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# Design and control strategy of an AC/DC microgrid for collective housing with management of the shared EV charging infrastructure

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**Summary**

The rapid development of electric loads and sources such as electric vehicles (EVs), photovoltaic systems (PVs) and battery energy storage systems (BESS) has led to an increasing need for adopting energy and power management strategies in distribution grids and microgrids. By applying optimization algorithms and modern control methods with peak shaving, load scheduling and vehicle-to-grid (V2G) strategies, an optimal integration of the distributed sources and controllable loads can be obtained. In this paper, the authors, from the Research Lab team of Eaton, describe the development of a hybrid AC/DC microgrid laboratory intended for the design and testing of a low voltage direct current (LVDC) microgrid and its control system. The lab realization was done within the project named 'Flexible AC/DC microgrid for collective housing' executed in cooperation with the Czech Institute of Informatics, Robotics and Cybernetics (CIIRC) of Prague. Also, a special mention in this paper is to the follow-up research and pilot demonstrator that is under development within EU Horizon 2020 funded project, run by the consortium 'Hyperride', whose Eaton is active member. The paper deals with the reference design of the microgrid and its practical implementation in a DC power system laboratory. A focus will also be on the control system and power management strategy that has been proposed, describing the development within the project and the adoption in the real demonstrator.

*Keywords: Microgrid, Power management, Renewable, V2G (Vehicle-to-Grid), Optimization*

## Nomenclature

AC: Alternate Current

AFE: Active Front End

BESS: Battery Energy Storage System

BEV: Battery Electric Vehicle

BMS: Battery Management System

DC: Direct Current

DCMG: Direct Current Micro Grid

DER: Distributed Energy Resources

EVCI: Electric Vehicle Charging Infrastructure

EVSE: Electric Vehicle Supply Equipment

LAN: Local Area Network

LVDC: Low Voltage Direct Current

MG: Microgrid

MPPT: Maximum Power Point Tracking

OBC: On-board charger

PCC: Point of Common Coupling

PE: Power Electronics

PHEV: Plug-in Hybrid Electric Vehicle

PV: Photovoltaic

SCADA: Supervisory Control and Data Acquisition

SoC: State of Charge

V2G: Vehicle-to-Grid

# 1 Introduction

Modern electrical networks integrate distributed and renewable resources, exploitation of which can be optimized by the employment of efficient energy storage and fast advanced control systems. Within this framework, the fast-growing penetration of EVs is pushing the improvement of the electric grid to facilitate the usage of charging stations as active components of the electric demand. These changes in the future of transportation and power generation require a revolution on the power systems and a transition from Centralized power distribution systems to the Microgrid and Smart Grid distribution systems. The transition to the distributed control has been widely discussed in the recent literature, in both academic and industrial environments, and the applied research often focuses on understanding the advantages and the challenges of DC microgrids and distribution grids compared to the 'traditional' AC ones. DC microgrids have a large range of practical applications, such as energy storages, aerospace, naval, electric vehicles, telecommunication systems, LED lighting and data center, as discussed in [1] and [2]. This trend is justified and supported by the fast development of the power electronics (PE), that enable the integration of DC/DC and AC/DC converters in the microgrid. The rapid improvement of high-efficiency PE converters has led to a beneficial usage of DC grids because many of the Distributed Energy Resources (DER) such as BESS and PV are ''by nature'' DC, therefore, their interface into DC grids can be obtained easily. In addition to these features, LVDC grids have considerable advantages when it comes to the control strategy, as the algorithm for control does not have to deal with frequency and reactive power management, following an easier grid control and better power quality, [3], [5], [7]. Nevertheless, as discussed in [1] there are many aspects that still need to be investigated in order to find solutions to the challenges of DC grids, such as lack of regulation and standardization and protection devices suitable for interrupting also DC currents. The

Eaton European Innovation Center (EEIC) in Prague is developing capabilities and knowledge of DC microgrids and hybrid AC/DC grids to address the challenges in this field. Currently a team of Eaton researchers in Prague is running two projects whose objectives aim at increasing the energy efficiency and the controllability of LVDC grids by integrating DERs, EV chargers with the controllable and uncontrollable loads. A Czech Government program named ‘’Flexible AC/DC microgrid for collective housing’’ is currently running in its last year, and it led to the realization of an AC/DC microgrid with DC voltage capability up to 1000V for testing the control system developed in the project for a LVDC microgrid of common areas of apartment buildings. The results and learning from this project will be also applied in a microgrid pilot demonstrator that is currently under preparation within the EU Horizon 2020 R&D program ‘’Hyperride’’, where the Eaton team of Prague is co-leading the demonstrator regarding the LVDC side of the grid.

## 2 EV charging and AC/DC microgrids: State of the Art

Up until recent past, the DC power system have been adopted predominantly in the high voltage applications, for the power transmission over very long distances. High voltage direct current (HVDC) transmission has exploited several advantages of DC lines over the AC ones: lower power losses and voltage drop, higher power quality due to the absence of reactive power, ease of grids interconnection (no frequency issues) and better cost efficiency, [2]. In the recent years, also LVDC grids have gained significant research interest. The adoption of DC voltage in the distribution grids facilitate the transition towards microgrids structures, where also EV chargers and electric vehicles can play an important role. The Electric vehicle charging infrastructure (EVCI) has an increasing tremendous impact on the overall load of a distribution grid; this impact, can be converted, using appropriate hardware and controlling techniques, in beneficial services for the grids. Vehicle-to-grid (V2G) is the technique and the capability that enables EVs to use the energy stored in their batteries as support to the interconnected grid, discharging the electricity through the charging infrastructure. V2G includes the capability of the car to communicate with the Electric vehicle supply equipment (EVSE), and vice versa, in order to exchange the necessary information to enable the transaction. At the current state of the art, the challenges to enable the exploitation of EVs in the grids and to manage their load as well as their demand response service capability, shall be overcome on two parallel fronts: the electrical grids and the EV chargers and vehicles manufacturers. Regarding the improvements that must be done on the grid side, the transition from the centralized power systems to the distributed and decentralized ones is inevitable, because AC and DC microgrids offer much better local controllability of the DERs and loads such as EVs. In general, the MGs can be classified for their bus type design in: AC, DC and hybrid AC/DC. Other classification, such as operation modes (grid connected or islanded/standalone) and usage (residential or commercial), can be applied to all the three of these layouts. While voltage levels and supply configuration of the AC grids are more standardized, when it comes to the LVDC MG few standards have been proposed for the voltage; this depends also on the polarity of the DC bus that can be unipolar (two wires, 0 and Vdc+) or bipolar (three wires DC bus system with Vdc-, 0, Vdc+), [1]. The most common nominal voltage levels adopted are 350V and 700V (that can be obtained in unipolar configuration or also from bipolar configuration of +350V, 0V and -350V). Recently also the 1000 Vdc standard has been investigated and proposed in several pilot demonstrators. Regarding the EVCI and their compliance with the commercial vehicles, there are currently many configurations available, and their classification is summarized in the table 1 and following discussed.

Table1: EV charging classification (Supply standard AC 230/400V, 50 Hz or DC)

| Power level | AC/DC conversion | Voltage (V) | Current (A) | Power (kW) | Charging mode | Connector standard |
|---|---|---|---|---|---|---|
| Level 1 (AC) | On-board | 230 | 16 | 3.3-10 | Mode 1, 2 | J1772 |
| Level 2 (AC) | On-board | 230/400 | 32 | 7-22 | Mode 1, 2, 3 | J1772, CCS |
| Level 3 (AC) | On-board | 400 | 32-63 | 22-43 | Mode 3 | J1772, CCS |
| Level 4 (DC) | Off-board | 100-800 | 50-400 | 50-350 | Mode 4 | CCS, CHAdeMO, Tesla |

In terms of output voltage of the EVSE, two different modes are classified:

- AC charging: it represents up to now the most widespread type of charging method as it requires lower cost of infrastructure, exploiting the AC/DC power conversion in the on-board charger (OBC) of the EV.
- DC charging: used as fast-charging method, through an AC/DC power conversion off-board, which requires higher investment cost, but it gets rid the power limit given by the OBC of the car.

As shown in table 1, AC charging covers all the use-cases for low to mid power demand for charging, including the slow overnight residential charging for private use and mid speed of charging that is usually performed through public charging points. The AC EVSEs are interfaced to the distribution grid through single-phase or three-phase supply, depending on the power required. The same is valid for the output voltage, which is then rectified by the OBC equipped by the Battery electric vehicle (BEV) or the Plug-in hybrid electric vehicle (PHEV). On the other hand, DC charging is implemented usually in those use-cases where time and speed are more important, such as public charging in the highways fuel stations. The infrastructure in this case is usually more expensive because the AC/DC conversion is performed directly in the charging station, providing the EV directly with DC power supply. DC charging standard offers also often compliance with the bidirectional and V2G standards, since the HW and SW in the EVSE can be developed with bidirectional functionalities for power (and information) exchange between the vehicle and the grid. Due to these features, the DC charging infrastructure has a more natural integration to the microgrids, thanks to the better connectivity to both the car side and the grid side. Furthermore, since the interface between the EV charging station and the microgrids is performed via controllable PE converters, it can be reasonably beneficial to implement solutions that exploit the DC nature of the car’s battery to interface a DC microgrid with the EVSE, so that is possible to maximize the efficiency of the EV charging and VG2 by reducing the conversion stages. This solution has been increasingly investigated in the recent years and the authors believe it can be a game changer for the adoption of DC microgrids and low voltage distribution grids.

# 3 AC/DC microgrid for collective housing: design and power control strategy

The goal of the Czech Government funded project ‘FlexCollective’’ is the development concept of AC/DC microgrid integrating to the DC power system DERs such as PV and BESS and EV chargers in condition of collective housing. The main deliverable is a modular control system based on communication between local controllers for each power unit and central controller that defines the different control modes, according to the inputs from an Optimization algorithm running in separate computer. In order to test the integration and control of the units, a DC microgrid is also being developed in a laboratory testing environment as one of the main deliverables of the project.

## 3.1 Reference design

The scope of hybrid AC/DC microgrid for collective housing is to replace the traditional low voltage electrical network of the common area of an apartment building with a modern DC microgrid. The DC microgrid (DCMG) interconnects, supplies and controls all the possible DC loads present in the common area of the building, such as elevators, stairways lighting, garage doors and lights etc. Moreover, this LVDC grid integrates also controllable power sources and loads, like PV systems in the common rooftop, a bidirectional EV charging infrastructure in the underground garage and a storage system to maximize the self-consumption and exploit the variability of electricity tariff. The proposed design does not affect the electrical network inside each apartment, which remains invariant from the classic distribution. On the other hand, the supply and the control of the DCMG is done ‘behind the meter’, with optimization, control system and measurements performed separately from the AC public grid. But the microgrids acts mainly in grid connected mode, accommodating the bidirectional power exchange between the AC and the DC sides. The connection to the public three-phase 230/400 V grid is done through a bidirectional AC/DC converter, namely Active-Front-End (AFE) which is placed at the Point of common coupling (PCC); if the selected converter does not have an isolated topology it is recommended to place an isolation transformer to galvanically separate the AC grid from the DCMG. The DC microgrid is proposed in a unipolar system (0-Vdc+) design with nominal operating voltage of 700 V. As per the grounding strategy both TN system and IT system are being investigated and proposed. Each DC power source, storage, controllable loads or group of big loads are interfaced to the DC bus at 700 V through PE DC/DC converters, which keep the output voltage in the range defined for the DC bus via distributed voltage DC droop control. The PE topologies for these converters are not strictly defined, except for the bidirectional features for the BESS and EV chargers (for V2G mode), and in the case of the EV charger also the galvanic separation is recommended, in order to ensure safe conditions to the car side. In figure 1 an example of reference design for the DCMG architecture is shown, in order to provide with a better understanding of described layout.

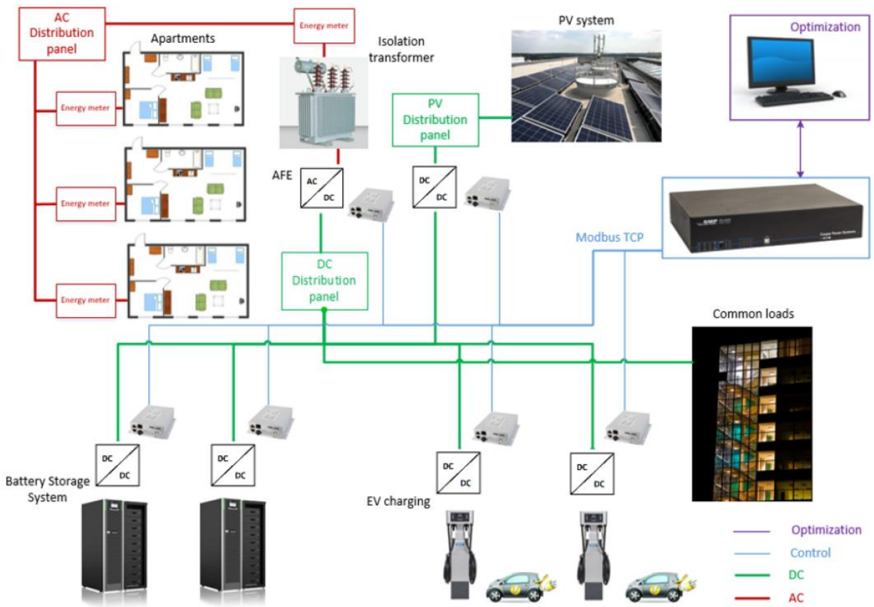


Figure 1: Layout of DC microgrid for apartment building

## 3.2 Control architecture and workflow

The management of power and information in a generic microgrid is guaranteed in a hierarchical structure and typically there are 3 control levels for the DC microgrid:

- Primary level: responsible for the local power, voltage and current regulation performed by the local controller on the converter unit
- Secondary level: responsible for the power flow control and coordination between controllers
- Tertiary level: responsible for the microgrid supervision, control and data acquisition as well as the exchange with an external grid interface, including a level of optimization and forecast

Regarding the control strategies on the primary and secondary level, usually the classification includes 4 types of control: centralized, decentralized, distributed and hierarchical (or hybrid centralized-distributed). In the centralized control, it is a central controller that gathers all the information from the DCMG, performing control operation and setting the reference values to the power components and units. The decentralized control consists of a local control of each unit by a different local controller, where all the controllers are independent from each other. The distributed control, instead, is a decentralized type of control where all the control units can communicate between each other. To maximize the advantages of these control strategies a hybrid one can be implemented, which is a mix of the centralized control and the distributed control; the hierarchical control is based on the hierarchy between a central controller and local controllers that manages the power units. The upper level (central controller) adjusts the primary distributed control of each converter to achieve the voltage regulation and the load sharing, [11]. The approach that has been proposed for the DC microgrid described in the previous paragraph consist of adopting a hybrid control based on a communication between the central controller and the local controllers, implementing the droop control method to ensure the voltage regulation and the current sharing. Using this control strategy is possible to exploit advantages such as: modularity, reliability, redundancy and therefore safety, which can be ensured only by a combination of control structures. The very basic principle of the droop control method is to decrease the converter output voltage when the current increases so to introduce a resistive behaviour in the system. The droop coefficient responsible for this resistive linearity is then the slope of the converter output curve Vdc-Idc and enables the voltage regulation and current sharing in the DCMG. Smaller droop coefficient means small variation of the DC bus voltage but at the cost of weaker current sharing between converters, and vice versa for the big droop coefficients. The general theory of droop control and similar approaches are described also in [5], [7], and [9]. The control scheme proposed in the DC microgrid in this work utilizes the distributed droop control method for the lower control level, managed by the local controllers for each PE unit, regulated and reconfigured by an upper control level lead by a central controller. The central controller in this grid reads and sends information from/to each local controller, regarding the status of the converters and the electric parameters/references. Through this communication lines the central controller can reconfigure and have access to all the droop functions for a more reliable control. One more level is above the central control, where an optimization algorithm runs in a separate computer unit to recalculate all the requests, tariff, forecast and information of the grid, in order to send optimal power setpoints to the central controller which will distribute to the local ones. The communication and control network proposed is based on the industrial protocol Modbus TCP/IP running on Ethernet technology for wired Local area network (LAN), while the direct control of the converters can be realized with Modbus protocol TCP/IP or RTU depending on the compliance with the units installed. Other types of communication protocol can be also adopted to achieve the same result. This control structure and hierarchy is also illustrated in the figure 1. The workflow illustrated in figure 2 describes the working principle of the DCMG control hierarchy. Information such as weather forecast (solar data), events and activities related to the building tenants (use of electric car) and historical data about consumptions are collected and utilized to create forecast of power profile consumption and generation. These, together with the local electricity tariff are computed by the optimization algorithm running on a computing unit at the tertiary control level and the output result is provided to the Central Control unit, in the form of optimized power setpoints. The central controller works as Client in the Modbus TCP/IP network that reads measurement and requests from the Local Controller units (servers) and send them the setpoints according to the droop control embedded in each local controller. The control on each PE unit is performed independently from the dedicated local controller that writes and reads registers for the converter control modes, voltage references, current limits etc.

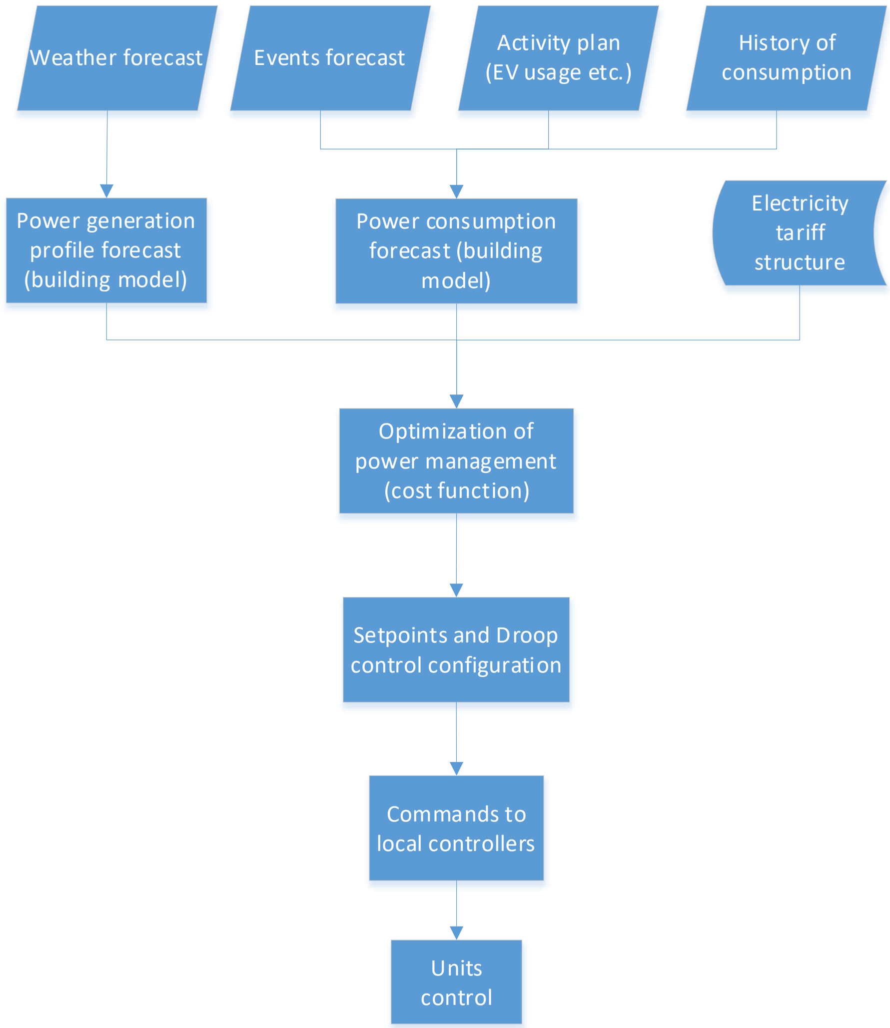


Figure 2: Communication, control and information Workflow

A more specific cases of interaction in the DCMG are the ones where the battery State-of-Charge (SoC) are relevant to define the charging/discharging modes. These two components are the BESS and the EV, which implies the EVCI placed in the garage of the building and it is the focus of the description that follows. The size (number of chargers) of the charging infrastructure depends on the use-case, but the working principle is scalable. In the event of an EV charging need, the central control must be able to sense when a vehicle is plugged and asks for charging and to read the time when the charging session start. At the same time, information such as current SoC at the time of plugging should be send from the EV to the EVSE local controller and then managed from the central controller. The time of leaving (un-plug time) should be declared from the user at the time of arrival in the parking lot, because it will used by the optimization algorithm to calculate the amount of power that should be guaranteed to the car in every instant in order to achieve a pre-defined SoC at the end of charging. The SoC should guarantee a safe amount of driving range for the following trips and should be kept target including also potential availability of the car to offer V2G service, if approved by the owner of the EV. The other electrical quantities and measurement of the DC EV charging are exchanged normally between the controller inside the vehicle and the local controller in the charging station, in this case is normally the EV the client and the controller in the EVSE acts as server for the car's voltage and current limits requests.

# 4 Lab integration and experimental testing of control system

In the DC Power System laboratory of the Eaton European Innovation Center in Prague the authors of this paper led the effort to build a hybrid AC/DC microgrid, focused mostly on the research on the DC power systems and the testing of LV DCMG control system. The aim of this realization is the testing of the power converters, control devices and power management strategy to be applied in the project. The DC electric grid designed consists of a multi-DC buses power system with maximum voltage up to 1.5 kV capable of managing self-generation and controllable loads as well as exchanging bidirectional power with the AC network of an office building. A simplified single bus schematic of the current-status of the laboratory grid is shown in figure 3, as well as its interconnection to the AC grid side.

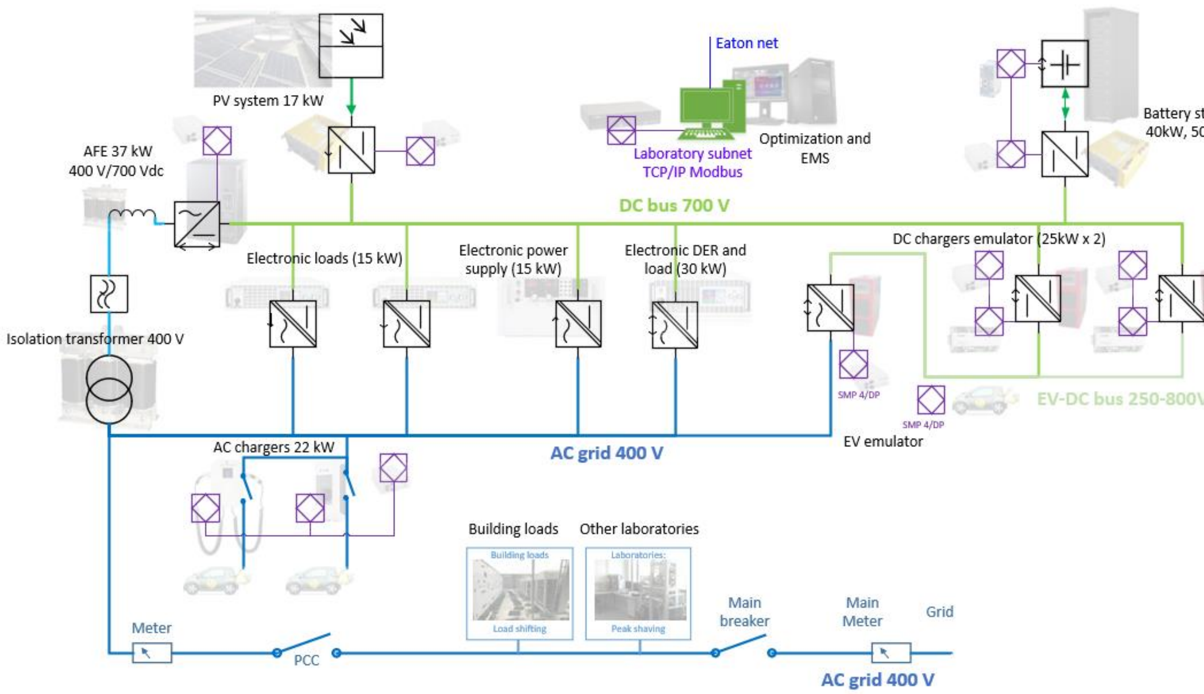


Figure 3: AC/DC microgrid realization in the lab (power and control)

As shown in figure 3, the connection to the three-phase 400 V grid is performed by means of a bidirectional AFE, that is playing the role of grid forming component in the grid, setting the voltage value of the main DC bus to 700 V. The galvanic separation between the two grids is made through an isolation transformer, and between the transformer and the AFE an inductor filter is placed. The AC infrastructure is directed supplied by the external power transformer, and it supplies also the AC loads in the other building laboratories, while in the DC power system lab its branch can supply 2 commercial AC Eaton EV chargers, whose power rating is 22 kW three-phase. From the three-phase AC sockets of the grid inside the laboratory connection it is also provided to electronic components such as loads, DER simulators and power supply. The DC microgrid has a nominal voltage level of 700 V in the main DC bus and it was designed unipolar and isolated. The AFE has a nominal power of 37 kW for continuous supply support to the DCMG when it is needed. The main local generator is the PV system, which consists of 17 kWp of photovoltaic array in the rooftop of the building interfaced to the lab by means of a DC/DC converter installed in the lab and controlled locally from the control system developed. The Maximum power point tracking (MPPT) algorithm as well as the droop control are realized in the local controller in programming environment Codesys. The DCMG includes also a BESS realized integrating a commercial EATON 'XStorage' battery system of 50 kWh interfaced to the DC bus by a bidirectional DC/DC converter rated at 40 kW; the BEES includes the Battery management system (BMS) controller EATON 'XC3000' which sends the data to the local controller of the PE unit. Furthermore, to test different load profiles scenarios and to balance PV generation and battery discharge, 2 electronic load units (max 15 kW) are integrated in the grid, capable of regenerating the power to the AC grid. Two more units are added for emulation of DERs, each of 30 kW rated power. Due to the challenges to find commercial EV chargers that can be interfaced to the DC grid and of using real vehicles for testing, a separate cabinet was realized in the lab for emulation of EV DC/DC charging, which is shown in figure 4 and it is following discussed. To complete the description of the DC microgrid laboratory it is important to focus also on the communication network and the control links realized. The MG is based on the distributed hybrid control discussed in the previous chapter where two main controllers are used: EATON 'SG4250' and EATON 'SMP 4D/P'. The SG4250 is the DCMG central controller, that communicates to all local controllers SMP 4D/P via Ethernet LAN and protocol Modbus TCP/IP. Both types of controllers are programmed in Codesys for their functionalities. Modbus TCP/IP protocol is also used for the link between the central controller and the computer where the optimization runs. Regarding the direct control of power converters, some units are compatible with the same version of the protocol, others are controllable via serial communication Modbus RTU (RS-485 or RS-232).

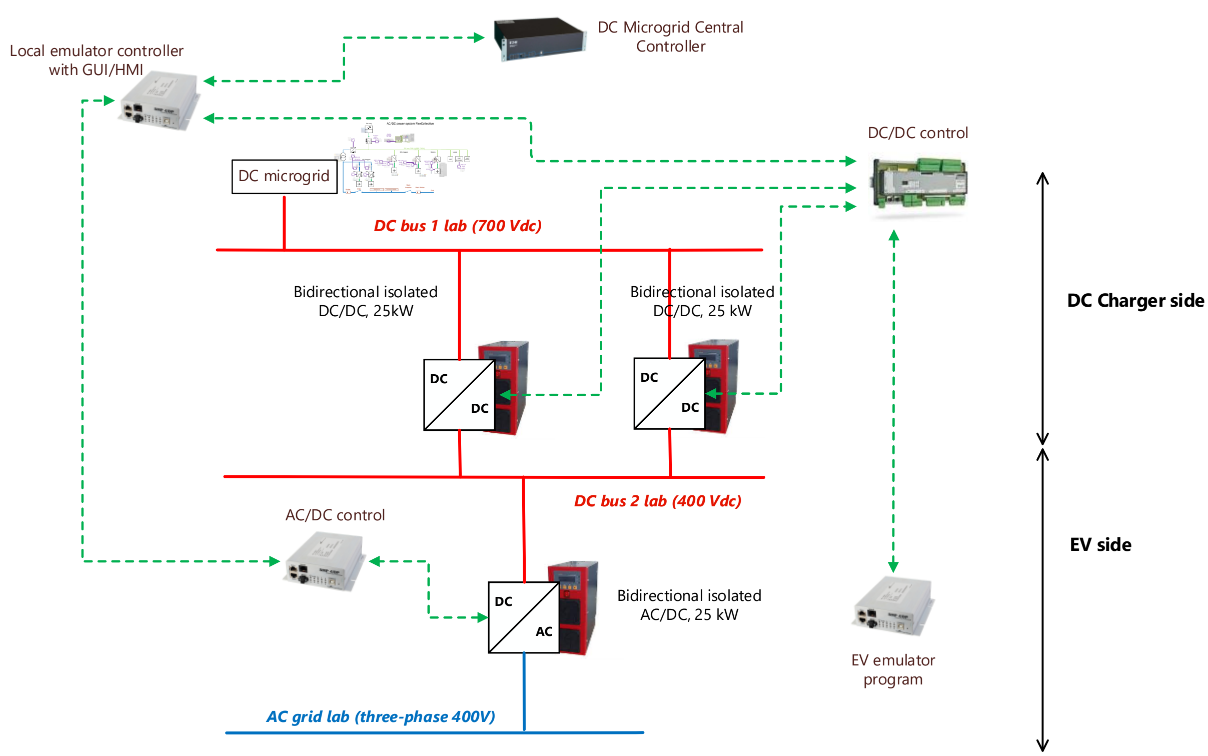


Figure 4: EV DC/DC charging emulator: lab realization

Figure 4 shows the realization and test bed to simulate the behaviour of an EV station and car charging session. This demonstrator was performed as proof of concept of the DC charging, exploiting one of the benefits of the DC microgrids: the direct interconnection between a DC load and the DC bus through DC/DC converters. The DC charging finds a good use-case in this scenario, where the electrical infrastructure is also present in the form of direct current bus and one conversion stage can be avoided resulting, in larger scale, in increased energy efficiency. To test the behaviour of DC charging through the DC bus there was no commercial DC input chargers, for this reason an emulator system was realized. For this demonstrator two DC buses and the three-phase AC grid were used. The electric vehicle emulation is realized by means of an AC/DC converter, whose AC side is connected to the AC network of the lab and the DC side is connected to a secondary DC bus (DC bus 2) used for testing with nominal voltage assigned by the battery of the emulated car (e.g. 400 V). The converter is bidirectional and isolated featuring the 4-quadrant control mode, so it is capable to push power to the AC grid when it acts as load (charging mode) and to push the power withdrawn from the AC grid it to the DC side when it simulates the V2G (discharging mode). The direct control of this converter is performed from a separate local control unit, of the same type as the ones described above, via Modbus RTU protocol. At the same time another control unit was dedicated in order to emulate the behaviour of an EV and its BMS. The EV emulator controller was programmed in Codesys with a program to perform variation and estimation of SoC based on the power exchange between the AC/DC and the DC/DC converters. This unit provides also the central controller and the optimization with the data regarding the EV charging needs (SoC, time of leaving, V2G mode, etc), which can be set by a graphic user interface (GUI) developed for the project. At the same time, it communicates the voltage target and the current limits required by the car to the EVSE controller (DC/DC control), like the BMS control unit in an electric car during the charging session. The DC charger side of the emulator was realized using two bidirectional and isolated DC/DC converter in parallel interfaced with the EV converter to the same DC bus 2 at 400 V. Their input side is supplied directly from the DC bus 1, the main one of the microgrid and their bidirectionality guarantees that the charging station can operate both in charging mode and V2G, pushing power to the DCMG when need of power is detected by the central controller and the optimization. Two converters were placed in the cabinet for the demonstrator in order to test scalability of charging infrastructure, redundancy and test different scenarios where the charging is supplied by different buses switched opportunely. Also, this choice will let the authors test other scenarios where different cars with different voltage levels are requesting for charging, when another converter will be integrated in the EV side.

# 5 Conclusion

In this paper, the authors presented the development of a project aimed to propose a reference design for LV DC microgrids of the common area of apartment buildings, replacing the traditional AC infrastructure, as well as a control architecture based on a hierarchical distributed control. In the article also a focus was on the development of the DC microgrid laboratory used for proof of concept and testing of different use-cases, including island modes, black start and different scenarios for emulated EV charging and V2G. A power management strategy was developed and implemented in the local and central controllers; also, graphic user interfaces were developed for each local units and group of units, as well as for the full microgrid control and supervision. Furthermore, a similar pilot site demonstrator for a 700 Vdc microgrid is being prepared within a follow-up project, dealing with power management of DERs and EV charging through the DC bus, exploiting the learning from this development. The challenges to be faced and discussed to enable the transition towards this modern type of grid are numerous, especially regarding the cost of infrastructure replacement, policy implications, grid codes, load predictability and safety. The authors leave these discussions to a future work when the project will come to an end and more results will be available to be analysed.

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