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Brief paper

Supervised control of buck-boost converters for aeronautical applications ☆

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ABSTRACT

Recent MEA (More Electric Aircraft) concepts require new approaches to design and management of the electric system onboard. Bidirectional Buck-Boost Converter Units (BBCU's) used like bridges between power buses with different voltage require intelligent supervisory control for autonomous selection of operating modes. In this paper at low-level, sliding manifold-based strategies are employed to track desired current references, or to recover from overload within a prescribed time. At a higher level, three working modes are defined, (Buck-, Boost- and Intermediate-Mode), and scheduled by a high-level supervisory strategy. Stability proofs of the overall strategy require estimates of the Region of Attraction (ROA) for each controller, that are discussed in the paper. A typical aeronautic scenario is presented, with standard operating conditions followed by two types of overloads (the second more severe than the first) and finally a return to standard condition. Detailed numerical simulations show the effectiveness of the proposed novel control strategy in terms of stability and performance of the smart converter.

1. Introduction

In the aeronautic field, the use of "more electric" and "all electric" concepts has been an important research topic in the last decade. For large aircraft, say the size of the Airbus A380 or the Boeing B767, electric solution with focus on the "power distribution" and on "power management" are currently under study. While in traditional aircraft the pilot has the full control of the aircraft, including the electric distribution system, in the MEA concept some sort of automatic management system (supervisor) is required. At this point, completely new scenarios open to supervisor designer, for there are many points that can be addressed. For instance, all the Energy Storage Systems (batteries, supercapacitors) are involved in recovering energy, supplying extra-peaks, and so on (Buonanno, Sparaco, Cavallo, Guida, Wu, Todd, and Forsyth, 2016). Moreover, replacing traditional hydraulic actuators with electric ones, reduces weights onboard, while increasing reliability and fault tolerance capabilities. All this topics call for application of possibly known electric technologies to new aeronautic frameworks. Indeed, in the last years European Community has funded a large number of research projects devoted to the MEA, like the CleanSky and CleanSky2 (http://cleansky.eu) initiatives.

Obviously, in highly safety-critical applications like aeronautic ones, replacing the pilot's decision with automated strategies requires strong reliability of the controller, that can only be based on rigorous mathematical stability proofs and detailed simulators. As a starting point a minimal electrical configuration for medium-size aircraft requires two DC power buses. A high-voltage (HV) bus is powered by an electric generator, usually a three-phase generator followed by a rectification stage. Typical values of DC voltage on the HV side are 270 V (regional aircraft) and 540 V (large aircraft) (http://cleansky.eu). The low-voltage (LV) bus at 28 V DC is supplied by batteries. Usually, the HV bus supplies all the electric equipment onboard, while the battery acts only at engine start-up or in exceptional cases (e.g., fault of all the other electric generators). Power between HV and LV sides is exchanged by using bidirectional BBCU's so that the battery can be used to inject power on the HV side, and the generator to recharge the battery. It is known (Ghosh, 2012) that electric generator design is based on the so-called "5 seconds" and "5 minutes" overload capability, that are a simplified version of the true overload curve of the generator. It is assumed that the generator for 5 s can supply high power peaks, that gradually decrease until a suitable overload level P_{OL} is attained after 5 min. Since the generator sizing is based on the 5 min power capability, if after 5 s the power request is reasonably low, size and weight of the generator would be reduced (Guida & Cavallo, 2013). Obviously, the extra power required by the loads must be supplied by the batteries through the BBCU. This idea has

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been the basic motivation for three Projects (namely, SUPREMAE, I-PRIMES and EPOCAL) funded by the European Community in the framework of the CleanSky project.

Since BBCU's are switching devices, a natural control strategy turns out to be sliding mode control (Martinez-Salamero, Cid-Pastor, Giral, Calvente, & Utkin, 2010). Implementations with finite switching frequency have been proposed, like Hysteresis-Modulation Sliding Mode (Chen & Kang, 2011) or PWM implementations using $\Sigma\Delta$ modulation (Sira-Ramirez & Silva-Ortigoza, 2006) or constant switching frequency sliding-mode (He & Luo, 2006). Other approaches have been used, like backstepping strategies (Cavallo, Canciello, & Guida, 2017; El Fadil & Giri, 2017), passivity-based approaches (Chan, 2008; Sira-Ramirez, Perez-Moren, Ortega, & Garcia-Esteban, 1997), where a Lagrangian point of view to the control design is adopted. However, since mathematical proofs of stability become more and more complex as the order of the converter increases, usually only local stability is assessed by means of linearisation. The BBCU considered in this paper is the one in Cavallo and Guida (2012), where a supervisory control has been designed. The solution presented in this paper is an improvement of the design in Cavallo, Buonanno, Guida, and Sparaco (2015), with low-level controllers ensuring *regional stability* along with an estimate of the Region of Attraction (ROA). Moreover, an exponential parameter can be used to enlarge the size of the ROA. The BBCU is normally used to recharge the battery. However, if other loads request power exceeding standard generator capabilities, the control law first operates a "soft" disconnection of the battery, to reduce the load on the generator. Next, if this action is not enough, the converter operates so that the battery supplies power to the loads to help the generator during the transients. However, switching among different controllers requires care, since it may lead to undesired behaviours, even instability. Different papers discuss supervisory control of switching systems (see Tousi, Karuei, Hashtrudi-Zad, & Aghdam, 2008 and references therein). In this paper the approach proposed in Koutsoukos, Antsaklis, Stiver, and Lemmon (2000) is used, due to its simplicity in this application. Due to the estimate of the ROA mentioned above, the supervisory control strategy can safely switch among different control policies, if the "old" controller leaves the state of the system in the ROA of the "new". Otherwise, the controller may try a regulation towards a reduced performances control policies (with larger ROA) then refining the performances when the state of the system approaches the steady-state. A simulation scenario considering a normal operating condition, with two varying loads such that no overload occurs, followed by a mild overload, a "severe" overload and finally a return to normal conditions is analysed, showing the effectiveness and robustness of the proposed strategy.

2. BBCU model

The BBCU is the one in Cavallo and Guida (2012) and shown in Fig. 1. E_H represents the generator voltage after the rectifier, E_L the battery. The switches couple $Q_1 - Q_2$ operates in complementary switching. The battery is charged at constant current (Buck Mode). The resistor R_D models the loads. Since the loads change dynamically, the value of this resistor is varied in time. A generator power overload results into a generator current I_{gen} to reach an overload value I_{OL}. The equations of the converter are

$$\dot{x}_1 = -\frac{1}{L}x_3 + \frac{1}{L}x_2 u \tag{1}$$

$$\dot{x}_2 = -\frac{1}{C_H}\left(\frac{1}{R_H} + \frac{1}{R_D}\right)x_2 - \frac{1}{C_H}x_1 u + \frac{E_H}{R_H C_H} \tag{2}$$

$$\dot{x}_3 = \frac{1}{C_L}x_1 - \frac{1}{R_L C_L}x_3 + \frac{1}{R_L C_L}E_L \tag{3}$$

$$y = x_1 \tag{4}$$

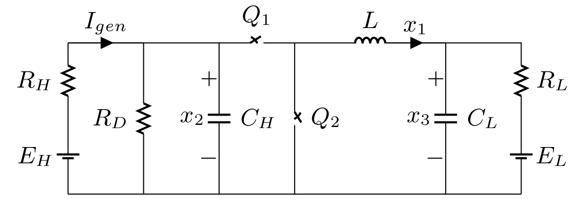

Fig. 1. Bidirectional Buck-Boost converter schematic.

where x_1 is the current through the inductor L, x_2 is the voltage on the capacitor C_H on the HV bus side and x_3 is the voltage on the capacitor C_L on the LV bus side. The control (switches on and off) is $u \in \{0, 1\}$.

3. Low-level sliding control

A preliminary result is needed on the solution of nonlinear equation with the structure

$$\dot{x} = -x + a - b(t)/x.$$

This is the differential equation that a normalised version of the voltage across the capacitor C_H obeys, when the current exactly follows a reference profile, as it will be clear later, in the proof of Theorem 3. When the term $b(t)$ is constant stability is easily characterised (Cavallo & Guida, 2012). When $b(t)$ varies the stability of the solutions of this equation is far from trivial. The following lemmas consider $b(t)$ exponential with an offset.

Lemma 1. *Consider the non-autonomous differential equation*

$$\dot{x} = -x + a - \frac{b(t)}{x} \tag{5}$$

where $x \in \mathbb{R}^+$, $a > 0$, and $b(t) = b_0 + b_1 e^{-ct}$, $c > 0$. Assume that $0 < b_0 < (a/2)^2$ and $2x^*\sqrt{b_0} - ax^* < b_1 < (a/2)^2 - b_0$ and define

$$x^* = \frac{a + \sqrt{a^2 - 4b_0}}{2}, x_1 = \frac{b_0 + \max\{b_1, 0\}}{x^*}, \beta = \frac{|b_1|}{x^*}. \tag{6}$$

Select $r = x^* - x_1 - \alpha$, with

$$\alpha = \frac{x^* - x_1 - \beta - \sqrt{(x^* - x_1 - \beta)^2 - 4\beta x_1}}{2} \tag{7}$$

let $k = \alpha/(x_1 + \alpha)$ and assume $k > 0$. Then the solutions of (5) converge exponentially to x^* for all $c > 0$, and any $x(0)$ in the region $\mathcal{R} = \{x : x > x^* - r\}$.

Proof. First, note that as the exponential term in $b(t)$ vanishes, solutions to Eq. (5) starting from the region of attraction converge to the steady-state solution x^*. Using the change of coordinates $z = x - x^*$, Eq. (5) becomes

$$\dot{z} = -z + \frac{b_0 z}{x^*(z + x^*)} - \frac{b_1 e^{-ct}}{z + x^*}, \quad z(0) = x(0) - x^*. \tag{8}$$

By algebraic computations, it is possible to bound the RHS of Eq. (8) and, by resorting to the Comparison Lemma (Khalil, 2002 Lemma 3.4), to study the stability of

$$\dot{q} = -q + \frac{(b_0 + b_1 e^{-ct})}{x^*(q + x^*)}q - \frac{|b_1|e^{-ct}}{x^*}, \quad q(0) = z(0), \tag{9}$$

$$\dot{w} = -w + \frac{(b_0 + b_1 e^{-ct})}{x^*(w + x^*)}w + \frac{|b_1|e^{-ct}}{x^*}, \quad w(0) = z(0). \tag{10}$$

Note that $q \le z \le w$. By using the Theory of Stability of Systems with Nonvanishing Perturbations (Khalil, 2002 Lemma 9.4)