Active Filter real time simulation using RCP and HIL

Juan Marinero dissertation

Power lines feed **non-linear loads** that create electrical distortions. The **attenuation of these electrical distortions** in the low voltage Gridwork is the purpose of this work. Using a compensating device called Active Filter, the **loads are fed** at the same time as they are protected to the electrical distribution grid and the transport of **reactive power is minimized**. The compensating equipment is developed by means of simulation in Matlab/Simulink and real-time simulation using RCP and HIL techniques. The range of the Active Filter is mainly determined by the degree of current distortion of the loads it is able to compensate.

1º) **Introduction and purposes**

2º) Theory

Setpoint/reference current

Scalar Sliding

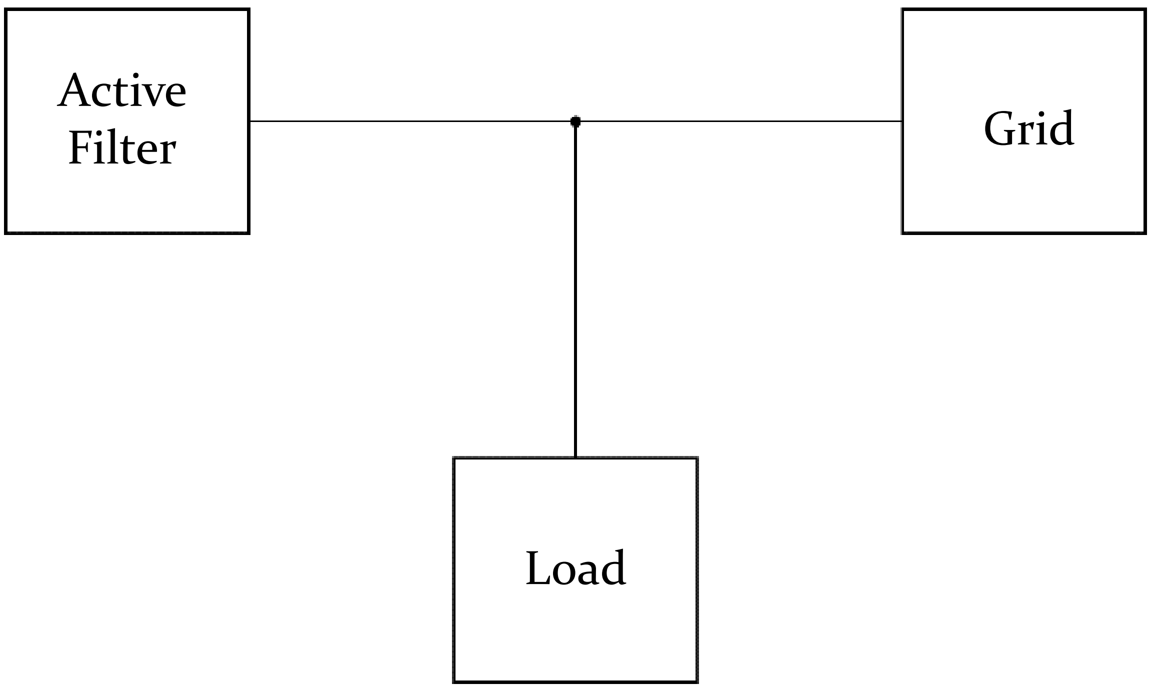
3º) Simulations

4º) Simulations results

5º) Conclusions

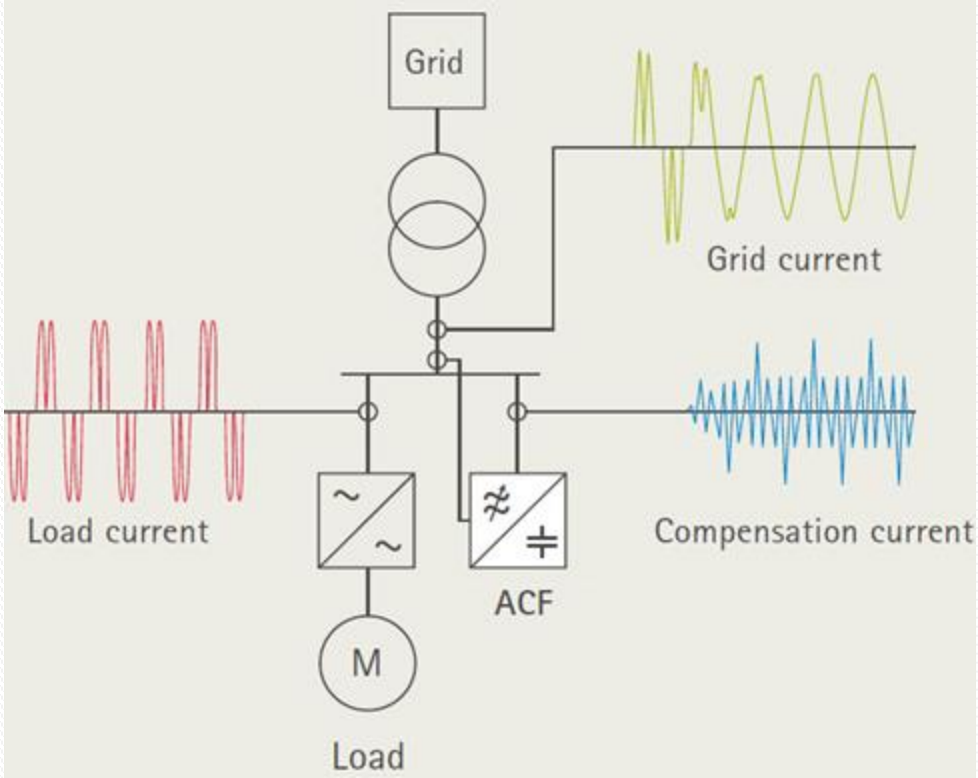
Introduction and purposes

The load demands current with harmonics. Our Active Filter demands pure senoidal power to compensate those, so at the end, the Grid is low affected by the harmonic (neither from the load, nor from the compensator devide).



Introduction and purposes

Electric Circuit



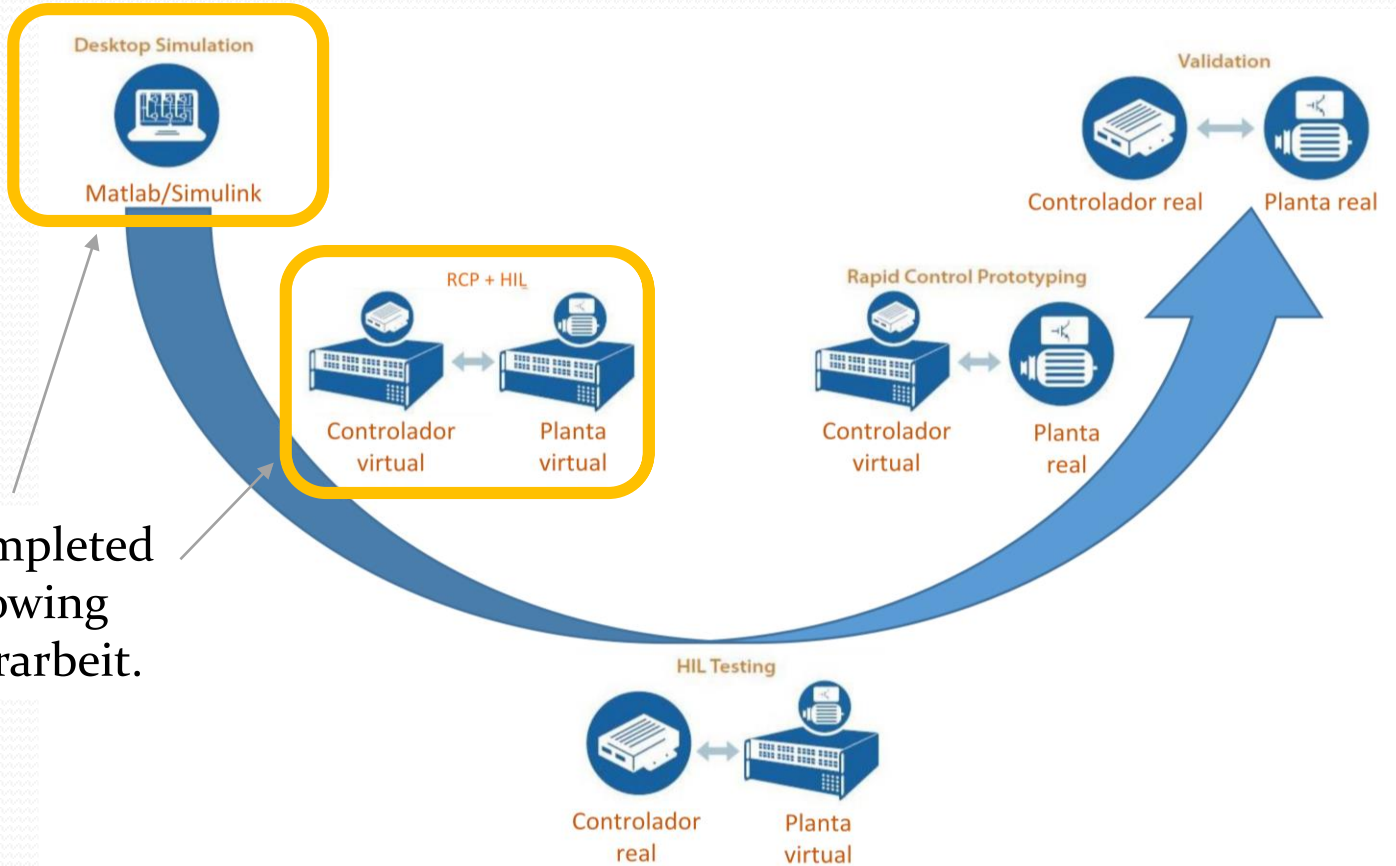
Introduction and purposes

These are the main goals to achive or main limitators to optimaze:

- IEC 1000-3-2: current harmonics in Grid
- IEC 1000-2-2: voltaje harmonics in Grid
- Balance of Electric power
- Switching frequency
- Inverter DC capacitor voltage

In addition to limiting the harmonics current in the Grid, other main objectives are:
-the power used by the Active Filter to be moderate
- bring the switching frequency of the inverter poles to about 20kHz
- surpass with other regulations, such as harmonics in mains voltage (EN -61000-2-2)

Introduction and purposes



Steps completed in following Bachelorarbeit.

"V-Model" applied to development of electronic items

1º) Introduction and purposes

2º) **Theory**

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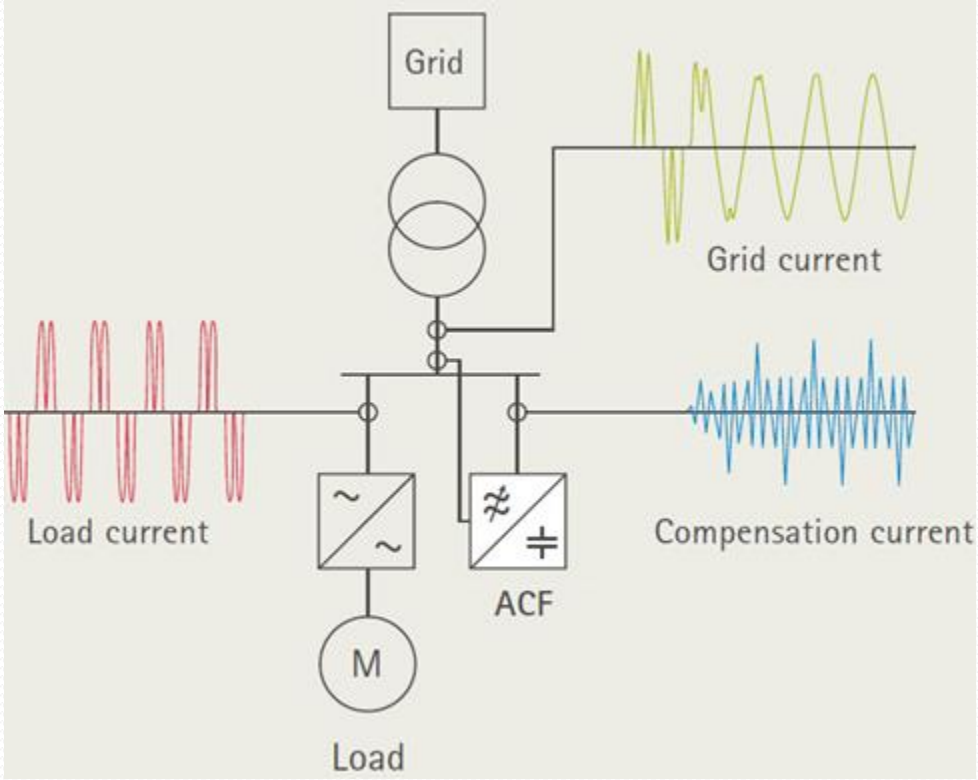
4º) Simulations Results

5º) Conclusions

Setpoint/reference current

Electric Circuit



We observe (in the image):
1) The **power grid**, supplier of all the energy, that we need to **only** inject active power at **50 Hz**

2) Electric load demands harmonics, reactive, noise, etc.

And 3) the Active Filter, in charge of supplying all the current demanded by the load that we do not want the grid to provide reference current

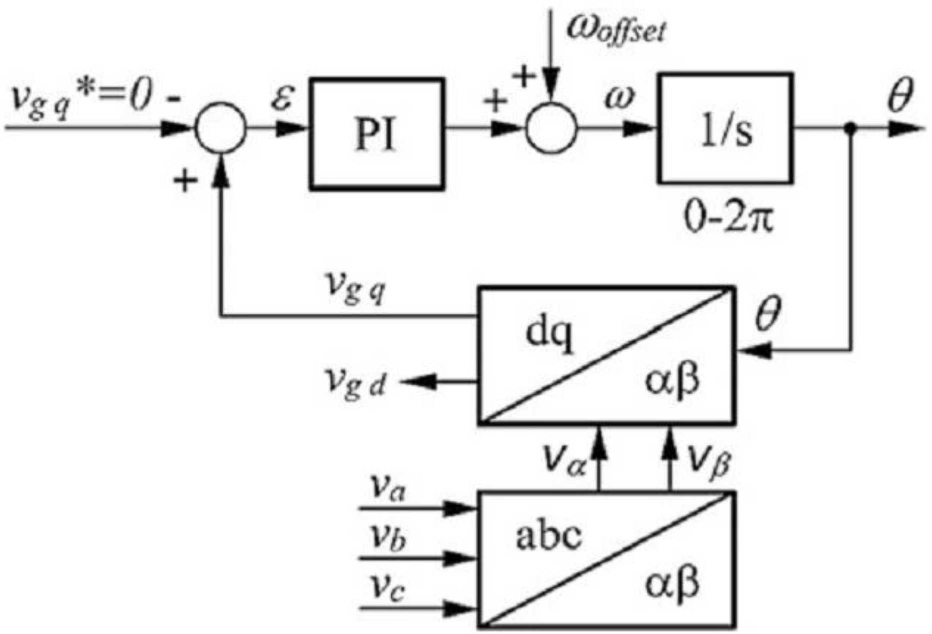
Setpoint/reference current

- Synchronous Reference System
- Instantaneous Power Theory

Setpoint/reference current

- Synchronous Reference System

dqPLL



The PLL synchronize me with a signal, in this case a Gridwork frequency.
That is, from the phase voltages of the Grid, Va, Vb and Vc of the figure, we **calculate the main voltage harmonic of the Gridwork** (aprox. 50 Hz).

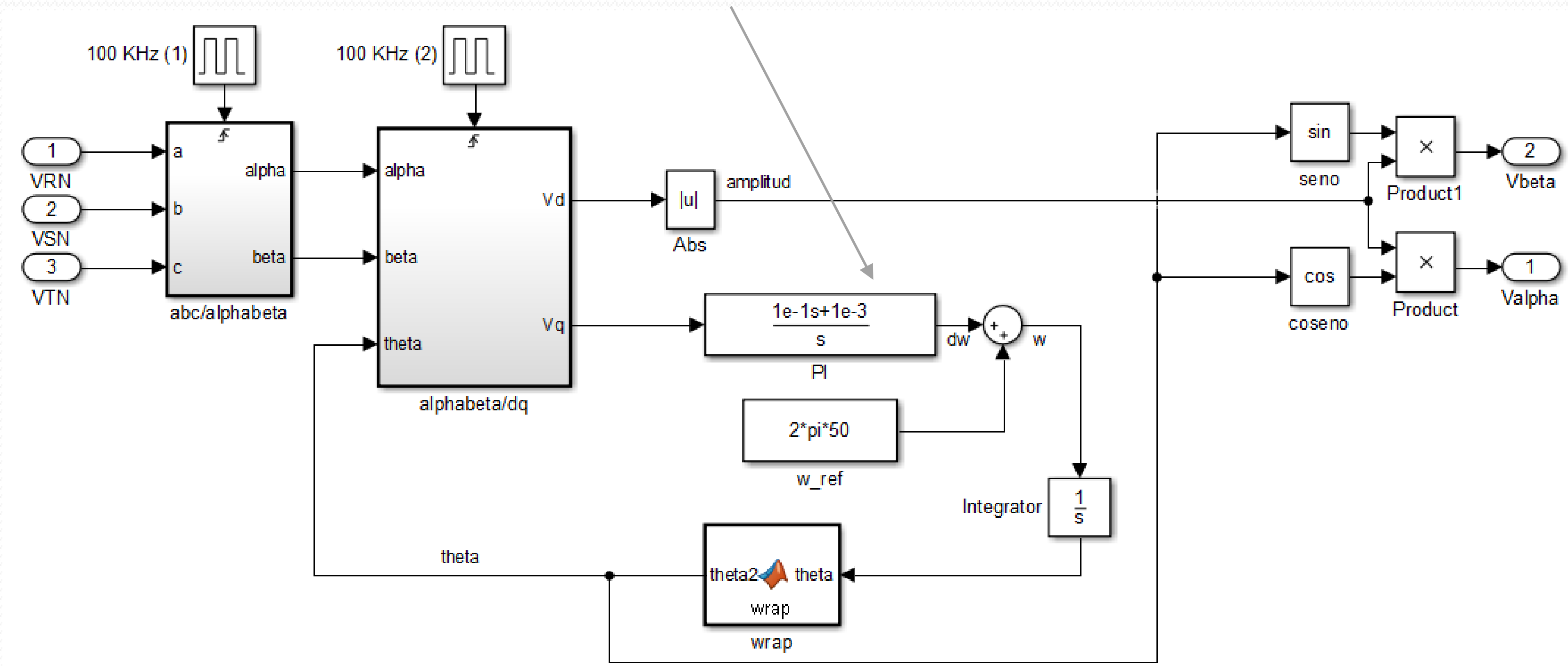
-its phase angle, theta of the image, and

-Its amplitude Vgd (any, not limited to 220Volts)

Setpoint/reference current

- Synchronous Reference System

dqPLL through PI controller



Setpoint/reference current

- Synchronous Reference System

Grid current (50 Hz) supplies :

- load: its active power
- inversor: its DC capacitor losses

$$\overline{I}_G^* = \mathrm{PI}_{\mathrm{output}} \begin{pmatrix} V_{G\,\alpha} \\ V_{G\,\beta} \end{pmatrix}_{PLL}$$

Grid current desired, i.e. proportional to pure sin voltage, thus: neither harmonics, nor reactive power

Setpoint/reference current:

$$\overline{I}_F^* = \overline{I}_L - \overline{I}_G^*$$

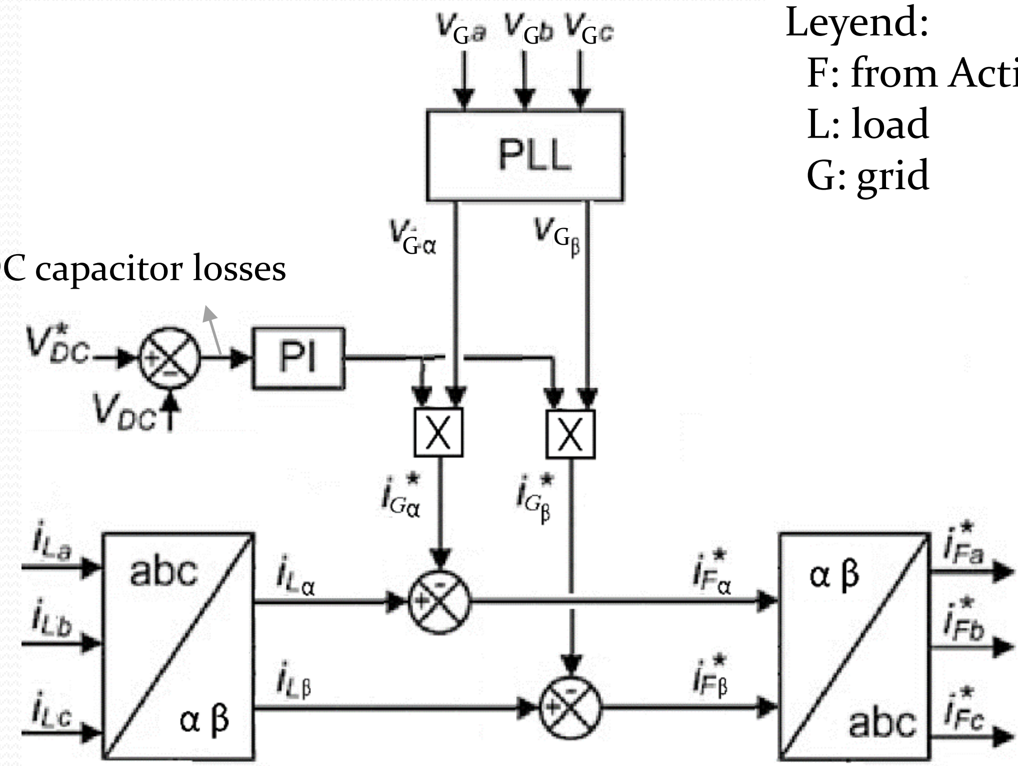
Load current

Setpoint/reference current

- Synchronous Reference System $\overline{I}_F^* = \overline{I}_L - \overline{I}_G^*$

Leyend:
F: from Active Filter compensator
L: load
G: grid

DC capacitor losses



These are the triphasic currents that we desired the compensator to create.

Setpoint/reference current

- Instantaneous Power Theory

Since the capacitors at the output of the three-phase Active Filter inverter consume a current independent of that consumed by the load, we must add that reactive current to the reference current.Once the reactance (or Farads) of these capacitors is known, its reactive current consumption is calculated.

Setpoint/reference current: $\overline{I}_F^* = (\overline{I}_L + \overline{I}_{C_{LPF}}) - \overline{I}_G^*$

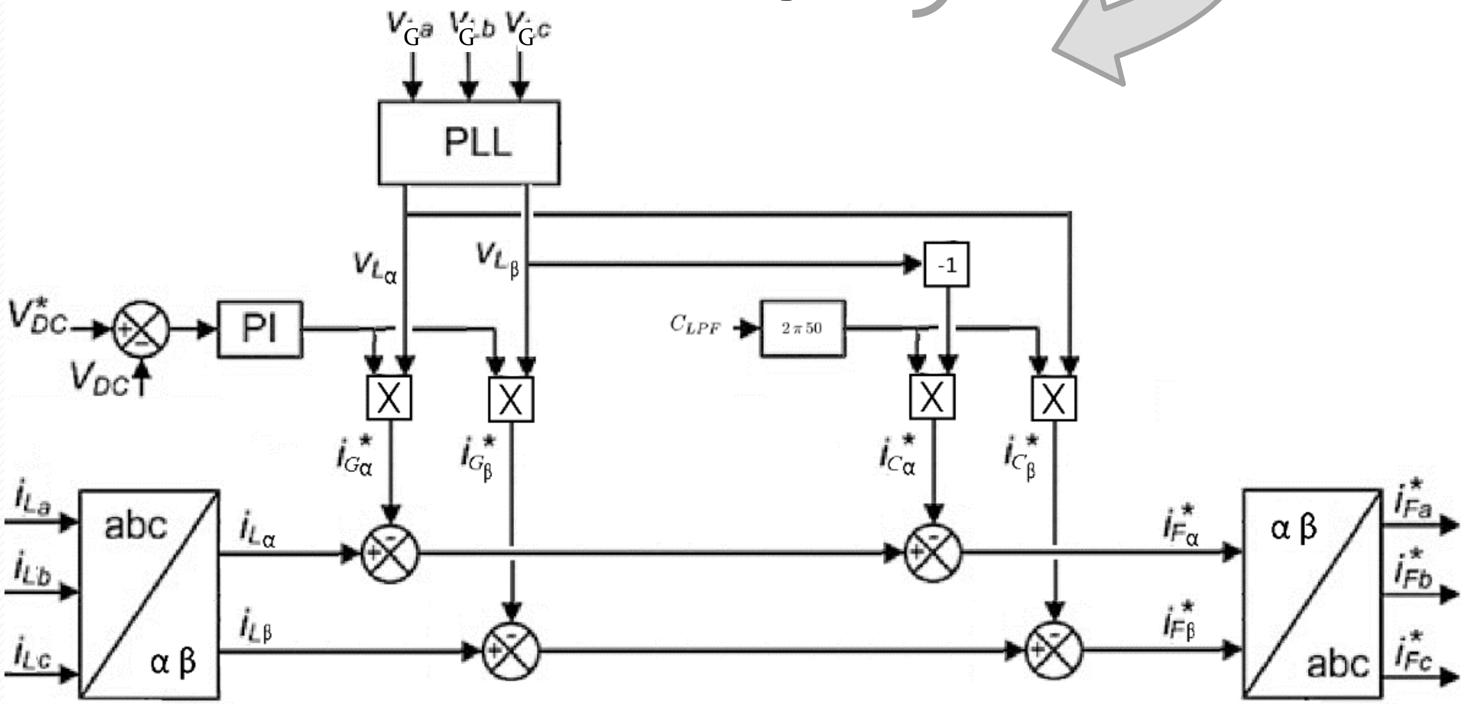
Reactive current 50Hz

Reactive current calculus:

$$\begin{pmatrix} P \\ Q \end{pmatrix} = \begin{pmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{pmatrix} \begin{pmatrix} I_\alpha \\ I_\beta \end{pmatrix} \Rightarrow \begin{pmatrix} I_\alpha \\ I_\beta \end{pmatrix} = \begin{pmatrix} G_p & G_q \\ -G_q & G_p \end{pmatrix} \begin{pmatrix} V_\alpha \\ V_\beta \end{pmatrix}$$

Setpoint/reference current

- Synchronous Reference System
- Instantaneous Power Theory



1º) Introduction and purposes

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Setpoint/reference current

Scalar Sliding

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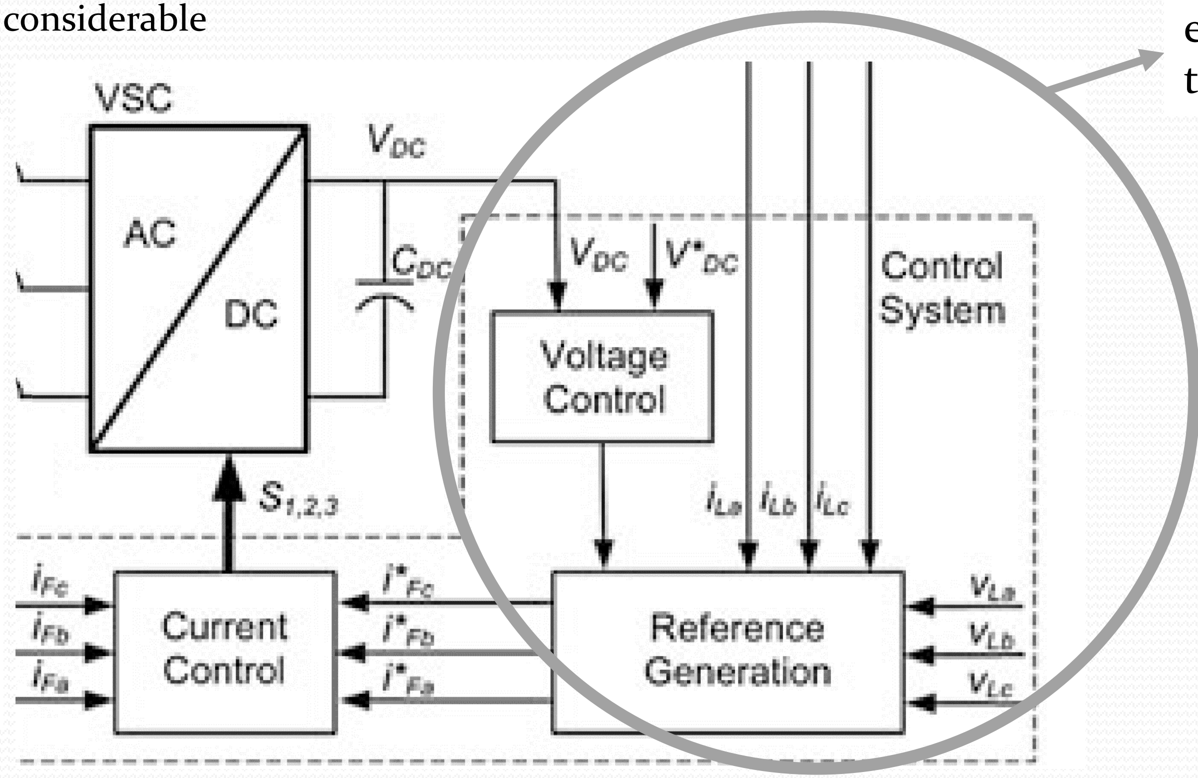
Scalar Sliding

Once the reference current of the Active Filter is cleared, we explain how to achive that current, Sliding control:

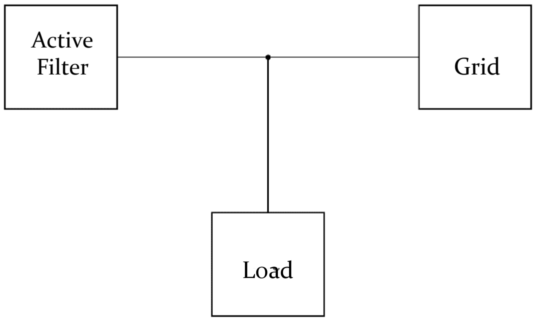
- good adaptation to sudden changes of the reference
- the permanent error is considerable

Till here, we explained this circle.

On the right, the blocks of the calculation of the reference current, noted with asterisks.
On the left, the current measured at the output of the inverter.
Both currents go to the **Current Control** block, which determines the **switching of the S1,2,3 inverter poles** for each phase.



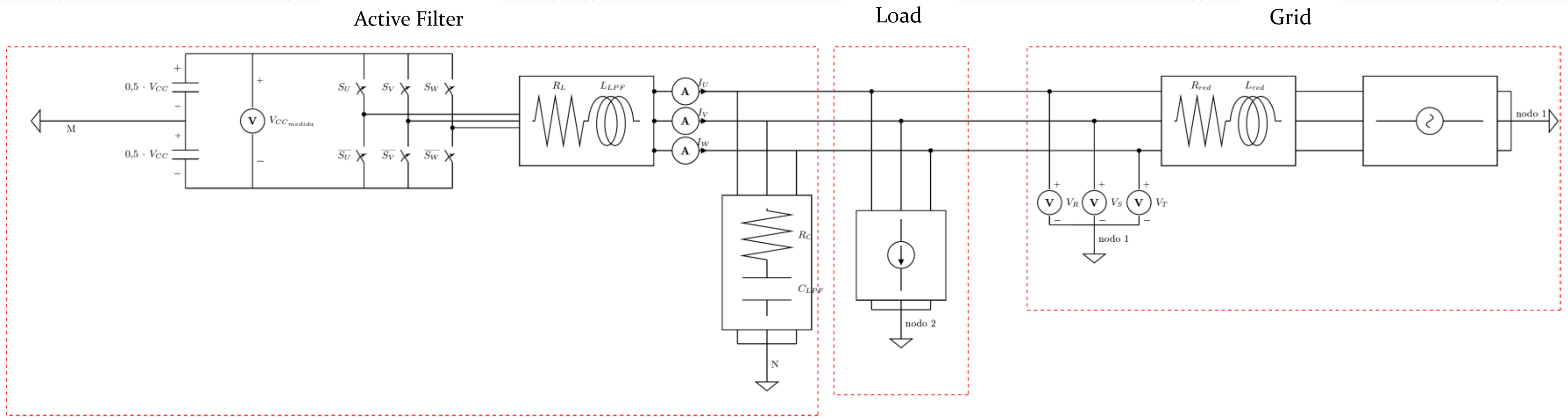
Scalar Sliding



Active filter compensator:

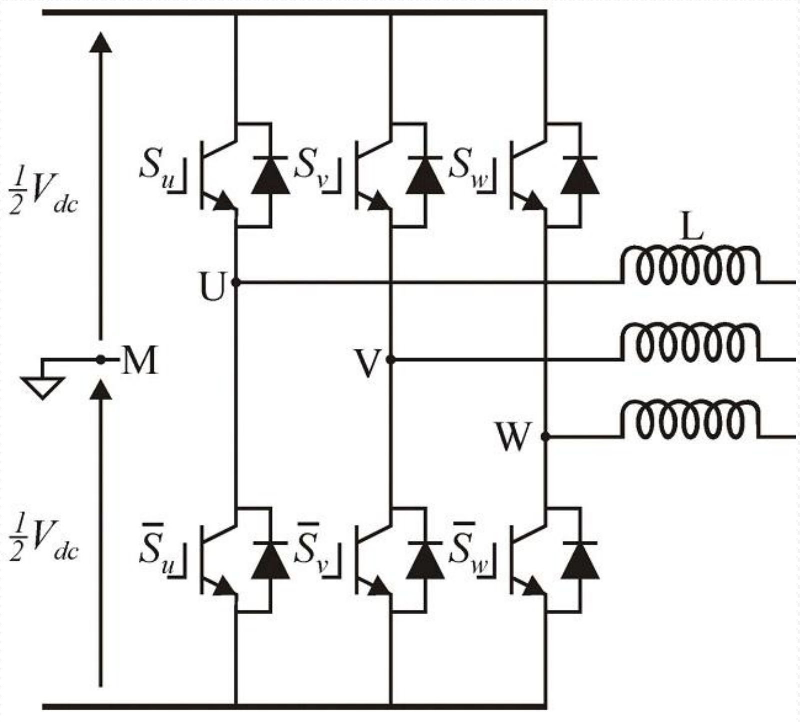
-triphasic invertir with inductances

- Parallel capacitor



Scalar Sliding

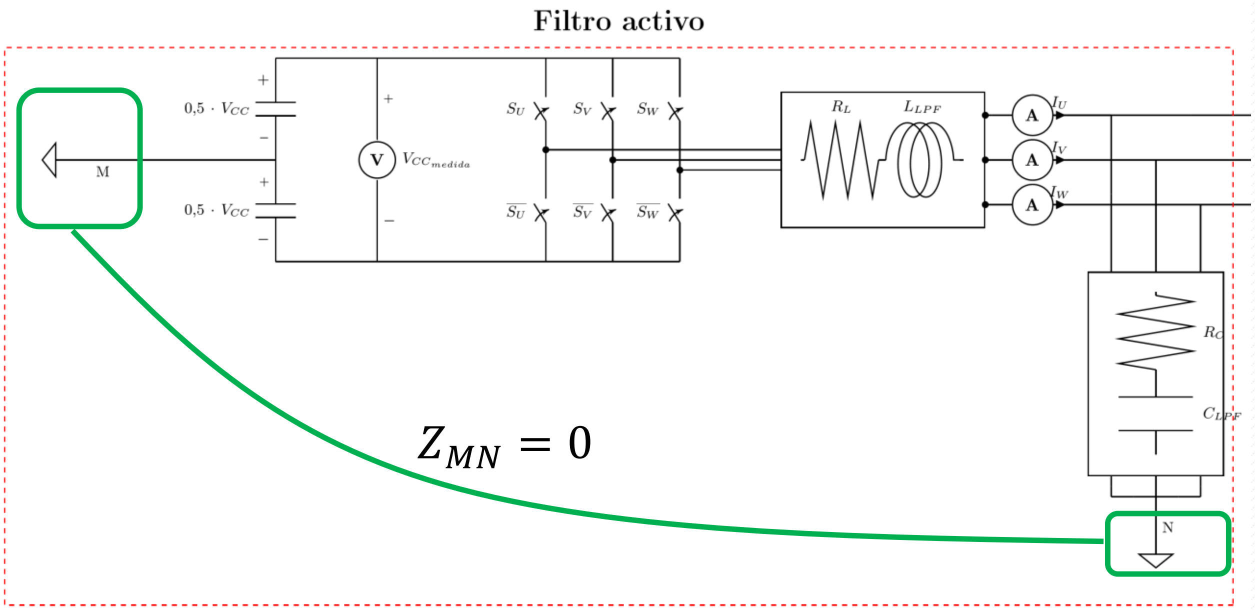
Triphasic Inversor



This three-phase inverter consists of 6 switches and each pair operates in a complementary way for each phase.

Scalar Sliding

Fixed neutral: connected midpoint of the inverter (M) with neutral of the low pass filter capacitor (N).



Our Active Filter system has specifications to **only compensate** loads that do **not** demand **homopolar** current (only α and β calculus, but no γ) and are **balanced**.

Scalar Sliding

Fixed Neuter

In summary,
1st The reference current is calculated
2nd It is determined what voltage there must be in each phase of the inverter to follow that current, that is, what pole switching

Inverter phase voltages

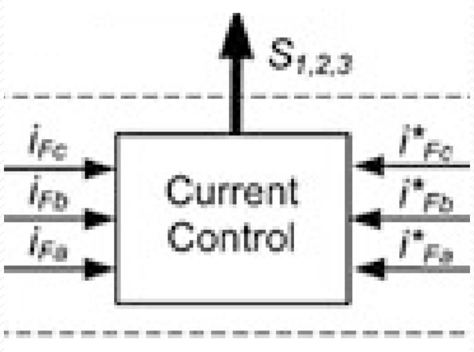
$$V_{UN}(t) = \pm\frac{V_{CC}}{2} + V_{MN}(t)$$
$$V_{VN}(t) = \pm\frac{V_{CC}}{2} + V_{MN}(t)$$
$$V_{WN}(t) = \pm\frac{V_{CC}}{2} + V_{MN}(t)$$

Scalar Control

$$V_{UN}(t) - V_{RN}(t) = L\frac{\mathrm{d}\, I_{RN}(t)}{\mathrm{d}\, t}$$
$$V_{VN}(t) - V_{SN}(t) = L\frac{\mathrm{d}\, I_{SN}(t)}{\mathrm{d}\, t}$$
$$V_{WN}(t) - V_{TN}(t) = L\frac{\mathrm{d}\, I_{TN}(t)}{\mathrm{d}\, t}$$

Scalar Sliding

Commutations



The control algorithm is dependent on the difference between the reference current of a phase and the current of the active filter in that phase, that is, according to the values of this error in each phase such are the commutations of each branch of the inverter.

$$e_{1,\,2,\,3} = i_{\mathrm{UN,\,VN,\,WN}}(t) - i^*_{\mathrm{UN,\,VN,\,WN}}(t)$$

Scalar Control:

$$V_{UN}(t) - V_{RN}(t) = L\frac{\mathrm{d}\,I_{RN}(t)}{\mathrm{d}\,t}$$

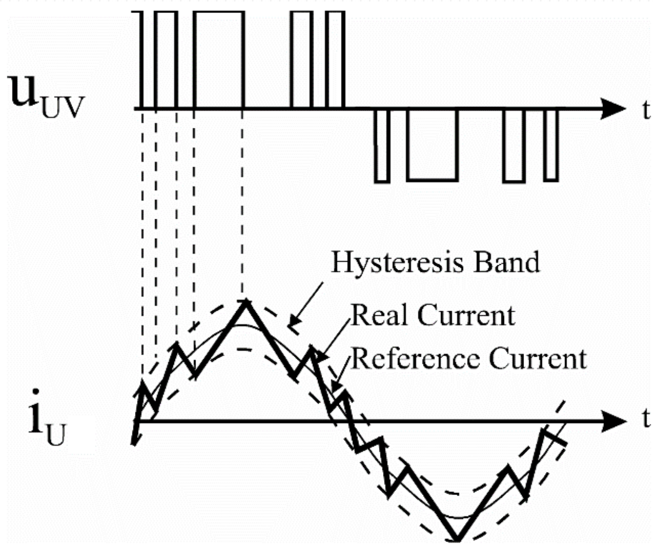
$$V_{VN}(t) - V_{SN}(t) = L\frac{\mathrm{d}\,I_{SN}(t)}{\mathrm{d}\,t}$$

$$V_{WN}(t) - V_{TN}(t) = L\frac{\mathrm{d}\,I_{TN}(t)}{\mathrm{d}\,t}$$

Scalar Sliding

Deadband (hysteresis band)

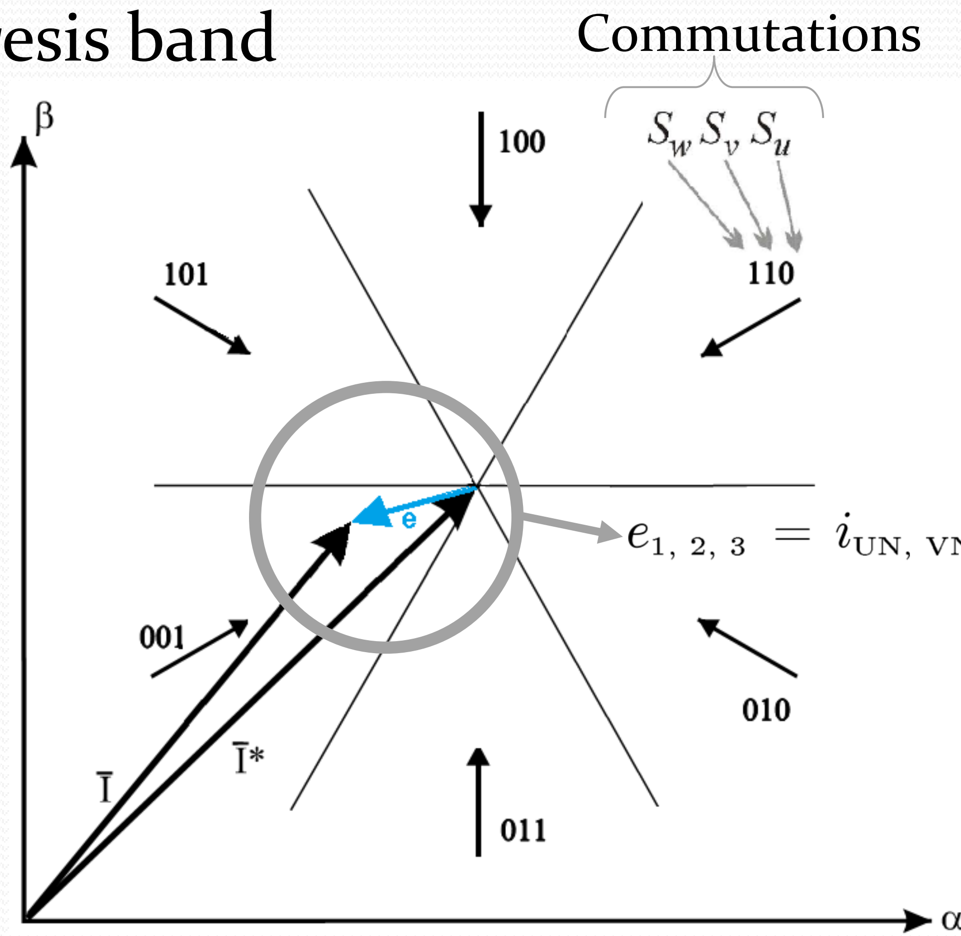
If (e_a>HB) then $s_u = 0$ else if (e_a<-HB) then $s_u= 1$
If (e_b>HB) then $s_v = 0$ else if (e_b<-HB) then $s_v= 1$
If (e_c>HB) then $s_w = 0$ else if (e_c<-HB) then $s_w=1$



So far we have seen that in each phase if the error was positive, switch 1 of that phase is activated and switch 2 of that phase is closed and vice versa. Now we add a deadband to that controller.

Sliding escalar

Null hysteresis band

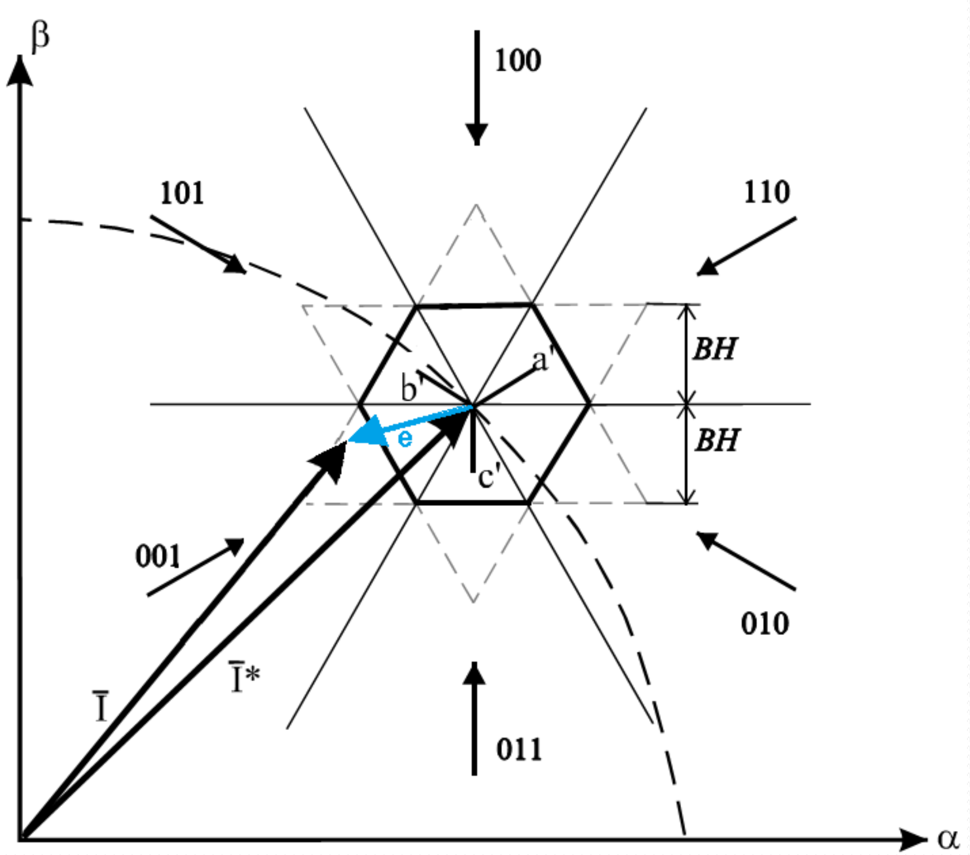


$$e_{1,\ 2,\ 3} = i_{\mathrm{UN,\ VN,\ WN}}(t) - i^*_{\mathrm{UN,\ VN,\ WN}}(t)$$

Note: α and β currents compensation, but no γ.

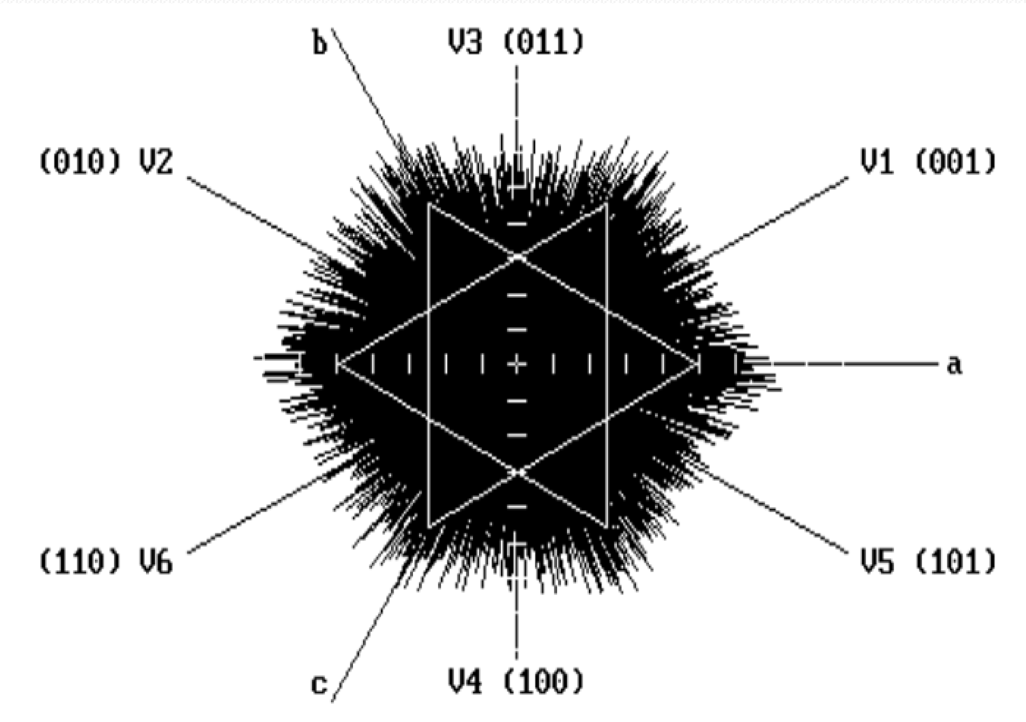
Sliding escalar

Constant hysteresis band



Sliding escalar

Constant hysteresis band, expected results:



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2º) Theory

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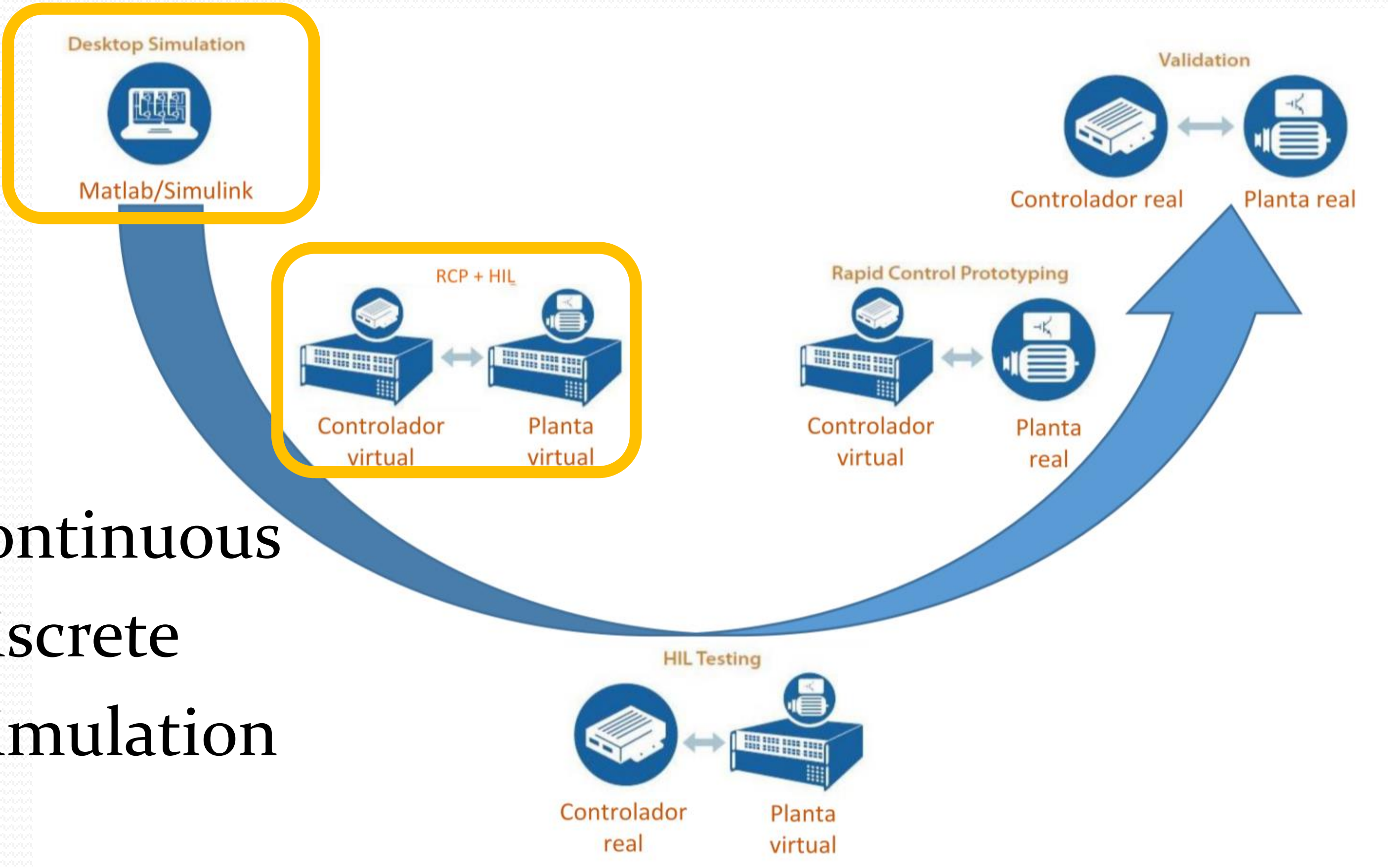
Scalar Sliding

3º) **Simulations**

4º) Simulations results

5º) Conclusions

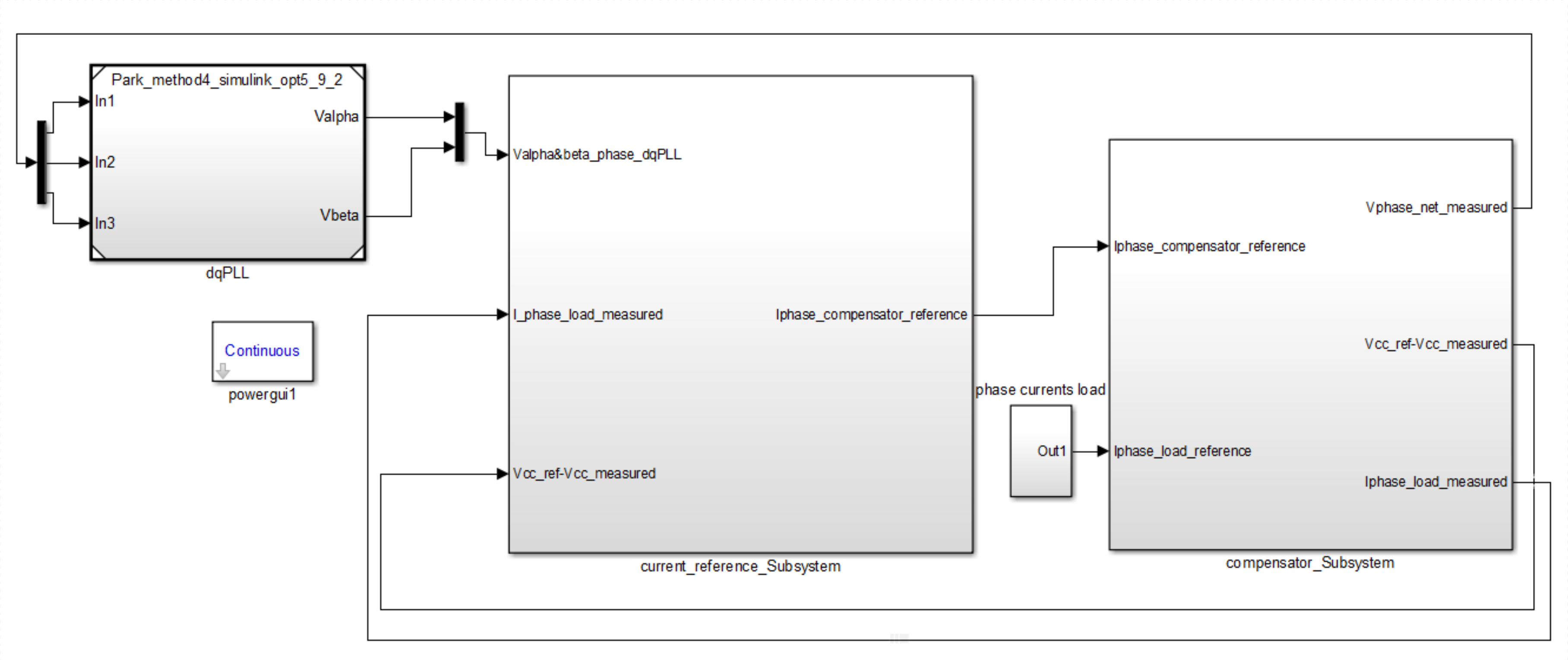
Simulations



- Simulink continuous
- Simulink discrete
- Real time simulation RCP-HIL

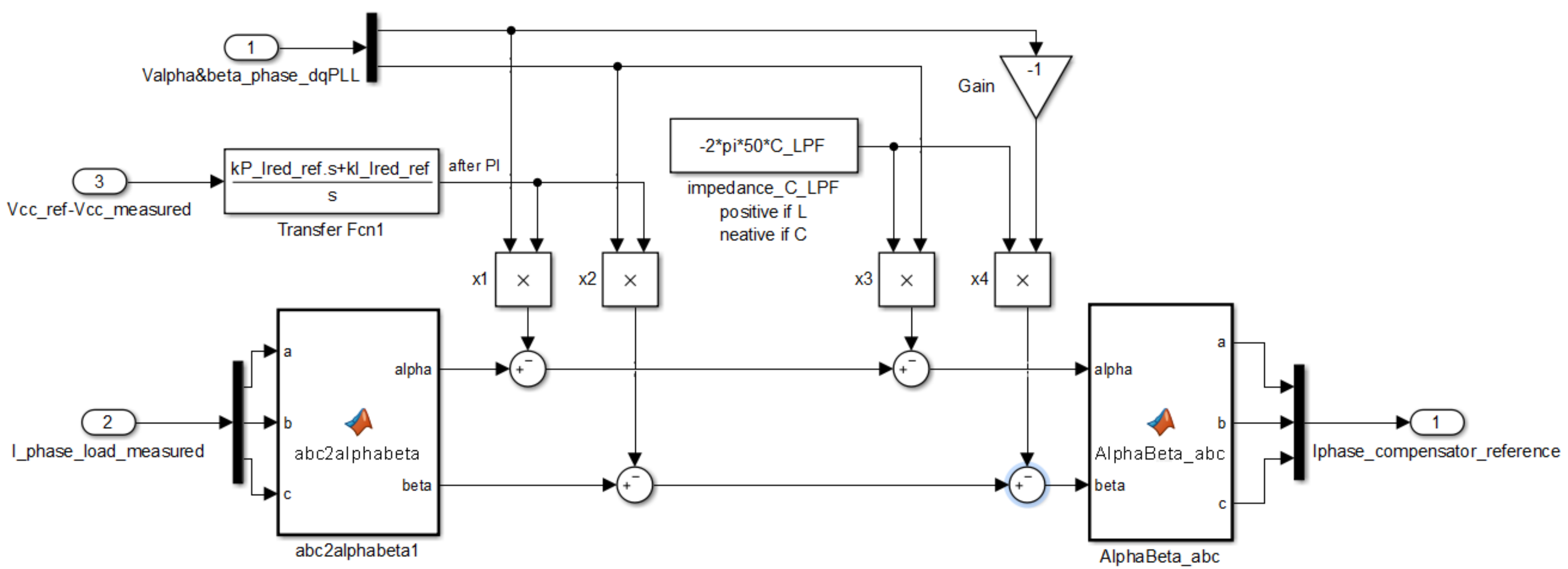
Simulations

- Simulink continuous



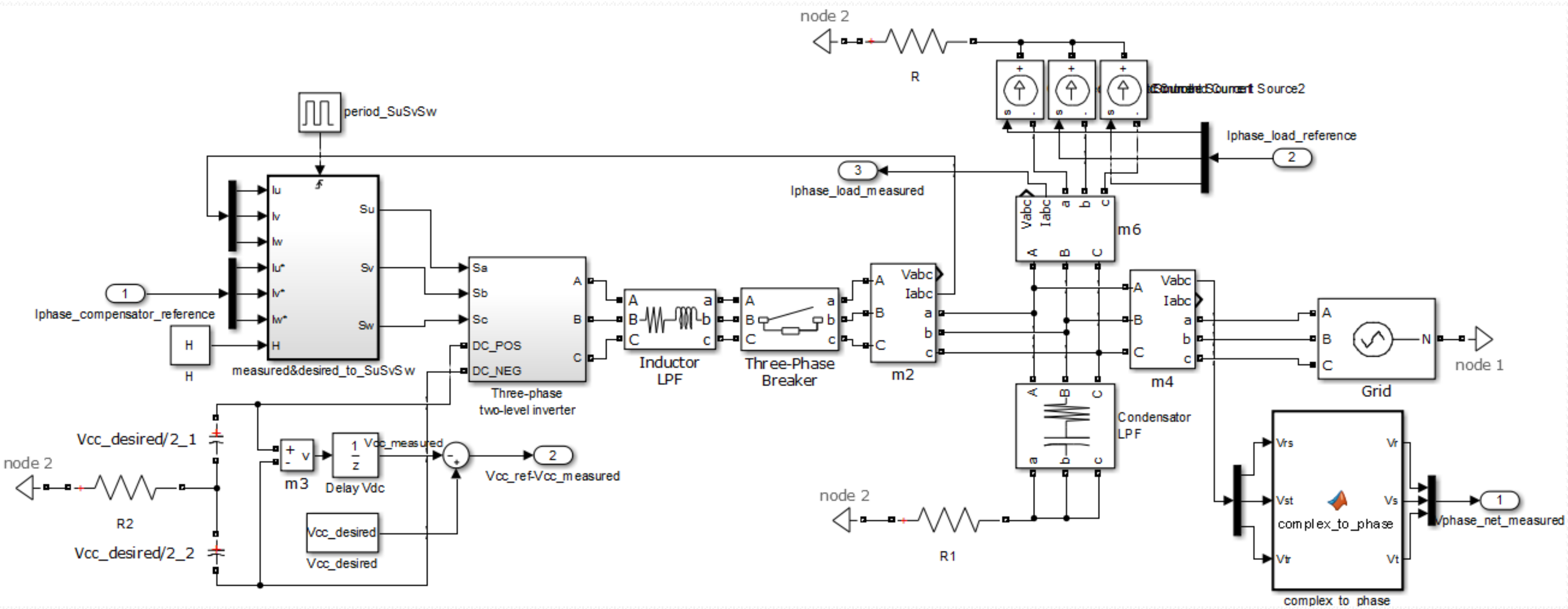
Simulations

- Simulink continuous



Simulations

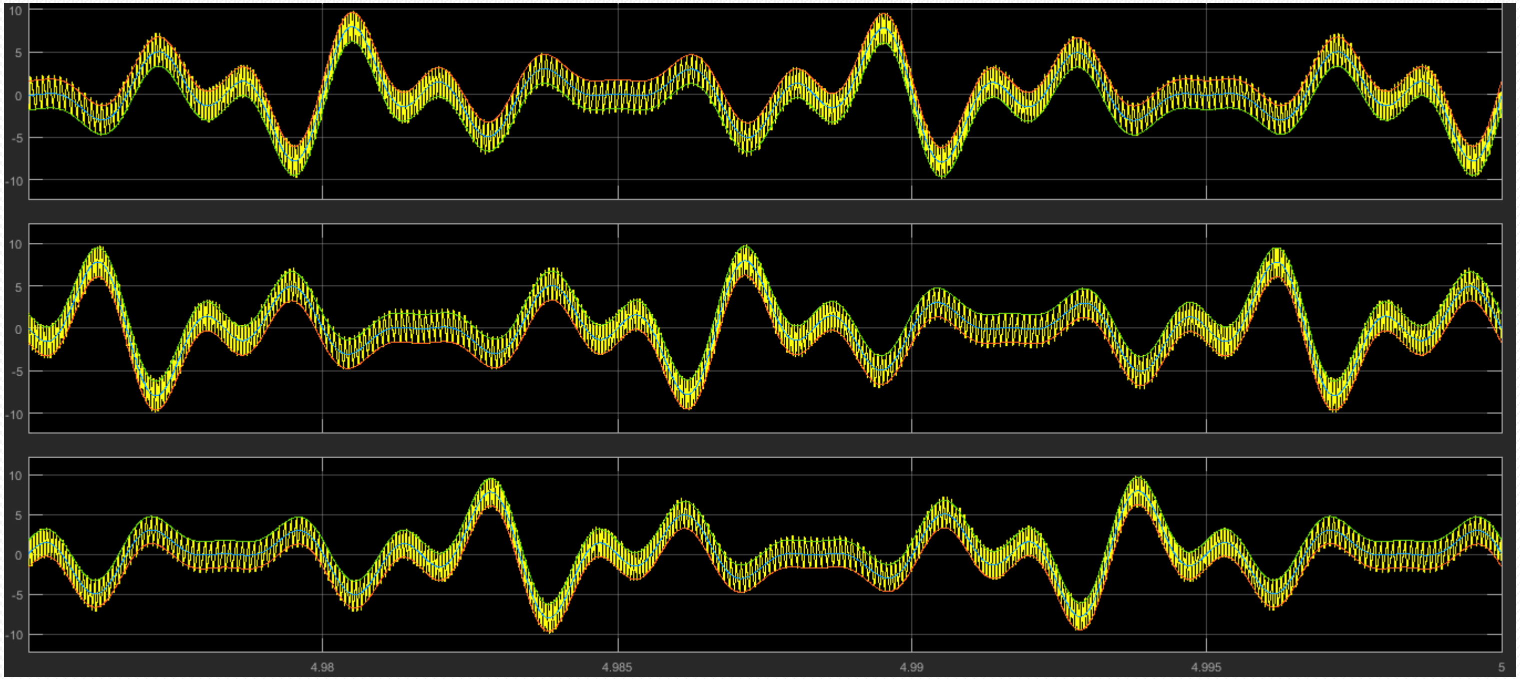
- Simulink continuous



Simulations

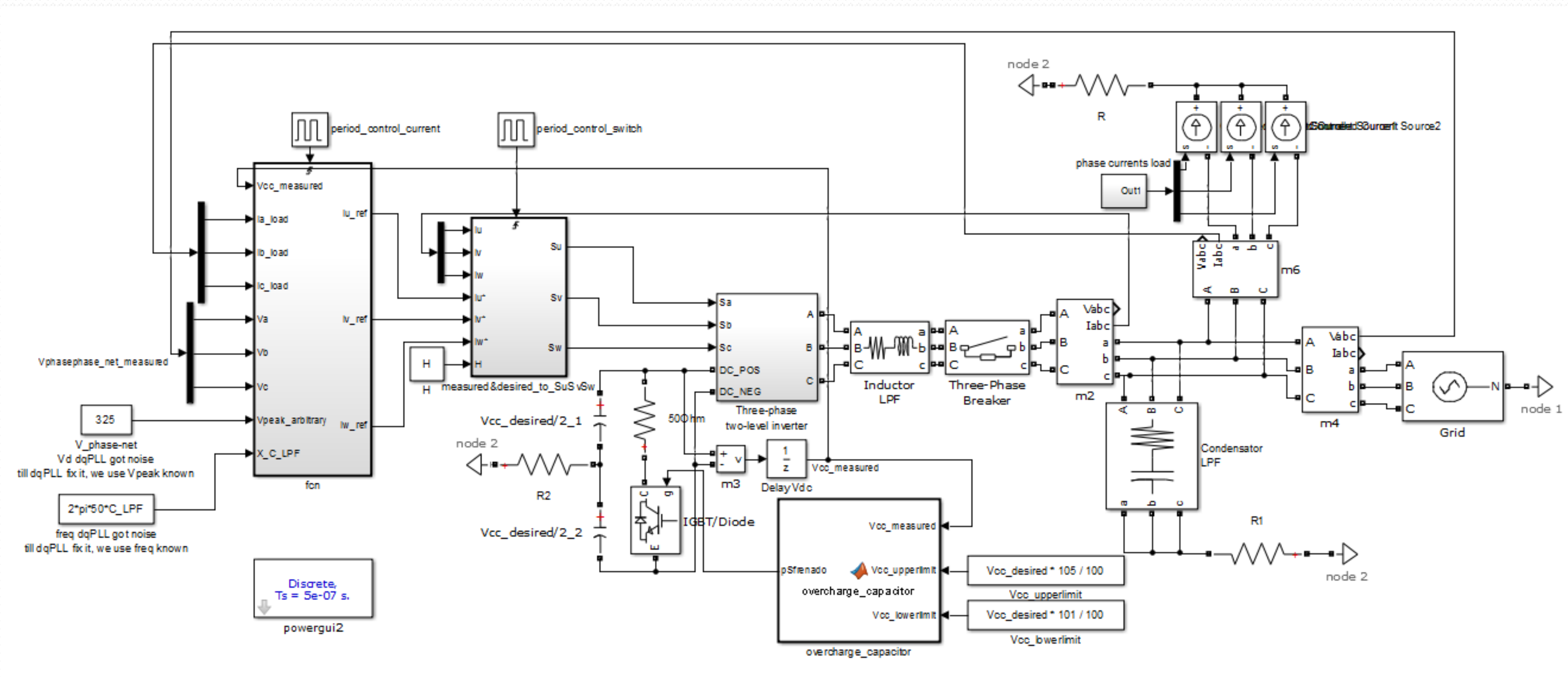
- Simulink continuous

The inverter currents of each phase in stationary and it is observed that they are **between their hysteresis bands** of each phase, that there are no sections of little or too much switching frequency, etc.



Simulations

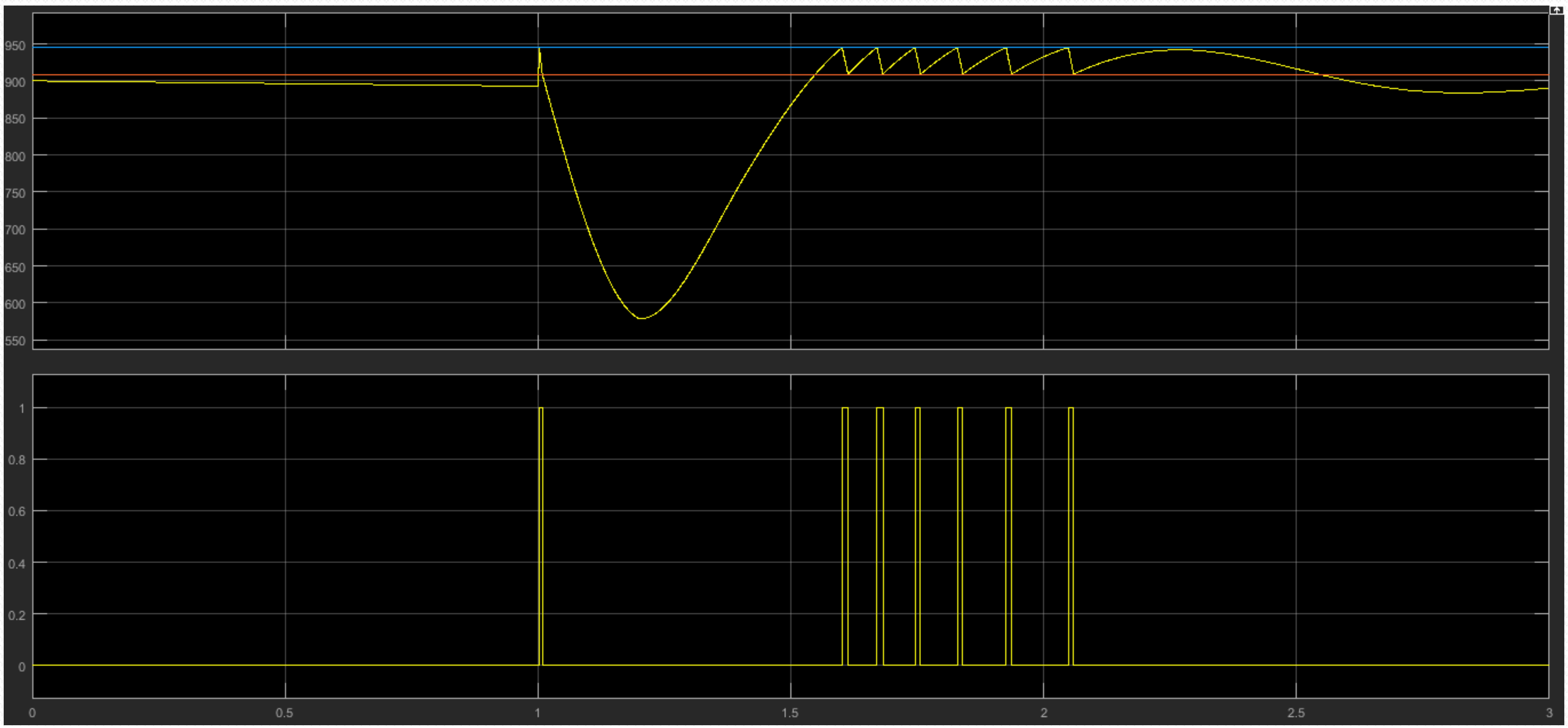
- Simulink discrete



Simulations

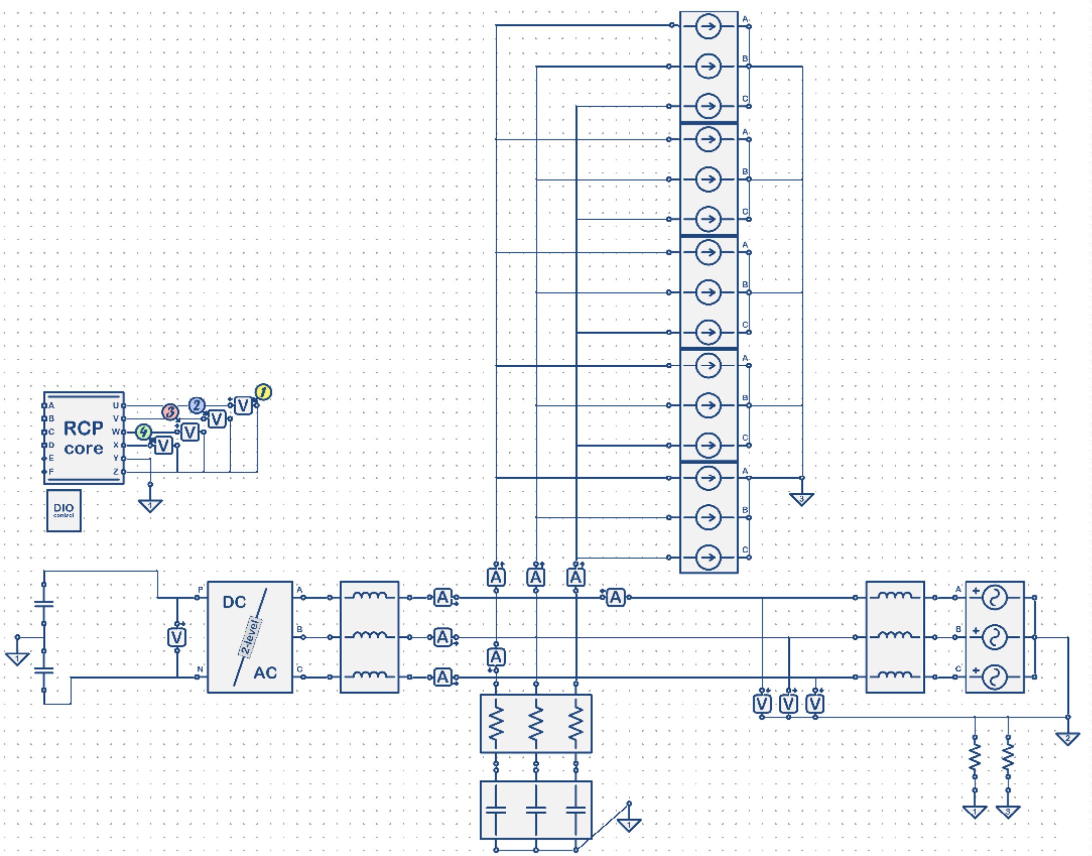
- Simulink discrete

In the upper subplot, the voltage of the inverter's DC capacitor is observed.
And in lower subplot the braking resistor trips.



Simulations

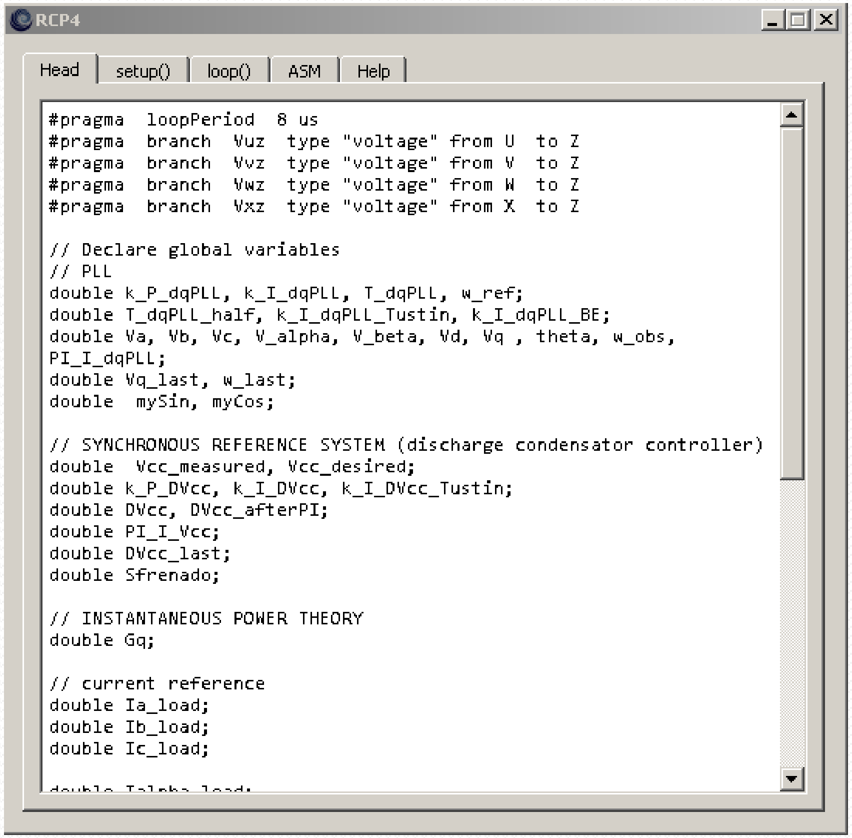
- Real time simulation: RCP-HIL



Simulations

- Real time simulation: RCP-HIL

Head

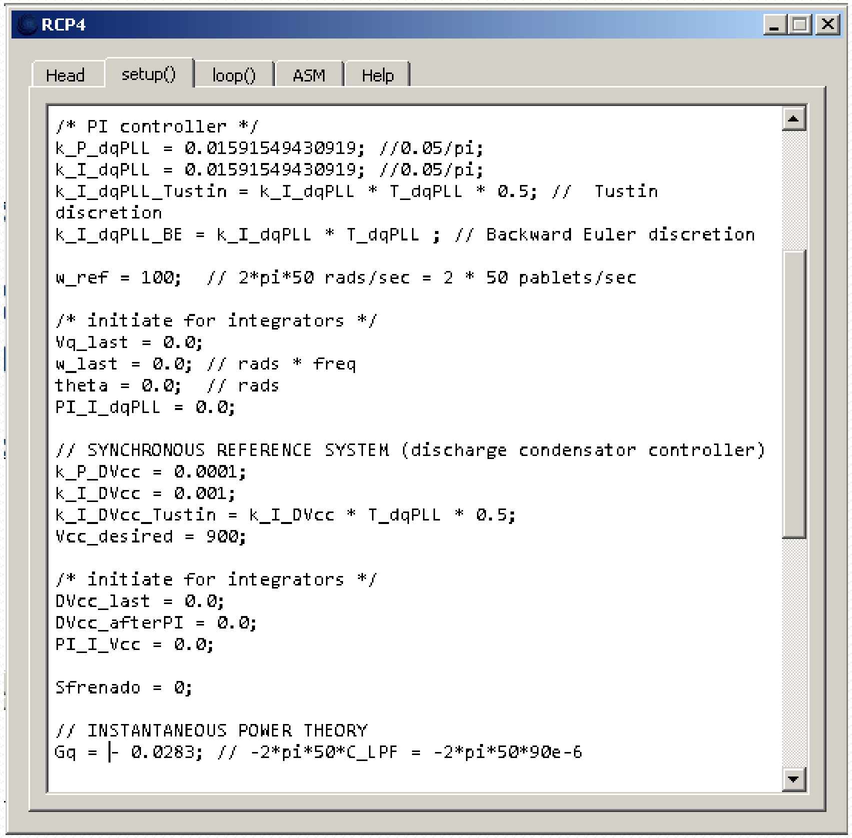



```
#pragma  loopPeriod  8 us
#pragma  branch  Vuz  type "voltage" from U  to Z
#pragma  branch  Vvz  type "voltage" from V  to Z
#pragma  branch  Vwz  type "voltage" from W  to Z
#pragma  branch  Vxz  type "voltage" from X  to Z

// Declare global variables
// PLL
double k_P_dqPLL, k_I_dqPLL, T_dqPLL, w_ref;
double T_dqPLL_half, k_I_dqPLL_Tustin, k_I_dqPLL_BE;
double Va, Vb, Vc, V_alpha, V_beta, Vd, Vq , theta, w_obs,
PI_I_dqPLL;
double Vq_last, w_last;
double  mySin, myCos;

// SYNCHRONOUS REFERENCE SYSTEM (discharge condensator controller)
double  Vcc_measured, Vcc_desired;
double k_P_DVcc, k_I_DVcc, k_I_DVcc_Tustin;
double DVcc, DVcc_afterPI;
double PI_I_Vcc;
double DVcc_last;
double Sfrenado;

// INSTANTANEOUS POWER THEORY
double Gq;

// current reference
double Ia_load;
double Ib_load;
double Ic_load;
```

Simulations

- Real time simulation: RCP-HIL

Setup

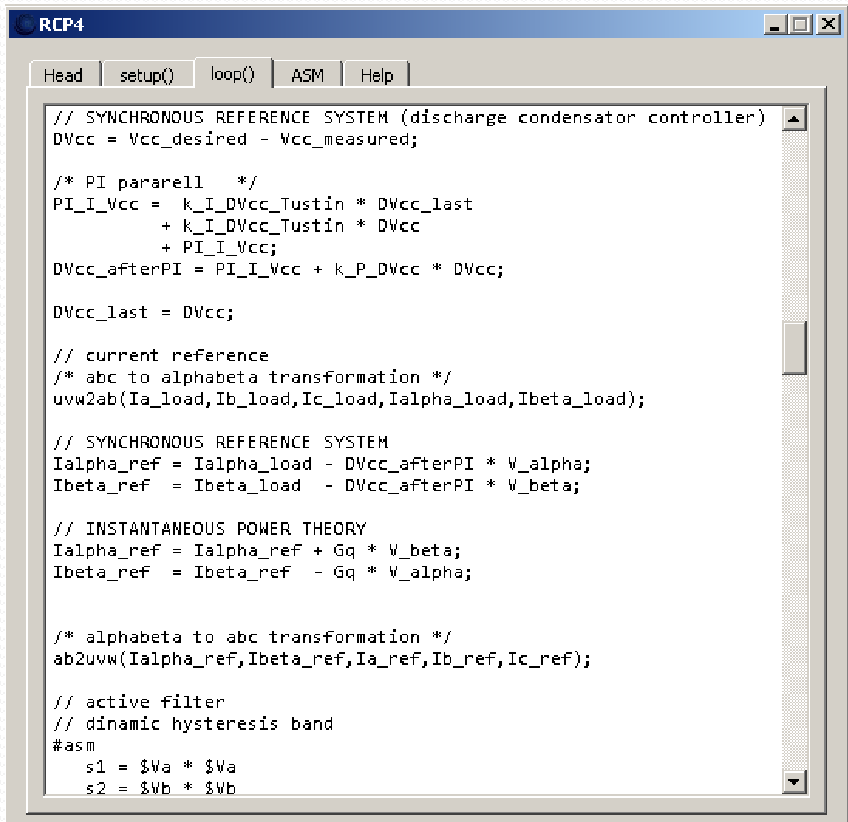



```
/* PI controller */
k_P_dqPLL = 0.01591549430919; //0.05/pi;
k_I_dqPLL = 0.01591549430919; //0.05/pi;
k_I_dqPLL_Tustin = k_I_dqPLL * T_dqPLL * 0.5; //  Tustin
discretion
k_I_dqPLL_BE = k_I_dqPLL * T_dqPLL ; // Backward Euler discretion

w_ref = 100;  // 2*pi*50 rads/sec = 2 * 50 pablets/sec

/* initiate for integrators */
Vq_last = 0.0;
w_last = 0.0; // rads * freq
theta = 0.0;  // rads
PI_I_dqPLL = 0.0;

// SYNCHRONOUS REFERENCE SYSTEM (discharge condensator controller)
k_P_DVcc = 0.0001;
k_I_DVcc = 0.001;
k_I_DVcc_Tustin = k_I_DVcc * T_dqPLL * 0.5;
Vcc_desired = 900;

/* initiate for integrators */
DVcc_last = 0.0;
DVcc_afterPI = 0.0;
PI_I_Vcc = 0.0;

Sfrenado = 0;

// INSTANTANEOUS POWER THEORY
Gq = - 0.0283; // -2*pi*50*C_LPF = -2*pi*50*90e-6
```

Simulations

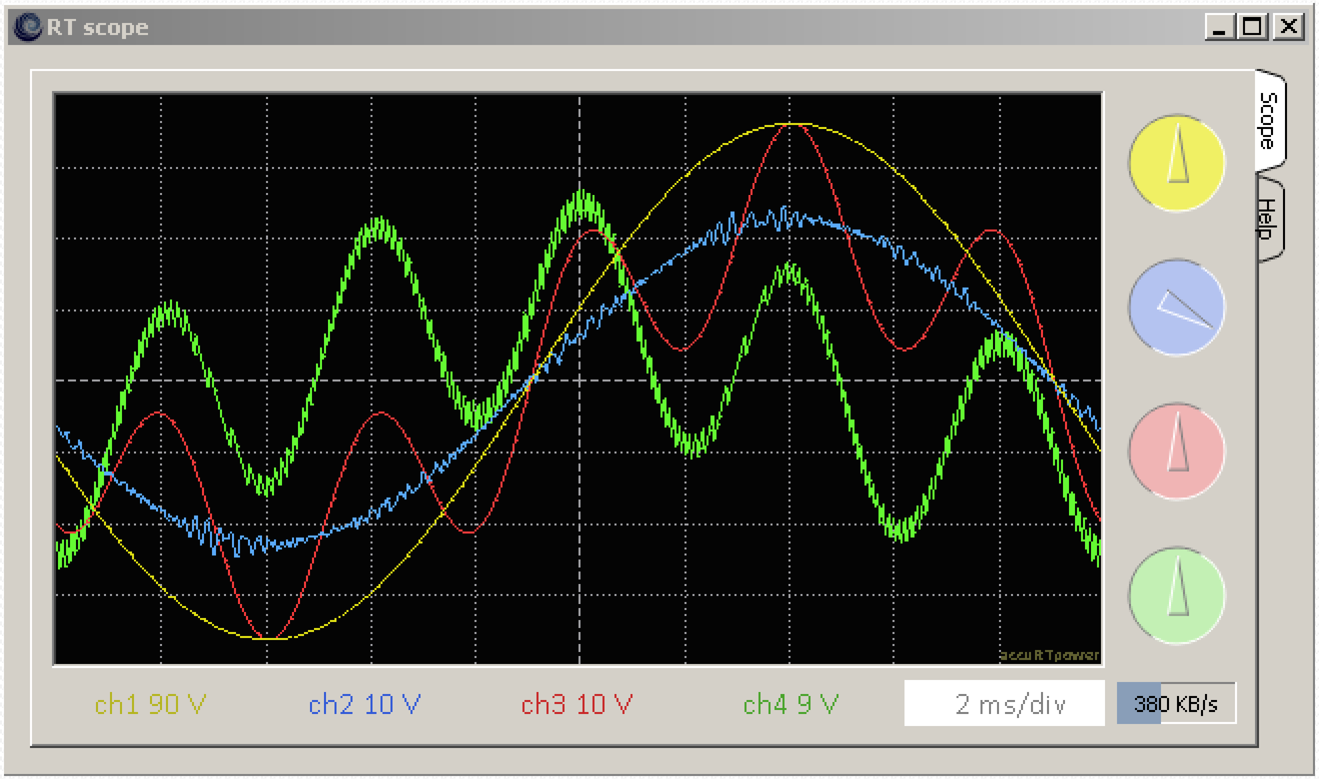
- Real time simulation: RCP-HIL

Loop



Simulations

- Real time simulation: RCP-HIL



Simulations Results

Electric circuit

	Valor	Unidades	Variable computacional
Inductancia serie con el inversor	5.5	mH	L_LPF
Resistencia serie con el inversor	0.1	Ω	R_ L_LPF
Condensador paralelo con el inversor	90	μF	C_LPF
Resistencia serie con el condensador anterior	0.65	Ω	R_C_LPF
Inductancia de conexión a red	15	uH	L_red
Resistencia de conexión a red	20	mΩ	R_red
Tensión nominal de la fuente de tensión del inversor	900	V	VCC_desired

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Scalar Sliding

3º) Simulations

4º) **Simulations Results**

5º) Conclusions

Simulations Results

Grid voltage: 325 Volts phase-phase RMS

Dynamic Hysteresis Band :
$$H_u(t) = \frac{\left(\frac{V_{CC}}{2}\right)^2 - V_{RN}(t)^2}{2 \cdot L \cdot F_{SW}^{*} \cdot V_{CC}}$$

PI Controller: k_P y k_I

Simulations Results

Load current

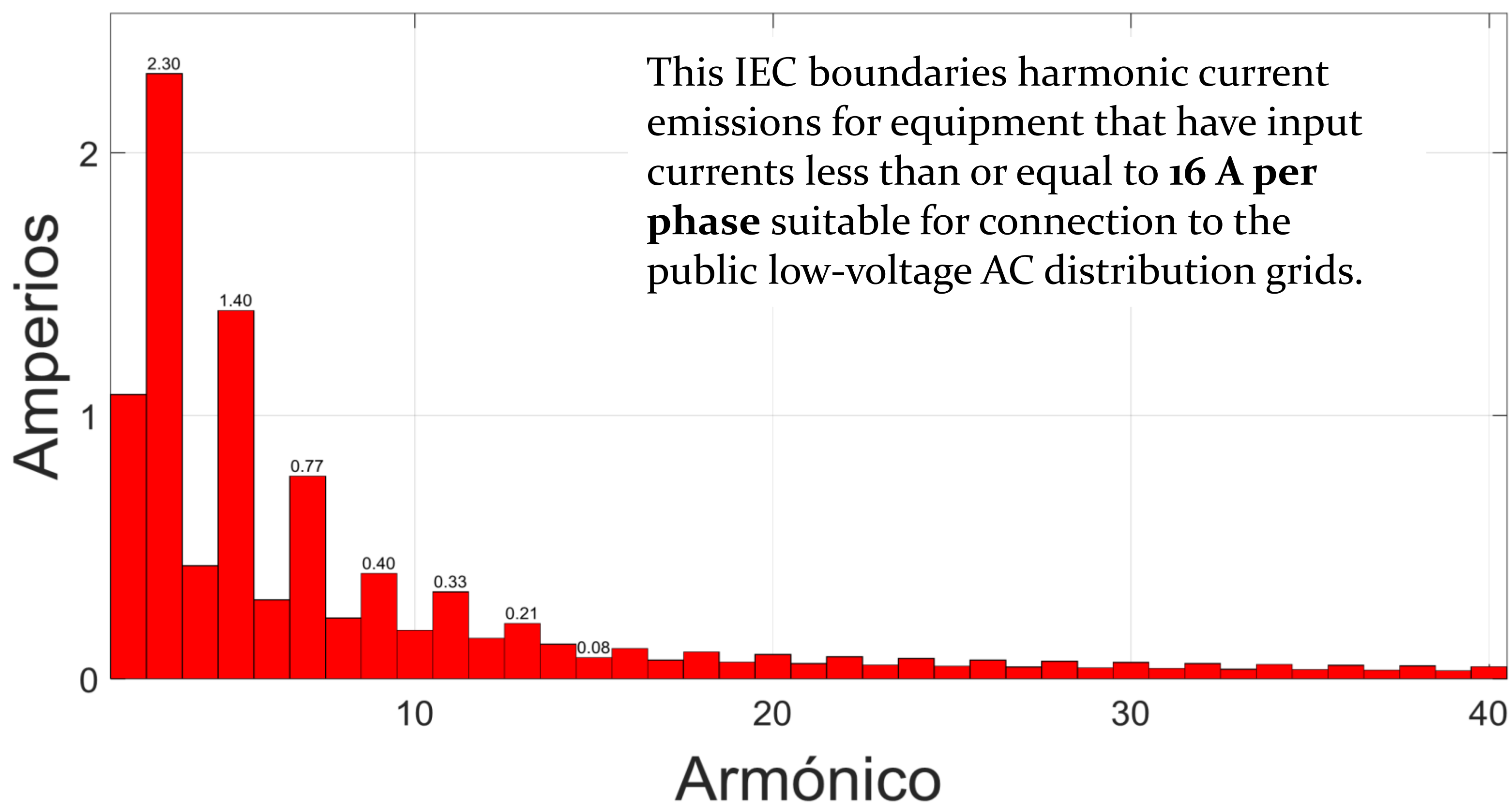
	Corriente de la carga				
Armónico	1	5	7	11	13
Power factor	0	0	0	0	0
Amperaje RMS					
Máximo del 5º armónico	16	60%			
Máximo del 7º armónico	16		43%		
Máximo del 11º armónico	16			24%	
Máximo del 13º armónico	16				22%
Máximo del 5º y 7º armónico	16	26%	26%		
Máximo del 11º y 13º armónico	16			7%	7%
Máximo del 5º, 7º, 11º y 13º armónico	16	5%	5%	5%	5%

We **tested how far the compensator works** increasing the harmonics amplitude (5º, 7º, 11º, 13º,.. alone and combined) and adding reactive load consumption to measure the Active Filter limits capacities.

Charts with 5º harmonics are shown in next slides, thus, we can check its evolution compensation.

Simulations Results

- IEC 1000-3-2: grid current harmonics (“A” class)

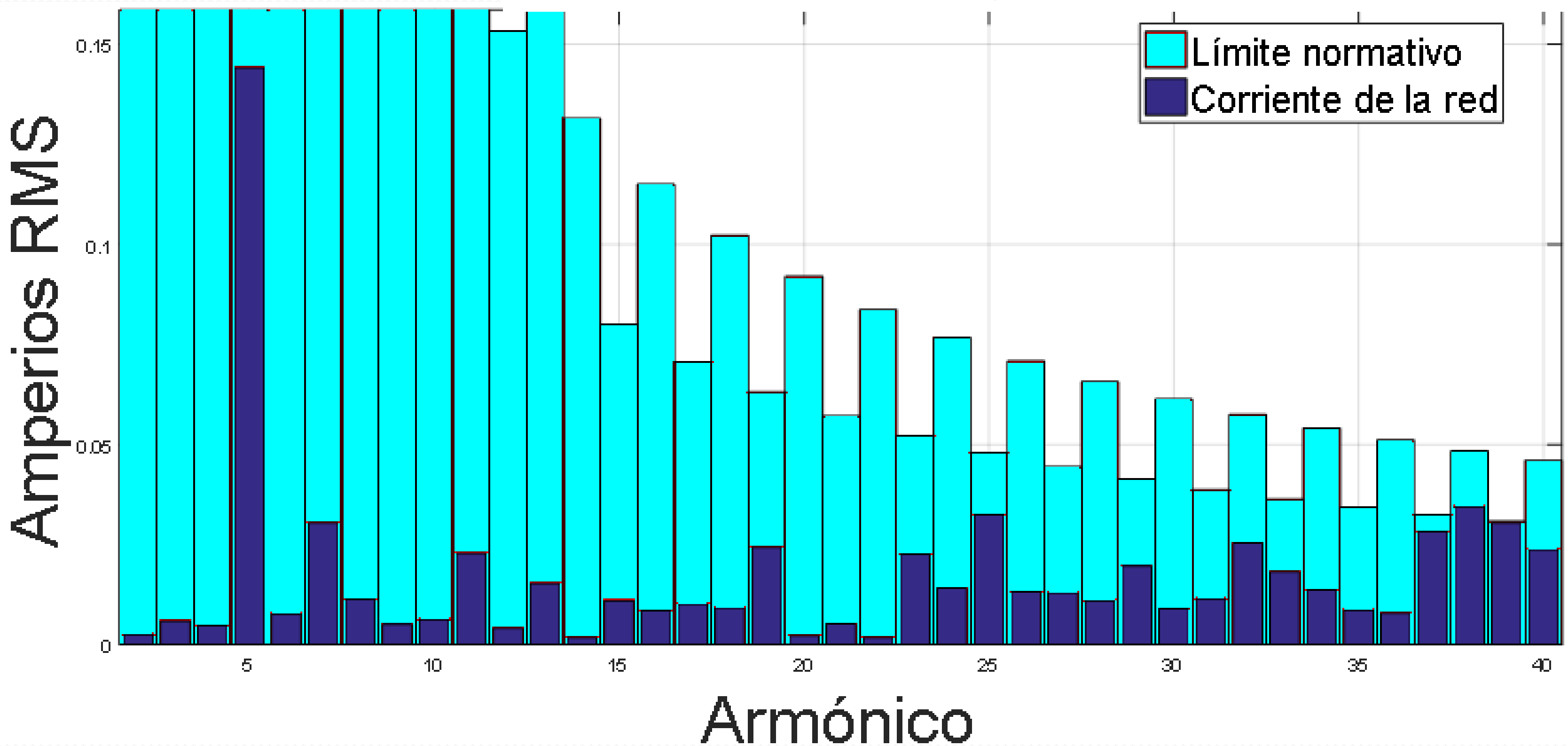


This IEC boundaries harmonic current emissions for equipment that have input currents less than or equal to **16 A per phase** suitable for connection to the public low-voltage AC distribution grids.

Simulations Results

- IEC 1000-3-2

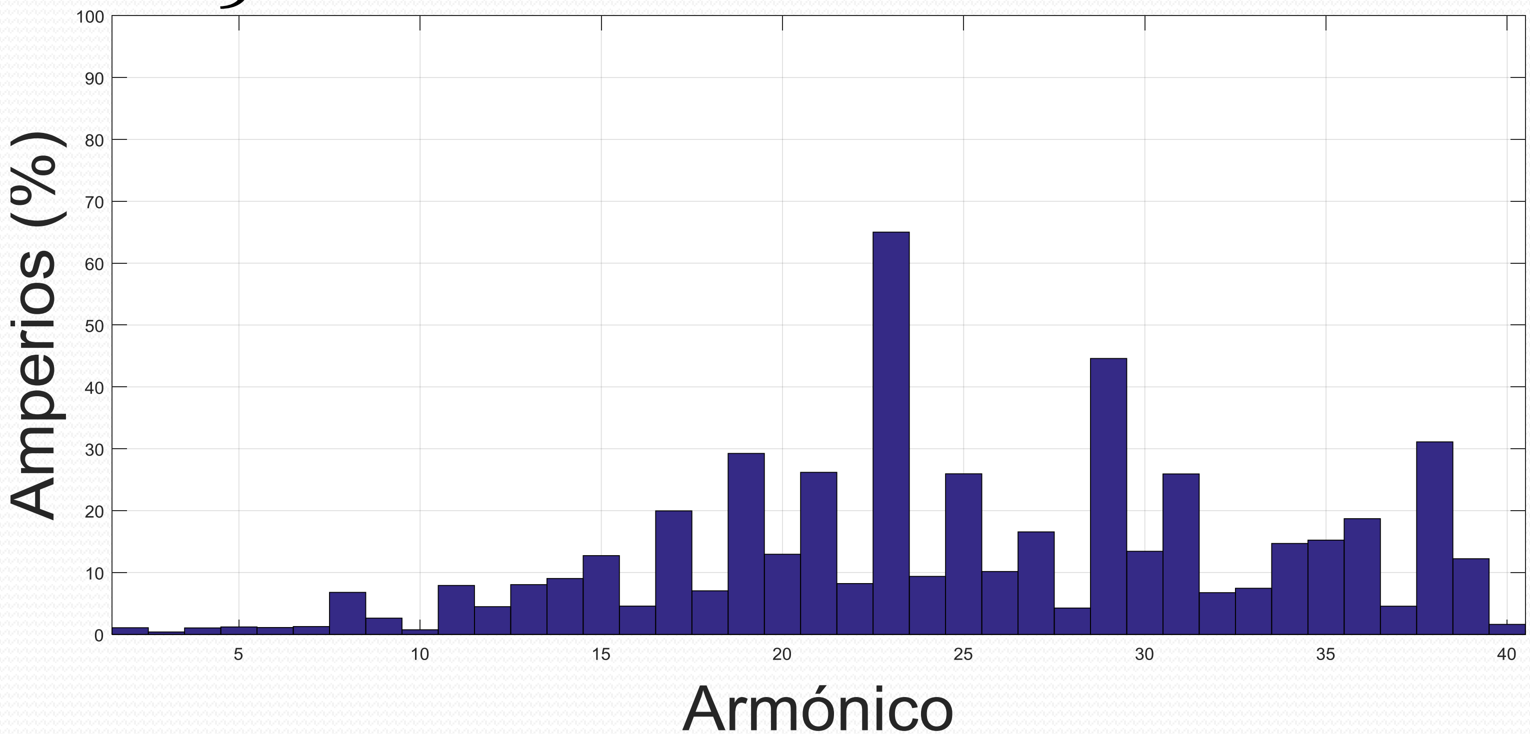
We can plot the amperage of harmonics in current of the network against the limit imposed by the norm, or percentage as it is observed in following slides



Simulations Results

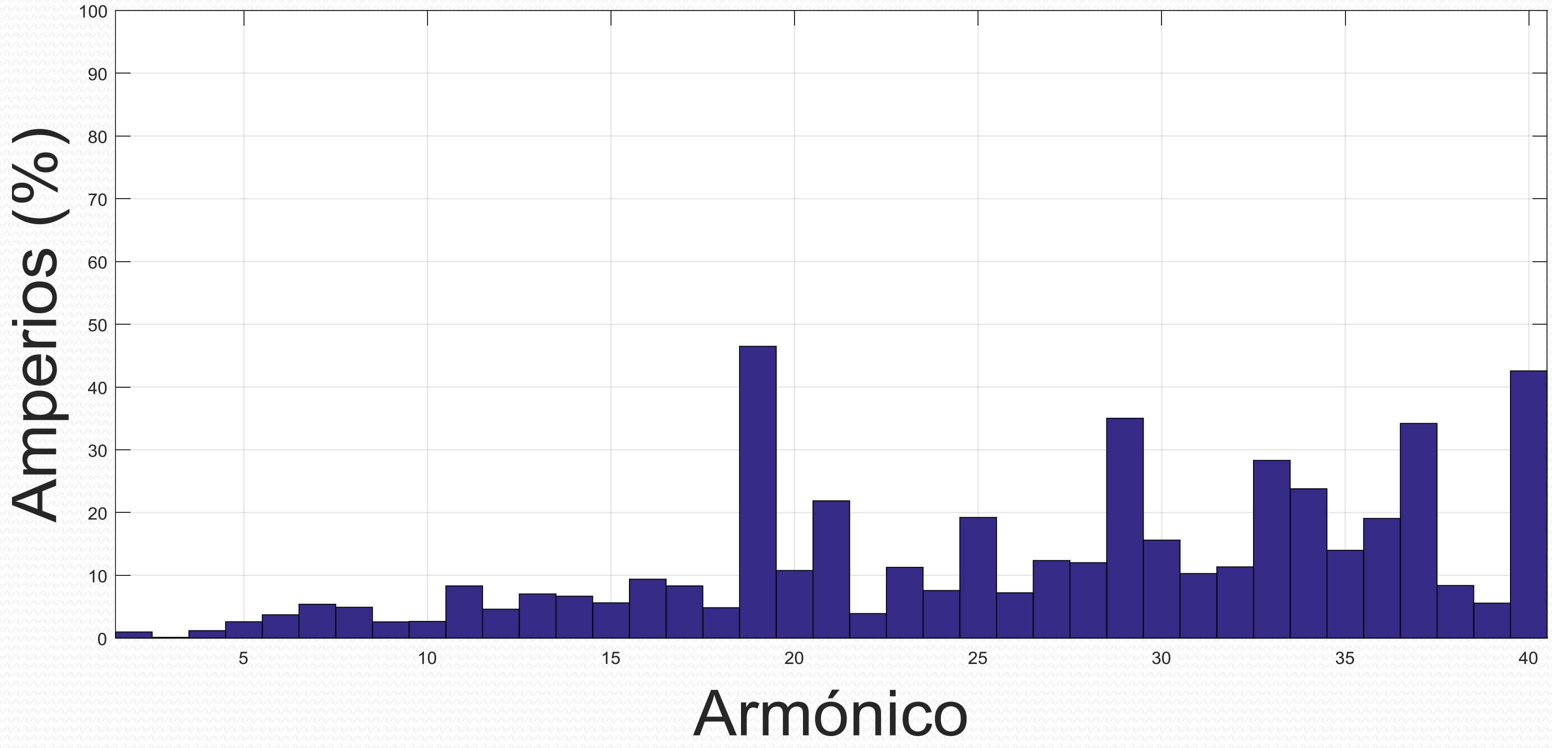
In following slides we **test how far the compensator works** increasing the 5th harmonic amplitude (from 0 to 60%*16 A per phase). The last value touchs the IEC limit, so we can compensate till taht value if there were only 5th harmonics.

0% of 5th harmonic



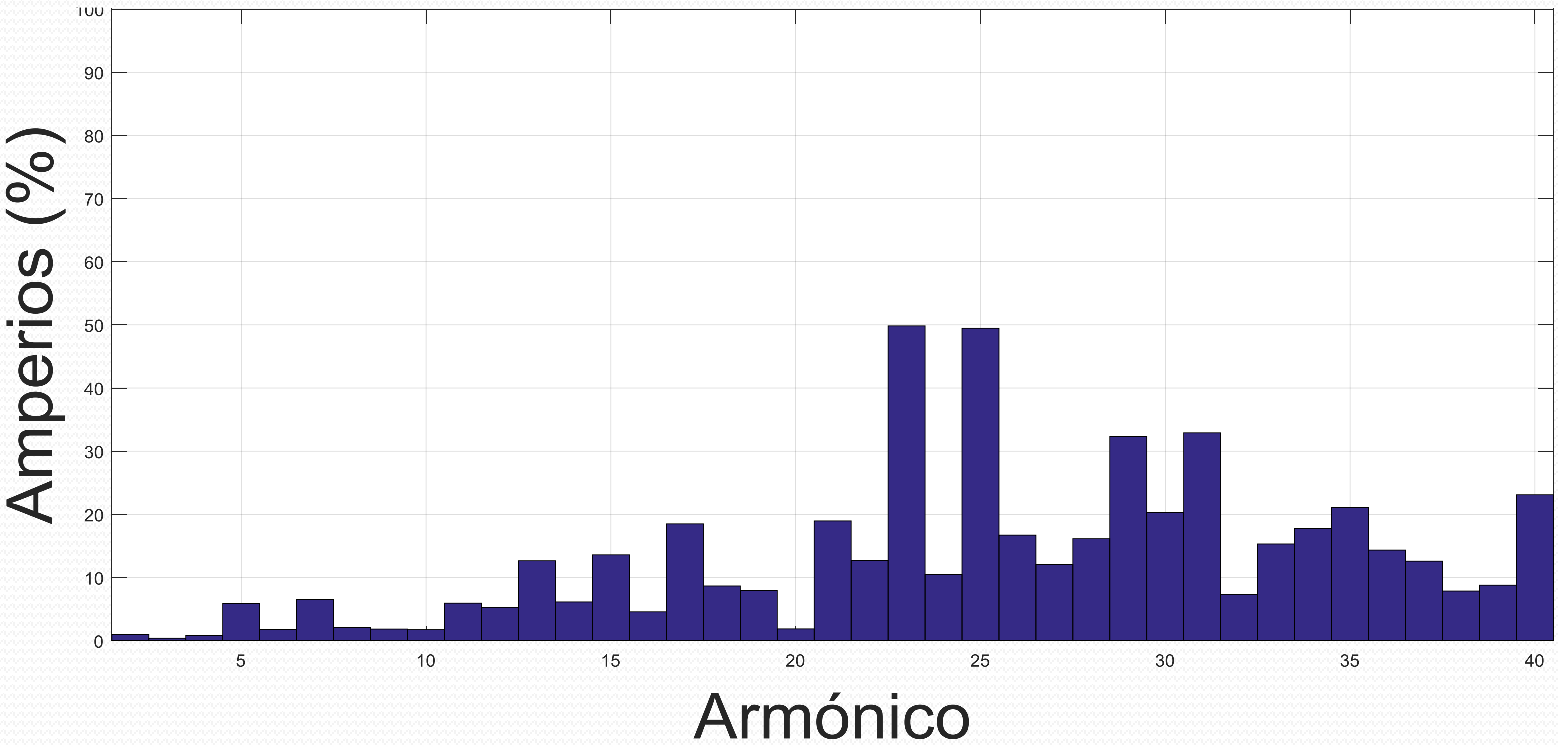
Simulations Results

20% of 5th harmonic



Simulations Results

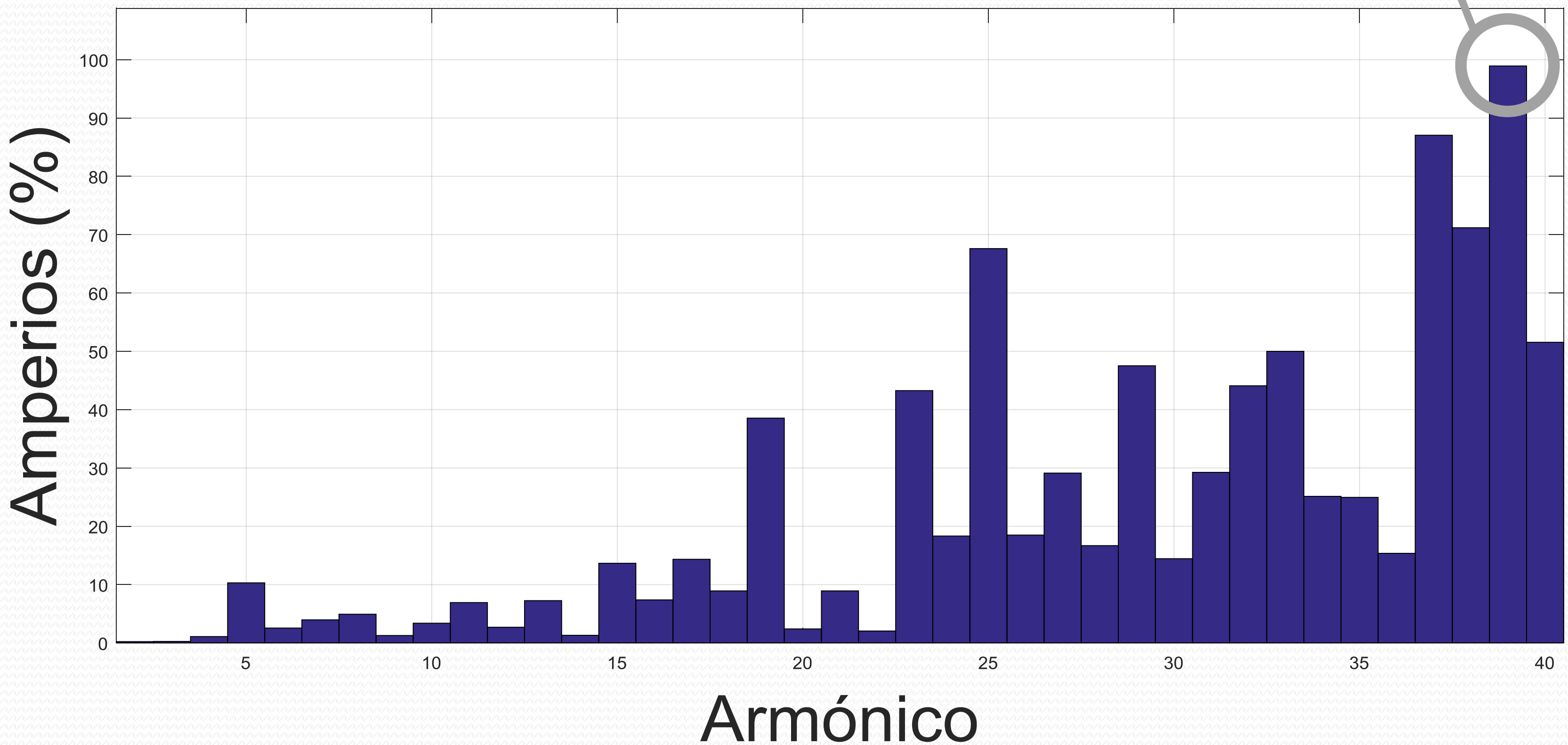
40% of 5th harmonic



Simulations Results

60% of 5th harmonic

Practically IEC limit



Simulations Results

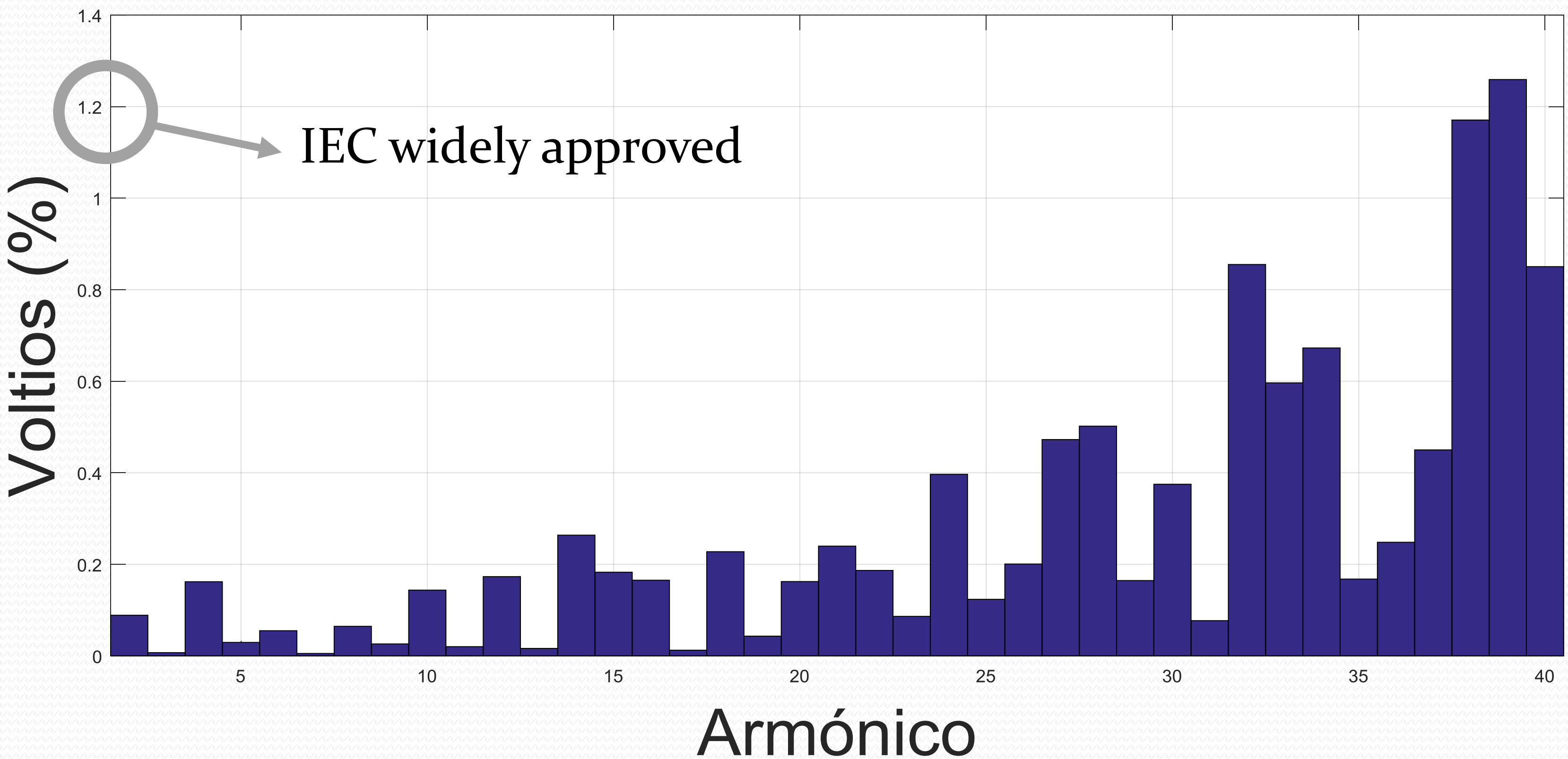
These are the main goals to achive or main limitators to optimaze:

- IEC 1000-3-2: current harmonics in Grid
- IEC 1000-2-2: voltaje harmonics in Grid
- Balance of Electric power
- Switching frequency
- Inverter DC capacitor voltage

In addition to limiting the harmonics current in the Grid, other main objectives are:
-the power used by the Active Filter to be moderate
- bring the switching frequency of the inverter poles under 20kHz
- surpass with other regulations, such as harmonics in mains voltage (EN -61000-2-2)

Simulations Results

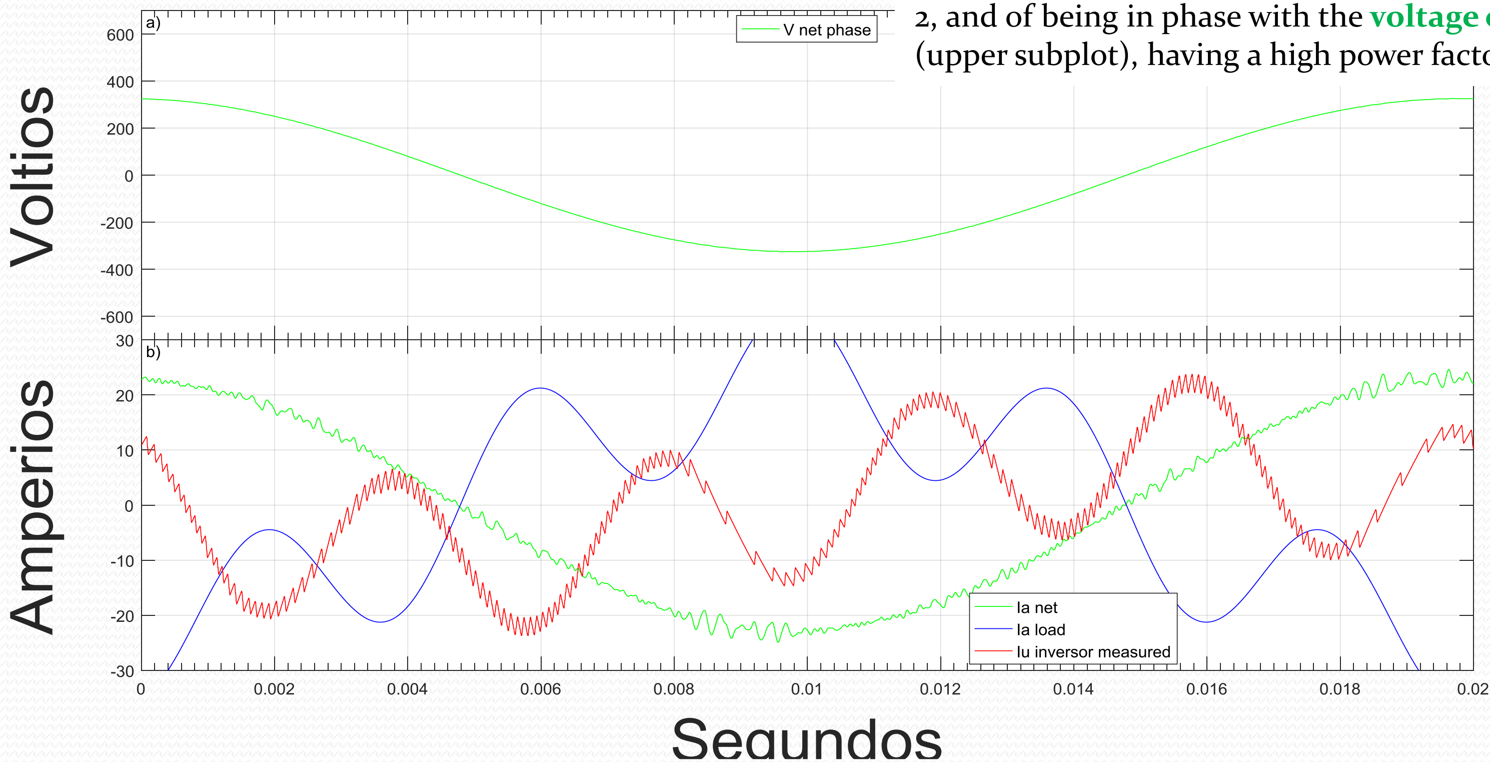
- IEC 1000-2-2: voltaje harmonics in grid. Plot of 60% 5th harmonic



Simulations Results

- Electric power balance

In blue: the **load current**, with the 5 harmonic at 60%
In red: the current generated by the **Active Filter**, as adjusted to a dynamic hysteresis band
In green: the current generated by the **grid**, which meets our objectives of not having more harmonics than those allowed by the standard as seen in the goal of IEC-1000-3-2, and of being in phase with the **voltage of the grid** (upper subplot), having a high power factor.



Simulations Results

- Electric power balance

  We expect the load to demand at 50 Hz (plus harmoncis):

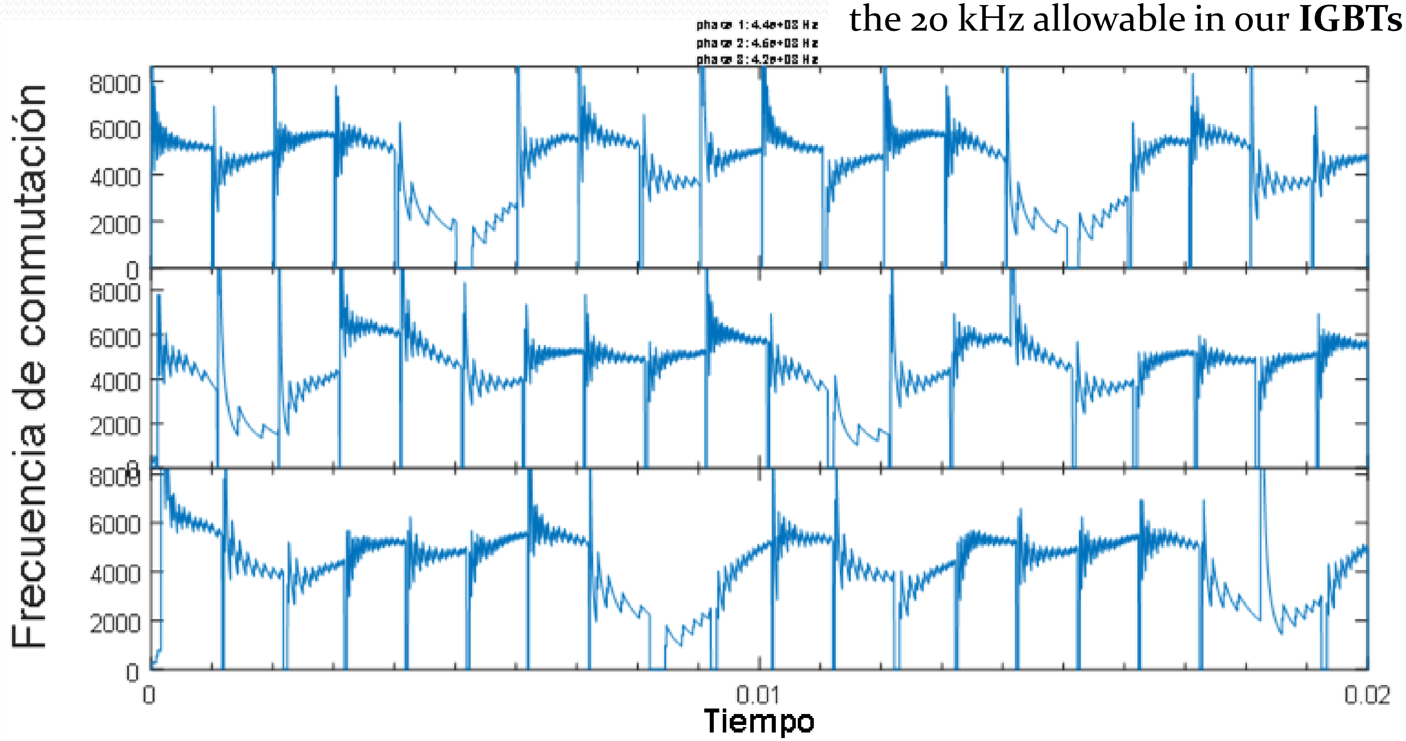
$$S_n = 3\,V_{fn}\,I_{fn} = 3 \cdot 230\,\mathrm{V} \cdot 16\,\mathrm{A} = 11\,\mathrm{kVA}$$

	Red	Inversor	Carga	C_{LPF}
Potencia útil (kW)	11.197	-0.146	-11.038	-0.012
Potencia reactiva (kVAr)	0.028	-4.482	0.010	4.499

Simulations Results

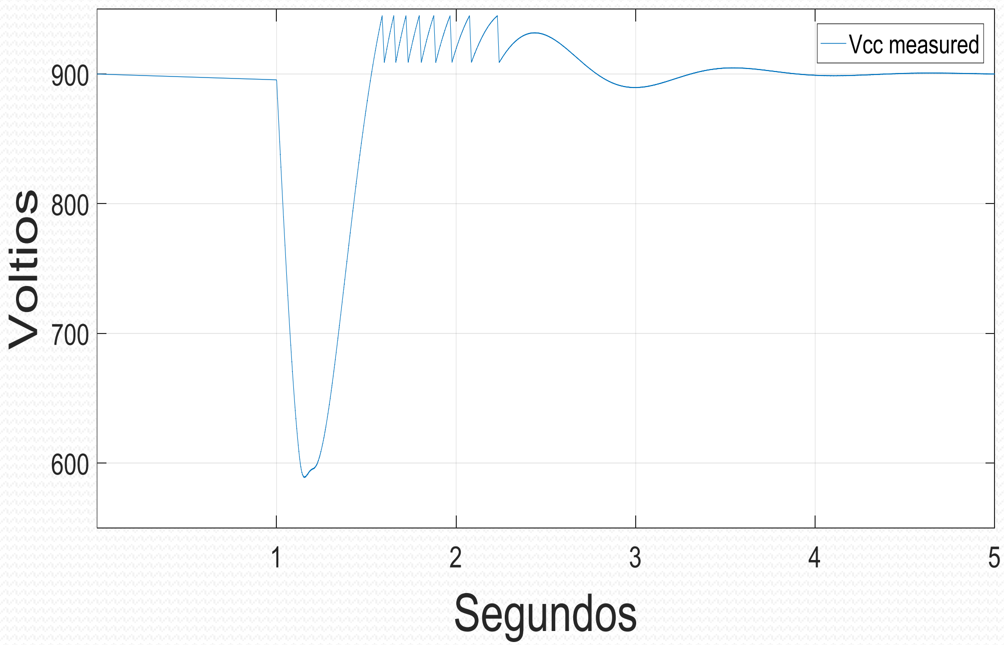
- Switching frequency

Switching **frequency** calculated according to the cumulative average in each phase.
That gives us an average frequency of the phases of about 4.5 kHz, and its peak frequencies about 8 kHz, very distant from the 20 kHz allowable in our **IGBTs**.



Simulations Results

- Inverter DC capacitor voltage



During the first seconds the Active Filter equipment is not connected, we simply let the PLL synchronize with the grid.
When we connect we find a **transient**, which we over-limit the overvoltage through a braking resistor.
Finally we **stabilize at the desired 900 Volts.**

1º) Introduction and purposes

2º) Theory

Setpoint/reference current

Scalar Sliding

3º) Simulations

4º) Simulations results

5º) **Conclusions**

Conclusions

- Active Filter
- RCP + HIL
- V-Modell
- Sliding Control

Conclusions

The main conclusion is that it meets the fundamental objective of an Active Filter, and it is that when faced with a demanding load of currents with harmonics, noise, reactive, ... the **grid supplies only the active power and** the rest of the current that the load demands is provided by the Active Filter.

The 2nd main conclusion is the correct implementation of real-time virtual controllers and plants, the RCP and HIL.
It has been compiled as thanks to these softwares can be performed:
- fast simulations, in real time
- simulations outside all material or human risk, since they are virtual simulations
- simulations with the desired specifications: very adverse conditions, test different elements of different commercial ranges,

It has been verified that the selected Sliding control is satisfactory, since it regulates signals with sudden changes, such as load currents.

Vielen Dank für Ihre Aufmerksamkeit!