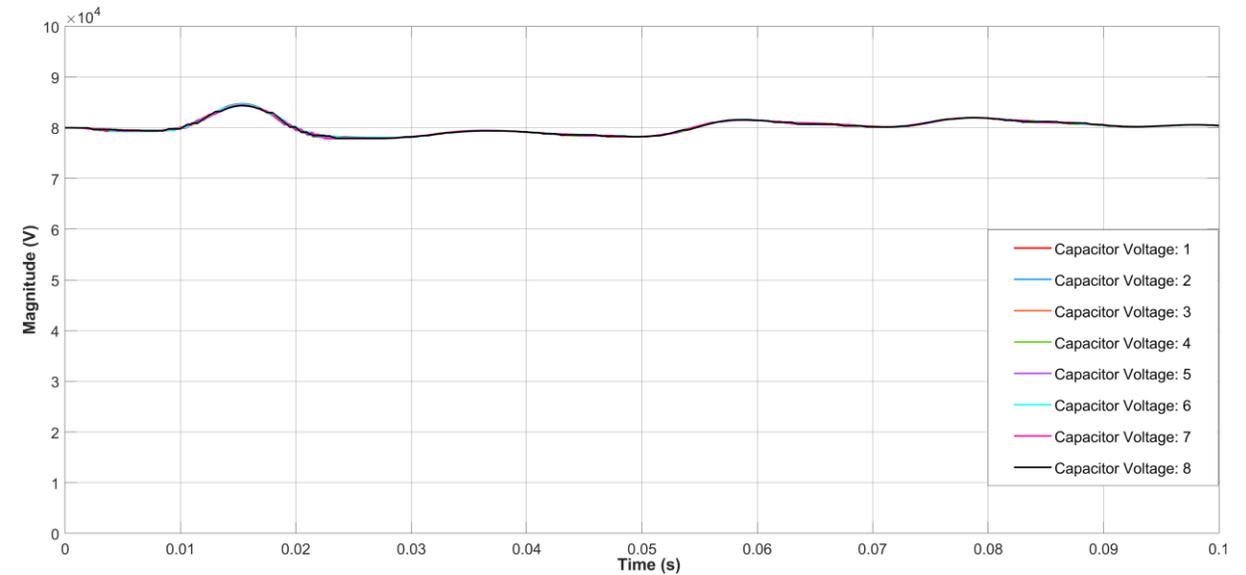


Sorting and Signal Disposition

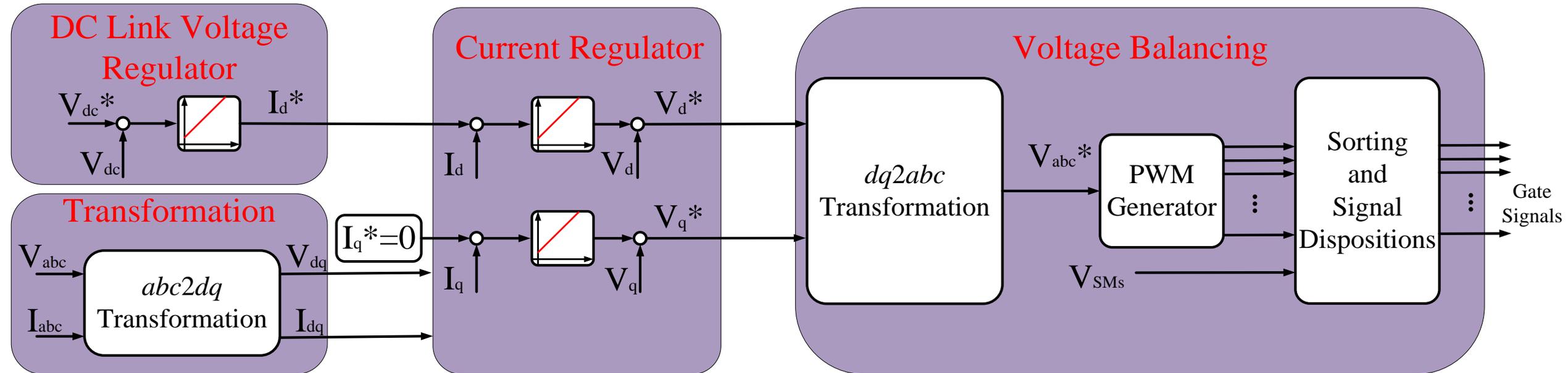
Capacitor Voltages for one arm of the converter
before sorting algorithm



Capacitor Voltages for one arm of the converter
after sorting algorithm

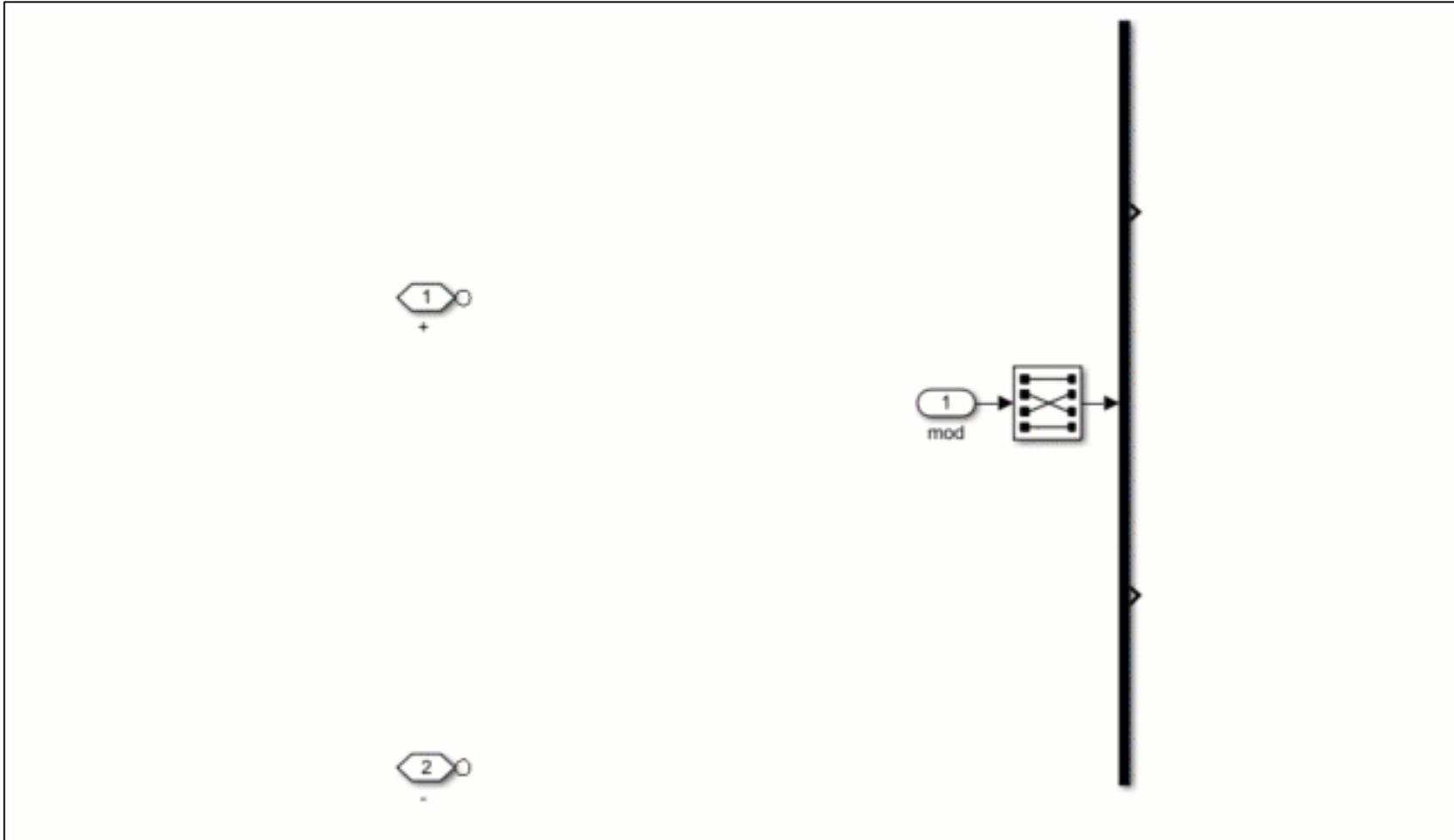


Control Algorithm

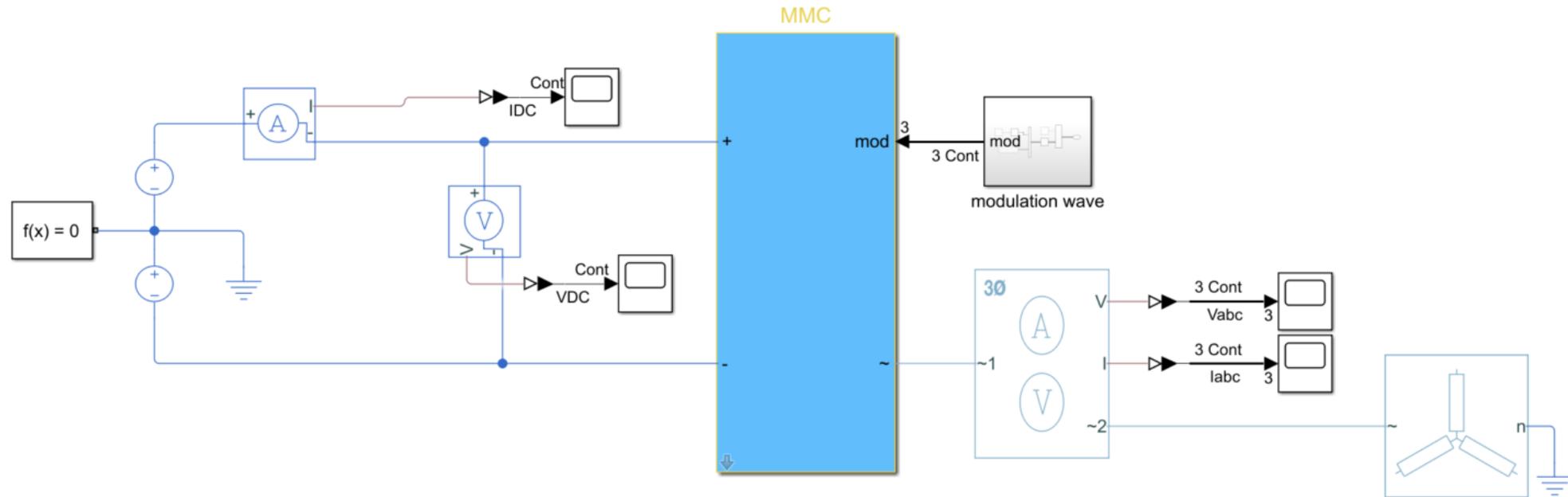


Build MMCs Programmatically

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

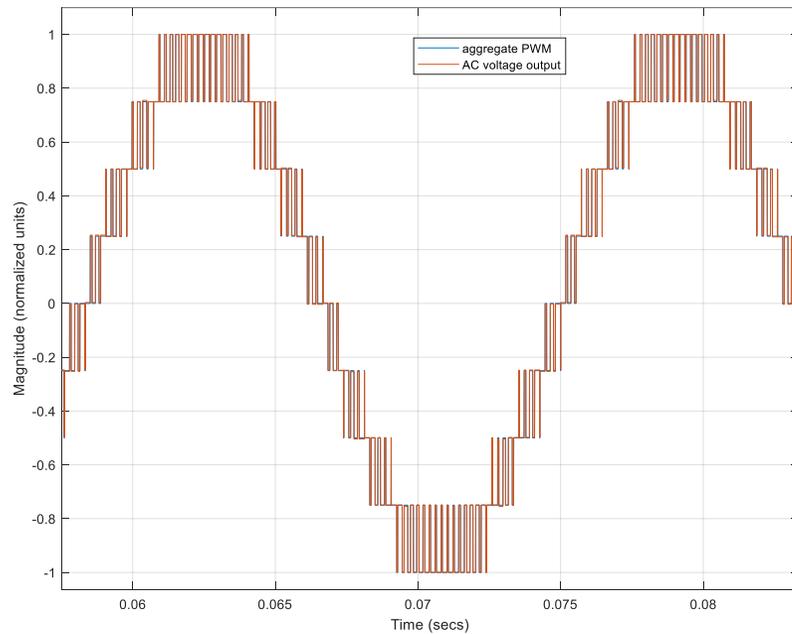


Desktop Simulation and Simulink Online

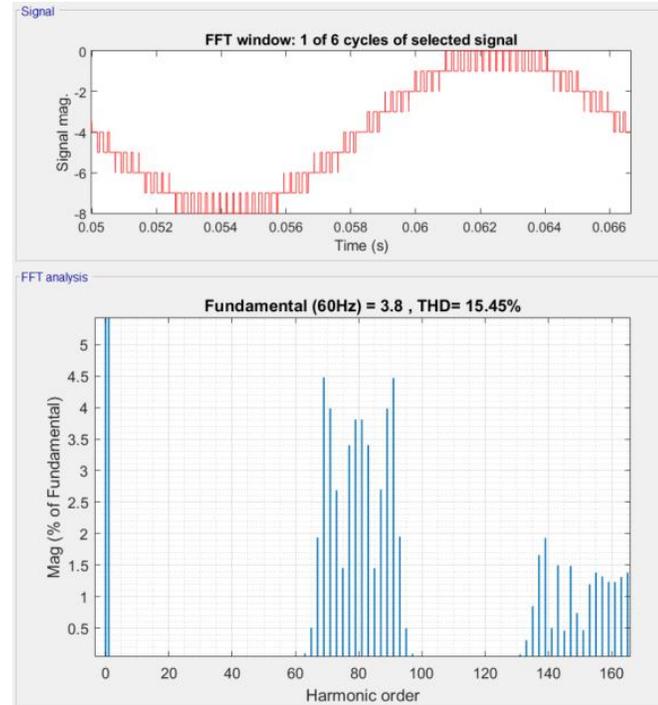


Desktop Simulation and Simulink Online

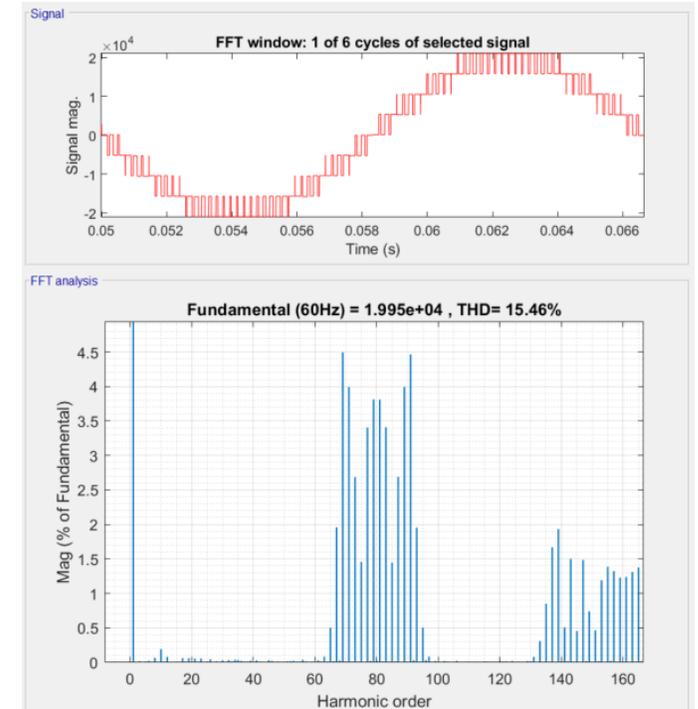
- After running a simulation, we compare the 'aggregate' PWM signal and the AC voltage output. A visual comparison is a good step, but a more rigorous evaluation is to compare the harmonics of the signals. With a stylized test-harness, we expect to see 'clean' waveforms and 'clean' harmonic profiles.



(a) Aggregate PWM and AC voltage output overlaid



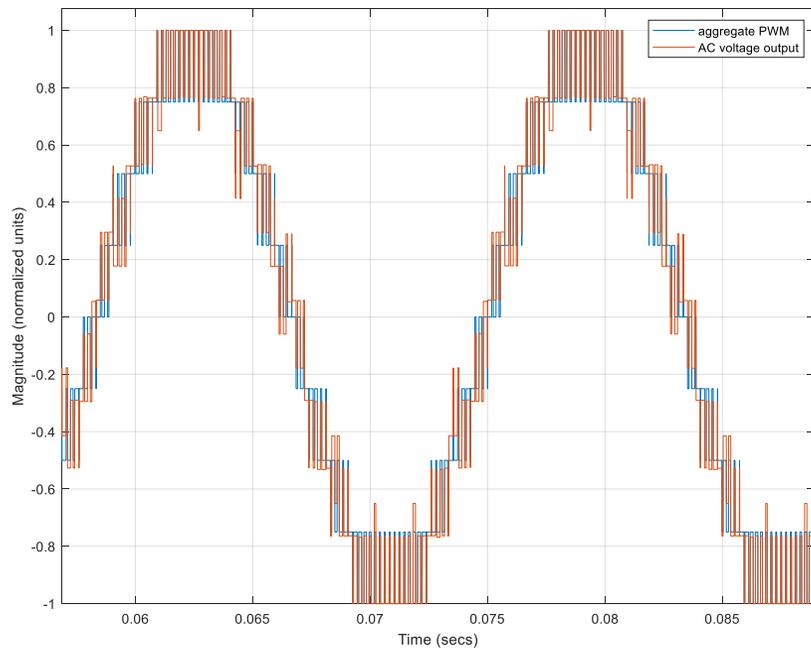
(b) Harmonic analysis of aggregate PWM



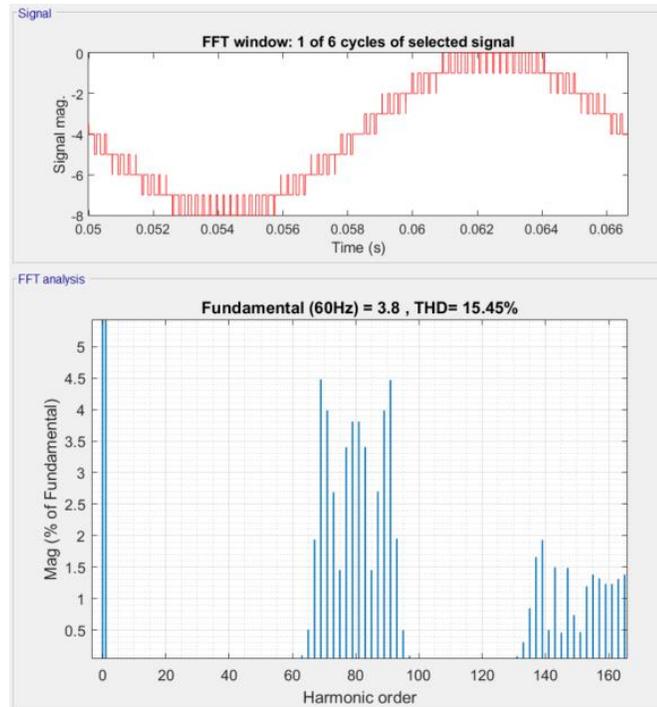
(c) Harmonic analysis of AC voltage output

Desktop Simulation and Simulink Online

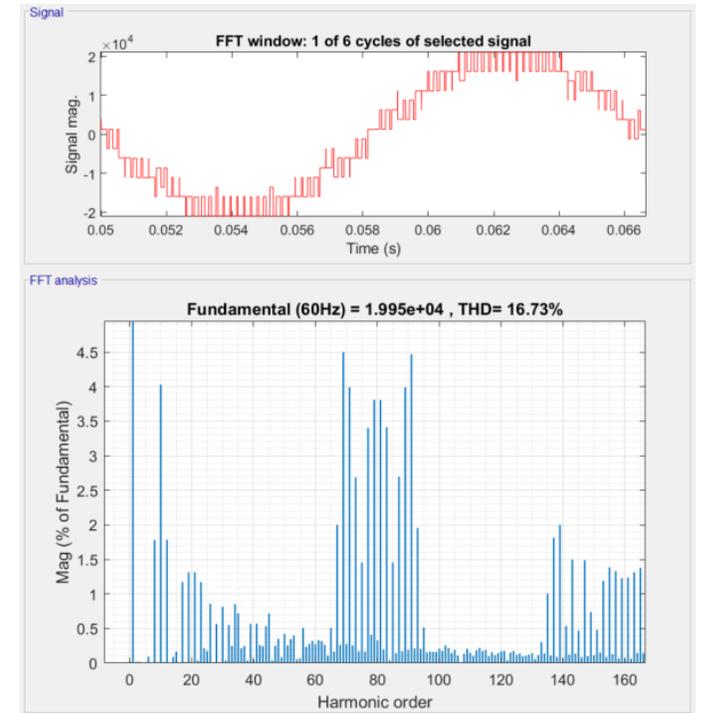
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(a) Aggregate PWM and AC voltage output overlaid



(b) Harmonic analysis of aggregate PWM



(c) Harmonic analysis of AC voltage output

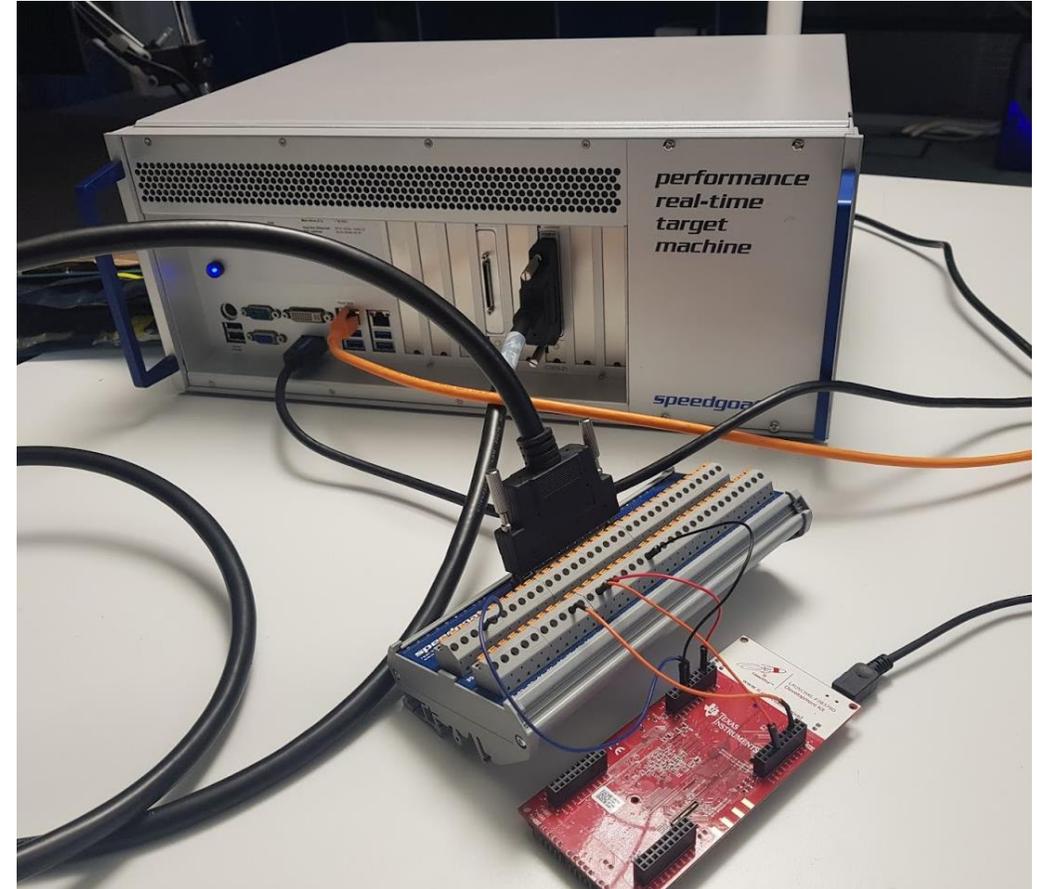
Desktop Simulation and Simulink Online

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:

- Navigation and Tools:** Includes tabs for HOME, PLOTS, and APPS, along with a search bar and user profile (Graham).
- File Explorer:** Shows the current folder structure, including files like `initParams.mat`, `MMC_8_PSPWM_test.slx`, and `MMC_8_PSPWM_test.sxc`.
- Workspace:** Lists variables: `Ts` (5.0000e-05, double), and `Vdc` (41000, double).
- Simulink Model:** The central focus is the `MMC_8_PSPWM_test` Simulink model. It features:
 - Simulation Controls:** Stop Time (5/60), Accelerator, Step Back, Run, Step Forward, and Stop buttons.
 - Model Components:** A block diagram showing a current source `f(x) = 0`, an ammeter (A), a voltmeter (V), a modulation block (`mod`), a modulation block (`modulation`), a current/voltage measurement block (30 A, -1 V), and a continuous block (`Continuous`).
 - Output:** Signals `vabc` and `iabc` are shown, along with a three-phase circuit diagram.
- Property Inspector:** Located on the right side of the Simulink window.

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 and Capacitor:** L and C blocks representing the motor's inductance and the DC link capacitor.

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.

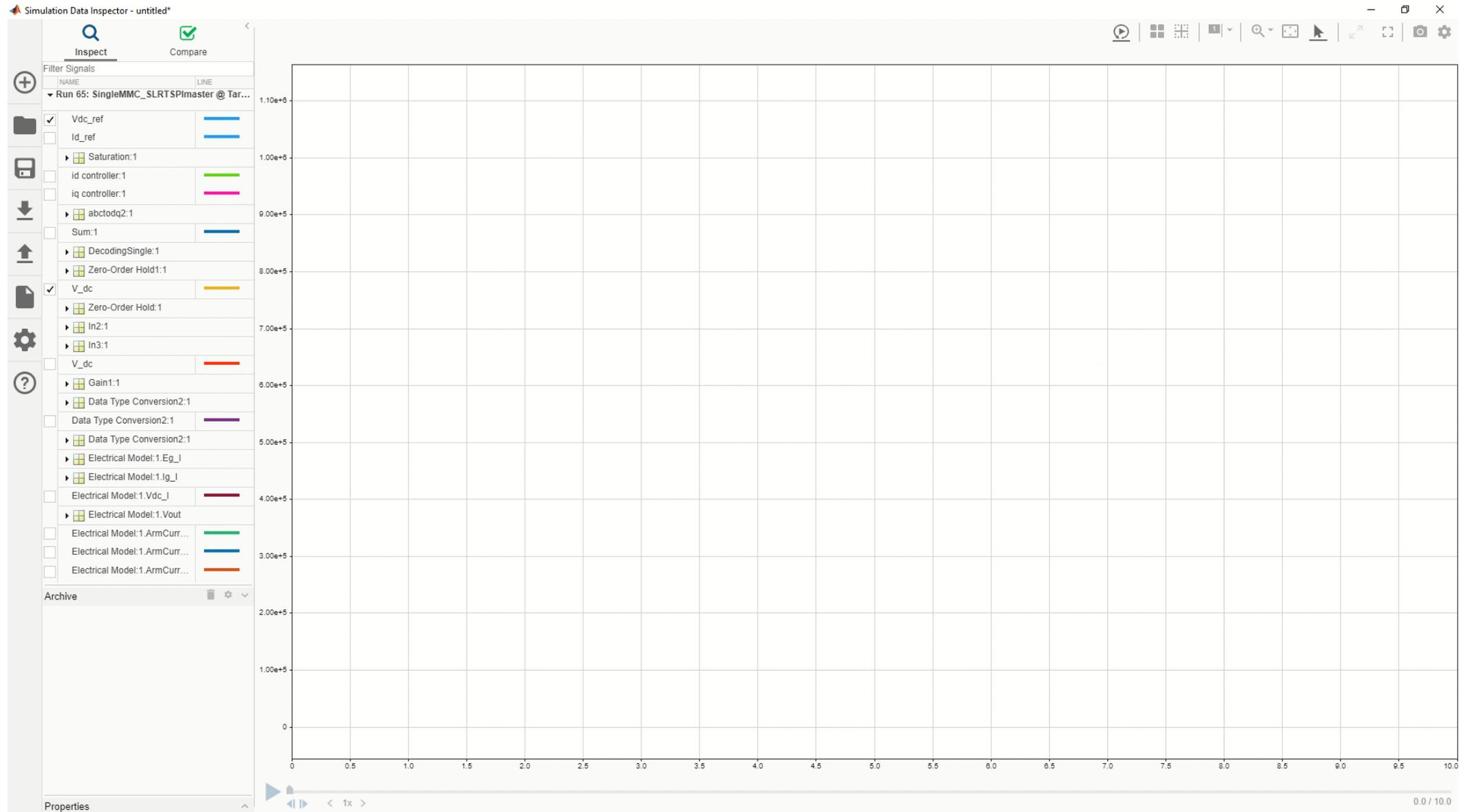
Configure and run model in real-time on Speedgoat

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.
- 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' is open. The workspace shows a table of variables:
- 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	[0.0,0.1250,0.2500,0.375...
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
- Git:** Shows 'Current branch: master', 'Branch status: Normal', and 'Coincident with /origin/master'.
- Command Window:** Shows the MATLAB prompt 'fx >>' with a cursor.

Configure and run model in real-time on Speedgoat



Generate Embedded Application on TI C2000 Microcontroller

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

- SPI outputs:** A block on the left that receives a signal of 5 and outputs three signals: V_{dc} (int16), V_{ab} (int16 (2)), and V_{lab} (int16 (2)).
- control algorithm single:** A central block that receives the three signals from the SPI outputs and outputs a signal of 5 labeled **Controls**.
- SPI:** A block on the right that receives the **Controls** signal (int16 (5)) and outputs a signal of 5 labeled **int16 (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. The right sidebar contains a Timing Legend and a Property Inspector.

Discrete	Period
	100.0000e-006

Event	Asynchronous
	1

Other	Constant
	Multirate

Ready View 14 warnings 243% 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 various toolbars and panels. The "Hardware Board" dropdown is set to "TI Delfino F28379D LaunchPad". The "Stop Time" is set to 8. The "Model Browser" on the left shows a tree view of the model. The "Timing Legend" on the right shows a table of timing parameters:

Discrete	Period
	100.0000e-006
	Asynchronous 1
	Constant
	Multirate

The "Property Inspector" on the right shows the "int16 (5)" block with a value of 1. 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 target. 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
    
```

Below the diagnostic viewer, a Simulink block diagram titled "SPI Master transfer" is visible. The diagram shows a data flow from an input port (int16 (5)) through a "Byte Pack" block to an "SPI Transmit" block (Slave select: SPISTE). The output of the SPI Transmit block is connected to an "SPI Receive" block (Slave select: SPISTE), which then feeds into a "Byte Unpack" block. The final output is an int16 (5) signal.

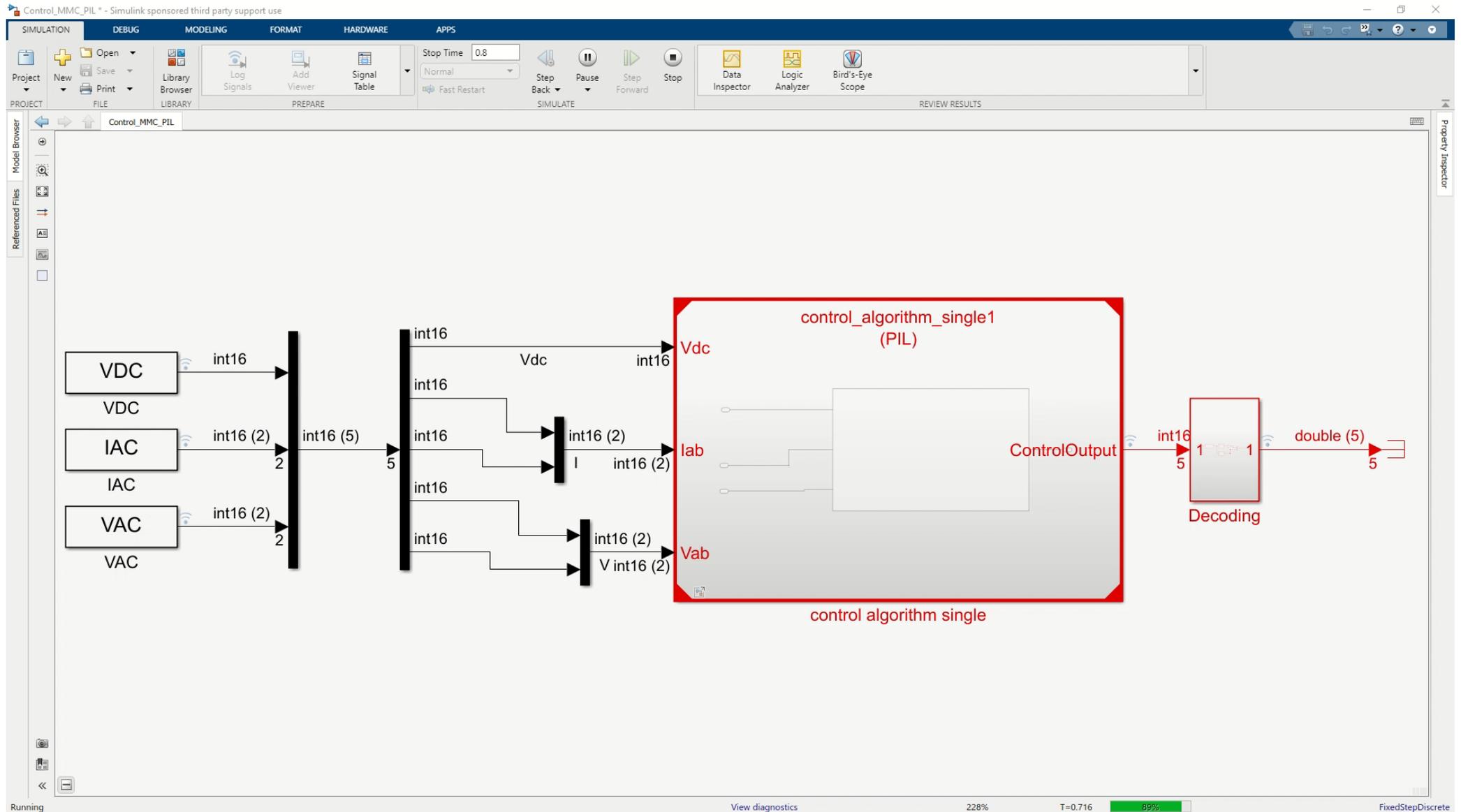
Processor-In-the-Loop (PIL) Testing

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:

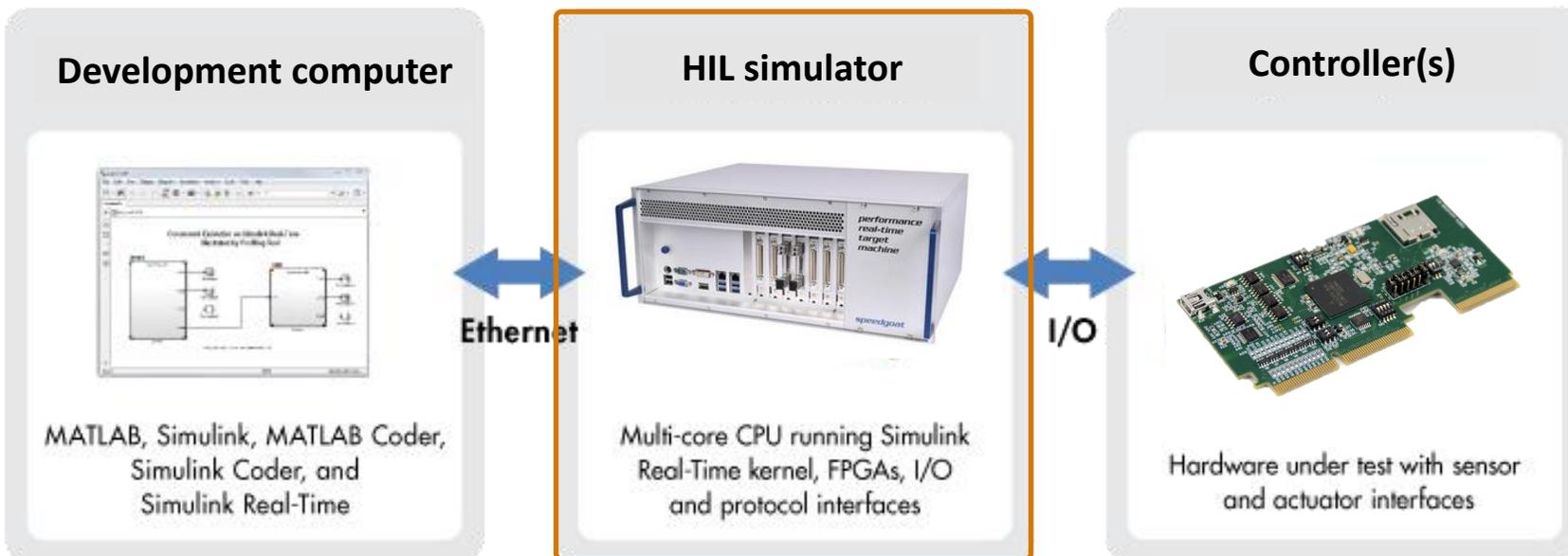
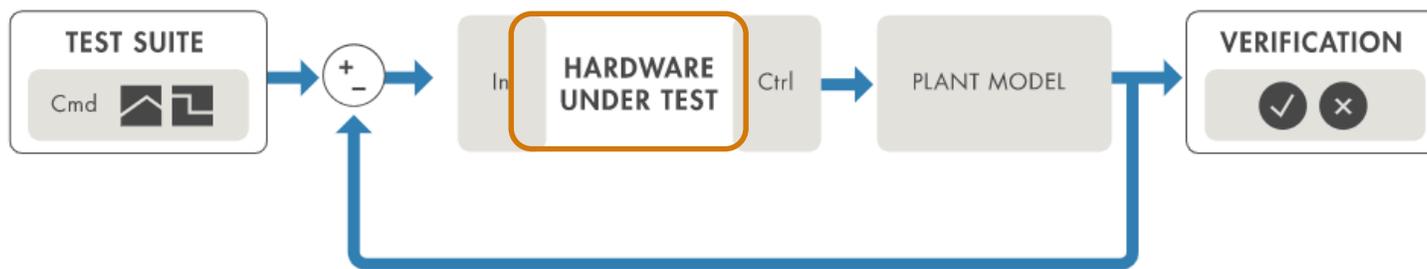
- Input Blocks:** VDC, IAC, and VAC, each with a 'Vdc' or 'Vab' label and an 'int16' data type.
- Signal Processing:** A series of multiplexers and signal lines connecting the inputs to a central block.
- Central Block:** A block with three outputs labeled 'Vdc', 'I', and 'V'. It is highlighted with a red border, and a context menu is open over it.
- Output Block:** A 'Decoding' block that takes an 'int16' signal and outputs a 'double (5)' signal.

The context menu is open, showing options such as 'Explore', 'Cut', 'Copy', 'Paste', 'Delete', 'Format', 'Mask', 'Model Slicer', and 'Block Parameters (ModelReference)'. The 'Block Parameters (ModelReference)' option is currently selected.

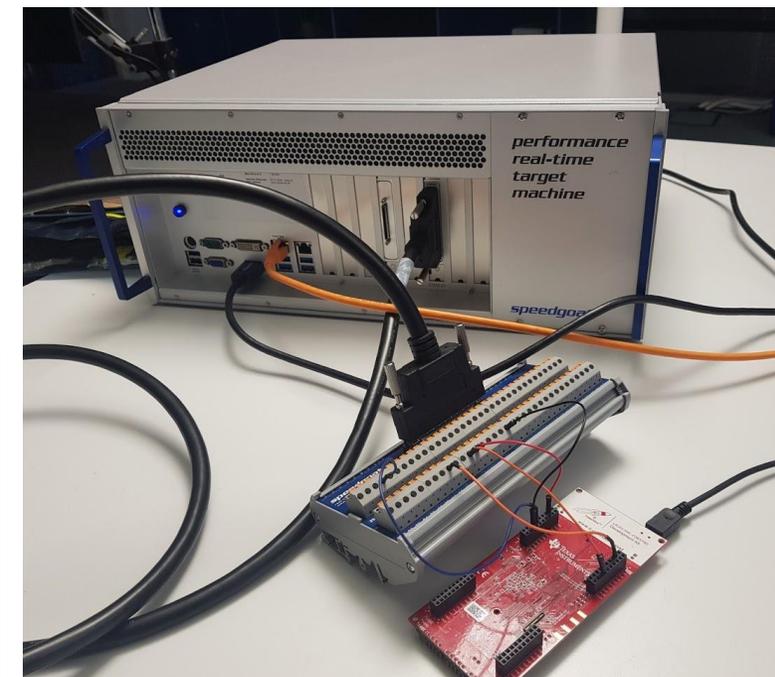
Processor-In-the-Loop (PIL) Testing



Hardware-in-the-Loop Simulation



Plant simulation application autogenerated from Simulink

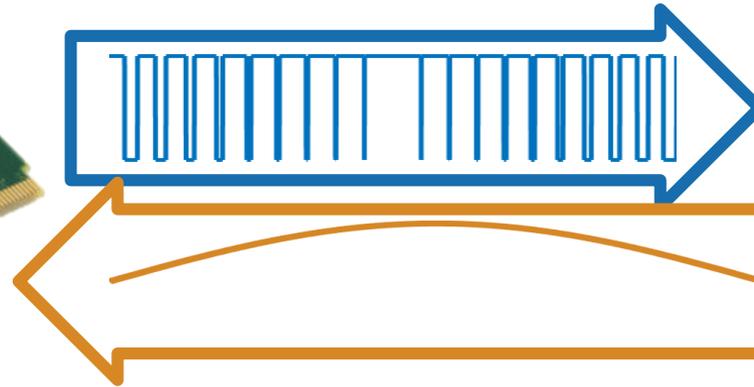


Advantages of Hardware in the Loop (HIL) Testing

- 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

Property Inspector

Current Controller

Parameters Properties Info Execution

HIL

Script Reference

Timing Legend

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

Continuous	
Cont.	Continuous

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

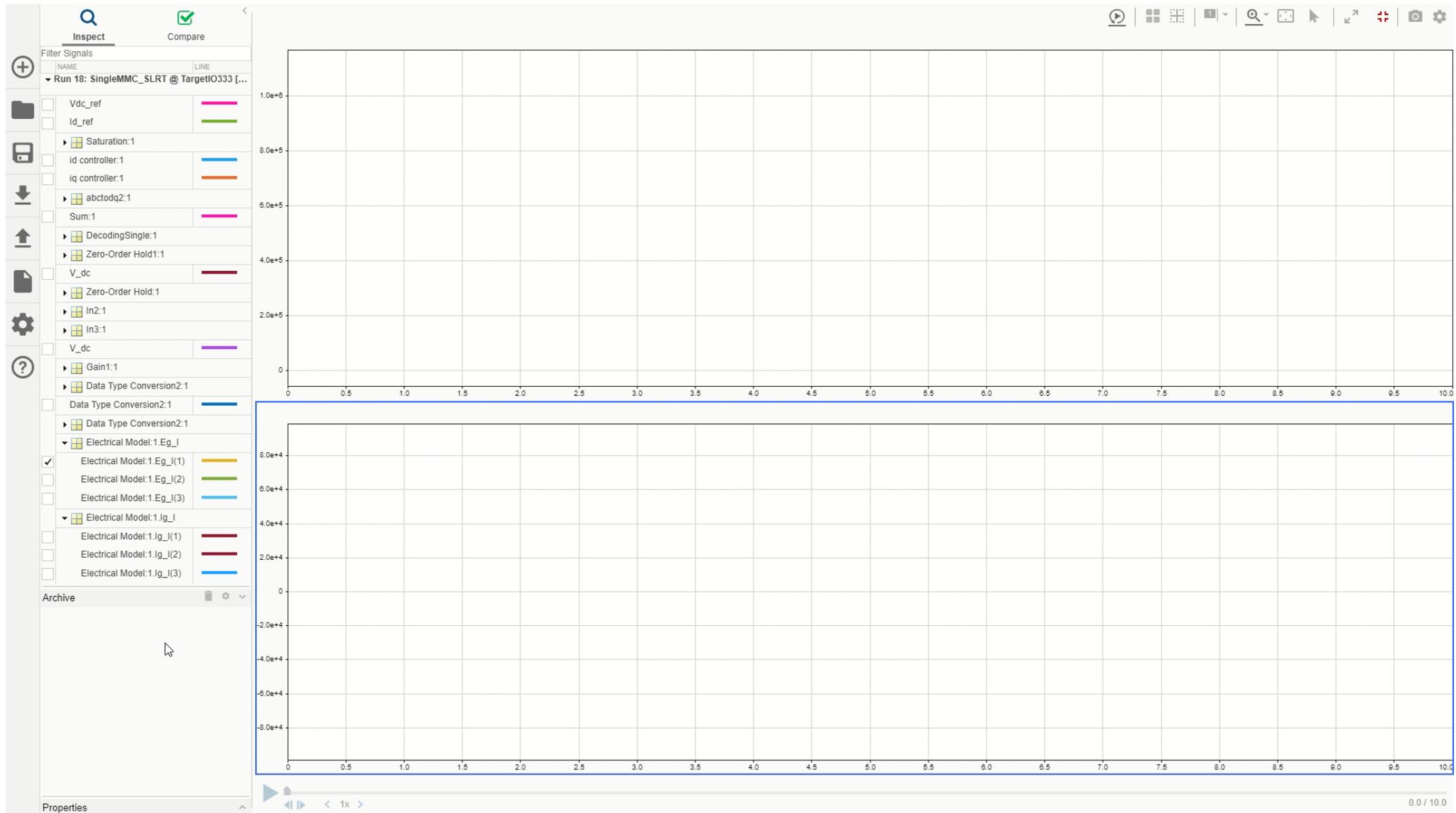
Ready View 3 warnings 74% FixedStepDiscrete

Hardware-in-the-Loop Simulation

The screenshot displays the MATLAB R2020b interface for a project named 'Project - MMC_Christoph'. The workspace contains several files and folders, including 'Data', 'Documentation', 'helpers', 'Scripts', and 'SimulinkModels'. A 'Dependency Analyzer' is visible, showing the project's structure. The 'Workspace' window on the right lists various variables and their values, such as 'alpha_f' (100), 'C' (0.0200), and 'num_sm' (8). The 'Command Window' at the bottom shows a prompt 'fx >>'.

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

Hardware-in-the-Loop Simulation



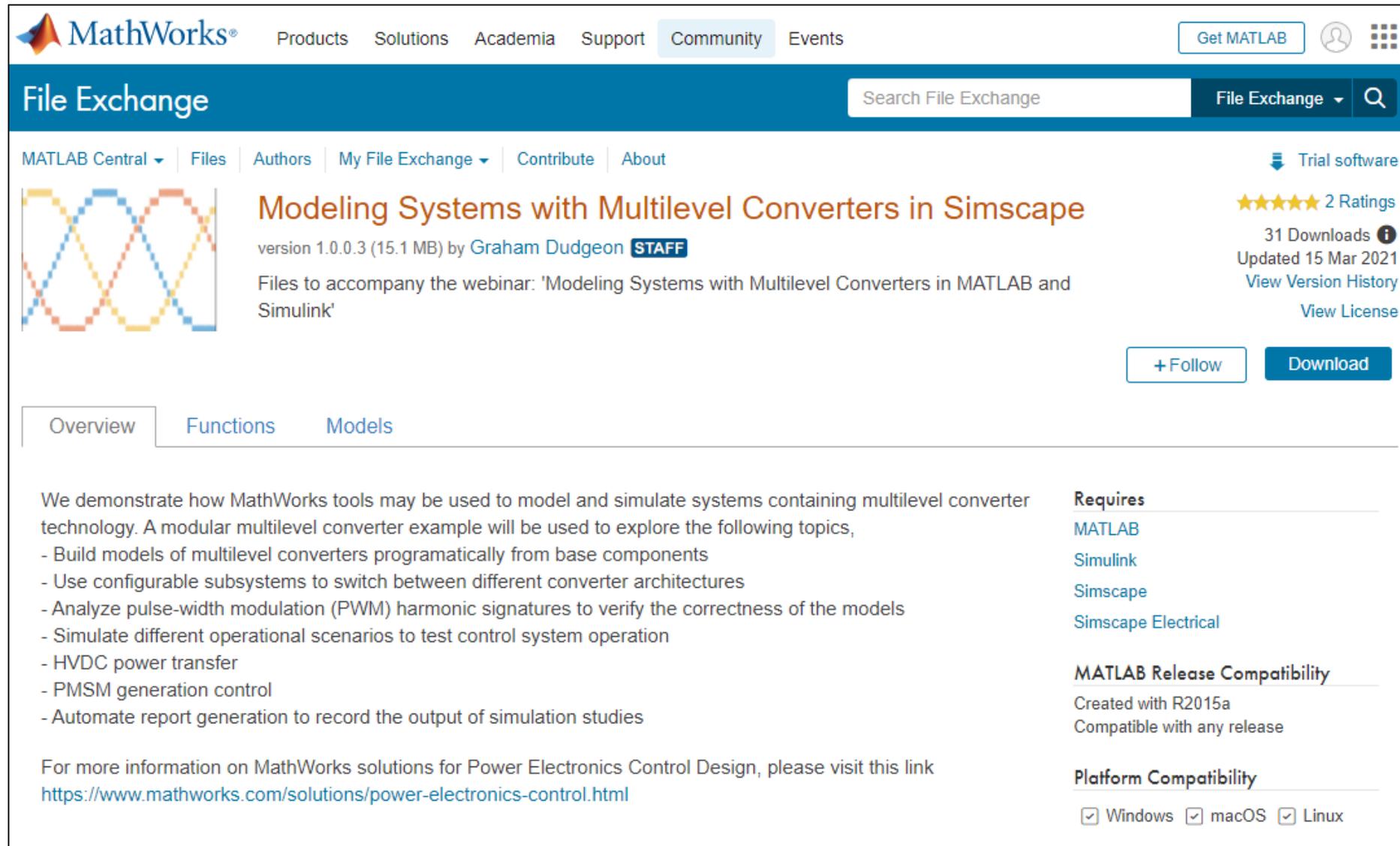
Hardware-in-the-Loop Simulation



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's a navigation bar with 'MathWorks' logo and links for Products, Solutions, Academia, Support, Community, and Events. A 'Get MATLAB' button and user profile icons are on the right. Below this is a 'File Exchange' header with a search bar and a dropdown menu. The main content area features a card for a file titled 'Modeling Systems with Multilevel Converters in Simscape' by Graham Dudgeon (STAFF). The card includes a thumbnail image of a waveform, the version number (1.0.0.3, 15.1 MB), and a description: 'Files to accompany the webinar: 'Modeling Systems with Multilevel Converters in MATLAB and Simulink''. On the right side of the card, there are statistics: 'Trial software', '5 stars 2 Ratings', '31 Downloads', and 'Updated 15 Mar 2021'. There are buttons for '+ Follow' and 'Download'. Below the card, there are tabs for 'Overview', 'Functions', and 'Models'. The 'Overview' tab is active, showing a detailed description of the file's purpose and a list of topics to be covered. To the right of the description, 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).

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Overview Functions Models

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>

Requires
 MATLAB
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