MIL-Standards Verification of Battery Control for More Electric Aircraft Application

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Abstract. As a consequence of the increase of air traffic, the innovative topic of the More Electric Aircraft (MEA) has received increasing attention. In this paper, the control of a bidirectional DC/DC converter for battery management in the MEA framework is described. A detailed simulator and simulation campaign have been designed in order to verify the satisfaction of the MIL-STD-704F standard which regulates the behaviour of electric devices on-board the aircraft.

1. Introduction
Since the beginning of this century, motivated by the rapid increase of the air traffic, there has been a renewed effort towards the design and implementation of the so-called More Electric Aircraft [1]. This interest translated into economic investments by the European Union under the research initiatives CleanSky and CleanSky2, and the incoming CleanSky3 [2]. These initiatives have a large number of projects oriented to the MEA concept. One of the main goals of the MEA is the reduction of air pollution and the increase of operational aircraft capacity through a gradual electrification of traditional aircraft.

Two different levels of innovation are possible: the design of electric propulsion based aircraft [3], and the adoption of electric devices in place of their pneumatic and hydraulic counterparts. While electric propulsion represents a big leap towards a fully electric aircraft, we are still far from having this technology available for commercial flights. On the other hand, replacing hydraulic and pneumatic devices with their electric counterparts represents a first significant step towards the electrification of the aircraft [4]. According to the aeronautic standards, the size, and thus the weight, of the electric generator increases with the increase of the highest power demand during flight operations. However, power peaks are needed only during some operations such as taxing, take-off and landing. Therefore, only during relatively short time intervals the main aeronautic generator is required to provide these power peaks.

A possible solution for the reduction of the generator size is the installation of an auxiliary **energy storage device (ESD)**, such as batteries [5] [6] or supercapacitors [7] [8] [9], on-board the aircraft capable of supplying power to the loads connected to the grid whenever the load demand overcomes the generator security threshold (also called **overload** threshold). The main idea is the following: during normal flight operations (e.g. cruising) the main generator is capable of supplying power to the loads connected to the grid and, at the same time, recharge the auxiliary ESD with a constant current; when an overload occurs, i.e. when the generator current overcomes the overload threshold, the ESD can either absorb less current than the nominal case or reverse its current in order to help the main generator to satisfy the loads demand. Such a strategy requires the adoption of properly designed control techniques.
aimed at automatically managing the different cases and either control the auxiliary ESD current to a prescribed value or limit the generator current to the overload threshold [10].

The power flow between the generator and the ESD can be adjusted through the action of a controlled DC/DC bidirectional converter connected to the main aeronautic bus on one side and to the ESD on the other side. In this paper, the solution for the control of the bidirectional converter presented in [11] is revisited. The control algorithm proposed in [11] is based on the design of an adaptive sliding surface and the adoption of a sliding mode control algorithm [12] capable of steering the system trajectories to the adaptive sliding manifold in finite time. The main focus of the results presented in [11] was on the theoretical design of the controller. Therefore, not much effort was put into the verification of the MIL-STD-704 standards [13], a document defining a standardized power interface between an aircraft and its equipment.

In this paper, higher attention is given to the satisfaction of the standard which is verified through a detailed MATLAB/Simulink/SimPowerSystem that shows the effectiveness of the proposed control strategy and the fulfilment of the required standard.

2. DC/DC Bidirectional Converter Model

The topology of the bidirectional converter is shown schematically in Figure 1. The network presents the 270V aircraft electric generator, represented by an ideal generator $E_H$ and its internal resistance $R_H$, the loads modelled with a variable resistance $R_D$ and a converter with two switches $Q_1$ and $Q_2$ that operates in complementary mode (i.e. $Q_1 = 1$ and $Q_2 = 0$ or $Q_1 = 0$ and $Q_2 = 1$), capacitors $C_H$, $C_L$ and the inductor $L$. Finally, a 28V battery is represented by an ideal generator $E_L$ and its internal resistance $R_L$. The bidirectional converter allows the power transfer between two sides. In normal operating condition the generator charges the battery at constant current, conversely when the generator overloads the battery is charged with less current or in critical case it helps to satisfy the demands network.

\[
\dot{x}_1 = \frac{1}{L} [-x_1 + x_2 u] \\
\dot{x}_2 = \alpha x_2 - \frac{1}{C_H} x_1 u + \beta_H \\
\dot{x}_3 = \frac{1}{C_L} x_2 - \frac{1}{R_L C_L} x_3 + \beta_L
\]

where

\[
\alpha = \frac{1}{R_{DH} C_H}, \quad R_{DH} = \frac{R_D R_H}{R_D + R_H}, \quad \beta_i = \frac{E_i}{R_i C_i}, \quad i = \{H, L\}
\]

where $x_1$ represents the current flowing through the inductor $L$, while $x_2$ and $x_3$ are the voltage across the capacitors $C_H$ and $C_L$, respectively. The control input $u \in \{0, 1\}$ models the two possible configurations of the switches, that is $u = 1$ when $Q_1 = 1$ and $Q_2 = 0$ while $u = 0$ models the opposite
case. Let us define \( x := [x_1, x_2, x_3]^T \) being the state vector. In the following, we will assume that the state vector is completely available for measurements.

### 3. Control Design

The main objective this aeronautic application is dual:

1) during nominal conditions, i.e. when the generator current \( I_g \) is lower than a given threshold \( \bar{I}_g \), the main control objective is to drive the battery current \( x_1 \) to a prescribed threshold \( \bar{x}_1 \);
2) when an overload occurs, i.e. when the generator current increases above the threshold \( \bar{I}_g \) due to connection of loads with low resistance, the control objective is to control the generator current to \( \bar{I}_g \) by regulating the battery current \( x_1 \).

Note that, in the second scenario, according to the value of the total resistance of the load connected to the grid, two cases may occur: in the case of “light” overload the generator can still constrain its current below the threshold \( \bar{I}_g \) by charging the battery with a lower current than \( \bar{x}_1 \); in the case of “heavy” overload instead, the battery current is reversed in order for the battery to help the generator fulfilling the load request. The two cases, i.e. nominal conditions and overload, and the two sub-cases for the overload conditions need to be automatically managed by an automated control strategy.

It is interesting to note that in [14], due to the switching nature of the control input, system (1)-(3) was approached as a switched system [15] and the authors managed to prove the Input-to-State Stability (ISS) [16] uniformly with the switching sequence. This in turn implies that the system trajectories will remain bounded for any arbitrarily chosen control law bounded in the closed interval \([0,1]\).

The control of the converter is structured in a hierarchical framework comprising of a high and a low-level control layer. First, the low level is shown, where the goal is to drive the selected variable to reference. Next, the high level is presented through a supervisor, that aims at selecting the objective of the controller in order to satisfy the power management policy.

#### 3.1 Low-Level Control

The current control is based on the definition of sliding manifold. In order to drive the inductor current to the reference \( \bar{x}_1 \), let us define a sliding surface

\[
S = \{(t,x) \in \mathbb{R}_2 \times \mathbb{R}^3 | \sigma(t,x) = 0\}
\]

(5)

where the sliding function is designed as

\[
\sigma(t,x) = k(t)x_2 - x_i
\]

(6)
and \( k(t) \) is an adaptive smooth function. Note that when the system trajectory lies on the sliding surface, i.e. \( \sigma(t,x) = 0 \), a proper choice of the parameter \( k \) allows the selection and the accomplishment of one of the two control goals. The main idea behind the choice of this sliding function has been presented in [17], where it was proven that for a proper choice of the parameter \( k \), one could achieve proper tracking of \( x_1 \) by \( x_1 \) or tracking of \( \bar{I}_g \) by \( I_g \). Specifically, in the case of battery current tracking

\[
k = \frac{E_H - \sqrt{E_H^2 - 4R_H^2C_H \bar{x}_1(R_I \bar{x}_i + E_i) \alpha}}{2R_H(R_I \bar{x}_i + E_i)}
\]

(7)

while for generator current tracking

\[
k = -\frac{E_i + \sqrt{E_i^2 - 4R_H \bar{x}_2(\alpha C_H \bar{x}_2 - E_H/R_H)}}{2R_H \bar{x}_2}
\]

(8)

where \( \bar{x}_2 = E_H - R_H \bar{I}_g \).

The principal drawback of the approach presented in [17] is that the computation of the parameter \( k \) highly depends on the electrical grid parameters. This in turn implies poor robustness performance of the control algorithm with respect to parameters uncertainty. Subsequently, in [11] and adaptive algorithm for the selection of \( k(t) \) was proposed. More precisely, in [11], such control parameter was dynamically updated according to

\[
k = \gamma e
\]

(9)
where $\gamma$ is a constant positive gain while $e = \bar{x}_1 - x_1$ in the nominal case (that is battery recharge mode) or $e = I_g - \bar{I}_g$ in the overload case (that is the generator current limiting mode).

In both [11] and [17], the control law was designed as to directly operate the switching

$$u = \begin{cases} 
0 & \text{when } \sigma(t, x) \leq 0 \\
1 & \text{when } \sigma(t, x) > 0
\end{cases}$$

(10)

with $\sigma(t, x)$ being designed as in equation (6).

In [11] it is proven that for sufficiently low values of the gain $\gamma$, the control algorithm (9)-(10) guarantees local asymptotic stability of the equilibrium point of the closed loop system. Local stability implies that there exist a Region of Attraction (ROA) such that the system trajectories will converge towards the equilibrium point if the initial condition of the system is inside the ROA. Otherwise, convergence cannot be guaranteed.

### 3.2 High-Level Control

In view of the above discussion, considering that there exist two different main objectives (i.e. battery current control and generator current control), it is clear that the entire control algorithm needs to switch among two different control strategies in order to properly fulfil the required control objective. This in turn calls for the need of a higher level logic capable of implementing a set of switching events between one objective and the other. In order to do so, a finite state automaton has been implemented comprising of two different states that will be hereafter referred to as modes. However, switching between one mode to the other may push the system trajectories outside the ROA of the active mode, hence inducing instability. In order to avoid this undesirable effect, a numeric estimation of the ROA can be computed through techniques proposed in [18] and starting from a Lyapunov function computed for the linearised case. A detailed analysis of how switching among the two modes is regulated can be found in [11].

### 4. Simulation Results

A detailed MATLAB/Simulink/SimPowerSystem simulator has been designed and implemented as shown in Figure 2. The simulator presents three relevant blocks:

- **Supervisor**: implements the supervisory logic and selects the active Mode (green block and Figure 3).
- **Low Level Controller**: implements the SMC strategy as described in Section 3.1 (red block).
- **RD**: implements the set of loads connected to the grid (yellow block).

![Figure 2. MATLAB/Simulink/SimPowerSystem model.](image-url)
Figure 3. Supervisor Scheme

Figure 4. Time evolution of the grid load.

Figure 5. $I_g$ time evolution.

Figure 6. $x_1$ time evolution.

Figure 7. $x_3$ time evolution.

Figure 8. $x_2$ time evolution.
Figure 9. Envelope of admissible voltage transient for 270V.

Figure 10. Envelope of admissible voltage transient for 28V.

The system and controller parameters considered in the simulation are shown in Table 1.

Table 1. System Parameters.

| Parameter | Value |
|-----------|-------|
| $E_H$     | 270 [V] |
| $R_H$     | 0.1 [Ω] |
| $C_H$     | 80 [mF] |
| $L$       | 10 [mH] |
| $\bar{x}_1$ | 10 [A] |
| $C_L$     | 40 [mF] |
| $R_L$     | 0.1 [Ω] |
| $E_L$     | 28 [V] |
| $\gamma$  | 4 |
| $\bar{I}_g$ | 16 [A] |

The main focus of the designed simulation campaign is to stress the control algorithm in order to ensure that the bidirectional converter operates within the operating ranges defined from the MIL-STD-704F. A rather stressful scenario is induced by variating the loads connected to the grid as shown in Table 2 and Figure 4. The initial value of the generator current is around 2A (see Figure 5), well below the threshold $\bar{I}_g$, hence the supervisor is initially in Mode 1 and the battery is charged with a constant current $\bar{x}_1$, see Figure 6. The connected load changes every 2 seconds and when the total resistance of the load assumes low values the generator current rises above the overload threshold. Therefore, the supervisor switches to Mode 2 in order to steer the generator current back to $\bar{I}_g$. Observing Figure 9, it is possible to note that, when the supervisor is in Mode 2, the battery is either charged with a current lower than $\bar{x}_1$ or discharged in order to help the generator feeding the load. Note that these two cases are automatically handled by the control algorithm. The satisfaction of the MIL-STD-704F can be endorsed by comparison of Figure 7 and Figure 8 with Figure 10 and Figure 7 respectively. It can be observed that the MIL-STD-704F is satisfied for both the 270V bus and the 28V bus despite the highly stressful conditions the grid undergoes event during heavy transient generated by the abrupt change of load.

5. Conclusions

In this paper, one of the challenges offered by the innovative framework of the More Electric Aircraft is tackled. A hierarchical control strategy comprising of a sliding mode control with adaptive manifold and a finite state machine supervisor is described. A detailed MATLAB/Simulink/SimPowerSystem simulator has been implemented in order to verify the satisfaction of the MIL-STD-704F standard under harsh conditions.

Table 2. Load Values.

| Load [Ω] | Time [s] |
|----------|----------|
| 300      | 0-2      |
| 17       | 2-4      |
| 250      | 4-6      |
| 16       | 6-8      |
| 200      | 8-10     |
| 15.5     | 10-12    |
| 150      | 12-14    |
| 15       | 14-16    |

| Load [Ω] | Time [s] |
|----------|----------|
| 150      | 12-14    |
| 15       | 14-16    |

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| 200      | 8-10     |
| 15.5     | 10-12    |
| 150      | 12-14    |
| 15       | 14-16    |
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References

[1] Jones R 2002 The more electric aircraft - Assessing the benefits Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering 216(5) 259-269
[2] Clean sky website 2008. [Online]. Available: http://www.cleansky.eu.
[3] Wheeler P and Bozhko S 2014 The More Electric Aircraft: Technology and challenges IEEE Electrification Magazine 2(4) 6-12
[4] Canciello G, Cavallo A and Guida B 2017 Robust control of aeronautical electrical generators for energy management applications International Journal of Aerospace Engineering 2017 1-12
[5] Cavallo A, Canciello G and Russo A 2018 Supervised Energy Management in Advanced Aircraft Applications European Control Conference (ECC) (Limassol, Cyprus)
[6] Cavallo A, Russo A and Canciello G 2019 Hierarchical control for generator and battery in the more electric aircraft Science China Information Sciences 62(9) 1-14
[7] Russo A and Cavallo A 2020 Supercapacitor stability and control for More Electric Aircraft application in 2020 European Control Conference
[8] Cavallo A, Russo A and Canciello G 2019 Control of Supercapacitors for smooth EMA Operations in Aeronautical Applications American Control Conference (ACC), (Philadelphia, USA)
[9] Canciello G, Cavallo A and Guida B 2017 Control of energy storage systems for aeronautic applications Journal of Control Science and Engineering, 2017 1-9
[10] Canciello G, Russo A, Guida B and Cavallo A 2018 Supervisory Control for Energy Storage System Onboard Aircraft 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEIEC / I&CPS Europe), (Palermo, Italy)
[11] Cavallo A, Canciello G and Russo A 2020 Integrated supervised adaptive control for the more Electric Aircraft Automatica 117 1-12
[12] Utkin V, Guldner J and Shi J 2009 Sliding Mode Control In Electro-Mechanical Systems, (CRC Press)
[13] Department of Defense Interface Standards 2004 Aircraft Electric Power Characteristics (Department of Defense, Washington, DC, USA)
[14] Canciello G, Cavallo A, Lo Schiavo A and Russo A 2020 Multi-objective adaptive sliding manifold control for More Electric Aircraft ISA Transactions, 107 1-13
[15] Liberzon D 2003 Switching in Systems and Control (Birkhauser)
[16] Sontag E and Wang Y 1996 On Characterizations of the Input-to-State Stability Property Systems & Control Letters 24 351-39
[17] A. Cavallo A, Canciello G and Guida B 2018 Supervisory control of DC-DC bidirectional converter for advanced aeronautic applications International Journal of Robust and Nonlinear Control 28(1) 1-15
[18] Chesi G 2011 Domain of Attraction: Analysis and Control via SOS Programming, vol. 415, (London: Springer Science Business Media)