Control of Grid-Forming Power Converters

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***Abstract*— This thesis focuses on the study of converters for microgrids. These are small-scale grid which can supply local loads, by using distributed generation. The goal of this project is the analysis, simulation and experimental validation of microgrid (MG) converter control strategies. Moreover, an experimental testbench consisting of multiple converters has been assembled. First, different strategies of grid-forming control were analysed, implemented and then experimentally tested using a three phase two level inverter. Subsequently, a converter prototype was realized. This design involved both the mechanical structure (Solidworks) and the firmware implementation on a interface FPGA board. Finally, the complete system has been assembled and tested.**

I. INTRODUCTION

Microgrids (MGs) have been introduced as a solution for the future electrical grid challenges such as the rapid increase of electrical demand and energy produced from renewable sources, in order to ensure the quality and reliability of electricity supply. A MG is considered as a small-scale grid and it is formed by distributed generation systems, electrical energy storage systems and local loads. The Sendai MG in Japan is proposed as an example in Fig. 1.

In a MG, three types of power converters can be employed: grid-forming, grid-feeding and grid-supporting. The goal of this project is the analysis, simulation and experimental validation of MG converter control strategies. Moreover, an experimental test bench consisting of multiple converters has been assembled. **My work was divided in the following steps:**

1) Study of different grid-forming control strategies and validation in PLECS simulations. It is also analysed a grid-supporting control strategy.
2) Implementation of the simulated control structures in C code on a dSPACE rapid prototyping platform.
3) Experimental tests using a three phase two level inverter connective passive and active load to the PCC;
4) Mechanical design of two support structures where other two inverter units will be installed.
5) Assembly and testing of two FPGA interface boards. They will be used to interface the control implemented on dSpace and the two new inverters.
6) Implementation of the grid-forming control strategy on the new test bench. This step includes also the programming of the FPGA and the creation of communication protocol between dSpace and the board.

Figure 1: Sendai Microgrid in Japan (https://building-microgrid.lbl.gov/sendai-microgrid).

II. CONTROL OF GRID-FORMING POWER CONVERTERS

The system under study is shown in Fig. 2. It is composed by a three phase two level inverter equipped with an LC output filter. The inverter is supplied by a DC/DC converter. The AC/DC converter is controlled as grid-forming.

In a MG the Grid-forming power converter has the crucial role to set the reference voltage E^* and frequency f^* at the point of common coupling (PCC) of the microgrid. It is controlled as an ideal AC voltage source. In this thesis two methods were analysed and tested:

- **Single loop Voltage Control (SL):** a single voltage regulator controls the voltage at the PCC;
- **Dual loop Voltage Control (DL):** a nested scheme which regulates the PCC voltage and the converter output current.

For both strategies the control was implemented in the (d, q) rotating frame synchronous with the reference frequency f^*

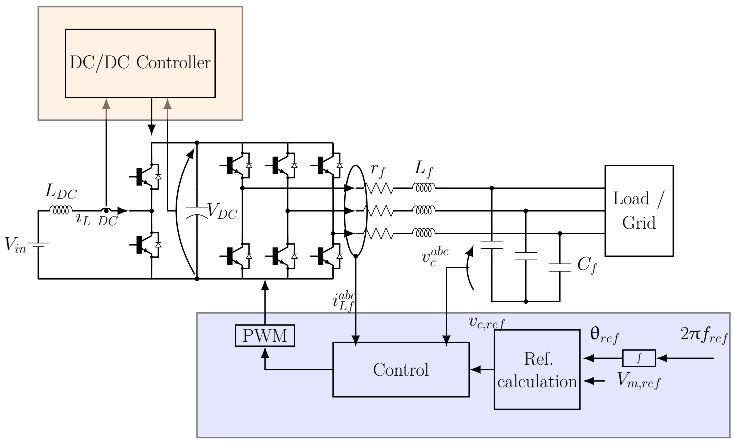

Figure 2: Equivalent circuit of the system under study.

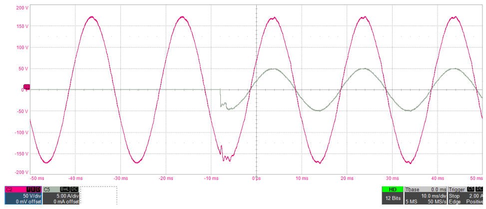

Figure 3: SL control strategy using PI regulator. R load. C2: v_a; C5: i_a.

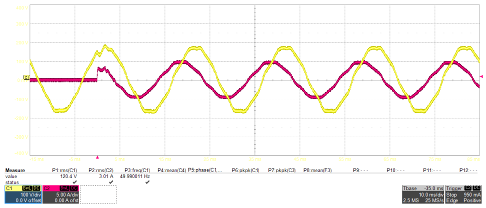

Figure 4: DL control strategy using PRES regulator. RL load. C1: v_a; C2: i_a.

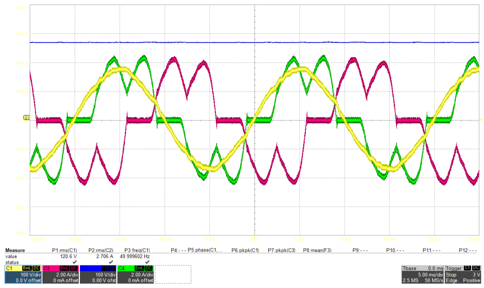

Figure 5: SL control strategy using PRES regulator. Diode rectifier as active load at the PCC.
C1: v_a; C2: i_a; C4: i_b.

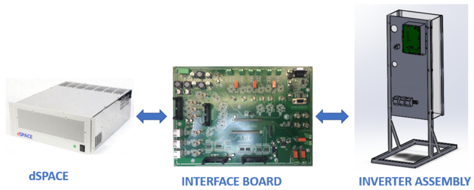

Figure 6: Block diagram of the designed and assembled grid-forming test bench.

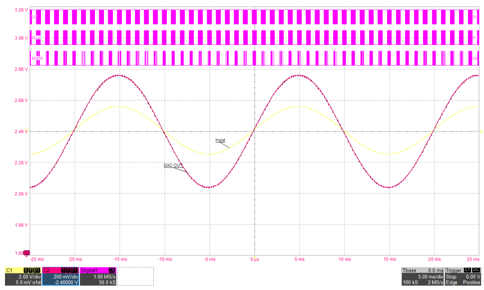

Figure 7: ADC and DAC transmission test results.
C1: input signal; C2: DAC output; Digital1: ADC SPI transmission line.

using PI regulators and in the (α, β) stationary reference frame adopting PRES regulators. The work has been developed following these steps:

- Modelling of the system and tuning of the regulators;
- Implementation and validation of the control schemes in PLECS simulations with a digital control implemented in C code;
- Experimental test on the real setup.

On the experimental setup the different grid-forming control strategies analysed were tested connecting passive and active load. Fig. 3, Fig. 4 and Fig. 5 shows some waveforms recorded using an oscilloscope connecting to the PCC a resistive load, an inductive load and a diode rectifier as active loads. Experimental tests involving PRES regulators shows that there are a little percentage of 5^{th} and 7^{th} that could be eliminated inserting a supplementary resonant filter. Moreover, it is visible in all the acquisitions a little distortion due to the dead-time effect, that is not compensated. However, experimental tests validated the simulated behavior.

III. FPGA Board

The second part of this thesis involved the programming of the FPGA-based interface board between the converter and dSpace. First, the interface board was assembled. Then, their correct functionality was verified by implementing verification tests programming the FPGA board using the Vivado software. As an example of the work done, the results of the test carried out on the analog to digital converter (ADC) and digital to analog converter components (DAC) are shown in Fig. 7 as an example. During this test, a signal is acquired using one of the seven channels of the ADC component, and it is correctly redirect to one channel of the DAC.

Therefore, this FPGA-based board:

- communicates with the control implemented in dSpace;
- monitors the acquired measurement value and if an anomalous situation arises, it commands the system to operate in a safety state;
- manages the contactors, relays, hardware protections and user signalling of the converter;
- transfers the gate signals from the control to the converter unit.

IV. Conclusion

In this thesis I analysed different grid forming control solutions for MGs. Their operation were verified both in simulation and experimentally. These control strategies obtain satisfactory results using either of the implemented internal controller (PI or PRES). Moreover, I mechanically designed and assembled an extra experimental test bench, composed of a grid-forming inverter, an FPGA-based interface board and a dSPACE controller. This process involved both hardware assembly and VHDL programming of the interface board.