# POWER ELECTRONICS MANUFACTURING IMPROVEMENTS FOR HEAVY-DUTY FUEL CELL VEHICLES

PRINCIPLE INVESTIGATOR: IAN BYERS
PRESENTER: CALEB BURGESS

Project ID: MNF-BIL013
DOE Project Award: DE-SC0023801

Date: 03/08/2024

**DOE Hydrogen Program 2024 Annual Merit Review and Peer Evaluation Meeting**



POWER REIMAGINED

March 26, 2024

# PROJECT GOALS

- To understand the contributing factors of efficiency in heavy-duty hydrogen fuel cell vehicles with an emphasis on power electronics, through the use of multiple levels of simulation. These layers include full vehicle models, detailed power converter simulations and code generation simulation.

- Integrate MAREL's building blocks to validate the use cases via simulations, and integrate inductive and capacitive components, and address power density optimizations that could allow the integration of the power electronics into the fuel-cell housing.

# PROJECT OVERVIEW

MAREL POWER SOLUTIONS

- Project Partners
  - Investigators: Ian Byers, Caleb Burgess, Mark Feller, Gary Miller
- Project Vision
  - Understand the benefits of state-of-the-art power electronics on efficacy of heavy-duty hydrogen fuel cell vehicles through simulation
- Project Impact
  - Fuel cells require high quality power electronics in order maximize the performance of a fuel cell stack.

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|---|---|
| Award # | DE-SC0023801 |
| Start/End Date | 07/10/2023-03/09/2024 |
| Funding | $200,000 |

# APPROACH – SUMMARY

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|---|---|
| **Project Motivation:**<br><br>To simulate hydrogen fuel cell system tradeoffs pertaining to the electronic power conversion stages.<br><br>Marel Power Solutions has a new and unique building block approach to power systems that will allow motor drive and fuel cell conversion systems to use the same low level power architecture. | **Key Impact:**<br>Commonizing power electronics architectures in fuel cell conversion, battery management and charging, and 3-phase motor drive will help drive cost reductions and economies of scale when evaluating overall vehicle optimizations.<br><br>We also look at how multiple modules can potentially be combined into one packaged assembly, further driving cost, weight and size reduction. |
| **Barriers:**<br><br>One of the largest barriers that this team faced was understanding the state of the current hydrogen fuel cell architecture for vehicles, in a relevant and public format.<br><br>The team also uncovered underlying issues with power magnetics, realizing that today's magnetic core material is a major limiting factor. | **Partnership:**<br><br>None |

# APPROACH – INNOVATION

- Overview
  - The project was broken into 3 main components that the team wanted to investigate
- DC/DC Converter
  - With the team's background in power dense switches what did the overall DC/DC look like, what made sense in terms of size and topology?
- Vehicle Simulation
  - What factors made significant contributions to the efficiency of a hydrogen fuel cell vehicle?
- Code Generation Simulation
  - Using Marel Power Solutions hardware and the simulation work that we have done, what would implementation look like to reduce customization costs and allow for rapid fuel cell development

# POTENTIAL IMPACT

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- Supporting Clean Energy & Addressing Climate Change

  At the core of all clean energy technologies is the need to make efficient use of the energy generated to accomplish meaningful tasks and activities. Furthermore, for these technologies to have a future they must be economical to be adopted by interested parties. At the heart of these concerns are the need of efficient power electronics. The efficiency of these technology drives both a reduction in the total energy consumed to accomplish a task and reduces the cost of both the hardware needed through reduction in requirements and further reduces the cost to operate.

  Optimizing cooling architecture will also make the most efficient use of materials when building these systems. With our technology we can show a 25%+ reduction in usage of silicon carbide switches, lighter and more compact materials, as well a reduction in cost.

# ACCOMPLISHMENTS – DC/DC CONVERSION (MAGNETICS)

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- Why are magnetics important?
  - At the center of any DC/DC converter is an inductor, by pulsing current running through an inductor converters are able to alter the voltage across the inductor resulting in different output voltage. This output voltage of the converter is determined by the topology of the converter and the duty cycle of the switches.
- What are Magnetics?
  - In power electronics magnetics is used to refer to inductors and transformers which can be expressed as coupled inductors. These devices store energy in a magnetic field created by changing current flowing through the device. However, these magnetic components are only able to store a limited amount of energy in the magnetic field. This quantity is described as the saturation current of an inductor and is determined by the characteristics of the core material and the cross-sectional area of the material.

# ACCOMPLISHMENTS – DC/DC CONVERSION (TOPOLOGY)

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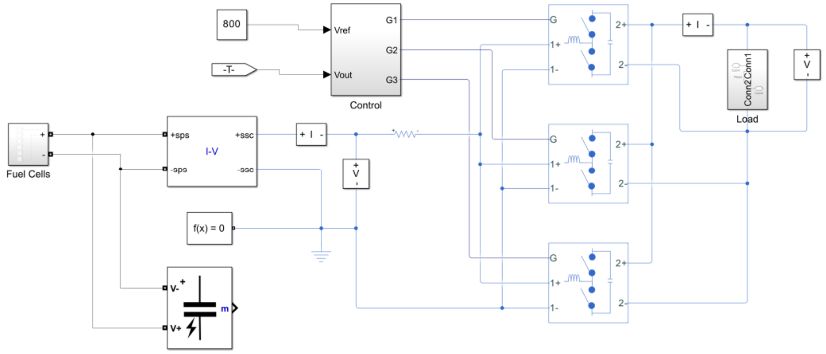
- Base topology
  - The base topology that was selected was the **synchronous-boost converter.** The vehicle parameters that were selected meant that the voltage of the fuel cell stack was always lower than the motor voltage, this leads to using a synchronous boost converter as it is particularly efficient due to using a switch instead of a diode reducing the switching losses of the converter.
- Phase count
  - With the base topology selected and modeling using Marel Power Solutions Trident switches the limiting factor of the converter is the saturation current of the inductor, as inductors of this size will be custom ordered components there is a question of efficiency based on a single large inductor or a number of inductors in parallel

# ACCOMPLISHMENTS – DC/DC CONVERSION

- Key Findings
  - 3 phases interleaved is the most efficient option
  - For this application the benefits in the reduced current that needs to be supported is canceled out by the increase in the required inductance value to achieve the same output parameters
  - By using 3-phases interleaved inductor values can be reduced while maintaining the same voltage ripple
  - Utilizes 3 half bridges, a common module size

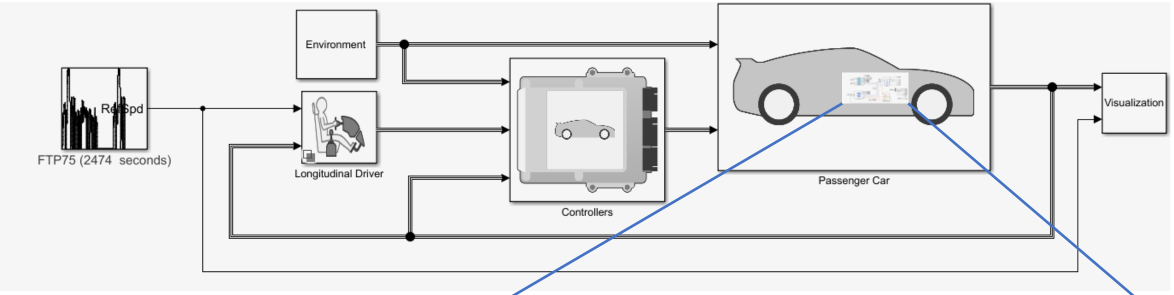
| Number of Phases | Required Cross-sectional Area |
|---|---|
| 1 | 53391 $mm^2$ |
| 2 | 17797 $mm^2$ |
| 3 | 5932 $mm^2$ |
| 5 | 5932 $mm^2$ |

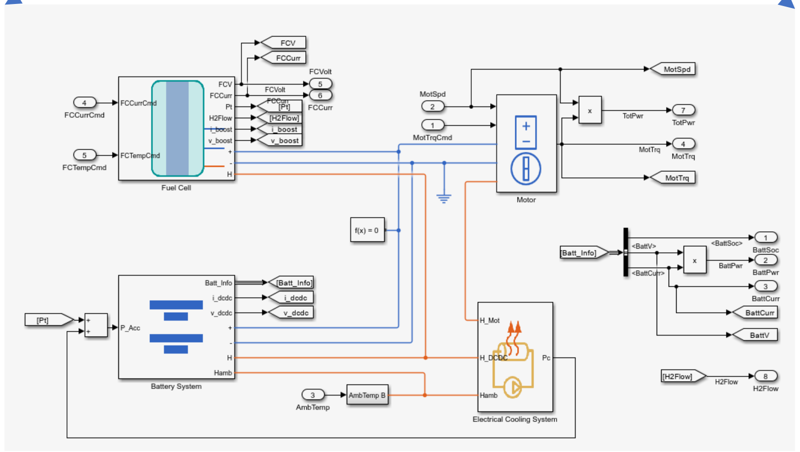


Simulation of Boost Converter

# ACCOMPLISHMENTS – VEHICLE SIMULATION

Simulated Vehicle




Simulated Power Plant w/ Fuel Cell and Battery

- What are benefits for improving efficiency of power electronics?
- Weight and cost savings
    - From optimizing cooling system
    - From optimizing fuel cell / battery architecture (number of fuel cells for example)
- Simulations show how efficiency of overall vehicle (MPGe) are impacted when adjusting key fuel cell parameters
    - Number of cells
    - Cell area
- Other modifications to fuel cell / battery architecture can be considered

# ACCOMPLISHMENTS – VEHICLE SIMULATION

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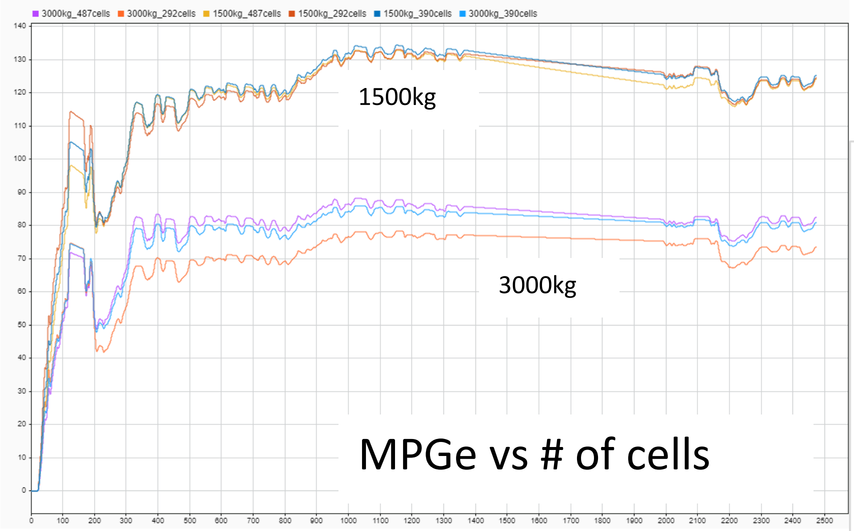
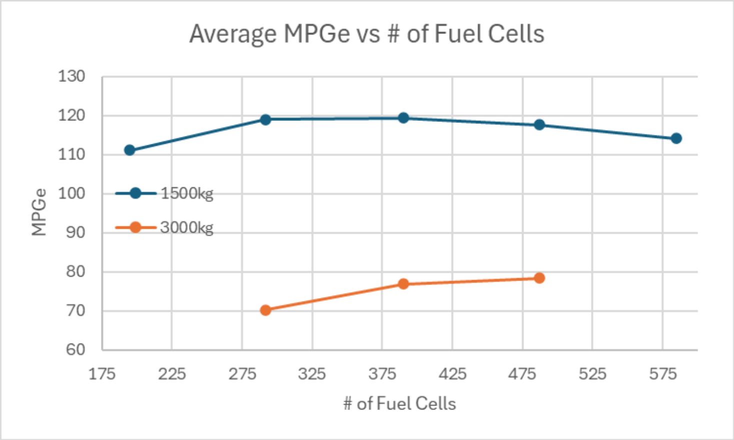
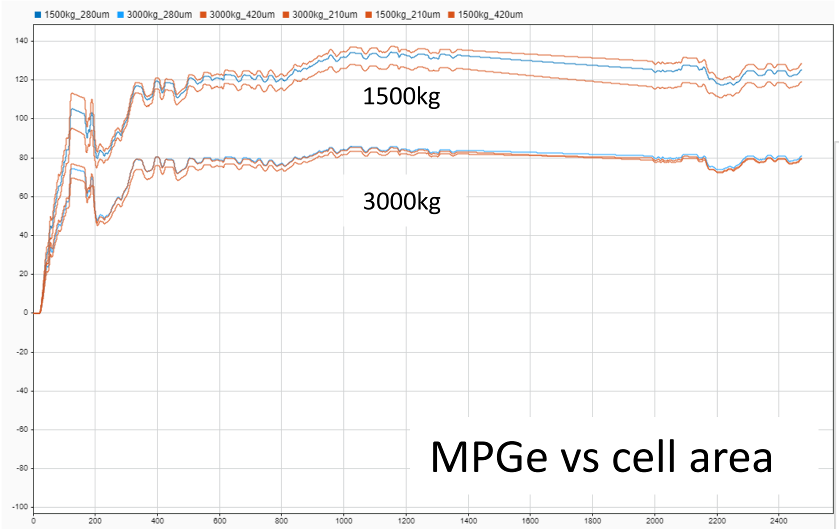
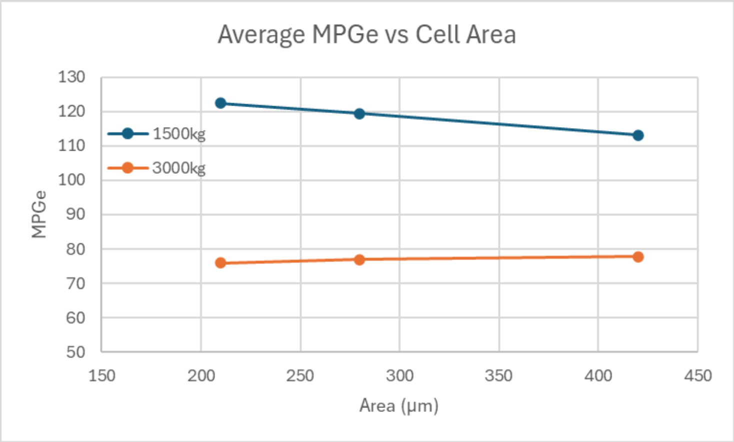



Number of Fuel Cells has a larger impact on heavier vehicles



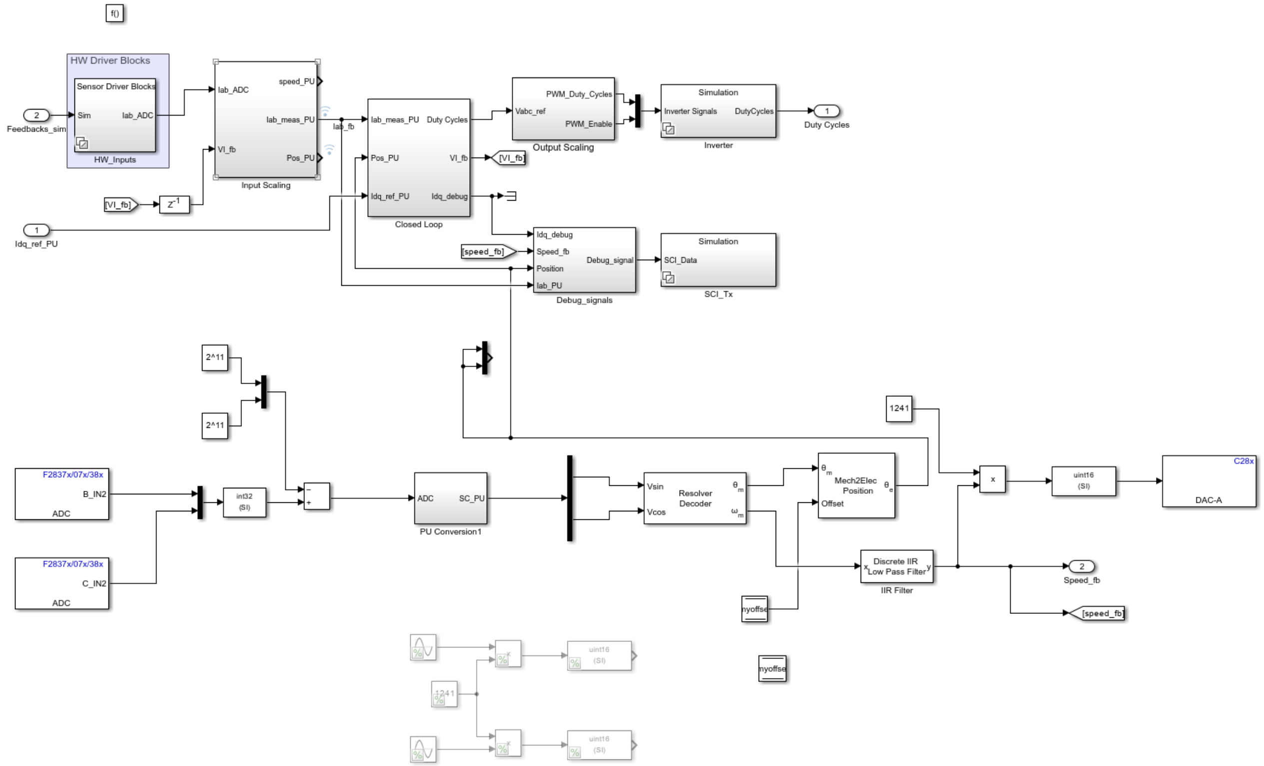

Cell Area has a larger impact on lighter vehicles




- Adding efficiency in the power electronics can offset the impact of changes in the fuel cell architecture

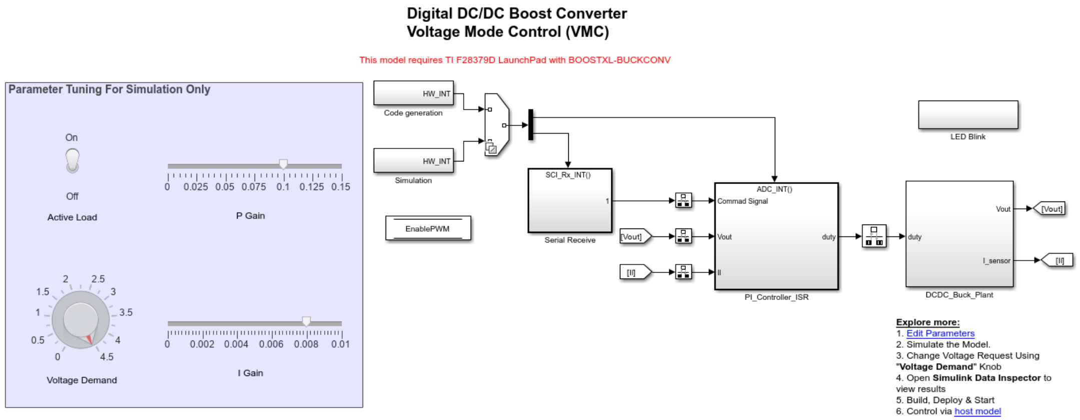
# ACCOMPLISHMENTS – CODE GENERATION SIMULATION

- Simulation of 3ph motor drive system as well as separate boost converter
- Used baseline sensorless field oriented control example, modified to run with resolver rotor position feedback as well as map to Marel functional hardware I/O
- Goal is to use simulations to drive auto code generation to also run on embedded target
- Evaluation of performance on low cost microcontroller with above code gen, Texas Instruments F28379d chosen as initial microcontroller.
- Future work plan to build complete environment and execute in real-time
- Also benefit from Simulink tooling to communicate with MCU, as well as compare data and performance between simulation and real execution

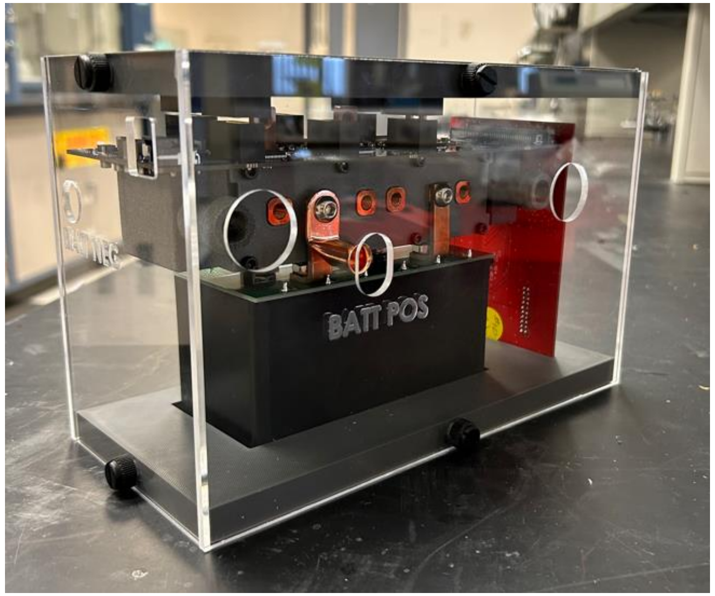


Simulink model for FOC

# ACCOMPLISHMENTS – CODE GENERATION SIMULATION - IMPLEMENTATION




Simulink Model for DC/DC Converter Hardware Control




Titan 3-Phase Module, Marel Power Solutions

- Marel 3-ph power stack shown below along with executable DC/DC Boost converter
- Goal is to combine DC/DC stage and 3-ph motor drive stage into one 5-ph power stack unit
- Low cost processor must be able to execute control loops to handle both algorithms
- Simulations show that this is possible with chosen hardware

# COLLABORATION & COORDINATION SLIDE

- The team did not work directly with exterior organizations on this project

# REMAINING CHALLENGES & BARRIERS

- Inductor & Capacitor Technology
  - Inductor and Capacitor technologies remain a barrier to further minimization of the total footprint and weight of inverter systems
- Simulation Technology
  - True edge cases are proving difficult to simulate with the current simulation systems utilized

# PROPOSED FUTURE WORK

- 2024/25 FY
  - Further tuning of the simulation models prior to custom magnetics design
  - Optimization of the Marel power stack components to fit application.
  - System module design including power stack, magnetics, control architecture and cpu design
  - Optimization of module design to commonize and combine where appropriate to realize most effective and cost efficient solution.
  - Final simulations and report for Phase 1

# PROJECT SUMMARY

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- DC/DC Converter
  - Using current magnetics technology, a 3-phase interleaved topology is necessary to efficiently convert power
  - The current limiting factor in size reduction of high-powered DC/DC converters is the inductor technology
- Vehicle Simulation
  - Fuel cell system architectures have multiple components that can be adjusted to tailor performance to the vehicle requirements (e.g. large vs small), but work is required to find an optimum configuration.
  - Improvements in the electrical power architecture can provide performance improvement at the system level on existing fuel cell systems or help provide more flexibility to make other changes in new fuel cell system designs.
- Code Generation Simulation
  - Successfully implemented a 3-phase motor drive model with resolver interface
  - Configured embedded target for above and utilized Simulink code generation to execute and measure model on cpu
  - Successfully implemented boost converter model with similar code generation to execute and measure model
  - Based on above results, it is possible to combine and run full system software (boost converter and 3-phase motor drive) on one cpu, allowing further exploration to combine hardware building blocks into one functional unit in vehicle