Implementation of grid-forming algorithms in inverter-based generation

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Master's Project

STUDENT REPORT

AALBORG UNIVERSITY

This report has been written using LaTeX.During the project *MATLAB/Simulink* has been used for simulations. OPAL-RT and dSPACE 1103 have been used for hardware in the loop (HIL) simulations and experimental part.

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Abstract:

Synchronous machines are desired to be replaced in future electrical energy production by distributed energy resources. Since the majority of DER are based on renewable energy and need to be interfaced with the electrical grid by power electronic devices, some issues can appear. This report presents a design model of droop control as grid forming algorithm.
Concepts and topics such as grid-following, grid-forming algorithms were discussed. Droop-control technique is presented and simulations of droop-control were performed in Simulink and the concept of hardware in the loop was presented with an example.

Contents

Preface

This document describes the report of the Master Thesis entitled 'Implementation of grid-forming algorithms in inverter-based generation'. The project was developed at Aalborg University with the co-supervision of Austrian Institute of Technology from the 1st of February 2020 to the 16th of November 2020. The report discusses the implementation of grid-forming algorithms as a solution to the high penetration of renewable energy generation into the electrical grid. The literature references are shown in square brackets, with a number referring to a specific document which can be found in the bibliography. If the reference is after the dot, it means that it refers to the whole previous paragraph. Pictures and tables will be denoted in the X,Y format, with X representing the chapter and Y the figure or table number. The process and development has been based on the Problem Based Learning method.

Aalborg University, November 16, 2020

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Nomenclature

Abbreviations:

DG-Distributed Generation
AC-Alternative Current
US-United States DC-Direct Current
RoCoF-Rate of Change of Frequency
PV-Photovoltaic
PWM-Pulse Width Modulation
PI-Proportional Integral
VOC-Virtual Oscillator Control
dVOC-dispatchable Virtual Oscillator Control
PLL-Phase Locked Loop
IGBT-Insulated-Gate Bipolar Transistor
HIL-Hardware in the loop
FPGA-Field-Programmable Gate Array
PC-Personal Computer
DSP-Digital Signal Processor
ADC-Analog to Digital Converter
DAC-Digital to Analog Converter
I/O-Input Output
VSM-Virtual Synchronous Machine
APDC-Active Power Droop Control
VSI-Voltage Source Inverter
VSC-Voltage Source Converter

1 Introduction

The electrical energy generation is facing a transition from centralized power generation to decentralized distributed power generation due to high penetration of renewable energy sources into the power grid [1]. This transition involves the major challenge of substituting synchronous machines and their well-known dynamics and controllers with power electronics-interfaced generation .

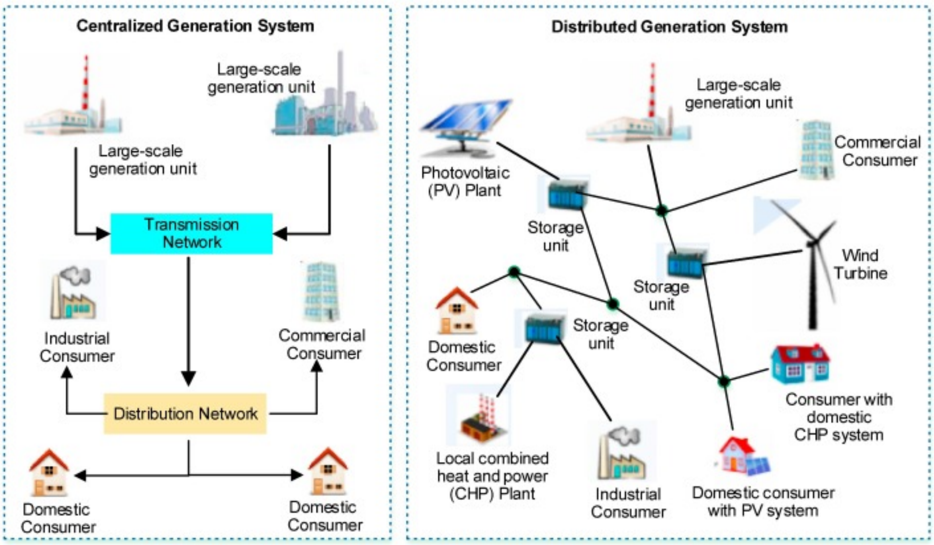

Figure 1.1: Centralized power generation (left).Distributed power generation (right). [2]

Some drawbacks regarding this changes are unavoidable. One of the biggest drawback is the lack of inertia in inverter interfaced distributed generation occurring because in power electronic devices there are no rotational masses, thus no spinning reserve and kinetic energy exchange will take place between them and the AC grid, as it is the case for synchronous machines.

The way that the converter controllers are implemented today results in the incapability of the grid to operate 100% inverter-based because the grid connected converters are programmed to operate as grid-following. In other words, they behave as a current source which is dependent on the grid's phase angle and provide the necessary active and reactive power. Removing all the synchronous machines from the grid will lead to the absence of a voltage reference which will make the grid-following converters unpractical. Therefore, it is absolutely necessary that some of the converters control the frequency and the grid's voltage. These converters are called grid-forming and have the task to ensure a stable voltage and ferquency in various cases such as connection/disconnection of a load, a generation unit or a fault in the system.[3]

An example of how the future energy generation will look like can be seen in Figure 1.2 provided by the National Renewable Energy Laboratory which shows the Renewable Energy Projections for the US.

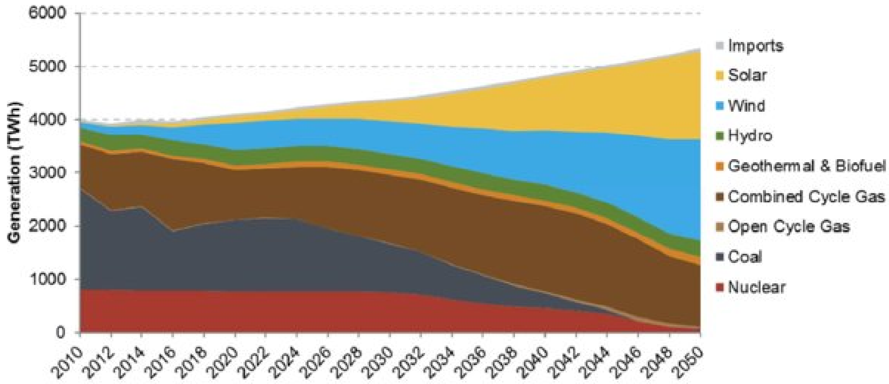

Figure 1.2: *R*enewable Energy Projections for the US. [3]

1.1 Scope of the project

The characteristics of the grid face a drastically change as conventional generation is replaced by non-synchronous sources. As a consequence, stability issues such as frequency stability may arise. As a possible solution to these new conditions of the grid, new functionality for inverter-based generation has been proposed in order to mimic the existing dynamic behaviour of conventional generation. Therefore, investigations need to be done in order to test the feasibility of this solution in two steps which are simulating the possible scenarios and perform hardware in the loop experiments. In this way, the student has the opportunity to understand and implement grid forming algorithms and, after validating them in simulations, to test them in an experimental setup to prove their functionality.

1.1.1 Problem statement

Currently, the traditional electrical grid dominated by synchronous machines is substituted with one comprising inverter interfaced generation of electric energy on a large scale due to high penetration of renewable energy. This can not be obtained with no consequences and one of the biggest drawback is the loss of the spinning reserve resulting in low inertia systems. Since low inertia can cause instability in the functionality of the electrical grid, implementing methods of controlling inverter interfaced energy generation is a topic of high importance.

1.1.2 Objectives

In order to fulfill the initial problem statement and achieve efficient results, various objectives need to be fulfilled:

- Implement control techniques for inverter-based generation in simulation.
- Run parametric studies to demonstrate the feasibility of those techniques under different grid conditions, for instance: modifying the load and disconnecting the grid.
- Perform hardware in the loop tests.

1.2 Project management

Project management was adapted for a project with both internal and external supervision, meaning that meetings were being done with the supervisor in person or with the supervisor and the co-supervisors via online platforms such as Skype for Business. Also, the progress was being observed by the supervisor and the co-supervisors on online communication platform Slack. The meetings were split into status meetings which were usually done every two weeks and shorter meetings where the student could ask questions or present intermediary progress.

Using the *Trello* application, different cards were designed and were used to track the dependency between tasks and to determine the critical path of the work. They were also used to show milestones and deadlines, which have to be met.

After the restrictions imposed by the Government due to the pandemic we are living in, the first deadline of submitting this Master's project could not be met. Therefore, the deadline was extended until 16th of November 2020 since the laboratories were also unavailable. Starting from 1st of September the activity was resumed. The *Trello* cards had to be updated and also meetings with the supervisor could take place face-to-face. The meetings with the external supervisors were still taking place on dedicated online platforms.

2 Low inertia systems

In the effort to obtain more sustainable electric power systems, various changes need to be done. The main objective is to replace as much as possible on a high scale the well known fossil fuel based power plants with the less polluting and more energy efficient renewable energy resources. One of the main concerns about this transition is the absence of the physical property of the synchronous machines, inertia. This will become an important problem which needs to be overcome while the electric power grid will become more and more populated by inverter interfaced energy resources. Also, this phenomenon will lead to issues such as virtual inertia, novel control techniques for grid-forming algorithms and the role of fast DC energy storage.[4]

Some countries around the world already have the capability of becoming 100% green energy producers thanks to wind and solar power plants. Together with other countries which have a high capability of producing clean energy they already face the low-inertia effects e.g Australia, Central Europe, Nordic grid.[4]

2.1 Causes

Low inertia systems can become very easy unstable when an event such as disturbances and supply/demand imbalances appears in the electric power system. This problems are usually solved by the inertia of the system in traditional power systems but will have a different behaviour in the low inertia ones. Also, low inertia implies a higher rate of change of frequency (RoCoF) which is again a big problem and will therefore be analyzed.

In order to have a better understanding of what the inverter interfaced energy generation needs to replace, a short overview of the synchronous machines' main functions will be presented:

According to [4], the main functions of synchronous machines are to generate active power, regulate the frequency and the voltage and provide kinetic energy. The rotor of the synchronous machine has an important role in the first seconds after an event happens to compensate fluctuations and disturbances and after that, primary and secondary control are applied. A schematic that shows different types of control applied to the system and the time frame in which they are provided can be seen in Figure 2.1.

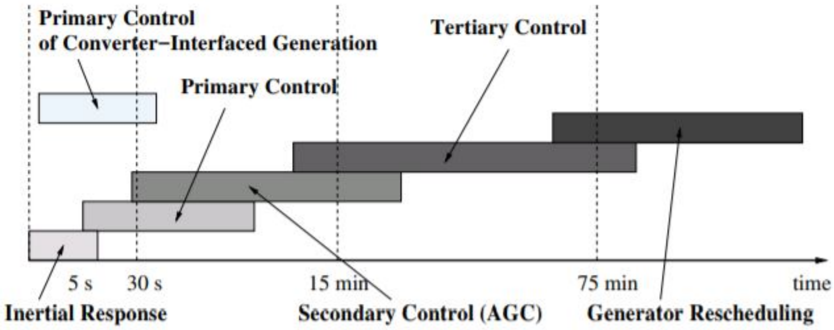

Figure 2.1: Typical time scales of frequency-related dynamics in conventional power system and the ones that can be provided by converter interfaced generators.[4]

As it can be observed, a crucial time represents the first few seconds after a disturbance. In a system with both synchronous and non-synchronous generation units the total inertia can be calculated trough Equation 2.1.

$$M\dot{\omega}(t) = p_s(t) + p_{ns}(t) - p_l(t) - p_j(t) \tag{2.1}$$

Where M is the total inertia of the synchronous machines, $\omega(t)$ is the average frequency of the system, p_s and p_{ns} represent the power of synchronous and non-synchronous generation and p_l and p_j are load demand and losses. From the equation it can be observed that bigger the M, the higher the kinetic energy of the system.

It can also be observed that on short time scales, synchronous machines affect the power balance through instantaneously available physical storage but not through their primary control. On the other hand, for the converter integrated generation it is exactly the opposite so if they are equipped with fast DC energy supply they can contribute faster to power balance. Although, since their response is not natural and depends on the available amount of energy they can provide this case does not guarantee a long term and sustainable alternative. In a hypothetical system containing no synchronous machines M will be approximately 0. In this case, a control system needs to be provided to keep the power balance which is not a realistic scenario at the moment but it can happen for short periods or when some parts of the system are islanded.[4]

When an event such as those enumerated before happens, the rotating masses of the synchronous generators will immediately absorb or inject the stored kinetic energy into or from the grid to balance the system. However, this is not the case in a decreased inertia system, the converter connected generation must supply the system with virtual inertia. Since small isolated system are already presenting issues concerning low inertia there is a high chance they will face operational issues caused by large scale penetration of inverter interfaced generation. The proposed solution for low inertia in small systems may provide valuable new operational practices and control methods for higher scale power systems.[5]

[5] defines inertia as the resistance of a physical object to a change in its state of motion, including changes in its speed and direction. In a traditional electrical power system, the physical objects that are in motion are the rotating machines are which connected to the power system and the resistance to the change in rotational speed (ω_g) is their rotating mass. Therefore the motion of a traditional generator can be expressed as:

$$\frac{dJ_{SG} \cdot \omega_e}{dt} = T_m - T_e \tag{2.2}$$

Where T_e and T_m are the electrical respectively the mechanical torque, J_{SG} represents the moment of inertia and ω_e is the electrical angular frequency. This equation is also know as the swing equation and in power system engineering it is usually expressed in power instead of torque:

$$\frac{d\frac{J_{SG} \cdot \omega_e}{2}}{dt} = P_m - P_e \tag{2.3}$$

In the future power systems some of this units will be substituted by the once which characterize renewable generation units. As an example, since the link between the rotational speed of the generator and the system frequency is removed, the converter connected generation units do not contribute to the total system inertia. Also, the kinetic energy buffer available in traditional power generation units is often missing because only a small amount of energy can be stored in the capacitors of the inverters or as it is in PV systems for example, additional storage can be added in the form of batteries. Thus, the way of counteracting the change of frequency in this cases is by measuring the grid frequency deviations and feeding them as input for the converter's control.[5]

2.2 Effects

The impact that low inertia has on the power system is a very important information in order to have the system working under nominal parameters and thus it is of high importance to be known because it can have multiple effects.

2.2.1 Low security

For synchronous machines there is a psychical connection between RoCoF and primary frequency control but the primary frequency control may happen with a delay. This is not the case in systems containing non-synchronous devices because their response is given on how well the control is designed. This implies control loops and can face delays, unexpected coupling with other dynamics, saturation and limitations.[5]

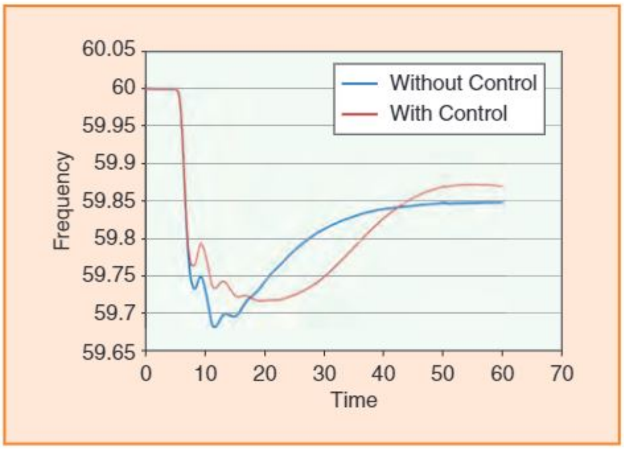

Figure 2.2: Variable renewable energy with and without synthetic inertia controls.[6]

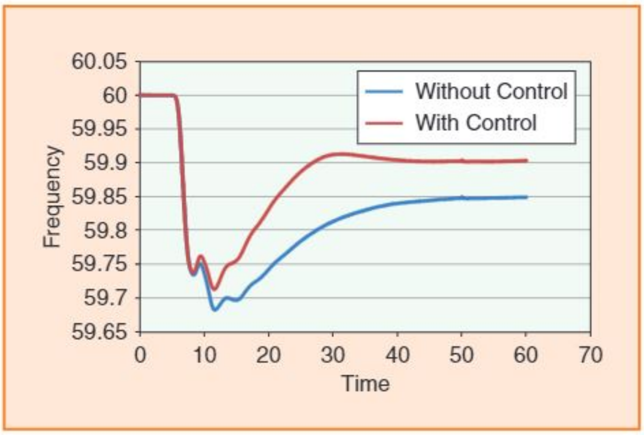

Figure 2.3: Variable renewable energy with and without both synthetic inertia and primary frequency response.[6]

Another issue connected to low security is the power system protection. By removing a significant number of synchronous generators from the grid may arise some problems regarding over-current protection since a synchronous machine can produce approximately six times rated current during a fault. This is unfortunately not the case for power electronics which can withstand maximum twice of the rated current for a short period of time. Thus, in inverter-dominated systems overcurrent protection can encounter malfunctions by means of not sensing the overcurrent in order to act on the circuit breakers.[6]

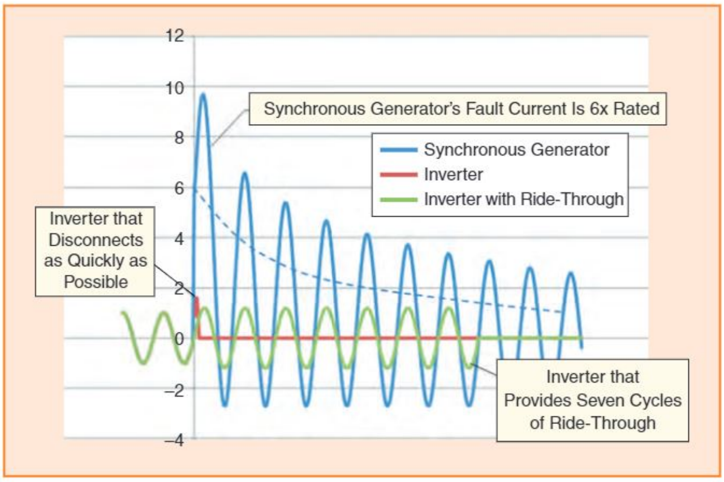

Figure 2.4: Fault currents compared to time for a synchronous generator, an inverter with rapid disconnect and an inverter with ride-through capability.[6]

2.2.2 Transients stability

Transients stability represents the stability of the system after a large disturbance such as loss of generation, faults and sudden load changes and it can occur during the first seconds after the event. Depending on various characteristics of the synchronous machine such as the grid to which it is connected, the load parameters, the location and magnitude of the disturbance and so on, the synchronous machine may lose the synchronisation to the with the system and this is why post-event actions are very important. For example, after a fault occurs, the voltage across the machine's terminals is highly reduced and the machine's capability to provide synchronization power decreases so that the rotor accelerates according to Equation 2.3. This will lead to a more vulnerable to disturbances machine in terms of transient stability because of the larger rotor swings in systems with decreased inertia. Another example can be the importance of the fault-ride through capability of photovoltaics (PV) in order to ensure transient stability as the loss of a big proportion from PV generation units may result in high oscillations.[5]

2.2.3 Frequency stability

Frequency stability describes the capacity of the system to maintain a steady frequency after a significant imbalance between generation unit and load. If the balance is not restored, the generating unit and/or the load may trip due to large frequency swing. If the power system contains any synchronous machines, these will release or absorb kinetic energy in or from the grid. Also, each generator unit equipped with a speed controller will act soon by increasing or decreasing the power set-point. This control is also known as primary control which has the role to stabilize the frequency. The next step, also known as secondary control is to restore the frequency as close to its initial value. In a system with high penetration of converter based generation the consequence is that the RoCoF increases and the minimum frequency, also known as nadir frequency, decreases. The increasing of RoCoF is one of the main concerns in the operation of a low inertia system because it reduces the reaction time of the system but also has an impact on current protection devices.[5]

2.2.4 Unintentional islanding and blackstart

When talking about distributed systems, the risk of unintentional islanding represents an important subject. Islanding represents the disconnection of a part of the power system that will continue to provide energy even though the electrical grid is no longer present and may lead to abnormal frequency and voltage levels. Since the power system will become more distributed, the risk of islanding increases. Blackstart represents the operation in which the grid is restated after being down and is an important ability of the grid in terms of reliability. In order to perform blackstart, the generation system needs to act as a voltage source and to provide adequate power to start electrical equipment.[6]

2.3 Solutions

Some solutions to improve the stability from the transients point of view is to assign conventional power plants as synchronous condensers that can provide synchronous inertia and deliver the necessary amount of reactive power or connect the distributed generation in the vicinity of the loads so that the power flow will be as short as possible.[5]

Most of distributed systems are protected against islanding by RoCoF relays. Islanding is an unwanted process because the generation unit will continue to produce but it will not be calibrated with the remaining system and thus the frequency will change rapidly. The purpose of the RoCoF relay is to disconnect the islanded subsystem when it senses a certain threshold of the RoCoF. The optimal functionality of the RoCoF relays may be affected by low inertia systems due to the higher chance of a big RoCoF so their threshold value must be adapted to the system taking into account various events. As example a high converter generation system may need to withstand 1Hz/s instead of 0.5Hz/s in order to allow more than 75% of converter connected generation.[5]

In terms of solutions for low security, there are a couple of suggestions. One of the possible solutions is to use synchronous condensers to provide fault current. They can provide both reactive power and inertia to a faulty system. For example Denmark has adopted this protection measure by installing several synchronous capacitors. Another solution consists in redesigning the protection scheme with more advanced devices such as relays that can measure RoCoF.[6]

The solution at low penetration of power electronics interfaced generators is to acquire anti-islanding techniques. These techniques monitor the grid conditions and try to trip the inverters in order to avoid islanding. A drawback to this technique is that it destabilizes the grid so in order to use it on large scale, some new techniques need to be developed.

As a final solution and the one which will also be analyzed in this report are the grid-forming strategies. One of these is droop control, a control strategy which has multiple applications in microgrids and due to its simplicity it has a great chance to see further extensions on a bigger scale.[4]

3 Grid-following algorithms

Grid-following also known as grid-feeding algorithms are used in order to control inverters which support the grid to which they are connected in terms of exchange active and reactive power. This type of inverters act as a controlled current source which work by maintaining the amplitude, phase and frequency levels derived from the voltage reference dictated by the synchronous machines connected to the grid. The configuration of such an inverter can be seen in Figure 3.1.

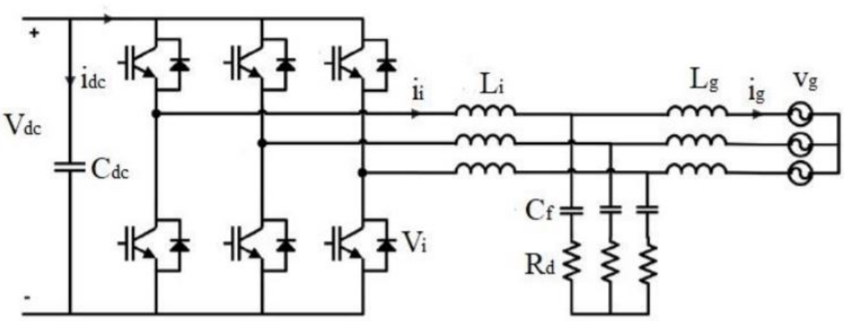

Figure 3.1: Grid connected inverter.[7]

Where V_{dc} is the DC side voltage across C_{dc} which is the DC side capacitor generating DC side current i_{dc}. V_i is the voltage generated by the inverter and i_i is the controlled current. L_i, C_f, R_d and L_g are the line and filter parameters and i_g and V_g are the grid side current and voltage.

3.1 Grid synchronization

The current which is injected in the grid has to be synchronized with the grid voltage, which means to have the same angle. Synchronization algorithms play a vital role in the control of the distributed penetration generation systems. The synchronization algorithm works as follows: it outputs the phase of the grid voltage vector which is next used to synchronize the control loops using Clark and Park transformations. One of the most popular method which has also been used in this paper is the phase-locked Loop (PLL). The basic structure of a PLL consists of three fundamental blocks as it can be seen in Figure 3.2.

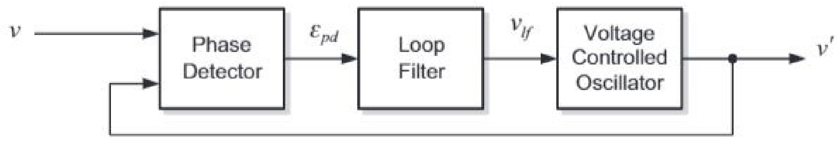

Figure 3.2: Basic structure of a PLL.[7]

The phase detector block will output a signal which is proportional with the phase difference between the reference voltage and the voltage generated by the internal oscillator of the PLL. The loop filter block is usually made up of a first-order low-pass filter or a PI controller which will attenuate the high frequency components of the signal output of the previous block. The voltage-controlled oscillator generates an AC signal whose phase is compared with the input signal of the phase detector block and by adjusting the oscillator will keep the phases matched.[7]

3.2 Current control loop

The way an inverter such as the one from Figure 3.1 can be controlled is with a current control loop and a pulse-width-modulator (PWM) as presented in the schematic from Figure 3.3.

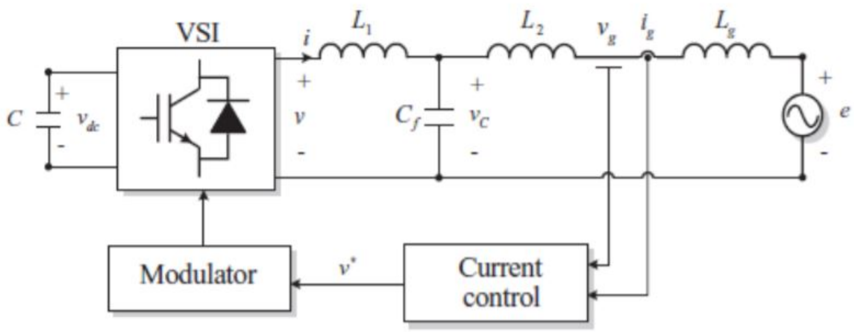

Figure 3.3: Grid connected voltage source inverter model with LCL filter, current control algorithm and modulation.[7]

The algorithm for the current control loop is based on a PI controller and has been widely used in grid converters applications. Since PI controllers behaviour is not satisfactory when their input is a periodic signal, a reference frame transformation needs to be performed. In this way, constant signals will be fed in the controllers and the steady state error issue will be solved. This problem together with its solution are graphically represented in Figure 3.4.

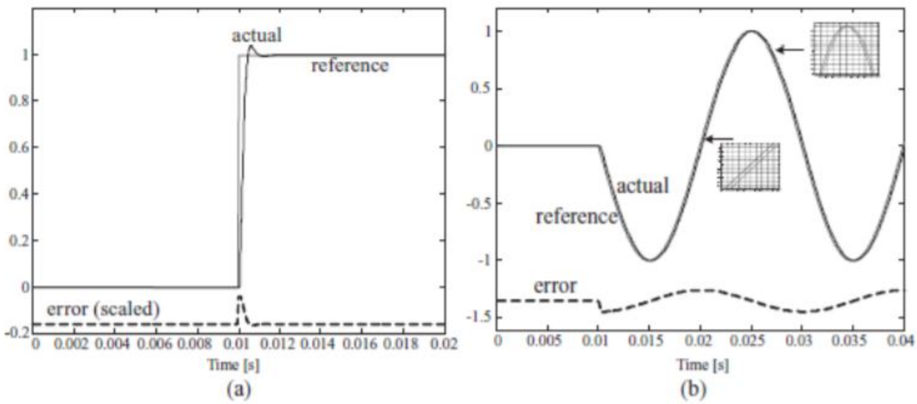

Figure 3.4: Comparison of reference and actual input signals for (a) Step input and (b) Sinusoidal input. [7]

The PI controller contains as its name suggests a proportional gain and an integral gain which together compose the controller's transfer function:

$$G_{PI} = K_p + \frac{K_i}{s} \tag{3.1}$$

After having K_i and K_p calculated, the relation between input and output of the controller is described by the following equations:

$$u_{id} = K_p(i_d^* - i_d) + K_i \int (i_d^* - i_d)\, dt \tag{3.2}$$

$$u_{iq} = K_p(i_q^* - i_q) + K_i \int (i_q^* - i_q)\, dt \tag{3.3}$$

After having the value of u_{id} and u_{iq}, the output of the PI controller is obtained and the values can be further used in order to calculate the output of the current control by adding the grid voltages and the decoupling term as follows:

$$v_d^* = v_{gd} + u_{id} + \omega L * i_q \tag{3.4}$$

$$v_q^* = v_{gq} + u_{iq} - \omega L * i_d \tag{3.5}$$

Equation 3.4 and 3.5 represent the output of the current control. After performing a reverse transformation from dq_0 to abc frame, the resulting three phase signals are used for controlling the duty cycles in the modulation block.

The schematic of the current control loop is represented in Figure 3.5

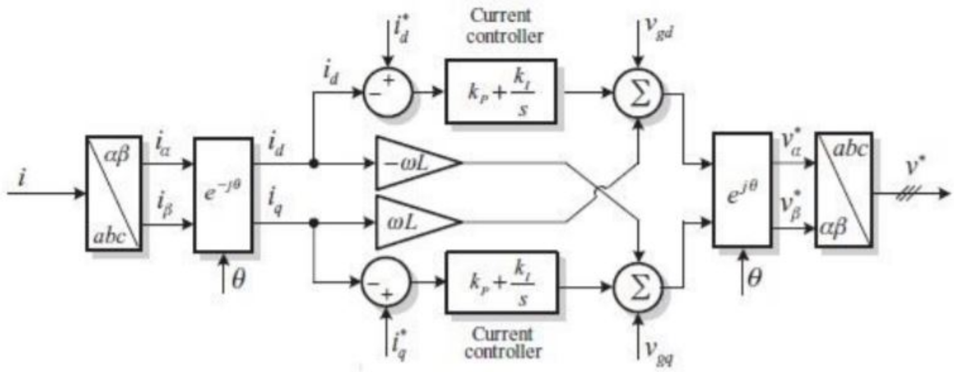

Figure 3.5: Current control loop.[7]

3.3 Discretizing

Since the current control will further need to be used on digital processors, the whole control analog strategy needs to be changed to discrete time domain. Since the switching frequency of the hardware available in the laboratory is 10 kHZ, the corresponding sample time used for discretizing the controller will be $T_s = 100\ \mu s$. Furthermore, the discretization is done using trapezoidal (also know as Tustin) theorem leading to the transfer function:

$$G_{pi}(z) = K_p + K_i \frac{T_s}{2} \frac{z+1}{z-1} \tag{3.6}$$

4 Grid-forming algorithms

Due to high penetration of renewable energy generation units, the amount of synchronous machines will slowly be out of use so their tasks will need to be taken by other devices. In this case these devices are the inverters which interface the renewable generation with the grid. As explained in the previous chapters they need to provide by themselves the voltage and the frequency level under which the power system will function in stability. Since power electronics lack mechanical moving parts to provide inertia, the stability of the grid under different events needs to be maintained by various control techniques. These techniques are called grid-forming algorithms. There are a couple of different grid-forming algorithms such as droop control, virtual oscillator control (VOC), dispatchable virtual oscillator control (dVOC), virtual synchronous machine and matching control. In this paper the active droop control method will be used.

4.1 Cascaded AC Voltage and AC Current Control

This control represents a standard control architecture which by using Proportional-Integral (PI) controllers manages to provide a voltage reference for the Pulse Width Modulation (PWM) block. Having this reference voltage as the input of the PWM block the necessary gate signals are provided in order to operate the inverter optimal.As it can be seen in Figure 4.1, The outer control which is the voltage control will output the current reference for the inner control loop, the current controller. Due to stability reasons the input of the controllers needs to be a continuous signal, thus a abc-dq_0 transformation needs to be done by using the reference angle provided by a PLL.

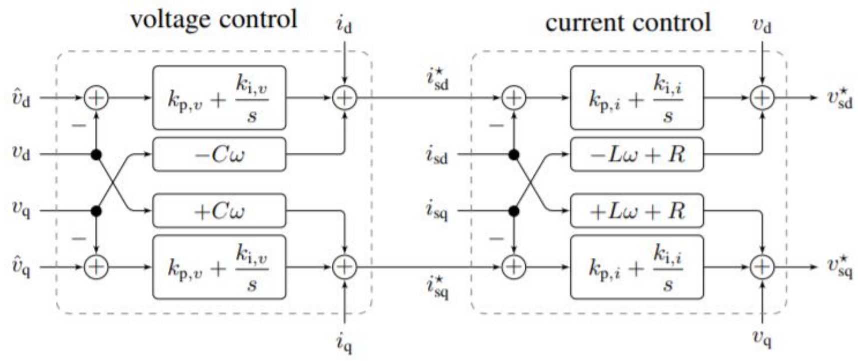

Figure 4.1: Block diagram of the cascaded AC voltage and current control. [8]

Where $\hat{v}_d$ and $\hat{v}_q$ are the reference voltages in dq_0 system, v_d and v_q are the measured voltages, $k_{p,v}$, $k_{i,v}$, $k_{p,i}$ and $k_{i,i}$ are the proportional and integral coefficients of the voltage controller respectively current control and ω is the angular frequency. C, L, R are the filter values. $\mathbf{i_s}^*$ = $[i^*_{sd} i^*_{sq}]^\top$ are the references for the current controller computed by the voltage controller and i_s = $[i_{sd} i_{sq}]^\top$ are the is the measured currents.[8]

From Figure 4.1 the following equations can be derived:

$$\dot{x_v} = \hat{v} - v \tag{4.1}$$

$$i_s^* = \underbrace{i + C\omega I_2 v}_{\text{feed-forward terms}} + \underbrace{K_{p,v}(\hat{v} - v) + K_{i,v} x_v}_{\text{PI control}} \tag{4.2}$$

$$\dot{x_i} = \hat{i_s} - i_s \tag{4.3}$$

$$v_s^* = \underbrace{v + (L\omega I_2) i_s}_{\text{feed-forward terms}} + \underbrace{K_{p,i}(I_s^* - i_s) + K_{i,i} x_i}_{\text{PI control}} \tag{4.4}$$

Where

$$I_2 = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

is the 2-D identity matrix [8].

4.2 Droop control

Droop control mimics the speed droop property of a synchronous machine governor and calculates the deviation of the power injection and frequency:

$$\dot{\theta} = \omega \tag{4.5}$$

$$\omega = \omega^* + d_\omega(p^* - p) \tag{4.6}$$

Where p^* and ω^* are the nominal values for power and frequency and d_ω is the droop gain [8].

In order to replicate the service provided by the automatic voltage regulator of the synchronous machine a PI controller is used to adjust the output voltage error to obtain the direct axis reference $\hat{v_d}$ [8].

$$\hat{v_d} = k_p(v^* - \|\mathbf{v}\|) + k_i \int_0^t (v^* - \|\mathbf{v}(\boldsymbol{ø})\|)\, d\tau \tag{4.7}$$

4.3 VSM

Another grid-forming algorithm is the Virtual Synchronous Machine which was studied in [9]. It was proved that under certain conditions VSM and droop-control techniques can be similar. The main difference being that VSM involves the addition of an extra parameter called virtual inertia which can be seen in Equation 4.8 and is adapted to inverter parameters. By controlling the parameters in this equation and not being constrained by any physical values, the VSM can achieve similar performances with synchronous machines.[9]

$$\frac{d\omega}{dt} = (\frac{1}{J}) \cdot (P_{ref} - P_{meas} - D_p \cdot (\omega_{VSM} - \omega_{grid})) \tag{4.8}$$

Where: J is the rotor inertia, ω_{grid} and ω_{VSM} are the angular frequency of the grid and of the VSM, P_{ref} is the reference power, P_{meas} the measured power and D a coefficient associated with the the damper windings during transient conditions.[9]

5 Simulations

In this chapter the simulation of each step will be presented. First of all, the results of grid-following method will be shown and in this way the current control loop will be validated. The next validation will be for the voltage control and finally tests for validating the droop control loop as grid-forming algorithm will be performed. Each of the simulations mentioned previously will be simulated under particular scenarios which will be described in advance and the results will be discussed accordingly.

Simulations were performed in MATLAB/Simulink and some of the blocks are imported from Simulink libraries since it was not the scope of the project to design them. The parameters for the DC source and the LCL filter are constant in all the simulations because they correspond to the values used in the hardware available in the laboratory. Therefore, in the eventuality of implementing the simulated cases on the real setup, the design of other parameters (such as PI gains from the current control) and different type of test designs can be performed without changing the simulated values. Therefore, in this way the simulations can be validated with the real hardware and comparisons and optimization can be done. These simulation parameters as well as others are presented in following table.

Simulation parameters		
Frequency	f	50 [Hz]
Angular frequency	ω	314.15 [rad/s]
Carrier frequency (switching frequency)	f_c	10 [kHz]
DC supply voltage	V_{DC}	650 [V]
Nominal (RMS) voltage	Vn	400 [V]
Grid nominal (RMS) voltage	Vn_{Grid}	25 [kV]
Active power of the permanent load	P	3 [kW]
Sampling time	T_s	100 [μs]
Filter capacitance	C	4.7 [μF]
Filter inductance	L	1.8 [mH]
Proportional gain for the PI in voltage controller	$Kp_{voltage}$	0.05
Integral gain for the PI in voltage controller	$Ki_{voltage}$	50
Proportional gain for the PI in current controller	$Kp_{current}$	1.3
Integral gain for the PI in current controller	$Ki_{current}$	300
Droop gain in droop controller	d	0.00005
Proportional gain for the PI in droop controller	Kp_{droop}	0.2
Integral gain for the PI in droop controller	Ki_{droop}	0.05

5.1 Current control

Following the block diagram and the equations from Chapter 3, the current control was modeled. The system contains the current control block, the modulation block, the inverter, the LCL filter, a three-phase generator as grid and the PLL. In this simulation case the output of the inverter and the way the measured currents follow the reference are of interest. The overall simulation design can be seen in Figure 5.1

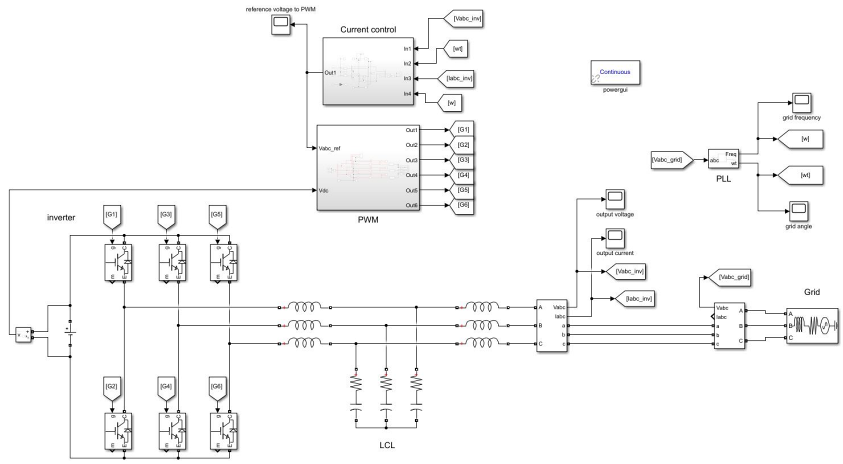

Figure 5.1: Configuration of the current control design.

In this simulation design, the grid is reduced to a non-ideal three-phase voltage source with internal impedance. The voltage measured across the output of the three-phase source is fed into the PLL block which outputs the frequency and the angle of the grid's voltage which will be further used to model the current control. As previously mentioned, the LCL filter is the one available as hardware in the laboratory with the mention that the grid side inductance is not a proper inductor but the primary of a transformer. The inverter is designed with 6 IGBT/Diode blocks from Simulink library. The DC side of the inverter is connected to a DC source also available in the laboratory. The gate signals for the inverter are obtained by a classic PWM structure which has its reference signal provided as an output from the current control block. The switching frequency of the inverter is 10 kHz and can also be achieved by the real inverter. A detailed overview of the current control block can be seen in Figure 5.2

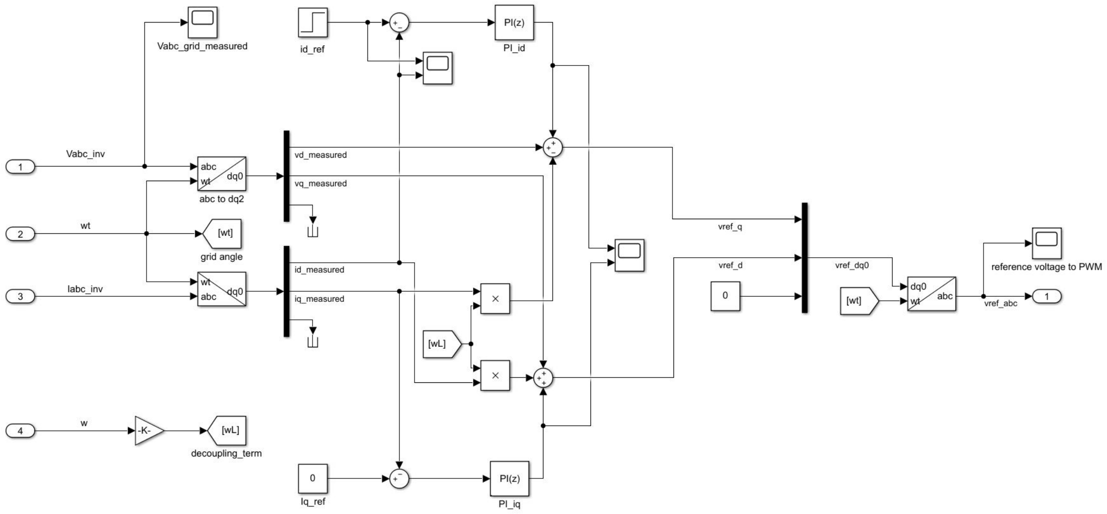

Figure 5.2: Detailed overview of the current control block.

5.1.1 Results

The purpose of this simulation is to validate the current control. In this case the way the inverter current (measured after the LCL filter) is following the references, the output of the control block and the inverter output voltage and current. The event in this case takes place at second 0.5 of the simulation when a step is applied in id_{ref} from 5 A to 10 A and the focus will be at that time instant.

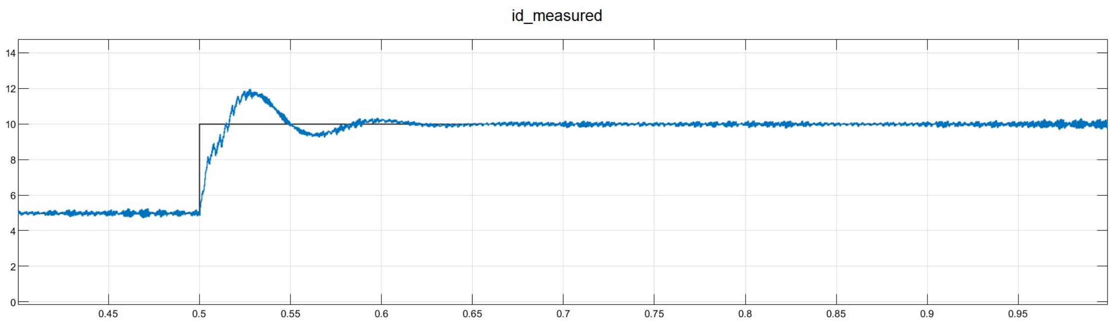

Figure 5.3: Current control block - response of the direct component (id) of the measured current (blue) when a step from 5 to 10 is applied at t=0.5 to the direct component of the reference current (black).

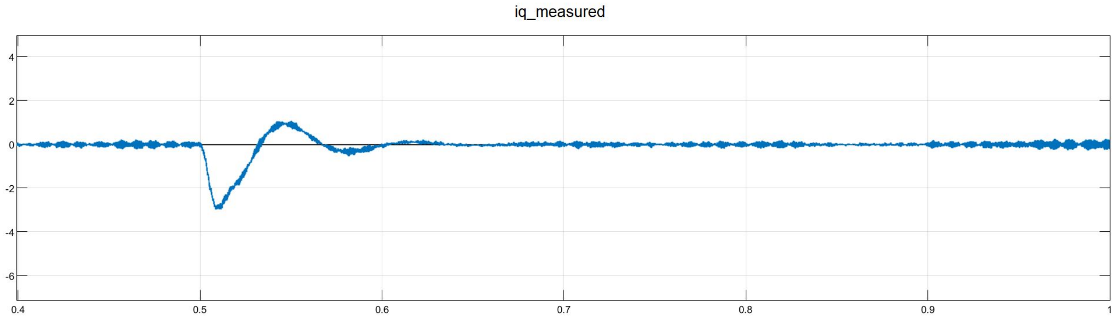

Figure 5.4: Current control block - response of the quadrature component (iq) of the measured current (blue) compared to the quadrature component of the reference current (black) when a step from 5 to 10 is applied at t=0.5 to id.

Figures 5.3 and 5.4 represent how good the d-axis and q-axis references are followed by the output current. A trade-off has to be done between the overshoot, response time and settling time and rise time. As it can be observed, the overshoot has quite a high value $\approx$ 20 percent but any further tuning of the controller in order to decrease its value would lead to instability.

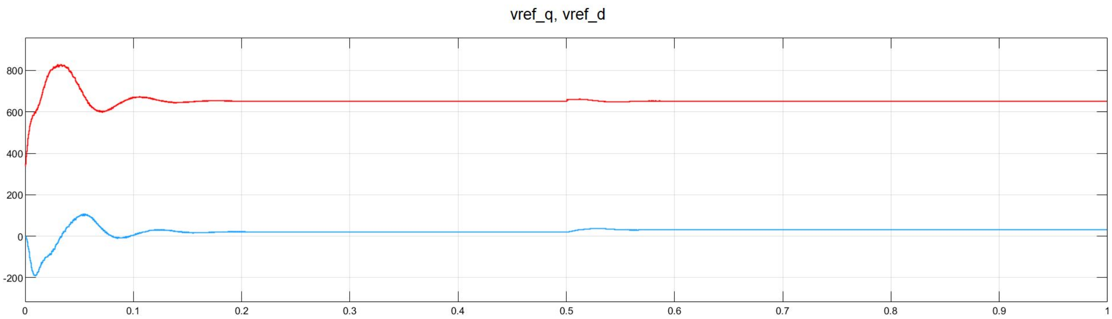

Figure 5.5: Vd and Vq current control block output voltages.

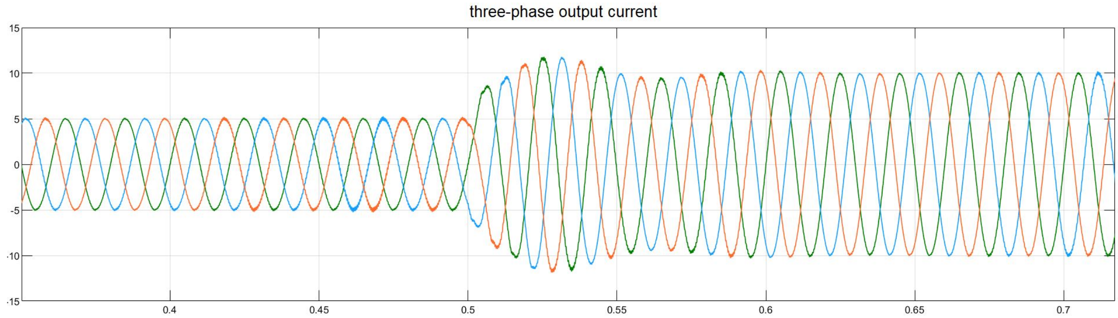

Figure 5.6: Inverter three-phase output current measured after the filter when a step from 5 to 10 is applied in the reference current in the current control block.

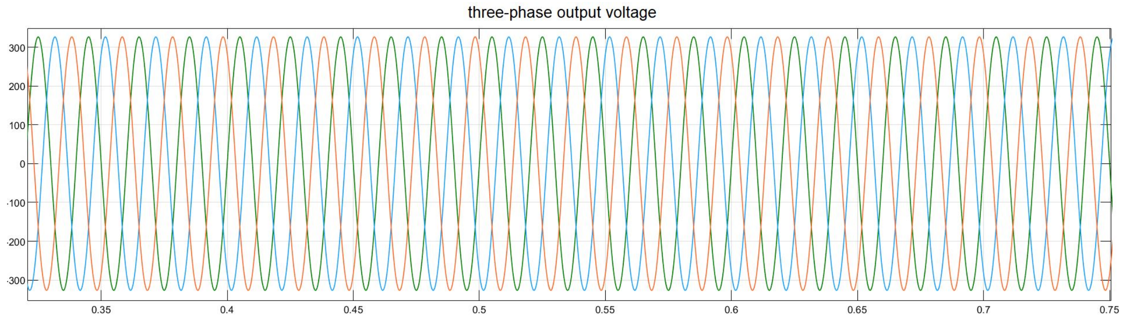

Figure 5.7: Inverter three-phase output voltage measured after the filter.

From the inverter's output current and voltage point of view, the waveforms indicate that the control is well done, the inverter output following the grid voltage and besides the small oscillatory behaviour of the output current as a consequence of the overshoot in the control block, the inverter outputs the current dictated by the current references. Taking into account the simulated results, the current control is considered well designed.

5.2 Voltage control

The next step in order to achieve a grid-forming algorithm is to design a voltage control block. As stated in Chapter 4 the technique is called cascaded ac voltage and ac current control. The idea is to create a control block which will output a current reference for the current control. Following the same design concept as in the current control, the schematic of the voltage control is presented in Figure 5.8.

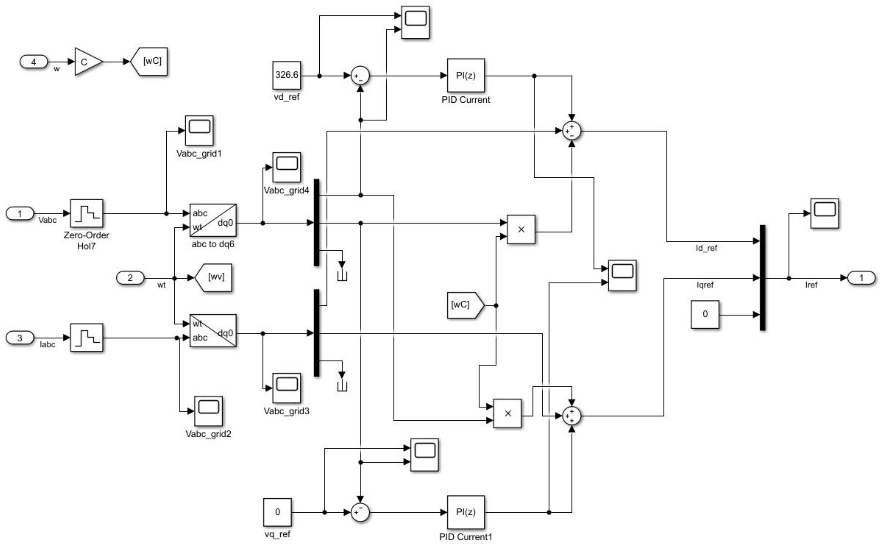

Figure 5.8: Design of the voltage control block.

Since this is an intermediary step, no results will be presented.

5.3 Droop control

Lastly, the simulation including the droop control block is attached as an outer loop to the cascaded voltage and current control blocks. This configuration is presented in Figure 5.9.

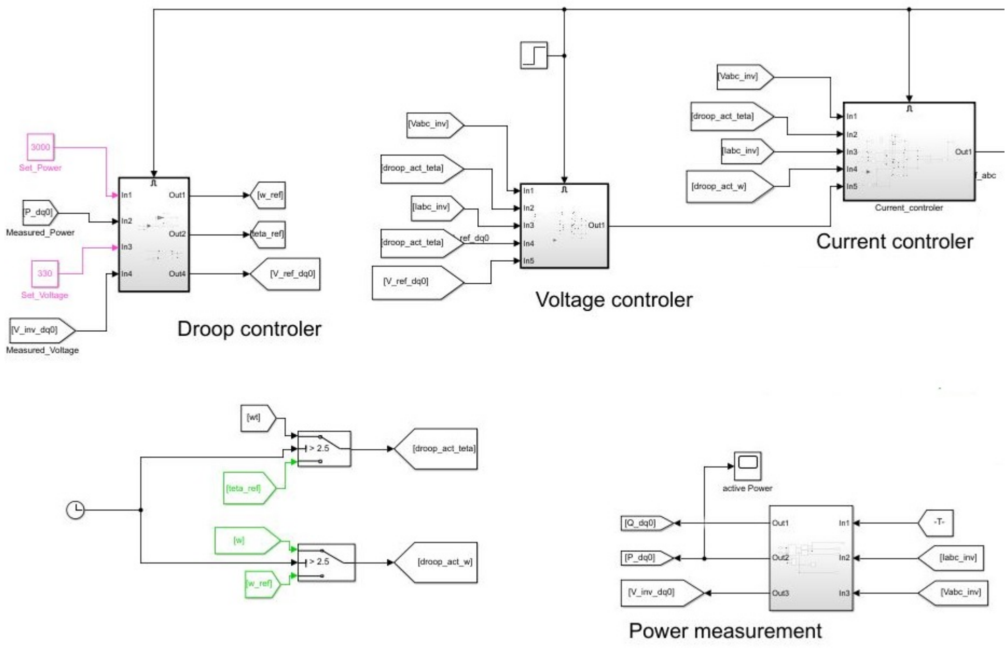

Figure 5.9: Overview of the simulation including all the control blocks .

As grid-forming control, the output of this block are voltage and frequency references which are provided in case of the loss of grid. In this way, the system attached to the generation unit being controlled in this manner will be able to provide the necessary power to its loads working in islanding configuration. Voltage and frequency references are obtained by implementing Equations 4.6 and 4.7 as it can be seen in Figures 5.10 and 5.11 respectively.

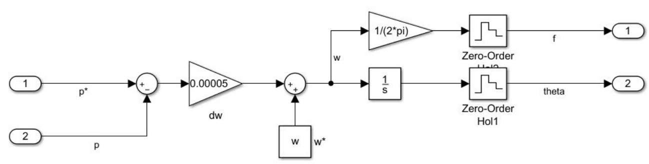

Figure 5.10: Equation 4.6 implemented with specific Simulink blocks.

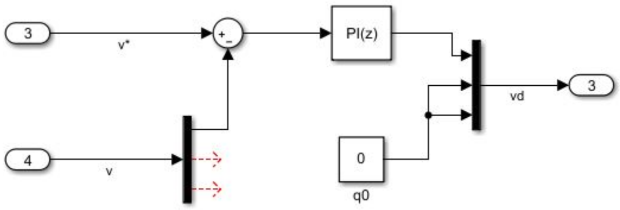

Figure 5.11: Equation 4.7 implemented with specific Simulink blocks.

In terms of the network configuration, it is designed as follows:

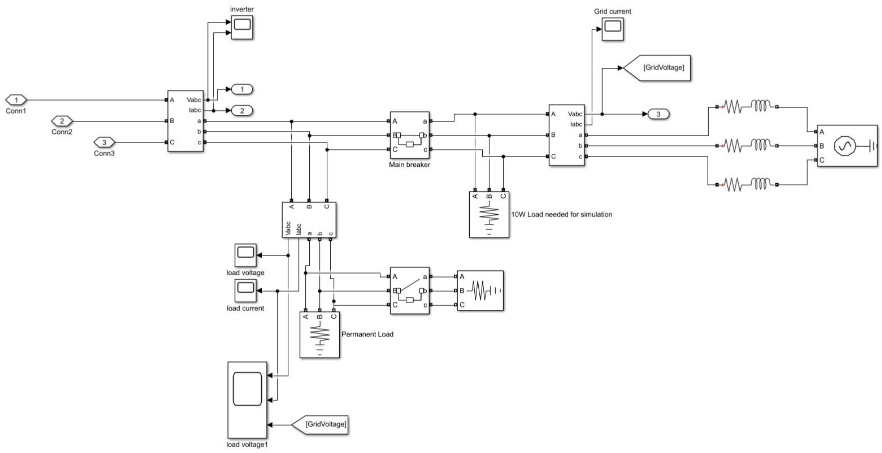

Figure 5.12: Network configuration for the droop control schematic.

In this test scenario, the inverter starts as grid connected and its control is synchronized to the grid. At 0.5 s the load is doubled to 2000 W. At 1 s, the system loses the grid and the inverter begins to behave as grid-forming by providing a voltage and frequency for the rest of the system.

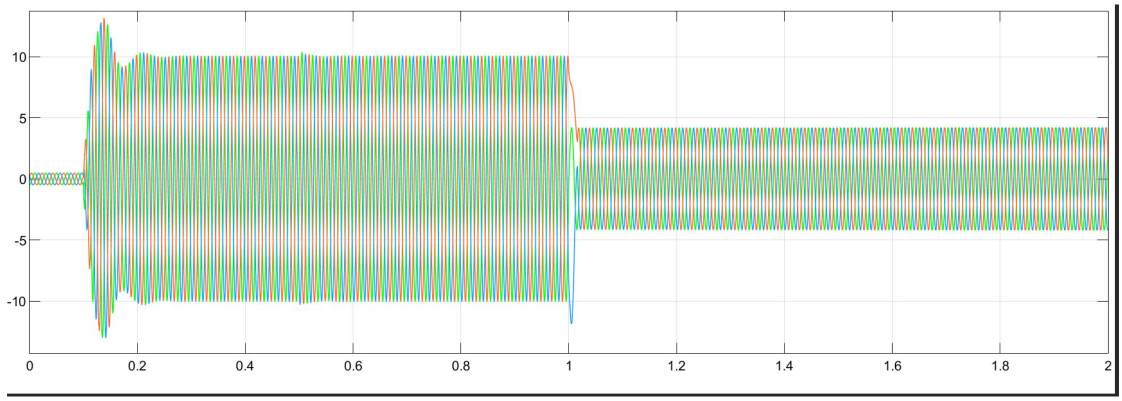

Figure 5.13: Three-phase output current measured after the LCL filter. At t=0.5 the load is doubled and at t=1 the grid is disconnected.

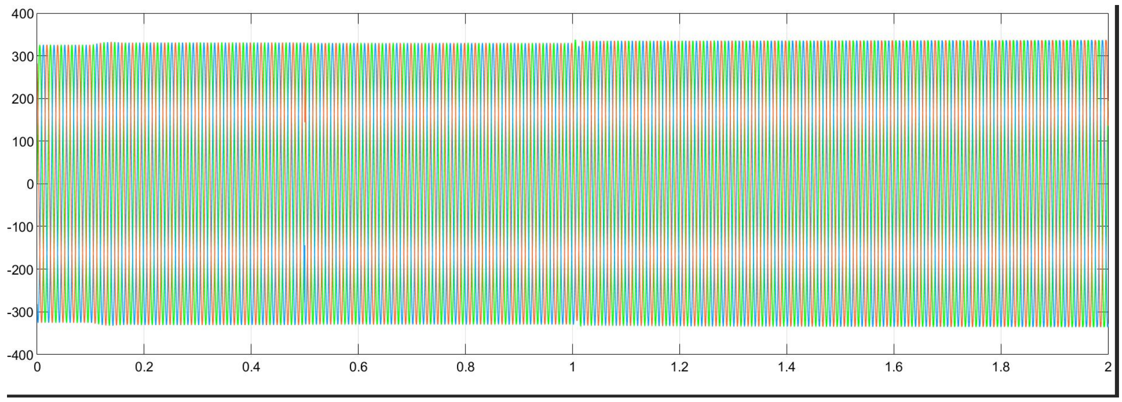

Figure 5.14: Three-phase output voltage measured after the LCL filter. At t=0.5 the load is doubled and at t=1 the grid is disconnected (full scale).

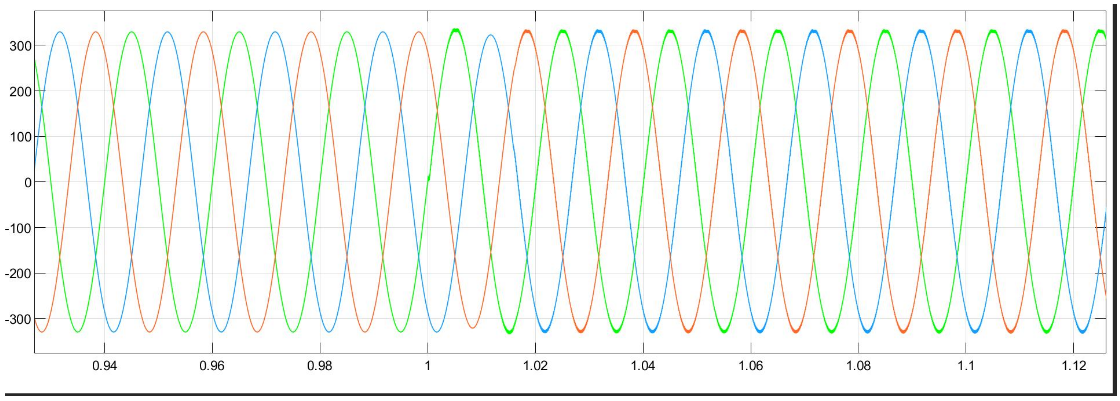

Figure 5.15: Three-phase output voltage measured after the LCL filter. At t=0.5 the load is doubled and at t=1 the grid is disconnected (zoomed at t=1).

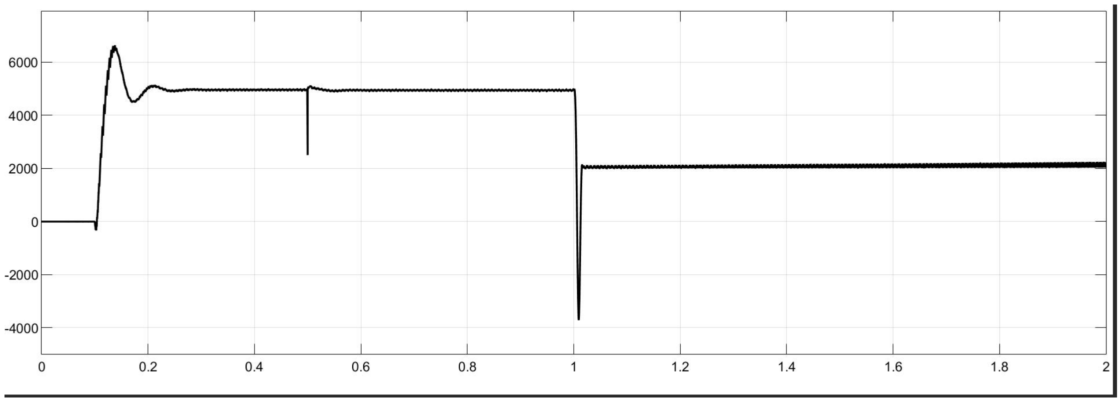

Figure 5.16: Inverter active power when the load is doubled at second 0.5 the grid is lost at second 1.

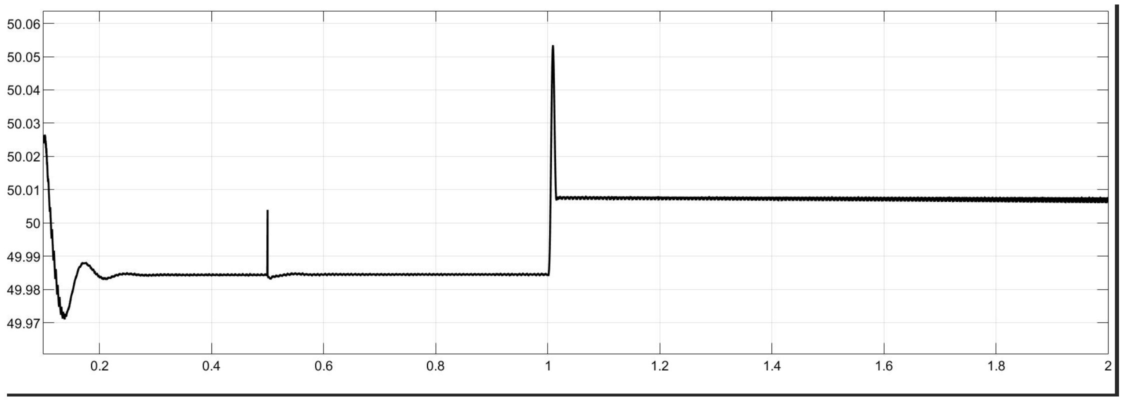

Figure 5.17: Frequency reference of the droop control block when the load is doubled at second 0.5 and the grid is lost at second 2.

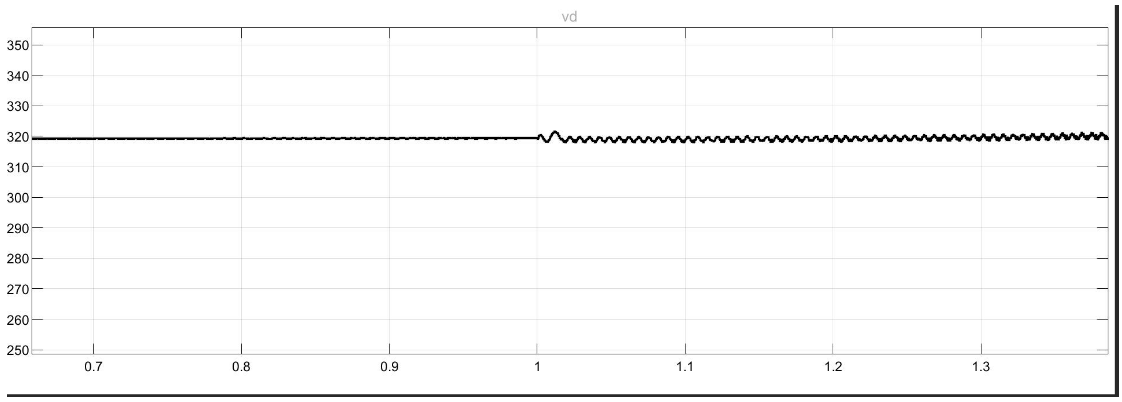

Figure 5.18: Voltage reference of the droop control block when the load is doubled at second 0.5 and the grid is lost at second 2.

6 Hardware-in-the-loop test and results

An intermediary step between simulating the algorithms and implementing them in a practical setup is performing hardware in the loop (HIL) tests. In this way, a real time simulation ca be done by using some specific hardware devices which are expected to show how the system will behave when the control will be loaded on the real inverter. This might be also a way to protect the hardware and the user from malfunctions caused by improper control methods. HIL tests ca be performed on different hardware devices such as PLECS RT-box or OPAL-RT. In this case OPAL-RT was chosen. Thanks to its multiple input and output ports and to its embeded FPGA, OPAL-RT can simulate an inverter connected to a grid. The control of the inverter will be then implemented on a dSPACE board or on a DSP and together with a host PC, a real time simulation of an actual power system can be done. One advantage is that by interconnecting this hardware parts, various test cases and grid configurations can be tested. Such a setup can be observed in the block diagram from Figure6.1.

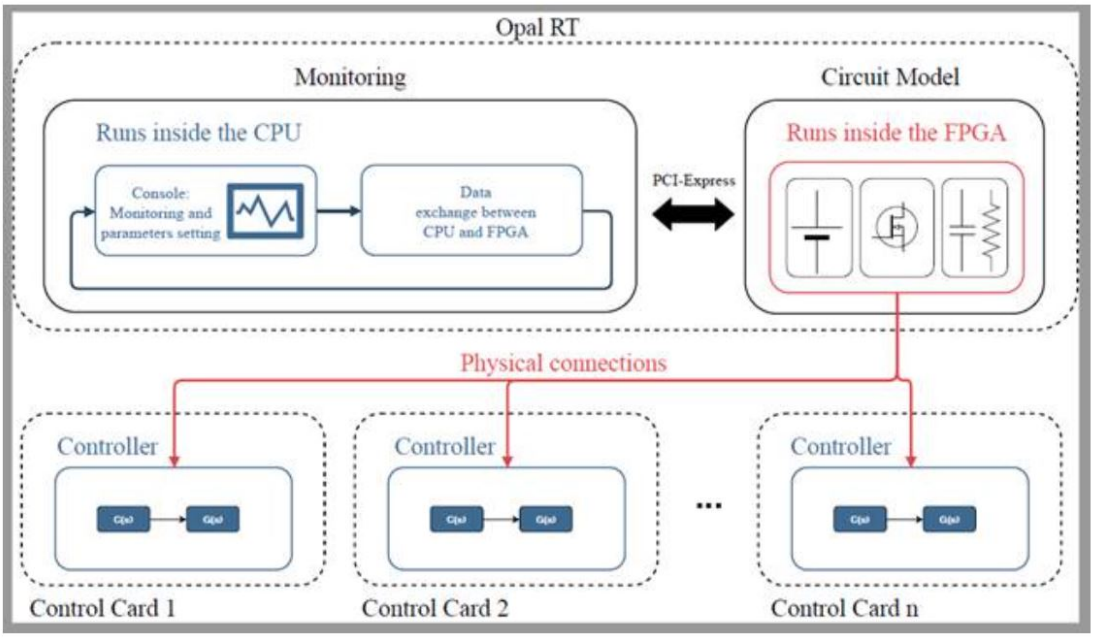

Figure 6.1: Block diagram which represents an overview about the HIL setup.

6.1 OP4510 Simulator and dSPACE 1103

The OP4510 Simulator is a compact entry-level simulator produced by OPAL-RT Technologies that combines OPAL-RT's core strengths: RT-LAB high-performance Rapid Control Prototyping and HIL systems. Some of the general specifications are [10]:

- Kintex-7 FPGA.
- Minimum time step of 250 nanoseconds for models executed on FPGA.
- 32 digital output and 32 digital input channels.
- 16 analog input and analog output channels.

dSPACE DS1103 board facilitates the implementation of the control algorithm due to its capability to receive analog signals and output digital signals. This process is being done in through the dSPACE I/O board where via the Control-desk software, simulations performed in Simulink can easily be adapt to receive and send signals thanks to its multiple ADC and DAC channels. A fast communication is assured by the fiber optical cables which transmit digital signals to the OPAL-RT. The advantage of using dSPACE in this configuration instead of a DSP for managing the control algorithm is that in case of moving to the real inverter setup as a next step, a dSPACE board is also the connected.

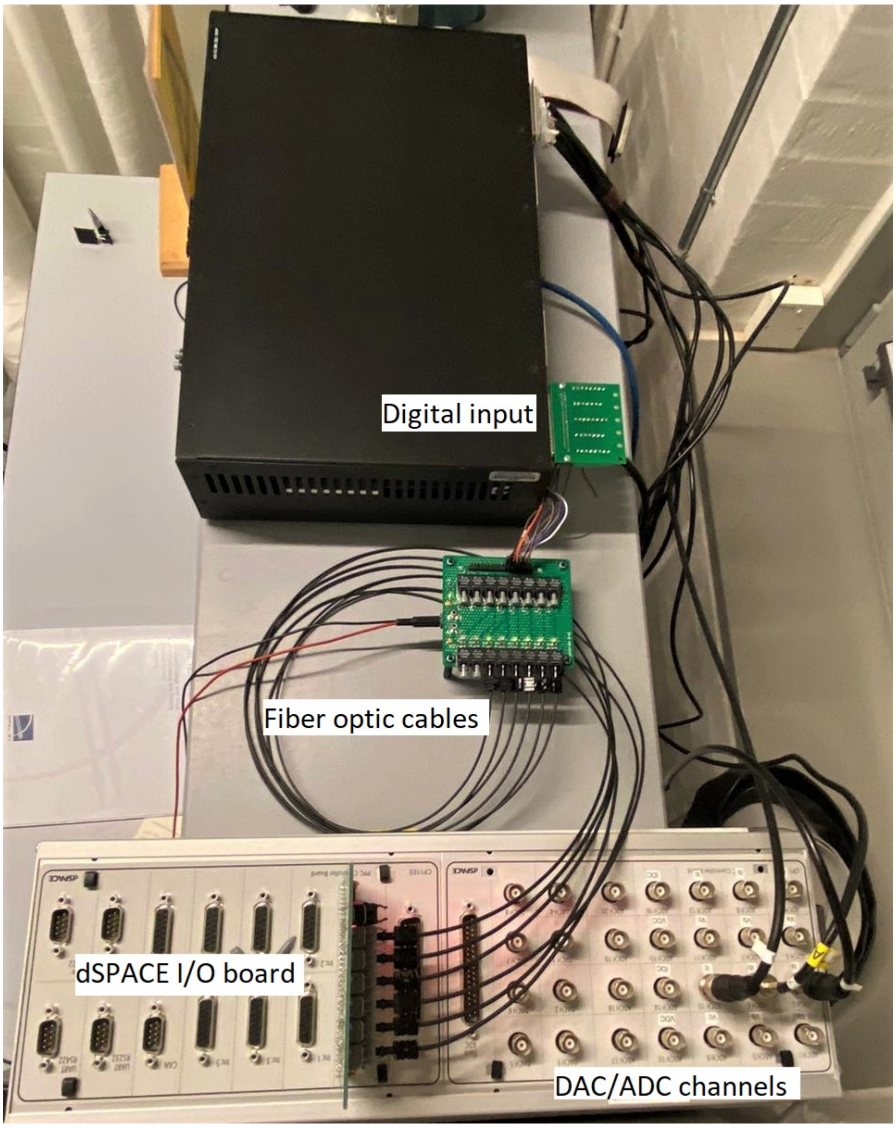

Figure 6.2: Connections between OPAL-RT and dSPACE I/O board.

6.2 Test setup

The test setup is represented in Figure 6.2 which is available in the PV Lab of Aalborg University and it contains a PC with RT-Lab and Control-desk software installed, OP4510, dSPACE DS1103, dSPACE I/O board, a DC source needed for the transmitter-receiver board for the fiber-optic cables and an oscilloscope.

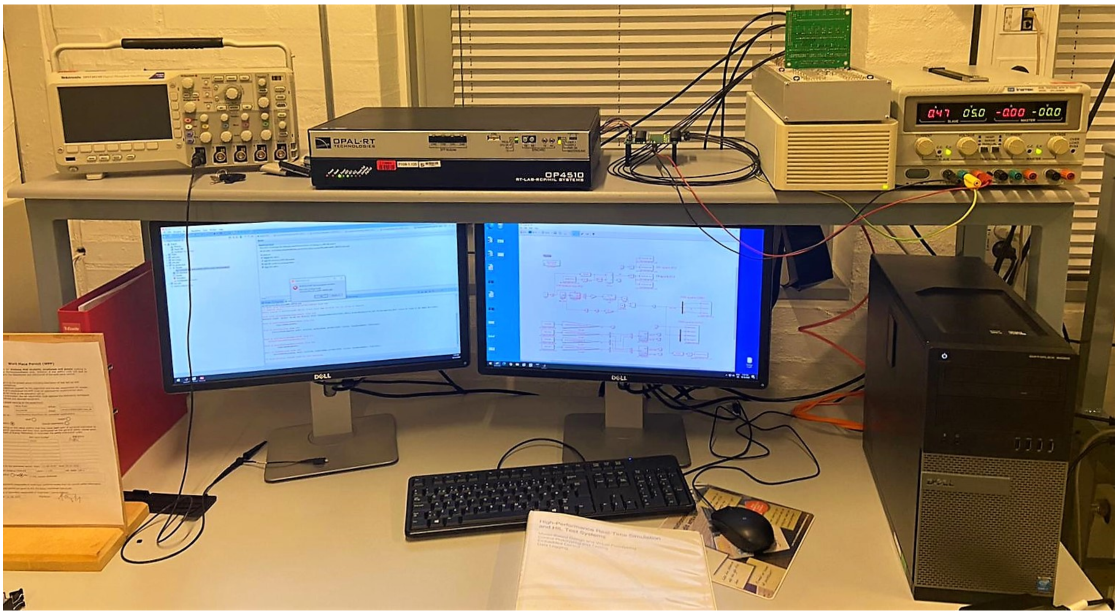

Figure 6.3: HIL setup available in the laboratory.

6.3 Design and results

After the setup has been configured and some loop-back tests were performed in order to get familiar with the OPAL-RT, the system simulated in Simulink was planed to be tested. Due to some limitations, only an intermediary step could be achieved. The dSPACE board was used to send gate signals to RT-Lab in order to control the inverter connected in the configuration from Figure 6.7. By using voltage and current measurement blocks named accordingly (Y01, Y02 and so on), the currents and voltages were sent to the dSAPCE board via the Analog output. These signals are read by the ADCs from the I/O board and processed in the system showed in Figure 6.5 by using special blocks such as 'DS1103MUX_ADC_CON1' and 'DS1103SL_DSP_PWM3' which will send the gate signals back to the OPAL-RT via optical fiber cables, intermediary board and cables to the Digital input of the OP4510. Therefore, the closed-loop is done.

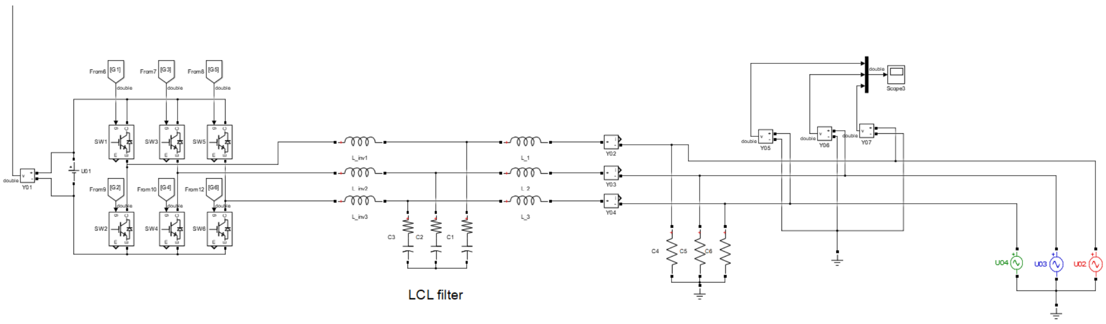

Figure 6.4: Simulink model representing the inverter, the filter and the simplified grid implemented in RT-Lab.

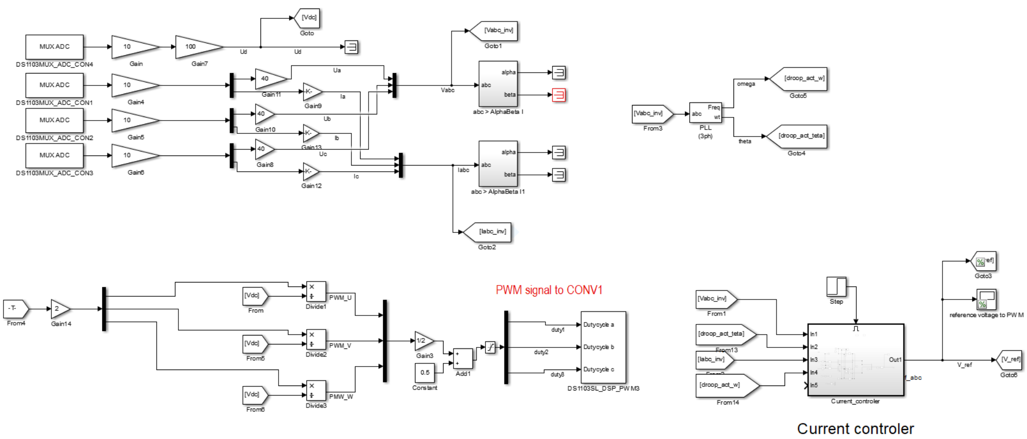

Figure 6.5: Model developed in Simulink and uploaded in Control-desk which allows the user to send and receive signals via dedicated Control-desk blocks and Simulink blocks.

The results of this closed-loop system can be visualized in Control-desk graphic user interface as in Figures 6.6, 6.7, 6.8 and 6.9

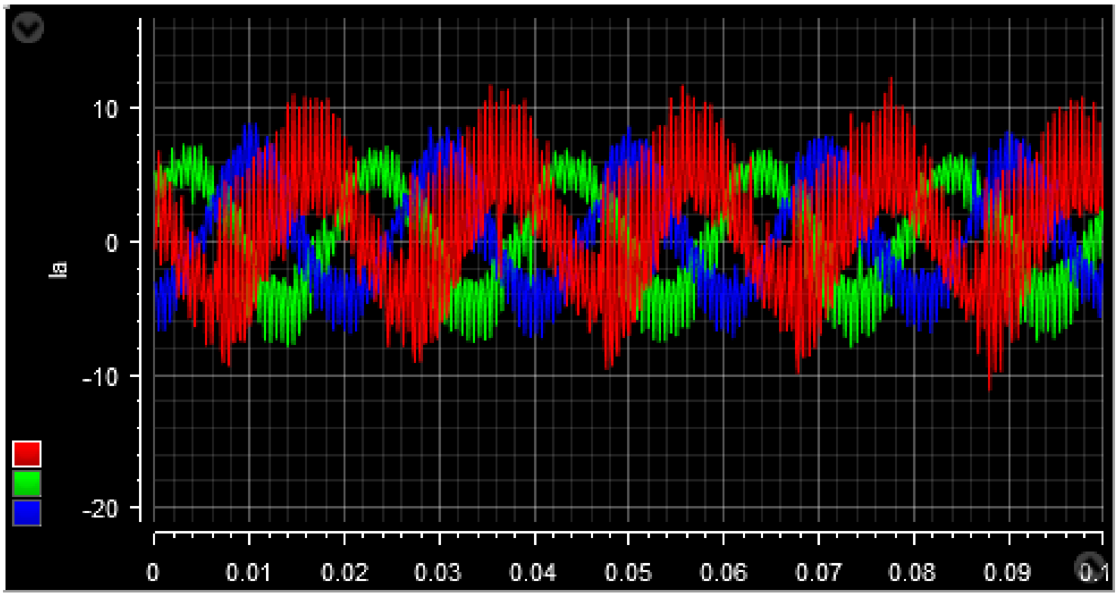

Figure 6.6: Capture from the graphic user interface from Control-desk with the inverter output three-phase current measured after the LCL filter.

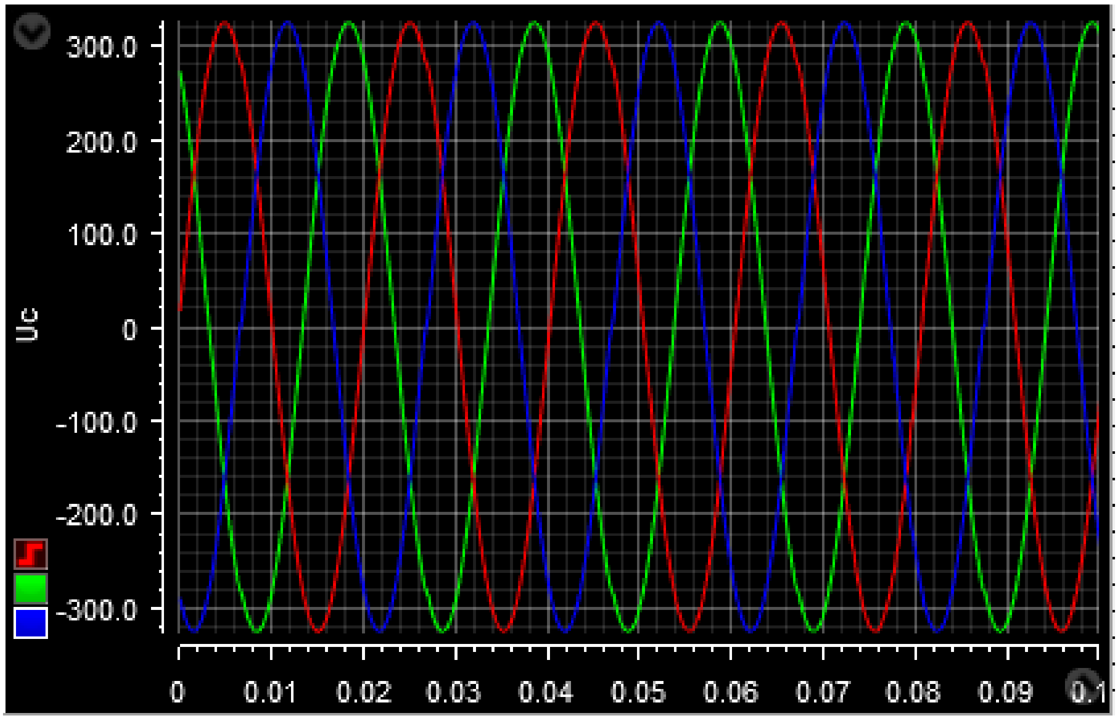

Figure 6.7: Capture from the graphic user interface from Control-desk with the inverter output three-phase voltage measured after the LCL filter.

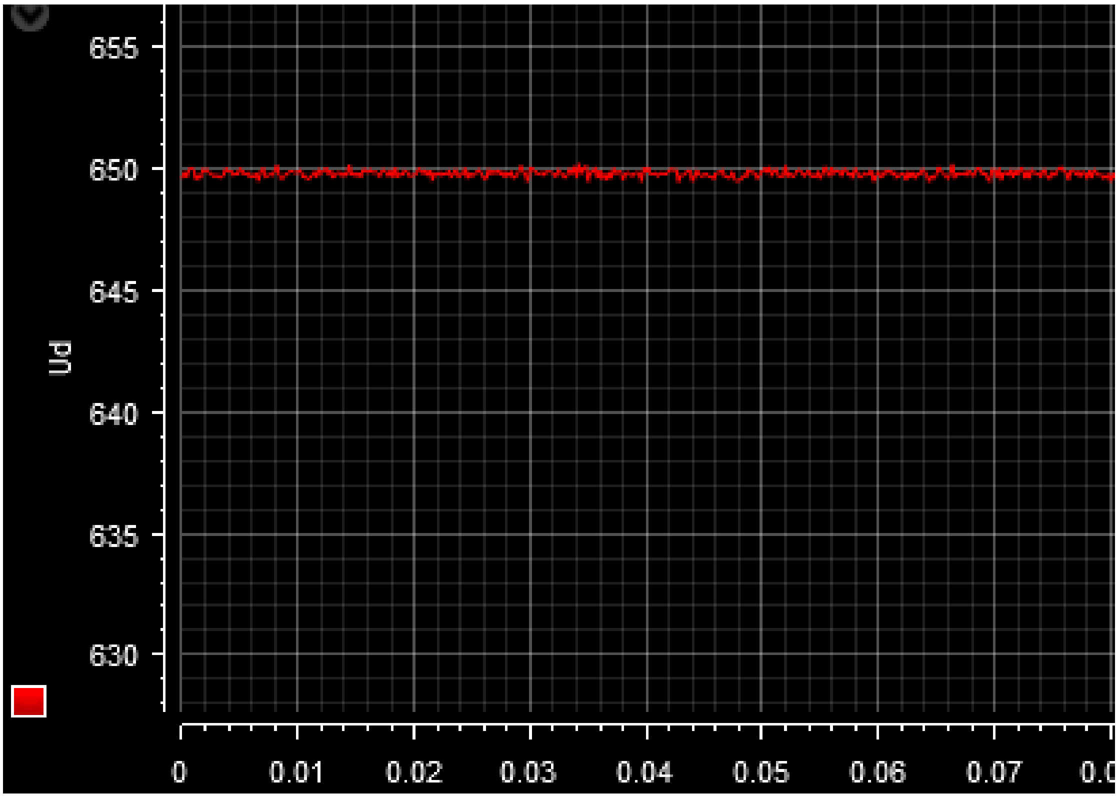

Figure 6.8: Capture from the graphic user interface from Control-desk displaying the inverter DC voltage.

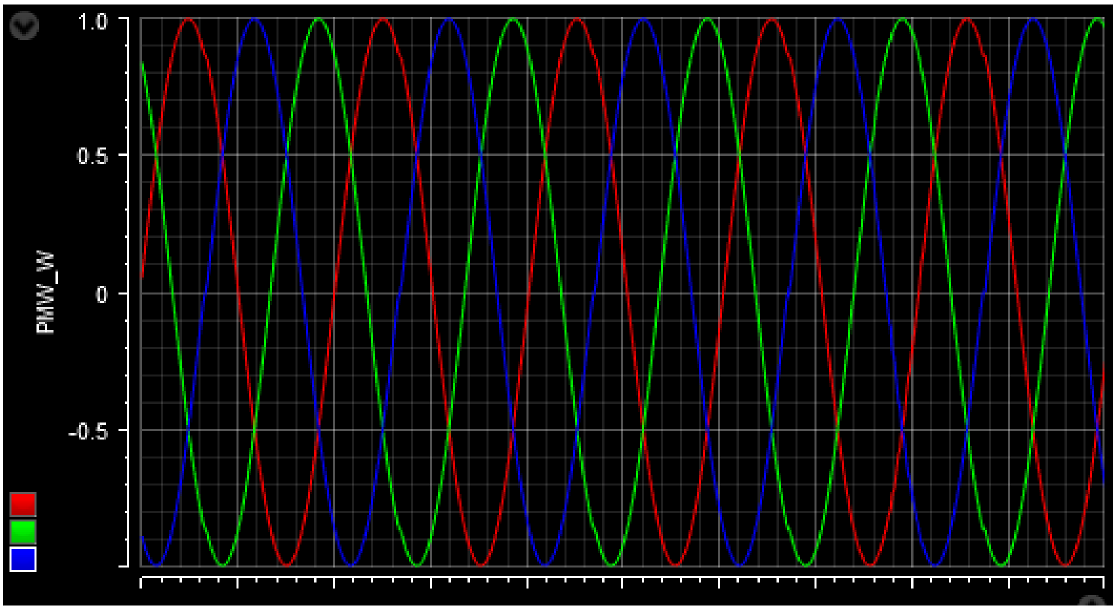

Figure 6.9: Graphic user interface from Control-desk displaying the controlling the gates of the inverter.

7 Conclusion and Future Work

In conclusion, grid-forming algorithms are a must when it comes to high penetration of renewable energy generation units into the power grid. Being a very important topic when it comes to future power systems, a couple of grid-forming algorithms have already been implemented. The most basic one is droop-control but it was proved to be sufficient under certain circumstances to provide voltage and frequency control. Talking about virtual synchronous machines, they have a great chance to succeed in replacing traditional generation units up to a point due to their artificial inertia.

HIL tests are relevant as an intermediary step between simulations and real life application because they can be a validation that the control strategy is well designed and it are expected to give show results as the real inverter.

7.1 Future Work

Since grid-forming algorithms are a relatively new topic compared with traditional energy generation, there is a lot of research to be done. First of all, the simulations can be extended to different types of algorithm designs in order to have a clear idea of advantages and disadvantages of each of them. Having a clear knowledge of how this algorithms are implemented, the difficulty of the power system simulated can be increased to achieve a better overview of different real life cases that can occur. For example, it is worth simulating a system with more generation units such as synchronous generators and hybrid PV-battery systems to test the capability of the hybrid system to fully overcome the duties of the synchornous machine in a power grid. Also, the complexity of the grid can be increased to test more events such as faults.

In terms of HIL tests, now that the way to operate the hardware is clear,the next step will be to test all the simulated cases and extend it to more advanced simulations.

After having one or more control strategies validated with the HIL, tests can be moved to the experimental setup available in the laboratory. Since the inverter can be connected to the grid there are more possibility to investigate how inverter interfaced generation units will behave when controlled as grid-forming units.

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A

Experimental setup

The schematic of the experimental setup ca be seen in Figure A.1.

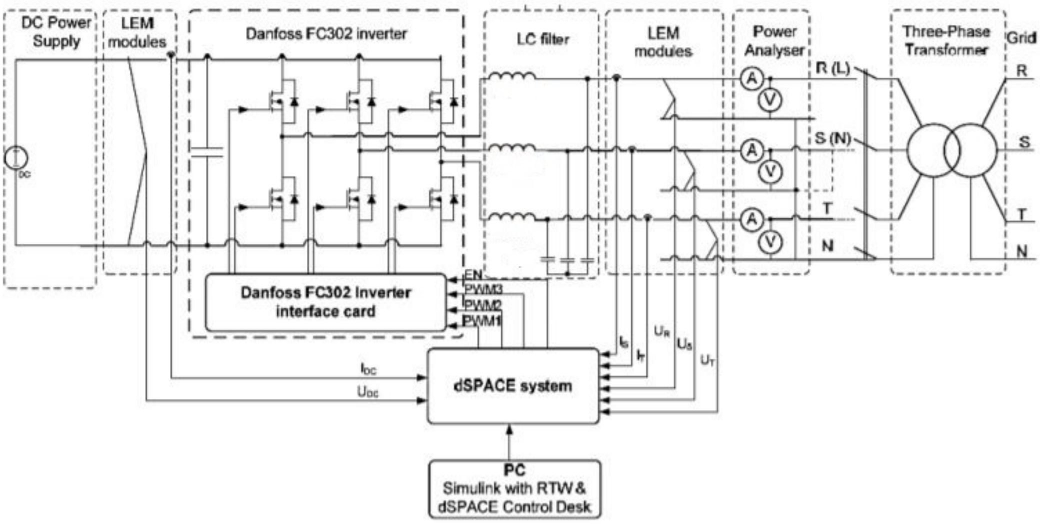

Figure A.1: Schematic of the experimental setup.