Department Of Infustrial Engineering

STATCOM-BASED CONTROL TECHNIQUES TO REBALANCE DISTRIBUTION GRIDS

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Abstract

Data l'evoluzione osservata negli ultimi anni inerente alle reti elettriche e ai carichi connessi ad essa, il problema della *power quality* ha assunto via via sempre più importanza al fine di tutelare tutti i dispositivi connessi alla rete. Come da titolo di questa tesi, l'enfasi è posta su un preciso parametro della *power quality* ovvero gli sbilanciamenti.
Lo scopo del mio lavoro è stato quindi quello di trovare una o più strategie di controllo allo scopo di bilanciare nuovamente reti di distribuzione trifase sbilanciate.

Lo scritto si suddividerà quindi in 3 principali macrosezioni:

Controllo in Regime Bilanciato Questa prima parte espone l'importanza della sincronizzazione con la rete alla quale siamo collegati così come varie soluzioni per, appunto, sincronizzarci con essa, controllare il nostro inverter ed infine operare un controllo di varie tipologie di grandezze di interesse(ad esempio potenza attiva oppure tensione del bus DC).

Controllo in Regime Sbilanciato In questa parte verranno esposte varie soluzioni al fine di riuscire a controllare un'inverter anche nel caso la rete trifase risulti sbilanciata: come vedremo ciò comporterà l'utilizzo di specifiche architetture di controllo.

Tecniche di Ri-bilanciamento Nell'ultima parte verranno spiegati le principali strategie da me escogitate così come i vari risultati ottenuti tramite simulazioni nell'ambiente Simulink; seguirà quindi una comparazione tra i metodi sfruttati, così come una valutazione delle implicazioni che suddetti metodi possono avere se utilizzati.

1 Introduction

The "power quality" topic has become more important and interesting as matter of study during the last 50 years: we've experienced a big change in our society from a technological point of view. Together with a lot of other things, also the electrical power grid and the load connected to it evolved from a rather primitive and linear behaviour(just think of resistive loads like a filament light bulb) to more complex and non linear ones: just think of the introduction of semiconductive components like diodes or thyristors or the usage of permanent magnet motors instead of the classical induction machines.
The introduction of susceptible loads to our houses (e.g. computer's microprocessors) that could be damaged due to over voltages, led to the birth of the so called "power quality" issue: we started studying the topic and caring more about the condition of the electrical grid's voltage.
Together with the adoption of semiconductive devices e.g. inverters or line commuted rectifiers the concept of THD(Total Harmonic Distortion) arose to the attention of the electrical community leading to the creation of regulations on the topic. The power quality issue is becoming more and more important as time passes since we're aiming to electrify as much as we can of our world; given the recent trend for electric vehicles we saw the rise of several EV chargers and also the renewed interest in renewable energy sources has led to the rise of lots of wind farms and photovoltaic plants that use lots of sensible components: just from this fact we can simply see how the grid we have nowadays is more susceptible to a "bad" power quality than the grid we had 20 or 30 years ago.
This thesis focuses more on the problem of the unbalances mainly created by different current absorption in each phases in distribution grids:thinking of a residential area, if back then the "balancing" of an electrical grid would have been done by connecting the same number of houses to one phase, the same strategy nowadays could not be valid anymore since we saw the rise of active users(e.g. an house with a rooftop photovoltaic generator) leading to a more unpredictable current absorption.

It is for this reason that i decided to study this topic and to learn something on the balancing of electrical grids exploiting 3-phase inverters: in this thesis I'll talk about how to control an inverter connected to a balanced and unbalanced grid as well as 3 main control techniques to balance an unbalanced grid in which the inverter is connected.

2 Why this Thesis?

2.1 Attributes of an Electrical Grid

I'll start by defining what do I mean by the attributes "symmetric" and "balanced" when we are talking about a 3-phase electrical grid:

- When the adjective "symmetric" is used the emphasis is put on the impedance of the grid:if there were to be different impedances in the 3 phases we would classify the grid as asymmetric; vice versa if there were to be only symmetric loads(like 3-phase induction machines and such) the grid will be classified as symmetric.
- When the adjective "balanced" is used the emphasis is put on the various quantities that characterize the grid which are the voltages and the currents:if we ever have a grid with unbalanced voltages and/or currents we would classify it as unbalanced; vice versa, if we had a grid with all quantities which are equal in amplitude and 120° from each other(e.g. in a three phase system) we would classify it as balanced.
  It is also not unusual to have balanced operating conditions as well as unbalanced ones in the time span of a day maybe, because it depends heavily on the loads connected to the grid such as single phase loads.

2.2 Causes and Effects of an Unbalanced Electrical Grid

2.2.1 Causes

The main factors that play a role in unbalancing a grid are mainly 2:

- Voltage of the grid
- Loads connected to the grid

Usually, in the vast majority of cases, the responsibility of an unbalanced grid is due to the loads connected to it. Although I don't rule out the possibility of having an unbalanced voltage feeder, I'll mostly talk about the cases in which the unbalance is given only by the unbalanced currents absorbed by some unbalanced load(s).

2.2.2 Effects

Given the fact that the interests in renewable energy sources is increasing as well as the overall sensitivity of the global population on the topic and given the European guidelines about the energetic transition, the money spent on photovoltaic and wind power plants is not anymore irrelevant.
It is not new the fact that an unbalanced voltage causes a not optimal working condition for various type of devices like induction machines and uncontrolled rectifiers causing phenomena like hot-spots or torque ripples with the possibility to damage such devices[3][4];so, since renewable energy sources rely mostly on such type of components, even a small unbalance in the grid's voltages can lead to faults and sub optimal working condition especially in the case of induction machines used as generators in wind power plants[3] where the turbine could be placed at the end of a long rural area's electrical grid.

Possible Solutions In order to avoid unbalances in the grids, the first technique used was to spread single phase loads between the three phases, but as said in the introduction, nowadays the rebalancing via this method is more unpredictable due to the rise of "active" users. One rather simple solution could be the implementation of one or more STATCOMs(static compensators) in the grid we want to rebalance: these STATCOM are basically three phase inverters controlled in some specific way such that they're able to rebalance grids; so in order to understand how those devices are able to rebalance we need to comprehend how the basic control of an inverter works!

3 Inverter's Control Technique in a Balanced Grid

When we want to comprehend how the control of a three-phase inverter works, we have to divide the overall argument in two main macro-areas:

- Synchronization with the grid the inverter's connected to.
- Actual control of the quantities of interests requested to the inverter, like torque if we are controlling an electrical motor, or active and reactive power in the case of a grid-oriented type of control(actually, in the case we are controlling an electrical motor the torque demand could be translated to an active power demand and we could also include a reactive power demand by considering the flux management).

Then, when we have achieved these two points, usually we get two voltage references which can be "followed" or "created" by the inverter through the generation of "n" signals, where "n" equals the number of semiconductor devices present in the inverter as depicted in Fig. 1 as "g_{1-6}".

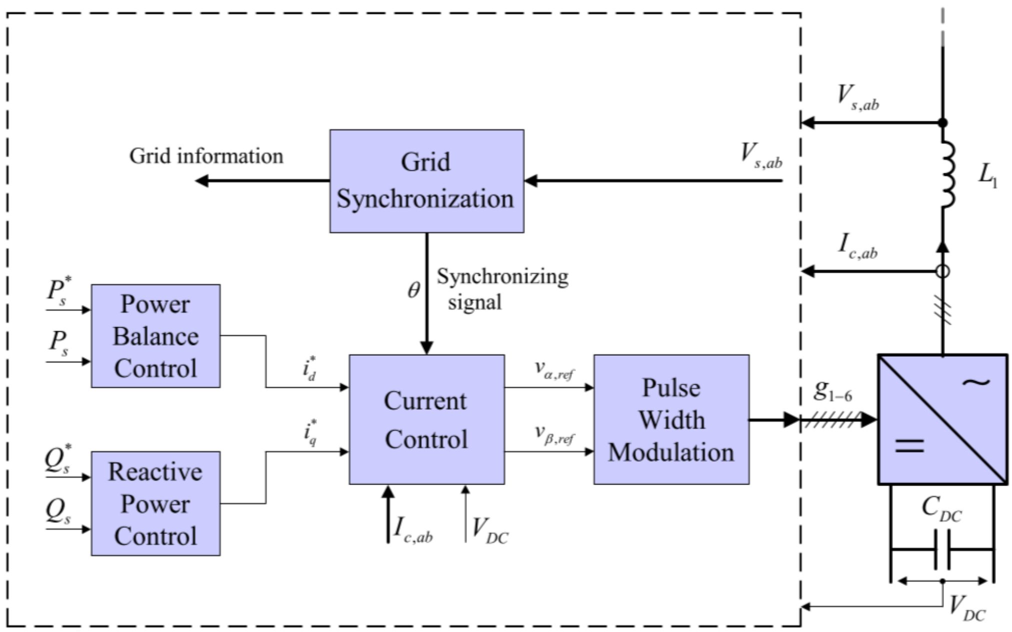

Figure 1: Generic Control Structure For A Three-Phase Inverter [1]

The block that generates the "g_{1-6}"(gate signals) is called Pulse Width Modulation since this is the main technique used to generate the desired waveform, which consists in confronting the reference voltages with a triangular waveform called carrier that in some extent "scans" it and allow the inverter to generate the classic PWM waveform as seen in Fig. 2.

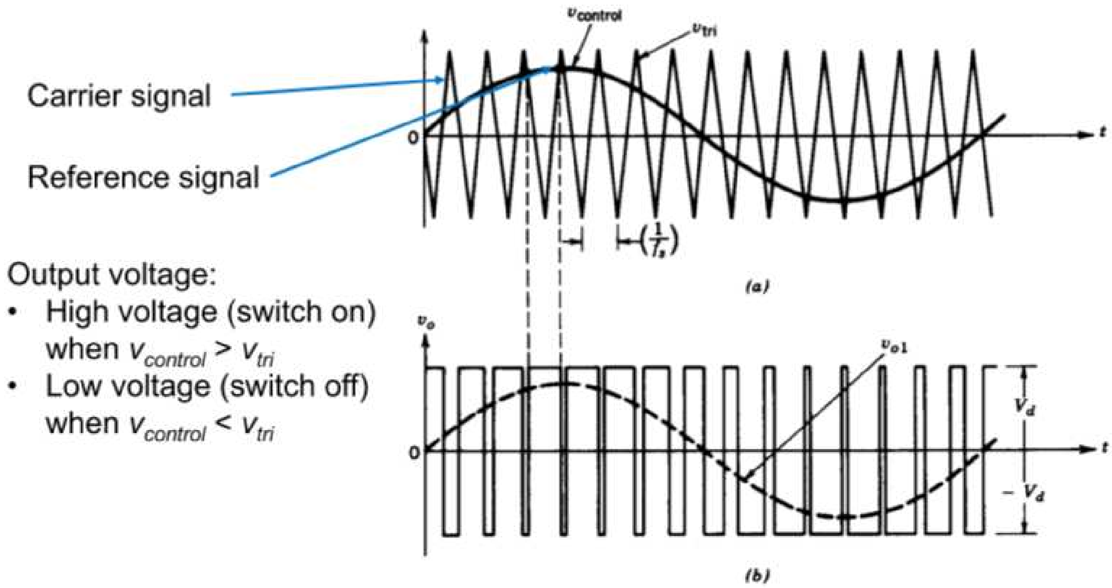

Figure 2: Pulse Width Modulation [2]

3.1 Synchronization:Why and How

One could think that yes, to be synchronized is a key factor to achieve the control of our inverter and it indeed is a straightforward thought, but why is it so important? I found the answer quite simple and self explanatory:in a generic (balanced) grid our goal is to tell the inverter how much power to absorb/inject from/to the grid and to do so we use one of the most powerful tool we have when we are analyzing three-phase quantities:Clarke and Park transformations!

3.1.1 Clarke Transformation

With "Clarke Transformation" we aim to make our three-phase system become a two-phase system; the general definition of the Clarke transf. is the following:

$$V_{\alpha\beta\gamma}(t) = T_C * V_{abc}(t) = \frac{2}{3} * \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} * V_{abc}(t) \quad (1)$$

So, in this general case, we just shifted to a different three-phase system with a two axis reference frame, but if we think the premises of this chapter(balanced grid) we can notice one small thing:in the equation (1) since the coefficient are all the same we could neglect the γ component of the transformed vector $V_{\alpha\beta\gamma}(t)$ given the fact that in a balanced system the sum $V_a(t) + V_b(t) + V_c(t) = 0$ in any given time, leaving us with the next simplified version of our equation (1):

$$V_{\alpha\beta}(t) = T_C * V_{abc}(t) = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} * V_{abc}(t) \quad (2)$$

We ended up with a bi-phase two axis reference frame, or in other words, we could see this operation like a method to combine three separate rotating vectors into a single one!

Power Invariant Clarke Transformation if we try to compute the three-phase active and reactive power in the "abc" and "$\alpha\beta\gamma$" we can notice that they're not equal, but we could make one more definition: the so called power invariant Clarke transformation(given the name, if we compute the three-phase active and reactive power it will be equal in the two frames) which is the following:

$$V_{\alpha\beta\gamma PowerInv}(t) = T_{C-PowerInv} * V_{abc}(t) = \sqrt{\frac{2}{3}} * \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} * V_{abc}(t) \quad (3)$$

3.1.2 Park and dqz Transformations

The Park transformation is quite brilliant in my opinion because allows us to setup a control scheme based on the most simple of all controllers:PIDs! But how can this tool allow us to do that? We could start by looking at the general matrix definition of it:

$$V_{dqz} = T_P * V_{xyz} = \begin{bmatrix} cos(\theta) & sin(\theta) & 0 \\ -sin(\theta) & cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} * V_{xyz} \quad (4)$$

If we try to combine the simplified Clarke and Park transformations we could obtain the so called "dqz" transform, passing from a three-phase system "abc" through an "$\alpha\beta$" one and arriving at a "dq" reference frame(the zero component has been neglected since the γ one is equal to zero in a balanced grid).

P & Q Control The key to understand how powerful the "$dq(z)$" transformation, is to understand how it changes our point of view: we are used to define a static reference frame, just think of "abc" and "$\alpha\beta\gamma$" ones, but in the so called "$dq(z)$"(direct-quadrature-zero)" the frame is no longer static but it starts rotating at a certain angular speed and here comes up the importance of the synchronization: we can depict a two axes rotating frame(in which we call the "x" axe the direct one and the "y" axe the quadrature one) as well as a single vector, rotating at the same angular speed as the "abc" ones as seen in Fig. 3.

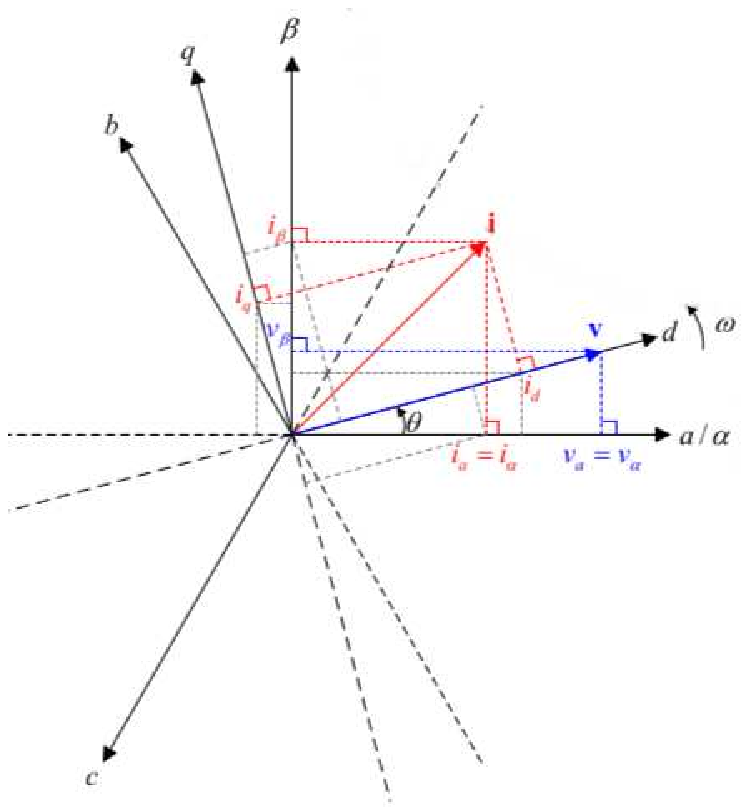

Figure 3: $abc, \alpha\beta\gamma, dqz$ reference frames [1]

The target here is to have a rotating reference frame aligned with the rotating vector on the direct axe(we can do that by knowing the angular coordinate θ); if we compute the complex power in the "dq" reference frame we obtain:

$$S = V * \overline{I} = (V_d + jV_q) * (I_d - jI_q) = V_d I_d + V_q I_q + j(-V_d I_q + V_q I_d) \tag{5}$$

Assuming we are aligned and synchronized with the voltage vector(since we shifted from the "abc" reference frame to the "$\alpha\beta(\gamma)$" one, we ended up with a single rotating vector), from now on V_d and V_q will have only constant values, but to be more specific $V_d \neq 0$ and $V_q = 0$ leaving us with the following complex power relatioship:

$$S = V_d I_d + j(-V_d I_q) \tag{6}$$

So at the end we can comprehend how a perfect synchronization allow us to control active($V_d * I_d$) and reactive($-V_d * I_q$) powers by "simply" controlling the direct and quadrature currents outputted by our inverter(as seen in Fig. 1): in fact the inner control loops over which the main control strategy is based are called current loops; together with the inner loops could be implemented also outer loops which can have various purposes like controlling in fact the active and reactive powers(as depicted in Fig. 1) or controlling the DC-link voltage.

3.1.3 Synchronization:How Can We Achieve It?

The aim is to know θ in any give time: θ is the angular coordinate of the single rotating vector built with the $\alpha\beta(\gamma)$ transformation from the abc starting reference frame. To do so we use a technique called "PLL:Phase Locked Loop" with which we can, thanks to a PI controller and a smart choice of the reference signal, track the desired vector.

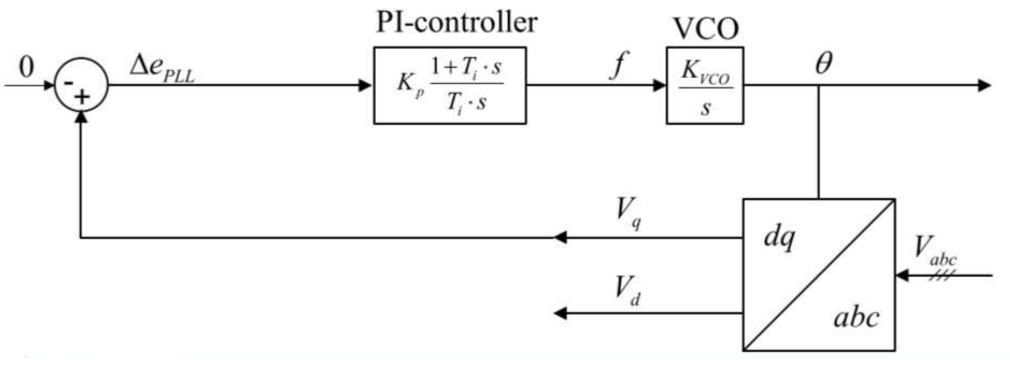

Figure 4: Basic PLL Control Scheme [1]

Usually the general principle to make a PLL is to measure the three-phase voltage, obtain the dq components and generate a feedback using V_q as signal as seen in Fig. 4 or some other signals based on some further elaboration of the two dq components. The error is then fed to a PI controller giving us the frequency which will be integrated(by the Voltage Controlled Oscillator in Fig. 4) allowing us to get to the angle estimation(which will be fed to the "abc to dq" block, closing the loop).

Choice of the Feedback Signal We could use directly the V_q measurement but that won't be our best choice for sure: one small improvement we could make is the filtering of the signal("$h_f(s)$" in Fig. 5) since we'll expect some noise/harmonics in the measurement. Another improvement we could think of is the implementation of the "per unit" method:if we use it we won't have to worry about the loop gain dependence on grid voltage amplitude. Finally one last improvement could be using the estimated angle error as feedback signal: since the condition to declare we are properly aligned is to have $V_q = 0$ we could compute the estimated angle error exploiting the 4-quadrant $\tan^{-1}$(atan2 in MATLAB):

$$\Delta\theta = \arctan_2\left(\frac{v_q}{v_d}\right) \tag{7}$$

Now the best solution is to put together all the mentioned improvements and to feed-forward the rated frequency of the grid after the PI giving us a robust PLL scheme like the one shown in Fig. 5.

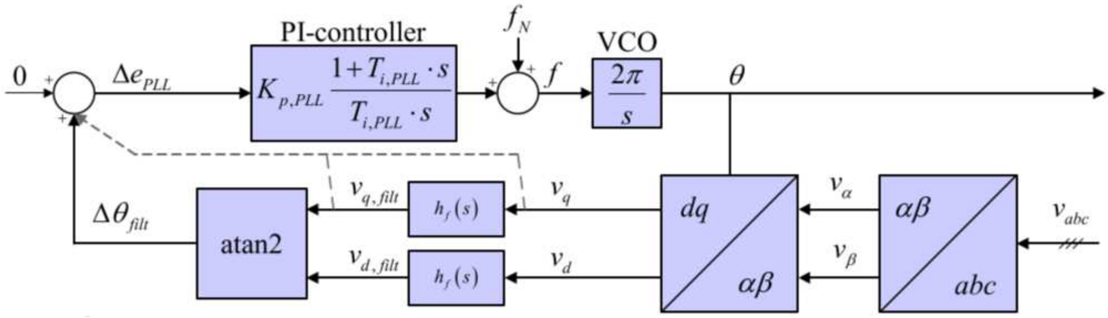

Figure 5: Advanced PLL Control Scheme [1]

PLL's PI Tuning To know how to tune our PI we have to first look at the open loop transfer function of our PLL:

$$h_{OL,PLL} = K_p \frac{1 + sT_i}{sT_i} \frac{2\pi}{s} \frac{1}{1 + sT_f} \tag{8}$$

Where K_p and T_i are the parameters of our controller and T_f is the time constant of the filter $h_f(s)$ as seen in Fig. 5. Since we have the PI zero and the filter pole to place we could place them in a clever way, the so called "Symmetrical Optimum", in order to achieve the maximum phase at the crossover frequency as seen in Fig. 6.

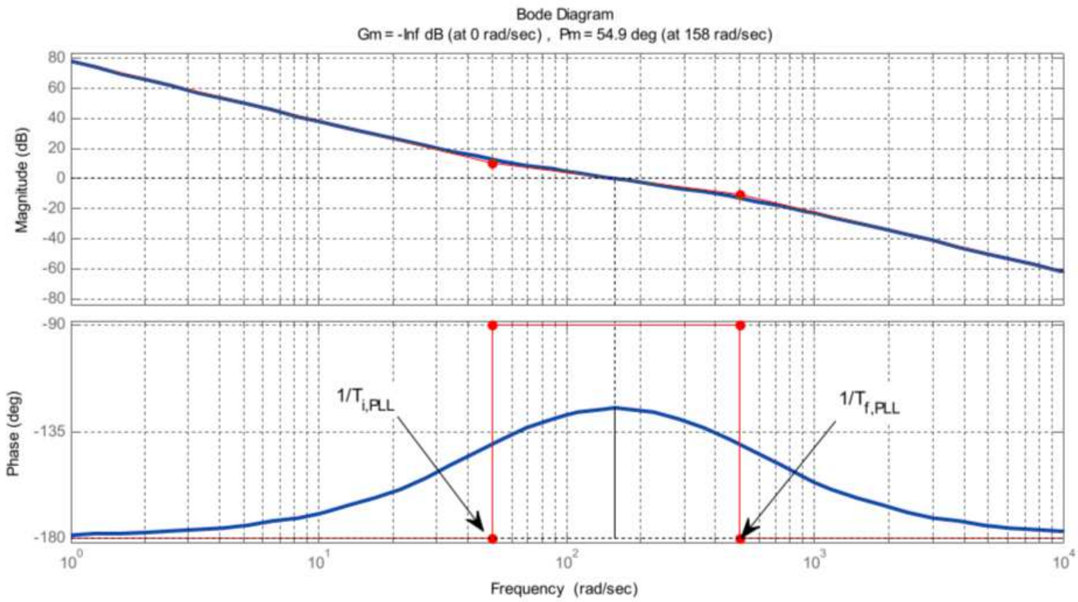

Figure 6: PLL's Bode Diagram [1]

Since the phase characteristic is symmetrical, it implies that:

$$T_{i,PLL} = a^2 T_f \tag{9}$$

so the ω at which the phase margin is maximum is the following:

$$\omega_{\Psi max} = \frac{1}{\sqrt{T_{i,PLL} T_f}} = \frac{1}{aT_f} \tag{10}$$

and by simply evaluating $h_{OL,PLL}(j\omega)$ in $\omega_{\Psi max}$ and by substituting $T_{i,PLL}$ with $a^2 T_f$ we could find a relationship that gives us K_p:

$$K_p = \frac{1}{a 2\pi T_f} \tag{11}$$

In the end we could start by defining the two parameters which are a and T_f and starting from there we could evaluate K_p and T_i in order to achieve the maximum phase margin of our transfer function.

a **meaning** While T_f is chosen in regards of how we want to filter our measured signal, the parameter a is one degree of freedom we have: smaller values would lead to faster(and more unstable) systems with more overshoot and some oscillations while greater values would lead to slower but more damped systems. We can see an example of this behaviour of the step response in Fig. 7

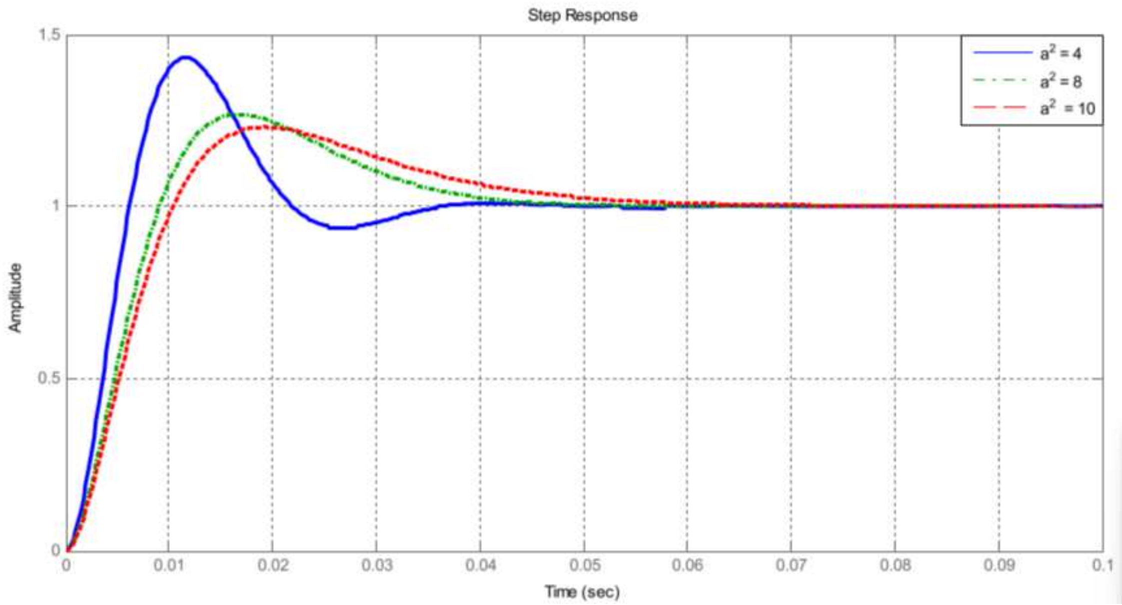

Figure 7: Step response in regards of different a values [1]

3.2 General Voltage Source Converter Control Structure

We'll see in this chapter how to setup a general control structure for a VSC starting from the "Current Control" block as seen in Fig. 1 as well as some of the outer loops options.

3.2.1 Filter Inductance Modeling and Current Control Structure

To know how to build a properly functioning control we have to analyze the behaviour of the system depicted in Fig. 8 and try to derive some sort of equation that gives us V_c in function of the current I_c.

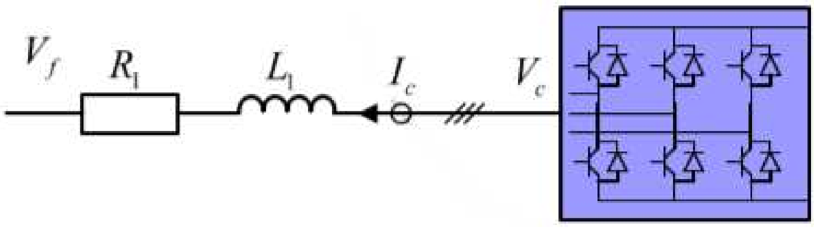

Figure 8: Filter Inductance Model [1]

To start we can write the equation of the voltage V_c in the $\alpha\beta$ reference frame:

$$V_c^{\alpha\beta} = V_f^{\alpha\beta} + R_1 I_c^{\alpha\beta} + L_1 \frac{d}{dt} I_c^{\alpha\beta} \tag{12}$$

Then we want to put ourselves in the dq rotating reference frame:

$$\begin{aligned} V_c^{dq} &= V_c^{\alpha\beta} e^{-j\theta} \\ V_f^{dq} &= V_f^{\alpha\beta} e^{-j\theta} \\ I_c^{dq} &= I_c^{\alpha\beta} e^{-j\theta} \end{aligned}$$

So Eq. (12) becomes the following(given that $\theta = wt$) by simply multiplying e^{-jwt} to both the equation members:

$$V_c^{dq} = V_f^{dq} + R_1 I_c^{dq} + L_1 \left(\frac{d}{dt} I_c^{\alpha\beta} \right) e^{-jwt} \tag{13}$$

And by computing the $\frac{d}{dt}$ term we obtain:

$$\frac{d}{dt} I_c^{\alpha\beta} = \frac{d}{dt} \left(I_c^{dq} e^{jwt} \right) = \frac{d}{dt} \left(I_c^{dq} \right) e^{jwt} + I_c^{dq} \left(j * w * e^{jwt} \right) \tag{14}$$

Leading us to the final equation in the dq frame:

$$V_c^{dq} = V_f^{dq} + R_1 I_c^{dq} + L_1 \frac{d}{dt} I_c^{dq} + jwL_1 I_c^{dq} \tag{15}$$

And by defining "per unit" quantities in the following manner(relating to the peak values):

$$\begin{aligned} S_b &= \frac{3}{2} \hat{V_{line}} \hat{I_{line}} \\ V_b &= \hat{V_{line}} \\ I_b &= \frac{S_b}{V_b} \frac{2}{3} \\ V_b &= Z_b I_b \\ Z_b &= R_b = w_b L_b \end{aligned}$$

We introduce Eq. (15) in p.u.:

$$v_c^{dq} = v_f^{dq} + r_1 i_c^{dq} + \frac{l_1}{w_b} \frac{d}{dt} i_c^{dq} + jw_{pu} l_1 i_c^{dq} \tag{16}$$

dq Components and Axes Decoupling By splitting the converter voltage(v_c) equation in the two components, direct(real) and quadrature(complex), we obtain the following result:

$$v_c^d = v_f^d + r_1 i_c^d + \frac{l_1}{w_b} \frac{d}{dt} i_c^d - w_{pu} l_1 i_c^q \tag{17}$$

$$v_c^q = v_f^q + r_1 i_c^q + \frac{l_1}{w_b} \frac{d}{dt} i_c^q + w_{pu} l_1 i_c^d \tag{18}$$

Right away we can notice that the direct component of the voltage is dependent also on the quadrature component of the current and vice versa: since the PI controllers, on which the strategy is based, can work well on SISO systems(Single Input Single Output) the goal now is to somewhat decouple the two axes from each other so that we have a direct voltage depending solely on the direct component of the current(and in a dual way, having the quadrature component of the voltage that depends solely on the quadrature component of the current). One simple way to do that is by simply adding to Eq. (17) "$w_{pu}l_1i_c^q$" and subtracting to Eq. (18) "$w_{pu}l_1i_c^d$"; since we're controlling i^{dq} we are measuring them, with the purpose to use them as feed-back signal for our PI controllers so we can just compute the "$w_{pu}l_1i_c^q$" and "$w_{pu}l_1i_c^d$" terms and add them to our control structure as see in Fig. 9(we know w_{pu} from the PLL).

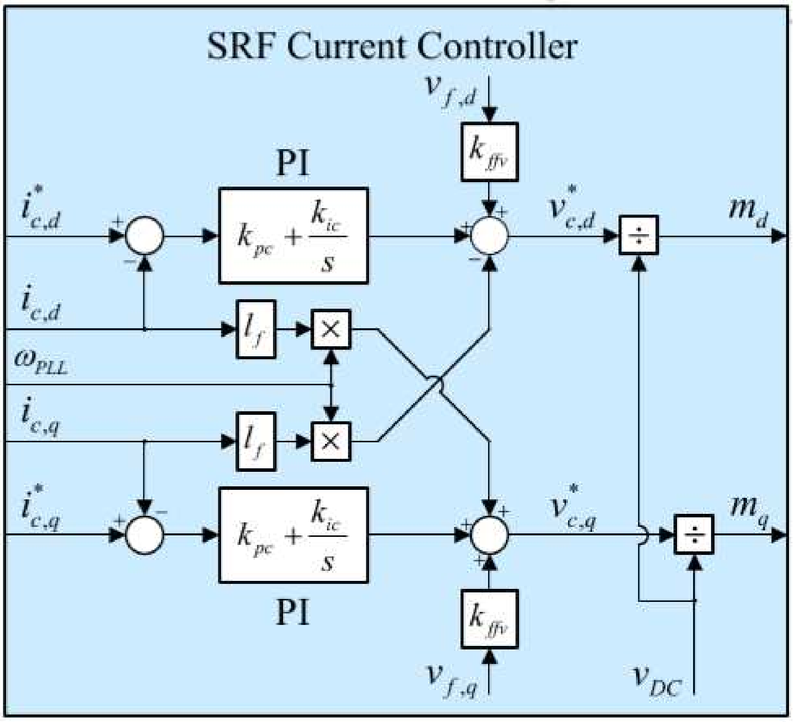

Figure 9: Decoupled PI Controllers Control Structure [1]

In the figure above we can see the main structure useful to generate the proper voltage references starting from the measured current values $i_{c,dq}$ and the reference values $i^*_{c,dq}$; once we have the direct and quadrature voltage references we could compute the so called "modulation indexes", "m_d" and "m_q" in Fig. 9, which will then be fed to our PWM pulse generator in order to obtain the "g_{1-6}" signals to control each semi-conductive device of our converter as seen in Fig. 1. The modulation indexes are obtained by simply dividing by the DC link voltage, absolute or in p.u., depending on which definition system we're working with.

Current Control's PI Tuning To know how to tune our PI controller we can start by looking at the filter inductance transfer function in the dq reference frame:

$$v_{PI}^d = r_1 i_c^d + \frac{l_1}{w_b}\frac{d}{dt}i_c^d \tag{19}$$

$$v_{PI}^q = r_1 i_c^q + \frac{l_1}{w_b}\frac{d}{dt}i_c^q \tag{20}$$

$$h_{L_1}^{dq} = \frac{I^{dq}}{V_{PI}^{dq}} = \frac{1}{r_1}\frac{1}{1+T_1 s} \tag{21}$$

$$T_1 = \frac{l_1}{r_1\omega_b} = \frac{L_1}{R_1}$$

We can now define the overall open loop transfer function as:

$$h_{OL,cc}^{dq}(s) = K_p\frac{1+T_{i,cc}s}{T_{i,cc}s}\frac{1}{1+T_{delay}s}\frac{1}{r_1}\frac{1}{1+T_1 s} \tag{22}$$

So, how do we tune our PI parameters? One way is to design our controller by the "Modulus Optimum" criteria: the strategy here is to neglect the largest time constant in the open loop transfer function, which is the filter inductance in this case:

$$T_{i,cc} = T_1 \tag{23}$$

The next step is to choose our K_p and we're going to do that by looking at the closed loop transfer function:

$$h_{CL,cc}^{dq}(s) = \frac{\frac{K_{p,cc}}{r_1 T_1 T_{del}}}{s^2 + \frac{1}{T_{del}}s + \frac{K_{p,cc}}{r_1 T_1 T_{del}}} \tag{24}$$

since we want to tune our controller in the best way possible, we can choose K_p in order to achieve an optimally damped system(this is a second order transfer function) which is a system with a "ζ" coefficient equal to $\frac{1}{\sqrt{2}}$:

$$\zeta = \frac{1}{2}\sqrt{\frac{r_1 T_1}{K_{p,cc}T_{del}}} = \frac{1}{\sqrt{2}} \tag{25}$$

$$K_{p,cc} = \frac{r_1 T_1}{2T_{del}} = \frac{l_1}{2\omega_b T_{del}} \tag{26}$$

In the end, if we choose $K_{p,cc}$ and $T_{i,cc}$ as described earlier we end up with the following OL and CL transfer functions:

$$h^{dq}_{OL,cc}(s) = \frac{1}{2T_{del}} \frac{1}{1 + T_{del}s} \tag{27}$$

$$h^{dq}_{CL,cc}(s) = \frac{1}{1 + 2T_{del}s + 2T^2_{del}s^2} \tag{28}$$

First Order Equivalent of the Inner Loop Transfer Function To ease the tuning of the outer loops we could represent our second order inner loop TF as a first order TF and to define it we have to ensure an equal error integral in response to a reference step:

$$h_{errorInt,cc}(s) = \frac{1}{s} - \frac{1}{s} \frac{1}{1 + 2T_{del}s + 2T^2_{del}s^2} \tag{29}$$

$$h_{eq}(s) = \frac{1}{1 + T_{eq}s} \tag{30}$$

$$h_{errorInt,eq}(s) = \frac{1}{s} - \frac{1}{s} \frac{1}{1 + T_{eq}s} \tag{31}$$

Now we have to use the final value theorem to evaluate the steady state value of $h_{errorInt,cc}(s)$ and $h_{errorInt,eq}(s)$ transfer functions in order to to obtain a relationship to define T_{eq}:

$$\lim_{s \to 0} (s \cdot \frac{1}{s} h_{errorInt,cc}(s)) = 2T_{del} \tag{32}$$

$$\lim_{s \to 0} (s \cdot \frac{1}{s} h_{errorInt,eq}(s)) = T_{eq} \tag{33}$$

So we can define an equivalent first order TF by simply choosing:

$$T_{eq} = 2T_{del} \tag{34}$$

3.2.2 Outer Control Loops Options

Outer loops have the purpose of providing the adequate current reference to the inner current loop. We can have multiple types of outer loops:

- Frequency support control
- Voltage support control
- Active power control
- Reactive power control
- DC link voltage control

Usually we don't ask our converters to support frequency nor AC side voltage, but it could be done very simply just by knowing some parameters of the electrical grid we're working on. Active power control loops are more "popular" i would say, just think of a control of a motor in which you have to request a torque which translates to a power demand; the most interesting for me is the DC link voltage control, since I'll be using that as you could see in a latter chapter of this thesis:but how does it work?

DC Link Voltage Control Scheme As most of the outer loops, it works by imposing a reference to track and through some measurement, an error signal is generated which is then fed to our PI controller. Now, since the DC link voltage is strictly related to the active power flow, the overall purpose of this kind of loop is to somewhat influence it, and to do so, as seen in Eq. (6), we have to provide a direct axis current reference as seen in Fig. 10. In Fig. 12 we can see an example of a controlled DC link voltage where, after a transient, the system reaches the reference value which, in this case, is set to $800V$.
One further step we could do is, instead of using v_{dc} as reference and feedback signal, we could use v_{dc}^2: by doing so we're not directly controlling the capacitor voltage, but its energy since:

$$W_{C,dc} = \frac{1}{2}CV_{dc}^2 \tag{35}$$

The purpose of doing so is to have a more linear system[1] to deal with in order to have a better performance from our PI controller. In Fig. 11 we can see the scheme I implemented in my Simulink model.

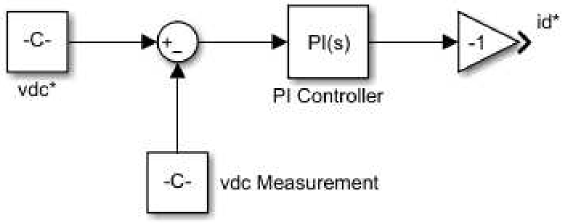

Figure 10: Basic DC Link Voltage Control Scheme

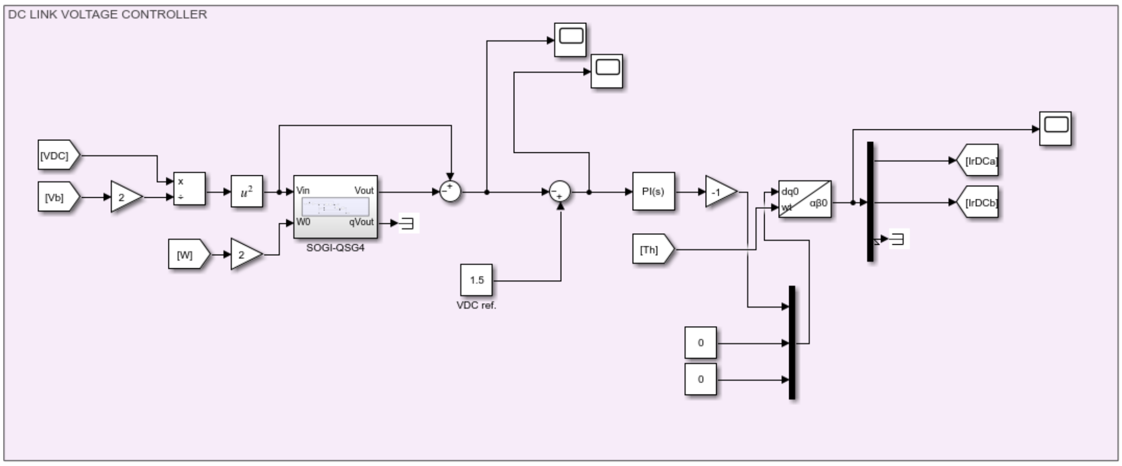

Figure 11: DC Link Voltage Control Scheme Implemented in the Simulink Model

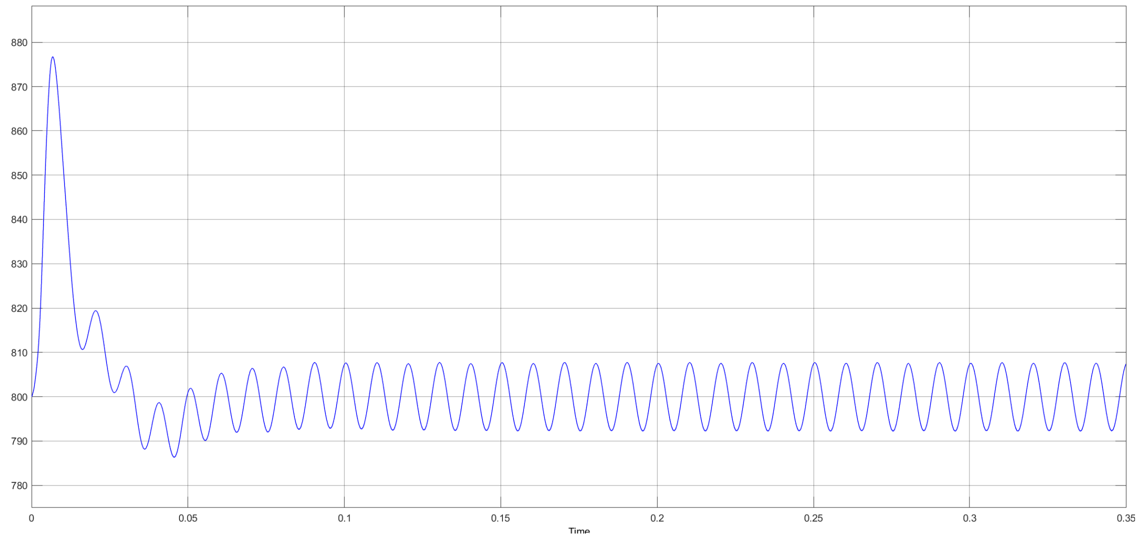

Figure 12: Example of DC Link Voltage Profile

3.2.3 LCL Filter and Active Damping

Since we're telling our device to generate a PWM waveform, we should expect a relevant number of current harmonics, of order related to the switching frequency we're working with, injected into to the grid: as the introduction of this thesis says, power quality has become, in recent years, more and more relevant so we should address the problem in the best way we can; to filter these harmonics there are a wide range of filters we can use but the simplest three are:

- L
- LC
- LCL

As seen in Section 3.2.1 we thought the overall model of the VSC as an inverter plus a RL branch which is the simplest version of a filter we could have but as it is said in [5] L-type filters tend to have a slow dynamic response when dealing with larger power applications and introduces a relevant voltage drop in our system: it is for these facts that I implemented a LCL filter in my model(in a "T" configuration as seen in Fig. 13) in order to reduce the harmonics injected towards the grid and, consequently, the footprint of "my" device on the THD of the grid. The design of the LCL filter I implemented has been done following the procedures described in[5].

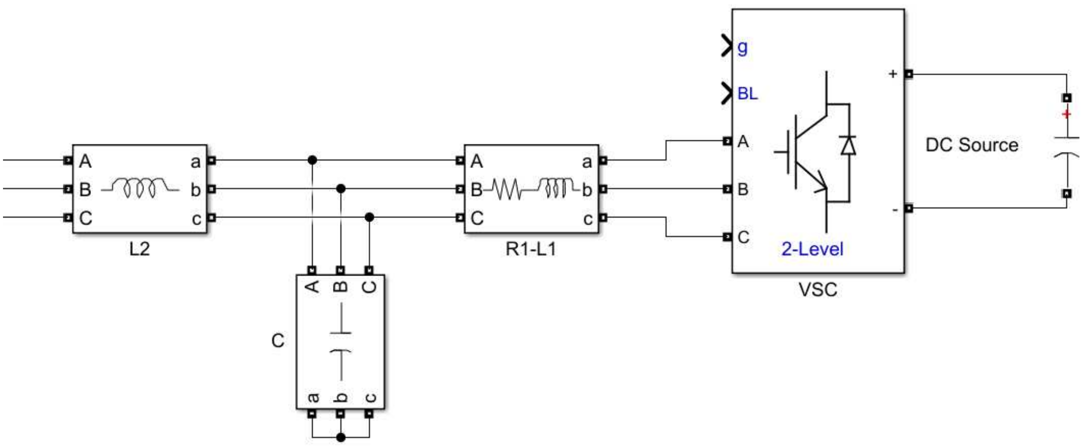

Figure 13: LCL Filter "T" configuration

Passive and Active Damping Perhaps the most interesting thing regarding the LCL filter is the way we damp its oscillations: one drawback of this type of filter is that it has a resonance problem(depending, of course, on the values of L_1 L_2 and C) and it could be the cause of some bad oscillations in either voltage or current, so, in order to avoid this we have two solutions:

- Passive Damping
- Active Damping

As the name suggests, passive damping is done by implementing a resistor(the name of the method derive from this fact,since it is a passive dipole) in series to the filter's capacitor; the other method is more interesting since it doesn't involve any physical device to be connected(hence we're not wasting any energy like we do with the resistor) but instead it is done in clever way by adding some terms in our inverter's control chain!
The control branch that achieve the active damping in my simulink model can be seen in Fig. 14

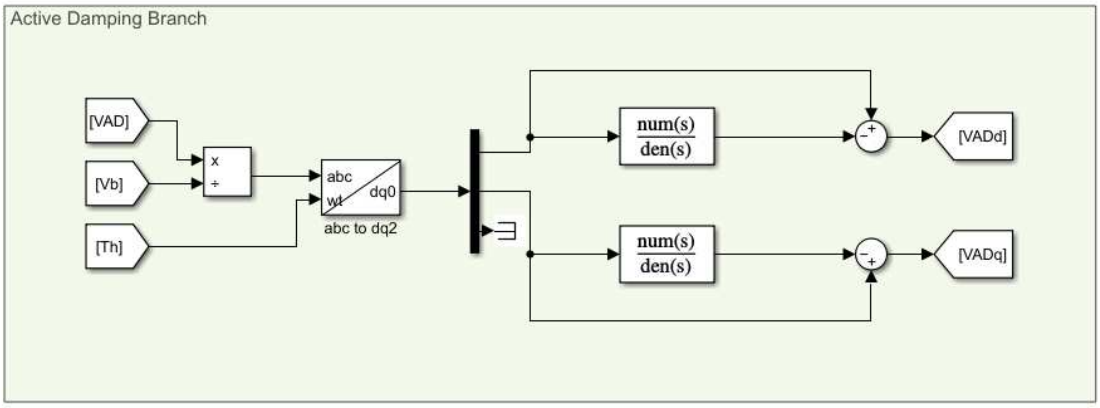

Figure 14: Active Damping Structure

The idea behind this type of damping is to feed forward a d and q voltage/current high frequency components counter-phased to the one we are measuring in the grid in order to cancel poorly damped oscillations: to do so we measure the filter capacitor voltage, transform it in the per unit system, calculate the dq components and finally we extract the high frequency component as seen in Fig. 14 given the fact that the "$\frac{num(s)}{den(s)}$" block is a low pass filter. I've chosen to implement this type of damping since it minimize the energy loss as compared to the passive one and also could be done by simply writing some extra "code" in our control chain!

THD Evaluation To check the performance of our LCL filter in our model we could run a simple FFT analysis on the grid's voltage:

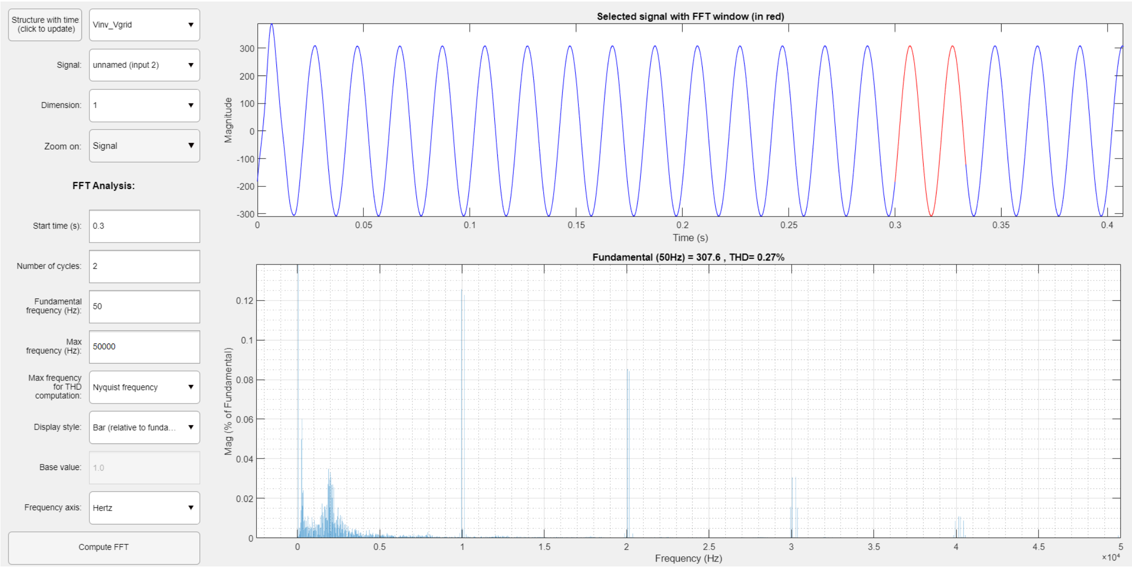

Figure 15: FFT analysis

In the upper part of Fig. 15 the waveform we're analyzing is shown while in the lower part we can see the magnitude of each harmonics present in the voltage.

It is interesting to note that there are some harmonics around 2 kHz due to the presence of the LCL filter but also there are several harmonics around the switching frequency and its multiples as stated in [2]. In fact I've chosen to work with a switching frequency of 10050 Hz so:

$$m_f = \frac{10050}{50} = 201$$

The measured harmonics are present at the frequencies:

$$h = j(m_f) \pm k$$

Where for odd values of j the harmonics exist for even values of k and vice versa[2]. The measured THD is equal to:

$$THD = 0.27\%$$

and given the fact that the maximum value admissible ranges between 4% and 8% we can say that this type of filter does a wonderful job in reducing the harmonics outputted by our inverter.

4 Inverter's Control Technique in an Unbalanced Grid

In this case the hypothesis of a balanced grid is not valid anymore, and to comprehend how it affects the control chain of our device, we'll need to watch how a three phase set of unbalanced voltages(or currents) transform into its dqz components:

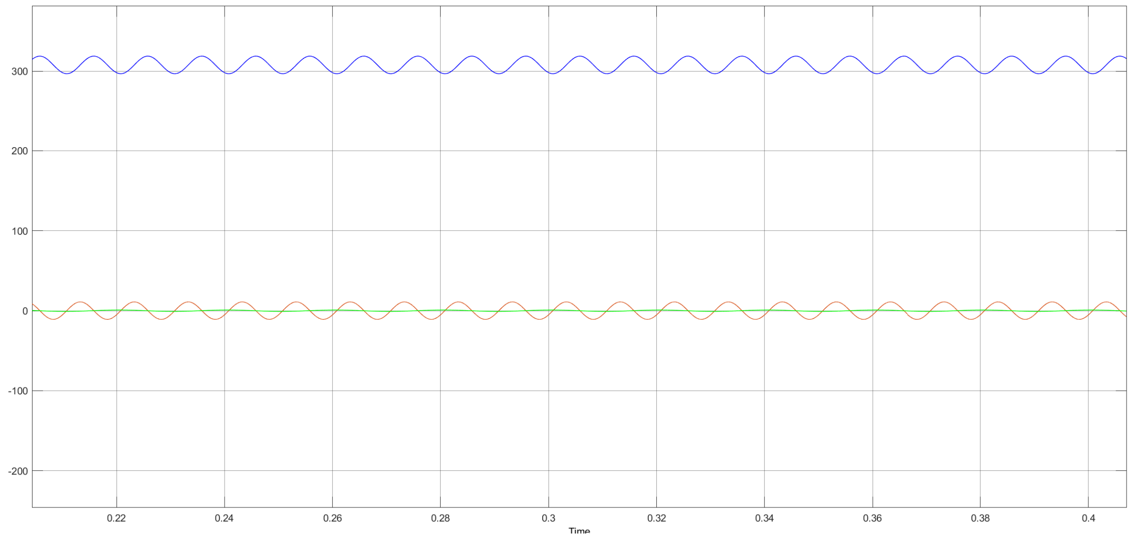

Figure 16: Unbalanced Voltage dqz Components

Since we are in an unbalanced working condition, we can't neglect anymore the γ component($\alpha\beta\gamma$ reference frame) nor the z component(dqz reference frame) and in fact you can see it in green in Fig. 16, but this is not the thing we should be worried about the most: the dq components are not constant anymore! And this, for our control strategy, is a huge change since we can't use anymore PIDs as main the type of controller(or perhaps if we do, we'll have some disadvantages in respect to other typology of controllers).
As said in Section 3 there are two main aspect when we want to control an inverter connected to an electrical grid:

- Synchronization
- Current control(inner loop) and eventual control of various quantities(outer loops)

In this section we'll see how to achieve these two goals in an unbalanced working condition.

4.1 PR Controller and Reference Frame Choice

4.1.1 PR Controller

To deal with the sinusoidal *dq* component on one hand we could use a very fast PI controller to constantly track the *dq* sine wave but this solution, while a choice that could work, is not the best one since it would mean to introduce an error in the control chain; on the other hand we have what is known as "PR" Controller which stands for "Proportional Resonant Controller":

$$C_{PR}(s) = K_p + K_i \frac{s}{s^2 + \omega^2} \tag{36}$$

Eq. (36) represent the transfer function of this type of controller: we can see that it is very similar to a classic PI controller but the thing that does the trick is the term that multiply K_i, that's a resonant term that, tuned to the right frequency ω, can give us a very high gain and thus is able to eliminate the steady state error when trying to track sinusoidal signal [6]. It is useful to note that, to ensure the proper working condition of our PR controller, we have to tune it as close as possible to the grid's frequency value; it is also possible to add Eq. (37) to the controller transfer function in order to improve its performance when handling harmonics[6]:

$$C_{HC}(s) = \sum_{h=3,5,7...} K_{ih} \frac{s}{s^2 + (\omega h)^2} \tag{37}$$

SOGI and Simulink PR Controller Implementation In order for my model to work I had to build a PR controller from scratches and in order to do that I'm going to introduce a fundamental "brick" i used to cope with the unbalanced working conditions: the "SOGI" which stands for "Second Order Generalised Integrator"; the main structure of the SOGI can be seen in Fig. 17:

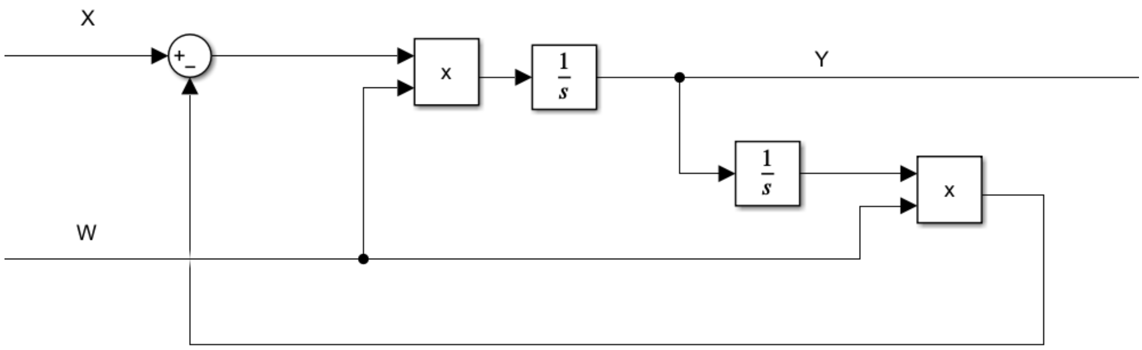

Figure 17: Second Order Generalised Integrator Structure

The SOGI transfer function is the following:

$$h_{SOGI}(s) = \frac{\omega s}{s^2 + \omega^2} \tag{38}$$

And right off the bat we could see that by simply adding a K_p term, we could obtain a PR controller; the structure of such controller in my model is the following:

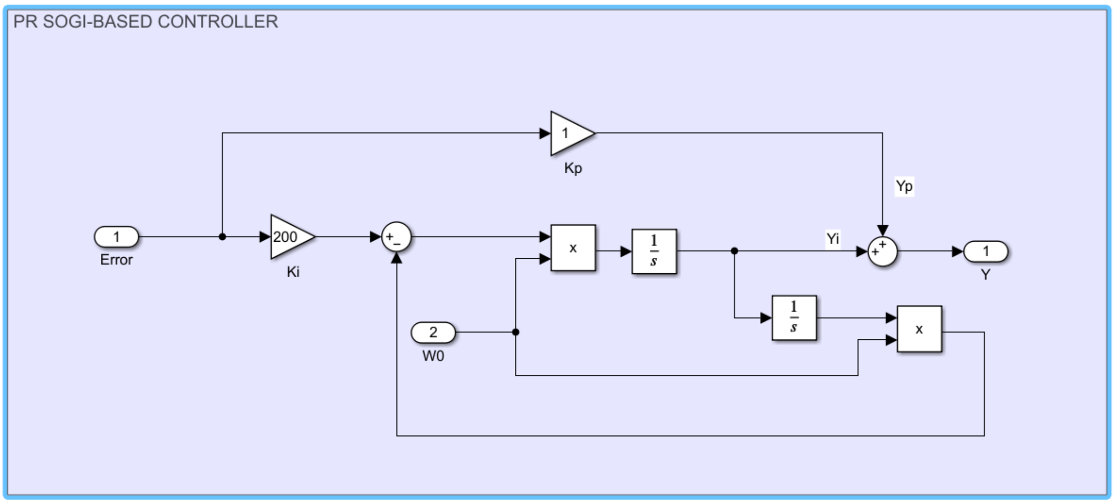

Figure 18: Simulink PR controller Implementation

4.1.2 Reference Frame Choice

In a balanced working condition we choose to work in the *dq* reference frame so the usage of PI controllers could be possible; now we've seen that to cope with the problem of sinusoidal signal tracking, PR controllers had been chosen since they gave us a better performance than the PI ones, so we are not bound anymore to the *dq* reference frame in fact the $\alpha\beta$ system is preferred when trying to control an inverter in an unbalanced working condition. One could also think that since we're working with sinusoidal waveform we could setup a control based in the *abc* reference frame, and indeed it is possible as described in [6].
Since we're working in a static reference frame, we are now forced to specify our reference values in the *dq* system and then transform them via a "*dq* to $\alpha\beta$" block in order to feed them to our new PR controller. The overall control scheme is shown in Fig. 19:

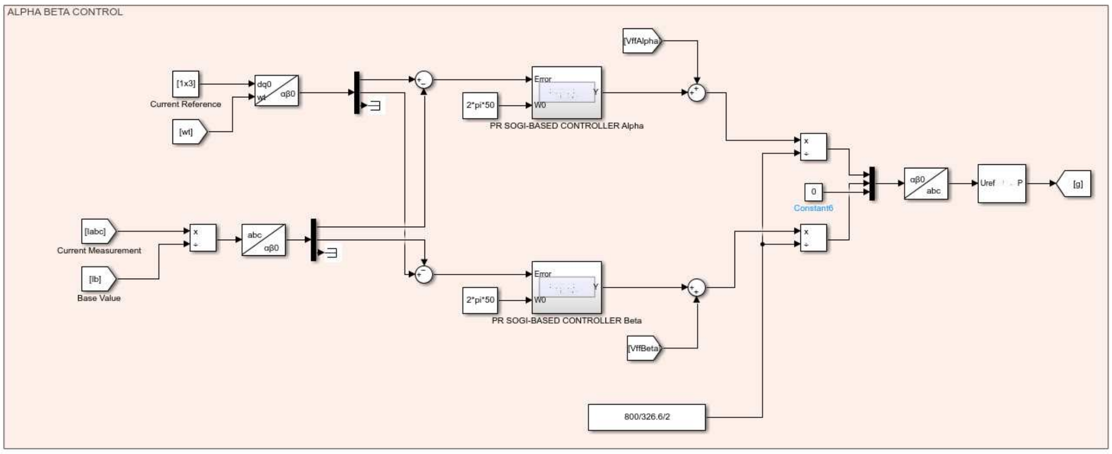

Figure 19: Inner Current Control Loop in the $\alpha\beta$ Reference Frame

In the figure above we can recognise in the upper-left corner the generation of the reference values starting from the *dq* system and in the center of the figure the two PR controller, controlling each, one of the two components in the $\alpha\beta$ reference frame.

4.2 Synchronization in an Unbalanced Working Condition

We've seen that one consequence of an unbalanced grid is to have the *dq* components that are not anymore constant(Fig. 16), so we can't use the PLL structure described in Section 3.1.3: we have to change it a little bit in order for it to deal with the sinusoidal signals.

4.2.1 PLL Variation in an Unbalanced Working Condition

There are two main solution to the problem which are kinda related one to each other:

- We could filter the *dq* measured signal with a low pass filter or a more selective filter(notch filter)
- We could "re-symmetrize" the measurement

Of course both the solution would lead to a working PLL, but the first one is perhaps more tricky and complicated than the second one since we're adding more "transfer functions" in the PLL loop so the overall tuning of the system will result more complex. The second option is what I've chosen to implement in my model since I've found it very clever and simple.

Re-symmetrization of an Unbalanced Three Phase Quantity Maybe the title of this paragraph is misleading but the overall strategy is to extract a balanced three phase quantity from an unbalanced one: the sequence theory helps us a lot in doing so!
Charles LeGeyt Fortescue is the father of this theory, which states that any set of N unbalanced phasors could be expressed as the sum of N symmetrical sets of balanced phasors; in the case of a three phase system we could extract the so called "positive","negative" and "zero" components.
So the idea behind the re-symmetrization is to take the measure, transform it in the $\alpha\beta$ reference frame and finally synchronize ourselves to the positive sequence signal, which is a signal that transformed back in the *abc* reference frame gives us a set of three balanced phasors.

Formulation for the Sequence Separation in the $\alpha\beta$ Reference Frame Starting from the *abc* system we have the following matrix that defines the positive and negative sequences:

$$a = e^{j\frac{2\pi}{3}} \tag{39}$$

$$\begin{bmatrix} v_a^p \\ v_b^p \\ v_c^p \end{bmatrix} = \begin{bmatrix} 1 & a^2 & a \\ a & 1 & a^2 \\ a^2 & a & 1 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ V_c \end{bmatrix} = T^p v_{abc} \tag{40}$$

$$\begin{bmatrix} v_a^n \\ v_b^n \\ v_c^n \end{bmatrix} = \begin{bmatrix} 1 & a & a^2 \\ a^2 & 1 & a \\ a & a^2 & 1 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = T^n v_{abc} \tag{41}$$

Since we want to work in the $\alpha\beta$ reference frame, we must introduce the corresponding matrix as seen in Eq. (2):

$$T_{\alpha\beta} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \tag{42}$$

Now to find an useful matrix relationship to shift from $\alpha\beta$ to $\alpha^p\beta^p$, we have to follow these steps:

$$v_{abc}^p = T^p v_{abc} = T^p T_{\alpha\beta}^{-1} v_{\alpha\beta}$$

$$v_{\alpha\beta}^p = T_{\alpha\beta} v_{abc}^p = T_{\alpha\beta} T^p T_{\alpha\beta}^{-1} v_{\alpha\beta}$$

$$T_{\alpha\beta}^p = T_{\alpha\beta} T^p T_{\alpha\beta}^{-1} \tag{43}$$

We could easily define also the negative sequence matrix in the same way:

$$T_{\alpha\beta}^n = T_{\alpha\beta} T^n T_{\alpha\beta}^{-1} \tag{44}$$

If we compute the two matrix we obtain the following result:

$$\begin{bmatrix} v_\alpha^p \\ v_\beta^p \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & -q \\ q & 1 \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \tag{45}$$

$$\begin{bmatrix} v_\alpha^n \\ v_\beta^n \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & q \\ -q & 1 \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \tag{46}$$

$$q = e^{-j\frac{\pi}{2}} \tag{47}$$

Leaving us with the following equations for the positive $\alpha\beta$ components:

$$v_\alpha^p = \frac{1}{2}(v_\alpha - qv_\beta) \tag{48}$$

$$v_\beta^p = \frac{1}{2}(qv_\alpha + v_\beta) \tag{49}$$

Simulink Phase Shift Implementation As seen in Eq. (48) and Eq. (49) in order to obtain the positive sequence components we have to multiply a combination of the two delayed by the term "q", the question now is: how can we achieve it?
In Section 4.1.1 I defined the SOGI a "fundamental brick" since once again "saves our day" because we can use it as "quadrature signal generator" taking the name of "SOGI-QSG":

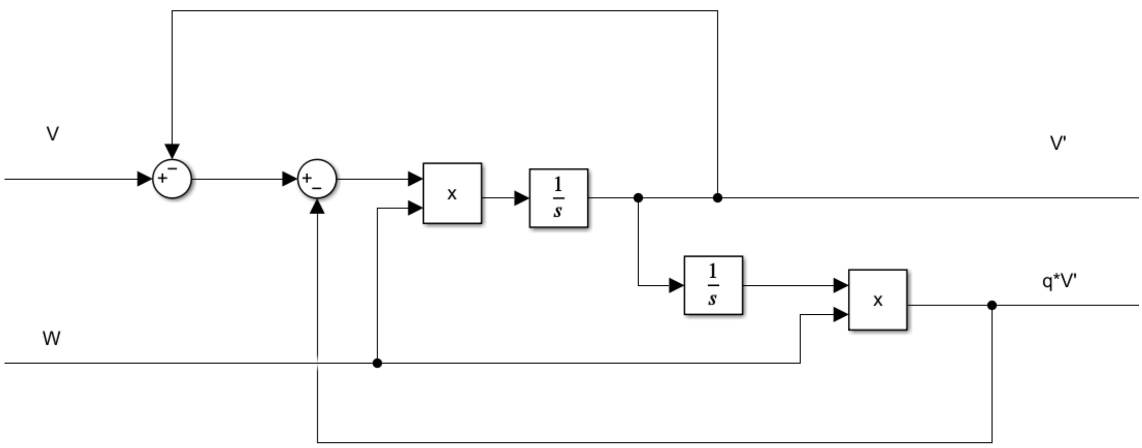

Figure 20: SOGI in the Quadrature Signal Generator Configuration

Now to obtain the two positive components we'll use basically two SOGI-QSG, one for v_α and one for v_β as depicted in Fig. 21:

In the end with this "trick", even if the voltage is unbalanced, we can exploit this DualSOGI-QSG configuration in order to extract a balanced set of voltage vectors in phase with the grid voltage; we're kinda filtering out the negative and zero component from the measurement leaving us with a signal that can be transformed again in the dq reference frame to be used as described in Section 3.1.3.

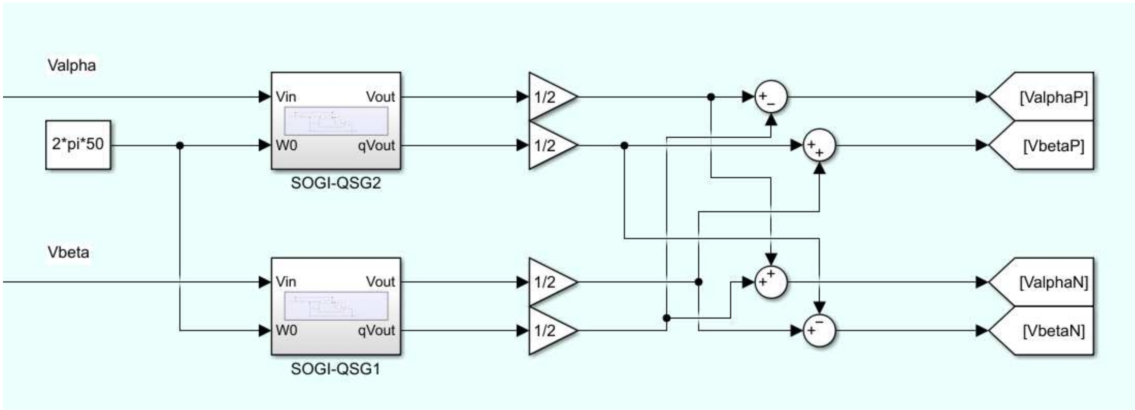

Figure 21: Dual SOGI in the Sequence Separation Configuration

5 Evaluation of control methods for rebalancing an unbalanced grid

In this section I'll explain the three main control techniques I implemented in Simulink in order to rebalance an unbalanced grid

5.1 Simulink Model

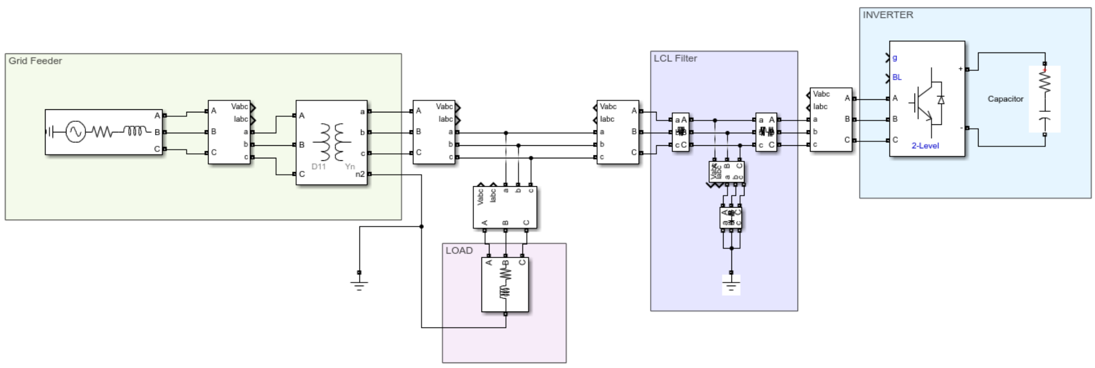

Figure 22: Simulink Model

In Fig. 22 we can see the model onto which I run the tests:

- In the green highlighted area we can see the so called "feeder" as well as the "Dyn11" transformer
- In the red highlighted area we can see the load I used to generate the unbalance

- In the cyan and violet highlighted areas we can see the inverter and the LCL filter

I've also tested the possibility to connect the inverter to the MV side via a Yy transformer: the thing turn out to be feasible and the only thing to worry about was the angles to use to transform the measurement in the dq reference frame, which were offset depending on the group of the transformer(s) and the reference value used; other than that the procedures to rebalance the grid remained the same as we were connected in the LV as depicted in Fig. 22.

Main Hypothesis The main hypothesis is to have the voltage provided by the grid to be balanced; also all the models work in the "per unit" system, so the values we'll be able to see on the graphs are related to the following base values:

- $V_b = 326.6[\text{V}]$ peak value
- $I_b = 40.82[\text{A}]$ peak value

5.2 DC Link

One of the most interesting facts I've found out while doing this thesis is that we could setup a self sustaining device that rebalance our grid: in fact, as seen in Fig. 22, in the DC side of our inverter there's only a capacitor! We could think that our device is using energy to rebalance our grid but that's not true, we can think of our device as a thing that rearranges the negative and positive sequence, a device that absorbs some type of energy and give it back to the grid "rearranged" as we like! And in order to do that we'll need a DC-link voltage control as seen in Section 3.2.2.
So in the end we don't need complex circuits/batteries in order to make our device operative, we just need a simple capacitor tuned in order to not have huge voltage oscillations while working; to choose a suitable capacitor we could use the following formula:[5]

$$C_{DC-link} = \frac{4P}{V_{DC,min}^2} t_1 \tag{50}$$

Where "P" is the rated active power of our inverter and t_1 is:

$$t_1 = \frac{1}{4f_g}$$

With f_g as the grid's rated frequency and $V_{DC,min}$ as the minimum value we could reach: usually it is set above 2 times the peak sinusoidal value.

Evaluation of Power Absorbed During operation To support the statement that as DC link device we can have a "large enough" capacitor, we could calculate the power absorbed while the inverter is working: for it to be "self sustaining" we should expect that(loss aside) the three phase power computed using the voltages of the nodes we're connected to and the currents flowing in/out the LCL filter gives a value equal to zero.

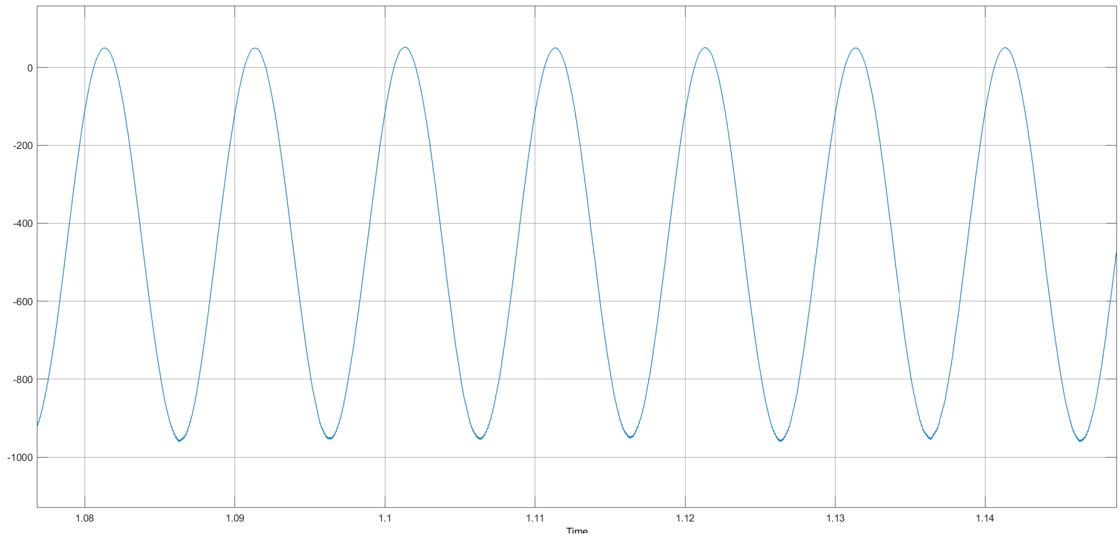

Figure 23: Phase A Instantaneous Power

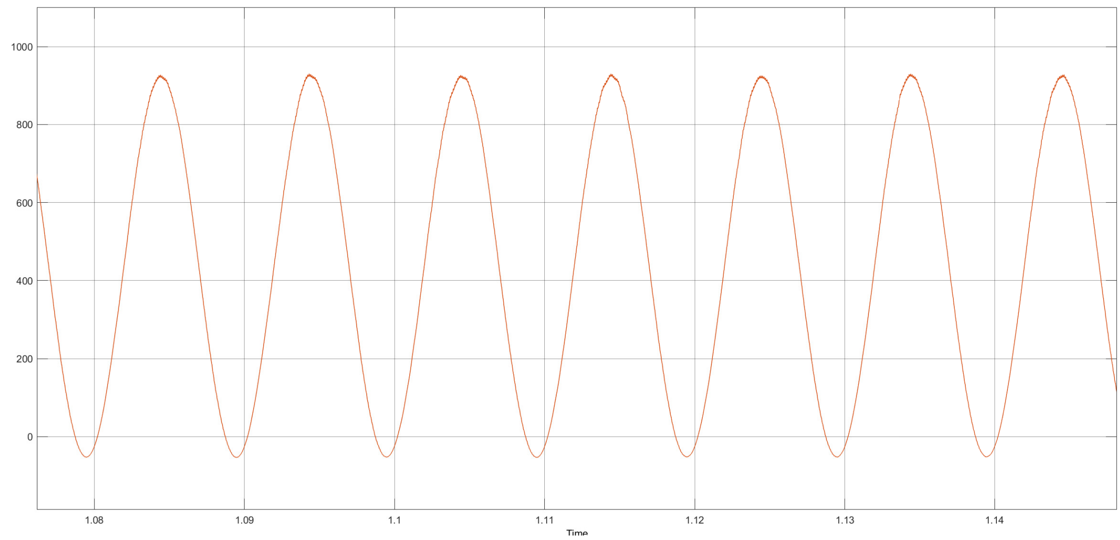

Figure 24: Phase B Instantaneous Power

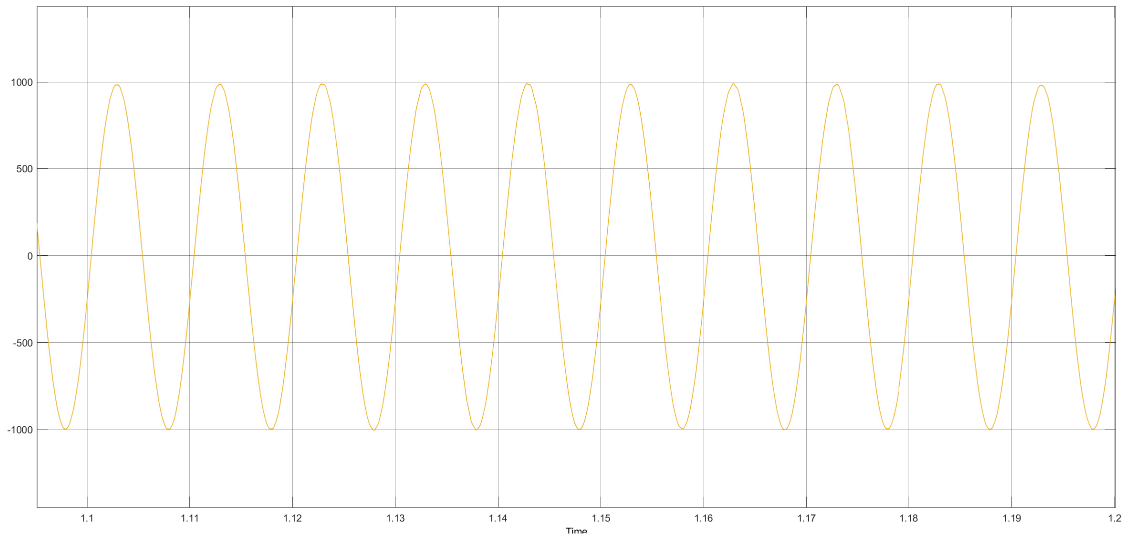

Figure 25: Phase C Instantaneous Power

By inspecting the three instantaneous power with the aid of Simulink's scope "signal statistics" I've found the following mean values for the power of the three phases:

$$\overline{P_a} = -442W$$

$$\overline{P_b} = +440W$$

$$\overline{P_c} = +3W$$

Since the sum of the three powers is almost equal to zero we can say that our device really is "self sustaining" since the only power it needs to operate will be the power lost in the filter or through the switching losses(which don't show up in the graphs since the inverter i used in the simulation is set to be ideal).
One more interesting thing to note is that our inverter is rebalancing the load by absorbing some power in one phase and injecting it into another thus confirming our theories on the principle of working as stated previously in Section 5.2.

5.3 Zero/γ Component

One thing I neglect entirely is how to cope with the zero/γ sequence. Since the work has been done with a two-level three-legged Inverter, I couldn't act on the zero sequence of the current/voltage(that's why in some cases the LV line currents won't look balanced); as I'm gonna say later, my work could be progressed by taking into account the rebalance also of the zero/γ sequence component.

5.4 Rebalance Methods

The three main method i used to rebalance the unbalanced grid are:

- Open loop fashion measuring the unbalanced load current
- Closed loop fashion using as reference signal the grid current
- Closed loop fashion using as reference signal the grid voltage

In the next subsections these three methods will be explained alongside some graphs of the tests I ran on the sample grid seen in Fig. 22.

Main Parameter of Interest You'll see that in all the three methods I' going to explain, the rebalance is done by providing a current reference to our current control loop: although we act on the currents of the grid, the parameter of major interest is going to be the MV grid voltage and we"l use that as main reference to judge if our rebalancing action has been successful together with the $\alpha\beta$ negative component of the measured quantity(current or voltage).

5.4.1 Open Loop Method

The idea behind this method is to measure a current, process it through the sequence separator block and feed it to the current control loop; the trick here is to know what to measure: we have to measure a signal that doesn't change thanks to the rebalancing effect since we're working in an open loop fashion.
So in order to accomplish this I chose to measure the unbalanced current of the load, extract the $\alpha\beta^n$ component and to feed it counterphased to the current control loop in order to balance the current coming from the feeder:

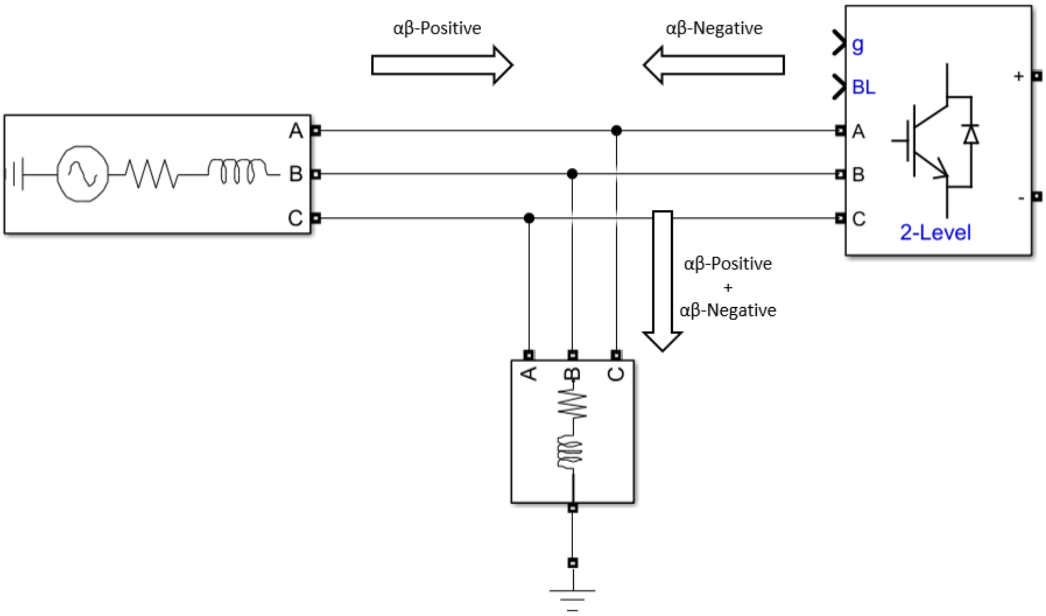

Figure 26: Simple Scheme for the Open Loop Rebalance

As seen in Fig. 26, the unbalanced load will absorb both a positive and negative set of currents: if we only had a positive sequence current requested to our source, the problem wouldn't arise but in this case all the current requested from our load must come from somewhere so in the case there's both a positive and negative sequence current that flows in the grid, the latter will be unbalanced; if we want to balance our grid we have to get rid of the negative sequence by providing it with our inverter as seen in Fig. 26; this is the idea behind this type of rebalancing method!

5.4.2 Open Loop Method Results

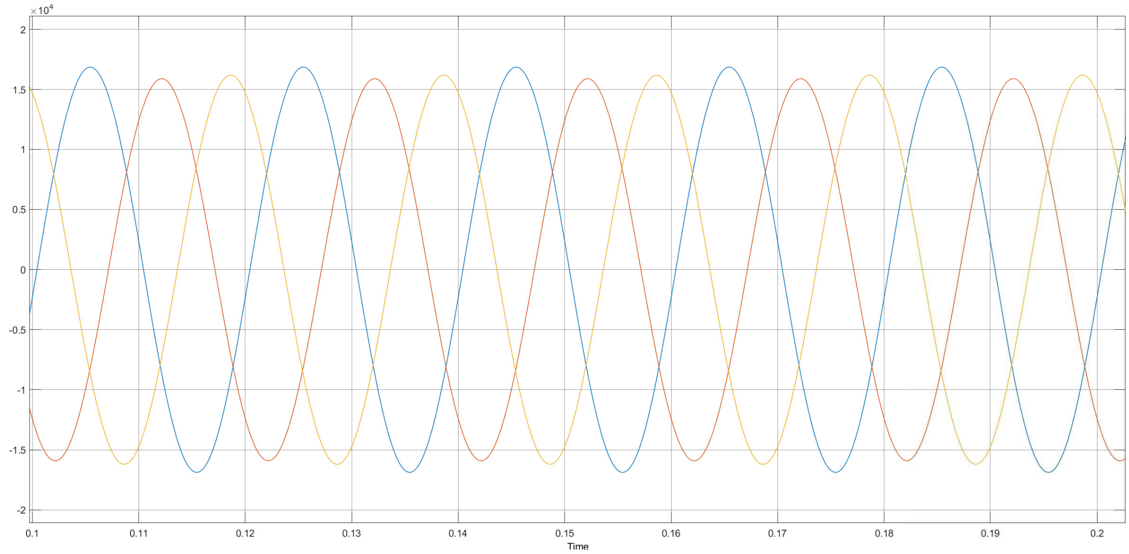

Figure 27: MV Unbalanced Voltage

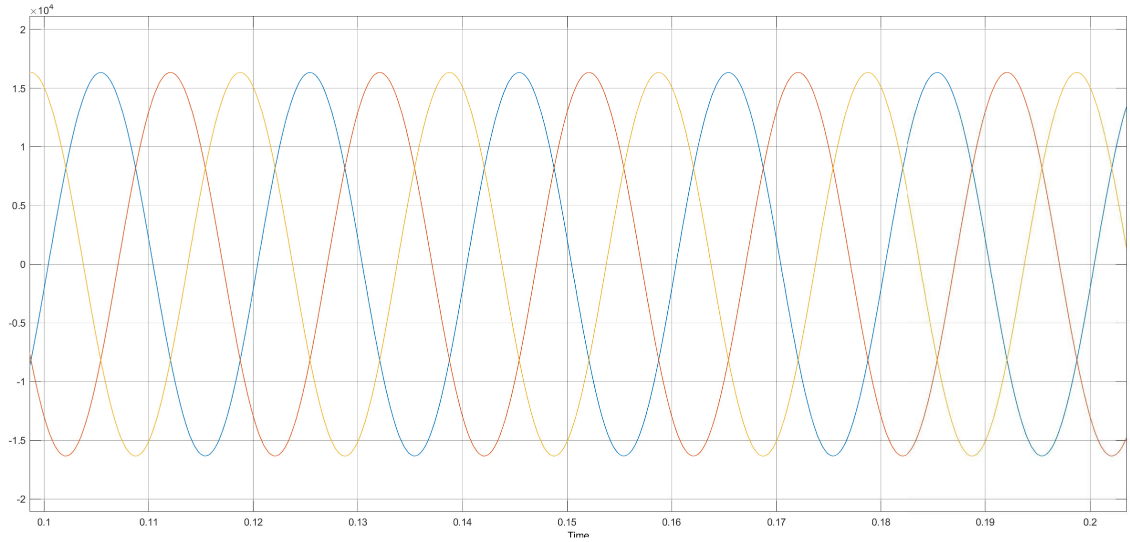

Figure 28: MV Balanced Voltage

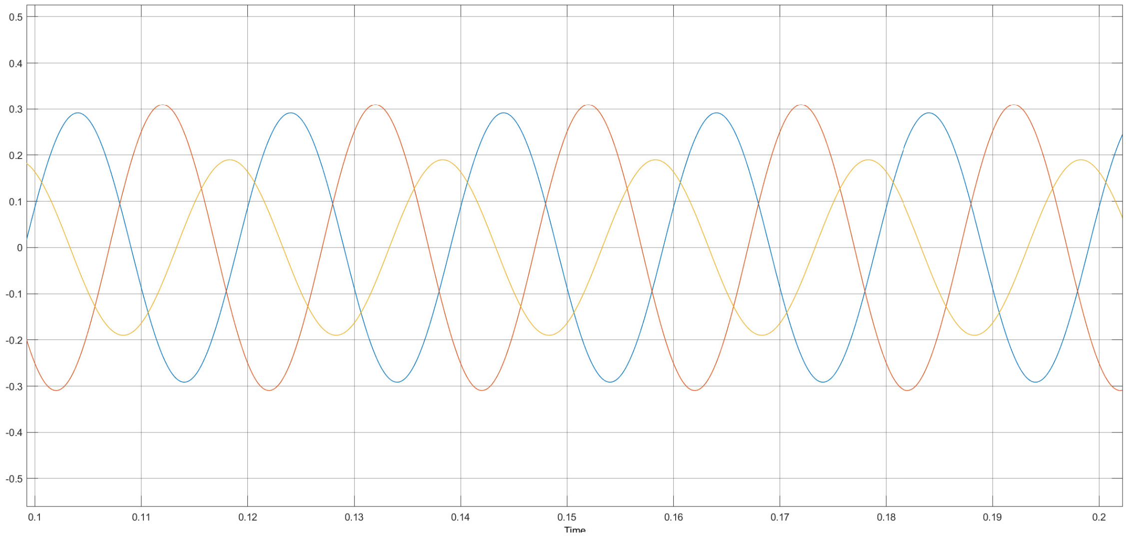

Figure 29: MV Unbalanced Current

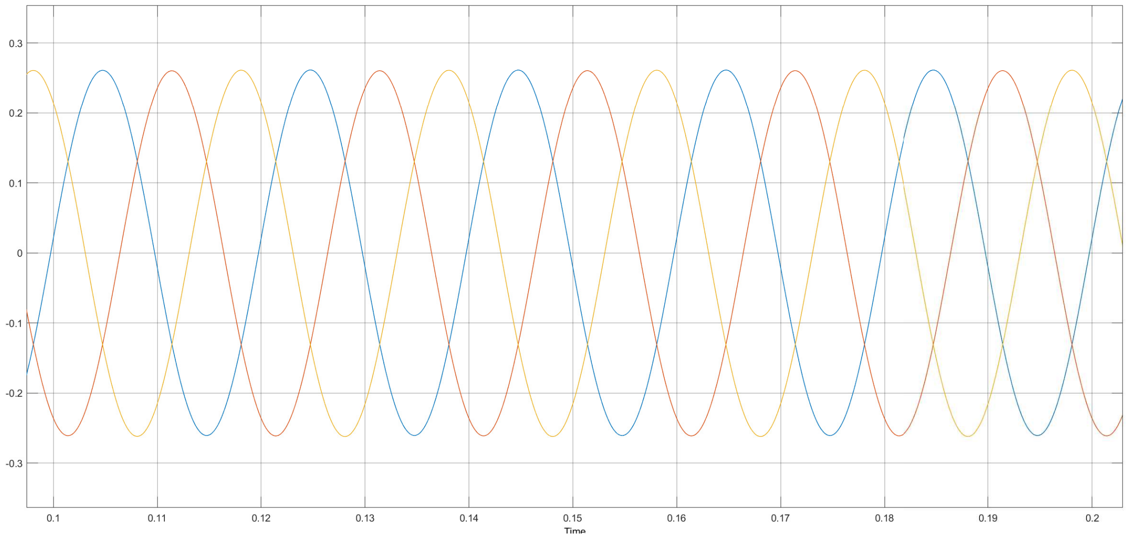

Figure 30: MV Balanced Current

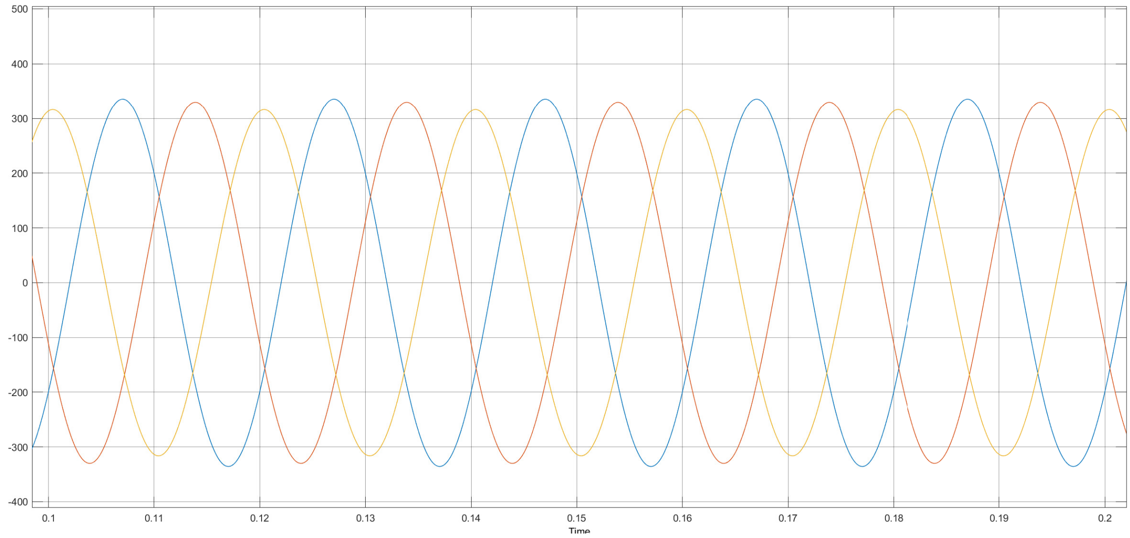

Figure 31: LV Unbalanced Voltage

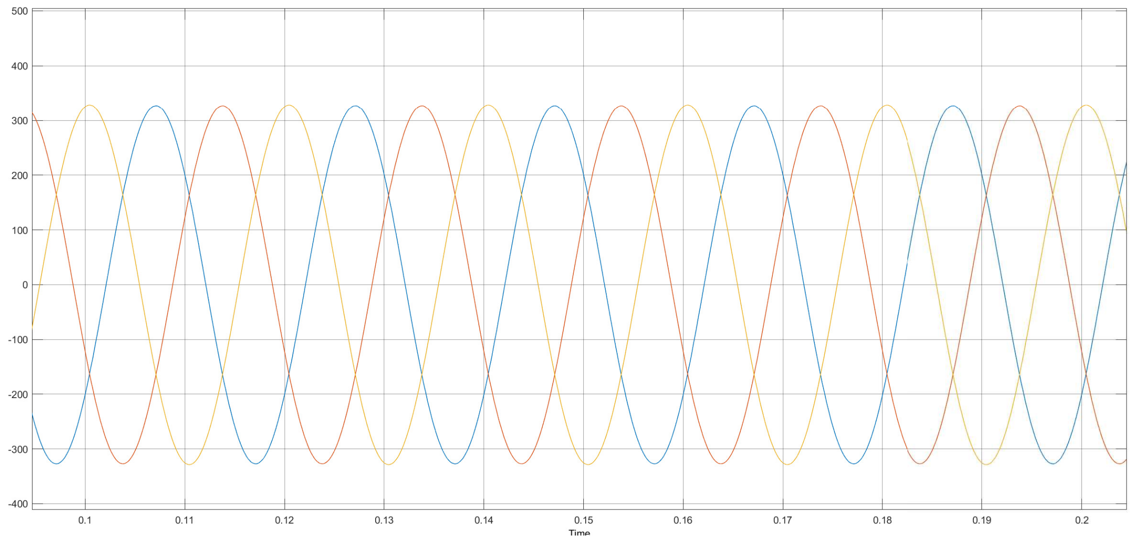

Figure 32: LV Balanced Voltage

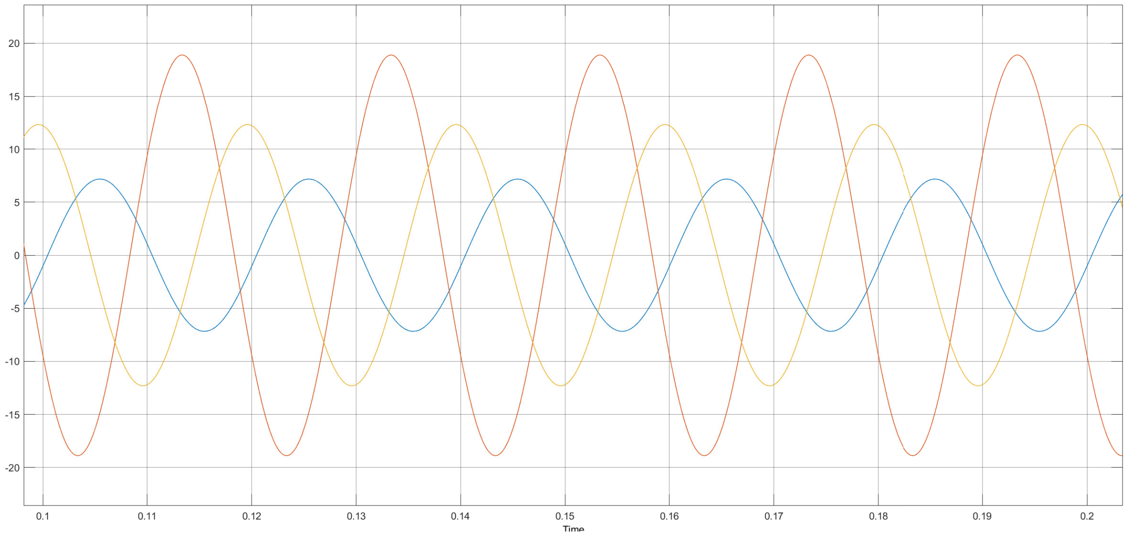

Figure 33: LV Unbalanced Current

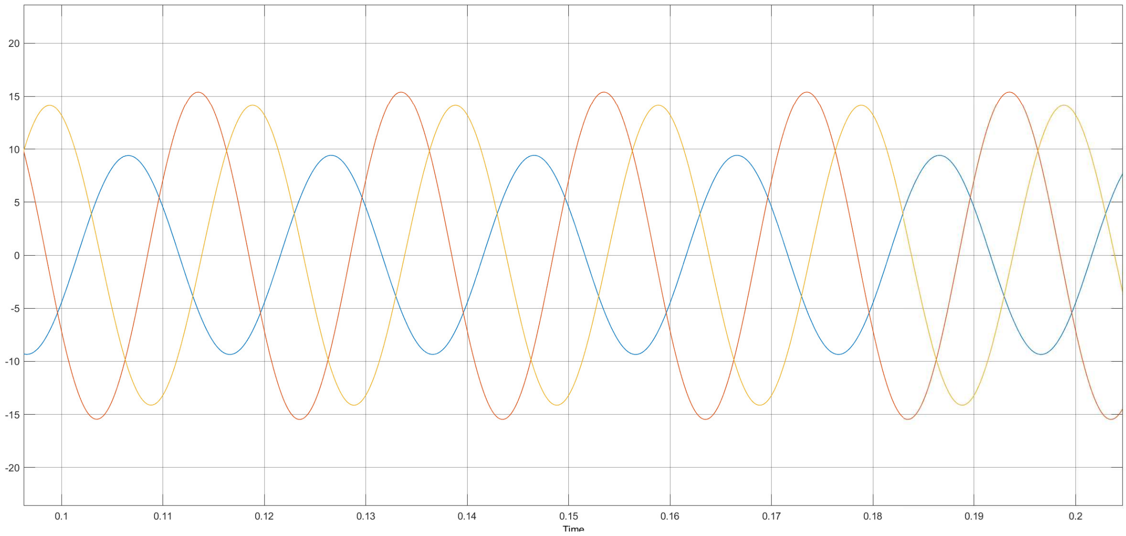

Figure 34: LV "Balanced" Current

Considerations One thing to note is that the LV line current is always unbalanced and this is due to the fact that we have a zero component and as said in Section 5.3 I'm not able to compensate the zero sequence component but we can feel satisfied just by watching the LV and MV voltages which are perfectly balanced versions of the unbalanced ones; on the other side, the MV current is well balanced since the system is connected through a Dyn11 transformer so the zero sequence component does not appear on the Δ side of it.

5.4.3 Closed Loop Method:Current Reference Version

The overall principle depicted in Fig. 26 remains almost the same; the thing that changes in this case is how we generate the current reference for the inner current loop, in fact we'll measure the grid side line current and we'll extract the negative $\alpha\beta$ sequence in order to use them to generate the error signal for a PI controller; the branch that do this can be seen in Fig. 35:

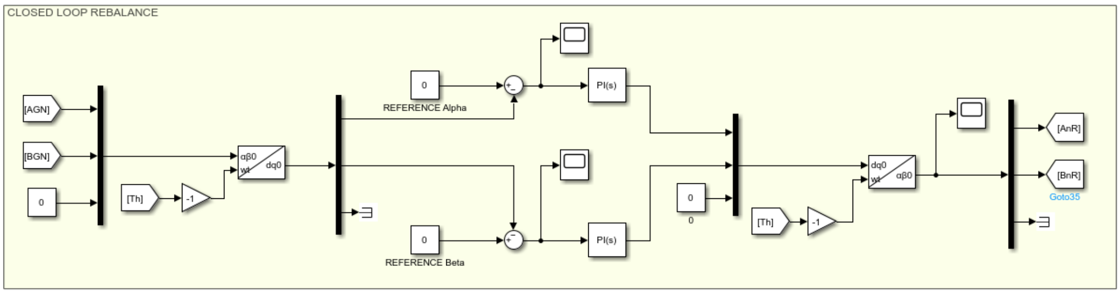

Figure 35: Closed Loop Rebalance Branch

One thing to note is that since we're transforming the negative sequence, the angle("Th" in Fig. 35) is multiplied by "-1"; the dq negative components are then used to create an error, and since we want to eliminate those components from the grid line current, the reference is set to zero as seen in the figure above.
Since the load used in the tests is the same, the balanced and unbalanced figures are the same as in Section 5.4.2; what is worth seeing, is the $\alpha\beta$ negative sequence behaviours presented in Fig. 37 and the grid voltages as usual.

PI Tuning Regarding the PI tuning for this method(as well as the next one based on the voltage measurement), I've done it simply by trial and error choosing a first "T_i" value such that the transient of the "rebalance action" would be slower than the inner current loop.

5.4.4 Closed Loop Method:Current Reference Version Results

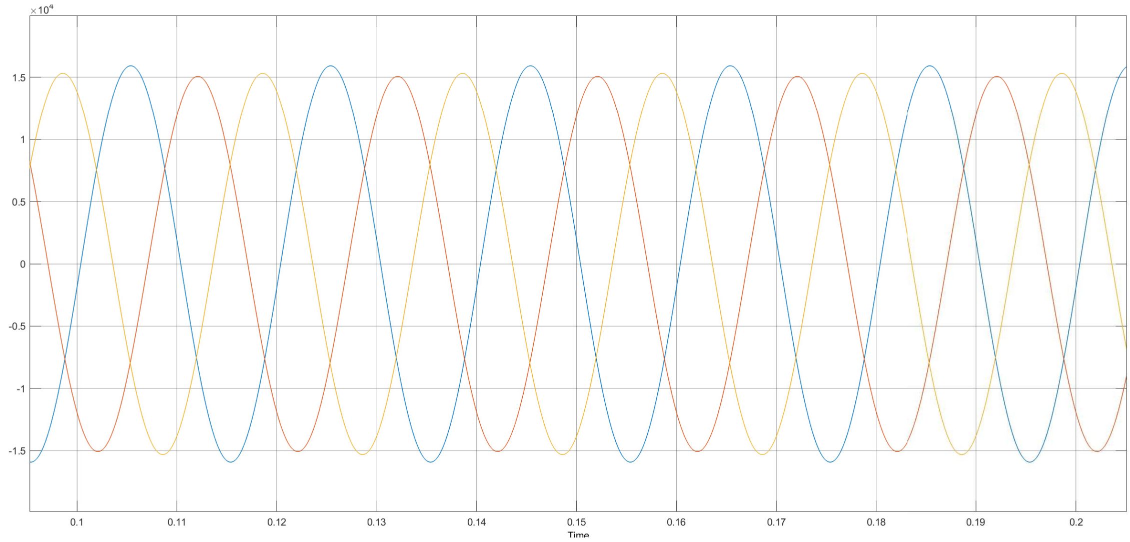

Figure 36: MV Unbalanced Voltage Closed Loop Method(Current Measure)

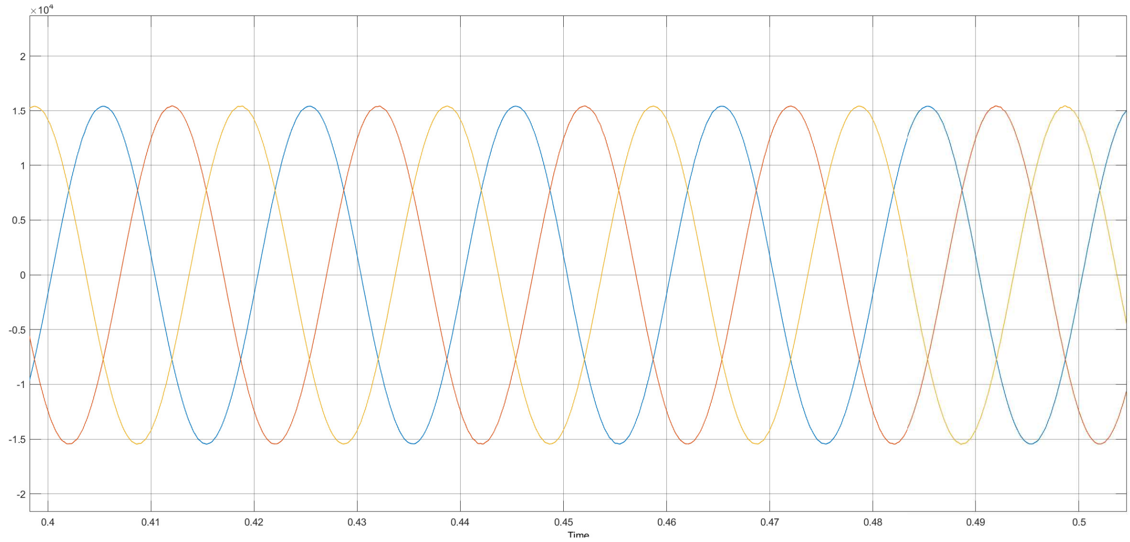

Figure 37: MV Balanced Voltage Closed Loop Method(Current Measure)

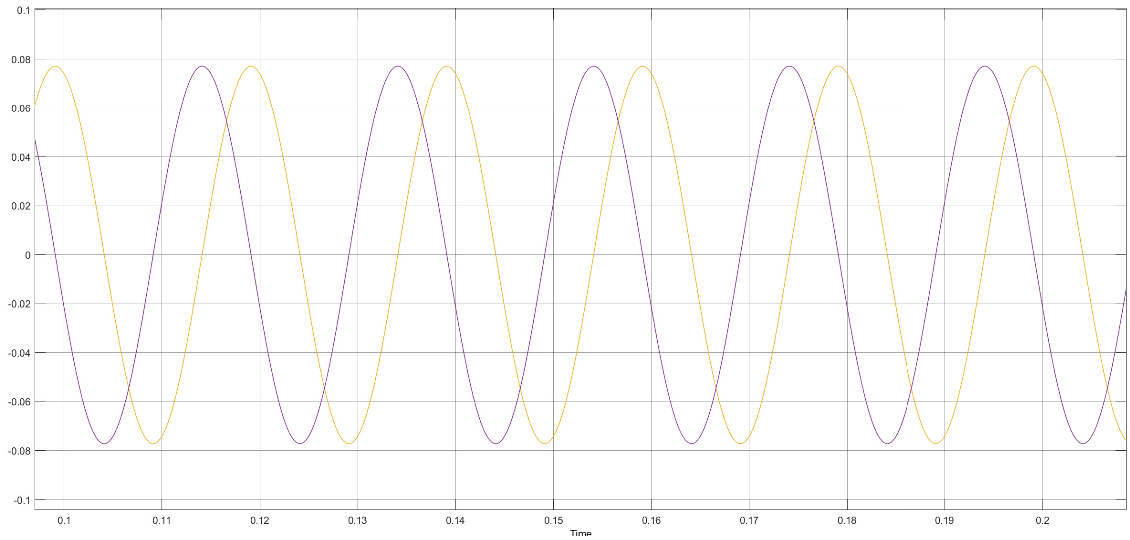

Figure 38: $\alpha\beta$ Negative Components in an Unbalanced Working Condition Closed Loop Method(Current Measure)

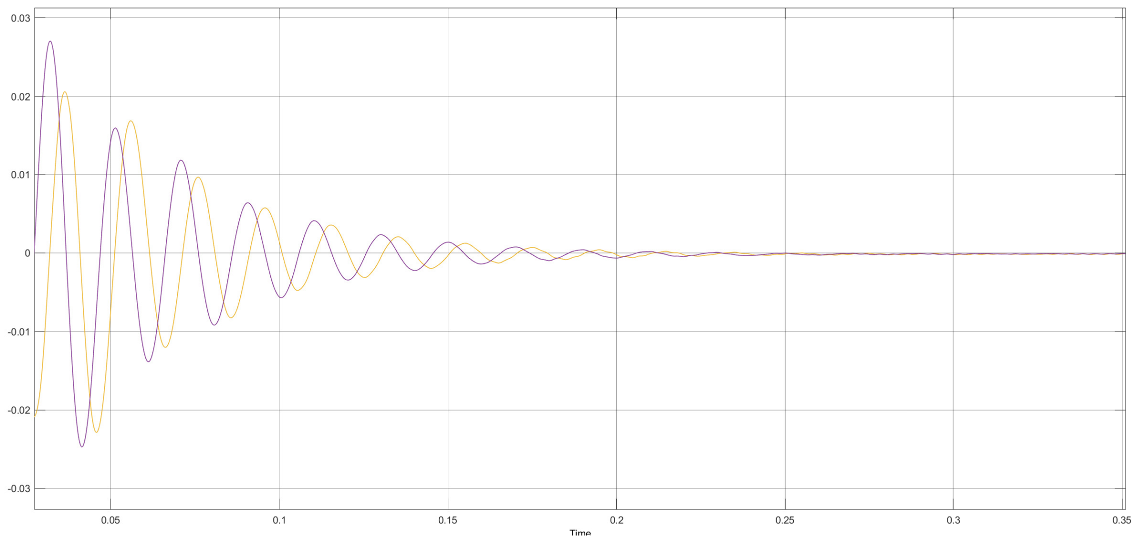

Figure 39: $\alpha\beta$ Negative Components Transient while Rebalancing Closed Loop Method(Current Measure)

Considerations We can see that the $\alpha\beta$ negative component are well managed by our control loop since in about 0.3 seconds are fully compensated. About the voltage graphs there's little to no things to say as it is rebalanced once again by our device.

5.4.5 Closed Loop Method:Voltage Reference Version

Last but not least we have the "voltage reference" version of our closed loop method; the idea behind it, remains the same(as always, refer to Fig. 26) so, after measuring the voltage we extract the negative $\alpha\beta$ sequence in order to generate the error for our PI controller(Fig. 35) the main changes here are on the values of K_p and T_i used in the PI controller. The transient in this case will be slower since we're acting on the current outputted by our device but as measured value we're using the voltage:we could expect that the impedance between the inverter and the node we choose to take as reference has to be taken in account if we want to finely tune our PIs; as said in Section 5.4.3 the PI has been tuned by trial and error starting from a T_i value such that the rebalancing action is slower than the current control.

5.4.6 Closed Loop Method:Voltage Reference Version Results

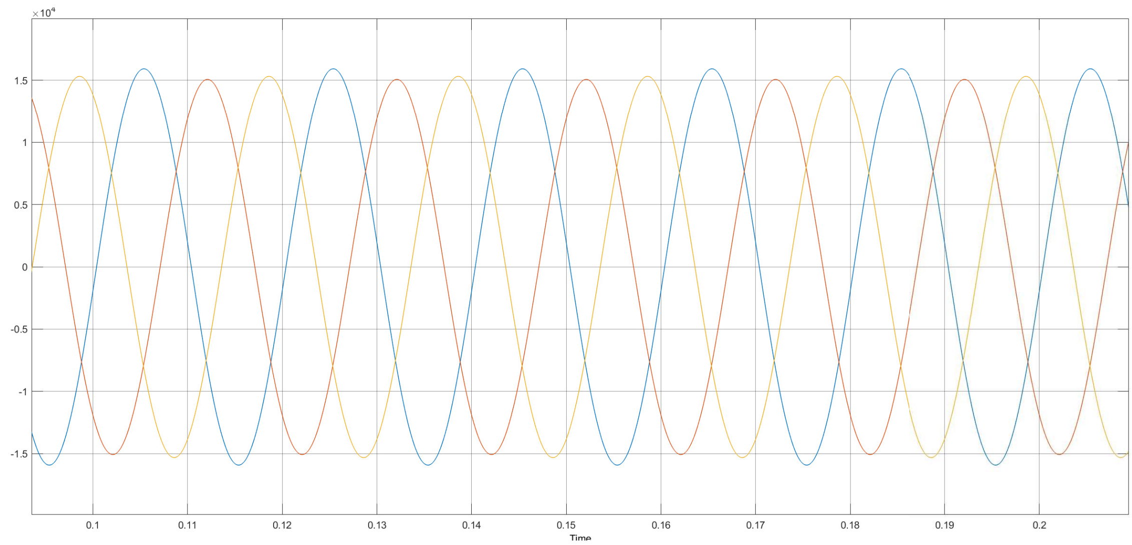

Figure 40: MV Unbalanced Voltage Closed Loop Method(Voltage Measure)

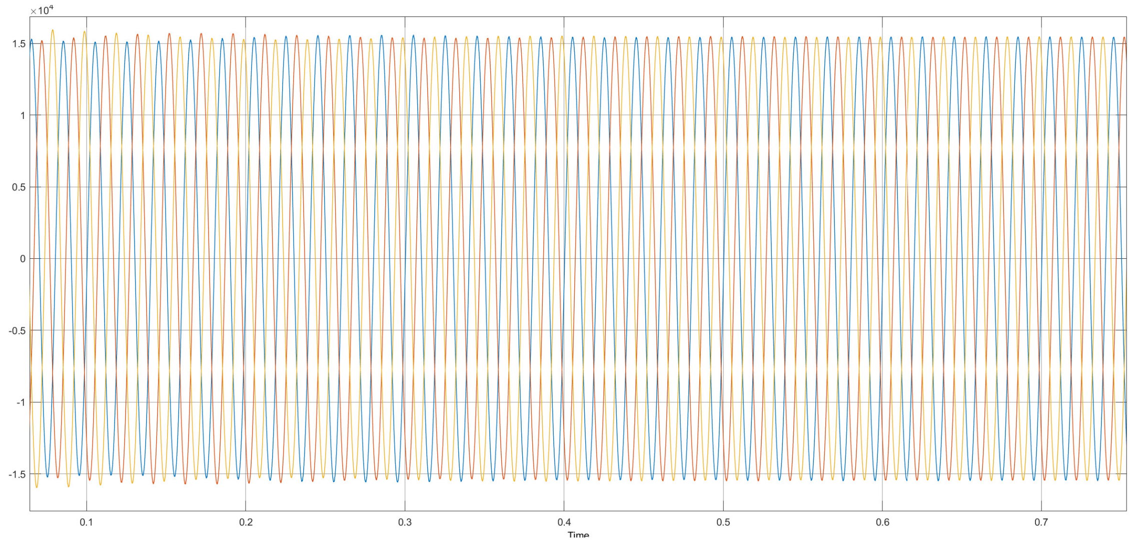

Figure 41: MV Balanced VoltageClosed Loop Method(Voltage Measure)

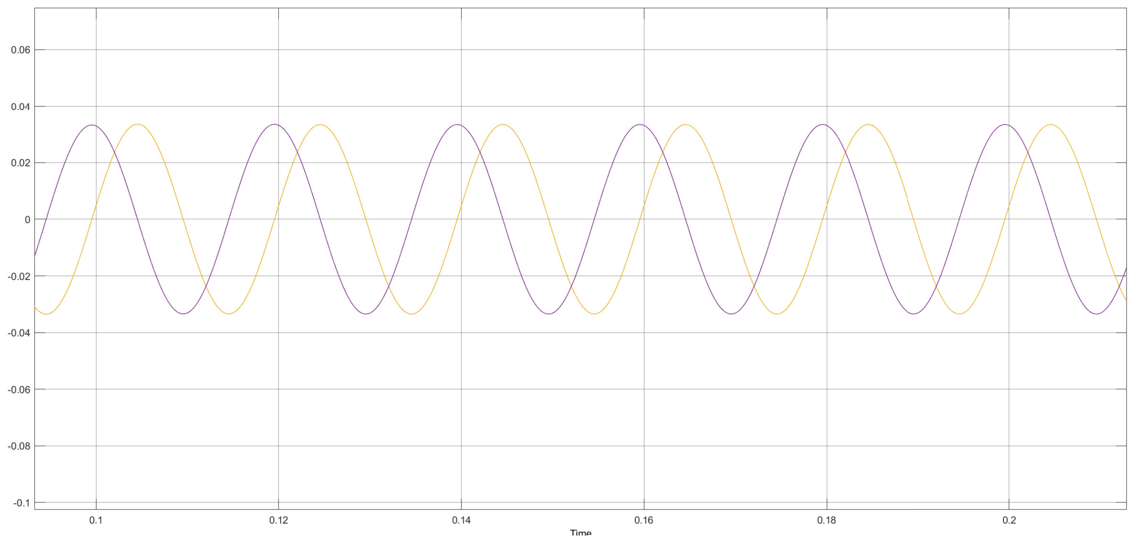

Figure 42: $\alpha\beta$ Negative Components in an Unbalanced Working Condition Closed Loop Method(Voltage Measure)

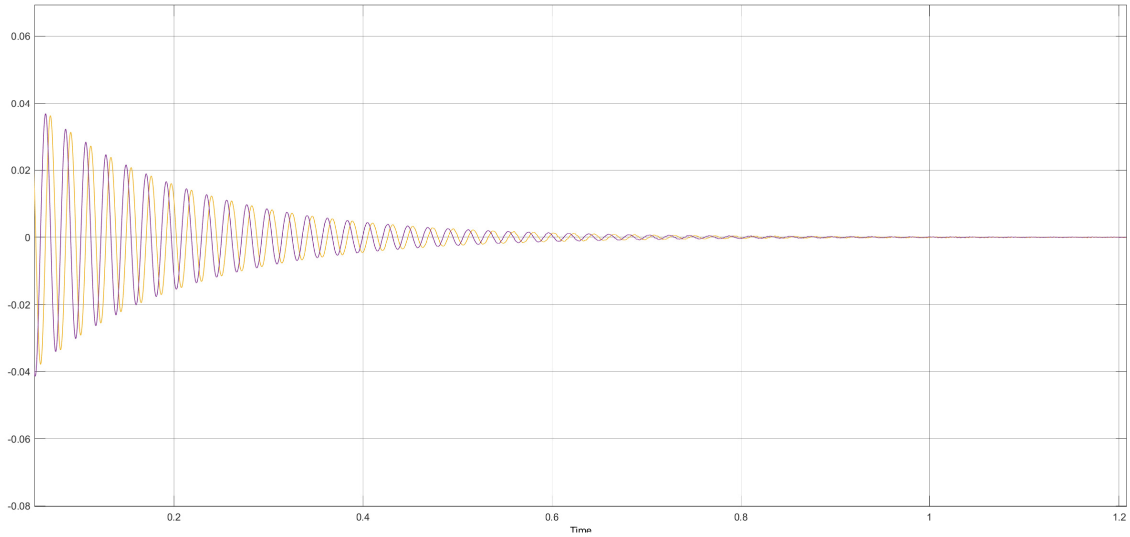

Figure 43: $\alpha\beta$ Negative Components Transient while Rebalancing Closed Loop Method(Voltage Measure)

Considerations Since the transient in Fig. 43 lasts about 0.8 seconds, in Fig. 41 can be seen the voltage that shift from unbalanced to balanced; overall I'm satisfied with the duration of transient: one could think that compared to one cycle, 1 second is a lot(50 cycles @ 50Hz), but from my point of view, the purpose of the rebalancing action is mainly to avoid having hotspots and localised overheating, effects that usually have time constants of order of magnitude that varies from minutes to hours.

6 Conclusions

6.1 Comparisons Between the Three Methods

The three methods described in Section 5 are somewhat similar but they all could have some use depending on the situation we encounter:

Open Loop Method This is the most simple of them all and also the least flexible in my opinion; by using this method we're able, by measuring the current absorbed by a three-phase load, to compensate its "bad" absorbed current; take note that we can't measure the grid's current otherwise the overall idea won't work(we need a measure that's not affected by our rebalancing action), so if some other unbalances were to be introduced somewhere else in the grid, we can't act on them.

Closed Loop Method:Current Measure With the adoption of a closed loop we gain a lot of flexibility as well as the opportunity to use as reference a signal that changes thanks to our action: the grid's current in this case; we could think this method as a way to balance a current that flows through a certain port we define: think of a device installed in the electrical substation of a large residential area that could "protect" the MV grid from the unbalances; of course we have some downsides like the introduction of a transient or, as said before the incapability to act in case some other unbalancing load were to be connected upstream to our device.
Also it is worth underlining that with the adoption of this method we're rebalancing the grid that is upstream to our device, leaving the downstream part of the grid unbalanced: this could be a problem, but if we suppose that most of the loads connected to the downstream unbalanced grid are single phase loads the problem is not relevant anymore since unbalances in the voltage affects mainly three phase loads.

Closed Loop Method:Voltage Measure This method is very similar to the second one since we're kinda measuring the level of unbalance exploiting some measurement(current previously, voltage now); in fact the working principle is very similar, but with this method is like we're balancing a given node of the grid! For me this is a very powerful thing since we could "protect" sensitive devices(just think of renewable energy plants) from the unbalanced voltage just by connecting our device to the node of interest. The downside of this method is that we don't really know what is happening in the other nodes of the grid that could be balanced or not, depending on the topology of the grid's loads.

In the end I would say that each method could be used in different situation even if they look very similar at first sight: so if a residential area is the reason behind lots of unbalances in the grid, the 2^{nd} method is suitable to get rid of the unbalances that affects the MV side the LV grid is connected to; while the 3^{rd} method I'd say it is more suitable in a situation where a three phase load is very sensitive to the unbalances of the grid's voltage so, in order to protect it, we could connect the inverter to the node the load is connected to.

6.2 Potential of this Thesis if Prosecuted

There are lots of things I didn't cover here in this thesis and I'd like to write few words about them, in the hope someone in the future wants to develop more this kind of topic:

Parameterization of the Three Methods One thing I didn't cover is how to finely tune our PIs to achieve better performance while rebalancing: in particular in the 3^{rd} method an interesting thing that could be done is to run some tests using a real grid as example to see how the connection in different nodes affects the system response. Also one thig to study more deeply could be the usage of three-phase impedances connected at the output of our device in order to ease its rebalancing action.

Effects on the Grid Regarding the 3^{rd} Method Another interesting thing to study is the effect of our rebalancing action on the other nodes of the grid while using the 3^{rd} method to rebalance a given node.

Zero Sequence Implementation Since I used three-legged inverters I couldn't be able to get rid of the zero/γ sequence and one interesting thing that could be done is to study the usage of a four-legged inverter to completely balance distribution grids. Although the problem is not that huge given the fact that usually the transformer between a MV and LV grid is a "Dyn11"(so the zero component doesn't affect the MV side) it is still an intresting topic to cover.

Usage of Already Present Devices One last interesting thing that could be studied is the possibility to balance a grid using the inverters already connected to it by making them work together in a way that the rebalancing action is split between them.

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Per Aspera Ad Astra