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Experimental Test Bench for Testing DC Microgrid Control Strategies

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***Abstract*—During the last decades the number of microgrids and their research have increased notably, as they offer a high versatility for the integration of distributed generation (DG) units and renewable energies. Among the different types of microgrids, dc systems are becoming more popular due to their advantages over conventional ac systems. However, their control techniques differ from the ones employed at ac networks, and depending on the device type—either generation, storage systems or loads—alternative control techniques need to be developed. Therefore, in this paper an experimental dc platform is developed with the aim of testing and evaluating these kind of control strategies. This test bench consists of a bidirectional four switch buck-boost converter together with a TMS320F28335 DSP for the implementation of the control strategy on each power converter. The proposed platform is suitable for integrating these systems at a 48 V dc bus and facilitates the evaluation of a wide range of control strategies as they are implemented in the Matlab/Simulink® environment. In this case, the validation of the experimental platform has been carried out by implementing a virtual-impedance-based control technique. The experimental results included in the paper corroborate the suitability of the platform for the evaluation of control techniques for dc microgrids.**

***Index Terms*—distributed generation (DG), energy storage systems (ESS), microgrids, renewable energy sources (RES), virtual-impedance, control of power converters, microgrid central controller (MGCC), test bench.**

I. INTRODUCTION

The actual environmental and climate situation is asking for a change in terms of energy generation model and types of energy sources. In the last decades, mainly due to the increasing penetration of distributed generation (DG) systems—usually based on small-scale renewable energy sources (RESs)—the energy model is shifting from a top-down mainly non-renewable topology to a decentralized system with a higher contribution of alternative generation systems.

However, more advanced approaches where these DG systems can be integrated are necessary, due to their intermittent and distributed nature. Microgrids, which are low-scale smart electric grids, are arising as one of the most interesting alternatives to handle this integration. The advanced control strategies they include enable the management of different generation, energy storage systems (ESSs) and loads [1]. These characteristics make them suitable for a grid-connected or islanded operation.

Most of the challenges of these control techniques originate from the fact that usually the elements connected to a microgrid are interfaced by a power converter, which deteriorates the dynamic behaviour of the system [2]–[4]. Depending on the device type connected to these converters and its purpose, the applied control techniques need to be different.

In addition, depending on the type of microgrid, the control strategies that need to be employed are also diverse. In the literature three types of microgrids can be found based on their current nature [5], [6]: ac, dc and hybrid ac/dc. Most of the current microgrids are purely ac microgrids, making use of the actual grid infrastructure. However, hybrid ac/dc and dc systems are causing great interest due to the advantages they offer with respect to purely ac systems. Nowadays, many equipment and devices are based on dc or include a dc stage, so by employing a dc network the number of these intermediate stages could be decreased. Besides, the control becomes simpler because no frequency/phase control is necessary and the absence of reactive power circulation helps to improve the overall efficiency compared to ac systems [7], [8].

The main purpose of this paper is to develop a fast-prototyping and flexible test bench to evaluate different types of control techniques for dc-based microgrids. Nowadays most part of the research regarding microgrid control is carried out by employing hardware in the loop (HIL) or real-time simulators through mathematical models of real systems [9], [10]. Even though HILs are capable of emulating very fast transients, the aim of the platform developed in this paper is to provide a more realistic environment for testing and validating different types of control strategies. This test bench consists of a four switch buck-boost dc-dc converter controlled by a TMS320F28335 DSP. This configuration enables a rapid prototyping and testing process as the control strategies can be developed in the Matlab/Simulink® environment.

The rest of the paper is structured as follows. The microgrid scenario is explained in Section II. Subsequently, the theoretical analysis and dimensioning of the dc-dc converter together with the control strategy is explained in Section III. In Section IV the developed platform is shown, and the performed tests as well as the experimental results are included. Finally, in Section V, the paper concludes with the most important remarks and conclusions of the research.

II. MICROGRID SCENARIO

Fig. 1 shows a concept of the microgrid to be built in the laboratories of Mondragon Unibertsitatea, where the platform developed in this paper will be integrated. In this section the main features of this microgrid are introduced, as the experimental platform will be designed accordingly.

The microgrid consists of different DG, ESSs and loads, and the aim is to integrate an ac/dc converter so that the microgrid can operate both in islanded mode or grid connected (Fig. 1). As it can be seen on the figure, different types of energy generation systems are included in the microgrid. On the one hand, various solar panel arrays and a mini wind-power system are installed on the roof, connected to the microgrid through dc-dc and an ac-dc converter, respectively. On the other hand, two programmable dc sources have been included with the aim of programming different generation profiles and emulating the behaviour of other DG units.

Regarding the loads connected to the system, in this case different programmable loads are employed. This enables the emulation of different load profiles to test diverse operation conditions in the microgrid.

In order to compensate energy generation and demand differences, different ESS units are used on the microgrid. Taking into account that with a high penetration of renewable energy sources dynamic variations are high, ESSs—and their advanced control strategies—need to be capable of responding with different dynamics. Therefore, the aim is to integrate a hybrid storage system composed by a lithium-ion battery and an ultra-capacitor module. By operating with these two elements, a resulting high energy and high power ESS is achieved, since the battery can provide power over longer periods of time whereas the ultra-capacitors handle higher dynamic power variations.

One of the key components towards the integration of the above mentioned systems is the dc-dc converter (highlighted in green in Fig.1). Each system requires its own converter and control so as to provide certain types of services; DG units for instance include maximum power point tracking (MPPT) algorithms to extract as much energy as possible from energy sources; ESSs, on the other hand, are responsible for regulating the power variations of the microgrid. This paper is hence focused on the development of a converter platform that can integrate the different generation, storage systems and loads to be connected in the microgrid. Moreover, the test bench will be responsible for communicating with the microgrid central controller (MGCC)—also known as SCADA in the classical grid—to monitor and carry out a high level management of all the devices in the future [11].

III. DEVELOPMENT OF THE EXPERIMENTAL PLATFORM

This section embraces the analysis, design and integration of the experimental platform used to evaluate control strategies for dc microgrids. The platform proposed in this paper, which

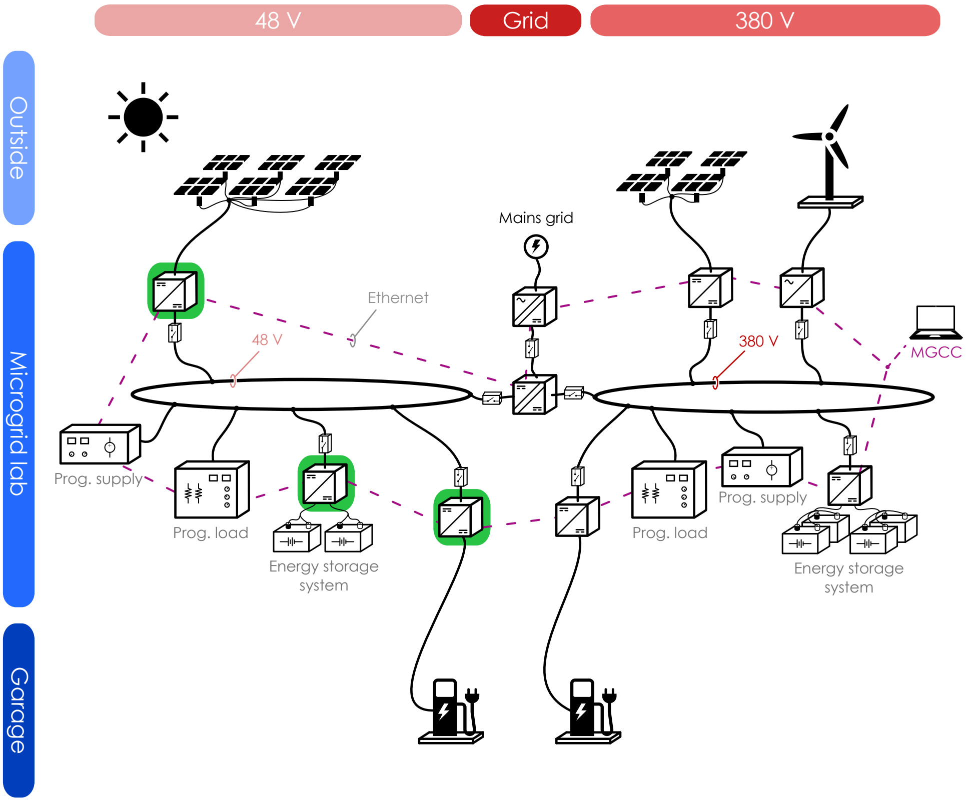

Fig. 1. Concept of the future dc microgrid experimental platform at the laboratories of Mondragon Unibertsitatea. The converters highlighted in green are developed in the present paper.

can be observed in Fig. 2, consists of a dc-dc converter with a DSP that enables the fast integration of different technologies of energy generation and storage systems at a 48 V microgrid.

A. *Converter topology*

Among the different converter topologies that are available in the industry for this type of applications [12], a four switch buck-boost converter has been chosen (Fig. 3). This topology provides a high flexibility as it is capable of operating with voltage levels above and below 48 V in the input and output, and enables the power transmission in both directions. Therefore, this type of converter is an interesting alternative to handle the varying behaviour of generation and storage systems. On the one hand, the converter must manage the intermittent nature of renewable-energy-based DG units and this device should be controlled so as to extract as much energy as possible from the energy source. On the other hand, the voltage of ESSs is not constant and varies depending on the state of charge (SOC), so the converter must be capable of operating at certain input voltage range.

B. *Converter design*

Based on the topology shown in Fig. 3, it can be noticed that the four switch buck-boost converter can operate differently depending on the position of its switches. Three main operation modes are distinguished in the literature, namely buck, boost or buck-boost mode. In this case, as the input and output voltages are very close to each other, the converter will operate entirely in the buck-boost mode. The switching states for this operation mode, taking into account that the power flows from left to right, can be observed in Fig. 4.

From these switching states the waveforms of the voltage and current of the inductor can be drawn (Fig. 5).

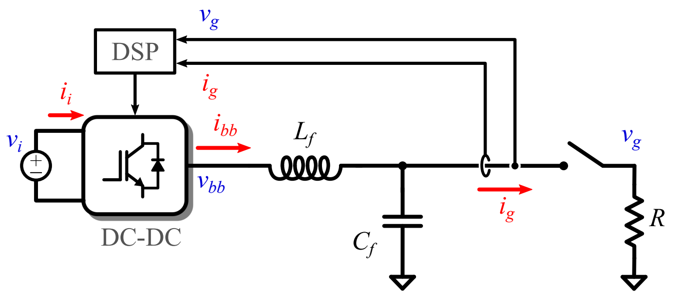

Fig. 2. Experimental test bench diagram.

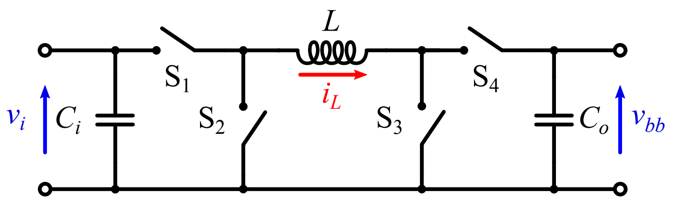

Fig. 3. Four switch buck-boost topology.

By applying the volt-second balance, the converter conversion ratio can be deduced, which depends on the value of the converter duty cycle (D) as follows:

$$\frac{V_{bb}}{V_i} = \frac{D}{1-D} \tag{1}$$

Assuming an ideal converter with no losses, the inductor average current equation can be obtained:

$$I_{L_{\mathrm{AV}}} = \frac{V_{bb}^2}{V_i D R} \tag{2}$$

where R is the output resistive load of the converter.

From this equation, the minimum value of the inductor can be deduced so that the converter operates in the continuous conduction mode:

$$L_{\min_{ccm}} = \frac{R(1-D)^2}{2 f_{sw}} \tag{3}$$

where f_{sw} is the switching frequency of the buck-boost converter.

Similarly, the minimum value of the inductor must be calculated to ensure a maximum current ripple in it:

$$L_{\min_{\Delta I}} = \frac{V_i D}{\Delta I_L f_{sw}} \tag{4}$$

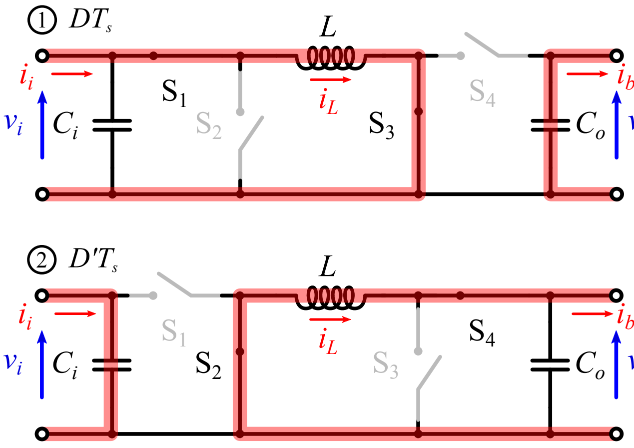

Fig. 4. Switching states of the four switch buck-boost converter.

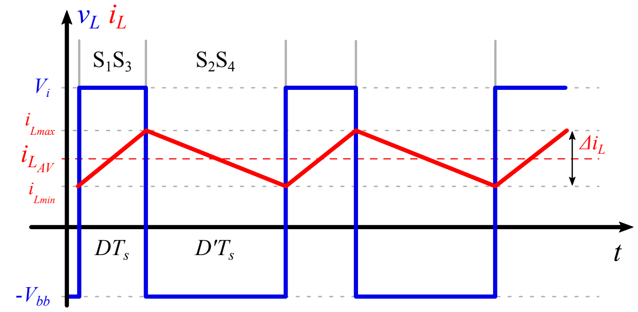

Fig. 5. Inductance voltage and current waveforms of the buck-boost dc-dc converter operating in buck-boost mode.

A similar procedure can be applied to deduce the minimum capacitor at the output of the converter to ensure a certain voltage ripple:

$$C_{o_{\min}} = \frac{V_{bb}D}{\Delta V_o R f_{sw}} \tag{5}$$

As the converter is symmetrical, in this case the same capacitance value will be established at the output and the input of the converter.

For the parameters defined in Table I, the following values have been obtained for the previous variables:

$$\begin{aligned} L_{\min_{ccm}} &= 293.88\ \mu\text{H} \\ L_{\min_{\Delta i}} &= 342.86\ \mu\text{H} \\ C_{o_{\min}} = C_{i_{\min}} &= 57\ \mu\text{F} \end{aligned} \tag{6}$$

Taking into account the most restrictive ratings for the parameters, the values finally chosen for the inductor and the capacitors of the converter are:

$$\begin{aligned} L &= 350\ \mu\text{H} \\ C_o = C_i &= 60\ \mu\text{F} \end{aligned} \tag{7}$$

As can be seen on Fig. 2, an LC filter has been included at the output of the converter to interface it to the 48 V. The values chosen for this filter are:

$$\begin{aligned} L_f &= 100\ \mu\text{H} \\ C_f &= 30\ \mu\text{F} \end{aligned} \tag{8}$$

TABLE I
FOUR-SWITCH BUCK-BOOST CONVERTER REQUIREMENTS

Parameter	Value
v_i	$[40-60]$ V
v_o	$[30-80]$ V
f_{sw}	100 kHz
Δi_L	1 A
Δv_o	0.5 V

C. *Control platform*

The aim of the experimental platform is to enable a fast yet reliable way of testing different control strategies that might be integrated in a dc microgrid. Therefore, a TMS320F28335 DSP from Texas Instruments has been chosen. This DSP provides a high flexibility as the control strategies and measurements can be easily programmed in the Matlab/Simulink environment. The control platform includes several inputs/outputs and peripherals so the communication of variables can be set up rapidly.

Fig. 6 is a diagram showing the variable exchange between the converter, the control platform, the connected device and the MGCC.

As it can be noticed, the local control of the converter is included in the DSP, while control references come from global control techniques integrated at the MGCC. In this case, the control is configured so that the converter operates autonomously with locally measured variables. Therefore, the MGCC in this case is only employed for monitoring critical values of the converter—currents, voltages, etc.

Apart from these connections, the platform includes a CAN transceiver in case a commercial battery pack is connected to the converter via a battery management system (BMS).

Regarding the control strategies, in this case the virtual-impedance technique developed in [3] has been employed in order to evaluate the experimental test bench. This virtual-impedance algorithm is a primary control strategy that enables to adjust separately the dynamics of the transient as well as steady-state response of the converter by adapting different control parameters. This technique is suitable for controlling parallel-connected converters regulating the bus voltage with the aim of sharing power variations and improving the stability of the microgrid.

The experimental test bench resulting from the previous development can be observed in Fig. 2. In this case, the component ratings have been calculated to design a converter that is capable of handling approximately 300 W.

IV. EXPERIMENTAL RESULTS

An experimental configuration has been set up in order to evaluate the behaviour of the developed experimental test bench. In this context, a programmable voltage source has been connected to the input of the buck-boost converter to emulate the voltage of a battery pack (Fig. 7. Similarly,

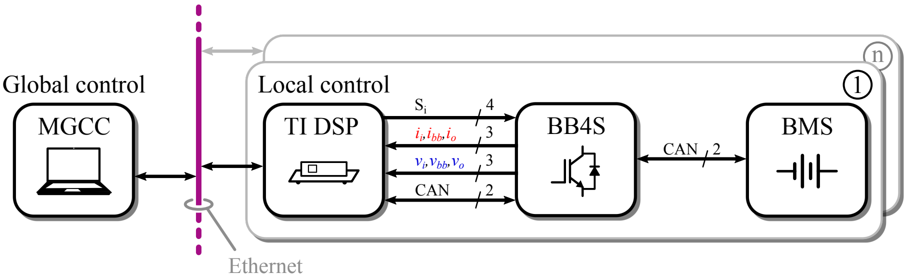

Fig. 6. Variable exchange between the DSP, the converter and the MGCC.

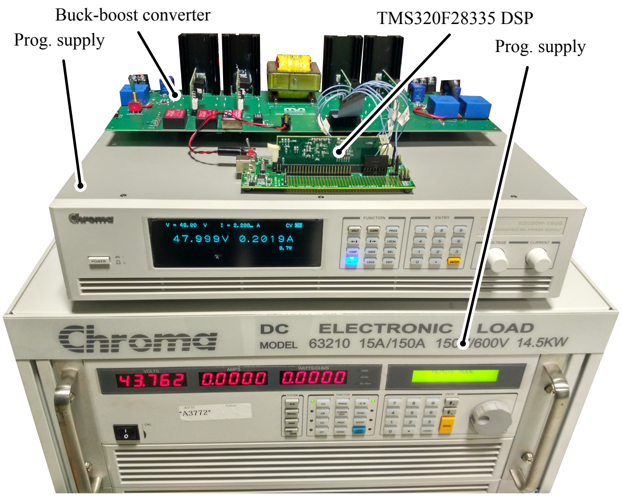

Fig. 7. Experimental test bench with a programmable power supply, converter and load.

a programmable load has been connected to the output of the converter, as the purpose is to evaluate the response of the converter and the control platform for different load variations).

In the experiment, the converter has been submitted to a step-shaped load current profile i_o, making it to transfer power from the battery to the load. Figs. 8 and 9 illustrate the voltages, currents and powers at the input and output of the four-switch buck-boost converter. In this case, the converter supplies the load while regulating the output voltage v_o according to the virtual-impedance Z_V control strategy (refer to [3] for more details).

Even though the input voltage v_i is constant and the output current i_o is defined by the programmed profile, an important difference can be observed between two figures in the output voltage of the converter. This is due to the fact that in each case, the implemented virtual-capacitor technique is configured differently. Although in both cases the low-pass filter gain K_LPF is set to 40 and the time constant τ_LPF to 0.01 s, the virtual-impedance Z_V is configured to 10 Ω and 4 Ω, respectively.

As it can be appreciated, Figs. 8 and 9 show that by varying the virtual-impedance value, the output voltage v_o steady-state response is modified. A higher Z_V value means a higher voltage drop at the output for the same current variation. Therefore, it can be noticed that Z_V would be equivalent to a classical droop controller.

The experimental results demonstrate that the test bench proposed in this paper is a flexible and useful tool to test differ-

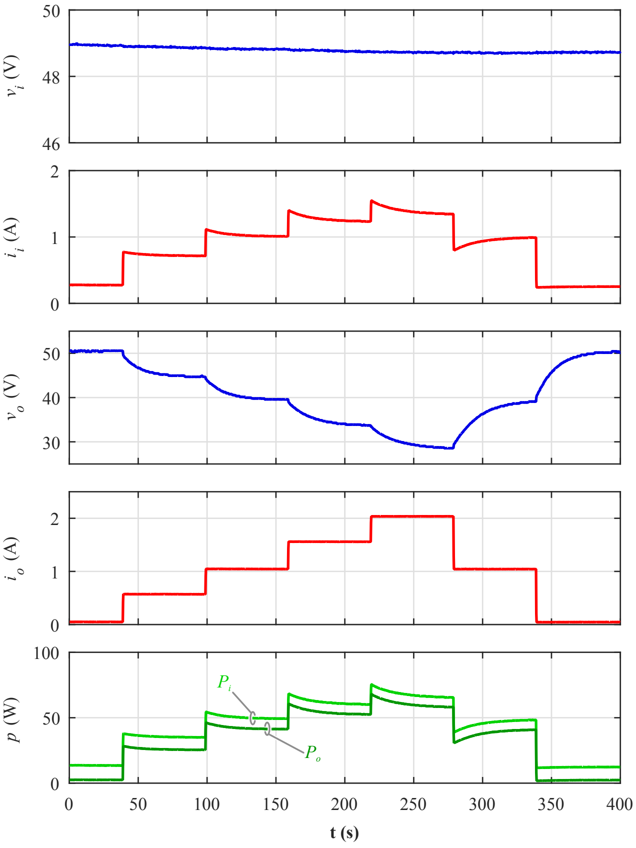

Fig. 8. Experimental results for a virtual impedance value of Zv 10, operating with a constant current profile.

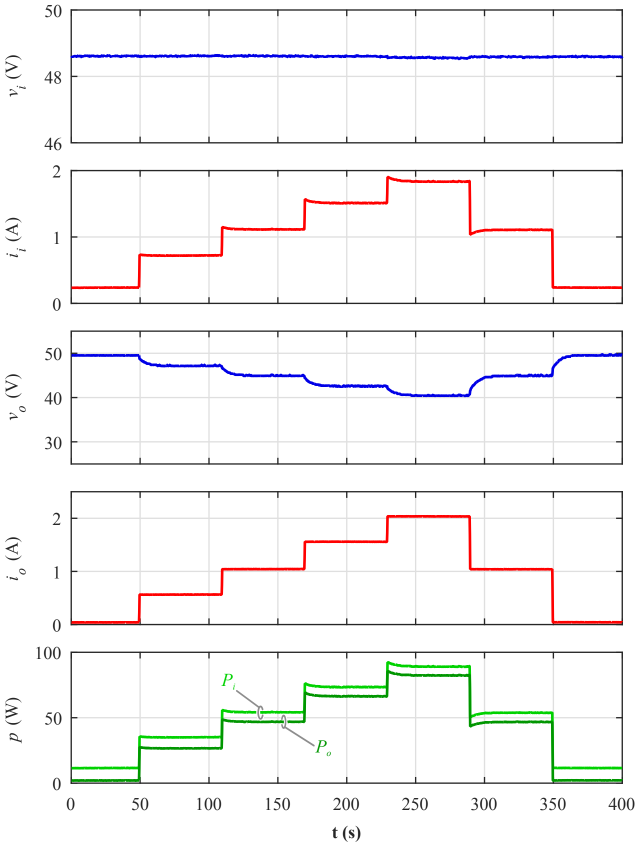

Fig. 9. Experimental results for a virtual impedance value of Zv 4, operating with a constant current profile.

ent converter control strategies for dc microgrids. Even though the control technique employed in this case is autonomous and relies on local measurements, the platform is designed to enable the communication with upper-level regulators such as secondary or tertiary controllers. This feature opens the path to the development of a diverse amount of control techniques.

V. CONCLUSIONS

In the last decades dc grids have gained a lot of interest and therefore they are being widely researched. These systems require more advanced control strategies for the integration of distributed generation and storage systems. In this context, different tools or platforms are being developed for the evaluation of these control techniques in realistic environments.

In this paper an experimental test bench suitable for testing and validating dc microgrid control strategies is proposed. The high versatility makes the platform ideal for research purposes: fast prototyping, flexibility to integrate different devices, capability to communicate with upper-level regulators, etc.

This test bench is composed by a four-switch buck-boost converter controlled by a DSP that can be programmed in the Matlab/Simulink environment. The paper has covered the design of this converter and the configuration of the communication between the different agents that are integrated in the platform.

The validation of the test bench has been carried out by employing a programmable voltage source and an electronic load. The voltage source is used to emulate the constant voltage of a battery pack, whereas with the programmable load a varying demand profile is reproduced. The experimental results demonstrate that the platform can be easily updated to integrate different types of controllers and control parameters. Moreover, the configuration of the communication network enables the integration of global controllers such as secondary or tertiary layers, and the interconnection to other converters connected in parallel. This confirms the suitability of the platform to develop diverse dc microgrid control algorithms in a realistic environment.

VI. ACKNOWLEDGEMENTS

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