Modelling and Sizing Framework for Hybrid-Electric Aircraft Architecture Development

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***Abstract*—This project aims to develop an electrical system for a hybrid-electric, regional aircraft as part of the drive towards more sustainable transportation. It wants to reduce the aviation industry's contribution to carbon emissions, looking at more green sources of power. This paper presents the design method for mathematical models to determine the electrical power system sizing for a parallel hybrid-electric aircraft architecture. The work includes an investigation of the power losses, volume, and weight of the gearbox, electrical machine, power electronic converters, circuit breakers, batteries, and fuel cells. The work shows potential weight savings by increasing machine speed and improving battery specific energy density. This EPS design has been conducted to form part of a larger study aiming to produce a hybrid-electric aircraft design.**

Keywords—Aircraft Architecture, Electrical Power System, Hybrid-Electric Aircraft, Hybridisation

I. INTRODUCTION

The drive for hybrid-electric aircraft that use electrical power for propulsion purposes has accelerated through the carbon-neutral agreement. This means that due to the promise of reducing the carbon emissions from aviation travel, which currently contribute to around 2% of the total carbon emissions in a year, greener methods are being explored [1]. Designing aircraft to incorporate an electrical propulsion system (EPS) allows for a variety of benefits, including reduced use of fossil fuels, less noise, increased reliability, and lower energy consumption.

Within the industry, conventional aircraft typically contain small amounts of electrical power required for some secondary systems. For example, on the Boeing 737, less than 100 kW of electrical power is used, while up to 30 MW of power is required for take-off from the combustion engines [2], highlighting the vast amount of power from fossil fuels.

The main electric propulsion classifications are turboelectric, hybrid-electric, and all-electric. These can be divided into six subsections, shown in Fig. 1. The different architectures require various components with turboelectric requiring a generator to convert power from the engine into electrical power, all-electric requiring electrochemical energy units as the only source of power, and hybrid-electric allowing for a combination of the different power sources.

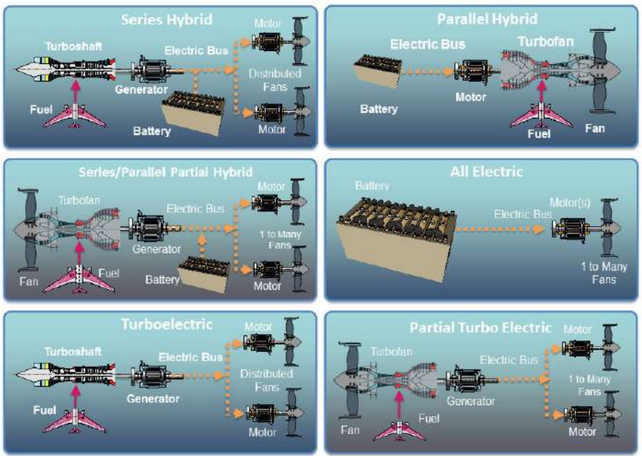

Fig. 1. Electric propulsion architectures [3]

The hybrid-electric architectures are the most suitable due to incorporating the key benefits of both internal combustion engines and all-electric aircraft. The electrochemical energy units can operate during high-power flight phases, to allow for the engine size to be reduced. Also, fewer technological advancements are required to implement the architecture in comparison to all-electric.

The parallel hybrid-electric configuration is most desirable for this project due to its design flexibility, high efficiency, and low electrical system weight. The other hybrid-electric configurations have more complexity and less flexibility, with higher electric system weight [4].

Fig. 2 shows the interactions between non-electrical and electrical systems, establishing the interactions between EPS models. The power management unit represents the components required between the electrochemical energy units to the electric machine (EM).

Developing models of the electrical system allows for reduced research costs and quicker progression of architectures, allowing for multiple case studies to be developed. This enables trade-off studies to be conducted at a range of operating points, with scalable solutions depending on aircraft size.

There are other projects in this area exploring the optimisation studies on hybrid-electric aircraft. For example, the Electrified Powertrain Flight Demonstration (EPFD) program, explores charge-depleting parallel hybrid-electric aircraft using multidisciplinary analysis and optimisation environment [5]. This work categorises the propulsion system components into energy, power, and thrust sources, using matrices to explain their relationships while focusing on the operational modes of the aircraft. Also, the Turbo Electric Aircraft Design Environment (TRADE) Clean Sky project looked at design and optimisation studies on specific aircraft configurations [6], concentrating on power flow to size the aircraft components.

This paper presents the methodology explored to produce mathematical models for the initial sizing calculations for the desired EPS. It displays key parameters as a function of weight, analysing the results to determine the optimum solution.

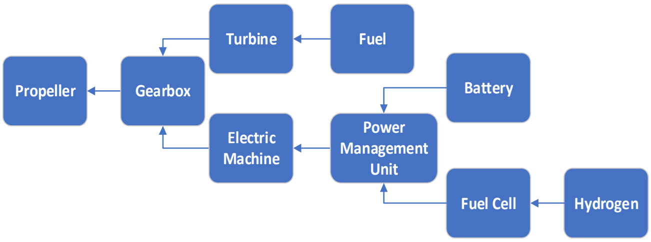

Fig. 2. Aircraft systems

The document is arranged into six sections, starting with the introduction. Following this, is section II which covers the hybrid-electric architecture, detailing the connections between electrical components. Section III explores the design methodology implemented for the mathematical models, with each component explored having its own subsection. This is followed by case studies in section IV. The penultimate section is V, with it exploring the future work with the expected next steps of the project. The final part of this document is section VI, which concludes the findings.

II. Architecture

The aircraft follows a parallel hybrid-electric architecture, containing both fuel cells and batteries. This allows for reduced power losses, scalability, and flexibility in the degree of hybridisation, while maintaining efficiency. This scalability can be seen in Fig. 3, with the aircraft being symmetrical on each side. Hence, the modelling considers the half-wing power, with the total power required being double the amount explored through the sizing equations.

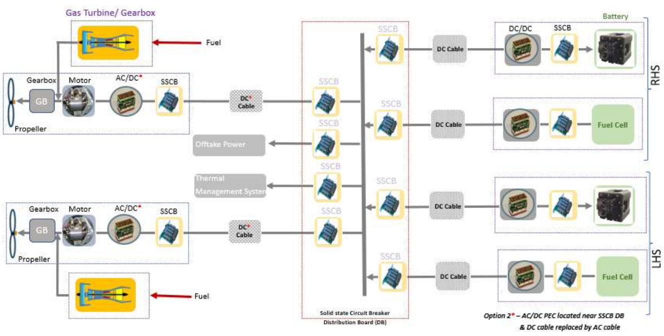

Fig. 3. Parallel hybrid-electric architecture

From the figure, the components explored during sizing can be noted. For example, within the EPS, both inverters and converters are required for different uses. From the motor to the EPS, an inverter is required to change from alternating current (AC) to direct current (DC). However, connecting the electrochemical cells to the rest of the EPS requires DC/DC converters to achieve the desired voltage levels. Also, the gearbox is the bridge between the electrical and mechanical components, with it having inputs from both the engine and the EM at different operating speeds, producing a single output to the propeller. The location of some components and the distribution board may vary to reduce system weight, as referred to in the figure by option two.

The main use of the EPS is to produce propulsive power to achieve the desired degree of hybridisation, while also providing off-take power for the onboard electrical systems and the thermal system. These loads receive their power from a battery and fuel cell combination. Depending on the flight phase, the battery can be both discharged to provide power and charged using the power from the engine, due to bidirectional connections and components within the EPS.

III. System Modelling and Sizing

The sizing models of the EPS aim to minimise the power losses of each component and determine the minimum weight and volume. These equations allow for the scalability of the solutions to ensure applicability for a range of systems, depending on the input parameters. Furthermore, the models can produce the thermal outputs of each component, allowing for trade-off studies to determine the optimum operating conditions and to explore potential solutions by looking at future technology.

The EPS requirements are determined through the power required by the propeller and the degree of hybridisation desired. This determines the power split between the engine and EPS system through the gearbox. This degree of hybridisation can be calculated by [7],

$$H_p = \frac{P_{EM}}{P_{total}} \tag{1}$$

Where P_{EM} is the EM power and P_{total} is the total power. This case study allows for a comparison between components' efficiency at a range of input powers.

Fig. 4 is based on a regional 90-passenger aircraft developed by Leonardo during the Clean Sky 1 activities. The figure shows the altitude compared to the required half-wing total power and electrical power for the aircraft, which are scaled with the maximum power requirement. This allows for the high-power flight phases during take-off, and cruise to be highlighted, which are where electrochemical energy units are expected to be in operation. The high altitude during the cruise allows for the use of fuel cells where thermal constraints are reduced. Whereas for the additional reserve phases considered, the total power can be seen coming from the engines, within none from the EPS.

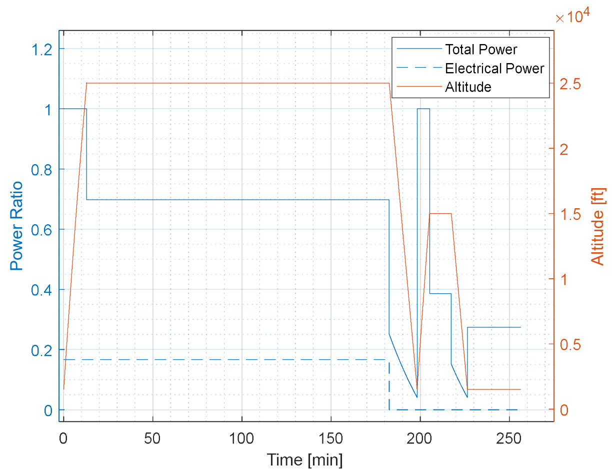

Fig. 4. Electrical power requirement for 90-seater regional hybrid-electric aircraft

A. Gearbox

The gearbox is being modelled alongside the EPS to show the effects of changing the EM speed on the connection between electrical and mechanical components, as EM speed can dramatically affect the gearbox sizing. Although, the gearbox sizing will only be an estimate in this paper.

The gearbox is modelled as one component with two inputs for determining the output torque, speed, and power. However, for determining the gearbox weight, the gearbox is considered as two different components due to it having two separate inputs, which have different efficiencies and gear ratios. These two gearbox weights are estimated using the powers and associated speed, by using equation (2) and equation (3) [8].

The equation below allows for the calculation of the parametric value,

$$Parametric\ Value = \left(\frac{hp}{RPM_{out}}\right)^{0.75} \times \left(\frac{RPM_{in}}{RPM_{out}}\right)^{0.15} \quad (2)$$

Where the parametric value is a parameter to be used in the following equation, hp is the input power to the gearbox, RPM_{in} is the input speed, and RPM_{out} is the output speed.

Then, from Fig. 5, the gearbox weight, in lbs, can be determined through the equation,

$$Gearbox\ Weight = -37.4246 + 116.3297 \times Parametric\ Value \quad (3)$$

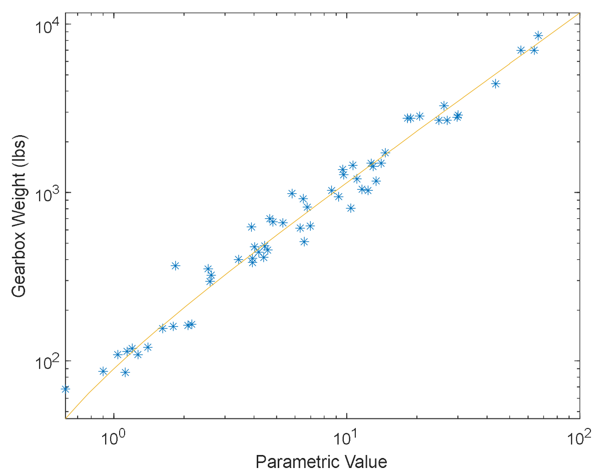

Fig. 5. Gearbox weight estimation from power and speed

Both the power and speed selected at the gearbox are then required to be fed into the EPS at the EM to determine the electrical components sizing.

B. Electric Machine

The EM is modelled as a permanent magnet synchronous machine (PMSM) during this study. This is due to its ability to provide greater specific power and current density while maintaining efficiency and being less than half the weight of its competitors [9]. This reduced weight for performance benefits indicates its suitability for aerospace applications.

Using the D²L sizing equation [10], the weight and volume of the EM can be sized, given that the mechanical inputs are received. These mechanical inputs (speed and power) are found through the gearbox sizing and the degree of hybridisation, with speed given as a range to determine an optimum speed-to-weight ratio of the EPS. The key parameters used to determine the volume for the EM are given in Table I. This D²L sizing equation is shown below,

$$[D^2L] = \frac{P_{EM}}{\left(\frac{\pi^2}{60}\right)\omega_{EM}\eta_{EM}PF\sigma_m X_m} \quad (4)$$

Where P_{EM} is the machine's mechanical power, ω_{EM} is the EM speed, η_{EM} is the efficiency of the EM, PF is the power factor, σ_m is the magnetic shear stress, and X_m is the machine topology scaling constant. For this equation, the operation speed can be varied, which is inversely proportional to the motor volume. This allows for a clear comparison between volume and speed, requiring fewer parameters than other sizing equations available for EMs.

TABLE I. ELECTRIC MACHINE PARAMETERS [10]

Description	Parameter
Efficiency (%)	98
Power Factor	1
Shear Stress (kPa)	51
Machine Scaling Constant	1

To obtain the weight estimate from the volume, the volumetric density is assumed to be 2700 kg/m³ [10].

This sizing method includes various assumptions to generate initial sizing estimates for powers, weight, and volume. For example, the assumption of machine shear stress is based on literature, rather than finite element analysis which many EM models look at.

C. Power Electronic Converter

Both the inverter and DC/DC power electronic converters (PECs) follow the same mathematical-based modelling for their sizing. The modelling follows a modular approach, allowing for a build-up of 200 kW and 500 kW modules, with specific power densities (SPDs) ranging from 20 to 25 kW/kg and nominal efficiency of around 96% [6].

Within Fig. 6, the PEC sizing is split into steps that will be conducted. This approach involves exploring the modules that make up the PEC block, as well as the cooling plates and controllers, before combining the sizes to produce an overall weight and volume for the component. These parameters calculated are then to be fed back into the structural model of the aircraft to determine an aircraft weight.

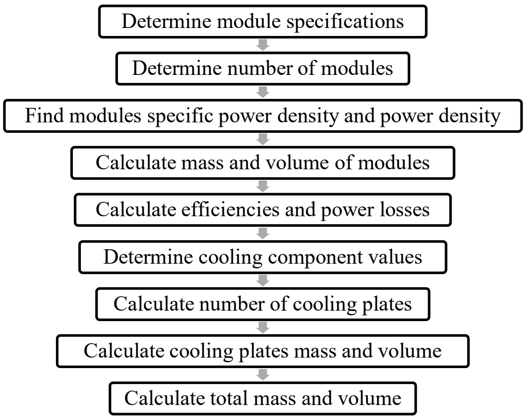

Fig. 6. PEC sizing flowchart

The cooling component considered for the PEC design is cold plates to disperse the power loss. These will then go on to determine the component's thermal outputs.

The total weight and volume of the PECs takes into consideration the modules, cold plates, and estimates an additional 3% for the controllers.

D. Battery

The battery is modelled assuming the composition to be lithium-ion, due to its high energy density and quick recharging capabilities. Its popularity onboard aircraft is due to its high energy density, with long service life and quick recharging, making it suitable for continuous usage.

Unlike the other electrical components, the modelling of the battery requires both energy and power demands to be met. As it must be able to supply the maximum power required over the timeframe. This requires the battery to be sized for the maximum of both conditions, for SPD, assuming 0.9 kW/kg, and for specific energy density, assuming 0.3 kWh/kg. Furthermore, the battery cooling system is the same cold plates as that used for the PEC.

The modelling of the battery looks at building up cells in series and parallel configurations to achieve the power and energy requirements, ensuring that it can achieve the maximum requirements. Furthermore, a minimum state of charge must be implemented into the battery design. Then, as shown in Fig. 7, the cell sizing can be fed into the cooling components of the battery, before determining the overall battery pack size.

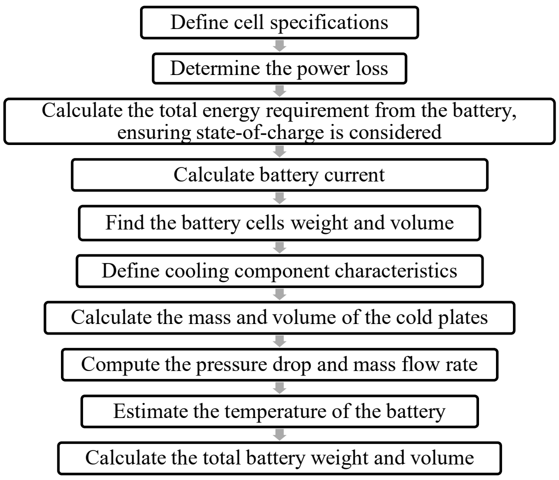

Fig. 7. Battery sizing flowchart

The battery is also more susceptible to changes in its environment than other components. The performance and lifespan of the battery cells are depended on the operating conditions, meaning that the battery thermal management and control systems play a key role in ensuring prolonged use for maximum performance benefits. This allows for the high efficiency at nominal power to remain at around 99%. A minimum state-of-charge is assumed to be set at 20% to avoid deeply discharging the battery, due to lithium-ion instability and voltage level drops at low state-of-charge [11, 12].

The battery management system plays a key monitoring role in ensuring safe operation, maintaining functionality, and controlling both the power and energy available [13]. Therefore, this management system is represented in the weight calculations in addition to the battery cells and cooling plates as an additional 5%, which is larger than the controllers represented in other models.

E. Solid State Circuit Breakers

The main function of circuit breakers is to operate as protective equipment to limit a failure from being propagated throughout the EPS. This encourages an alternative route for power flow through the system to provide sufficient power for a safe flight.

Solid state circuit breakers (SSCB) are a type of circuit breaker that allows for ultra-fast operation (within 100μs), meaning a much quicker reaction time to detect faults than other types available [14]. Although, this comes at the expense of high on-state losses.

The SSCBs modelling follow a similar 200kW and 500kW module approach as the PEC. Although, SSCBs are sized using only power densities, rather than considering energy. This means the modules can be stacked to form the power requirements and require thermal considerations due to their high on-state losses because of the substantial amounts of power being transmitted over a short time. Also, depending on if the SSCBs are required to be bidirectional or unidirectional, there can be a significant difference in the achievable power densities.

F. Fuel Cell

Fuel cells (FCs) allow for electrical power to be generated in a similar way to conventional kerosene used on aircraft while retaining positive environmental effects. This means that they can continuously produce electrical power if the hydrogen supply is maintained, causing their main limit to be the storage space available for hydrogen fuel. Therefore, when sizing the volume of FCs, the hydrogen requirement must be taken into consideration with it having a considerable effect.

For these initial studies, a basic FC model has been created, which follows a similar approach to battery sizing for simplicity.

They are modelled as stacks that can be scaled accordingly to provide both energy and power requirements. Although their main function is during cruise conditions, due to thermal requirements, the main drawback to FCs is their low efficiency at around 60% [15], and high thermal losses. Therefore, incorporating the FCs cooling components as part of the design can have a considerable effect on the overall size.

IV. SIZING CASE STUDIES

Within this section, some design case studies have been explored to find the optimum operating conditions of the components to determine the minimum weight of the system. The EPS components included in the total weight are displayed in Fig. 2, with the case studies displayed in the following subsections assuming half-wing power. Hence, the total weights given represent half of the EPS overall weight on the aircraft. For initial calculations, the battery is assumed to operate during the low altitude flight, with the FCs operating at higher altitudes where thermal constraints are reduced. This means that the FCs shall be used for a prolonged time during the cruise of the aircraft. The three case studies explored have large impacts on the sizing of electrical components within the system. The first case study looks at the EM speed as this affects the weight of both the EM and the gearbox, hence the exploration of gearbox sizing during this study. The second case study looks at the effects of varying cell specific energy density on battery weight. This is important when considering future technologies to see the potential weight savings if technological advances can be achieved. The final case study is the effect of varying the degree of hybridisation on power losses.

A. *Electric Machine Speed*

The balance between low-speed, high-torque and high-speed, low-torque EMs can have an influence on the sizing of multiple components within the system. The inclusion of the gearbox as part of the architecture was to allow for an optimum electrical machine speed to be determined for both electrical and mechanical systems.

Initial calculations show that the optimum speed for the EM to operate is between 9,000 and 10,000 RPM to achieve minimum weight within the system, as shown in Fig. 8. The slower the EM the faster the weight increase as the gearbox only gradually increases as speed increases, whereas the EM has the much faster decrease in weight with speed initially. As the weight increases at the fastest speeds shown on the graph, the weight of the EM remains almost constant with the gearbox weight continuing to slowly increase.

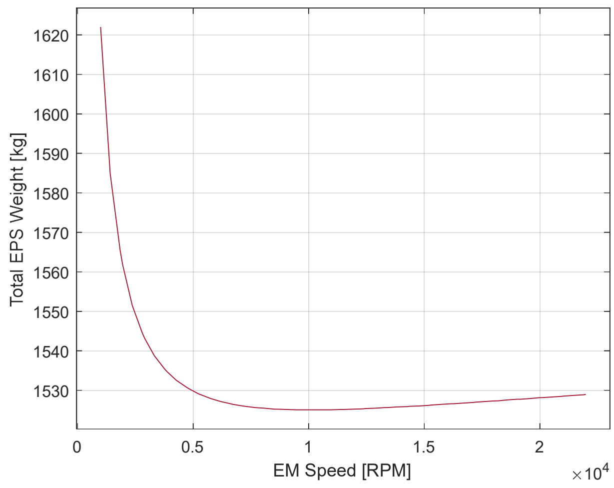

Fig. 8. EPS weight for the half-wing power as a function of EM speed

B. *Specific Energy Density*

The specific energy density (SED) of batteries is a limiting factor for battery use in the EPS. For example, low SED values make batteries undesirable for prolonged usage.

Varying the cell SED in relation to weight allows the influence to be highlighted, as shown in Fig. 9. This graph shows the potential weight saving if battery SED can be increased to the predicted values expected to be achieved in the future.

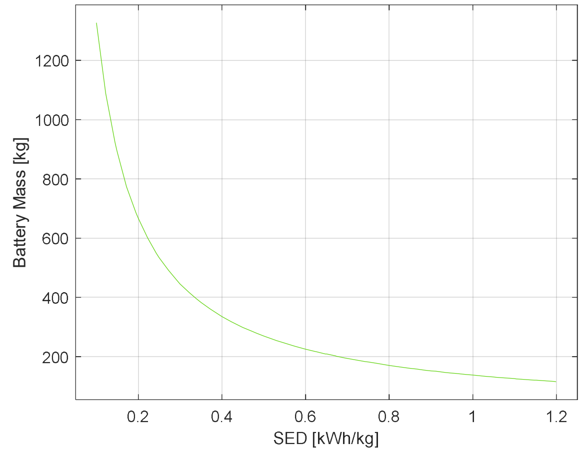

Fig. 9. Battery weight for the half-wing power as a function of the cell SED

This case study assumes that the SPD is not a driving factor in the battery design. Whereas, if the SPD is set at 0.9 kW/kg, the weight would no longer decrease after the SED reached 0.3 kWh/kg, due to the SPD becoming the driving factor rather than the SED. This is because there needs to be a balance between increased SPD and increased SED to achieve the minimum weight possible. Therefore, some of the weight values are idealised in the graph to show potential outcomes if only energy is concerned.

C. *Power Losses*

This case study explores the change in power losses with the power demanded from the electrical system. As the degree of hybridisation increases, the power losses also increase. It assumes that the EM speed is set to 9kRPM for this case study and that both the FCs and battery increase to cope with the higher degrees of hybridisation.

Within Fig. 10, the FC has the greatest power losses, with them increasing at a much steeper rate than the other components. This is due to their high thermal losses and low efficiency. Whereas the power losses for the battery are much smaller and increase at a slower rate due to their high efficiency.

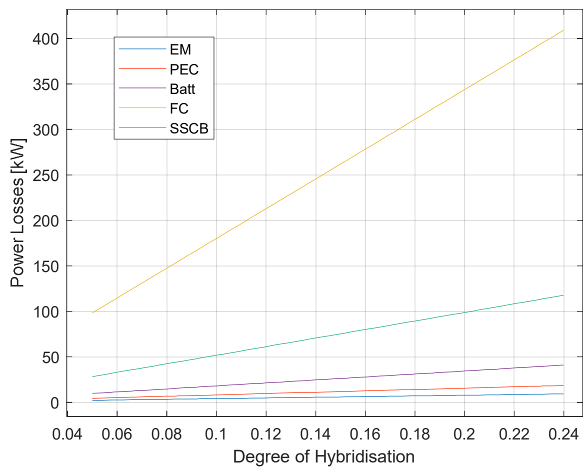

Fig. 10. Half-wing power losses as a function of the degree of hybridisation for each component

The increase in power losses has a direct correlation with the increased power demand and component sizing. As larger powers are demanded from the EPS, larger systems are required to cope with the increased demands, and hence larger losses because of the increased system sizes. Furthermore, the higher the initial power losses for each component, the greater the increase as the degree of hybridisation increases.

V. Future Work

The next stage involves increasing the detail of models, such as the EM and battery. This will allow for the exploration of voltage levels across the EPS, and how it affects the sizing of the system, which involves introducing cable sizing into the models. Then, multiple case studies and trade-offs can be conducted. For example, one case study will be conducted to compare the battery and fuel cell combination during the mission duration.

VI. Conclusion

This work displays the architecture for a future hybrid-electric aircraft being designed by the University of Nottingham and Leonardo Aircraft in an ongoing project. The document includes the mathematical modelling approaches used for the gearbox, electric machine, power electronic converter, circuit breaker, battery, and fuel cell. The case studies presented highlight the potential weight savings when varying machine speed and cell specific energy density. While future work looks to explore the effects of voltage variation over the EPS and the power split between the electrochemical energy units.

Acknowledgement

This project is a collaboration between the University of Nottingham and Leonardo Aircraft, with the joint aim to produce a hybrid-electric aircraft design.

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