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

Development computer
- MATLAB, Simulink, MATLAB Coder, Simulink Coder, and Simulink Real-Time

HIL simulator
- Multi-core CPU running Simulink Real-Time kernel, FPGAs, I/O and protocol interfaces
- Plant simulation application autogenerated from Simulink

Controller(s)
- Hardware under test with sensor and actuator interfaces
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

- Fundamental Science/Basic Research: 1
- Prove Feasibility: 2
- Technology Development: 3
- Technology Demonstration: 4
- System Development: 5
- System Test, Deployment & Operations: 6
- Medium Detail: 7
- High Detail: 8, 9

VIRTUAL ENGINEERING

Low Detail
Medium Detail
High Detail
Model-Based Design and Technology Readiness

System Test, Deployment & Operations
- 9
- 8
- 7
- 6
- 5
- 4
- 3
- 2
- 1

System Development
- Fundamental Science/Basic Research
  - Prove Feasibility
  - Technology Development

Technology Demonstration
- Technology Development
- Prove Feasibility
- Technology Demonstration

REAL-TIME TESTING
- High Detail
- Medium Detail
- Low Detail

DESKTOP SIMULATION

PRODUCTION
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

“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

Link to user story
Converter Submodules (SM)

Half-Bridge

Full-Bridge
Modular Topology

Module 1

Module 2

+  -

MATLAB EXPO
Sorting and Signal Disposition

For the entire fundamental cycle assume:

\[ Vc_1 < Vc_5 < Vc_3 < Vc_4 < Vc_2 < Vc_6 < Vc_7 < Vc_8 \]
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

DC Link Voltage Regulator

\[ V_{dc}^* \rightarrow I_d^* \rightarrow V_{dc} \]

Transformation

\[ abc \rightarrow dq \]

\[ V_{abc} \rightarrow V_{dq} \]

\[ I_{abc} \rightarrow I_{dq} \]

Current Regulator

\[ I_d \rightarrow V_d \rightarrow V_q^* \rightarrow I_q \]

\[ I_d^* = 0 \]

Voltage Balancing

\[ dq2abc \]

\[ V_{abc}^* \rightarrow PWM \]

Generator

Sorting and Signal Dispositions

\[ V_{SMs} \]

Gate Signals
Build MMCs Programmaticaly

- With MATLAB, we can use the Simulink API to build programmatically more complex power converter architectures.
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
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.
Desktop Simulation and Simulink Online
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
Configure and run model in real-time on Speedgoat
Configure and run model in real-time on Speedgoat
Generate Embedded Application on TI C2000 Microcontroller
Generate Embedded Application on TI C2000 Microcontroller
Generate Embedded Application on TI C2000 Microcontroller
Processor-In-the-Loop (PIL) Testing
Processor-In-the-Loop (PIL) Testing
Hardware-in-the-Loop Simulation

**Development computer**

- MATLAB, Simulink, MATLAB Coder, Simulink Coder, and Simulink Real-Time

**HIL simulator**

- Multi-core CPU running Simulink
- Real-Time kernel, FPGAs, I/O and protocol interfaces
- Plant simulation application autogenerated from Simulink

**Controller(s)**

- Hardware under test with sensor and actuator interfaces
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
Hardware-in-the-Loop Simulation
Hardware-in-the-Loop Simulation
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

Thank you