Optimal sizing of hybrid electric propulsion system for eVTOL

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Abstract. Electric propulsion unmanned aerial vehicles (UAVs) attract much attention in aviation industry, with electric vertical take-off and landing (eVTOL) aircraft tending to gain ground. The current development of hybrid eVTOL aircraft intended for urban air mobility is facing many technical challenges. Among these challenges rises the optimal sizing of its hybrid power system (HPS). The latter requires an energy management strategy (EMS). In this paper, the adopted management strategy is based on filtering techniques using frequency-separation. The EMS ensures the optimal distribution of the load power requirement between the different sources while considering their limits. In addition, the optimal sizing allows to strengthen the complementarity between sources and to indirectly reduce their mass. In this work, the studied HPS consists of a fuel cell associated with an energy storage system (ESS), composed of lithium polymer batteries (Li-Po) and supercapacitors. The onboard sources are connected in parallel on the power bus through three DC-DC converters. The results of this study are presented and discussed to highlight the relevance of the proposed approach.

1. Introduction

In recent years, with the increasing pressure of energy crisis and environmental protection, the search for innovative solutions to improve urban mobility has received wide attention. In fact, urban mobility and air quality have been deteriorating. This is explained by urban sprawl and the excessive use of internal combustion engines [1]. In this context, the use of clean energy sources is tending to gain ground in order to reduce greenhouse gas emissions [2]. Concerning those adverse effects, NASA calls on the aeronautic industry to reduce aircraft fuel burn by 70 % by 2025 [3]. The interest in electric propulsion UAVs and specifically eVTOL has been on an upward trend. These flying robots are able to carry out civilian or military applications. Among the tasks, we can mention delivering packages, search and rescue operations, firefighting, inspection and border monitoring [4][5]. In this context, Capgemini Engineering has set up multidisciplinary teams to work on urban air mobility solutions as part of the "Viable" R&I project [6].

To increase endurance and achieve good performance, promising conceptual designs for hybrid eVTOLs have been established. The hybrid power system may combine several types of power sources, such as electrical and thermal. The choice of a suitable hybridization with an optimal EMS is therefore crucial to enable an efficient operation of advanced UAVs [7][8]. This paper is dedicated to optimally distribute the power flow between the different sources of the hybrid power system. In addition, the aim is also the optimal sizing of the onboard sources. The adopted strategy is based on the frequency decomposition of the load power using a low pass filter. In fact, the optimal power distribution improves exploitation conditions of sources and contributes at reducing early aging.
2. eVTOL aircraft power sources

There are many power sources used onboard UAVs, such as fuel cells (FCs), batteries (BAT), supercapacitors (SCs), solar panel (SP), internal combustion engine (ICE), etc. Some of these power sources have been disregarded due to their inadequacy with certain specific applications or for ecological reasons [9]. The power system of an eVTOL is expected to have both high power density and energy density, namely fast power response and good energy storage capacity [8]. Unfortunately, no single electric source can meet these two abilities without any compensation in current technical condition [8]. Overall, the more interesting an element is in terms of energy, the less it is in terms of power and vice-versa [9]. For achieving similar overall performance to the thermal engine, a hybridization of fuel cell, battery, and supercapacitor is a good alternative [8]. In fact, this association allows to benefit from advantages of different sources and to balance their drawbacks. This can reduce early aging of sources. Moreover, this hybridization is motivated by the material redundancy and therefore the strengthening of the eVTOL safety.

2.1. Fuel cells

Hydrogen fuel cells are characterized by a high specific energy and a low specific power. The fuel can typically have an energy density up to five times higher than Lithium Polymer batteries [7]. This ensures a good autonomy in terms of several hours. However, one of the main well-known problems of fuel cells is their slow dynamic response due to the hydrogen delivery system. For this reason, the fuel cell is intended for low-speed long-endurance UAVs [7]. This can be very adapted for the cruise and descend periods [8]. Moreover, fuel cells can charge the batteries using the excess energy during the cruise phase. Many technologies are used in the fuel cell industry. The PEMFC is the most used type for UAVs propulsion system [7][8]. It is characterized with high efficiency, long life, and low operating temperature relatively. A comparison of characteristics of these different types is detailed in [7][8].

2.2. Batteries

Batteries are characterized by a relatively high specific energy and specific power, compared to supercapacitors and fuel cells, respectively. There are many different technologies of batteries used on board UAVs which are continuously developing [7][9]. Due to their high performance, lithium polymer (Li-Po) and lithium ion (Li-ion) batteries are most often used in UAV applications [9]. They are more suitable for applications with long term variations on the scale of minutes to several hours [10]. However, battery alone may not allow an UAV to conduct some maneuvers needing very fast power response [7]. In this context, a supercapacitor is a good option to balance battery limitations.

2.3. Supercapacitors

Supercapacitors are characterized by a much higher specific power and lower specific energy, compared to batteries and fuel cells. Thanks to its very quick response to peak power, supercapacitors are most suited to handle sudden transients on the time scale of several seconds [11]. This can be very adapted for take-off and landing phases [7]. In addition, they indirectly protect the fuel cell, batteries, and DC bus. Indeed, they absorb the DC bus voltage fluctuations and can extend battery lifetime [7]. Thus, they provide load smoothing and reduce the rate of change of current seen by the fuel cell during a dynamic flight [12].

3. Problem formulation

The faced problems are the exploitation of existing energy sources and the consolidation of their complementarity for optimal energy management. The main idea of this work is to optimize the use of sources to satisfy the power demand while respecting the limits of each device [7][8]. The participation of each source in the mission is determined by the introduction of a cut-off frequency. Once the energy supply is determined for each device, a load profile is assigned to each one. Based on the latter, source sizing can take place. The sizing is carried out intelligently so as not to recalculate it when there are changes in similar missions. In addition, the optimal sizing indirectly reduces the mass and the energy onboard.
At every moment $t$, the load power ($P_L$) can be provided by fuel cell, batteries, and supercapacitors as follows:

$$P_L(t) = \alpha(t) P_{FC} + \beta(t) P_{B} + \gamma(t) P_{SC} \quad (1)$$

Where $\alpha$, $\beta$, and $\gamma$ represent the solicitation rate of fuel cell, batteries, and supercapacitors, respectively. The total energy ($E_L$) is calculated from the load power ($P_L$) and the flight duration ($T$), as follows:

$$E_L = \int_0^T P_L \, dt \quad (2)$$

Also, the energy demand ($E_t$) can be expressed as follows [8]:

$$E_L(t) = \alpha(t) E_{FC} + \beta(t) E_{B} + \gamma(t) E_{SC} \quad (3)$$

In fact, these coefficients ($\alpha$, $\beta$, and $\gamma$) are an image of the depth of discharge (DOD) of the energy storage system (batteries, supercapacitors) and the quantity of hydrogen consumed from the PEMFC tank. Therefore, the DOD inversely reflects of the state of charge (SOC) of each device [13]. The constraints imposed on these coefficients mean that the maximum threshold of discharge for each source ‘$S$’ must not be exceeded.

$$DOD_{S}^{max} = 1 - SOC_{S}^{max} \quad (4)$$

Thus, the battery state of charge is given by (5).

$$SOC_{B} (t) = SOC_{B} (t_0) - \frac{1}{C_{B}} \int_{t_0}^{t} i(t) \, dt \quad (5)$$

Where $i(t)$ is the battery current and $C_{B}$ is the actual battery capacity. It should be noted that the equation (3) reflects the kinetic and potential energy but also the various losses which can take place.

4. Energy Management Strategy

4.1. Architectures and topologies for HEPS

The architectures for hybrid power system can be divided into three different types of power sources interconnections, namely series, parallel, and cascaded [14]. It has also been proven that the parallel architecture is most suitable, due to its high reliability and low component stresses [14]. This architecture combines several power sources in parallel ways with or without converters [7][8]. For parallel architecture, there are three categories of topologies, namely passive, semi-active, and active [14]. In passive topology, the power sources are directly connected to a DC link and supply the propulsion according to their own characteristics. The second type is the semi-active topology, where the association between the storage devices is achieved using a single bidirectional DC / DC converter. However, in active topology, each power source is connected to a DC link through DC-DC converter. Hardware parallel architecture with an active topology is most commonly used. Its main advantage is its high controllability while the disadvantage is its high cost and significant mass increase depending on the chosen active components.

4.2 Filtering using frequency-separation

According to the Ragone diagram, each source can be described in terms of two parameters, namely specific power and specific energy. By exploiting these two parameters, the notion of specific
frequency \( f_c \) is introduced [11]. This frequency is defined as the ratio between the power density \( \rho_{\text{power}} \) and energy density \( \rho_{\text{energy}} \).

\[
f_c [Hz] = \frac{\rho_{\text{power}} [W/kg]}{\rho_{\text{energy}} [W/kg]} \tag{5}
\]

It should be noted that this approach requires knowledge of the mission profile a priori. In addition, according to the technology used, each source is defined within a range of operating frequency.

The main idea of this approach is to decompose the total power demand \( P_i \) into three levels (high, medium, and low) for frequency component to take advantage of the three power sources [15]. For this end, two low-pass filters with two different cut-off frequencies \( f_{c1}, f_{c2} \) are used. The first component generates the lower frequency variations of the power demand \( P_{\text{low}} \). It will be assigned to the fuel cell \( \mathcal{F}_{\text{FC}} \) due its slow dynamic response [11]. The second component allows to generate the intermediate frequency of the power demand \( P_{\text{medium}} \). It will be sent to the battery \( \mathcal{F}_{\text{Bat}} \) due to its relatively fast operating dynamic. The remaining part of the power demand representing, consequently, the higher dynamic component \( P_{\text{high}} \) will be assigned to the supercapacitor \( \mathcal{F}_{\text{SC}} \).

The participation of each source in the mission can be expressed as follows, where “s” is the Laplace variable [11][15]:

\[
\begin{align*}
\mathcal{F}_{\text{FC}} &= P_{\text{fc}} \cdot \frac{2\pi f_{c1}}{2\pi f_{c1} + s} \\
\mathcal{F}_{\text{Bat}} &= (P_{\text{c}} - P_{\text{fc}}) \cdot \frac{2\pi f_{c2}}{2\pi f_{c2} + s} \\
\mathcal{F}_{\text{SC}} &= P_{\text{c}} - (P_{\text{fc}} + P_{\text{Bat}})
\end{align*}
\tag{7}
\]

This approach has shown good performance in hybrid electric vehicle (HEV) and electric locomotive applications [11][16]. However, to our knowledge, it has not been tested or used in eVTOL applications. In fact, the notion of specific frequency is based on the laws of physics by exploiting the technical characteristics of sources. Therefore, this specific frequency is an indication characterizing each device. It reflects the frequency of cycles that the element can withstand [16].

The frequency-separation approach is used to ensure an optimum distribution of the energy between the sources considering dynamic and energetic constraints of each device. In addition, this approach is used for the optimal sizing of the embedded sources. It should be noted that the choice of the cut-off frequency has a great influence on the sizing [11]. The optimal sizing is critical to determine the mass and cost of the hybrid power system. For all these reasons, we demonstrate in this work the applicability of the approach in eVTOL applications concerning the sizing.

4.3 Optimal sizing of the HEPS

The sizing of the hybrid power system consists in determining the number of cells of the fuel cell, batteries, and supercapacitors necessary to achieve the eVTOL mission. This is essential to determine the mass and cost of the different sources in order to avoid unnecessary oversizing.

The fuel cell is sized according to the maximum power \( P_{\text{fc,max}} \) assigned to the PEMFC and the power generated by a single cell \( P_{\text{fc,cell}} = 5\text{W} \). The number of cells \( N_{\text{fc,cell}} \) is determined as:

\[
N_{\text{fc,cell}} = \frac{P_{\text{fc,max}}}{P_{\text{fc,cell}}} \tag{8}
\]

The number of batteries cell \( N_{\text{Bat,cell}} \) depends essentially on the power profile \( P_{\text{Bat}} \) and the cumulative energy profile \( E_{\text{Bat}} \) assigned to the batteries during the mission [11]. This number is also calculated according to the maximum depth of discharge \( DOD_{\text{Bat}} \), power delivered \( P_{\text{Bat,cell}} \), and the energy stored \( E_{\text{Bat,cell}} \) in a single cell [11].
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Where $E_{\text{BA}1}$ and $E_{\text{BA}2}$ are the maximum and the minimum levels of the cumulative energy of the battery, respectively. Similarly, to the battery sizing procedure, the number of the supercapacitor cells ($N_{\text{SC}1}$) should satisfy the power and energy constraints.

$$N_{\text{SC}1} = \max \left\{ \frac{E_{\text{BA}1} - E_{\text{BA}2}}{DOD_{\text{BA}1, \text{BA}2}} \cdot \frac{\max \left( |P_{\text{BA}}| \right)}{P_{\text{SC}}} \right\}$$  \hfill (9)

Where $P_{\text{SC}}$ and $E_{\text{SC}}$ are the power delivered and the energy stored in a single cell of supercapacitor, respectively. It should be remembered that the maximum depth of discharge of each source reflects the minimum threshold of the SOC not to be exceeded.

5. Results
In this work, the considered case study concerns a fixed-wing eVTOL, composed of ten motors, namely eight lifter motors and two pusher motors. It is intended for an operation to rescue a victim during a road accident. It should be noted that this work is done on a reduced scale of an actual full sized eVTOL, for demonstration purposes. A typical flight profile was simulated using Mission Planner software for a single way flight (see ‘figure 1’).

![Figure 1. Flight profile, extracted from Mission Planner.](image)

During take-off and climb phases, the power demand is the largest and the peak power exceeds 1800 W. However, the load power during the cruise phase is relatively low and stable (230 W). The single power peak observed in the cruise phase is imagined avoiding collisions with a bird (630 W). The goal is to show the ability of the HPS to adapt to sudden peaks of power demand. The next high power demand occurs in descend and landing phases (1200 W) with remarkable fluctuation. The flight data used in this work is detailed in table 1.

| Times (s) | Energy consumed (Wh) | Maximum power (W) |
|----------|----------------------|-------------------|
| Take-off | 30                   | 8.85              | 1816              |
| Climbing | 15                   | 5.63              | 1802              |
| Cruise   | 1800                 | 118.95            | 680               |
| Descent  | 15                   | 6.47              | 1200              |
| Landing  | 30                   | 2.22              | 587               |

Table 1. Flight data.
Several hybridization scenarios have been tested. In this paper, we focus on a hybridization combining a fuel cell, battery and supercapacitor for an optimal energy distribution. The optimal distribution of the power flow using frequency-separation approach is given by ‘figure 2’.

The first curve shows the total power demand of the eVTOL. The second curve illustrates the part of the fuel cell in the mission while the third curve depicts that of the battery. The last curve shows the participation of the supercapacitor. We can clearly see that the supercapacitors absorb the peak power especially in take-off and landing phases. It is most adapted to handle sudden transients on the time scale of several seconds. $P_{sc}$ is defined positive during the discharge period and negative during the charging period. The fuel cell provides the constant energy required during the cruise phase in complete autonomy. Eventually, it provides more energy than that required by the eVTOL. The excess energy can be stored in the battery and the supercapacitor. The battery participates in the power peak demand, along with the supercapacitor. It can also replace the PEMFC in case of failure such as lack of hydrogen or overheating, ensuring redundancy.

This hybridization shows good complementarity between the sources. It should be noted that the importance of this hybridization is more apparent for a higher charge profile, namely a profile of an actual full sized eVTOL.

The energy sources data obtained in this work is detailed in table 2.

**Table 2. Energy source data.**

| Source        | Max Energy (Wh) | Min Energy (Wh) | Max Power (W) | Max DOD (%) |
|---------------|-----------------|-----------------|---------------|-------------|
| Fuel cell     | 119.35          | 0               | 300           | -           |
| Batteries     | 18.02           | 0               | 222           | 70          |
| Supercapacitors | 12.27         | 0.1             | 1571          | 70          |
Based on this table and the sizing equations, we can determine the number of fuel cells, batteries, and supercapacitors needed to perform the mission with complete safety. In this work, the power of each cell of the PEMFC is 5W. In addition, each supercapacitor is composed of three cells. The characteristics of the energy sources used in this work are detailed in Table 3.

**Table 3. Characteristics of the energy sources.**

| Number | Type          | Technical specifications        |
|--------|---------------|---------------------------------|
| Fuel cell | 1 PEMFC       | 60 cells, 300 W, 8.3 A, 36V     |
| Batteries | 1 LiPo        | 4 S, 14.8 V, 3000 mAh, 22 C     |
| Supercapacitors | 19 -         | 57 cells, 250 A, 2.7 V, 310 F    |

The evolution of the SOC of battery ($SO_{C_{BAT}}$) and supercapacitors ($SO_{C_{SCS}}$) is shown in ‘figure 3’.

![Figure 3. State of charge of the energy storage system.](image)

Throughout the flight envelope, the SOCs are maintained above a predefined threshold (30%). The significant drop of $SO_{C_{SCS}}$ (33%) is explained by the absorption of the peak power by the supercapacitors during take-off. At the end of the single way flight, the $SO_{C_{BAT}}$ (60%) and the $SO_{C_{SCS}}$ (75%) remain quite high. This is thanks to a hybridization with a fuel cell. In the considered case study, we keep those final SOCs above 60% to adapt to an immediate take-off. This is very useful for rescue missions, as time is of crucial importance. In addition, the final SOC varies according to the intended mission. Finally, we can imagine different scenarios depending on the SOC desired at the end of the single way flight or the entire mission.

6. Conclusion

The focus of this paper is to investigate the applicability of the energy management strategy using frequency-separation in eVTOL applications. More precisely, this is a first study on an eVTOL hybrid electric propulsion system (HEPS) composed of a fuel cell, battery, and supercapacitors. The developed method aims to optimally share the power flow between the different sources to ensure mission requirements while considering the limits of each source. This analysis of the power and energy distribution is essential for the optimal sizing of the embedded sources. In addition, auto-adaptive filtering in real time is a strong perspective of this work and constitutes the next step. Another important perspective of this work is to take into account more parameters for aircraft
design in order to be able to project the use of these methods (frequency separation, optimal sizing) in eVTOL applications with a full-size and more realistic use case. Finally, the recharge of the energy storage system and the fuel in the PEMFC tank are fundamental topics to study for an entire mission.

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