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Control of DC power distribution system of a hybrid electric aircraft with inherent overcurrent protection

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Abstract—**In this paper, a novel nonlinear control scheme for the on-board DC micro-grid of a hybrid electric aircraft is proposed to achieve voltage regulation of the low voltage (LV) bus and power sharing among multiple sources. Considering the accurate nonlinear dynamic model of each DC/DC converter in the DC power distribution system, it is mathematically proven that accurate power sharing can be achieved with an inherent overcurrent limitation for each converter separately via the proposed control design using Lyapunov stability theory. The proposed framework is based on the idea of introducing a constant virtual resistance at the input of each converter and a virtual controllable voltage that can be either positive or negative, leading to a bidirectional power flow. Compared to existing control strategies for on-board DC micro-grid systems, the proposed controller guarantees accurate power sharing, tight voltage regulation and an upper limit of each source's current at all times, including during transient phenomena. Simulation results of the LV dynamics of an aircraft on-board DC micro-grid are presented to verify the proposed controller performance in terms of voltage regulation, power sharing and the overcurrent protection capability.**

I. INTRODUCTION

IN the last few years, the hybrid electric aircraft initiative to combine conventional and electrical systems in aircrafts has significantly increased. This has stemmed from the need to improve efficiency and reliability [1], and to reduce emissions and lifetime operating costs of the aircraft. More recent models, such as Boeing 787 and the Airbus A380 [2], [3], have more electrical power components installed compared to older models, and this trend is expected to increase further in the future. As a result, a reliable and resilient power distribution system in an aircraft is of major importance and since it represents an isolated system with generators, power converters and loads, it can be regarded as an on-board micro-grid system, often of DC nature. Hence, with increased on-board power generation, the challenge of controlling and managing multiple sources that meet the increasing demand in the power distribution system arises.

On-board DC micro-grids with enhanced reliability that do not use communication among the units, often operate in a distributed control manner where the control method for each unit is based on the available local variables. Control methods employed in aircraft applications that do not require communication links but rely on optimization techniques have also been proposed in [4], [5]. A cascaded control structure with an outer loop has been adopted in [6] to prevent instabilities in the case of small output filters. Thus, overall system stability needs to be guaranteed by the sources that operate in parallel with a simulataneous tight control of the voltage bus. The most common employed technique for regulating the voltage of DC/DC converters uses traditional single or cascaded PI controllers [7], [8]. Based on linearization and the small-signal model of the converter, traditional PI controllers can be designed to ensure local stability of the desired equilibrium point. However, the nonlinear dynamics of the converter indicate a need for advanced control strategies that can be applied directly to the nonlinear model of the system, such as sliding control [9], [10] or passivity-based control [11], [12]. Such control strategies can guarantee nonlinear closed-loop stability based on strong mathematical background; however, in most cases they require global information of the system or load parameters that may change during the system operation.

The main challenges and problems of an on-board HEA DC-based system are the voltage stability and regulation, the power flow management and power sharing and the highly dynamic characteristics of the network [13]. Since modern load types introduce complex nonlinear dynamics that can complicate the existing system nonlinearities and increase the number of states of the overall system, there is a clear interest in designing more advanced controllers that can act independently from the system parameters and can also ensure stable operation of the converter at all times. Particularly, an overcurrent protection that limits the inductor current below a given value is of critical importance to protect the converter during fast transients or unrealistic power demands. The occurence of transients is very common, since the dc/dc converters operate with high switching frequencies to increase the power density. Furthermore, it is known that the switching frequency is proportional to the partial discharge [14]. Therefore, to mitigate these effects, a defined range for the switching frequency is usually selected for aircraft applications [15], [16], [17].

Even during fast transients, the current limitation, as defined in [18], [19], can protect equipment without violating the boundaries set by the technical specifications of the converters. Despite the converter being protected by protection devices

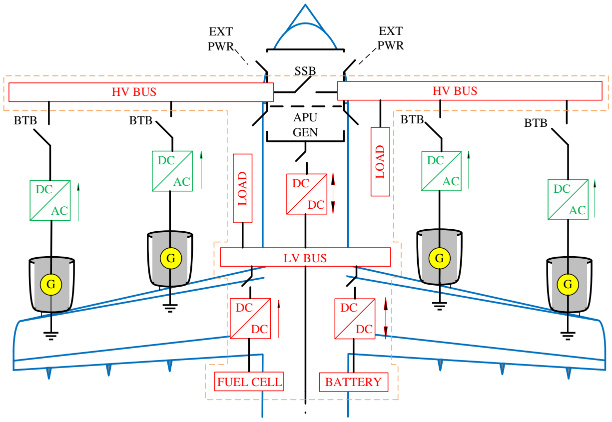


Figure 1. Typical topology of an on-board DC micro-grid of a hybrid electric aircraft

(e.g. additional fuses, circuit breakers and protection relays), there is ongoing desire towards guaranteeing overcurrent protection via the control design [20]. Existing traditional strategies can effectively change the original control structure to the overcurrent protection control structure [21]. However, since closed-loop stability cannot be analytically proven, the initiative to design a control structure suitable for all the aforementioned tasks is still of significance.

A nonlinear control scheme that acts regardless of the system and load parameters is proposed in this paper to guarantee voltage regulation and power sharing with an overcurrent protection for both unidirectional and bidirectional boost converters for a hybrid electric aircraft on-board DC micro-grid. The new concept adopts the droop control methodology to gurantee power sharing without communication and resides on the idea of applying a constant virtual resistance in series with the converter inductor and a virtual controllable voltage which varies according to a nonlinear dynamical system. Using input-to-state stability (ISS) theory [22], it is demonstrated that based on a suitable selection of the controller parameters, the inductor current of each converter will never violate a maximum limit imposed by the technical specifications, regardless of the droop control regulation scenario. Hence, the converter is protected against overcurrents at all times since the power injected by the sources is always limited, even in the case of an unrealistic scenario where the power demand could exceed the capacity of the converter. This offers a superiority with respect to existing cascaded control methods with saturation units, since the proposed controller limits the converter currents during transients, not only at the steady-state, and is based on a rigorous nonlinear theory that facilitates the stability of the entire system. Extensive simulations are carried out and presented to test the desired operation of the onboard DC micro-grid and its protection against overcurrents.

The remainder of this paper is organised as follows. In Section II the on-board DC distribution network under consideration is introduced and analyzed. Section III contains a brief description of the conventional droop control and the main challenges in a DC micro-grid, followed by the controller design and proof of the overcurrent protection introduced by each converter in Section IV. Simulation results of the on-board DC power distribution system are shown in Section V and, finally, the conclusions are drawn in Section VI.

II. NONLINEAR MODEL OF THE ONBOARD LV DC MICRO-GRID

In Fig. 1, a candidate on-board DC-based micro-grid architecture for a hybrid electric aircraft is shown, represented by various types of sources connected in parallel to a common DC bus, interfaced by DC/DC and AC/DC power converters. This paper is focused on the control of the low voltage (LV) DC side of the network, which is the highlighted part in Fig. 1, and includes the integration of the LV with the high voltage (HV) bus, a battery and a fuel cell unit. In Fig. 2, the detailed LV DC configuration of the on-board DC micro-grid system is depicted consisting of two DC/DC boost converters (one unidirectional and one bidirectional) connected in parallel and feeding a common low-voltage (LV) load, and another bidirectional boost converter that feeds a HV load and links the LV bus with the HV bus. Using Kirchhoff laws and average analysis [23], the dynamic model of the entire system that includes the nonlinear behaviour of the boost converters becomes

$$\begin{aligned}
L_{FC}\dot{i}_{L_{FC}} &= U_{FC}-(1-u_{FC})V_{FC} && (1)\\
C_{FC}\dot{V}_{FC} &= (1-u_{FC})i_{L_{FC}}-i_{out_{FC}} && (2)\\
L_{BAT}\dot{i}_{L_{BAT}} &= U_{BAT}-(1-u_{BAT})V_{BAT} && (3)\\
C_{BAT}\dot{V}_{BAT} &= (1-u_{BAT})i_{L_{BAT}}-i_{out_{BAT}} && (4)\\
L_{HV}\dot{i}_{L_{HV}} &= V_{LV}-(1-u_{HV})V_{HV} && (5)\\
C_{HV}\dot{V}_{HV} &= (1-u_{HV})i_{L_{HV}}-i_{out_{HV}} && (6)
\end{aligned}$$

Here L_{FC}, L_{BAT} and L_{HV} are the boost converter inductances (H), C_{FC}, C_{BAT} and C_{HV} represent the output capacitors (F), while the output line impedances are introduced by the resistances R_{FC}, R_{BAT} and R_{HV} (Ohms). The low-voltage and high-voltage loads are represented as R_{LV} and R_{HV} respectively. The state vector of the system consists of the inductor currents $i_{L_{FC}}$, $i_{L_{BAT}}$ and $i_{L_{HV}}$ in the input of every converter and the output voltages V_{FC}, V_{BAT} and V_{HV} (V). The control input vector consists of the duty-ratio inputs of each converter u_{FC}, u_{BAT} and u_{HV}, which by definition should remain bounded in the set $[0,1]$. The DC input voltages of the converters are given as U_{FC}, U_{BAT} and U_{HV}, and represent constant inputs for the system, as shown in Fig. 2.

It can be observed that system (1)-(6) is nonlinear, since the control inputs u_{FC}, u_{BAT} and u_{HV} are multiplied with the system states. By considering a steady-state equilibrium (i_{Li}^{e}, V_i^{e}) corresponding to a duty-ratio u_i^{e}, where i represents the appropriate converter for the fuel cell (FC), battery (BAT) and for the link to the HV bus (HV), it results from (1), (3) and (5) that $u_i^{e}=1-\frac{U_i}{V_i^{e}}$, which shows that when $u_i=1$ the inductor current continuously increases, thus the system becomes unstable. Imposing a given upper bound for the inductor current is of major importance that should be guaranteed at all times to achieve permanent device protection. Such a controller, equipped with this capability while also

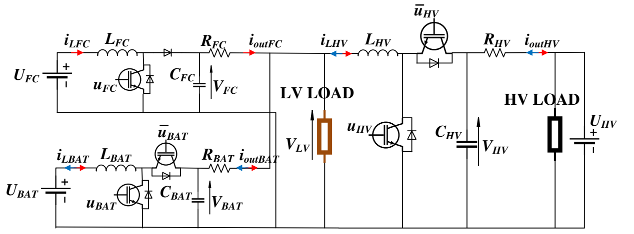


Figure 2. Onboard LV DC power distribution system of an aircraft

achieving desired operation i.e. accurate power sharing and tight voltage regulation, is investigated in Section IV.

III. PROBLEM DESCRIPTION AND OBJECTIVES

To guarantee LV regulation and power sharing among the several sources without communication among the parallel converters, the most commonly applied technique is based on droop control [24], [25], [26], [27], [28]. The conventional droop control method introduces for each of the 3 parallel-operated power converters an output voltage V_i of the form:

$$V_i = V^* - n_i\left(P_i - P_{set}\right) \tag{7}$$

where V^*, P_{set} represent the output reference voltage (V), and the set power (W) respectively, P_i is the power drawn out of each converter, and n_i is the droop coefficient. However, conventional droop control suffers from a trade-off between voltage regulation and load sharing, and also by the influence of the impedance and the slow dynamic response of the system. To tackle these drawbacks, the droop equation in (7) can take the following dynamic form

$$\dot{V}_i = V^* - V_{LV} - n_i\left(P_i - P_{set}\right) \tag{8}$$

where V_{LV} is the voltage (V) of the LV bus. At steady-state, there is

$$n_{FC}P_{FC} = n_{BAT}P_{BAT} = n_{HV}P_{HV} \tag{9}$$

which guarantees the accurate sharing of the power requested by the LV load.

Whilst accurate power sharing is guaranteed regardless of the power requested by the load, the technical limitations of the converters are not considered. Given the power rating $P_n = P_{in}^{max}$ of a converter and the rated input voltage U_{in}, a limitation for the input current of each converter is introduced. To ensure protection to the generating circuit and transmission system from harmful transients in cases of significant changes in the load demand, appropriate overcurrent protection is required. Hence, imposing an upper limit for the current that may be delivered to a load and guaranteeing that certain boundaries are not violated represents another major challenge for on-board HEA DC micro-grid operation.

IV. NONLINEAR CONTROL DESIGN AND ANALYSIS

A. The proposed controller

The purpose of the designed controller is to achieve all the aforementioned tasks without saturation units that can lead to integrator windup amd instability. The concept behind it relies on the idea of partially decoupling the inductor current dynamics, introducing a constant virtual resistance and a bounded controllable voltage. The virtual voltage will guarantee the desired upper limit for the converter current regardless of the direction of the power flow. This concept is applied to all three converters via the input U_i. In order to simplify the notations, in the following subsections, the subscript i is removed since the same structure applies to every converter, i.e. for the fuel cell, the battery and the interconnection of the LV with the HV bus. Hence, the control input u is proposed to take the form

$$u = 1 - \frac{r_v i_L + U - E}{V} \tag{10}$$

where $r_v > 0$ represents a constant virtual resistance and E a virtual controllable voltage which introduces the following nonlinear dynamics:

$$\dot{E} = cg\left(U, V_{LV}, E\right)E_q^2 - k\left(\frac{E^2}{E_{max}^2} + E_q^2 - 1\right)E \tag{11}$$

$$\dot{E}_q = -cg\left(U, V_{LV}, E\right)\frac{EE_q}{E_{max}^2} - k\left(\frac{E^2}{E_{max}^2} + E_q^2 - 1\right)E_q \tag{12}$$

with E_q being an additional control state, c, k, E_{max} being positive constants and $g\left(U, V_{LV}, E\right)$ a smooth function that describes the desired regulation scenario and has incorporated the expression of the droop control from equation (8) in the following form:

$$g\left(U, V_{LV}, E\right) = V^* - V_{LV} - n\left(\frac{UE}{r_v} - P_{set}\right)$$

where $\frac{UE}{r_v} = P$ represents the power at the input of each converter.

To further understand the choice of the controller dynamics (11)-(12), consider the following Lyapunov function candidate

$$W = E_q^2 + \frac{E^2}{E_{max}^2}$$

Taking the time derivative of W and incorporating the control system (11)-(12), then

$$\begin{aligned}\dot{W} &= 2E_q\dot{E}_q + \frac{2E}{E_{max}^2}\dot{E}\\ &= -2cg\left(U, V_{LV}, E\right)\frac{EE_q^2}{E_{max}^2} - 2k\left(\frac{E^2}{E_{max}^2} + E_q^2 - 1\right)E_q^2\\ &\quad + \frac{2E}{E_{max}^2}cg\left(U, V_{LV}, E\right)E_q^2 - 2k\frac{E^2}{E_{max}^2}\left(\frac{E^2}{E_{max}^2} + E_q^2 - 1\right)\\ &= -2k\left(\frac{E^2}{E_{max}^2} + E_q^2 - 1\right)\left(E_q^2 + \frac{E^2}{E_{max}^2}\right).\end{aligned} \tag{13}$$

From (13), it is clear that $\dot{W}$ is negative outside the curve

$$W_0 = \left\{E, E_q \in R : \frac{E^2}{E_{max}^2} + E_q^2 = 1\right\} \tag{14}$$

and positive inside except from the origin, where $\dot{W} = 0$. By selecting the initial conditions E_0, E_{q0} on the curve W_0, it yields:

$$\dot{W} = 0, \Rightarrow W\left(t\right) = W\left(0\right) = 1, \forall t \geq 0,$$

which makes clear that the control states E and E_q will start and move on the curve W_0 at all times. For convenience, the initial conditions E_0 and E_{q0} will be chosen as

$$E_0 = 0,\ E_{q0} = 1 \tag{15}$$

Since the control states are restricted on the curve W_0, then $E \in [-E_{max}, E_{max}]$ for all $t \geq 0$. The controller dynamics will result in

$$\begin{aligned} \dot{E} &\approx cg\left(U, V_{LV}, E\right) E_q^2 \\ \dot{E}_q &\approx cg\left(U, V_{LV}, E\right) \frac{E_q E}{E_{max}} \end{aligned}$$

Since $(E_0, E_{q0}) \neq (0, 0)$, the possible equilibrium points of the controller dynamics are any points on the curve W_0 that satisfy: i) $g\left(U, V_{LV}, E\right) = 0$, that will guarantee the desired operation i.e. voltage regulation and power sharing or ii) $(E_e, E_{qe}) = (\pm E_{max}, 0)$ which corresponds to the case of overcurrent protection as explained below.

B. Overcurrent protection

By applying the proposed controller expression (10) into the equations describing the dynamics of the converter (1)-(6), the closed-loop system equation for the inductor current i_L becomes

$$L\dot{i}_L = -r_v i_L + E, \tag{16}$$

and it becomes clear that r_v represents a constant virtual resistance in series with the converter inductor L.

To investigate how the selection of the virtual resistance and the bounded controller dynamics of E are related to the desired overcurrent protection, the following Lyapunov function candidate

$$V = \frac{1}{2} L i_L^2$$

for closed-loop current dynamics (16) can be used. The time derivative of V yields

$$\begin{aligned} \dot{V} &= L i_L \dot{i}_L = -r_v i_L^2 + E i_L \\ &\leq -r_v i_L^2 + |E||i_L| \leq -r_v i_L^2 + E_{max}|i_L|, \end{aligned}$$

given the bounded $E \in [-E_{max}, E_{max}]$, which implies that

$$\dot{V} < 0,\ \forall |i_L| > \frac{E_{max}}{r_v}.$$

Hence, if initially $|i_L\left(0\right)| \leq \frac{E_{max}}{r_v}$, then it holds that

$$|i_L\left(t\right)| \leq \frac{E_{max}}{r_v},\ \forall t > 0, \tag{17}$$

due to the invariant set property. Based on the desired overcurrent protection, it should hold true that

$$|i_L\left(t\right)| \leq i_L^{max},\ \forall t > 0, \tag{18}$$

for a given maximum value i_L^{max} of the inductor current. By substituting (17) into (18), one can clearly select the parameters E_{max} and r_v in the proposed controller in order to satisfy

$$E_{max} = r_v i_L^{max}. \tag{19}$$

Table I
CONTROLLER AND SYSTEM PARAMETERS

Parameters	Values	Parameters	Values
R_{BAT}	0.004Ω	L_{BAT}	$1.26mH$
R_{HV}	0.005Ω	L_{HV}	$3.95mH$
R_{FC}	0.001Ω	L_{FC}	$1.33mH$
U_{BAT}	$200V$	P_{LV}	$0.5MW$
U_{HV}	$2kV$	P_{HV}	$2MW$
U_{FC}	$300V$	C_{BAT}	$100\mu F$
n_{BAT}	0.6×10^{-5}	C_{HV}	$20\mu F$
n_{HV}	1.2×10^{-5}	C_{FC}	$80\mu F$
n_{FC}	0.4×10^{-5}	k	1000
r_{vBAT}	1Ω	i_{LBAT}^{max}	$4.5kA$
r_{vHV}	2Ω	i_{LHV}^{max}	$10kA$
r_{vFC}	0.5Ω	i_{LFC}^{max}	$2.5A$
c_{BAT}, c_{FC}	500	c_{HV}	100

Hence, any selection of the constant and positive parameters E_{max} and r_v that satisfy (19) results in the desired overcurrent protection (18) of the converter's inductor current regardless the load magnitude or system parameters.

From the closed-loop dynamics (16) combined with (11)-(12) at steady-state, there is $g\left(U, V_{LV}, E\right) = 0$, then $E = E_e$ on the curve W_0 and the value of the inductor current becomes $i_{Le} = \frac{E_e}{r_v}$. But since $E_e \in [-E_{max}, E_{max}]$, then the inductor current can be both positive and negative, thus, ensuring the two-way operation of the bidirectional converter. When $E_e = -E_{max}$ then $i_e = -\frac{E_{max}}{r_v} = -i_{max}$ that corresponds to the overcurrent protection in both directions of the current.

Compared to existing traditional overcurrent protection control strategies, it has been mathematically proven according to the nonlinear ISS theory that the proposed controller maintains the current limited during transients and does not require limiters or saturation units which are prone to yield instability in the system.

V. SIMULATION RESULTS

To validate the proposed controller, the onboard aircraft DC micro-grid displayed in Fig. 2 is considered having the parameters specified in Table I. The aim is to achieve tight voltage regulation around the reference value $V^* = 540V$, accurate power sharing in a $3:2:1$ ratio among the paralleled DC converters at the LV bus while also ensuring protection against overcurrents. The model has been implemented in Matlab Simulink.

During the first $5s$, it can be observed in Fig. 3b that the LV voltage V_{LV} is kept close the reference value of $540V$. The power sharing is accurately guaranteed (Fig.3c) in a $3:2:1$ manner having $i_{outFC} \approx 465A$, $i_{outBAT} \approx 310A$ and $-i_{LHV} \approx 155A$, since the input currents have not reached their imposed limits yet as shown in Fig. 3a.

For the next $20s$ the direction of the power flow of the battery's converter is reversed to allow the battery to charge and discharge. At $t = 5s$ the power set by the battery controller becomes negative $P_{setBAT} = -320kW$, thus forcing the battery to be supplied by the fuel cell and the HV bus. The input current goes negative, while the other two input currents increase to satisfy the new amount of power requested at LV bus (Fig. 3a). The power sharing ratio between the fuel cell and the HV bus is kept at $1:3$ with, $-i_{LHV} \approx 250A$ and $i_{outFC} \approx 750A$, as shown in Fig. 3c. The LV voltage remains closely regulated to the desired $540V$ value. After $10s$ the set value of the power return to its initial 0 value, allowing the battery to return to its former discharing state. The power sharing ratio comes back to $3:2:1$ as displayed in Fig.3c.

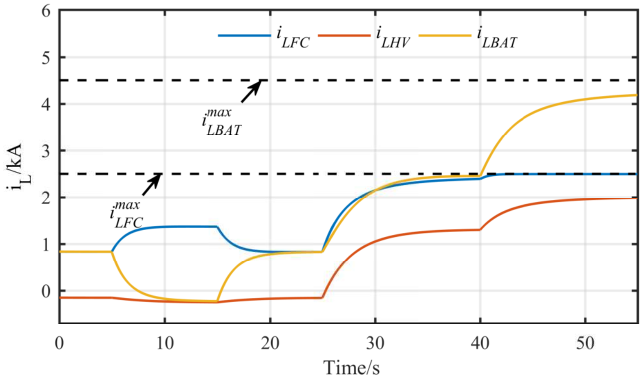
At $t = 25s$ the set value of the power of the HV bus becomes negative $P_{setHV} = -950kW$ and, thus, power is needed from the battery and the fuel cell to be injected in the HV bus. After a short transient, the LV bus voltage drops down to $537V$ according to Fig. 3b. The input current becomes positive and, therefore, starts flowing towards the HV bus (Fig. 3a) while the power sharing between the battery and fuel cell is kept close the desired proportion of $3:2$ having $i_{outFC} \approx 1.33kA$ and $i_{outBAT} \approx 0.89kA$, as presented in Fig. 3c given the fact that none of the inductor currents have reached their maximum allowed current.

To test the overcurrent protection capability, the HV power demand is further increased. Thus, at $t = 40s$ the set value of the power required by the HV bus goes even higher than before, $P_{setHV} = -1.5MW$, forcing the battery and the fuel cell to increase their power injection in the HV bus. As noticed in Fig. 3a, the input current of the fuel cell reaches its limit $i_{LFC} = i_{LFC}^{max} = 2.5kA$, and the power sharing is sacrificed (Fig. 3c) to ensure uninterruptible power supply to the LV and HV loads. The LV voltage remains within the desired range, $V_{LV} = 535V$ with a voltage drop of $5V$, which is less than 1%.

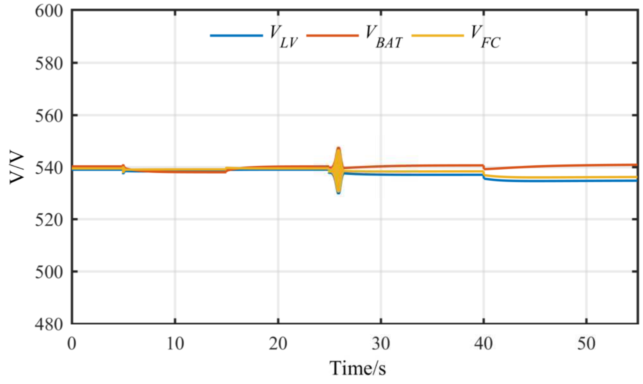
Consequently, to further verify the theory presented, the controller state E is presented in Fig. 3d. When the input current of the fuel cell reaches its maximum, the virtual voltage of the fuel cell also arrives at its imposed limit $E_{FC} = E_{maxFC} = i_{LFC}^{max} r_{vFC} = 1.25kV$.

VI. CONCLUSIONS

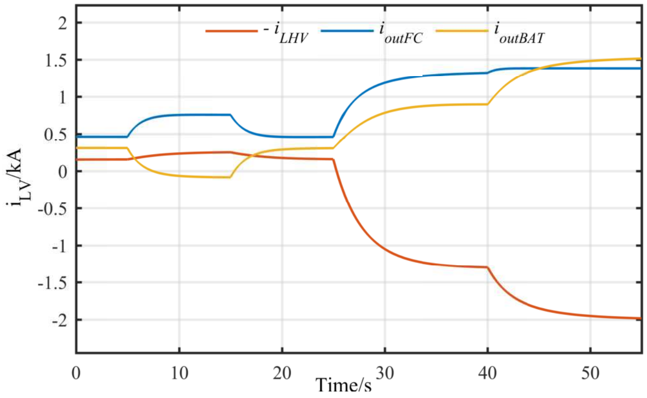
In this paper a detailed control design was presented for an on-board aircraft DC power distribution system. The nonlinear dynamic control scheme was developed to ensure power sharing and DC bus voltage regulation, with an inherent protection against overcurrents. By incorporating a constant virtual resistance and bounded virtual voltage dynamics, it has been proven that the input currents of the converters will never violate a maximum given value. This feature is guaranteed without any knowledge of the system parameters and without any extra measures such as limiters or saturators, thus, addressing integrator wind-up and instability problems that often happen with the traditional overcurrent controllers' design. The effectiveness of the proposed scheme and its overcurrent capability was tested by simulating an on-board aircraft DC micro-grid under several scenarios. Future work will look into the integration of the HV side of the DC network and the AC/DC three-phase power converters.



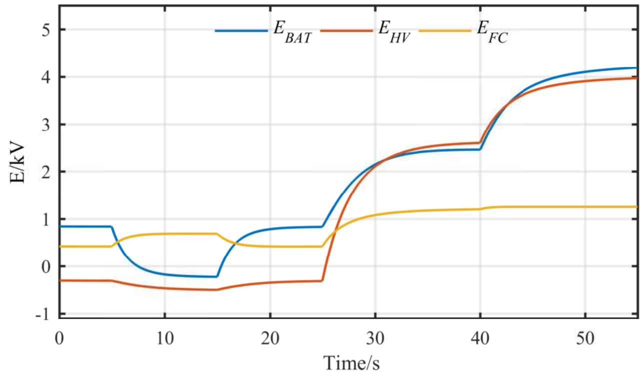
(a) inductor currents



(b) LV bus voltages



(c) LV bus currents



(d) virtual voltages

Figure 3. Simulation results of the bidirectional DC/DC converter equipped with the proposed controller

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