Extending a Multicopter Analysis Tool using Modelica and FMI for Integrated eVTOL Aerodynamic and Electrical Drivetrain Design

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Abstract

This paper describes how the Functional Mock-up Interface (FMI) standard for model-based systems engineering can be used to expand the capabilities of aerodynamic multicopter analysis tools to perform integrated design of electric vertical take-off and landing (eVTOL) systems. The proposed eVTOL system, which consists of a drivetrain and battery, was developed using Modelica and exported to MATLAB/SIMULINK using model exchange to interact with a domain-specific tool specializing in calculating the aerodynamics of the aircraft. This shows the value of FMI to extend the capabilities of tools for multicopter aerodynamic analysis to design eVTOL using integrated multi-domain system simulation.

Keywords: eVTOL, multi-domain modeling, FMI

Glossary

BLDCL	Brushless DC Drives Library
eVTOL	Electric Vertical Take-Off and Landing
FMI	Functional mock-up interface
FMIT	FMI Toolbox for MATLAB and SIMULINK
FMU	Functional mock-up unit
PWM	Pulse width modulation
RMAC	Rensselaer Multicopter Analysis Code

1 Introduction

1.1 Motivation

Distributed electric propulsion has enabled the development of electric vertical take-off and landing (eVTOL) systems, such as NASA's Advanced Air Mobility (NASA 2020 (retrieved Nov 3, 2020)) and Uber Elevate (Holden and Goel 2016). The design of such systems requires to engineer sub-systems of multiple engineering domains, where simulation studies of each sub-system can provide insight on which components and designs provide the greatest benefit prior to building a physical prototype. However, specialized design tools tend to focus on a specific domain only, which creates difficulties for integrated system desing.

The development of distributed electric propulsion systems would greatly benefit from well-defined multi-engineering models at various levels of modeling fidelity to understand system behavior. However, expanding domain specific tools to encompass all domains poses a tremendous development challenge. On the other hand, the Functional Mock-Up Interface (FMI) standard can enable the interaction of models that do not exist in domain specific tools, using commercial as well as open-source Modelica models, to further expand their capabilities and understand the overall integrated system. This would only require the domain specific tool to implement the FMI's import specification, providing a faster route to expand the capabilities of existing domain specific tools. The biggest benefit for this approach to modeling is that it allows for collaboration with researchers and developers that are not familiar with Modelica but have created domain specific tools, just by adding support to the FMI Standard to their software. This allows us to fully integrate tools created for previous research and development, enriching simulation studies with relatively low effort.

In this paper, the Rensselaer Multicopter Analysis Code (RMAC) (Niemiec and Gandhi 2019) developed within the MATLAB/SIMULINK environment, is extended to support the FMI standard using the FMI Toolbox (FMIT)(Modelon 2018; Henningson, Akesson, and Tummescheit n.d.). This allows to import electrified drivetrain models developed in Modelica, which once imported into RMAC, can be used for integrated analysis of eVTOL vehicles. To illustrate the new capabilities of RMAC, its aerodynamic vehicle model is coupled with a electrified drivetrain modeled in Modelica and exported as an FMU to MATLAB/SIMULINK to study the interaction between the the aerodynamics and electrified drivetrain. The RMAC tool contains mathematical models for the aircraft rotor dynamics, which are coupled to the FMU, so that the drivetrain can be studied with accurate aerodynamics used within the multicopter domain. The use of the FMI standard creates a flexible environment that can be easily interfaced with RMAC's code, expanding analysis capability for multi-domain studies.

1.2 Related Works

The development of eVTOL systems has been of interest recently, especially focused on applications to Urban Air Mobility for passenger transport operations. Many of these systems, such as Uber Elevate (Holden and Goel 2016), do not have large-scale physical prototypes, making model-based systems engineering an attractive approach for development and analysis of new architectures.

Novel electrified aircraft concepts, such as fixed-wing aircraft, have been studied using Modelica. The More Electric Aircraft Systems (MOET) project utilized Modelica to develop and study novel aircraft concepts to understand system behavior prior to building physical prototypes (Bals et al. 2009). In addition, distributed electric propulsion concepts have been modeled using Modelica to better study the electrical architecture as other disciplines improve their specific components, for example electrical energy storage devices increasing capacity (Zhou et al. 2018). However, these projects have not coupled their electrical drivetrain models to other programs for integrated multi-domain system design, which could be beneficial in designing the entire vehicle.

A unique example of multi-domain system design is presented in (Velden and Casalino 2021), where multiple tools have been integrated to conduct studies on eVTOL systems for flight and noise assessment using multi-fidelity models. This study shows how FMI can be applied to utilize the features of other tools in the Dassault 3DEXPERIENCE suite for analysis of the eVTOL system. However, the electrified drivetrain models were not included in the system design.

1.3 Paper Contributions

This paper contributes a framework for eVTOL design through integrated multi-domain model development where the electrified drivetrain can be defined with multiple levels of modeling fidelity using Modelica. These models are coupled to a domain specific multicopter aerodynamics tool, RMAC, developed in the MATLAB/SIMULINK environment using the FMI Toolbox to study the eVTOL drivetrain dynamics. This application highlights the benefits expanding the capabilities of preexisitng tools by incorporating models developed using Modelica, which is possible thanks to the FMI standard.

1.4 Paper Organization

The paper is organized as follows. Section 2 outlines the development of the drivetrain models using Modelica. Section 3 discusses FMU development and interfacing with the RMAC toolbox in MATLAB/SIMULINK for integrated multi-domain dynamic simulation. Section 4 shows results of the drivetrain studied at various levels of modeling fidelity. Section 5 describes the conclusions of this work.

2 eVTOL Model Development

The aircraft modeled in this work is a 300 lb quadcopter used in (Walter et al. 2020). The rotors are assumed to be linearly twisted and tapered and have a 10% R tip clearance. The motor parameters are based on the Hacker Q150-45-4 (*Hacker Q150-45-4 Series Datasheet* 2021). The drivetrain models are described in further detail with their behavior validated in (Podlaski et al. 2021).

The aircraft was configured using two different power system architectures: (1) with a centralized battery (one battery powering all four drivetrains) and (2) with individual batteries powering each of the drivetrains (four batteries in total). These two architectures allow to study the performance of the battery and electrical system configuration on the eVTOL system aerodynamics. The schematic of the system with a centralized battery is shown in Figure 1, and the schematic of the system with a distributed battery is shown in Figure 2. Each drivetrain has a speed input to determine the duty cycle of the inverter and a torque that is applied to the machine's rotor. The torque and speed of each motor is used as an output to adjust the controller as necessary and interact with the RMAC rotor aerodynamics.

2.1 Drivetrain Model

The drivetrain consists of four components: a controller, pulse width modulation (PWM) of the converter, a DC/DC converter, and a DC machine. The component models are from Dassault System's Brushless DC Drives (BLDCL) (Dassault Systemes 2022) and the Modelica Standard Library (MSL). The drivetrain was developed in Modelica using the Dymola software, and is shown in Figure 3. The system consists of multiple domains, with the electrical, mechanical, and control domains represented.

The components of the drivetrain system in Figure 3 are labeled as follows:

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 controller, modulation method, inverter, and machine models are all modeled as `replaceable` components, meaning that components with different levels of detail can be easily replaced using different model *variants* for various dynamic simulation studies. For example, the machine was modeled with different losses and dynamic behaviors included, resulting in four different machine models to be considered in the studies. By using `replaceable` models, these cases can be easily changed to observe different dynamic behaviors in the model.

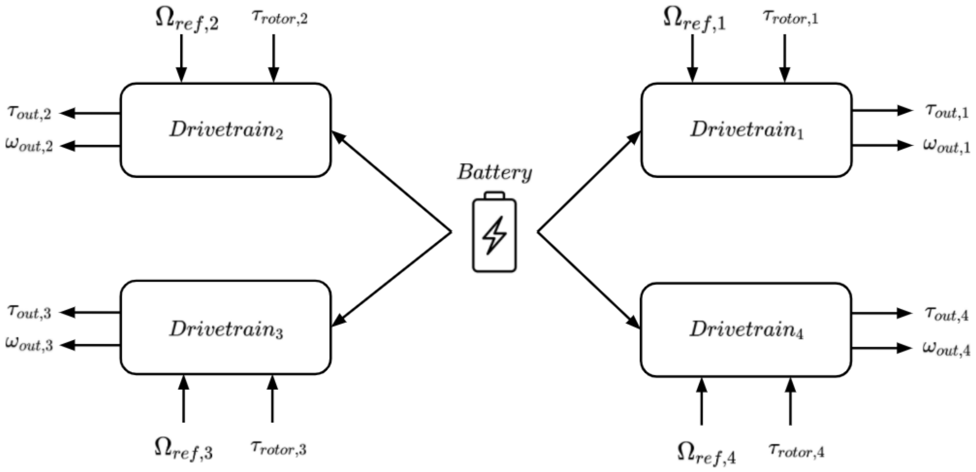

Figure 1. Multi-rotor aircraft model with a centralized battery.

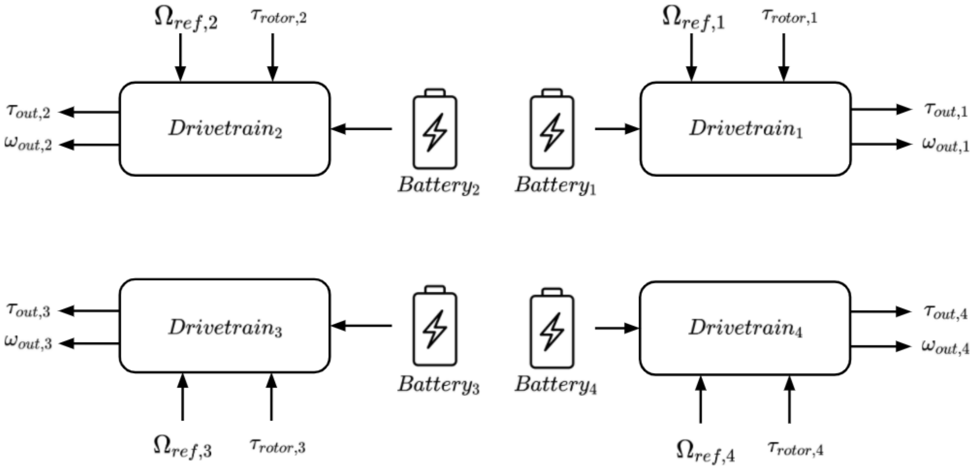

Figure 2. Multi-rotor aircraft model with a distributed battery.

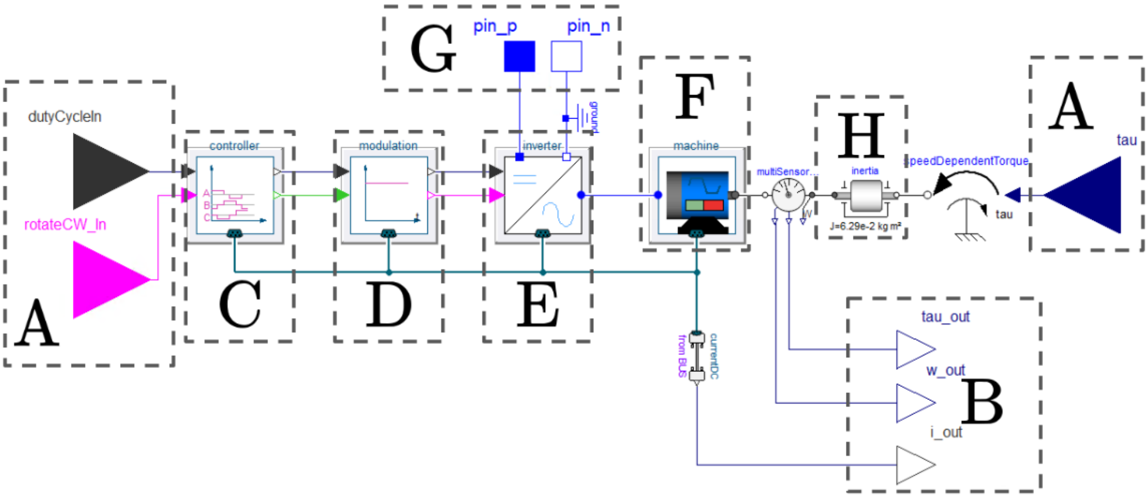

Figure 3. Drivetrain in Modelica using BLDCL and MSL.

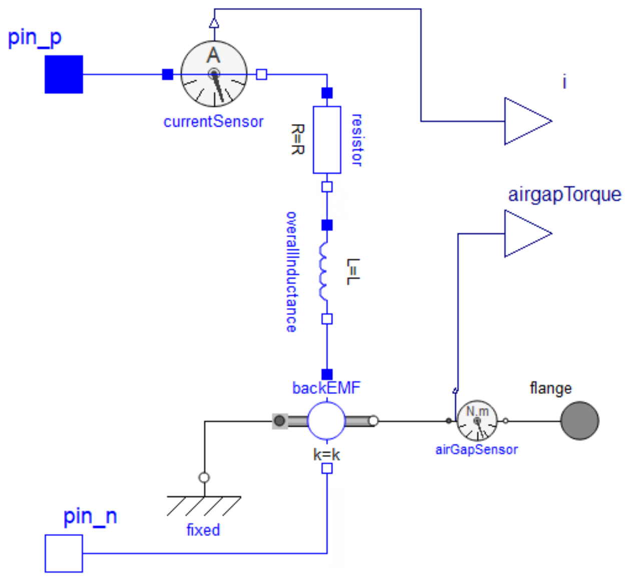

Figure 4. Implemented simplified variant of the motor model.

2.1.1 Machine Models

The machine model is shown as block F in Figure 3, which can be modeled at multiple levels of modeling fidelity. A simple motor model was developed as shown in Figure 4. This model is typically used to represent entire electrified power trains in the eVTOL community (Podlaski et al. 2021). While useful for preliminary studies, it limits the ability to perform integrated design of both aerodynamic and electrical sub-systems concurrently. In contrast, the BLDCL (Dassault Systemes 2022) contains machine models with averaged and trapezoidal back-EMF (see Figure 5, which enables studies to consider various non-ideal behavior and the electrical switching effects from the inverter. The model's architecture allows to use all three variants for different analysis, with low effort, for example, the averaged model helps to better represent frictional losses while the trapezoidal model allows to capture electrical and mechanical heat of the machine.

The speed of the motor in Figure 4 is calculated by Equation 1, where I is the rotor inertia, and the right-hand side of the equation is the net moment applied to the drivetrain. The motor torque is proportional to the current as calculated in Equation 2. Equation 3 gives the current drawn by the motor as a function of the resistance, inductance, and voltage applied to the motor. The motor can also be further simplified by setting the inductance $L = 0$, which eliminates any current delay in the electrical dynamics.

$$I\frac{d\Omega}{dt} = Q_{\text{motor}} - Q_{\text{aero}} \tag{1}$$

$$Q_{\text{motor}} = K_e i \tag{2}$$

$$L\frac{di}{dt} = V - Ri - K_e\Omega \tag{3}$$

The trapezoidal motor is the most complex model considered in the study, which is shown in Figure 5. The trapezoidal motor model uses a three phase input connector, as designated by `plug_sn` and `plug_sp`. This is due to the three-phase input needed to produce the trapezoidal back-EMF waveform that is produced by the switching of the inverter.

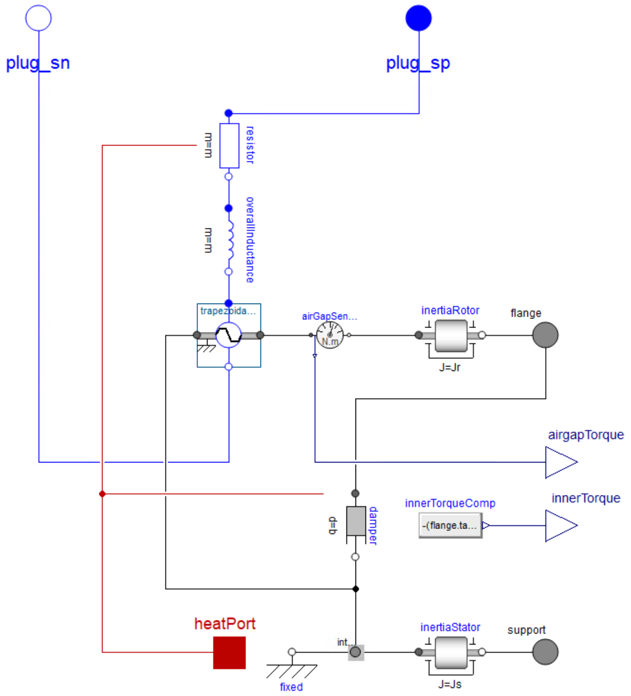

Figure 5. Trapezoidal variant of the machine model from the BLDCL

2.1.2 Controller, Inverter, and Modulation Models

The selection of the machine model defines which controller, inverter, and modulation models are used. When the averaged back-EMF and simplified motor models like the one in Figure 4 are used, the inverter model is an ideal buck DC-DC converter with a feed-through controller and modulation method as the duty cycle is a function of the actual and desired speed of the motor. The ideal buck converter steps down the battery voltage to the motor voltage as a function of the duty cycle as denoted by Equations 4 and 5.

$$V_{motor} = V_{battery} * \text{dutyCycle} \tag{4}$$

$$i_{battery} = -i_{motor} * \text{dutyCycle} \tag{5}$$

In the case of the trapezoidal motor, more complex power electronics converters, controllers, and modulation methods must be considered. The inverter now includes diodes and switches to created a three-phase signal to be applied to the motor, resulting in a trapezoidal back-EMF. The inverter is shown in Figure 6, which includes the same buck converter calculations in Equations 4 and 5. A three-phase star connection from the ideal buck component creates the three-phase voltage applied to the switches, `upperSwitch` and `lowerSwitch`, and

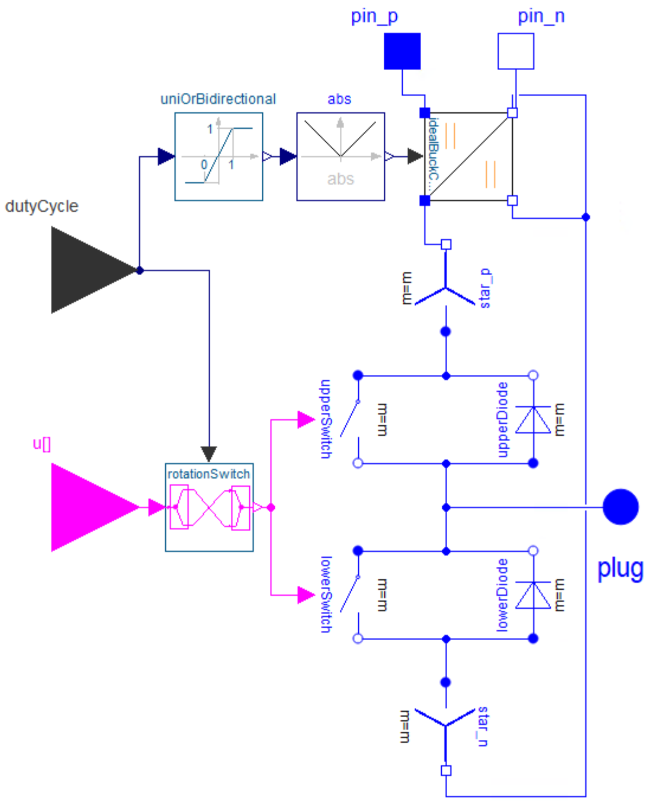

Figure 6. Inverter model with switching components from the BLDCL.

diodes, `upperDiode` and `lowerDiode`. Input `u[]` controls the switching on and off of the `upperSwitch` and `lowerSwitch` to produce a trapezoidal signal to apply to the motor via three-phase output `plug`.

The input `u[]` in Figure 6 comes from the a six-step control command generated by Hall sensor outputs to control each of the half-bridges in the inverter model. This is exemplified in Figure 7, where for the instant denoted by the black line the PWM signals denote that the upper switch for the third phase and the lower switch for the first phase are closed. This means that V_a is connected directly to ground, V_b is falling linearly between $V_{battery}$ and ground, and V_c is equal to $V_{battery}$. The `Modulation` block converts the `boolean` states from the six-step controller into switching signals to control the half-bridges, effectively linking the different domains in the model.

2.2 Battery Model

The battery model is a look-up table-based open-circuit voltage (OCV) model from the Dassault Systems Battery Library (Dassault Systems 2022). The model considers both electrical and thermal behavior, and utilizes data collected from experiments to populate look-up tables. These tables are then used to determine the parameters of the battery's electrical components for various operating conditions. The electrical schematic of the OCV battery is shown in Figure 8, where each cell of the battery is powered by an ideal voltage source. The values of the resistors and capacitors in the circuit in Figure 8 are determined from the operational state and values from the look-up tables.

The battery model in Dymola is shown in Figure 9 and shows both the thermal and electrical domains modeled. The components are modeled as follows:

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

The battery cell model in Figure 9, block E consists of the electrical circuit shown in Figure 8. The `electricalScaling` in block C of Figure 9 scales the number of cells by m cells in parallel and n cells in series, as shown in Figure 8. Every cell produces a voltage given by Equation 6. The impedance in each cell is given by Equation 7, where the values of $R1$, $C1$, $R2$, and $C2$ are determined from the look-up tables as a function of battery state of charge and operating temperature.

$$V_{battery,ij} = OCV_{ij} - Z_{battery,ij} i_{ij} \tag{6}$$

$$Z_{battery,ij} = (R1_{ij} || C1_{ij}) + (R2_{ij} || C2_{ij}) + R_{ij} \tag{7}$$

For the vehicle studied in this paper, the battery in a centralized configuration in Figure 1 has 15 cells in series and 20 cells in parallel for a 60 V with a capacity of 43 Ah. In the distributed battery configuration in Figure 2, the capacity of each battery is a quarter of the centralized battery: 15 cells in series and 5 cells in parallel. This results in a 60 V battery with a 10.75 Ah capacity.

3 Coupling FMUs to RMAC

The drivetrain model in Figure 3 was coupled to the battery model in Figure 9, then exported as an FMU using the model exchange specification supported in Dymola. The FMU is imported into Simulink through a FMU for model exchange provided by the FMI toolbox (Modelon 2018) to be simulated with RMAC. The interfaces between the FMU and RMAC are shown in Figure 10. The FMU uses an input of a desired speed command, rotor torque, and a rotation direction of the motor (clockwise/counter-clockwise). The speed command is derived from the vehicle's attitude and heave control; the rotor torque is produced from RMAC's aerodynamic model. The FMU outputs the speed of the motor to interact with RMAC, as well as machine current and torque for monitoring and analysis. The motor speed output from the FMU is used to model the aerodynamic forces and moments about the rotor hub. These forces and moments are then coupled with the vehicle dynamics model.

Because the model in Figure 3 requires the duty cycle as an input, RMAC must also provide a controller. The

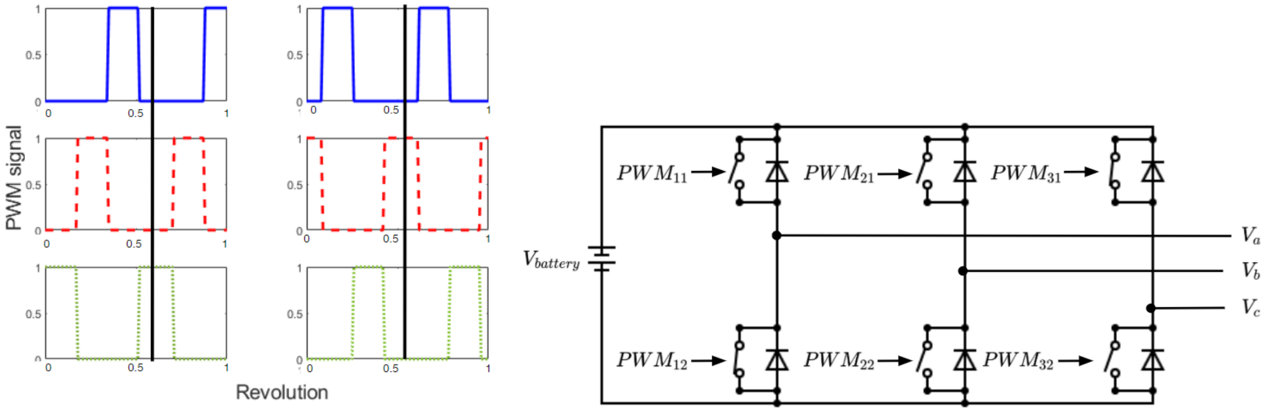

Figure 7. Switched three-phase converter with averaged input voltage.

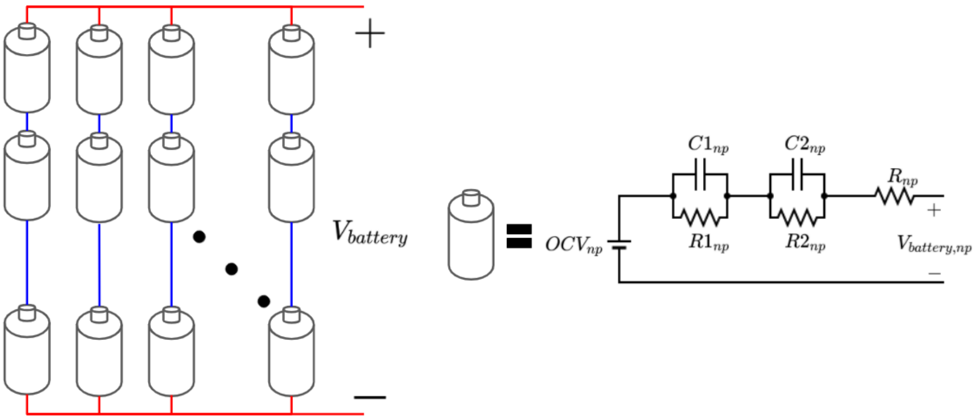

Figure 8. Electrical schematic of battery.

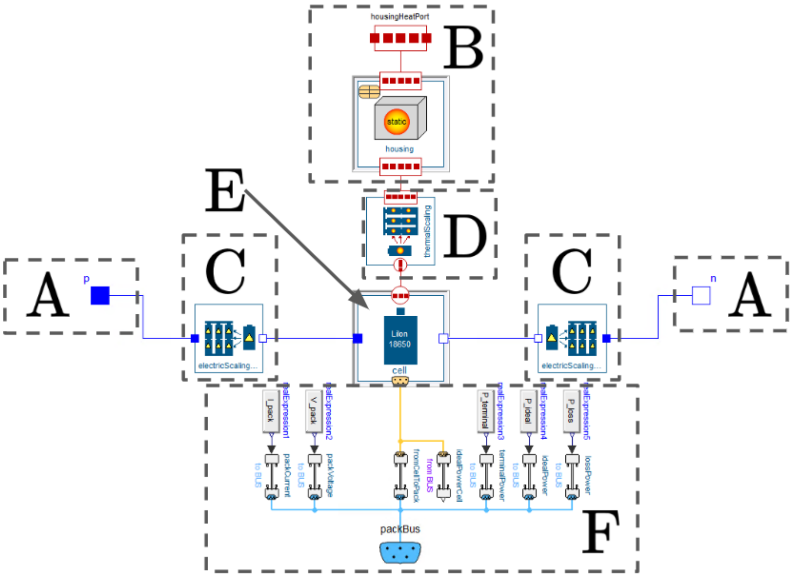

Figure 9. Battery model in Dymola using the Dassault Battery Library.

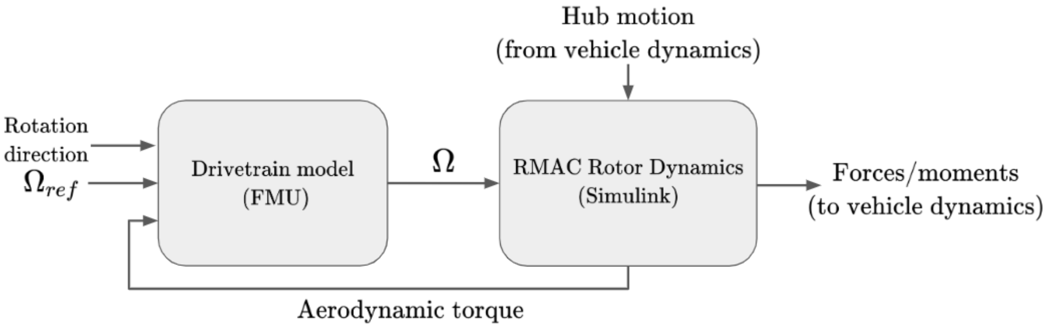

Figure 10. Interfaces between the electric drivetrain FMU and the RMAC rotor model in MATLAB/SIMULINK.

controller calculates the duty cycle of the drivetrain as a function of the rotor speed and the commanded speed. The controller is an explicit-model-following controller that can be tuned based on handling qualities requirements such as those in (Niemiec, Gandhi, et al. 2020), (Walter et al. 2020), and (Bahr et al. 2020).

Different electrified drivetrains can be used with the proposed interfacing approach, as long as the generated FMU can provide the same inputs and outputs for each variant, which are simple to define in Modelica. In this way, different model variants and architectures can be simulated by simply loading the desired FMU into the `FMIme` block from the FMI Toolbox (Modelon 2018). Thus, the integrated aerodynamic of RMAC and the electrical drivetrain developed in Modelica are simulated in MATLAB/SIMULINK.

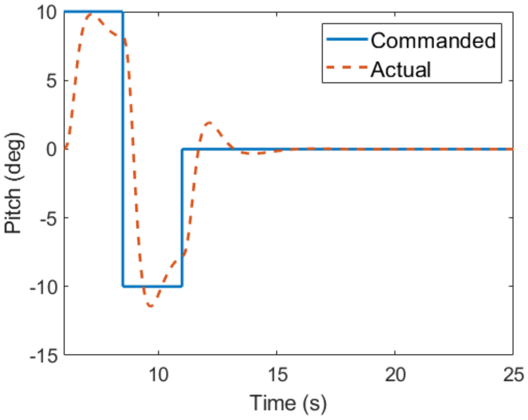

Figure 11. Pitch command and vehicle response.

4 Results

Using the proposed integration of RMAC with the FMI standard using the FMI Toolbox, both electrical architecture configurations of the eVTOL system in Figures 1 and 2 are analyzed next. All case studies simulate a heave command that is applied to study the interplay between the electrical drivetrain configuration and the aircraft dynamics. Six different cases were considered:

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) starting at 100% state of charge.
5. Centralized battery starting at 30% state of charge.
6. Distributed (individual) starting at 30% state of charge.

For the ideal voltage source cases, the battery is assumed to stay at a constant 60 V and would be able to supply power to the multicopter indefinitely, which is unrealistic. Thus, to highlight the importance of adequately modeling the battery, the model in Figure 9 is used for cases 3-6, where we apply the maneuver to the aircraft at the beginning of a flight (100% state of charge) and at the end of flight (30% state of charge).

To observe the closed-loop dynamic behavior of the vehicle subject to pitch, the command in Figure 11 is applied to the electrified drivetrains. The system is subject to a 10 degree pitch command for 5 seconds and a -10 degree pitch command for 5 seconds, as denoted by the blue line. The actual response of the controller is denoted by the red line in Figure 11. The command model in RMAC for pitch is a second-order model ($\zeta = 0.7, \omega_n = 3.46$ rad/s).

The front and rear rotors receive opposite commands to achieve the pitch behavior, as shown in Figure 12. The current drawn at each of the motors is shown in Figure 13, where the opposite speed commands are also reflected in the current draw. Since all of the motors are connected to one central battery, the current spikes in the motors cancel each other out when observing the total current draw from the battery (Figure 14).

Next, the distributed battery system in Figure 2 is subjected to the same pitch command. The speed response and current draw of the front and rear motors are identical to the centralized battery case, as shown in Figure 12. Since the spikes in the current draw from the front and rear motors cannot cancel each other out in this configuration, this ripple is observed in the battery voltage shown in Figure 15.

By exporting these mutlicopter models as FMUs to interact with RMAC, we can produce commands to show

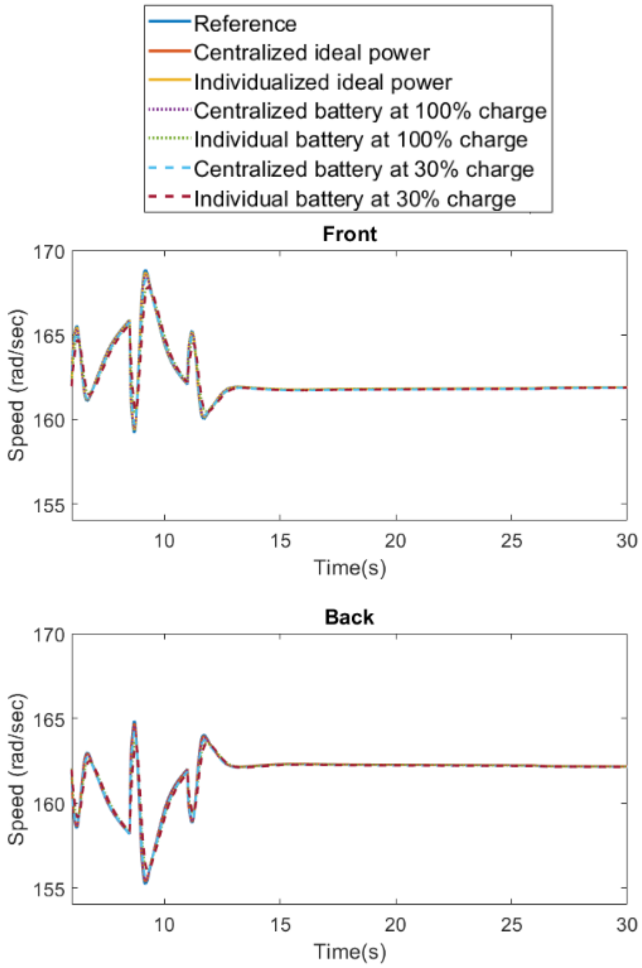

Figure 12. Speed response of multi-rotor system to pitch command.

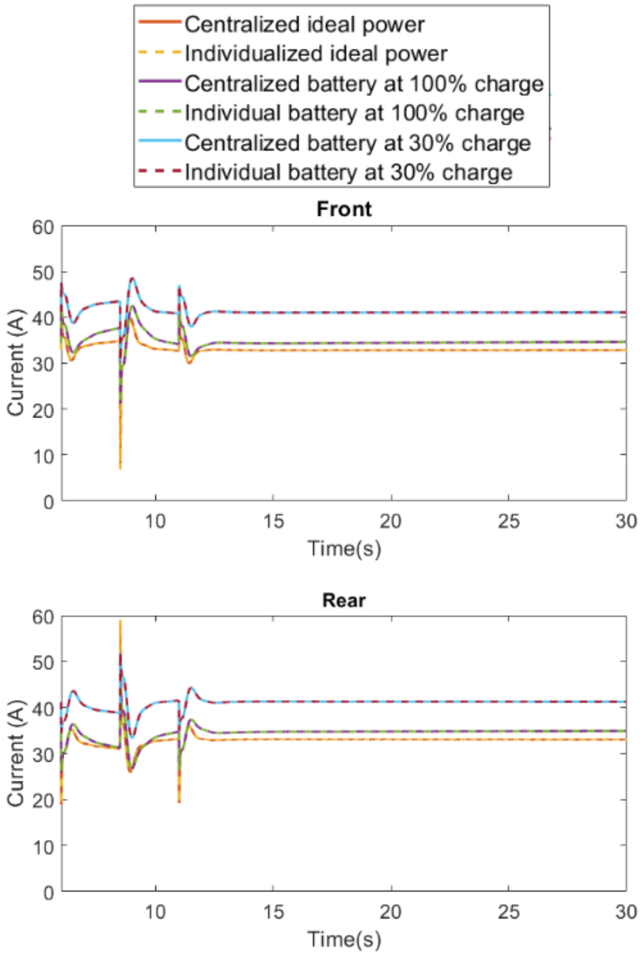

Figure 13. Current response of front and rear motors of multi-rotor system to pitch command.

that the system must be sized to accommodate the system architecture and desired commands. This modeling method allows us to compare both a centralized and distributed battery architecture, where both architectures produce the same speed response for a pitch command and thus have the same current draw per motor. This behavior is not observed in the electrical dynamics, where the current spikes are cancelled out when observed from the battery for a centralized architecture. If a centralized battery architecture is selected for the vehicle, the pitch command will not be the limiting factor that the battery must be sized to complete. When a distributed architecture is considered for a vehicle, the battery must be sized to accommodate for the current spikes produced by cases such as those of the pitch command.

5 Conclusions

The premise of the FMI standard is to enable model portability and re-usability, i.e. the usage of one model in many tools. This provides tremendous opportunities to extend the modeling capabilities of existing domain-specific tools. In the case of the emerging field of eVTOL, existing multicopter aerodynamic analysis tools can be expanded with relatively low effort to incorporate electric power train modeling capabilities.

In this multi-domain electrified drivetrain study for eVTOL, we showed how the FMI standard allowed us to integrate Modelica models with an existing specialized multicopter aerodynamic research tool (RMAC). To couple both modeling domains, RMAC provided aerodynamic inputs and feedback for the aircraft model in MATLAB/SIMULINK. Then, using the FMI Toolbox from Modelon, RMAC was extended to support electrified drivetrain models with specific input/output interfaces. Meanwhile, the FMI standard enabled us to utilize a multi-domain eVTOL drivetrain model developed in Modelica by using Dymola's export support for the Model Exchange specification. Thus, to couple the electrified drivetrains with RMAC it was possible to simply import the different model variants into MATLAB/SIMULINK to interact with RMAC.

The proposed coupling approach helped to obtain simulation results that enable a new understanding of the trade-offs between different types of propulsion architectures for new eVTOL vehicles. A centralized battery architecture can take advantage of canceling effects in the required

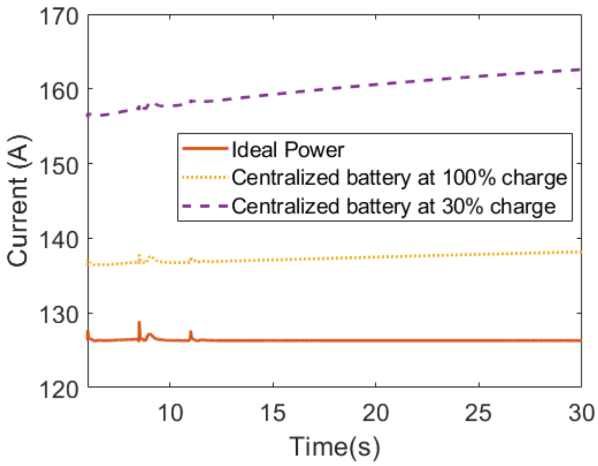

Figure 14. Current response of centralized battery of multi-rotor system to pitch command.

voltage/current, while a distributed architecture will need the battery to be sized by considering the load requirements resulting from heave commands.

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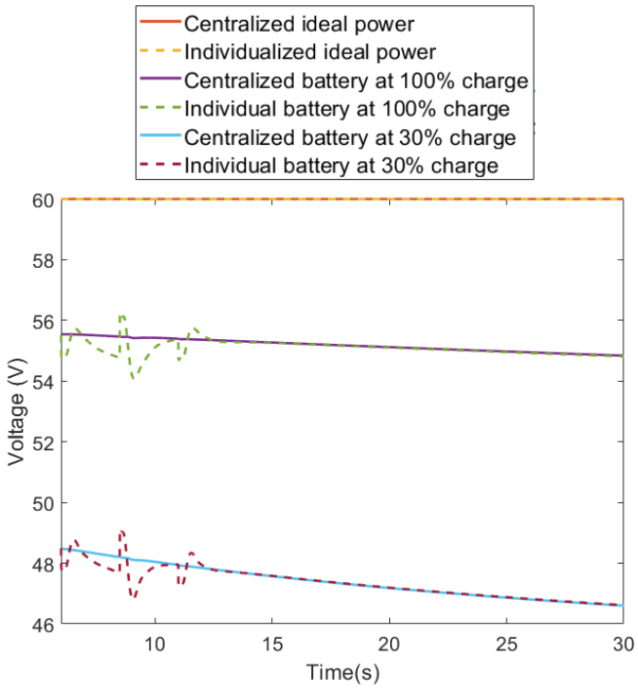

Figure 15. Voltage response of front and rear motors of multi-rotor system to pitch command.

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