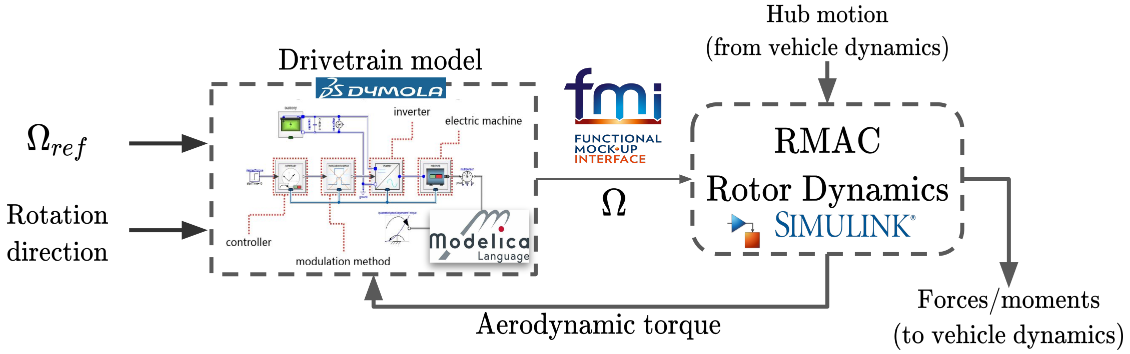

Extending a multicopter analysis tool using Modelica and FMI for Integrated Aerodynamic and Electrical Drivetrain Design

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Introduction

- Distributed electric propulsion has enabled the development of electric vertical take-off and landing (eVTOL) systems.
- Required to model multiple engineering domains to test design concepts prior to constructing physical prototype.
  - Specialized design tools tend to focus on specific domains, creating difficulties for integrated system design.
  - **Solution:** Functional Mock-Up Interface (FMI) allows us to integrate models that do not exist in domain-specific tools, expanding the capabilities of these tools.
- In this work, the Rensselaer Multicopter Analysis Code (RMAC) developed in MATLAB/Simulink, is extended to support the FMI standard using the FMI Toolbox.
  - Allows us to import electrified drivetrain models developed using Modelica to **perform integrated eVTOL analysis.**

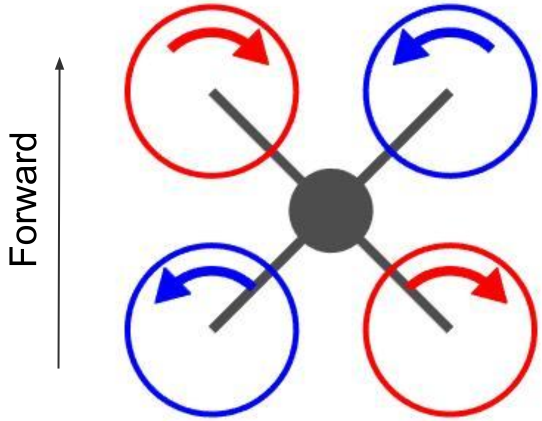
Q150-4M 12,000 watt brushless motor
Source: Hacker (link)

eVTOL Model Development

- Modeled an electric drivetrain using a 300lb quadcopter from Walter et al.
  - Vehicle is scaled based on the 1200lb reference quadcopter used at MOVE

- Rotors are 4ft in diameter, with a 6psf disk loading
  - 10% Radius tip clearance between rotors

- Motor parameters are taken from the 12 kW Hacker Q150-45-4



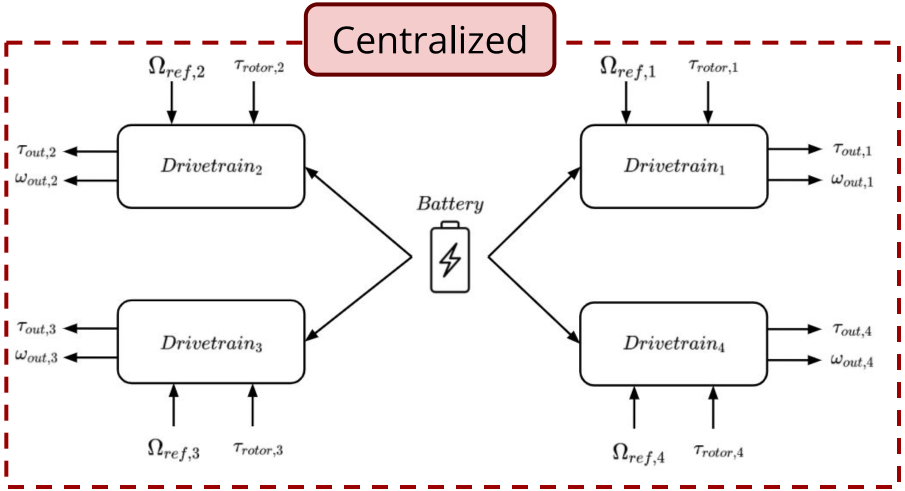
Vehicle parameters	
Boom length	0.905m
Gross weight	136kg
Rotor Radius	0.6096m

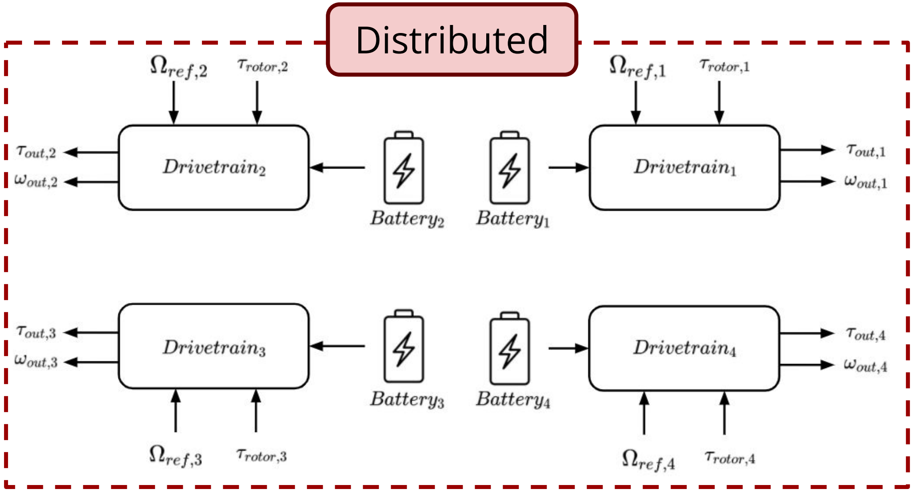
eVTOL Model Development

The aircraft was configured for two different power system architectures:

1. Centralized battery
2. Individual batteries powering each of the drivetrains

Allows us to study the performance of the battery and electrical system configuration with the eVTOL system aerodynamics.

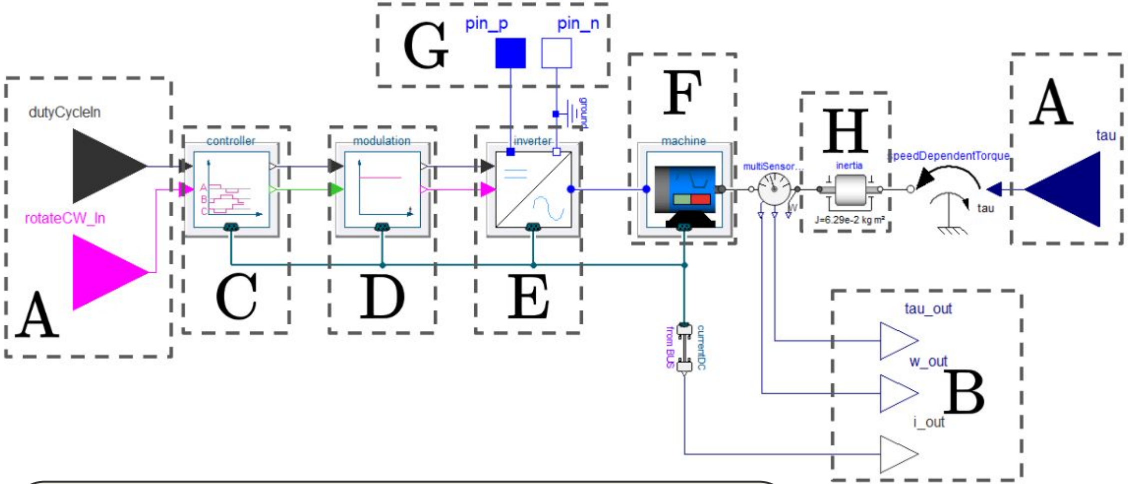




Drivetrain Model

Developed the drivetrain model in Dymola using the Dassault Electrified Powertrains Library.

A. FMU inputs
B. FMU outputs
C. COntroller (`replaceable` model)
D. Modulation method (`replaceable` model)
E. Inverter (`replaceable` model)
F. Machine (`replaceable` model)
G. Electrical connection to battery
H. Rotor inertia



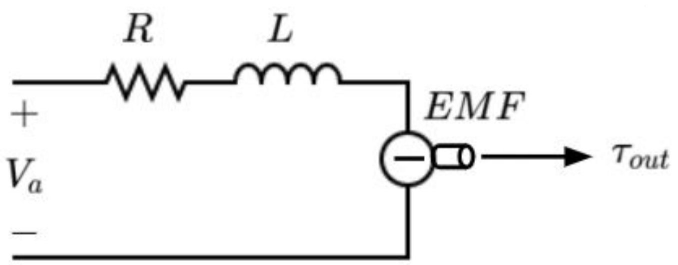
The `replaceable` components can be modeled with different levels of detail using different model variants to perform dynamic simulation studies.

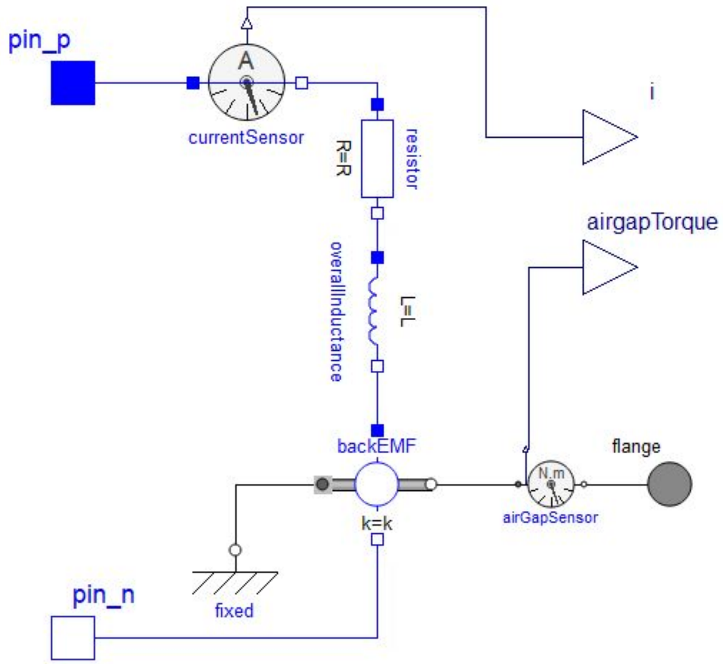
Machine Models

- Model the motor at different levels of detail.
- Simplest representation of the motor model where:

$$
\begin{aligned}
I\frac{d\Omega}{dt} &= Q_{\text{motor}} - Q_{\text{aero}} \\
Q_{\text{motor}} &= K_e\, i \\
L\frac{di}{dt} &= V - Ri - K_e\Omega
\end{aligned}
$$

- This model is typically used by the eVTOL community to represent entire electrified powertrains
- Useful for preliminary studies, but it limits the ability to perform integrated design of both aerodynamic and electrical domains.

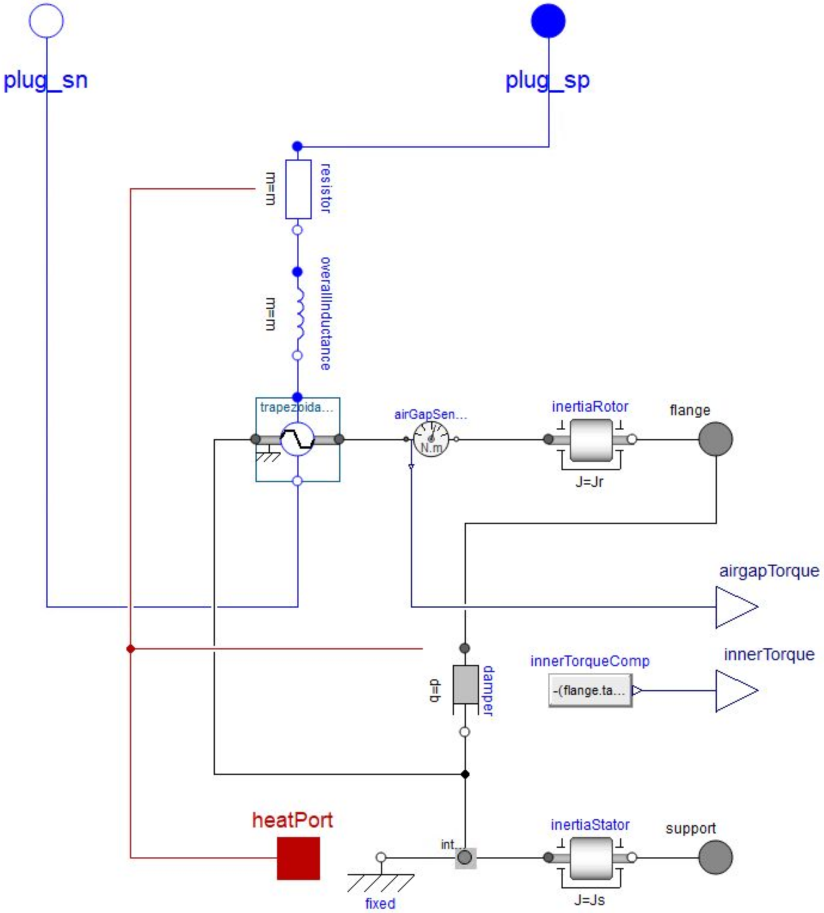




Machine Models

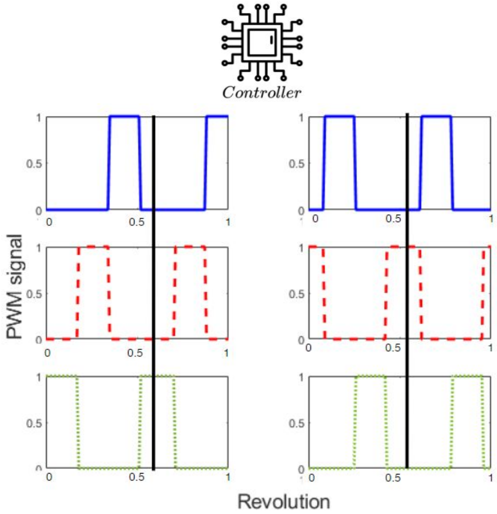
The **brushless motor with trapezoidal back EMF** has a three phase voltage that is dependent on the speed and position of the motor

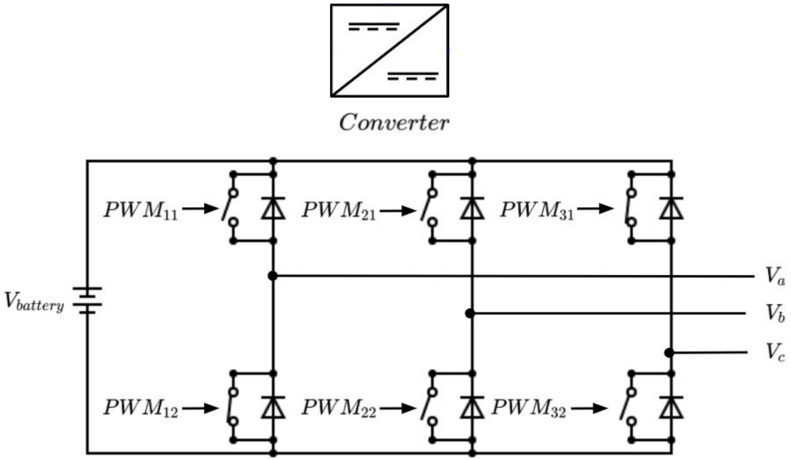
- Switching is caused by the switching of transistors in the converter
- Averaged back EMF would be the RMS of the trapezoidal EMF
- This is the most detailed model considered in this study.

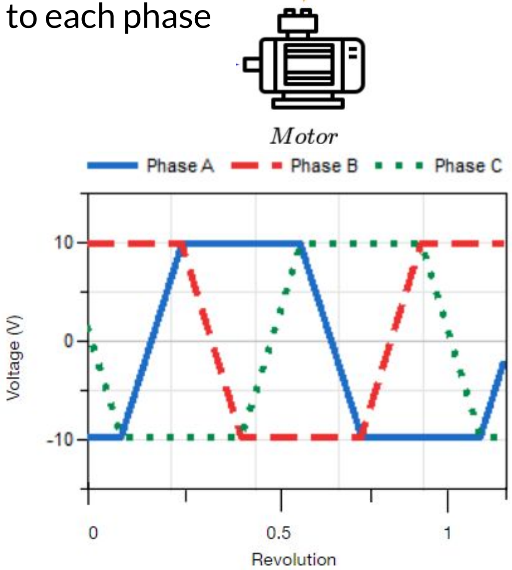


Controller, Inverter, and Modulation Models

- The selection of the machine model dictates which controller, inverter, and modulation models are used.
  - e.g. simplified motor model uses averaged converter models with a feed-through controller.
- When a trapezoidal motor is used, more complex power electronics converters, controllers, and modulation methods must be considered.
  - Converter model is modeled as a switching component that regulates voltage to each phase





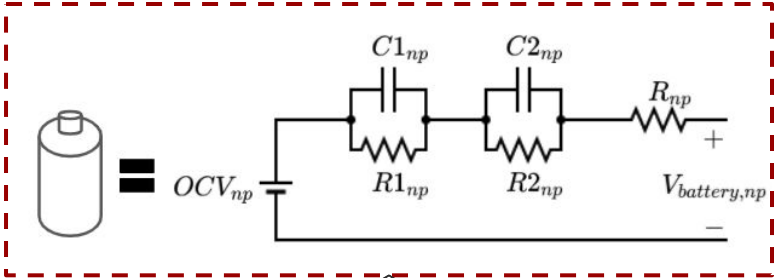


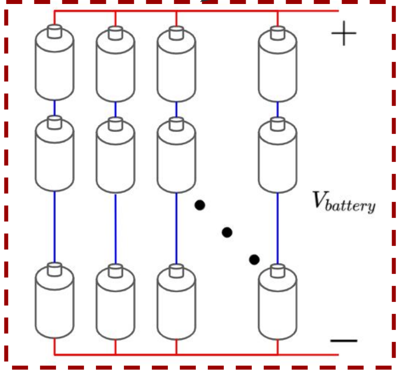
PWM signal to switches → Three phase converter → Trapezoidal voltage

Battery Models

- The eVTOL community has previously used constant voltage sources to represent the battery.
- The battery model is an open-circuit voltage (OCV) battery based on the Sanyo 18650 Li-Ion battery.
- 15 cells in series (60V) and 20 cells in parallel (43 Ah)
- The voltage is determined as a function of impedance, where the resistance and capacitance values are determined from the lookup tables:

$$
\begin{aligned}
V_{battery,ij} &= OCV_{ij} - Z_{battery,ij} i_{ij} \\
Z_{battery,ij} &= (R1_{ij} || C1_{ij}) + (R2_{ij} || C2_{ij}) + R_{ij}
\end{aligned}
$$



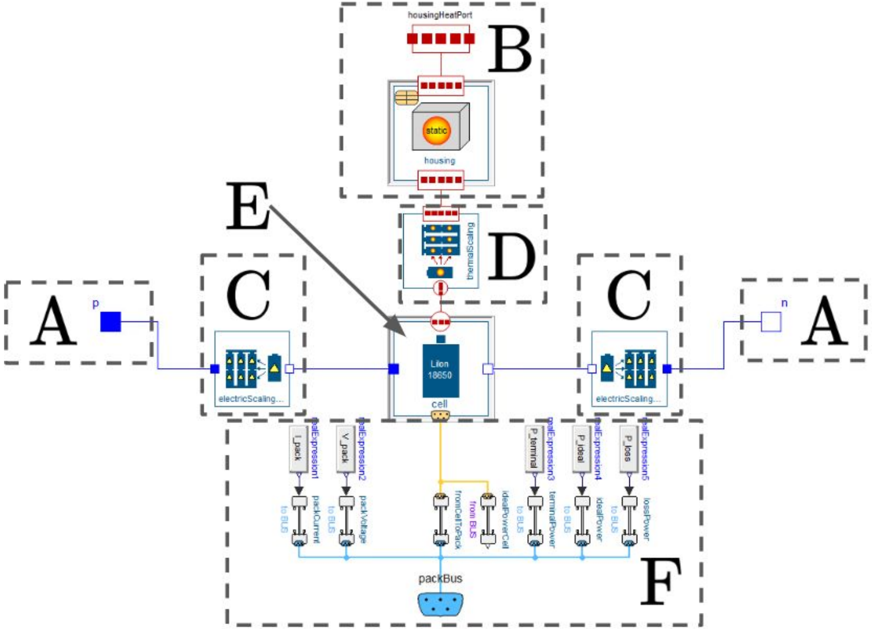


13s6p custom battery with Sanyo NCR18650 GA cells
Source: EV Madrid (link)

Battery Models

These battery models were developed in Dymola using the Dassault Battery Library where:

A. Electrical connections to the drivetrain
B. Thermal housing model and connection to outside thermal models
C. Electrical scaling component
D. Thermal scaling component
E. Battery cell electrical model
F. Data connections for analysis of the battery



Rensselaer Multicopter Analysis Code (RMAC)

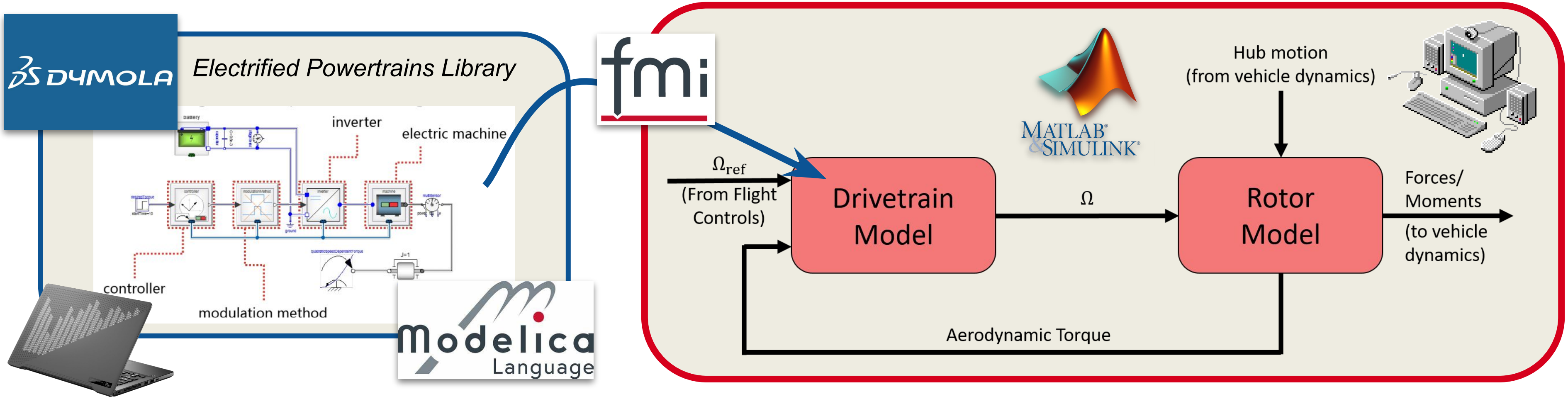
Vehicle dynamics and rotor aerodynamics are modeled using the Rensselaer Multicopter Analysis Code (RMAC)

- This is a domain-specific tool meant for aerodynamic analysis.
- Blade element theory is coupled to a 10-state Peters-He dynamic inflow on each rotor to evaluate loads at the rotor hub
- Rotor forces/moments are summed, along with fuselage drag and gravity at the vehicle C.G. to determine acceleration
- 6DOF linear models are obtained via perturbation about hover, with high-frequency rotor states eliminated through static condensation

Coupling FMUs to RMAC

ALSETlab

- The drivetrain is modeled using the Modelica language (https://modelica.org/) in the Dymola software and exported to interact with RMAC in MATLAB/Simulink as an functional mock-up unit (FMU)
  - **Functional mock-up interface** is an open interface standard for model exchange between different tools, useful for large-scale multiphysics analysis with more than 150 tools supported: https://fmi-standard.org/
  - Two main approaches:
    *1. **Export** models from one tool, **import** into other tools for **simulation** using new tool's solver*
    2. **Co-simulation** of models in different tools using the solver from the original tool to simulate



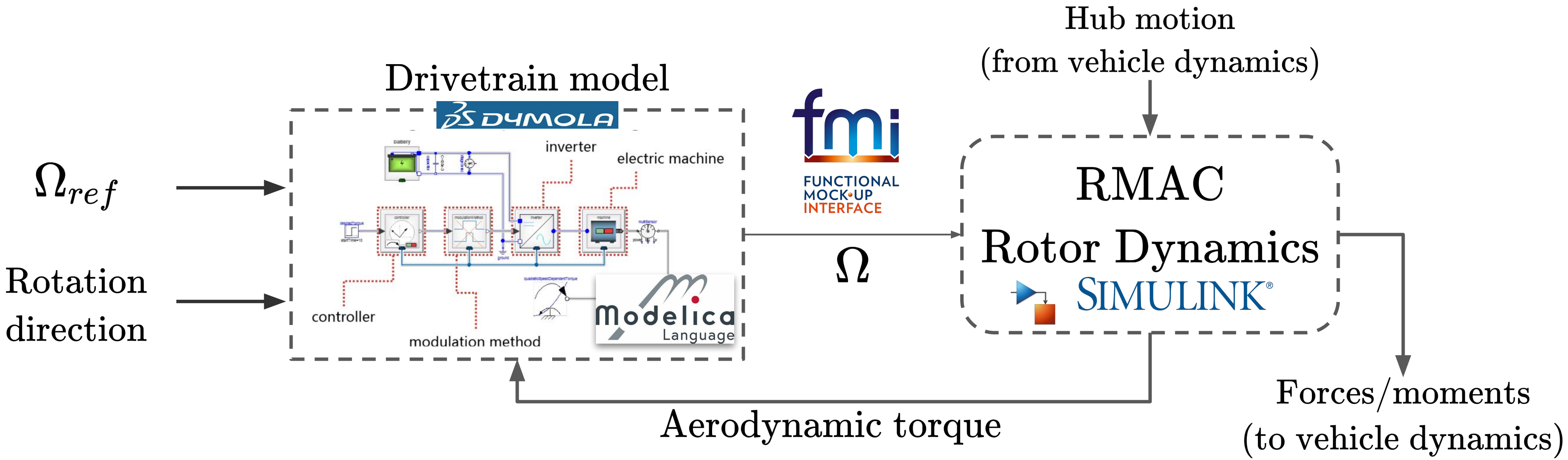
Coupling FMUs to RMAC

FMU inputs: desired speed command, rotor torque, and rotation direction of the motor.

- Speed command is derived from vehicle's attitude and heave control.
- Rotor torque is **produced by RMAC's aerodynamic model.**

FMU outputs: speed of motor (to interface with RMAC)

- Used to model the aerodynamic forces and moments about the rotor hub to couple to vehicle dynamic model in RMAC.

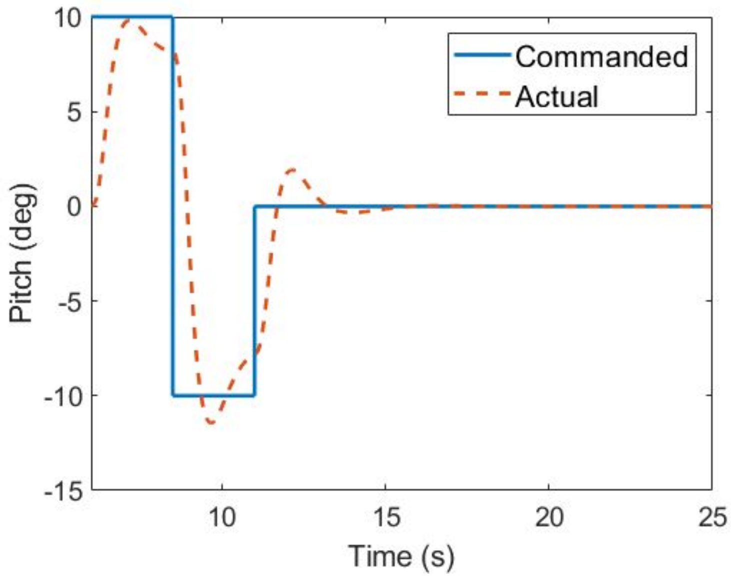


Case Study

Using the integration of RMAC with the drivetrain FMU via the FMI toolbox, we consider the following cases:

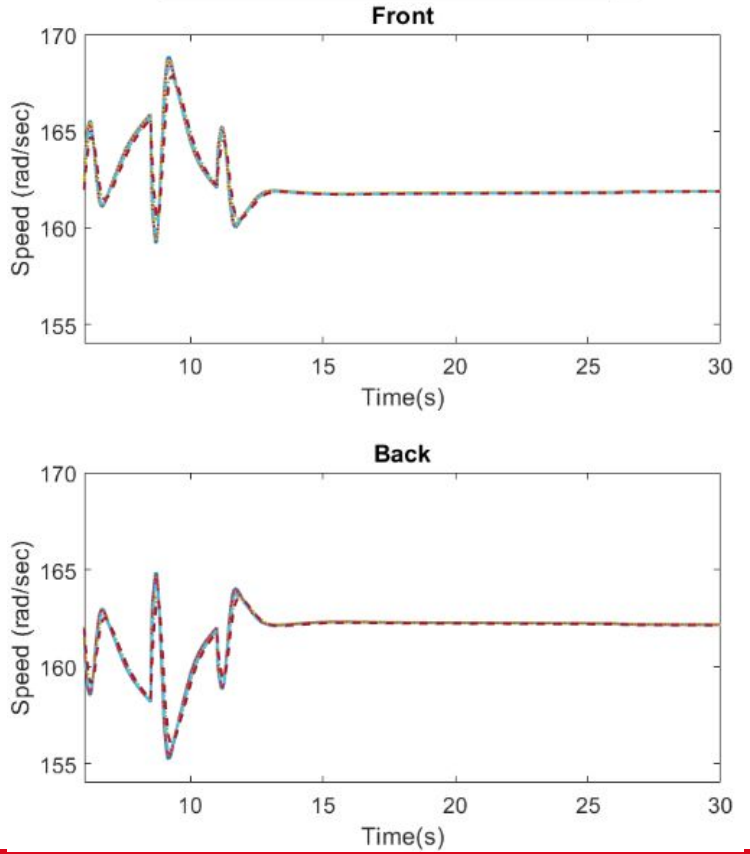
1. Centralized battery modeled using an ideal 60V voltage source.
2. Distributed (individual) battery modeled using an ideal 60V voltage source.
3. Centralized battery starting at 100% state of charge.
4. Distributed (individual) battery starting at 100% state of charge.
5. Centralized battery starting at 30% state of charge.
6. Distributed (individual) battery starting at 30% state of charge.

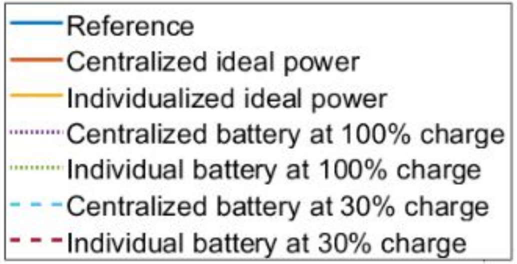
Apply pitch command to observe the closed-loop dynamic behavior of vehicle for all 6 cases.



Case Study - Speed Response

- The front and rear rotors receive opposite commands to achieve the pitch behavior
- The speed response is identical for all cases, showing that the power system configuration has little effect on the **aerodynamic** response of the system.



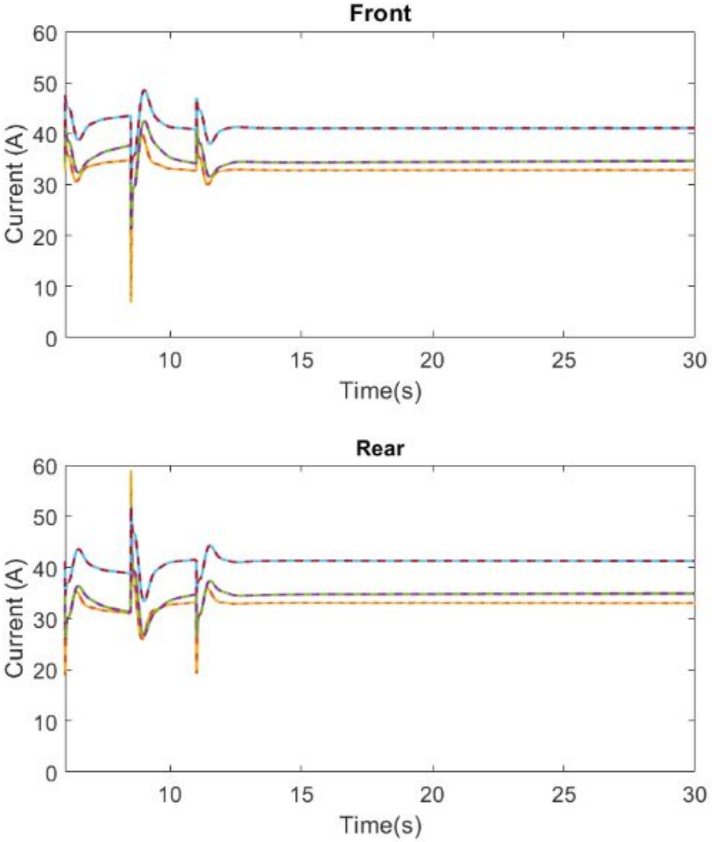


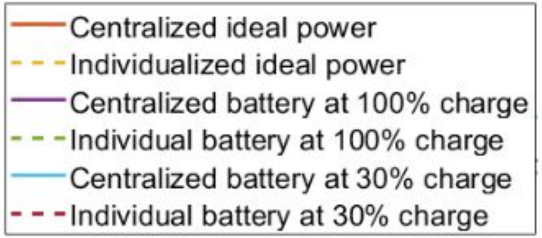
Case Study - Battery current

ALSET lab

- In a **centralized** configuration, the current spikes between the front and rear motors will cancel each other out.

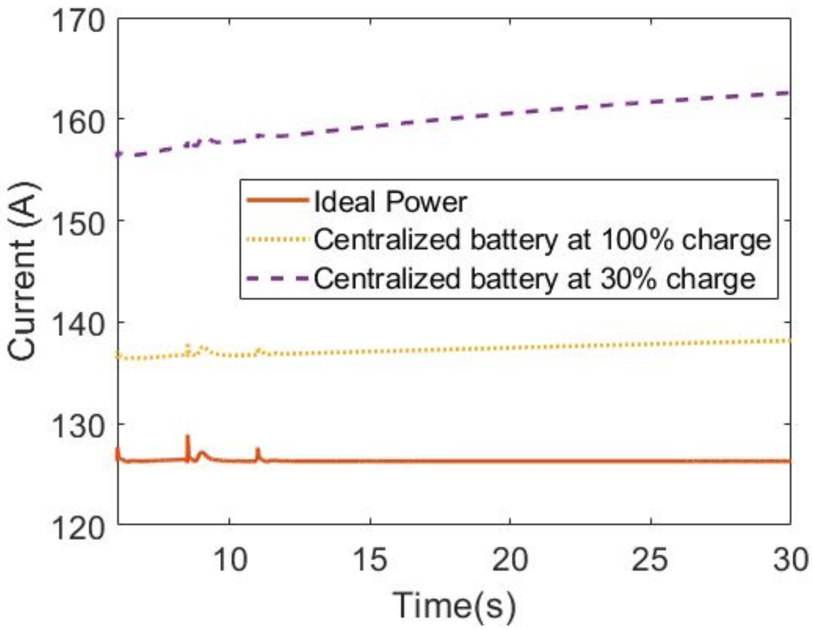
- In a **distributed** configuration, the current spikes directly affect the battery as the demands of the front and rear rotors do not cancel each other out.
    - This would require us to size the battery according to the worst case scenario of current spikes.





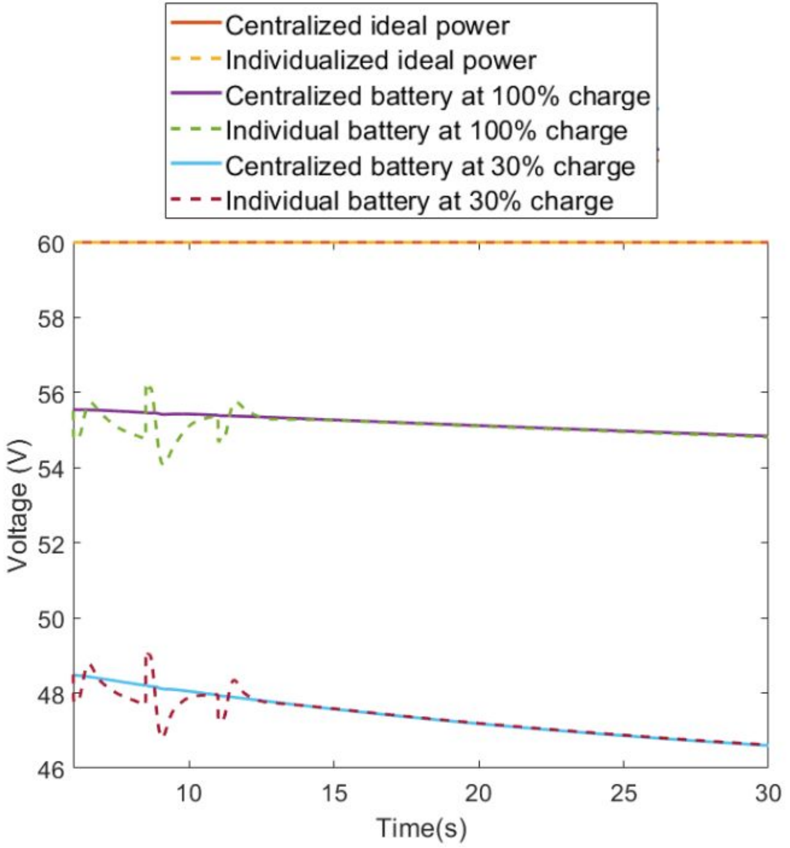
Case Study - Centralized battery current

- In a **centralized** configuration, the current spikes between the front and rear motors will cancel each other out.
  - As a result, this pitch command would not be a limiting factor for the system.
- In a **distributed** configuration, the battery current is identical to the motor current because all drivetrains are **independent**.



Case Study - Battery voltage

- While the motors have similar speed response, the battery voltage varies.
- In a **centralized** configuration, the current spikes between the front and rear motors will cancel each other out.
- In a **distributed** configuration, the current spikes are reflected in the voltage.
    - This would require us to size the battery according to the worst case scenario of current spikes.



Conclusion

- The purpose of the FMI standard is to enable **model portability** and **reusability**
  - In the eVTOL field, we can integrate multi-domain models with existing aerodynamic analysis tools for **expanded model analysis**.
  - This also allows us to have ***one model in many tools!***
- The proposed approach provided simulation results that enable a new understanding of the trade-offs between various model configurations and architectures.
  - FMI Standard enables simulation with **domain-specific tools**, allowing us to study our models with broader applications.
  - e.g. the power system architecture and its effects on system dynamics

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