# Power Electronics

## Project: *DC to AC switch mode converter intended for PV applications*

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# Contents

# 1. Introduction

The project we've been requested to solve is about a grid imposed frequency inverter for photo voltaic applications which has to follow the next specifications:

- Convert a DC input voltage of 450V into an output voltage of 230V RMS (50Hz).
- Inject to the grid power in these terms: 5000W of active power and 2000VAr of reactive power.
- The control system has to work at a switching frequency of 100kHz.
- As power is injected to the grid by an inductor, its current ripple has to be at the most of 20% of the signal.

For accomplishing these design specifications the team has worked step by step:

- At first, the general scheme of a DC-AC converter was implemented, without even controlling it or making it work, just the structure.
- Next, we calculated the appropriate values for the current through the inductor to control, with a fixed current reference, the switches' signals for injecting to the grid the correct amount of power and choosing the inductor for getting a ripple of 20%.
- The control in these initial stages was made with a hysteresis comparator, for making it easier and discarding possible sources of errors.
- Once the fixed reference current control worked properly, its design was changed, adding the adequate measurements for closing the loop.
- Then, the system was ready to perform a closed power loop control, consisting in two PI controllers which had to maintain the proper values of active and reactive power, even if disturbances occurred, the system should be able to reject them.
- Finally, once failures were discarded to happen because of the comparator, we changed the ideal hysteresis comparator for the pulse width modulator (PWM), working at a finite frequency value of 100kHz.
- At this point everything worked properly and tasks for improving control were done.

These steps are totally detailed in next parts of this document.

In personal terms, for the team it has been difficult in some aspects to carry out with the project because it was about a subject and an environment of work (Simulink) not very well known.

For the group it has been a very interesting way of learning power electronics concepts and usages, because you have to deal with real problems and think about solving them by yourself.

Moreover both members of the group have improved their skills of technical English.

## 2. Design of the inverter and how it works

The design of the whole inverter consists in two parts: the power elements and the control elements.

The power elements deal with the function of converting power and the control ones have to generate the control signals depending on the power variables.

### 2.1 Power elements

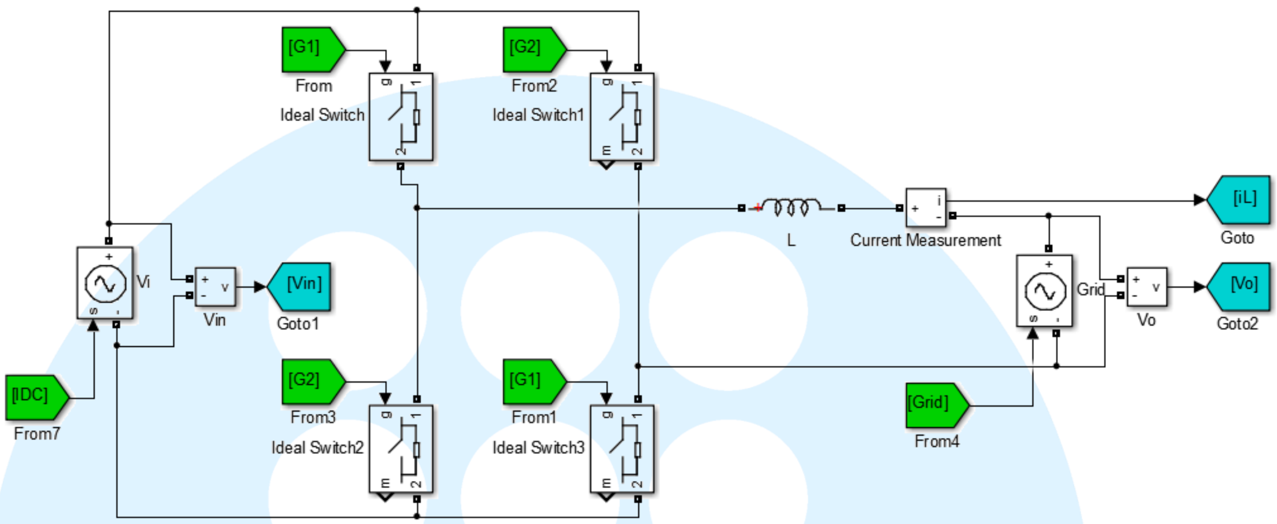


*Figure 1: Power elements of the inverter*

In the power elements can be differentiated several parts. In the input of the system there is an ideal DC source *"Vi"* which represents the PV panels. There are two half-bridge branches consisting in two ideal switches each one which have to convert the DC signal into an AC one in function of the control signals that are received from the control subsystem. At the output of the bridge, there is an inductor *"L"* which injects power to the grid, which is the element at the output of the inverter *"Grid"*.

In this system can also be seen some parts that are necessary for the control subsystem to perform its work, such as voltage and current measurements, and signals that come and go from the control subsystem.

The values of the different elements are:

Vi= 450V DC

Grid=230Vrms, 50Hz, phase of 0º [1]

L=1mH

The inductor value is appropriated for getting an inductor current ripple of 20%. [2]

[1] Take in account the value of the phase, it will become very important when talking about the control subsystem

[2]Justifications of the values are on next chapters of this document.

Depending on the signals of the control subsystem, switches close and open by pairs to generate an AC signal that accomplishes the needs of power by changing the current that flows through the inductor. Needs of power depend on the current state of the voltage of the grid, so that if the grid suffers any change, the control subsystem reacts and changes the signals of the switches in order to obtain the necessary value of the inductor current.[3]

[3] Signals and behavior of the system will be shown on next parts of the document *(2.3 System behavior)*

## 2.2 Control subsystem parts

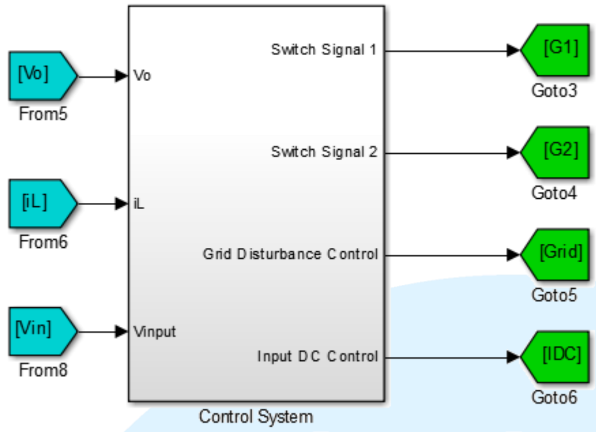


*Figure 2: Outward appearance of the control subsystem*

As can be seen in *figure 2*, the control system receives three signals from the power elements of the circuit which are the output voltage (*Vo*), the input DC voltage (*Vin*), and the inductor current (*iL*). The response of the control are *G1* and *G2*, which are the signals that control the switches, and depend on the values of *iL* and *Vo*. It can also be seen that there are another two output signals (*Grid*) and (*IDC*) that control the disturbances and the values of the voltage in the input and the output of the inverter.

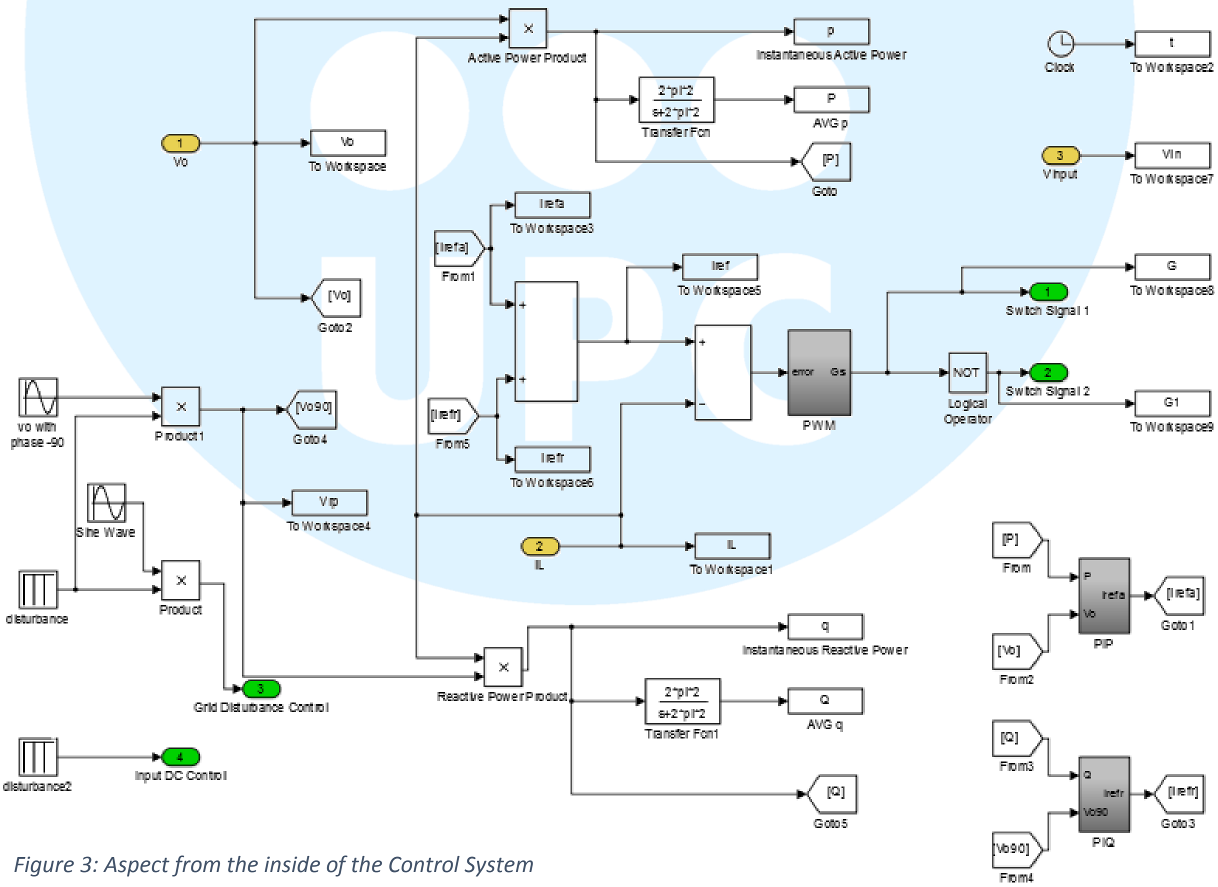


*Figure 3: Aspect from the inside of the Control System*

The aspect of the elements inside the control system can be seen on figure 3. The parts that can be seen inside the control system are:

The main structure, which is the one from the left side. It consists in various blocks that:

- Generate a reference voltage for reactive power.
- Calculate reactive and active instant power, and later both are filtered to obtain its average values.
- A sum that adds the two control signals for active and reactive power that come from two PI controllers: *PIP* and *PIQ (in gray, at the right bottom corner of the picture)*
- A comparator which generates the error between the real inductor current and the desired one in order to reach the amount of active and reactive power in the conditions of the circuit.
- Depending on this error, a pulse width modulator (*PWM*, *in gray at the centre of the figure*) generates the appropriate control signals for the switches in order to get the circuit working as expected.

The PI controllers receive the current values of *p* and *q* and of*Vo*and *Vo90 respectively* in order to generate the reference current values (active and reactive) needed.

There are other blocks which function is to generate disturbances at the input and the output of the inverter.[4]

[4] Reasons and mathematical justifications of the design are explained with detail in the next chapter *(3. Steps for designing the whole system)*

## 2.3 Behaviour of the system

At this chapter it will be shown with detail the behaviour of the system and its signals (power and control signals) without disturbances and introducing them.

### 2.3.1 Behaviour without disturbances

#### *2.3.1.1 Power signals*

The next figure it can be seen the input voltage of the inverter: 450V DC. This voltage come from a photovoltaic system.

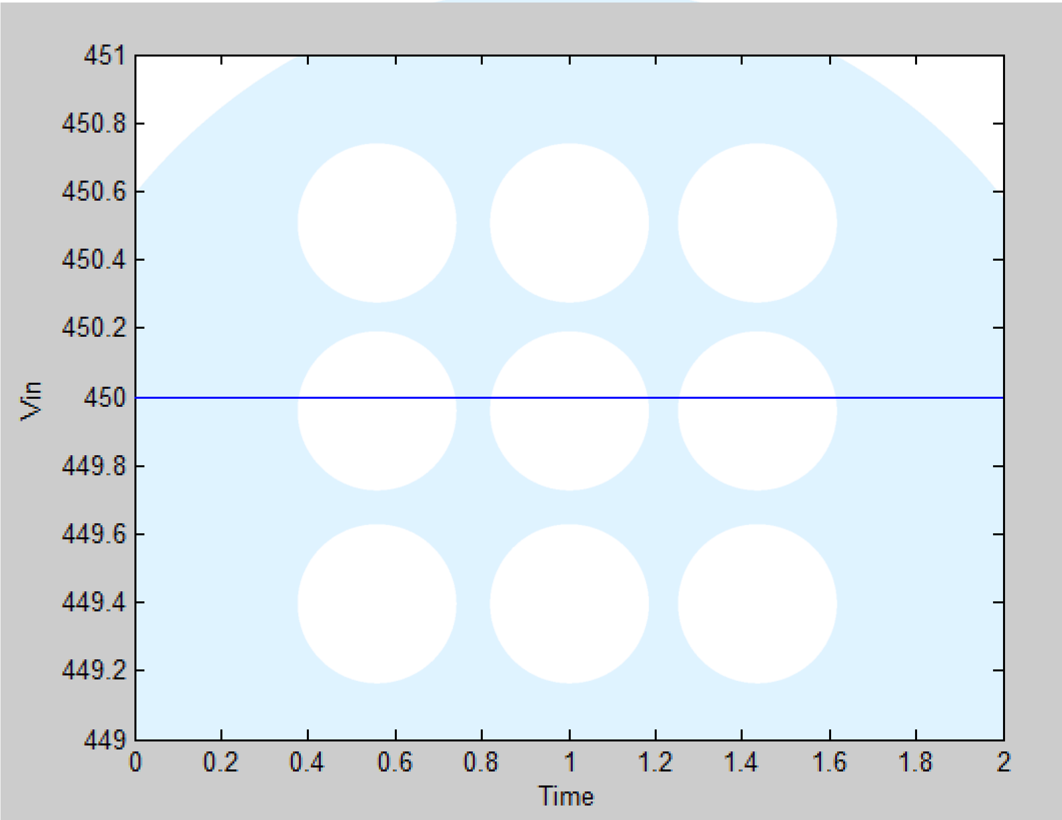


*Figure 4: Input voltage of the inverter(Vin)*

The next figure is about the output voltage of the system is imposed in terms of value and frequency by the grid, that voltage is 230V RMS AC (325V peak), the frequency imposed is the European frequency,50Hz.

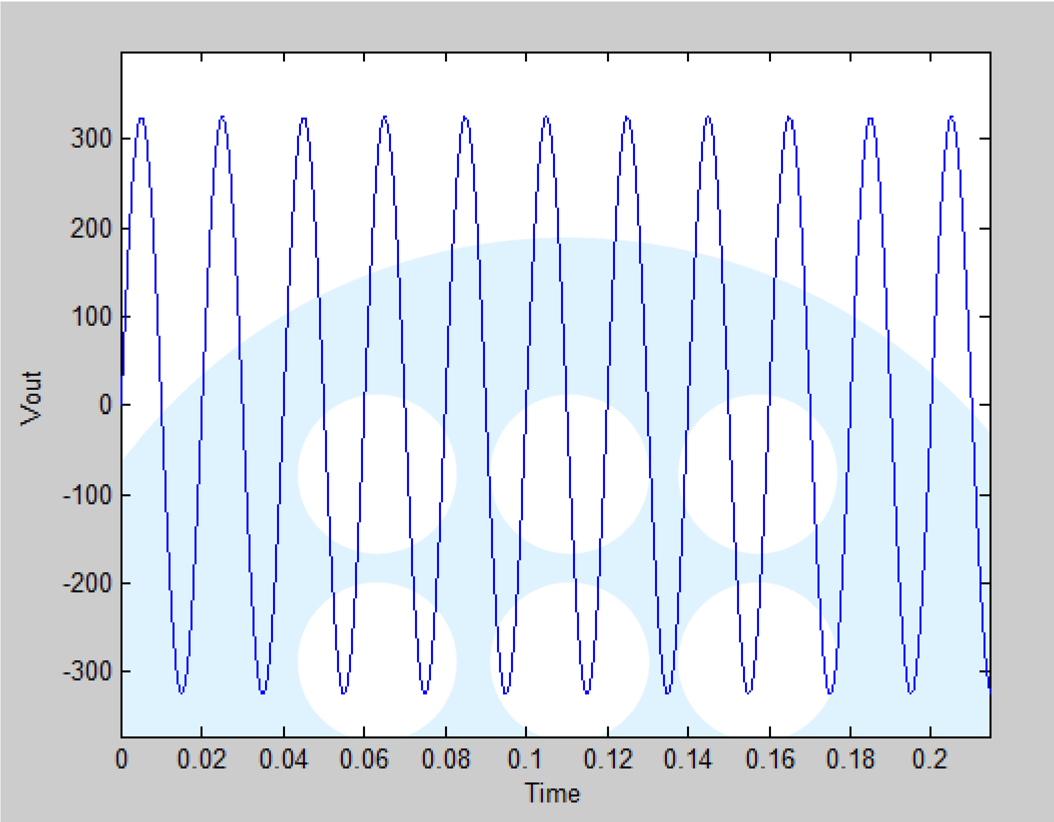


*Figure 5: Grid Voltage (Vout)*

The main specification of the circuit is injecting active and reactive power to the grid that is connected at the output of the inverter. The amount of power necessary to inject is in average value terms of 5000W of active power and 2000VAr of reactive power.

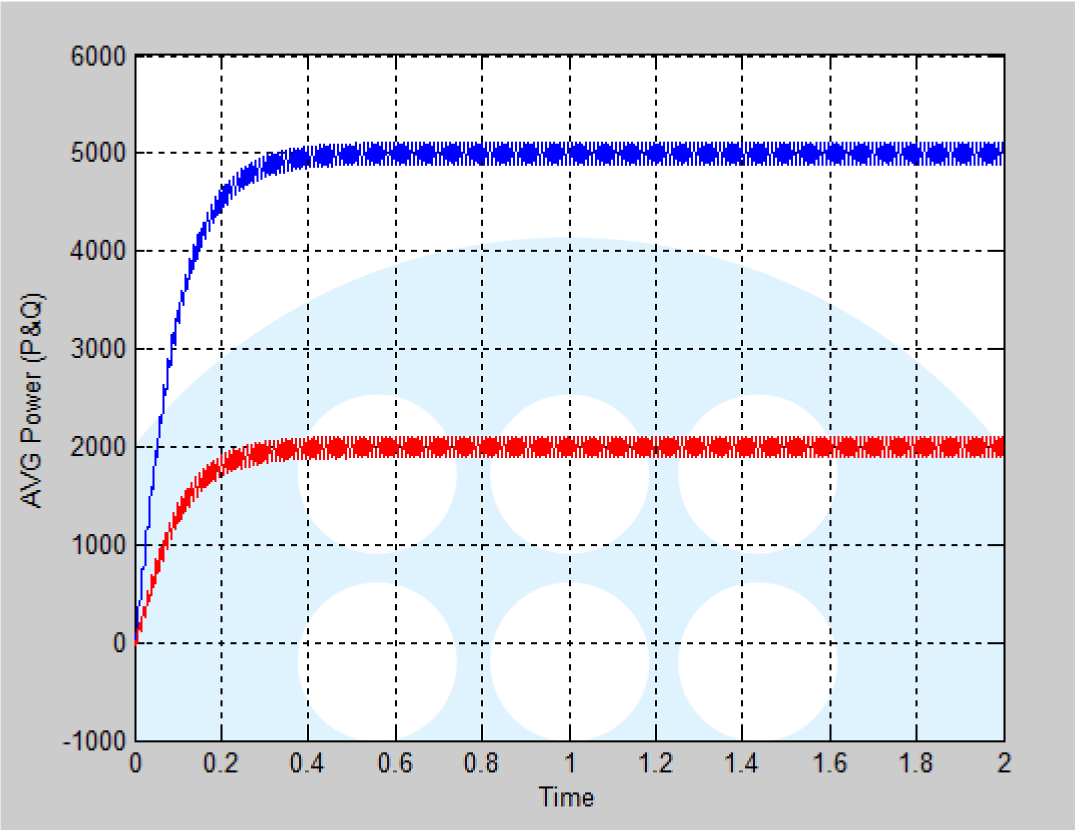


*Figure 6: Active (BLUE) and reactive (RED) output power*

The way to get this values of power is by controlling the current that flows through the inductor (L). By combining the output voltage and the inductor current correctly it is possible to regulate both powers. In this conditions, the inductor current necessary is the one that can be seen in the next figure:

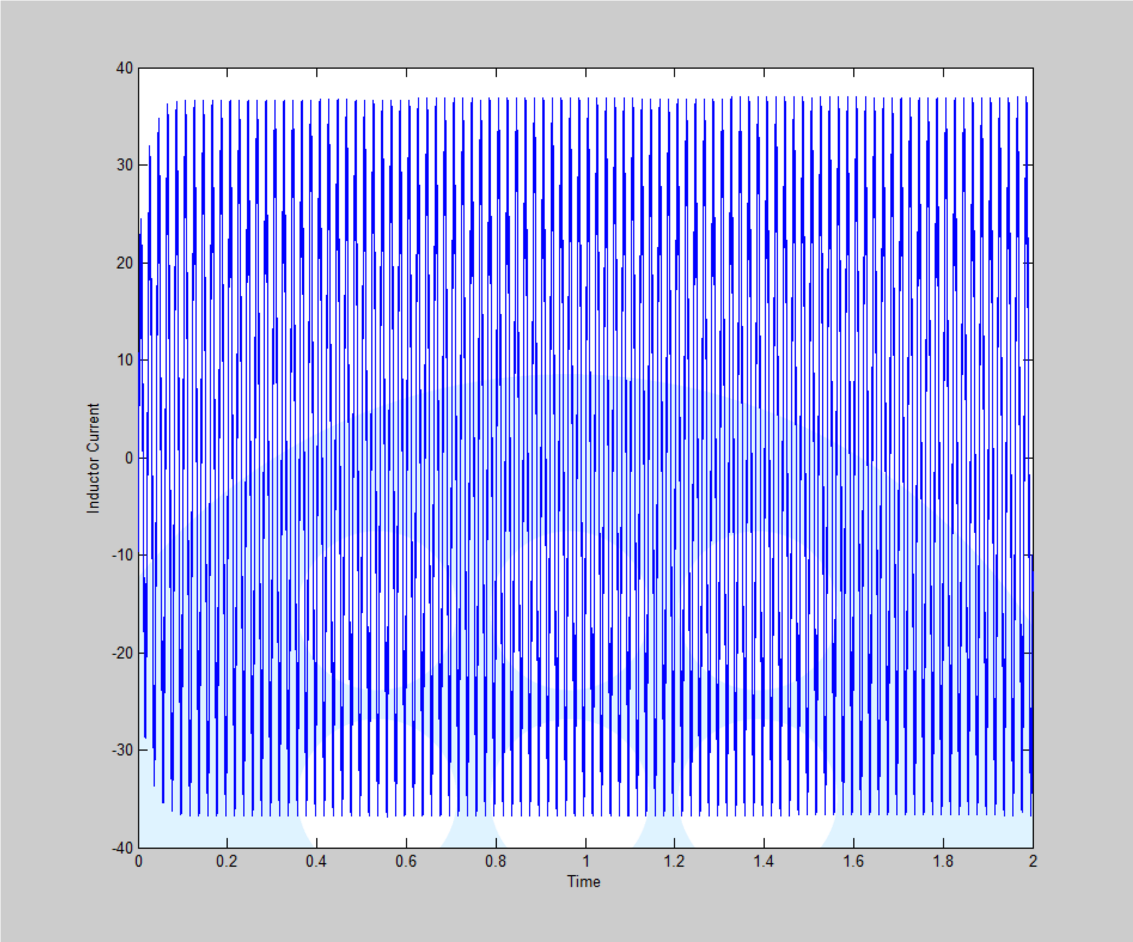


*Figure 7: Inductor Current*

#### 2.3.3.2 Control signals

In the next figure it can be seen the two reference voltages that are needed in order to generate the active and reactive power by multiplying it with the inductor current.[5]

[5]The explanation of the reason for the 90 degree delay is in the chapter*(3. Steps for designing the whole system)*

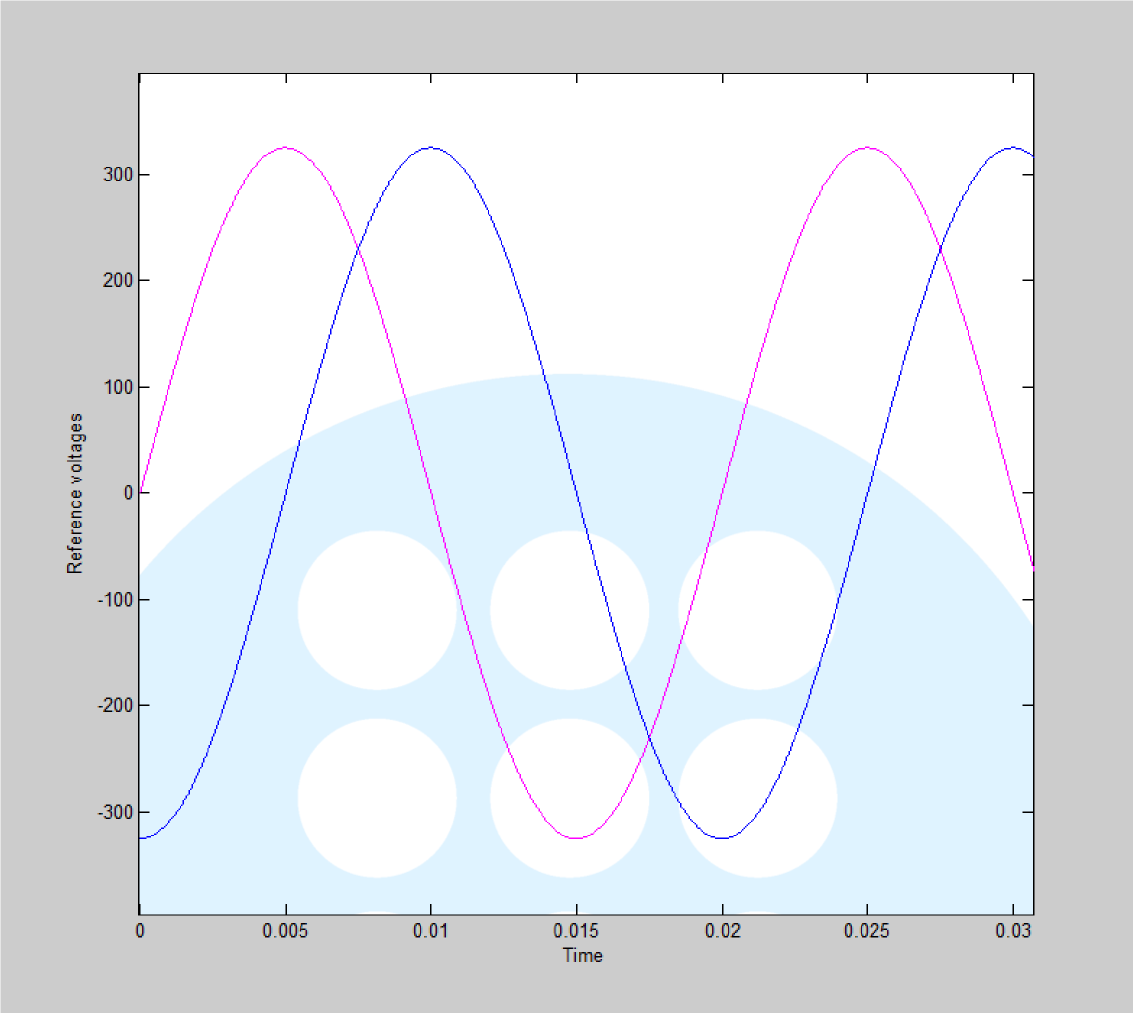


*Figure 8: Reference Voltages: Vout(Magenta); Vout with 90Deg. phase (Blue).*

In the next figure it can be seen the two reference currents generated by the PI controller in order to combine each other for obtaining the error by taking off the actual inductor current (iL). Once this has been done the result is the error that can be introduced to the comparator to generate the switching signals for the switches.

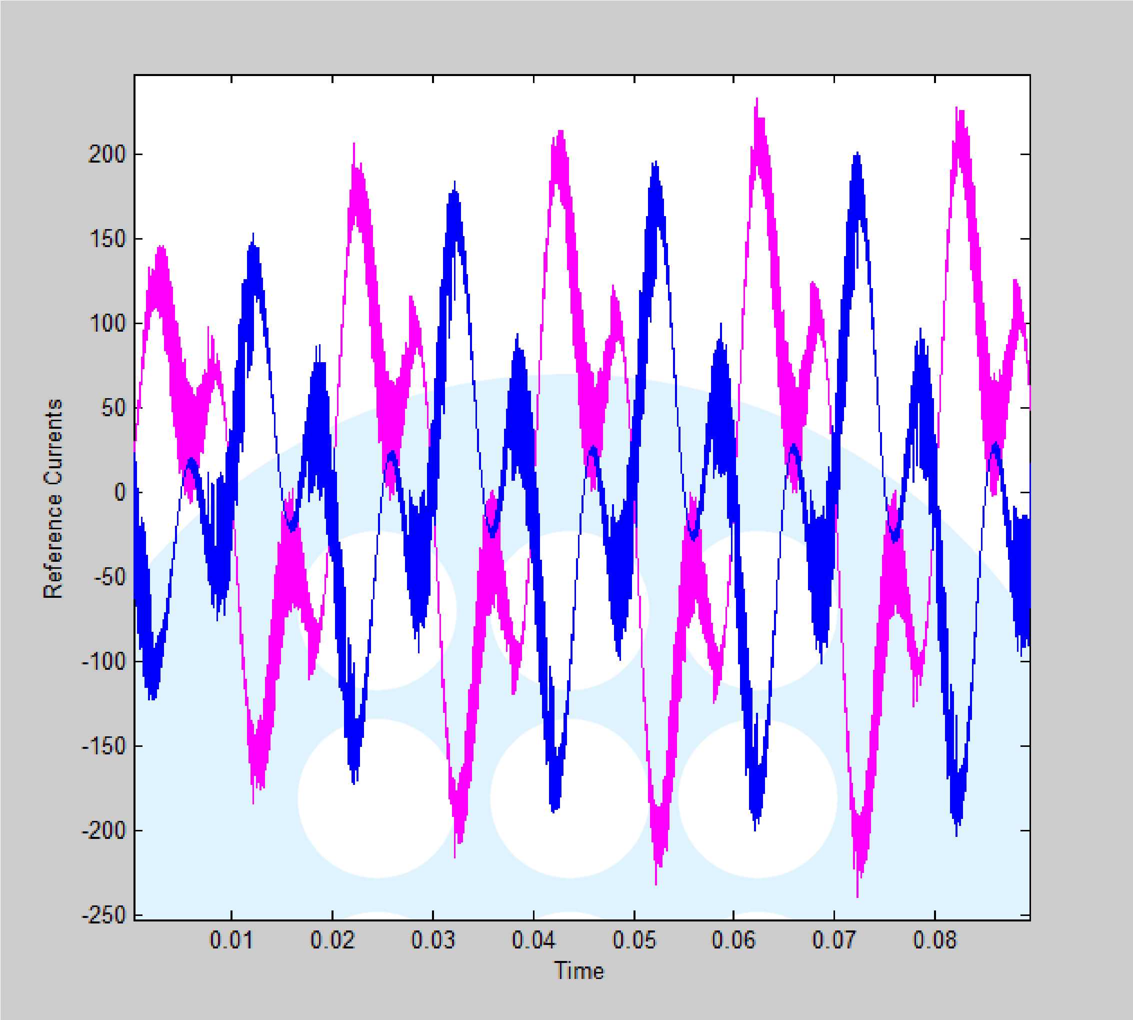


*Figure 9: Reference currents: I active (Magenta);I reactive (Blue).*

It can be seen in the next figure the switches signals, these signals come out from the comparator when it processes the error between the combination of the two reference current and the current of the inductor, and are the ones that control the open and close time for the switches.

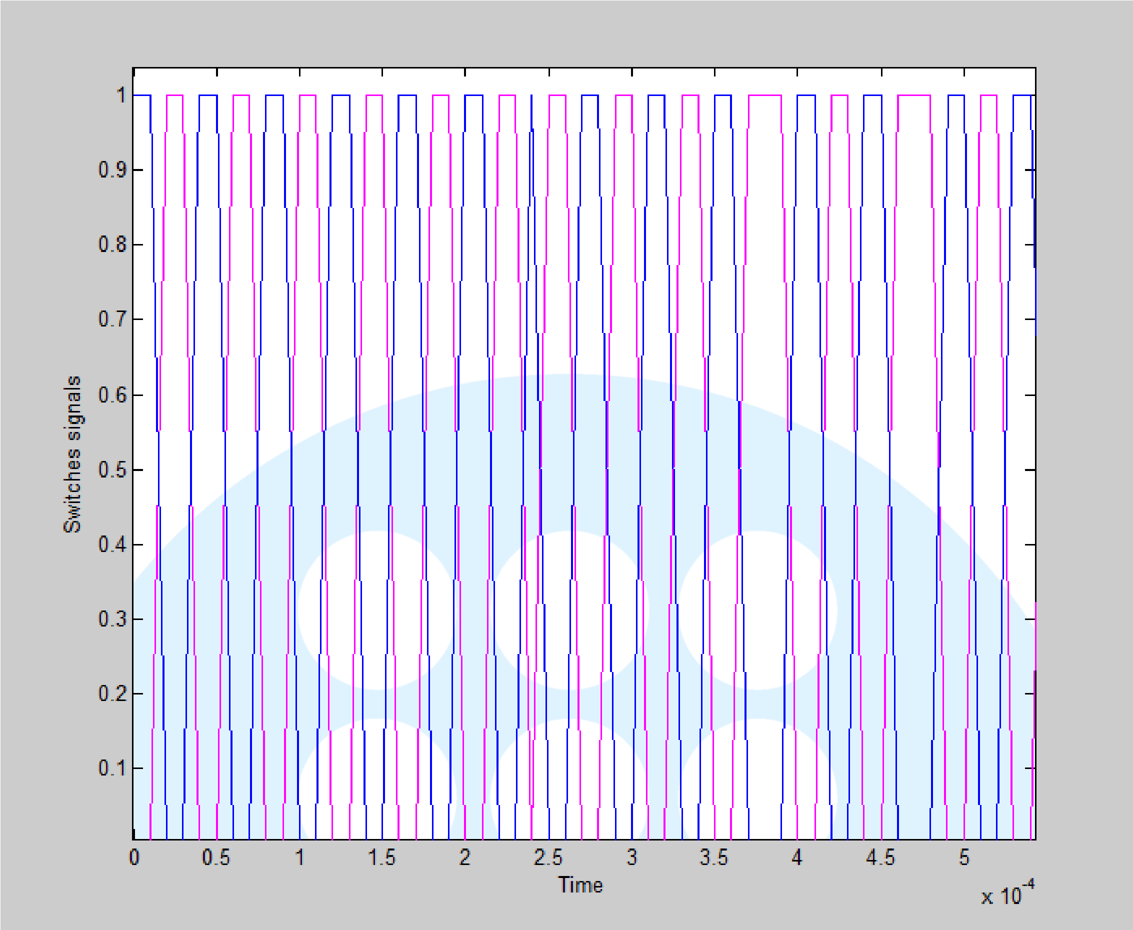


*Figure 10: Signals for the switches*

## 2.3.2 Behaviour with disturbances

### *2.3.2.1 Power signals*

The next figure it can be seen the input voltage of the inverter: 450V DC. This voltage come from a photovoltaic system. Now, it's not constant because of a disturbance introduced at 0.6 seconds for testing the response of the circuit to disturbances in the input. In real life the reason for this disturbance could be a cloud passing over the solar panel. The disturbance finishes at 1 second.

It's a 30% disturbance in order to see some effect at the output power. (A 20% disturbance didn't make the difference comparing to nominal steady state).

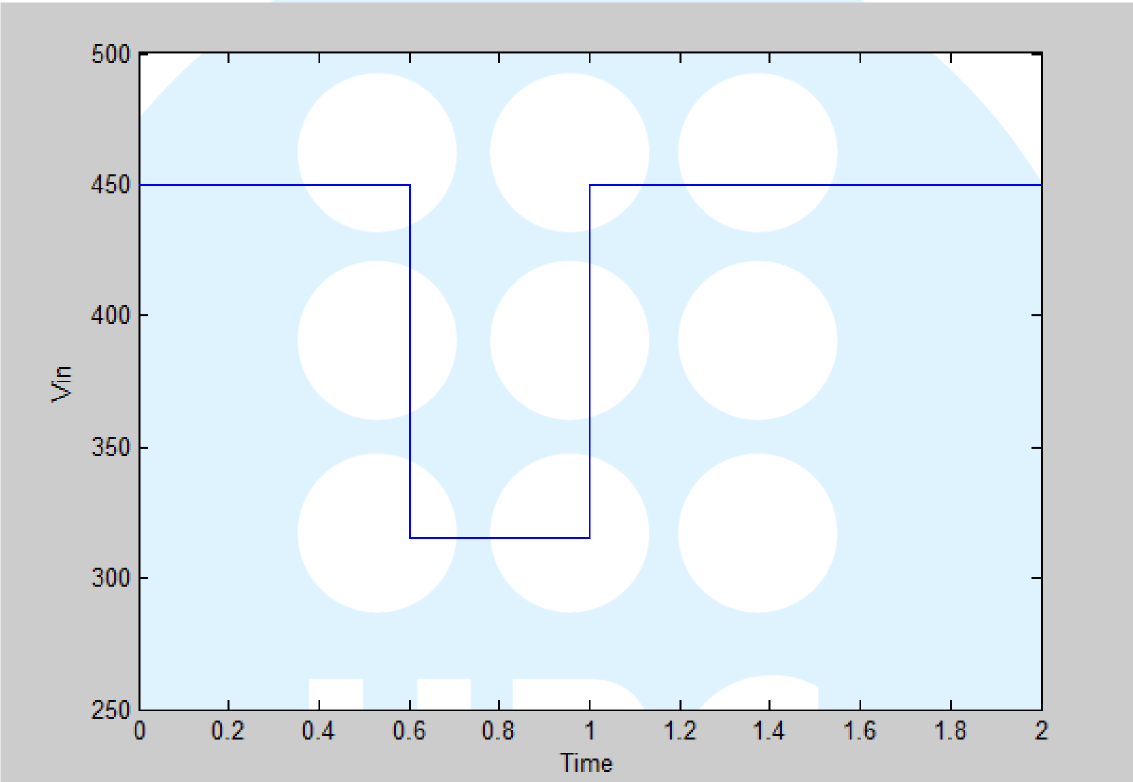


*Figure 11: Input voltage of the inverter (Vin)*

The next figure is about the output voltage of the system is imposed in terms of value and frequency by the grid, that voltage is 230V RMS AC (325V peak), the frequency imposed is the European frequency,50Hz. At 1.4 seconds it's introduced a disturbance of 30% in order to see some effect at the output power. As it happened before with the input voltage, a 20% disturbance was unnoticeable.

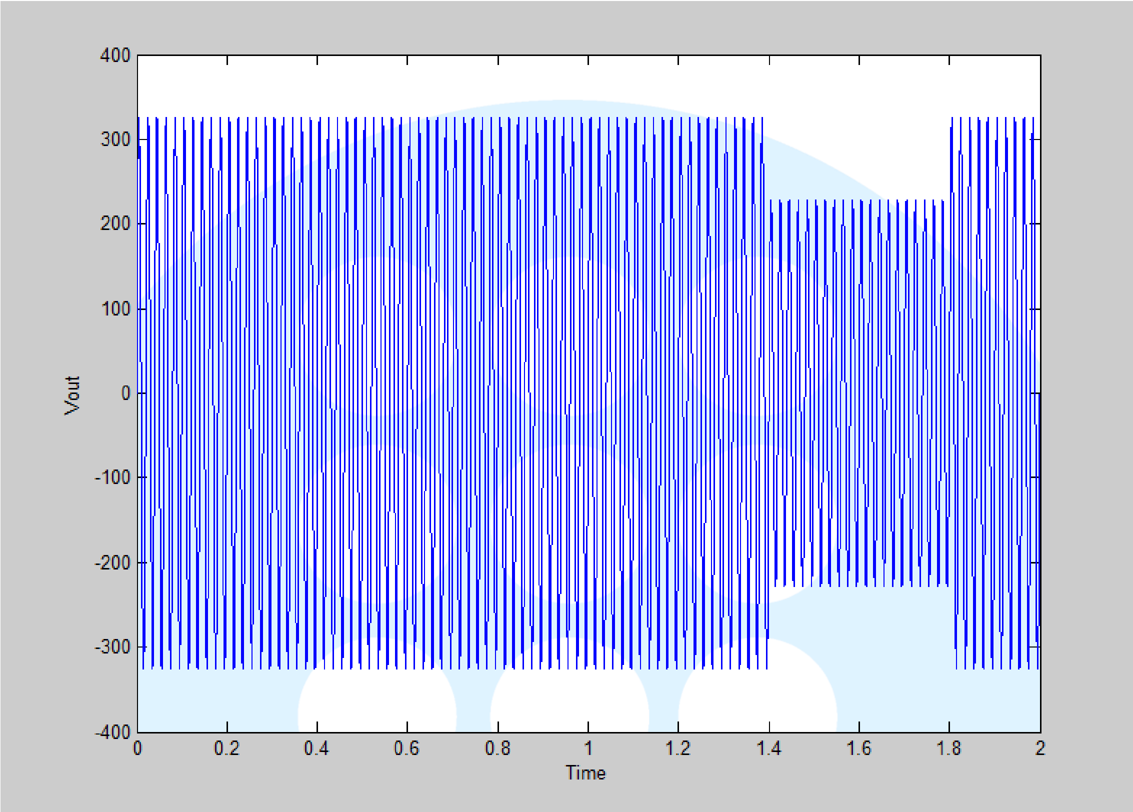


*Figure 12: Grid Voltage (Vout)*

The main specification of the circuit is injecting active and reactive power to the grid that is connected at the output of the inverter. The amount of power necessary to inject is in average value terms of 5000W of active power and 2000VAr of reactive power.

This specification has to be accomplished even if disturbances occur.

In the next figure, we can see that from 0.6 to 1 seconds the system recovers from the loss of input voltage. At 1 second, when the input voltage recovers its nominal value, it can be seen that the system reacts again to this increase of voltage and stabilizes at about 1.3 seconds of the disturbance at the input.

At 1.4 seconds it is introduced a new disturbance, but now at the output voltage. It is possible to see that the system reacts quite quickly and at 1.5 seconds it recovers the specifications of power. When the output voltage recovers its nominal value, it can be seen that the system reacts again to this increase of voltage and stabilizes at about 2 seconds of the disturbance at the output.

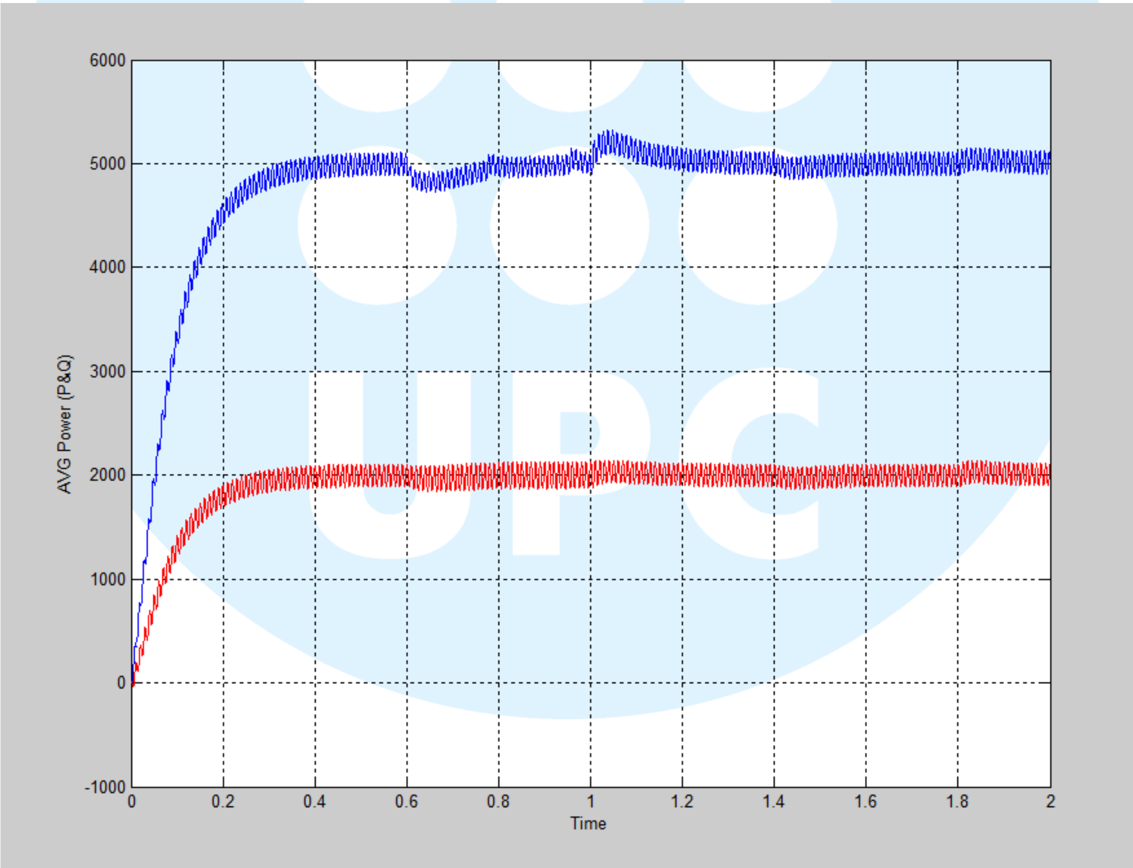


*Figure 13: Active (BLUE) and reactive (RED) output power*

The way to get this values of power is by controlling the current that flows through the inductor (L). By combining the output voltage and the inductor current correctly it is possible to regulate both powers. In this conditions, the inductor current necessary is the one that can be seen in the next figure, where it’s possible to see the reactions of the system to the disturbances. When there is a loss of voltage, it is necessary to increase current in order to maintain power specifications. It can be seen from 0.6 to 1, and from 1.4 to 1.8 seconds.

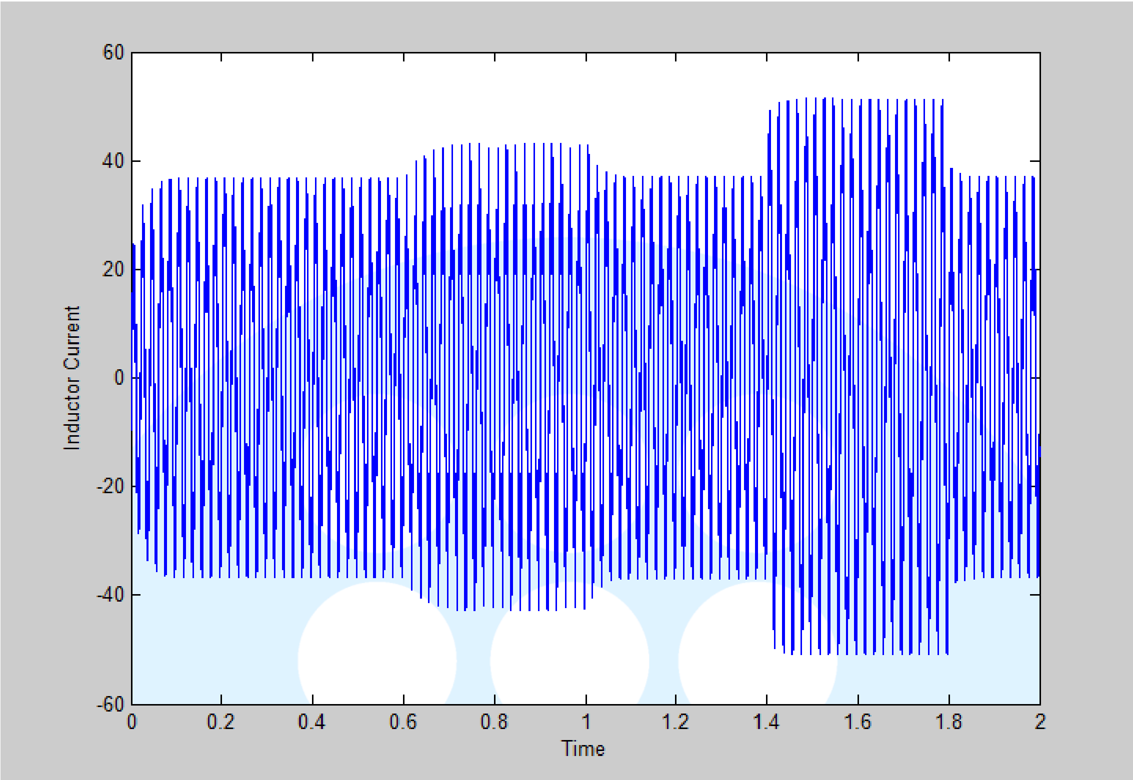


*Figure 14: Inductor Current*

### 2.3.3.2 Control signals

In the next figure it can be seen the two reference voltages that are needed in order to generate the active and reactive power by multiplying it with the inductor current. Both suffer the disturbance at the output in order to make the system react as expected. [6]

[6]The explanation of the reason for the 90 degree delay is in the chapter *(3. Steps for designing the whole system)*

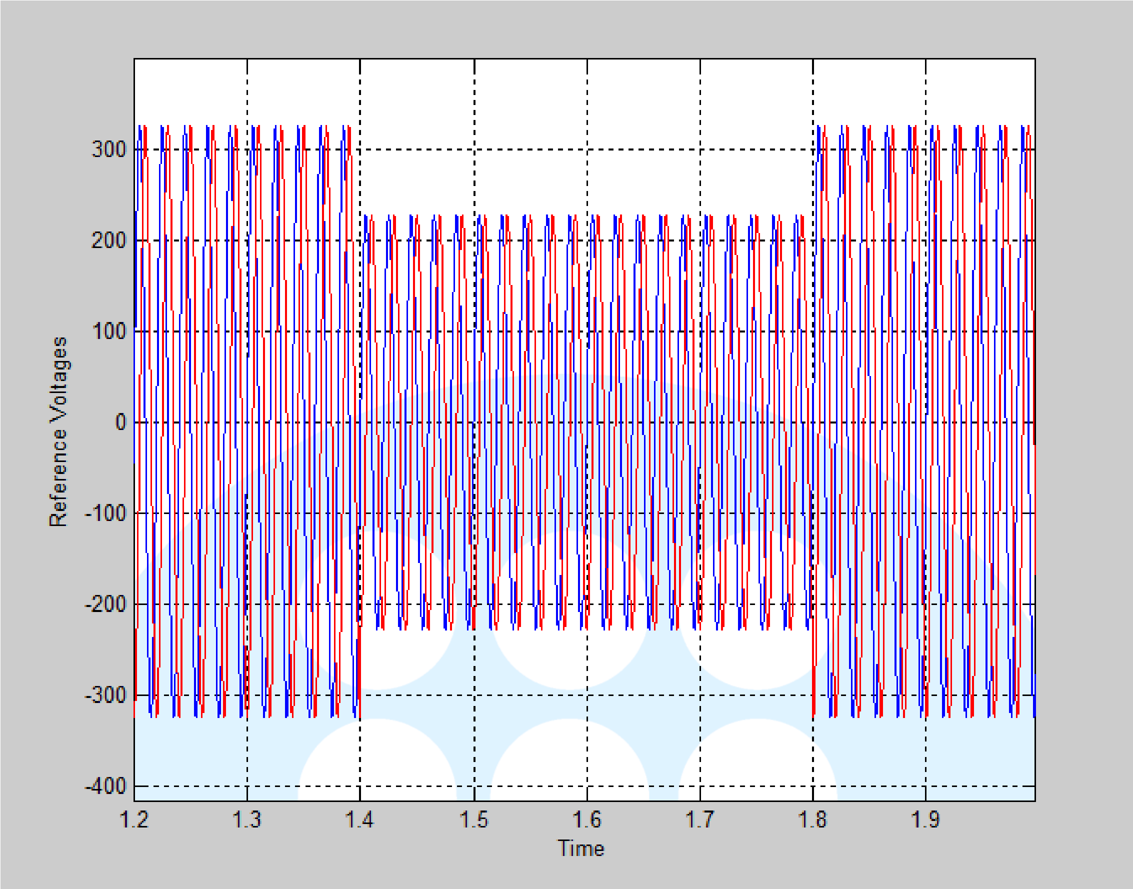


*Figure 15: Reference Voltages: Vout(Magenta); Vout with 90Deg. phase (Blue).*

In the next figure it can be seen the two reference currents generated by the PI controller in order to combine each other for obtaining the error by taking off the actual inductor current (iL). Once this has been done the result is the error that can be introduced to the comparator to generate the switching signals for the switches. It is possible to see that when the system suffers the disturbances, the reference currents react in order to modify the response of the system.

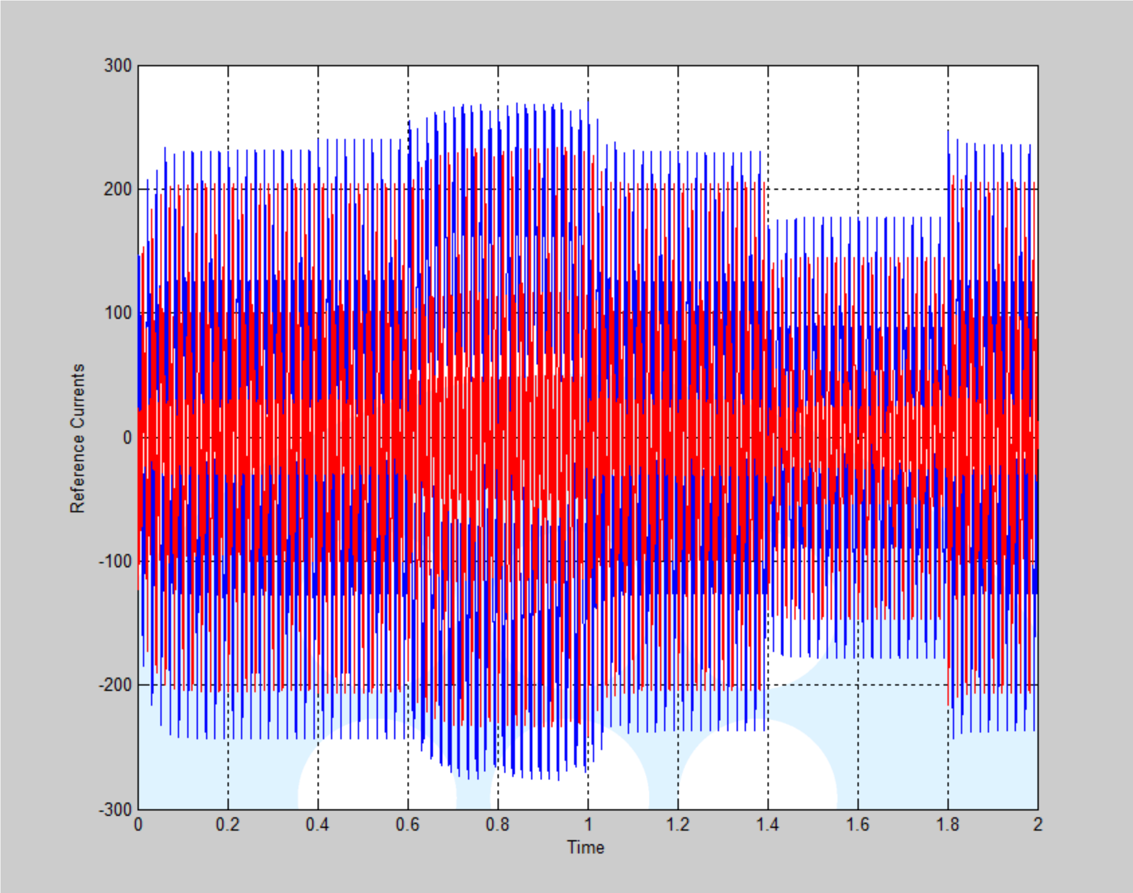


*Figure 16: Reference currents: I active (Magenta);I reactive (Blue).*

It can be seen in the next figure the switches signals, these signals come out from the comparator when it processes the error between the combination of the two reference current and the current of the inductor, and are the ones that control the open and close time for the switches. They are the final element for controlling the system and react to the disturbances thanks to the error generated by reference currents and the inductor current when it is introduced to the PWM. The frequency of switching is variable depending on the error.

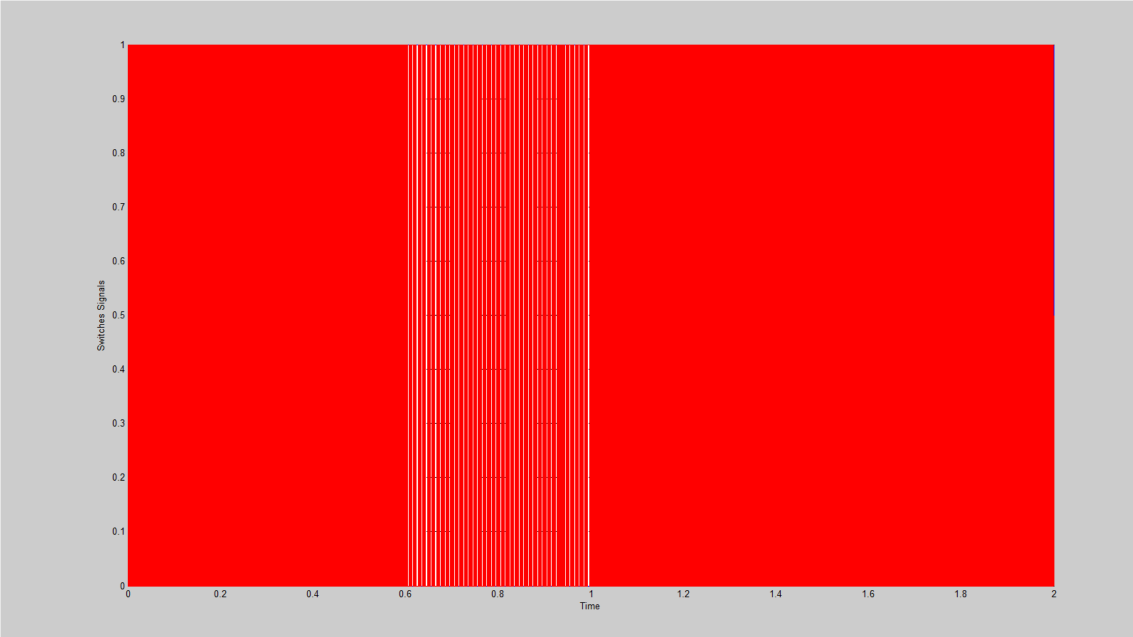


*Figure 17: Signals for the switches*

# 3. Steps for designing the whole system

## 3.1 Internal current loop design

For designing the fixed reference current control system, it was necessary to know how active and reactive power were generated.

For generating active power, it is necessary for voltage and current to be in phase. In the other hand, to generate reactive power, it is necessary for the current and the voltage to have a 90 degree delay.

In the project, the specifications not only demand a kind of power but a combination of both: 5000W and 2000VAr. So, it's necessary to combine current and voltage in order to generate this terms of power.

This is the reason why the control system has two reference voltages: Vo and Vo with 90 degree delay.

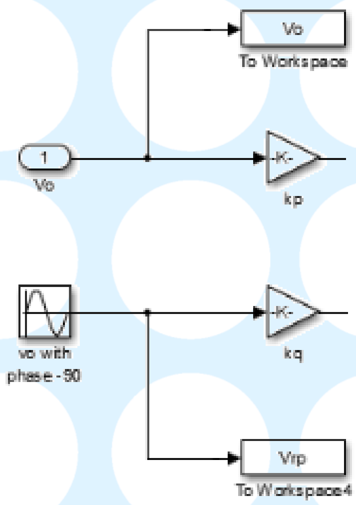


*Figure 18: Reference voltage blocks for the fixed current reference*

### 3.1.1 Calculating the correct values of current

Once here, it was necessary to know the amount of current necessary in order to generate the power specifications with an output voltage of 230V RMS.

The design specifications are P=5000 W and Q=2000 VA, so:

$$S = \sqrt{P^2 + Q^2} = 5385'16\,VA$$

$$\propto_s = arctan\frac{Q}{P} = 21'8^{o}$$

It's known that

$$S = I^* \cdot V$$

$$I^* = \frac{5385'16|_{21'8^{o}}}{325|_{0^{o}}} = 16'57|_{21'8^{o}}\,A$$

So:

$$I = (15'385 - j6'153)\ A$$

This is for peak values, so for average values it is:

$$2 \cdot I = 2 \cdot (15'385 - j6'153)\ A$$

### 3.1.2 Generating the reference current

Once the currents were obtained, in order to generate them, it was necessary to multiply the reference voltages by two constants (with a gain block) for later adding both currents for generating a reference current that included both active and reactive one.

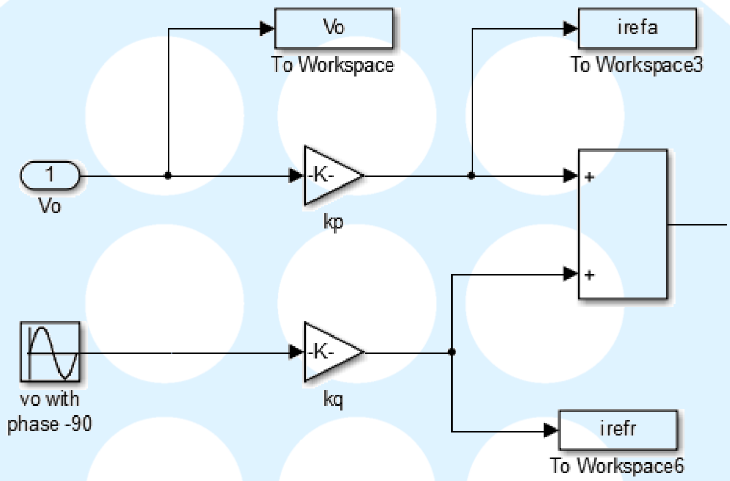


*Figure 19: Fixed  reference current generation*

### 3.1.3 Generating the error signal and designing the control

In that moment the only step for ending the internal current loop control was to generate the error between the reference current and the actual current flowing through the inductor. With the combination of the error with a hysteresis comparator were obtained the signals for the switches.

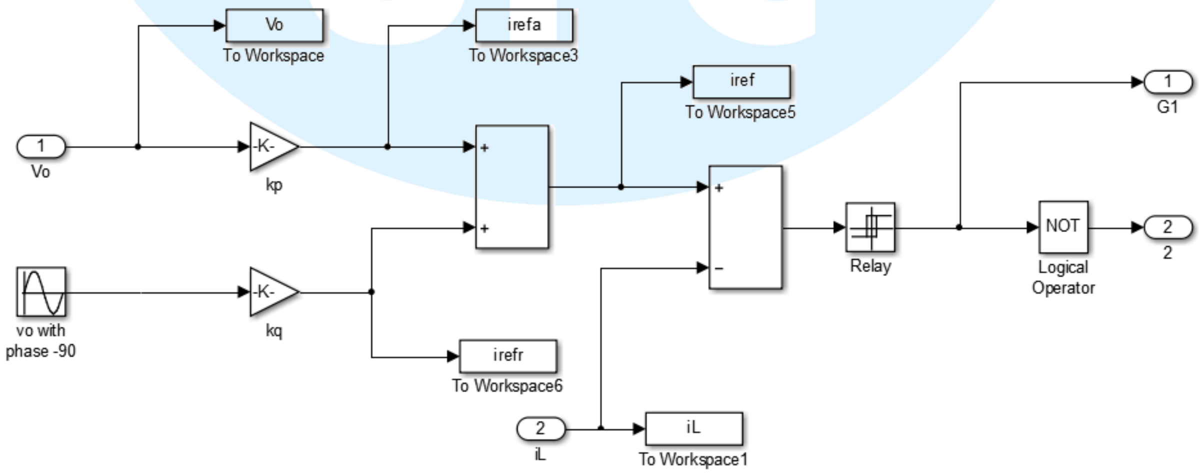


*Figure 20: Internal current loop control system*

To know if the system was doing what it was expected to, it was necessary to plot active and reactive power and see if there were 5000W and 2000VAr respectively. For doing this, it was necessary to multiply both active and reactive voltage reference by the current through the inductor and later filter the results with a low pass filter to see its average values.

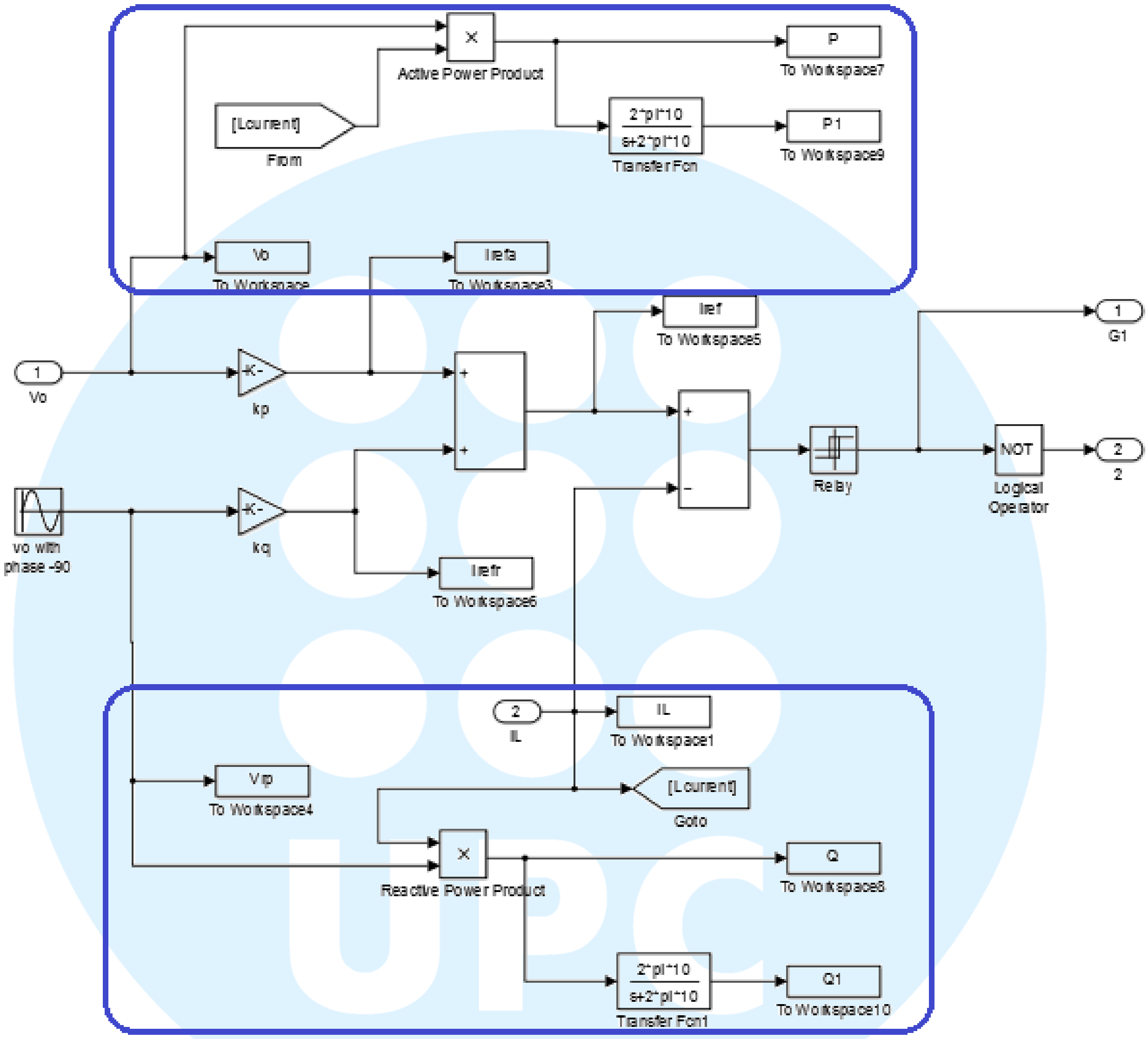


*Figure 21: Complete fixed reference current loop system (Highlighted in blue the calculated power)*

In the next figure it can be seen the result of the system with the internal current loop control, active and reactive power in instantaneous terms, there can be easily seen that the results of the simulation were pretty good and the system works as it should if there wasn't any disturbance.

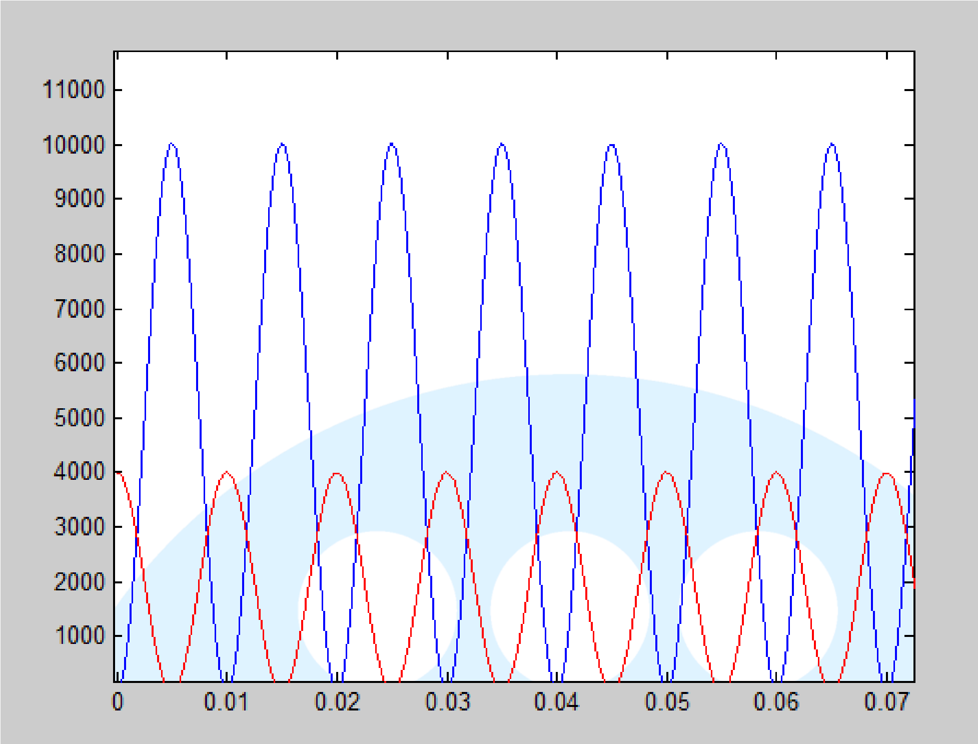


*Figure 22: Objective of power to generate. Active (Blue) & Reactive (Red)*

## 3.2 Closed power loop design

Once the internal current loop controlled system worked properly it was time to try to improve it by closing the loop and making it more robust.

The idea is the next:

- The switches are controlled by an error generated by the interaction of the reference currents with the inductor current.
- In fixed reference current loop, reference currents values were constant, they didn't depend on the inductor current or power injected to the grid. Also they didn't depend on output and input voltages. If something changed in the system, the control was unable to correct it.
- If reference currents are generated depending on the main variables of the system, which are the voltage references (that depend on the output voltage directly) and active and reactive power, the control would be sensitive to variances that affect the system and able to react against them.

The way to satisfy this necessity is by two PI controllers.

### 3.2.1 Design of the PI controllers

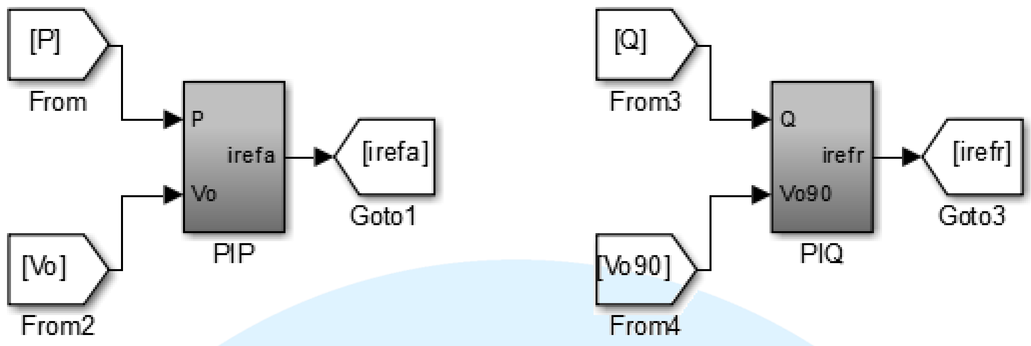


*Figure 23: The PI from the outside*

As before, to generate the reference currents it's necessary to multiply the corresponding reference voltage by a gain. Now, this gain won't be constant as it was before. The gain will depend on the error between the power expected (5kW or 2kVAr) and the current power injected to the grid. In function of this error the PI generates the corresponding gain and gives as output the corresponding reference current by multiplying this gain with the reference voltage.

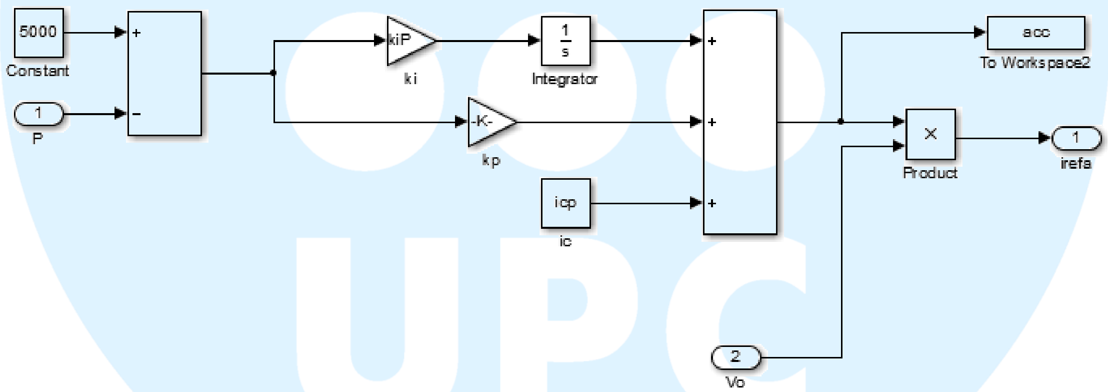


*Figure 24: Inside the PI (for active power)*

Here comes the moment to tune the PI controllers in order to control the stabilizing time and behavior of the system. By trial and error it's determined that both gains for proportional and integral action have to be lower than one, more concretely proportional gain has to be 1/150/100 and integral gain has to be 1/300. These are the values which give the quickest response with less overshoot.

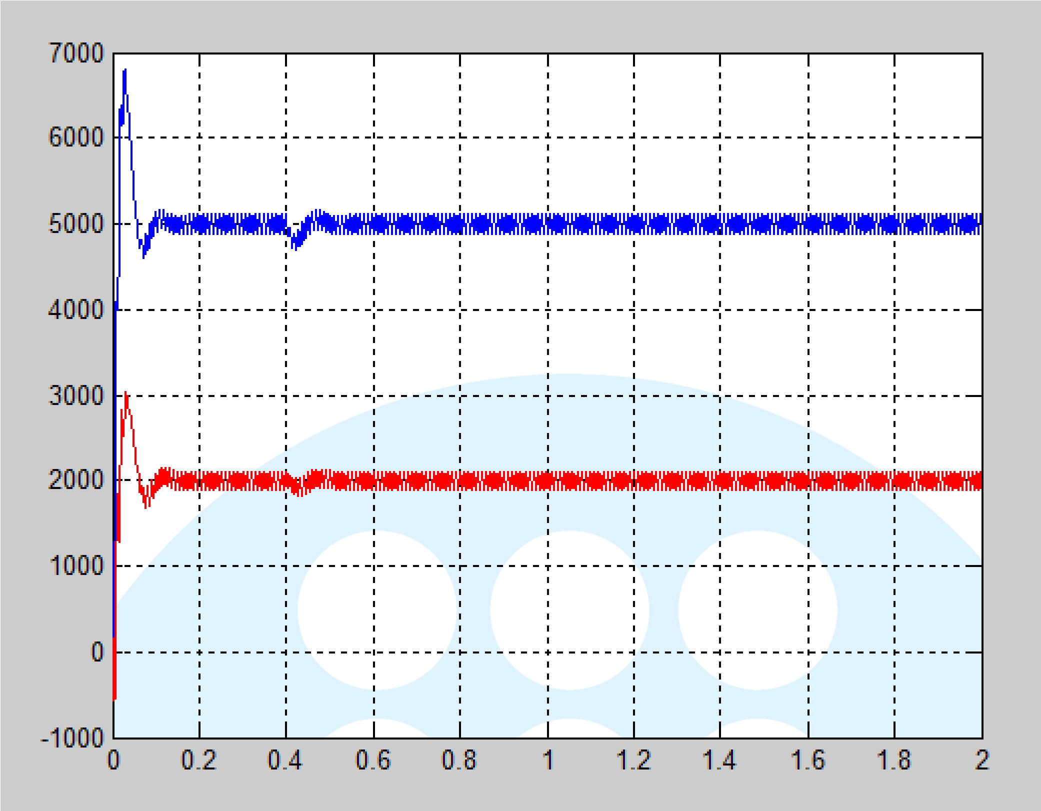


*Figure 25: Power response of the system; Transitory and disturbance at 0.4s*

It was time to introduce disturbances to the system and improving the PI for a better response in case that disturbances happened, in case that improvement was needed. Here we can see the result at the output powers when a disturbance is introduced in the output.

For trying to improve the response and following the suggestion of Miguel Castilla, instead of using filtered power for closing the loop, we tried to use directly non-filtered power. We realized that the response was quite better. Overshooting was reduced even that the response time was a bit slower than before. The response was sensibly cleaner, with less noise.

The reason for this better response without filtering the power is the next one:

- By introducing a low pass filter, it is added a pole to the system, which means the system is more difficult to control and easier to unstabilize, even that it gives a quicker response.
- If we put in the balance speed vs overshoot, and in these conditions were the system is not much slower but gives a better response in terms of overshoot and noise, it was chosen the system without filtering the power for closing the loop.

Here we can see the response of both systems (filtered and non-filtered power, in this order) with the next values:

```
kpP=1/150/100; kiP=1/300; kpQ=kpP; kiQ=kiP;
```

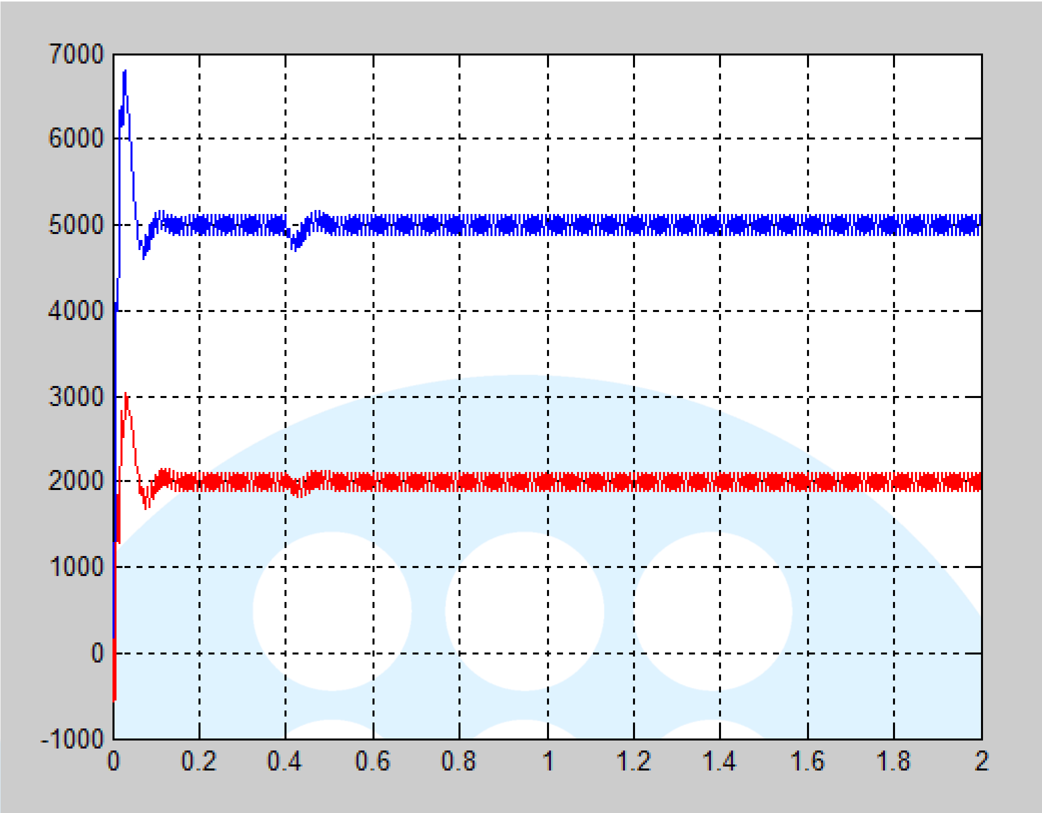


*Figure 26: Response of powers with filtered power; Transitory and disturbance at 0.4s*

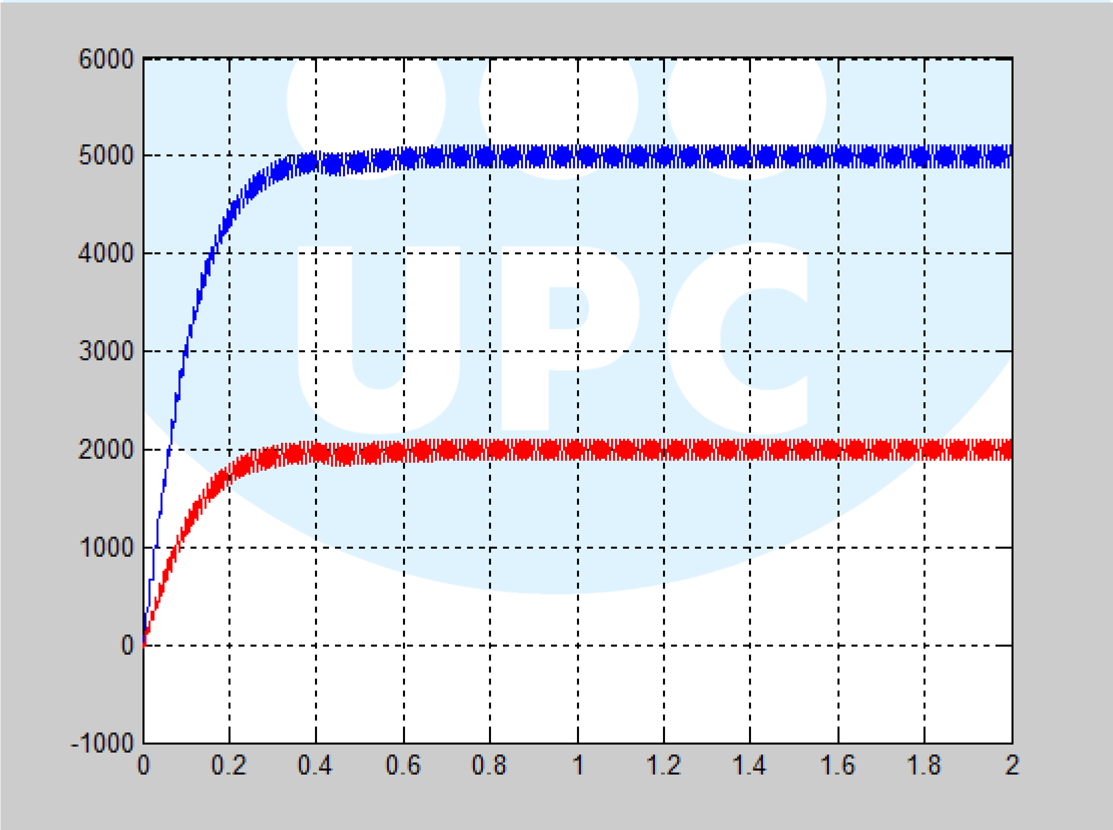


*Figure 27: Response of powers with NON-filtered power; Transitory and disturbance at 0.4s*

Here we can see the response of both systems (filtered and non-filtered power, in this order) with the values that give a better response, the final ones, that are:

```
kpP=1/100/100; kiP=1/100; kpQ=kpP; kiQ=kiP;
```

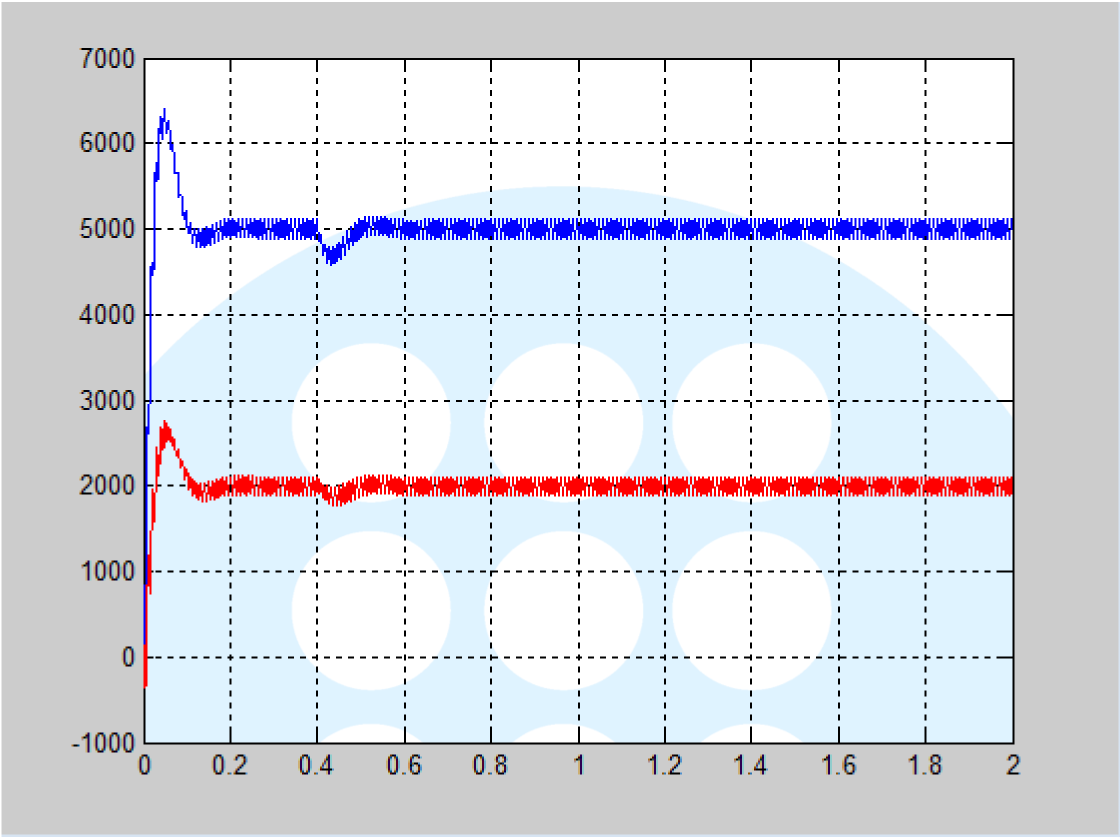


*Figure 28: Response of powers with filtered power; Transitory and disturbance at 0.4s*

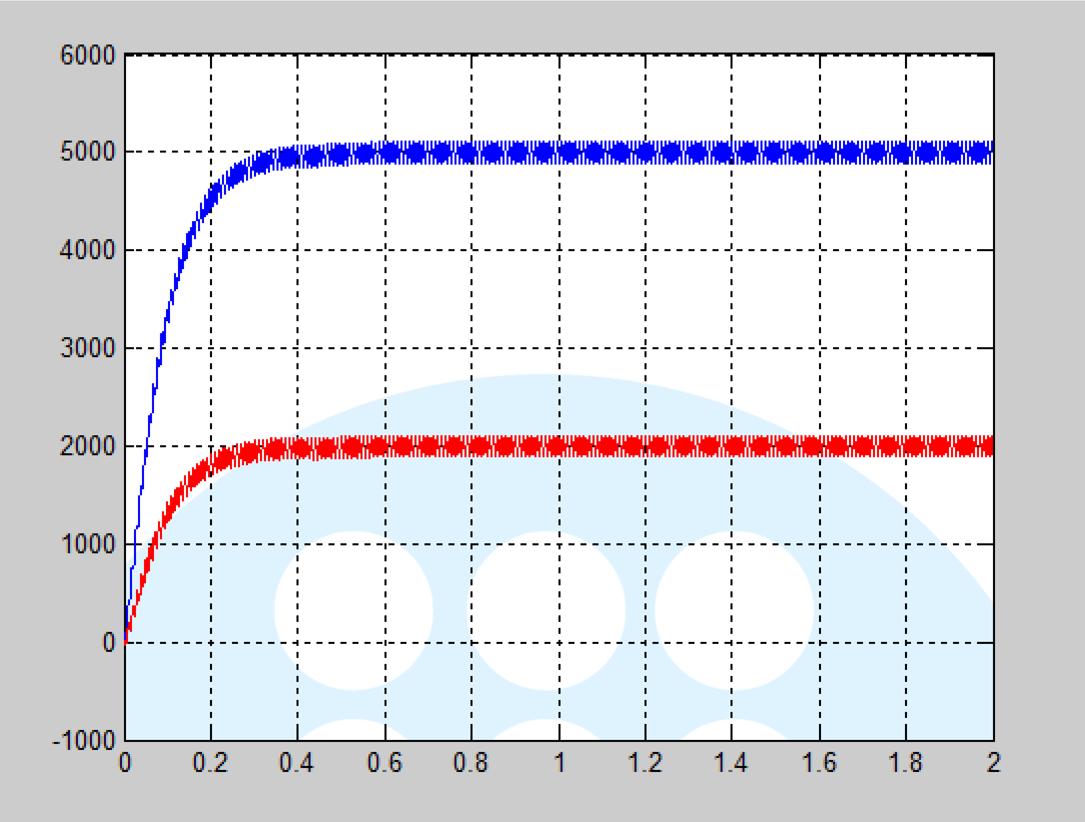


*Figure 29: Response of powers with NON-filtered power; Transitory and disturbance at 0.4s*

It is easy to see why it is chosen the second option of non-filtered power. Time of transitory very similar but without overshoot and very fast and strong response to disturbances.

With the next figures it is tried to give an explanation for the differences between both systems. It can be seen filtered and non-filtered powers and how they change in the transitory time and when disturbances happen, and it's an easy way to realize why the system is really different. When filtering the power, the filter introduces harder changes at the output filtered power in the transitory and the disturbances, while the non-filtered power evolves smoothly in both periods.

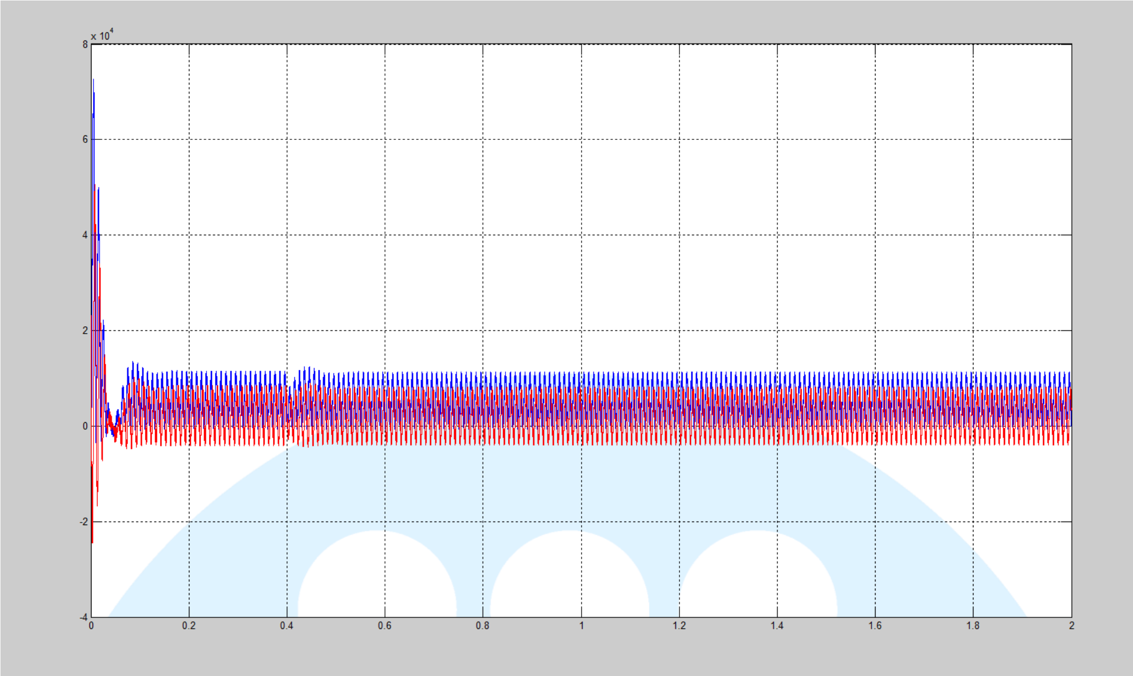


*Figure 30: Filtered power*

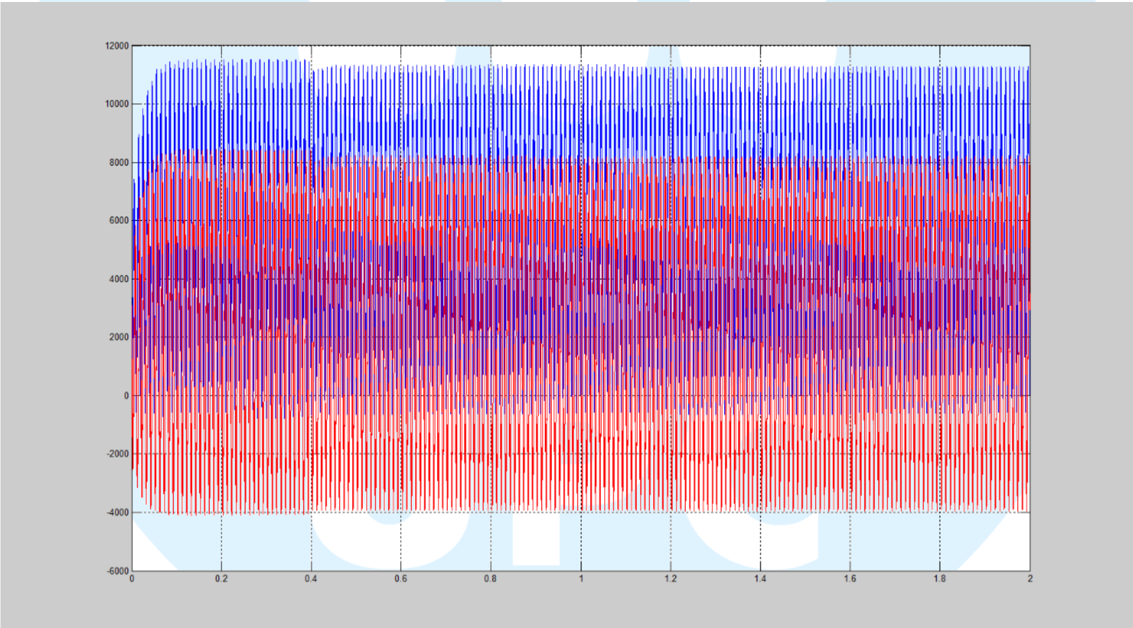


*Figure 31: NON-filtered power*

When the system was finally designed for responding the best possible way to disturbances in the output (grid) it was time to see if it was that strong with disturbances in the input DC voltage. When introducing in the input a disturbance of 20% the system is as robust as when the disturbance is introduced in the output.

The limit of the disturbance in the input is of 50% and the reason for this is that for maintaining the specifications of power at the output it is necessary for the voltage at the input to be higher than the output one. If it is not this way, the system has not power enough to inject the amount of inductor current necessary and unstabilizes. The circuit can't work as a power elevator.

### 3.2.2 Design of the PWM

At last but not the least, it was implemented a PWM instead of the hysteresis comparator, at a switching frequency of 100kHz. The structure of this PWM is the next:

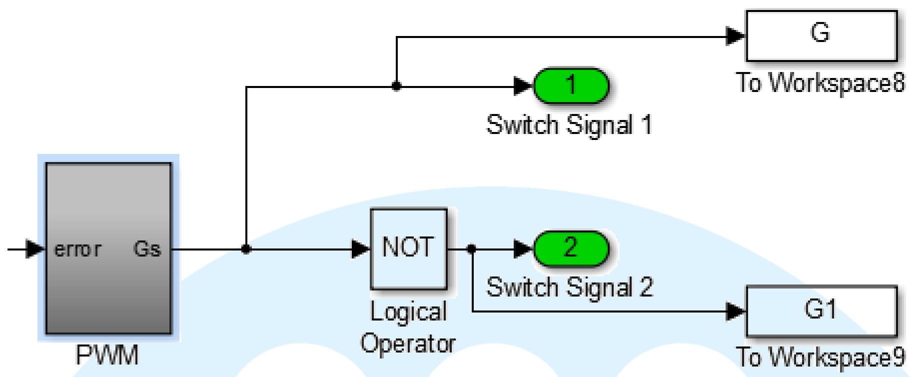


*Figure 32: PWM input and outputs structure*

The PWM receives the error of the inductor references with the inductor current and processes it for generating the switching signals.

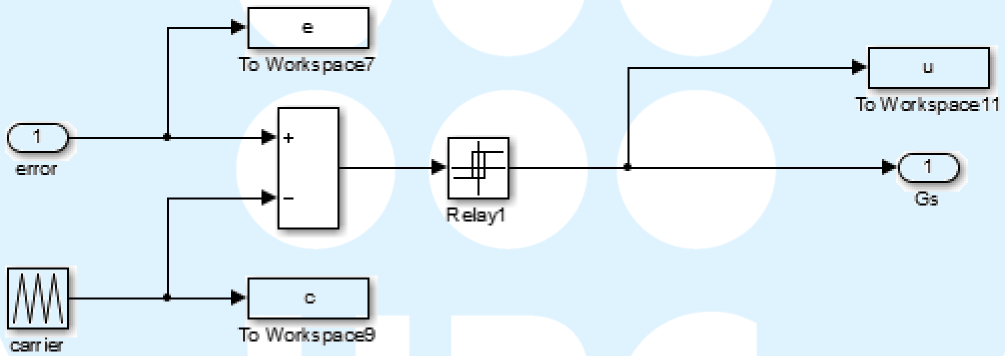


*Figure 33: Inside the PWM*

To work at a frequency of 100kHz it is necessary to configure the carrier signal correctly in order to process the information at that speed. The error and the carrier are comparated and when both signals cross, depending on when it happens, the width of the pulse at the output changes.