

Performance Enhancement of Power Conditioning Systems in More Electric Aircrafts

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Keywords

«More Electric Aircraft», «Aerospace», «Microgrid», «Power Quality», «DC-DC Power Converter», «Digital Control», «Supercapacitors».

Abstract

Power quality improvement constitutes a critical issue in the DC distribution networks of modern and future More Electric Aircrafts (MEAs). In this paper, an improved control strategy for power conditioning systems (i.e., aiming to mitigate DC bus voltage transients, mainly in feeders with critical loads) in MEA microgrids is proposed, to enhance the system dynamics. The studied power conditioner is based on the widely proposed bidirectional buck-boost DC-DC converter configuration, along with a supercapacitor bank. The proposed controller design enhances the system performance, employing an effective control loop (based on a current control method), taking into consideration the detailed converter average model, so as to enhance the performance of conventional power conditioning systems during transient operation. The proposed control strategy is validated by experimental tests, presented on a SiC-based scaled-down hardware prototype.

Introduction

Over the last decade the aviation industry is moving towards the More Electric Aircraft (MEA), as it is considered one of the most promising solutions for more efficient air transports with minimum environmental footprint [1], [2]. The electrification level of commercial aircrafts is constantly increasing, mainly thanks to the notable development of power electronics-dominated power systems (as the on-board distribution network of the MEA), whilst according to *Airbus'* predictions, the power rating of civil aircraft microgrids should finally reach 20 MW in the next few decades [3]. In this context, new types of power sources, hybrid energy storage units and more electronically controlled loads with various characteristics (e.g., constant power, pulsed power, intermittent operation, etc.) are emerging, imposing stringent requirements, in terms of stability, robustness, flexibility and dynamic performance, for the on-board microgrid [4].

As for the MEA microgrid architecture, currently several hybrid (both DC and AC) configurations have been employed (e.g., *Airbus* A380 and *Boeing* B787), whereas purely DC configurations have been investigated and proposed for future MEAs, within various research frameworks, such as Clean Sky JU

[5] and MOET EU [6], coming as a result of the emerging technology of DC microgrids [7]. In particular, in the MEA distribution network, Constant Power Loads (CPLs) i.e., tightly-regulated electronic loads such as inverter driven electric motors, and Pulsed Power Loads (PPLs) are mainly jeopardizing the DC microgrid stability and power quality, imposing new challenges for performance enhancement, as well as for advanced and sophisticated control schemes for the power conditioning converters [8]. In order to overcome these power quality issues, stabilize CPLs and effectively accommodate PPLs, the incorporation of enhanced (in terms of robustness, dynamic performance, stability and flexibility) power conditioning systems, especially in feeders with priority loads, becomes imperative.

The aforementioned PPLs are very common critical loads in on-board microgrids (e.g., wing de-icing systems, radars, sonars, etc.), demanding a large amount of energy within very short time intervals, featuring so a pulsed behavior with high power characteristics. In details, according to [8] and [9] in an MEA microgrid, the peak power may last for approximately 20-200 ms, whereas the peak-to-average power ratio may be more than 5-to-1, across a time scale of 50-500 ms. Hence, voltage transients may occur in the microgrid DC buses, leading to poor power quality and evoking critical conditions for various loads, when the DC voltage exceeds its allowed limits. In many cases, large PPLs require excess power source capacity or dedicated power generation to protect other aircraft equipment.

Generally, in DC microgrids, the term “power quality” denotes constant DC voltage waveforms throughout microgrid buses (or within clearly specified voltage levels), oscillations-free power supply in steady-state operation and fast transient response during dynamic conditions [10]-[12]. Moreover, the aforementioned transient phenomena may occur either due to normal disturbances, such as electric load steps (pulsed / intermittent operation) and engine speed changes or due to abnormal disturbances, such as momentary power interruptions and fault clearings. According to the *MIL-STD-704F* and *ISO 1540:2006* (standards related to aircraft electric power characteristics), transients are classified into three categories, namely lesser, normal and abnormal transients [13], [14]. Lesser transients are those that do not exceed the steady state limits; normal transients may exceed the steady state limits but they remain within the specified normal transient region; finally, transients that exceed normal transient limits (as a result of an abnormal disturbance) and eventually return to steady state limits are defined as abnormal transients.

In order to maintain the bus voltage within the specified limits (imposed by the relevant standards), power conditioning units are employed, comprising bidirectional DC-DC converters and Energy Storage Systems (ESSs) [15], [16], usually connected as parallel active filters (PAF); typically supercapacitor (SC) banks are utilized (as they feature high power density and fast dynamics) to counterbalance the capacity limit of the main energy sources, which are usually designed to supply the average loads, rather than meet the peak power demands (short duration transients), due to techno-economic considerations [8]. These systems may operate, either exclusively during transients, or under a cooperative energy management strategy, e.g., in a hybrid ESS, comprising both batteries (high energy density / slow dynamics) and SCs (high power density / fast dynamics), or in a multi-source DC MG with slow ramp rate energy sources. Such systems have been proposed and investigated in the literature over the last few years [15]-[18].

In light of the above, this work studies a power conditioning system with enhanced performance, by means of an improved control scheme, so as to effectively compensate for DC bus voltage transients (e.g., sags or swells) by sourcing or sinking power to / from the DC bus, respectively. The converter mathematical model is developed, taking into account the power losses; this leads to the proposal of a simple current controller with improved characteristics, minimizing the error between the reference and the real value during transients. Experimental tests are carried out on a scaled-down hardware prototype, indicating the functionality and improved performance of the proposed controller.

System Description

The studied power conditioning system has been proposed in [15] and it comprises a bidirectional DC-DC converter that interfaces a supercapacitor bank into the microgrid main DC bus. The incorporation

of the studied system in the MEA DC microgrid, as well as a detailed schematic diagram are depicted in Fig. 1. The well-established bidirectional buck-boost DC-DC converter topology has been selected, which is in favor for various two-quadrant applications (such as energy recovery and active power filtering) as it constitutes a compact configuration with minimum semiconductors and passive components count [15]-[20].

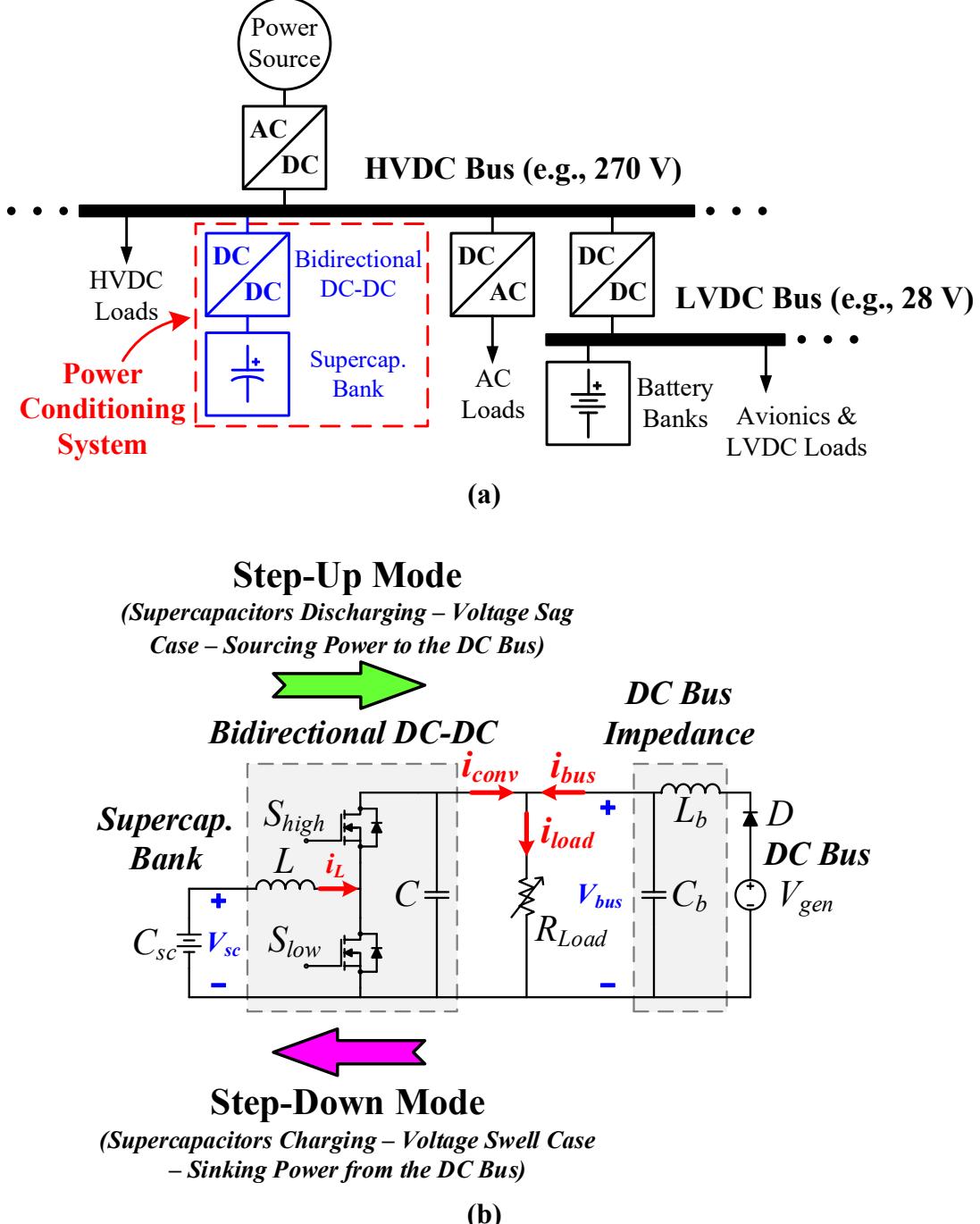


Fig. 1: A simplified block diagram of the MEA system under study: (a) incorporation of the proposed power conditioning system into the MEA DC microgrid and (b) detailed schematic diagram.

In this scheme, supercapacitors provide ultra-high energy storage capability and high power density, but low rated voltages [20]. On the other hand, the growing on-board power demand of MEAs is inevitably accompanied by increasing DC bus voltage levels of the distribution network, from the actual 540 V [15] to the 3-kV of the *E-Fan X* prototype, (i.e., a hybrid-electric demonstrator, developed by *Siemens*, *Airbus* and *Rolls Royce*) [3], and reasonably further. Therefore, the accommodation of high-voltage

ESSs in future MEAs is hindered, mainly because of ineffective, bulky and costly configurations. For this reason, the converter high voltage side is connected to the main DC bus, whereas its low voltage side is connected to the supercapacitor bank, where the inductor smoothes the current ripple, in order to extend the supercapacitors lifetime.

Owing to their aforementioned characteristics, supercapacitors are able to compensate for steep transients and effectively support the DC bus. When voltage sags occur, the bidirectional converter operates in the step-up mode, providing power to the DC bus, discharging the supercapacitor bank, as it is depicted in Fig. 1(b). On the other hand, in a voltage swell case the converter operates in the step-down mode, sinking power from the DC bus, charging the supercapacitor bank, as Fig. 1(a) depicts. In such a way, transient phenomena are effectively mitigated. As already discussed, the converter operates solely during transient intervals.

It is noted that the proposed concept can be also applied at any other DC network (either with single-bus or with multi-bus configuration), the voltage level of which needs to be preserved within strictly defined limits, ensuring high power quality. However, despite the functionality, robustness and compactness of the bidirectional buck-boost DC-DC topology, the controller design remains challenging, especially in the MEA microgrid application, where transients occur in the time scale of milliseconds; hence, rapid dynamic response is imperative [8], [9]. In this regard, the inductor current reference derivation by the aid of Proportional-Integral (PI) controllers is ineffective, due to their inherent phase lagging. In order to design an effective controller, the alternative of utilizing the converter average model, incorporating its power losses, is studied. As it will be shown in next Sections, the proposed model is of efficacy in steady-state and “slow” transients’ conditions. However, the terms “slow” and “fast” transients may refer to various time constants and are defined according to the MEA demand profile requirements (e.g., specific DC bus feeder, load type, generation unit capacity, etc.) [16]-[18].

Controller Design

According to [15], the control scheme is based on the load current monitoring (assuming that the power conditioning system is connected to a DC bus feeder with critical loads) and the decoupling of its AC component via a digitally implemented low-pass filter, so as the converter to operate solely during voltage transients. The necessary internal current control loop is based on the popular Peak Current Control (PCC) method [19]. This work focuses on the derivation of the inductor (i.e., the supercapacitor bank) current reference from the DC bus current reference, as it is presented in Fig. 2. It is assumed that the inductor peak and average current values are very close (continuous conduction mode with small current ripple), in order for the PCC method to operate effectively. Similarly, the converter average model for step-down operation can be derived.

In addition, according to the schematic diagram of Fig. 3, the average model of the bidirectional buck-boost converter (in step-up mode) under steady-state or “slow” transients’ operation, can be developed, so as to derive the current transfer function. Apparently, the use of the average model is rational, as long as the converter switching period is quite smaller than the time constant of the occurred transient phenomenon, in order for the inductor volt-second balance (during a switching period) to be considered valid. Hence, in the current work the term “slow” transients refers to time constants at the millisecond-scale or above (assuming switching frequencies above 10 kHz). In this way, the proposed power conditioning scheme is suitable for the above-mentioned normal transients that occur in MEA power systems.

Finally, based on the assumption that the converter operates solely during transients providing its full power (i.e., pulsed current), no significant thermal rise occurs; thus, changes in parasitic elements (such as supercapacitors Equivalent Series Resistance – ESR, inductor DC resistance or MOSFETs on-resistance) can be neglected. Last but not least, it is worth noting that for the considered bidirectional DC-DC converter both high-voltage and low-voltage sides can become input or output, although for the

following mathematical analysis the high-voltage side current is referred as “output current” (i.e., i_{conv}), since step-up operation (sourcing power to the DC bus) is considered.

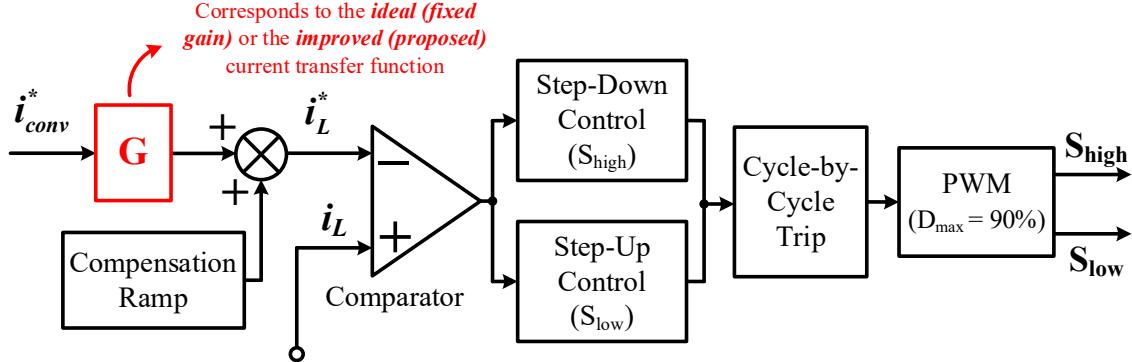


Fig. 2: Control concept, based on the PCC method (derivation of the inductor current reference from the DC bus current reference).

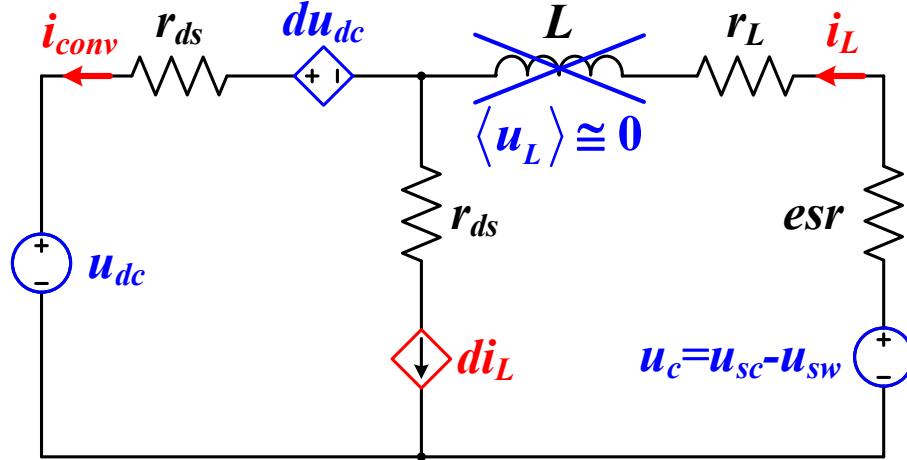


Fig. 3: Equivalent circuit for the average model development, considering step-up operation (voltage sag – supercapacitors discharging case).

According to the equivalent circuit of Fig. 3 and by applying the Kirchoff's current law (KCL) and voltage law (KVL), it is acquired:

$$KCL: i_L = di_L + i_{conv} \Rightarrow i_L \cdot (1-d) = i_{conv} \Rightarrow d = 1 - \frac{i_{conv}}{i_L} \quad (1)$$

$$KVL: u_c - u_{dc} = -du_{dc} + i_L \cdot (esr + r_L) + i_{conv} r_{ds} \quad (2)$$

where i_L and i_{conv} are the inductor (supercapacitors) and the converter output currents, respectively, d stands for the converter duty cycle, u_{dc} is the DC bus voltage (considered constant), u_{sc} is the supercapacitor bank voltage (considered constant), r_L is the inductor internal resistance, esr is the supercapacitors ESR value, r_{ds} is the power MOSFETs on resistance, and u_{sw} is a voltage drop which corresponds to the converter switching losses; it can be extracted by the total (turn-on and turn-off) energy losses, according to the semiconductor switches datasheet (given a specific switching frequency). After mathematical manipulations, the following quadratic equation is derived:

$$(esr + r_L) \cdot i_L^2 + (i_{conv} r_{ds} - u_c) \cdot i_L + i_{conv} u_{dc} = 0 \quad (3)$$

$$\Delta = (i_{conv} r_{ds} - u_c)^2 - 4u_{dc} \cdot i_{conv} \cdot (esr + r_L) \quad (4)$$

To ensure that the discriminant is greater or equal to zero (real roots), it should be:

$$(i_{conv} r_{ds} - u_c)^2 - 4u_{dc} \cdot i_{conv} \cdot (esr + r_L) \geq 0 \Rightarrow (i_{conv} r_{ds} - u_c)^2 \geq 4u_{dc} \cdot i_{conv} \cdot (esr + r_L) \quad (5)$$

By using the quadratic formula, it is obtained that:

$$i_{L_{1,2}} = \frac{(u_c - i_{conv}r_{ds}) \pm \sqrt{(i_{conv}r_{ds} - u_c)^2 - 4u_{dc}i_{conv}(esr + r_L)}}{2(esr + r_L)} \quad (6)$$

Both roots in (6) may be positive; however, the first one leads to an unacceptably high current ratio (i_L/i_{conv}), and thus to an unacceptable duty cycle value and poor efficiency. Hence, only the second root is valid (practical), as it leads to an acceptable current ratio.

$$i_L = \frac{(u_c - i_{conv}r_{ds}) - \sqrt{(i_{conv}r_{ds} - u_c)^2 - 4u_{dc}i_{conv}(esr + r_L)}}{2(esr + r_L)} \quad (7)$$

Eq. (7) is used for the proposed improved controller design, whereas for comparative assessment, the following ideal current transfer function (fixed gain) is also considered:

$$\left(\frac{i_L}{i_{conv}} \right)_{ideal} = \frac{u_o}{u_c} \Rightarrow i_L = \frac{u_o}{u_c} \cdot i_{conv} \quad (8)$$

Experimental Validation

In order to assess the performance of the proposed controller, a laboratory-scale SiC-based bidirectional buck-boost DC-DC converter is designed and constructed. The controller is digitally implemented by the aid of a TMS320F28027 microcontroller unit, which is dedicated for current control applications as it accommodates analog comparators that can be connected to its on-chip PWM (Pulse Width Modulation) module, whereas the slope compensation unit (ramp generator) is on-chip [19]; it is noted that the addition of a compensation ramp is imperative in current control applications, whilst the procedure for the design of a compensation ramp with properly calculated slope in the studied converter is presented in [15]. The foremost electronic components and parameters of the constructed power conditioning system are summarized in Table I.

In parallel, since the aim of this work is to study and evaluate the proposed controller effectiveness, various output current reference scenarios are considered, for both steady-state and transient operation. Hence, experimental results focus on the deviation between the real (measured) output current and the reference value. The latter one is arbitrary and thus no specific DC bus voltage waveforms are given.

Table I: Main components and parameters of the experimental test bench.

Description	Symbol - Product Code	Value [Unit]
DC bus voltage (ct.)	u_{dc} (electronic load in constant-voltage mode / EA-EL 9760-25 2400W 800R)	45 [V]
supercapacitors voltage (ct.)	u_{sc} (power supply emulated / SM 70-AR-24)	30 [V]
converter output (DC bus) capacitance	C	470 [μ F]
SiC Power MOSFETs	NVHL020N120SC1 [21]	-
MOSFETs on-resistance	r_{ds} (typical @ 25°C)	20 [$m\Omega$]
converter switching frequency	f_s	100 [kHz]
inductance value	L (custom / comprising two E55/28/21 ferrite cores)	188 [μ H]
DC inductor resistance	r_L	30 [$m\Omega$]
supercapacitors ESR	esr (power supply internal set / SM 70-AR-24)	70 [$m\Omega$]
microcontroller unit	TMS320F28027 [22] (C2000 Piccolo MCU F28027 LaunchPad evaluation board)	-
current sensor	LTS 25-NP [23]	-

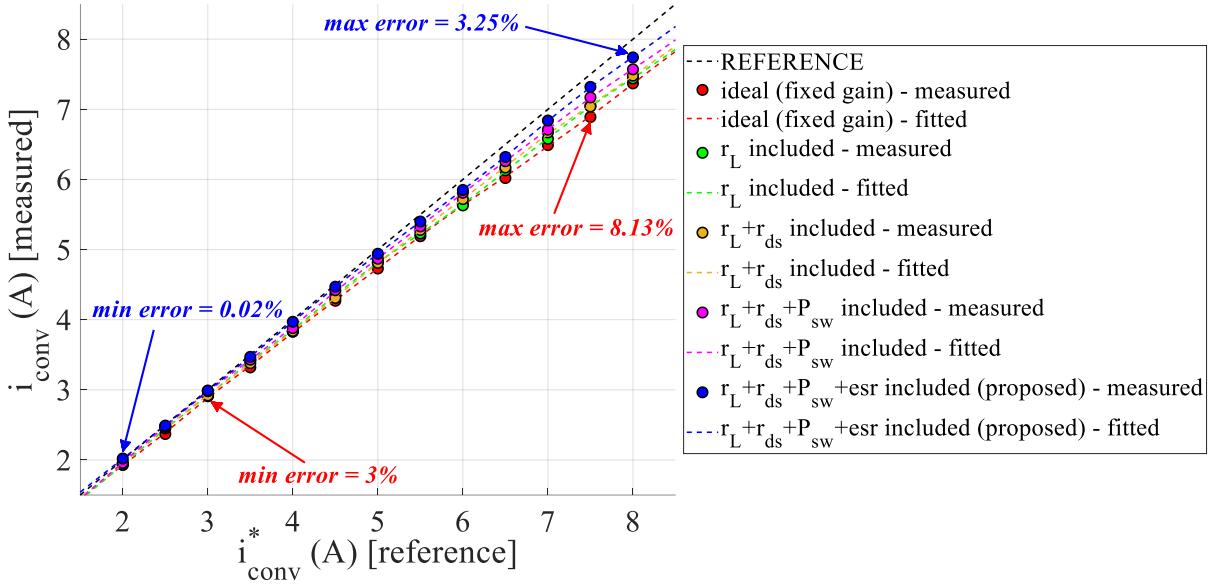


Fig. 4: Experimental results for steady-state operation.

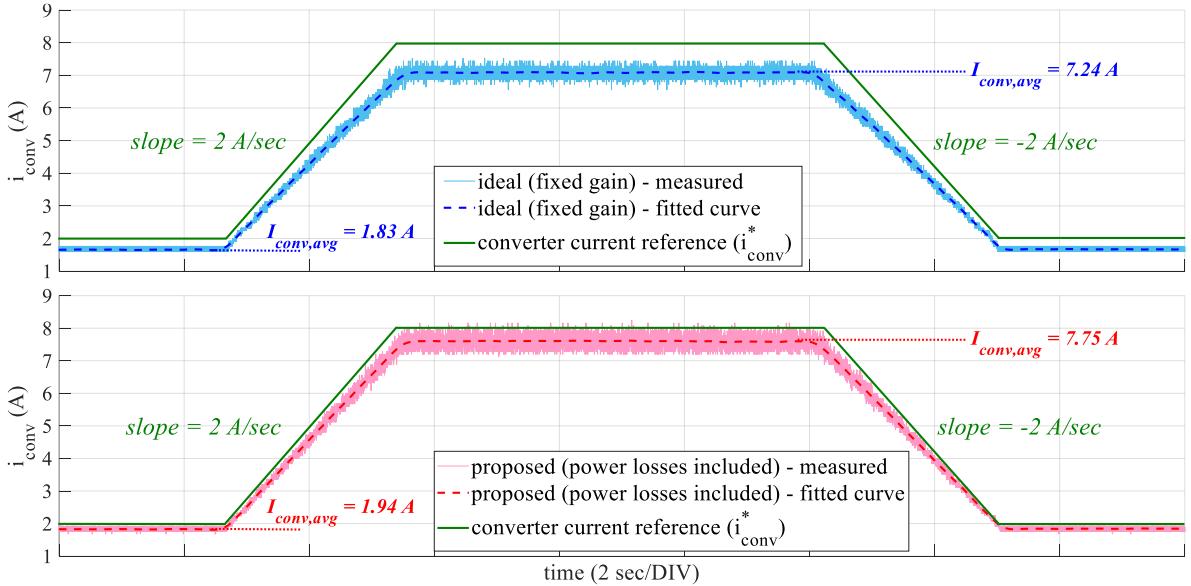


Fig. 5: Experimental results for “slow” transients’ operation ($2 \text{ A} \rightarrow 8 \text{ A} \rightarrow 2\text{A}$) with a slope value of 2 A/sec.

At first, the proposed controller performance is investigated, in steady-state converter operation. In Fig. 4, the converter output current (provided to the DC bus) is illustrated and compared to the converter current reference. The proposed controller (blue line) which takes into consideration the overall power losses excels the performance of the fixed gain ideal transfer function (red line), whereas three additional cases are given, for the inclusion of only a specific fraction of the overall losses. The real output current measurements indicate the enhanced controller performance, keeping the error among the reference and the measured values below 3.3% for a wide current reference range. On the other hand, this deviation for the fixed gain controller (which takes into account the ideal converter transfer function) may reach 8.2 %, exhibiting poor transient performance and thus ineffective load compensation.

Next, in Fig. 5, a slow transient occurs, driving the converter current reference (i_{conv}^*) from 2 A to 8 A and vice versa, with a slope of 2 A/sec. The improved performance that can be achieved with the proposed controller, compared to the ideal (fixed gain) transfer function is highlighted. Finally, in Fig. 6 steeper transients with positive slope (i.e., 4 A/sec and 6 A/sec) are depicted, indicating the fact that the proposed controller operates effectively for relatively “slow” transients (in the sec-time scale),

minimizing successfully the error between the real (measured) and the reference current value, injected to the DC bus.

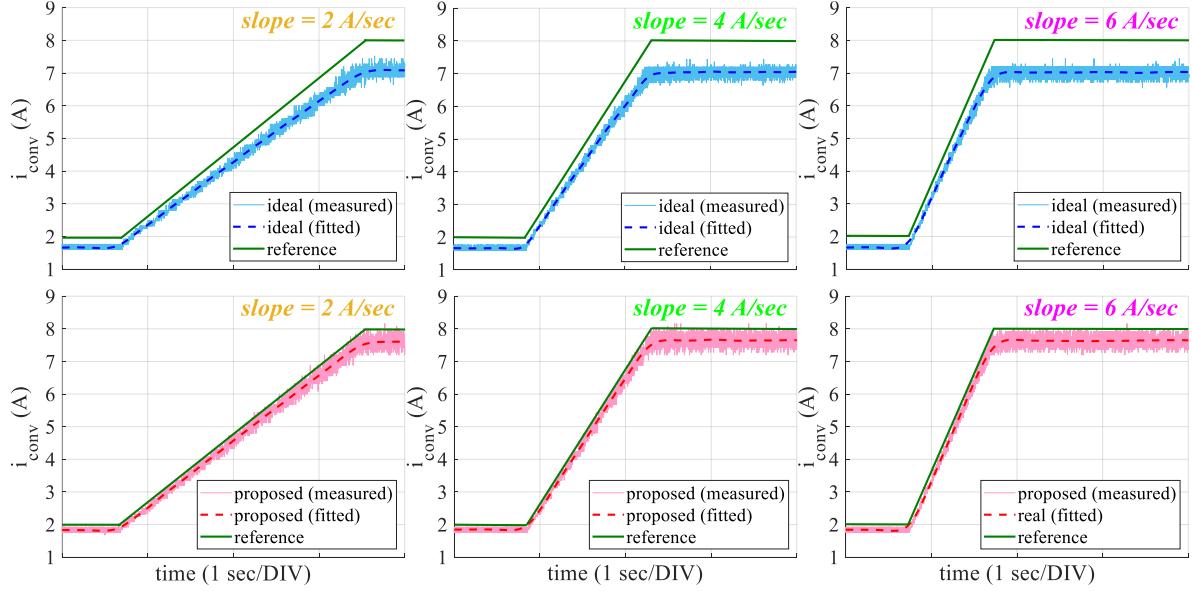


Fig. 6: Experimental results for “slow” transients ($2 \text{ A} \rightarrow 8 \text{ A}$) with various slope values (2 A/sec , 4 A/sec and 6 A/sec).

Conclusion

This paper proposes an improved controller design for power conditioning systems, applicable to MEA microgrids, taking into account the detailed bidirectional DC-DC converter average model (including power losses). The developed control scheme is able to significantly enhance the converter transient behavior, ensuring high power quality, whereas it is of extremely low computational burden. The presented experimental results on an all-SiC scaled-down hardware prototype highlight the functionality of the proposed (digitally implemented) control strategy, as well as the enhanced converter dynamic performance.

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