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Faculty of Technology
Department of Electrical Engineering
Academic Masters: CE+RE
Lab: Advanced power electronics

Lab: N° 04

Shunt Active Power Filter

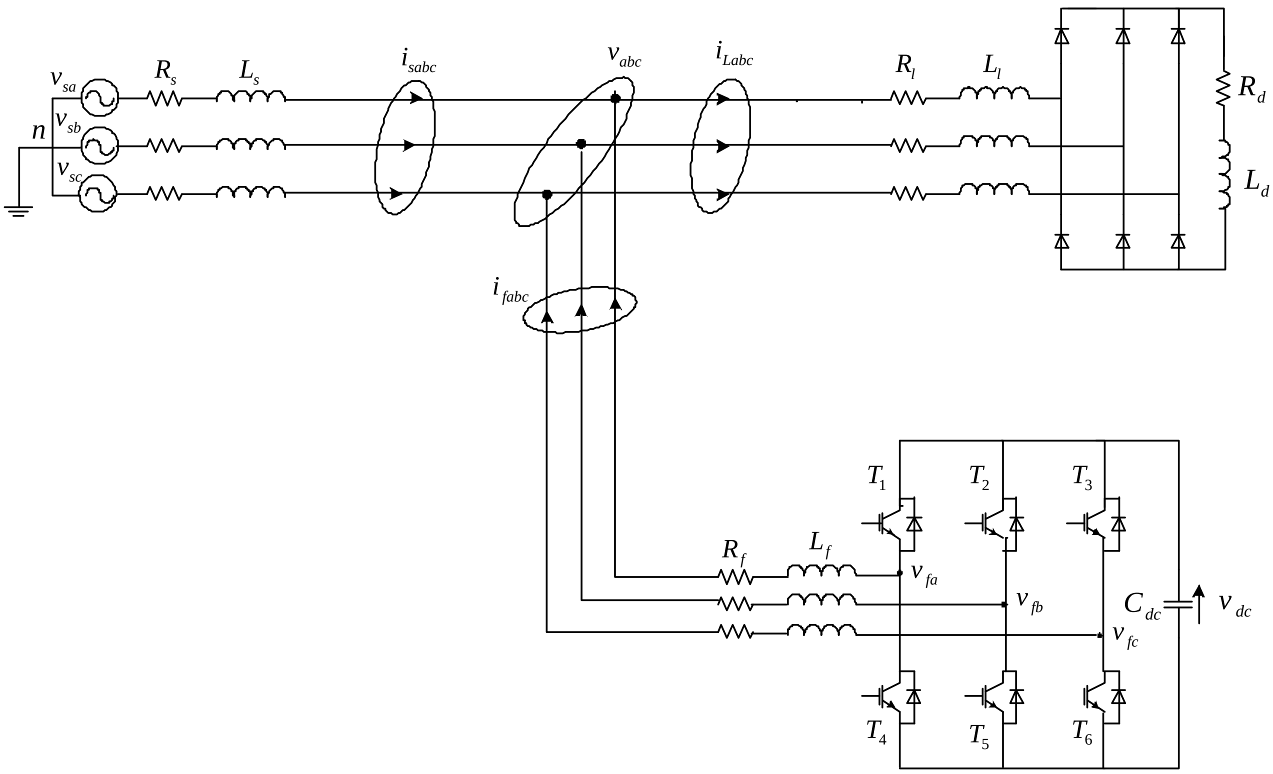
1. Lab objectives

Study and simulation of an active power filter connected in parallel with the electrical network in order to compensate for reactive energy and harmonic currents injected by nonlinear loads.

2. Theoretical study

Shunt active power filter structure

The figure below shows the structure of an active power filter connected in parallel to the electrical network. This system consists of a non-linear load, an active filter and a power supply network.

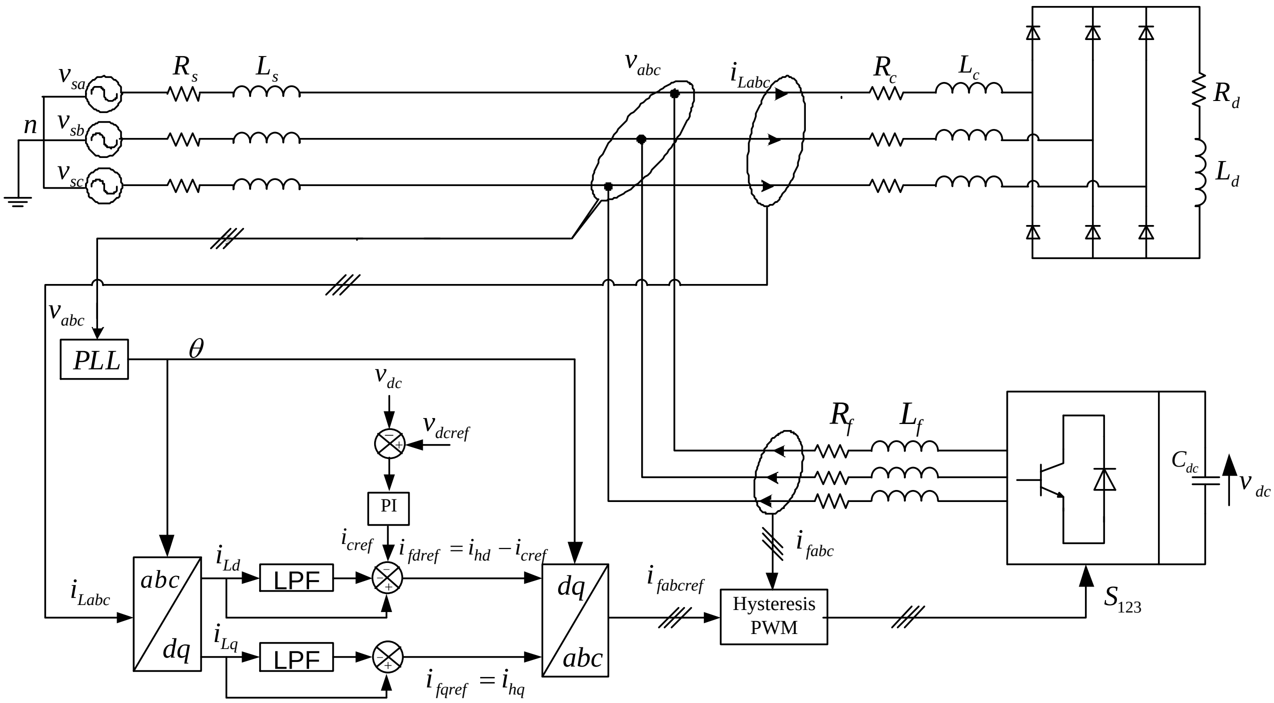


Principle

The parallel filter is capable to eliminate the harmonic currents produced by polluting loads in order to keep a sinusoidal form of the current supplied by the network. To do this, the filter injects into the network harmonic currents of identical amplitude to those absorbed by the non-linear load, but in opposite phase.

Filter control using the instantaneous current method

The figure below shows the block diagram of a shunt active filter and its control.



Identification of harmonic currents using the synchronous reference frame (SRF) method

In the synchronous frame method, also called instantaneous current method, the load currents are transformed into the synchronous frame dq in order to extract the harmonic components.

For a balanced load, the Park transformation is defined as follows:

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix}$$

Where θ, representing the angle of the rotating frame, is a linear function of the angular frequency. This reference frame rotates at a constant speed, and in which AC variables appear as DC quantities.

The harmonic component will be extracted from the load currents in the synchronous frame using a second order low pass filter with a subtractor. The currents on the axes can be decomposed into two components as follows:

$$\begin{cases} \boldsymbol{i_{Ld}} = \boldsymbol{i_{Ldc}} + \boldsymbol{i_{hd}} \\ \boldsymbol{i_{Lq}} = \boldsymbol{i_{Lqc}} + \boldsymbol{i_{hq}} \end{cases}$$

with :

i_{Ldc} and i_{Lqc} : DC components of i_{Ld} and i_{Lq}

i_{hd} and i_{hq} : Harmonic components of i_{Ld} and i_{Lq}

Depending on the function we give to the active power filter, we can compensate for either current harmonics and/or reactive power. The following table summarizes the possible compensation methods. In this table, the reference currents in the dq frame are calculated as a function of the output of the DC voltage regulator as well as the filtered (harmonic) or unfiltered components of the load currents.

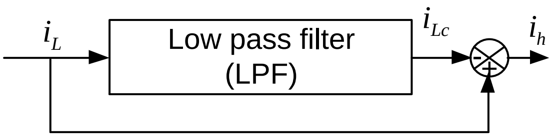
Type of compensation	Reference currents in the synchronous reference	
Current harmonic compensation	$i_{fdref} = i_{hd} - i_{cref}$	$i_{fqref} = i_{hq}$
Reactive power compensation	$i_{fdref} = -i_{cref}$	$i_{fqref} = i_{Lqc}$
Compensation of current harmonics and reactive power	$i_{fdref} = i_{hd} - i_{cref}$	$i_{fqref} = i_{Lq}$

Using the inverse Park transformation, the reference currents in the three-phase reference frame abc will be:

$$\begin{bmatrix} i_{faref} \\ i_{fbref} \\ i_{fcref} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & -\sin\theta \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i_{fdref} \\ i_{fqref} \end{bmatrix}$$

Harmonics extraction

To extract the harmonic components of the load currents, a low-pass filter is used as illustrated in the figure below. This filtering procedure makes it possible to eliminate the DC component and keep only the harmonic component of the load current.

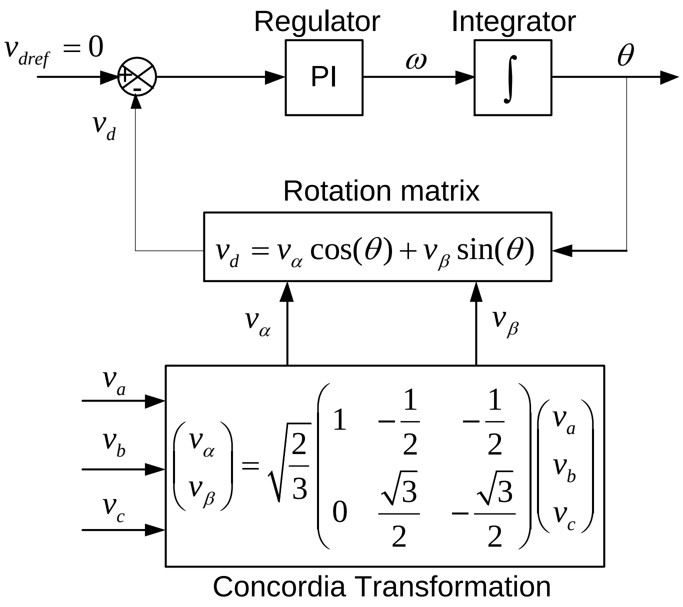


The transfer function of the adopted second-order low-pass filter is given by the following expression:

$$H_{LPF}(s) = \frac{\omega_c^2}{s^2 + 2\zeta\omega_c s + \omega_c^2}$$

Phase Locked Loop « P.L.L »

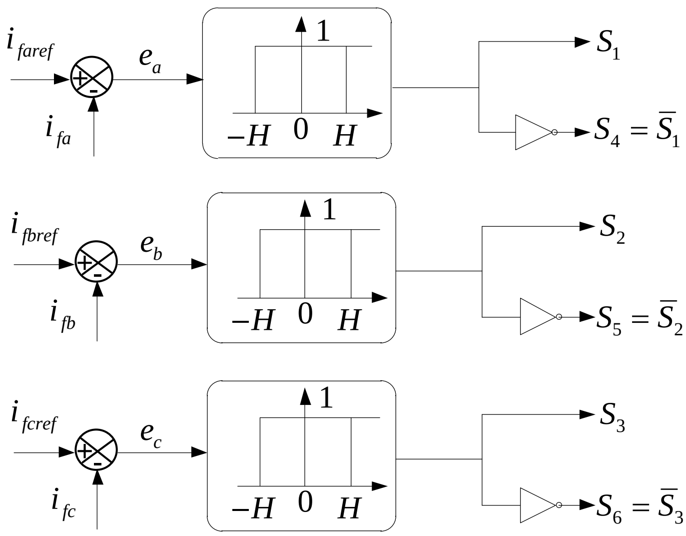
A PLL is used to determine the phase of the power grid voltage. Its schematic diagram is shown in the figure below. The loop will be locked when the estimated angle is equal to the actual voltage.



Fixed-band hysteresis control

The principle of hysteresis currents control consists of maintaining each of the currents generated by the inverter in a band enveloping the reference current. As soon as the error reaches the lower or upper band, a switching order is given to the inverter transistors to force the current to stay within the band.

The figure below shows the basic diagram of the hysteresis currents controller.



<u>Hysteresis current control algorithm</u>

Let us designate by e_i the difference between the reference current i_{firef} and the real current i_{fi} such as:

$$e_i = i_{firef} - i_{fi} \qquad i = \{a,b,c\}$$

The algorithm of this PWM strategy is given as follows:

$$\begin{cases} si \;\; e_i \geq H \;\; \Rightarrow S_i = 1 \qquad i = \{a,b,c\} \\ si \;\; e_i \leq -H \Rightarrow S_i = 0 \\ si \;\; -H \leq e_i \leq H \Rightarrow \text{no change} \end{cases}$$

where H is the width of the hysteresis band.

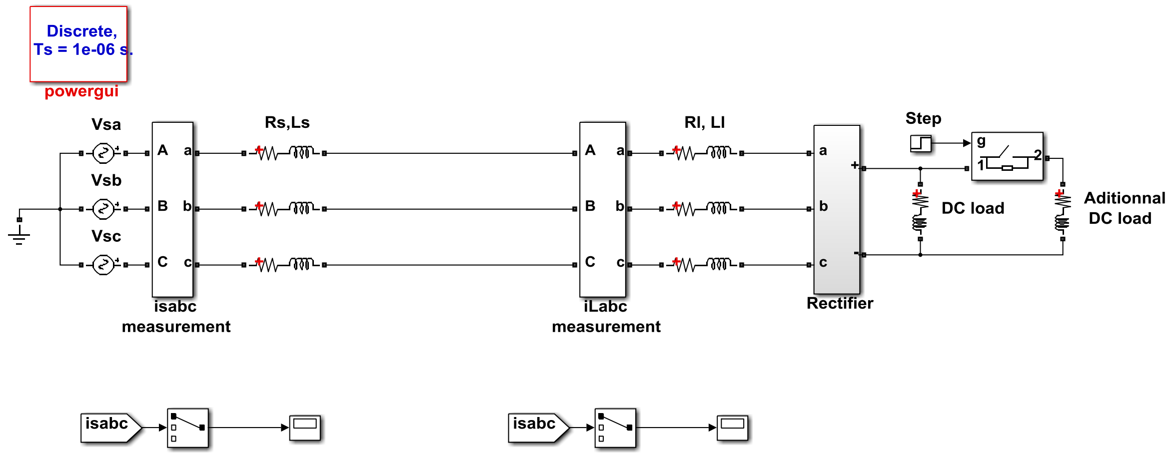
<u>Required theoretical work</u>

- Calculate the gains of the DC voltage PI regulator.
- Calculate the gains of the phase PI regulator, used in the PLL block.

<u>3- Simulation study</u>

<u>Simulation scheme without active filter</u>

The simulation diagram of a nonlinear load connected to the electrical network is illustrated in the following figure.

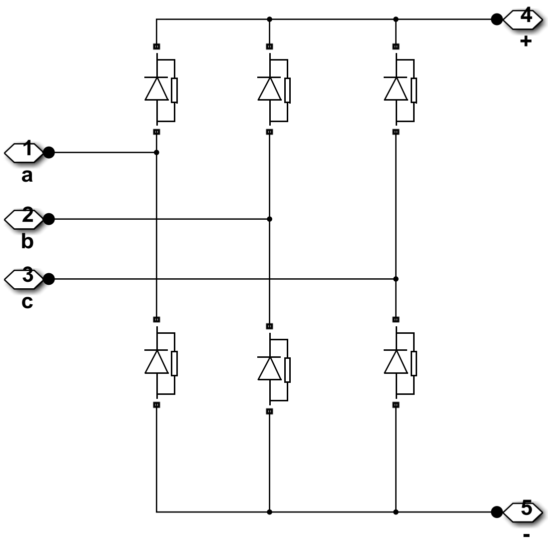


Each phase of the network can be modeled as a sinusoidal voltage source in series with impedance ($R_s = 3m\Omega,\ L_s = 2.6\,\mu H$). The voltages of the electrical network are given by the following three-phase system:

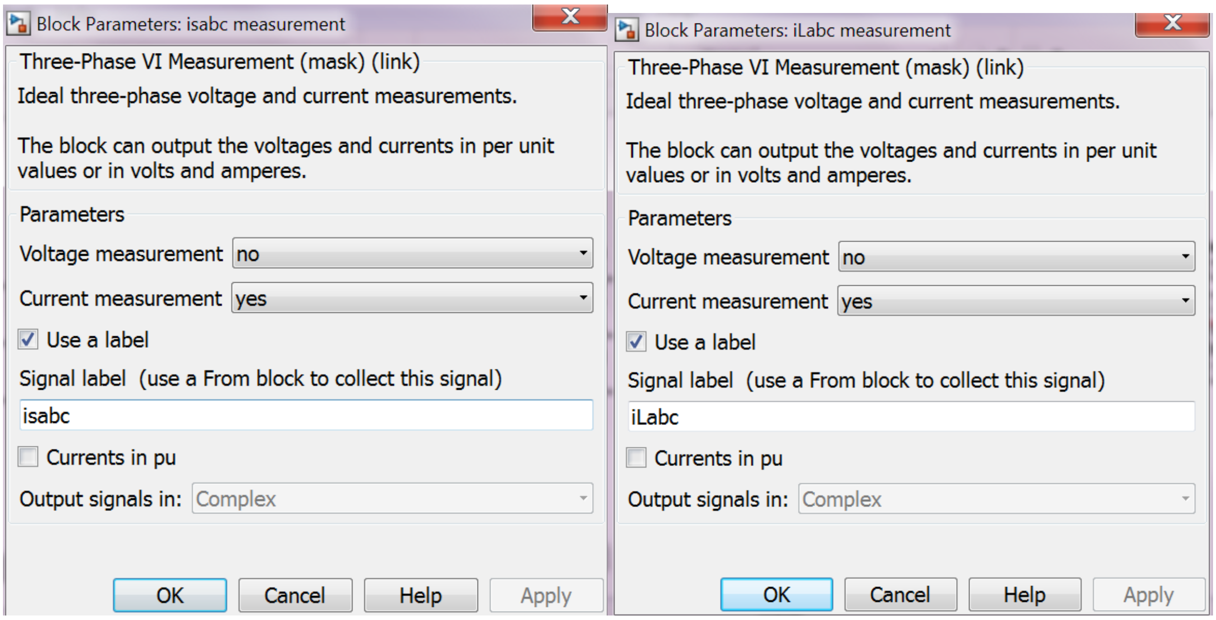
$$v_{sa} = \sqrt{2}V_{eff}\sin(\omega t)$$
$$v_{sb} = \sqrt{2}V_{eff}\sin(\omega t - \frac{2\pi}{3})$$
$$v_{sb} = \sqrt{2}V_{eff}\sin(\omega t + \frac{2\pi}{3})$$

where $V_{eff} = 220V$ is the RMS value of the network voltage, $\omega = 2\pi f_s$ is the angular frequency of the network where $f_s = 50\,Hz$ is the frequency of the electrical network.

The polluting load consists of a three-phase diode rectifier bridge (Graëtz bridge), connected to the network via a line impedance ($R_l = 10m\Omega,\ L_l = 300\,\mu H$), and supplying an inductive load ($R_d = 15\Omega,\ L_d = 2mH$) on the DC side. The simulation diagram of the rectifier is shown in the following figure.



Current measurements are carried out by two three-phase sensors from the SimPowerSystems library. The following figure shows how to label each measure with a name.

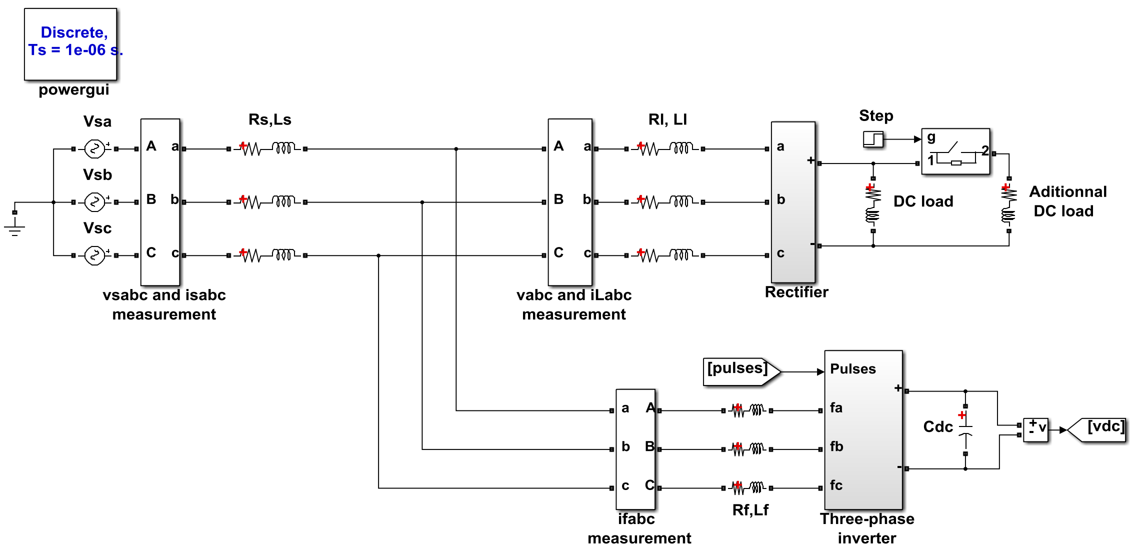


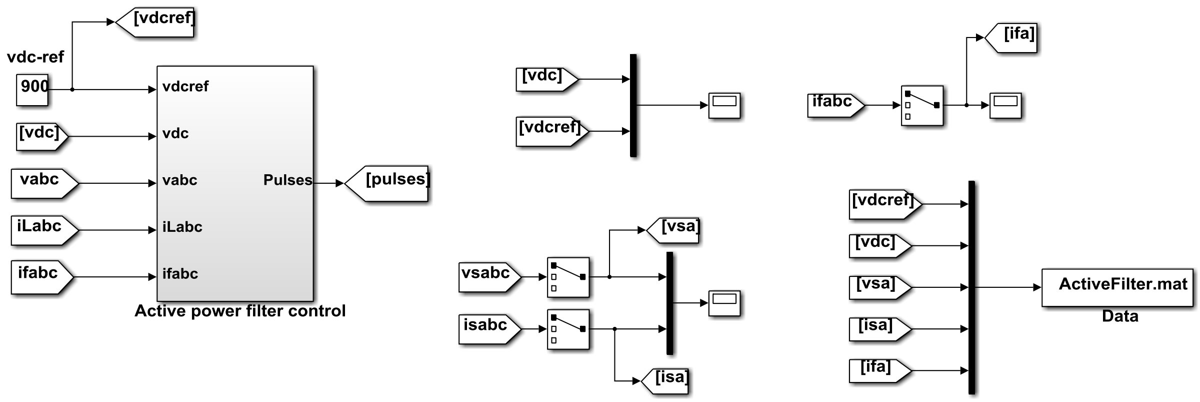
Required work

- Plot the waveforms of the source and load currents.
- Calculate the total harmonic distortion (THD) of the network current in this case.

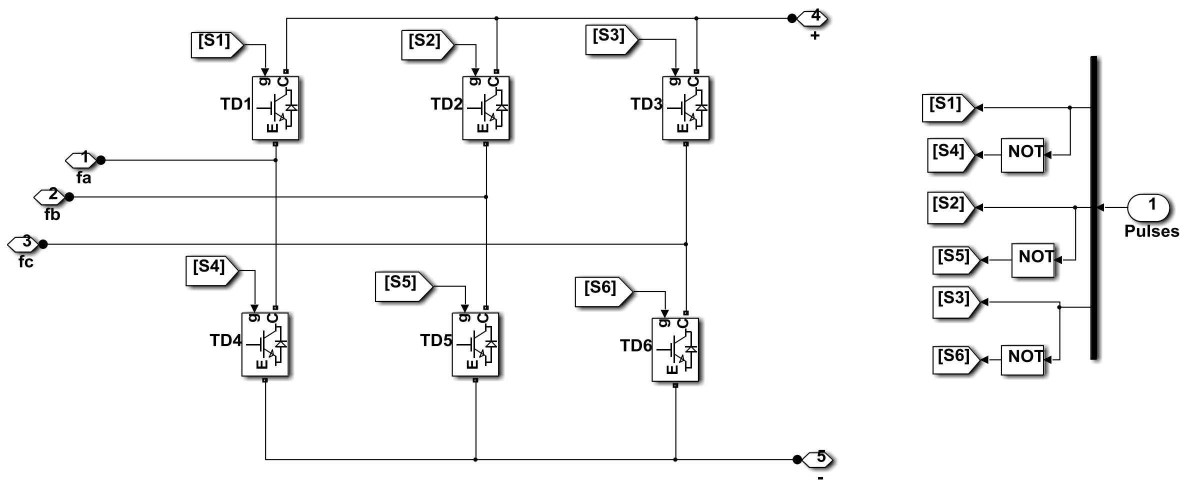
Shunt active power filter simulation scheme

The figure below shows an active power filter created in the SimPowerSystems environment. The power filter is connected in parallel via a passive line filter consisting of an inductance $L_f = 3mH$ in series with an internal resistance $R_f = 20m\Omega$.

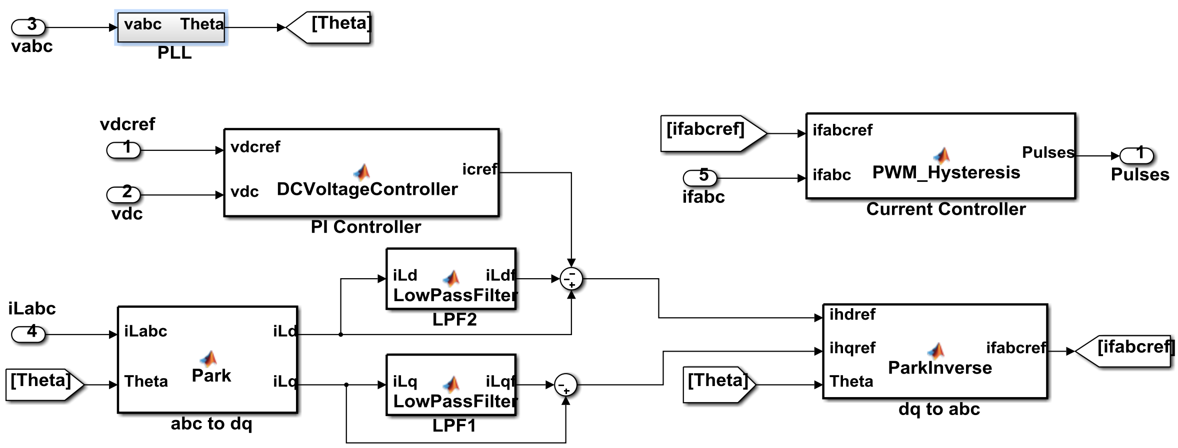




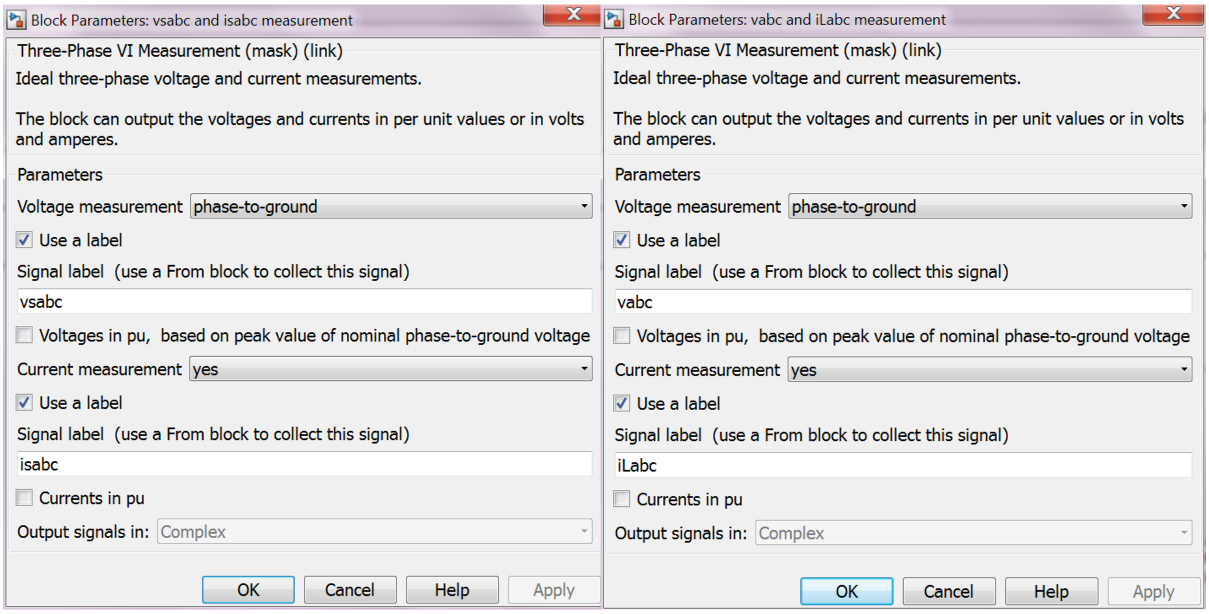
The “Three-phase inverter” block is detailed as shown in the following figure. The inverter is connected to a capacitance of $C_{dc} = 5mF$. The filter is controlled so that it compensates for the nonlinear load harmonic currents.



The control part of the filter, grouped in the “Active power filter control” block, is detailed as shown in the following figure.



Measurements of three-phase voltages and currents are carried out by two three-phase sensors parameterized as shown in the following figure.



The different parts of the filter control are carried out by Matlab function codes. These functions are listed below.

```
function icref = DCVoltageController(vdcref,vdc)
%#codegen
% DC voltage PI controller

% Parameters
fc=50;
ksi=0.707;
Cdc=0.005;

w=2*pi*fc;
kiv=w^2*Cdc;
kpv=ksi*2*Cdc*w;
Tsv=1e-6;

% Inputs

%vdcref: DC volatge reference
%vdc: DC volatge

% Error calculation

evdc=vdcref-vdc;

% Calculation of the integral of the error noted int_evdc

persistent int_evdc
if isempty(int_evdc)
int_evdc=0;
end
```

```
int_evdc=int_evdc+Tsv*evdc;

% PI regulator output

icref=kpv*evdc+kiv*int_evdc;
```

```
function [iLd,iLq] = Park(iLabc,Theta)

% Park transformation: from abc to dq

% Currents of the pollutant load in the abc frame

iLa=iLabc(1);
iLb=iLabc(2);
iLc=iLabc(3);

% Currents of the pollutant load in the dq frame

iLd=sqrt(2/3)*(iLa*cos(Theta)+iLb*cos(Theta-2*pi/3)+iLc*cos(Theta+2*pi/3));
iLq=sqrt(2/3)*(-iLa*sin(Theta)-iLb*sin(Theta-2*pi/3)-iLc*sin(Theta+2*pi/3));

% Outputs: iLd et iLq
```

```
function iLdf=LowPassFilter(iLd)

% 2nd order low pass filter (LPF)

% Input: Load direct courant component

persistent x1
if isempty(x1)
x1=0;
end

persistent x2
if isempty(x2)
x2=0;
end

% Sampling period

Ts=1e-6;

% Damping coefficient

ksi=0.707;

% Filter cutoff frequency
```

```
fc=20;
wc=2*pi*fc;

x1_dot=x2;
x2_dot=-wc^2*x1-2*ksi*wc*x2+wc^2*iLd;

x1=x1+Ts*x1_dot;
x2=x2+Ts*x2_dot;

% Output: Filtered direct courant
iLdf=x1;
```

```
function iLqf=LowPassFilter(iLq)

% 2nd order low pass filter (LPF)

% Input: Load quadrature current

persistent x1
if isempty(x1)
x1=0;
end

persistent x2
if isempty(x2)
x2=0;
end

% Sampling period
Ts=1e-6;

% Damping coefficient
ksi=0.707;

% Filter cutoff frequency
fc=20;
wc=2*pi*fc;

x1_dot=x2;
x2_dot=-wc^2*x1-2*ksi*wc*x2+wc^2*iLq;

x1=x1+Ts*x1_dot;
x2=x2+Ts*x2_dot;

% Output: Filtered quadrature current
iLqf=x1;
```

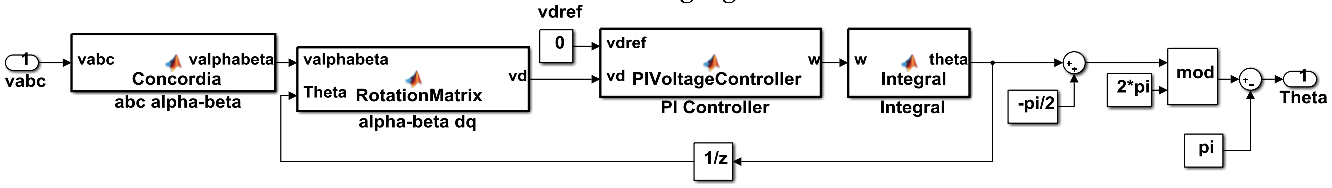
```
function ifabcref = ParkInverse(ihdref,ihqref,Theta)

% Inverse Park transformation: from dq to abc

% Inputs:
% - Reference harmonic currents in the dq frame
% - Rotation angle

% Reference harmonic currents in the abc frame

 ifaref=sqrt(2/3)*(ihdref*cos(Theta)-ihqref*sin(Theta));
 ifbref=sqrt(2/3)*(ihdref*cos(Theta-2*pi/3)-ihqref*sin(Theta-2*pi/3));
 ifcref=sqrt(2/3)*(ihdref*cos(Theta+2*pi/3)-ihqref*sin(Theta+2*pi/3));

 % Outputs
 ifabcref=[ifaref;ifbref;ifcref];
```

```
function Pulses=PWM_Hysteresis(ifabcref,ifabc)

% Hysteresis PWM technique

% Hysteresis band
H=0.5;

% Reference currents

ifa_ref=ifabcref(1);
ifb_ref=ifabcref(2);
ifc_ref=ifabcref(3);

% Filter currents

ifa=ifabc(1);
ifb=ifabc(2);
ifc=ifabc(3);

% Errors caluculation

eia=ifa_ref-ifa;
eib=ifb_ref-ifb;
eic=ifc_ref-ifc;

% States initialization

persistent sa_old
if isempty(sa_old)
sa_old=0;
```

```
end
persistent sb_old
if isempty(sb_old)
sb_old=0;
end
persistent sc_old
if isempty(sc_old)
sc_old=0;
end

% Pulses generation

  if eia > H

     sa=1;

  elseif eia < -H

     sa=0;

  else

     sa=sa_old;

  end

  if eib > H

     sb=1;

  elseif eib < -H

     sb=0;

  else

     sb=sb_old;

  end

  if eic > H

     sc=1;

  elseif eic < -H

     sc=0;
```

```
  else

     sc=sc_old;

  end

 % States update

  sa_old=sa;
  sb_old=sb;
  sc_old=sc;

 % Outputs
  Pulses=[sa;sb;sc];
```

The “PLL” block is detailed as shown in the following figure.



The Matlab functions that carry out the task of the “PLL” block are listed as follows:

```
function valphabeta=Concordia(vabc)

% Transformation from the abc frame to the alpha-beta frame

   % Inputs: Voltages of the common coupling point (PCC)

    va=vabc(1);
    vb=vabc(2);
    vc=vabc(3);

    % Voltages in alpha-Beta frame

    valpha=sqrt(2/3)*(va-0.5*vb-0.5*vc);
    vbeta=sqrt(2/3)*(vb*sqrt(3)/2-vc*sqrt(3)/2);

    % Outputs
    valphabeta=[valpha;vbeta];
```

```
function vd=RotationMatrix(valphabeta,Theta)

% Transformation from the alpha-beta frame to the dq frame

% Inputs
```

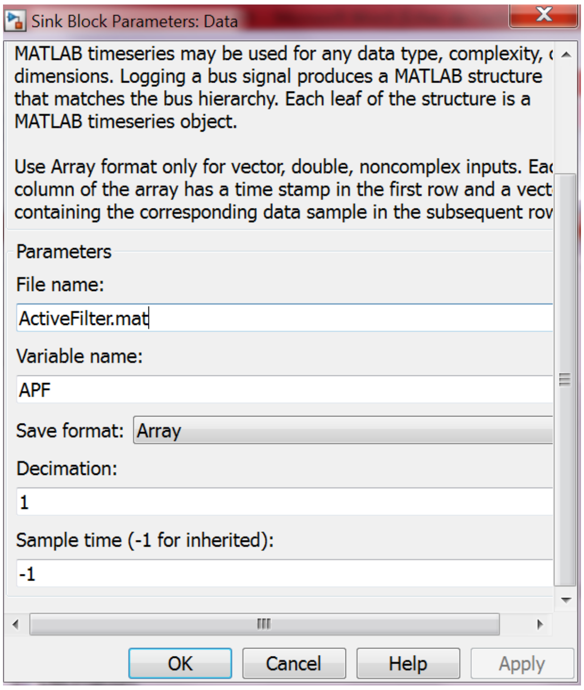
```
    valpha=valphabeta(1);
    vbeta=valphabeta(2);
    %Theta

    % vd and vq calculation
    vd=valpha*cos(Theta) + vbeta*sin(Theta);
    vq=-valpha*sin(Theta) + vbeta*cos(Theta);

    % Output: vd
```

```
function w = PIVoltageController(vdref,vd)

%#codegen
% PI voltage regulator along the d axis at point PCC

% Parameters
kp=10.9;
ki=48987;

Ts=1e-6;

% Inputs

%vdref: PCC direct voltage reference
%vd: PCC direct voltage

% Error calculation

evd=vdref-vd;

% Calculation of the integral of the error noted int_evdc

persistent int_evd
if isempty(int_evd)
int_evd=0;
end

int_evd=int_evd+Ts*evd;

% PI regulator output

w=kp*evd+ki*int_evd;

% Output: Angular frequency
```

```
function theta = Integral(w)

%#codegen
```

```
% Calculation of the angle by integration of the angular frequency

 % Parameters

Ts=1e-6;

% Input: Angular frequency

% Calcul de l'intégrale de la pulsation

persistent int_w
if isempty(int_w)
int_w=0;
end

int_w=int_w+Ts*w;

% Output: Angle
theta=int_w;
```

The results are stored in a ".mat" file. By clicking on this block, we obtain the following dialog window. Note that you must specify the file name, the variable name and the save format.



Once the results are stored in a file, they can be reloaded and plotted using the following Matlab code:

```
clc; clear all; close all;
```

```
load ActiveFilter.mat

t=APF(1,:);
vdcref=APF(2,:);
vdc=APF(3,:);
vsa=APF(4,:);
isa=APF(5,:);
ifa=APF(6,:);

taille=9;
figure(1)
plot(t,vsa,'k',t,isa,'k');
xlabel('Time (s)','FontSize',taille,'FontName','times new roman', 'FontWeight','bold');
ylabel('v_s_a (V),   i_s_a (V) ','FontSize',taille,'FontName','times new roman','FontWeight','bold');
axis([0 0.6 -335 335])

figure(2)
plot(t,vdcref,'k',t,vdc,'k');
xlabel('Time (s)','FontSize',taille,'FontName','times new roman', 'FontWeight','bold');
ylabel('v_d_c (V)','FontSize',taille,'FontName','times new roman', 'FontWeight','bold');
axis([0 0.6 0 950])

figure(3)
plot(t,ifa,'k');
xlabel('Time (s)','FontSize',taille,'FontName','times new roman', 'FontWeight','bold');
ylabel('i_f_a (A)','FontSize',taille,'FontName','times new roman', 'FontWeight','bold');
axis([0 0.6 -45 45])
```

Required work

1- Simulate the active filter over a horizon of 0.6s with a sampling period of $T_s = 1\mu s$. A second additional load $R_a = 15\Omega$, $L_a = 2mH$ is connected in parallel by closing the ideal switch. The reference voltage of the direct voltage is fixed at $v_{dcref} = 900V$.

a- Plot the waveforms of the direct voltage and its reference as well as the voltage and current of the first phase of the three-phase electrical network.

b- Plot the frequency spectrum of the network current and calculate its THD. Comment on the results found.

c- Repeat the same work when the active power filter compensates for this time:

- The reactive energy alone,
- The harmonic currents and reactive energy at the same time,
- Comment on the results obtained.

2- Using the method of real and imaginary instantaneous powers as a means of identifying harmonic currents:

a- Give the principle of the method of real and imaginary instantaneous powers,

b- Simulate the shut active power filter,

c- Compare the results with those obtained by the SRF method.

3- In the case where the inverter is voltage controlled using sinusoidal modulation (SPWM) and the filter currents are controlled by PI regulators:

a- Give the current control scheme and calculate the gains of the PI regulators used,

b- Simulate the shunt active power filter,

c- Compare the results obtained with those of hysteresis current control.