



Dual stage battery sizing and performance assessment on-board hybrid electric aircraft

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Abstract

Reducing the aviation industry's contribution to carbon emissions involves exploring increased electrified aircraft, including hybrid-electric and all-electric. As part of this, the aircraft architecture will have increased electrical components. The design of these components will dramatically affect the aircraft's sizing and performance. Hence, the advancement of technologies is essential to ensure the feasibility of such aircraft. For example, the advancement of battery systems, particularly power and energy densities, allows for more energy storage within the same space and weight. Modelling of these batteries allows the performance to be evaluated at both system and aircraft levels before implementation into an actual aircraft, reducing the uncertainties surrounding the design. This paper presents analytical modelling to produce a battery, split between sizing and performance. This allows for the battery to be sized for maximum conditions while the performance aspect of the battery can have multiple mission profiles applied for one size. The design follows industrial modelling requirements, sized for power and energy, to allow the model to be implemented within an aircraft design.

Keywords: Modelling, battery, on-design, off-design

1. Introduction

The increased electrification of transportation is an area that has seen large developments within the past 10 years. All sectors of transportation are aiming to reduce carbon emissions, to be carbon neutral by 2050. Some sectors, such as automotive, are paving the way for this and having success with electrical alternatives.

Within the aerospace sector, the number of electrical systems onboard have been increased. Although currently this is mostly restricted to secondary systems. Therefore, exploring possibilities for electrical and hybrid-electric propulsion is an area gaining more interest within research.

In hybrid-electric aircraft, electrochemical energy units are expected to provide some of the power. Therefore, accurate modelling of the electrochemical energy units, such as batteries, is essential to ensure sufficient power is maintained in the aircraft during flight.

As part of the battery design, there are various chemistries explored for aviation purposes, with lithium-ion showing the most potential for implementation into hybrid-electric aircraft. Within the lithium-ion category, there are six chemical compositions available, which are lithium nickel manganese cobalt oxide, lithium cobalt oxide, lithium-ion phosphate, lithium manganese oxide, lithium titanate, and lithium nickel cobalt aluminium oxide. Lithium-ion phosphate is considered the most suitable for aviation purposes with it being the safest. Other desirable properties of this composition include a long-life cycle, thermal stability, low resistance, and high current rating with enhanced safety [1].

Typically, mathematical battery models within literature concentrate on the performance aspect, with few exploring sizing. For example, some models concentrate on implementing the Shepherd model to determine the battery performance [1, 2]. While the work in [3] explores the number of cells required and the performance of the battery. Although, it does not explore the thermal system, or the estimated pack weight and volume. For implementation into aircraft models, both sizing and performance are crucial.

The purpose of this paper is to cover the equations and assumptions for both on-design and off-design modelling. The on-design refers to the sizing modelling, which determines the maximum weight and volume for the battery, including required cells and cooling plates, for nominal conditions. This sizing can be fixed, and various missions are applied during the off-design modelling, the performance of the battery, which includes actual voltage, state of charge, and power losses. Also, within the paper, case studies are explored to show the influence of power, energy, and voltage on battery sizing.

The document is arranged into seven sections, starting with the introduction. Following this section, is section 2 which explores the modelling approaches, detailing different methods to create battery models. Section 3 covers the methodology implemented within this paper, splitting it between the sizing and performance characteristics of the battery. This is followed by section 4 which displays the verification. Section 5 looks at the case studies. The last section concludes the findings of this paper.

2. Modelling Approaches

Modelling batteries for aircraft applications involves using the maximum design conditions. This allows for the battery to be capable of supplying power for the worst-case scenario. Setting the battery at the maximum size means that it can be capable of delivering a variety of missions.

When designing a battery, some key aims should be achieved through the model. The design aims to ensure that it is safe (not likely to have a thermal breakdown), can deliver power continuously (irrespective of the operating environment), is lightweight, small volume, and should have a long lifespan for operation, with low maintenance [5]. These are the essential requirements for a battery design, with the performance of the system being a lower priority.

The approaches used for battery modelling can vary depending on the desired outcomes and the level of fidelity required. The three main categories for designing batteries are electrochemical, analytical, and electrical circuit models [6]. Each of these models has a specific purpose.

The electrochemical model is used to explain the chemical processes occurring within the battery. This produces the most detailed model, exploring reactions occurring at the anode and cathode within the battery cell and the flow of electrons. Often, this level of fidelity is not required for battery modelling in aircraft applications, with them being complex and difficult to configure.

The analytical model is aimed to be a useful tool for system designers to predict behaviours through mathematical equations. This involves a detailed mathematical model to represent the key behaviours, with equations often derived from electrical models. This method is considered an easier-to-use approach with the main properties of the battery being represented through a few equations [7].

The electrical circuit model is used to build up a battery-equivalent electrical circuit, useful for building up other electrical system circuits for design and simulation purposes. This uses a block to represent electrical components, such as resistors, within the model. This model is useful to see the electrical interactions between components and performances. They often require lookup tables from experimental data on the battery's behaviour to simulate the performance [7]. This allows different cells to be explored with only a few differences in the build-up of the model.

The battery performance models may also be split into a series of different modelling approaches. The main performance-based approaches include the ideal battery, the Thevenin-based electrical, the impedance-based, and Shepherd's model. As part of this report, the only performance-based approach applied is Shepherd's model, with more detail relating to the others found in [8].

Within this paper analytical models have been explored for sizing and performance purposes, producing a mathematical-based model to show different characteristics of the battery design. This method of battery modelling was explored due to the desire for both sizing and performance within the model. The level of fidelity of an electrochemical model was unsuitable, and an electrical circuit model would not produce the desired outputs. Due to the mathematical nature of the model, Matlab and Simulink were used as a tool to create the desired model.

During the modelling process, the same battery characteristics can be assumed for both charge and discharge for simplicity [1]. However, the charge and discharge will be represented differently using equations, and the power flow will be in the opposite direction affecting the calculated values.

3. Sizing Methodology

The sizing of the battery is split into two sections, the on-design and the off-design. These look at the maximum sizing and performance for a given mission.

3.1 On-design

The on-design refers to the sizing of the battery for nominal power and total energy requirements. Therefore, in the event of failure, it is capable of higher power demands than the mission was originally intended to require. This also means that once the battery is sized, it can be used for a variety of given missions that do not exceed the maximum conditions set during the on-design modelling.

The on-design modelling should determine the weight and volume, as well as the temperature for maximum power demands, as shown in Figure 1.

Determining the cell and cooling plate data can dramatically affect the sizing of the battery design.

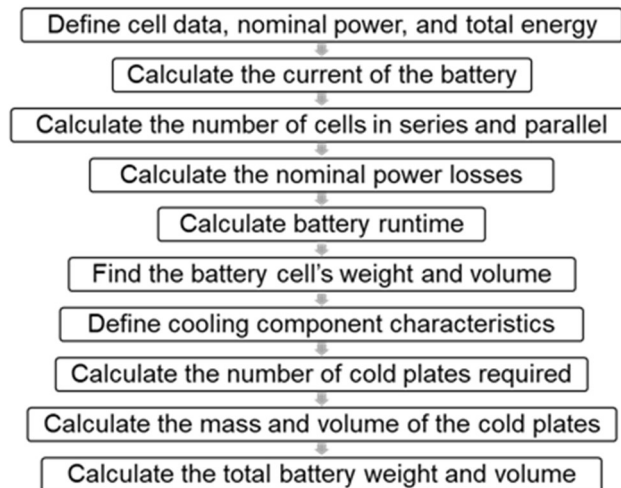


Figure 1: Sizing methodology flowchart

The battery composition can be determined by the number of cells in both series and parallel. This is because the number of cells in series makes up the voltage, while the number of cells in parallel makes up the current, as seen in equations (1) and (2), respectively. The total number of cells should be capable of delivering the maximum required energy.

$$N_{cell_series} = \frac{V_{nom_batt}}{V_{nom_cell}} \quad (1)$$

$$N_{cell_parallel} = \frac{I_{nom_batt}}{I_{nom_cell}} \quad (2)$$

where I_{nom_batt} is the nominal current of the battery, and I_{nom_cell} is the nominal current of one cell.

Included within the design of the battery is the cooling plate sizing. Designing a cooling system aimed to monitor and control the temperature is essential to ensure safe operation and optimum performance. The battery temperature must be maintained within the operating range usually considered to be 20 to 60°C. Therefore, sizing the cooling system to ensure the temperature remains constant across all the cells during operation involves calculating the maximum mass flow rate required for cooling.

$$\dot{m}_{in_max} = \frac{PL_{batt}}{\Delta T \times C_w} \quad (3)$$

where PL_{batt} is the power loss of the cells, ΔT is the temperature difference across the battery (5°C as a maximum but ideally 3°C), and C_w is the specific heat capacity of the cooling fluid, assumed as 2000 J/kgK in [9].

3.2 Off-design

The off-design modelling of the battery looks at performance characteristics for a given mission. This requires both nominal power and total energy values to be provided to the model. The inclusion of energy rather than time allows for integration into aircraft models.

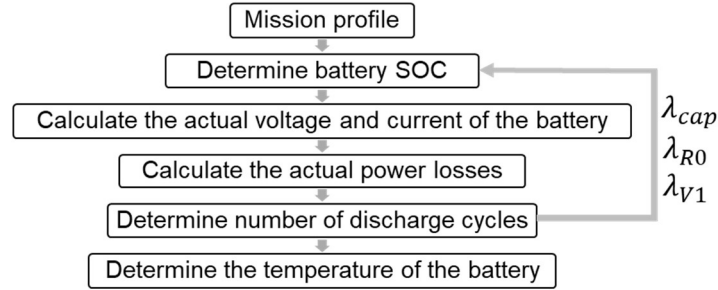


Figure 2: Performance methodology flowchart

Within the off-design modelling, control loops are introduced to ensure that an iterative approach is followed, allowing for both actual values and battery fade to be correctly implemented within the method.

3.2.1 State-of-charge

The state of charge (SOC) is determined as a comparison between the available energy within the battery compared to the amount of energy used at a given point.

The Coulomb counting equation is used to compute the SOC at a given point in time [10]. With the equations being in the continuous-time domain, a continuous current is also required, referred to as the actual battery current. This method of determining SOC relies on an accurate calculation of the current and is sensitive to parasite reactions that occur as the battery approaches full charge [11].

$$SOC_{batt} = SOC_{batt_0} - \frac{100}{3600 \times Cap_{batt}} \int_0^t I(t) dt \quad (4)$$

$$Cap_{batt} = \frac{E_{batt_total}}{V_{nom_batt}} \quad (5)$$

where the t is the unit of time (s), SOC_{batt_0} is the initial state-of-charge (%) at $t=0$, $I(t)$ is the current (A) flow into or out of the battery at time t , and Cap_{batt} is the capacity of the battery (Ah).

3.2.2 Voltage

For determining the battery voltage, the model follows the Shepherd equation, with the parameters being available from the manufacturer's datasheets rather than requiring experimental data. This is

a dynamic model for calculating actual voltage, developed from the equivalent circuit theory. The Shepherd equation (6) can be split into three parts to determine the output voltage, V , which includes the equivalent circuit, the polarisation effect, and the exponential voltage. Within the figure below, the combination of voltages can be seen that make up the terminal voltage.

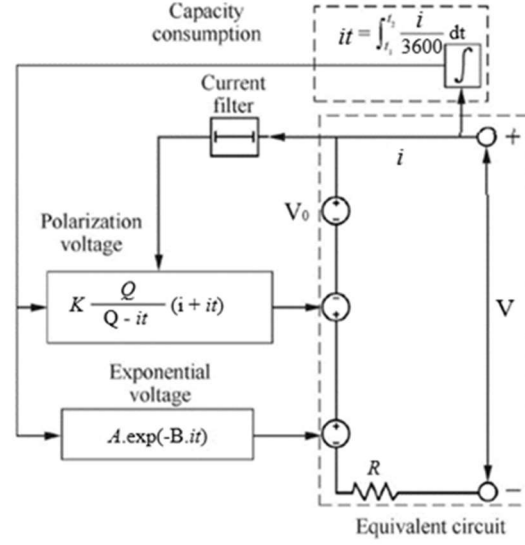


Figure 3: Dynamic model of battery using the Shepherd equation [12]

From this figure, the discharge voltage can be calculated as follows,

$$V = V_0 - R \cdot i - K \cdot \left(\frac{Q}{Q-it} \right) (i + it) + A \cdot \exp(-B \cdot it) \quad (6)$$

where V_0 is the constant battery voltage, K is the polarisation constant, Q is the maximum capacity, i is the current, it is the actual battery charge ($it = \int i dt$), R is the ohmic internal resistance, A is the exponential zone amplitude, and B is the exponential zone time constant inverse [2].

Whereas, the charging voltage can be determined by,

$$V = V_0 - K \cdot \left(\frac{Q}{it-0.1Q} \right) it - K \cdot \left(\frac{Q}{Q-it} \right) it - R \cdot i + A \cdot \exp(-B \cdot it) \quad (7)$$

Determining the parameters required for the Shepherd equation use the equations (8-11) [3] obtained from points on the discharge curve, shown in Figure 4. This curve shows the expected change in voltage as the capacity of the battery varies.

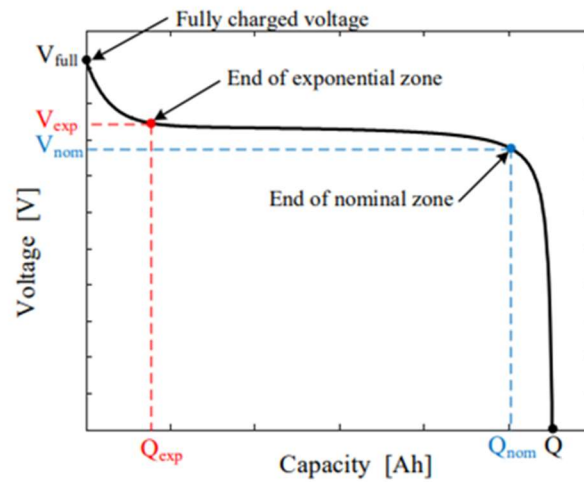


Figure 4: Typical lithium-ion phosphate battery discharge curve [3]

Considering the points shown on the discharge curve and the equation for the discharge voltage, the following equations can be obtained to calculate the required parameters.

$$V_{exp} = V_o - K \cdot \frac{Q}{Q - Q_{exp}} (i + Q_{exp}) + A \cdot e^{(-B \cdot Q_{exp})} - i \cdot R \quad (8)$$

$$B = \frac{n}{Q_{exp}} \quad (9)$$

$$V_{nom} = V_o - K \cdot \frac{Q}{Q - Q_{nom}} (i + Q_{nom}) + A \cdot e^{(-B \cdot Q_{nom})} - i \cdot R \quad (10)$$

$$V_{max} = V_o - i \cdot R + A \quad (11)$$

where n varies from two to four depending on the cell chemistry. For example, n is approximated to four for a lithium-ion phosphate cell, while for a nickel manganese cobalt it is approximated to two [3].

3.2.3 Battery fade

Within the battery models, a few performance characteristics will deteriorate over time as it begins to age. This can be represented through the fade equations which calculate the number of discharge cycles the battery has undergone and the effects this has on cell capacity, internal resistance, and voltage. The number of discharge cycles can be calculated by [13],

$$N_{cycle\,discharge} = N_{cycle\,discharge_0} + \frac{1}{Cap_{batt}} \int_0^t \frac{i(t) \times H(i(t))}{\lambda_{cap}(t)} dt \quad (12)$$

where $N_{cycle\,discharge_0}$ is the number of full discharge cycles completed before the start of the simulation, $H(i(t))$ is the Heaviside function of the instantaneous battery output current (the function returns zero if the argument is negative, and one if it is positive), $i(t)$ is the actual current, Cap_{batt} is the battery capacity, and $\lambda_{cap}(t)$ is the multiplier for the battery nominal capacity.

Determining the number of discharge cycles the battery has undergone allows for the performance deterioration to be determined. This can be done using a series of equations to calculate the decline in capacity, internal resistance, and voltage.

$$\lambda_{cap} = 1 - k_1 N_{cycle\,discharge}^{0.5} \quad (13)$$

$$\lambda_{R0} = 1 - k_2 N_{cycle\,discharge}^{0.5} \quad (14)$$

$$\lambda_{V1} = 1 - k_3 N_{cycle\,discharge} \quad (15)$$

where k_1 , k_2 , and k_3 are coefficients that are given the values 1e-2, 1e-3, and 1e-3, respectively [13].

3.2.4 Verification

The verification of the model was conducted by comparing the results of this model to that produced via a Simulink model. The battery is sized using a ANR26650M1 lithium-ion phosphate cell [14].

For on-design verification, the models required the same number of cells in series and parallel for a given power, meaning that the battery capacity was the same for both models. Whereas, for the off-design verification, the results are displayed in Figure 5. The battery model created using this methodology is shown against a Simulink battery model, displaying the cell discharge curves for both.

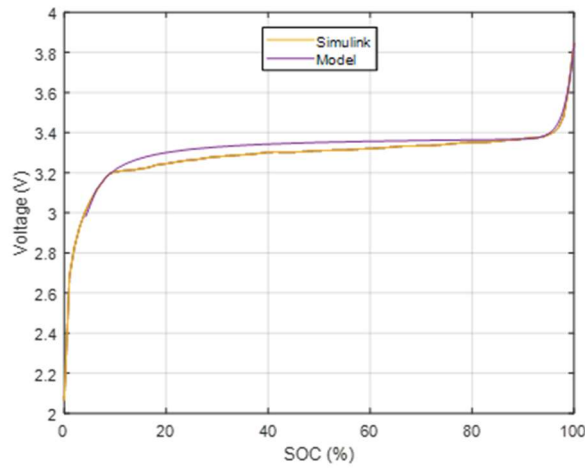


Figure 5: Battery cell discharge curve verification against the Simulink model

The differences between the models can be explained by the complexity of the equations implemented. Within the Simulink model, the internal resistance varies, while the model created using this methodology, assumes that internal resistance is constant. Therefore, the increased voltage drop in the discharge curve could be due to fluctuation in internal resistance and power losses.

3.2.5 Case Studies

Some design case studies were assessed to see the response of the model during different operating conditions, including high-power, high-energy, and voltage variation.

For these case studies, the battery cells are based on the EiG ePLBC C020 [15], and the cooling plates are based on the Lytron standard vacuum-brazed cold plate model CP20 [16].

These case studies were based on a mission profile obtained from literature [17], shown in Figure 6, and considered for both high power and high energy. For comparison between the case studies, the energy remains at 390kWh for the high-energy and high-power case studies, with the power value and duration of the mission changing.

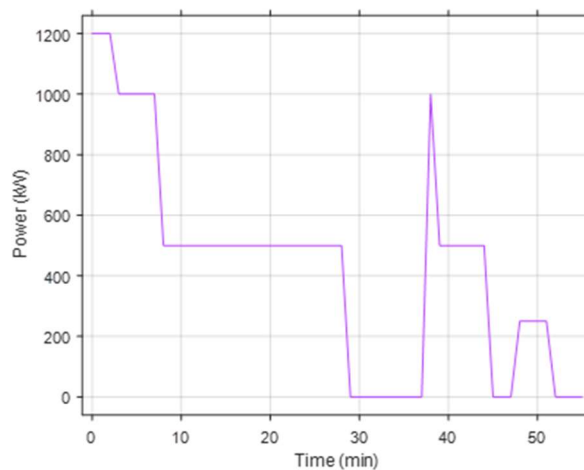


Figure 6: Case study mission profile

For the high power and high energy, the power values and mission duration were varied, with the total energy considered to remain constant throughout. As can be seen in the table below, the sizing varies between the two case studies considered.

Table 1: Case studies comparison for battery sizing

	Standard	High-energy	High-power
Nominal Power (kW)	1200	300	4800
Total Energy (kWh)	1201	500	4804
Cells in series	278	278	278
Cells in parallel	60	25	240
Capacity (Ah)	1080	450	4320
Mass (kg)	7196	2994	28783
Volume (m ³)	3.53	1.46	14.11

Furthermore, the final case study explores the variation in voltage for the on-design sizing of the battery. The voltage sensitivity study investigates parameter variations as the nominal voltage is varied. Within this study the capacity, number of cells in series, and number of cells in parallel change. Seen in the figure below, is the variation of capacity with nominal voltage, comparing this to the number of cells. Due to the number of cells required in both series and parallel, the total number will fluctuate to accommodate for both voltage and current. Therefore, due to the complete rows and columns required, the total number will vary.

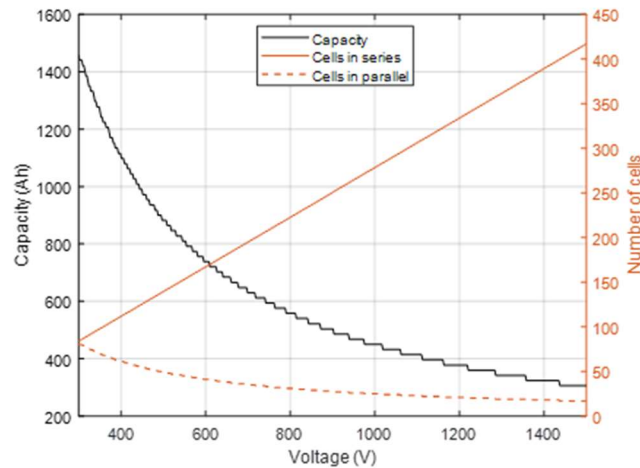


Figure 7: Number of cells and capacity variation with a nominal voltage

The number of cells in parallel decreases at a slower rate than the increase in cells in series. This is due to the total number required to provide the total energy. The number of cells in series is determined by the voltage, and the number of cells in parallel is determined by the current.

This variation in voltage influences the on-design sizing of the battery. As the number of cells varies, both the mass and volume vary. The steps in the values show the trend as the number of cells in parallel increases, the number of cells in series falls for the power and energy requirements, creating the fluctuation in sizing.

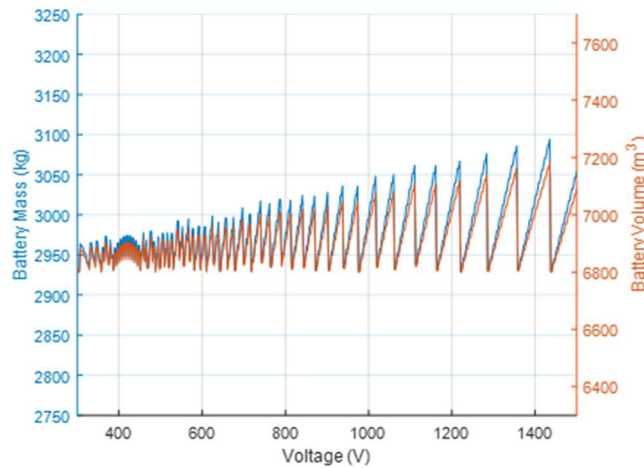


Figure 8: Variation of voltage on battery sizing

4. Conclusion

The analytical battery model produced allows for both the sizing and performance to be determined for a range of different power profiles. The model allows for scalability, with it being able to size a battery for a large range of different aircraft. Although, the cell data may need to be explored depending on the requirements of the design. For example, some cells are designed for high-energy purposes, while others are designed for high power. The model created is designed to be implemented within an aircraft design, with the battery sizing influencing the sizing of the aircraft.

5. Future Work

The next stage of this project involves exploring analytical models for other components within the powertrain, for example, the exploration of power electronic converters and electric machines. This involves determining the sizing and performance of each component to achieve the optimum voltage levels across the propulsion system.

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