Chapter 7

Conclusions

The main conclusions of my PhD work are here summarized for each topic covered in this dissertation. My activity comprehended theoretical and experimental studies on the PV systems, focusing the attention on their behaviour under non-ideal conditions, which lead to low levels of output power with great consequences in terms of efficiency of all the system's elements and Power Quality issues.

Chronologically, the first main research regarded the convenience of the master-slave concept with respect to the single centralized inverter. The attention has been focused on the influence of the installation site, the tilt angle of the PV modules, the DC-AC efficiency curves of commercial inverters and the number of slaves. The results put into evidence annual gains in the range 0.1–1.5%, according to the various locations.
Therefore, the M-S configuration is advisable in sites with more cloudy days than clear days: the best applications are on nearly flat roofs (higher diffuse radiation) and façades (lower direct radiation). Moreover, the DC-AC efficiency of M-S inverters must not be lower than the SC inverter.
Then, the number of M-S inverters can be limited to 3 for achieving almost the maximum gain. Regarding the costs, the manufacturers usually offer M-S and multiple MPPT units as alternative options, so the M-S solution does not imply extra-cost for installation. Moreover, the single inverters are units which exchange their role as master/slave and they are not exploited continuously, but the operation is controlled for tracking the working points with maximum effi-

ciency. This reduces the working time of each unit (i.e. the maintenance cost) and it assures a higher expected lifetime. Finally, the Master-Slave solution is therefore advisable with the application limits highlighted in chapter 1.

The research work on PERSIL project led to 1-year monitoring of thirteen PV systems in grid connection.
The two-year analysis of monthly irradiations put into evidence the role of an accurate and local measurement by pyranometers in the framework of the current climate changes. Actually, mutual distances between meteorological station and PV plant higher than 5–10 km and/or the lack of the radiation data for the year under study can cause noticeable errors in the calculation of the performance ratio.
The consequent experimental results in terms of operational parameters showed that three PV plants behave in excellent manner (PR = 0.80–0.83), whereas five PV plants exhibited poor energy production (PR = 0.41–0.55, mainly owing to loss of availability) and the remainder has average behaviour.
The simple model, without the assessment of the energy availability, exhibited adequate accuracy for the productivity, if the PV system is equipped with efficient and reliable components, suitably cooled and oversized. Moreover, the presented improvement of the model proved that the energy availability for old PV plants is less than 95%, while more recent PV plants show values up to 99%. When a new plant is characterized by low availability, as in the case of the factory p-Si plant or the CdTe one, in which the inverters are the same of the remaining part (excellent) of the PV systems, the reason can be found in the components with under-performance consequent to wide tolerance in their parameters.
The study also highlighted that the worst case in terms of energy availability is represented by the sun-tracking PV plant, due to the complete lack of mechanical maintenance.
The work produced guidelines for design, installation and maintenance of grid-connected PV systems, with the aim of maximizing the energy availability. These guidelines can be easily extended to the other Countries that accept the IEC or IEEE Standards.

About the main topic of this dissertation, it can be safely stated that a BIPV system subject to partial shading phenomenon will expect a great reduction of the power injected into the grid, and, if this issue is constant year-round, also the overall energy produced will be affected. The distortion of the I-V curves can be caused also by the shade over only few cells, even if they are not completely shaded.
A particular BIPV system has been considered as case study of this thesis and analysed from all the points of view.
The distortion of the current-voltage curves of one of its arrays affected by partial shading caused a power loss up to 60% of the rated power. Moreover, additional losses are introduced by the MPP tracker of the inverter, since it was not able to follow the absolute maximum on the static I-V curve of the PV field. This loss could reach also the 35%. In comparison the DC/AC efficiency is much less affected by the shading, but nevertheless it can be far from its best values.
This has to be well pondered when designing a BIPV system in an urban environment, since it can result in a strong drawback of the investment.
The analysis performed on the case study considered was focused on the I-V mismatch caused by partial shading, since this is the one of the main issues of a BIPV system, but it has a validity in general as a methodology to be applied to other systems with or without other mismatch problems.

Therefore the Power Quality impact in three real cases of Photovoltaic systems, characterized by an extended power range from a few kilowatts to some hundreds of kilowatts, was considered. If, in case of totally irradiated PV modules, the PQ parameters satisfy the limits imposed by the standards, when a partial shading condition occurs, there is a corresponding increase of harmonic content and unbalance, together with the decrease of power factor. This is, indeed, due to the fact that the shading effect in PV modules corresponds to power levels of about 10–30% of the rated power.

A Power Quality analysis on the case study was exposed, based on a week-lasting measurement campaign and extracting information on the harmonic distortion and unbalance from the Standard PQ indexes.

Finally, the focus was on the occurrence of different types of unbalance of the

currents in the three-phase system, due to the operating conditions of a BIPV system. A categorization of unbalance into three basic types was proposed: "structural unbalance", "unbalance from partial shading" and "mixed unbalance". For each type of unbalance, results from experimental analyses have highlighted that the unbalance in a PV system cannot be considered negligible in the presence of structural issues and can become more relevant with partial shading and unbalanced distorted loads. This aspect is important for designing a PV system and its grid connection, oversizing the distribution transformer if needed.
A number of indicators taken from the reviewed literature have been calculated for the first time for a PV system. The results obtained can be useful to promote changes in the current standards in order to account for the dependence of the unbalance components on harmonic distortion in the formulation of the unbalance indicators. On these bases, the values obtained in the application studied can provide some hints.
For example, considering the CUF as the traditional reference, the unbalance indicators TPU_I and $ITUD$ are the most suitable ones, as they can take into proper account the presence of distortion together with unbalance, providing values realistically higher than the CUF in a way depending on harmonic distortion, and becoming equal to the CUF when harmonic distortion is absent. From the results obtained, a possible limit on TPU_I or $ITUD$ could be indicatively set up to the value 0.1, meaning that a PV system with moderate structural unbalance does not exceed this limit.
Eventually, multiple indicators are computed to allow the direct use of the parameters provided by commercial PQ analyzer, as for those concise three-phase indicators, computed through the Symmetrical Component Based method.

However, in the application considered, the structural, partial shading and mixed unbalance occurred within a relatively long time frame with respect to the timing of the measurements, so that the possible saving in computational time was not a crucial aspect. Setting up the limits in the standards is matter of discussion inside the standardization body. According to the present trend of formulation of the standards, the power quality indicators are not assessed individually, but considering the values of the indicator obtained from a number of successive measurements during a predefined time period and taking for example the 95th percentile (i.e., the 95% non-exceeding probability) from the cumulative distribution of the values of the indicator as the number characterizing the system under test. The acceptability limit is then defined to be applied to the 95% percentile. For PV systems, a key aspect that has to be established refers to the conditions in which the values of the unbalance indicator are considered to be relevant, for example avoiding to compute the indicator with very low solar irradiance, as its value would be poorly meaningful in practice. These aspects are matter for future studies.

Appendix A

In the following, at first the MATLAB® code for computing the Solar cell equivalent single diode model parameters of chapter 3, from the experiment measurement on a PV panel, is reported.
Then also the code to compute the I-V characteristic of a PV module with mismatch, from different sets of cell parameters, is transcribed.

Solar cell model parameters

Computing of the solar cell equivalent single diode model parameters from the experiment measurement of the I-V curve of a PV panel.

```
clear all

close all


c=1; % number of the measurement considered


% PV panel datasheet

K = 0.002;

alpha = 0.005028;

beta = -0.12784;

NOCT=47;
```

```
% Constants

k=1.3806503*10^-23;

q=1.60217646*10^-19;

Eg=1.124;



% Environment data

Ta=27.9; %misura1

sonda1=56.29; %misura1

G=(sonda1/73.7)*1000


% PV generator composition

ns=60;

np=1;


% Cell temperature in K

Tc=Ta+G*(NOCT-20)/800 + 273.15



vT=k*Tc/q % cell thermal voltage

vt=ns*vT  % panel thermal voltage

vTstc=k*298.15/q

vtstc=ns*vTstc


%  file to be open with the data of time and of the signals,
```

```
%  one for each channel, in column

fname = sprintf('misura%d.txt', c);

fid = fopen(fname, 'r');
dati = textscan(fid,'%f%f%f');
fclose(fid);


% Saving the data
tempo = dati{1,1};
V = dati{1,2};  % segnale da canale 1, tensione
I = dati{1,3};  % segnale da canale 2, corrente

offset_cur=mean(I(2:502));

Vm=V;
Im=I-offset_cur;
Pm=Vm .* Im;


% Plot of experimental current and voltage

figure (1)
```

```
plot(tempo,Vm,'b');

% title('Capacitor charging');

set(gca,'YAxisLocation','left', 'Layer','top', 'YLim',[0 40],
'XLim',[0 0.3],'YTick',0:5:40,'XTick',0,'XTickLabel',[])
ylabel('Voltage (V)');
hold on

h1 = gca;
h2 = axes('Position',get(h1,'Position'));
plot(tempo,Im,'r')
set(h2,'Color','none', 'YAxisLocation','right', 'YLim',[0 8],
'XLim',[0 0.3],'YTick',0:1:8)
xlabel('Time (sec)');
ylabel('Current (A)')
hold off

% PV generator Voc
Voc=mean(Vm(2:102))
Voc_cell=Voc/ns;

% first sample to be considered for reconstructing the
% I-V curve and computing the Isc
sample1=find(Vm<(Voc/2),1)+50;
```

```
samplemax=length(Vm);
if (isinteger((samplemax-sample1+1)/2)==false)
  sample1=sample1-1;
end
sample2=sample1+2000;

c0=[1 0];
par_retta=nlinfit(Vm(sample1:sample2), Im(sample1:sample2),
@retta, c0)
modello=@retta;
retta_Isc=modello(par_retta,Vm(sample1:sample2));
Isc=par_retta(2)
Rsh0=-1/(par_retta(1))
Rsh=Rsh0

% Plot of the rect used to compute Isc

figure (2)

% zoom plot(Vm(sample1:sample2),Im(sample1:sample2),'b',
Vm(sample1:sample2), retta_Isc, 'r');
plot(Vm(sample1:samplemax),Im(sample1:samplemax),'k',
Vm(sample1:sample2), retta_Isc, 'r');
title('Short-Circuit Current Evaluation');
```

```
set(gca,'YAxisLocation','left', 'Layer','top', 'YLim',[0 12],
'XLim',[0 20])
xlabel('Voltage (V)');
ylabel('Current (A)')
%str = {sprintf('Isc = %0.2f', Isc)};
%text(5,  4, str);



% Rs evaluation


sample4 = samplemax-10000;
sample3 = sample4-22000;
%sample4 = samplemax-20000;
%sample3 = sample4-35000;
b0=[-2 2*Voc];
par_retta2=nlinfit(Vm(sample3:sample4), Im(sample3:sample4),
@retta, b0)
modello=@retta;
retta_Rs=modello(par_retta2, Vm(sample3:sample4));
Rs0=-1/(par_retta2(1))
Rs=Rs0


% Plot of the rect used to compute Rs
```

```
figure (3)

% zoom plot(Vm(sample3:sample4),Im(sample3:sample4),'b',
Vm(sample3:sample4), retta_Rs, 'r');
plot(Vm(sample3:samplemax), Im(sample3:samplemax),'k',
Vm(sample3:sample4), retta_Rs, 'r');
title('Serie Resistance Evaluation');

set(gca,'YAxisLocation','left', 'Layer','top', 'YLim',[0 2],
'XLim',[30 35])
xlabel('Voltage (V)');
ylabel('Current (A)')
%str = {sprintf('Rs = %0.3f', Rs)};
%text(35,  2, str);

% Reporting to the STC

Istc = Im(sample1:samplemax) + Isc*(1000/G - 1) +
alpha*(298.15-Tc);
Vstc = Vm(sample1:samplemax) - Rs*(Istc - Im(sample1:samplemax))+
 - K*Istc*(298.15-Tc) + beta*(298.15-Tc);
Pstc=Vstc .* Istc;

% MPP in experimental conditions
```

```
mpp=find(Pm == max(Pm(sample1:samplemax)),1);
Vmpp=Vm(mpp)
Impp=Im(mpp)

Iscstc=Isc *1000/G + alpha*(298.15-Tc)
Vocstc=Voc + beta*(298.15-Tc)
Imstc=Impp + Isc*(1000/G-1) + alpha*(298.15-Tc)
Vmstc=Vmpp + beta*(298.15-Tc)

% Cell parameters evaluation
m=1.1;
is_phang=(Isc-Voc/Rsh)/(exp(Voc/(m*vt))-1)
iph_phang=Isc*(1+Rs/Rsh)+is_phang*(exp(Isc*Rs/(m*vt))-1)

iph=iph_phang;
is=is_phang;
is1=is;

% Refining of the m and is evaluations
dVoc = abs(Voc - log(iph/is + 1)*m*vt);

while dVoc>0.0001,

    m1 = Voc/(log(iph/is1 + 1)*vt);
    is1 = (iph - Voc/Rsh) /(exp(Voc/(m1*vt)) - 1);
```

```
    dVoc = Voc - log(iph/is1 + 1)*m1*vt;
end

m1
is1

Rs1 =(1/Rsh - 1/Rs0 + is1/(m1*vt)*exp(Voc/(m1*vt)))/
(is1/(m1*vt*Rs0)*exp(Voc/(m1*vt))+1/(Rsh*Rs0));
Rsh1=(1-Rs1/Rsh0)/(1/Rsh0 - is1*(1/(m1*vt)*(1-Rs1/Rsh0)*
*exp(Rs1*Isc/(m1*vt))))
iph1=Isc*(1+Rs1/Rsh1)+is1*(exp(Isc*Rs1/(m1*vt))-1)

% Computing of the I-V curve with the parameters

no=(samplemax-sample1+1)/2;
dvdk=0.8*Voc/no;
vdk(1)=0;

for j=1:no
 % current computed iteratively
Ij = iph1 -is1*(exp(vdk(j)/(m1*vt))-1);
ik(j)= Ij - vdk(j)/Rsh;
vk(j) = vdk(j)-Rs1*ik(j);
vdk(j+1) = vdk(j)+dvdk;
```

```
end
di=iph1/no; % current step

% computing cicle for the almost constant voltage tract
for i=no+1:2*no
    Ij=Ij-di;
    if i==2*no
    Ij=0;
    end
    vdk(i)=(m1*vt)*log((iph1-Ij)/is1+1);
    ik(i)=Ij-vdk(i)/Rsh;
    vk(i) = vdk(i)-Rs1*ik(i);
end

%n=n+1;
err = sum((Im(sample1:samplemax)-transpose(ik)).^2)
%end

figure (4)

% Plot of the curves at experimental conditions and at STC
%plot(Vm(sample1:samplemax),Im(sample1:samplemax),'b',
Vstc,Istc,'b--');
% variante con solo condizioni sperimentali
```

```
plot(Vm(sample1:samplemax),Im(sample1:samplemax),'b',
Vstc,Istc,'k');
title('I-V and P-V characteristics');

set(gca,'YAxisLocation','left', 'Layer','top', 'YLim',[0 12],
'XLim',[0 40],'XTick',0,'XTickLabel',[], 'YTick', 0:1.5:12)
ylabel('Current (A)');
hold on


plot(vk,ik,'--kd','LineWidth',1,'MarkerEdgeColor','g',
'MarkerFaceColor','g','MarkerSize',3);
hold on

h1 = gca;
h2 = axes('Position',get(h1,'Position'));

% P-V curve only at experimental conditions
plot(Vm(sample1:samplemax),Pm(sample1:samplemax),'r');

set(h2,'Color','none', 'YAxisLocation','right', 'YLim',[0 240],
'XLim',[0 40], 'YTick', 0:30:240)
xlabel('Voltage (V)');
ylabel('Power (W)')
hold off
```

```
figure(5)
plot(1,1)
str = sprintf('La soluzione dei parametri ÃÍ Iph= %0.2f,
\n Is= %0.2d,\n m= %0.2f,\n Rsh= %0.2f,\n Rs= %0.2f',
iph1, is1, m1, Rsh1, Rs1);
text(0.1,  1.2, str);

% Ideal module I-V characteristic

%Videal=0:0.8*Voc/no:0.8*Voc;
Videal=0:Voc/(2*no):Voc;
for j=1:1:(2*no+1)
 % computing cicle for the almost constant current tract
Iideal(j) = iph1 -is1*(exp(Videal(j)/(m1*vt))-1);
end
%di=iph1/no; %passo sulla corrente
% computing cicle for the almost constantvoltage tract
%for i=no+1:2*no
%    Iideal(i)=Iideal(no)-di;
 %   if i==2*no
 %   Iideal(i)=0;
 %   end
 %   Videal(i)=(m1*vt)*log((iph1-Iideal(i))/is1+1);
```

```
 %end

figure (6)

plot(Vm(sample1:samplemax),Im(sample1:samplemax),'b',
Videal, Iideal,'k');
title('I-V and P-V characteristics');

set(gca,'YAxisLocation','left', 'Layer','top', 'YLim',[0 12],
'XLim',[0 40],'YTick', 0:1.5:12)
ylabel('Current (A)');
hold on

plot(vk,ik,'--kd','LineWidth',1,'MarkerEdgeColor','g',
'MarkerFaceColor','g','MarkerSize',3);
hold on

iphstc=iph*1000/G + alpha*(298.15-Tc)

is1stc=(Iscstc-Vocstc/Rsh)/exp(Vocstc/(m*vtstc))

parametri_cella = [iphstc, is1stc, m1, Rsh1/ns, Rs1/ns,
Vocstc/ns, Iscstc, Vmstc/ns, Imstc];
dlmwrite('parametri_STC.txt', parametri_cella,
'delimiter','\t')
```

```
parametri_cella = [iph1, is1, m1, Rsh1/ns, Rs1/ns,
Voc/ns, Isc, Vmpp/ns, Impp];
dlmwrite('parametri_EXPC.txt', parametri_cella,
'delimiter','\t')

if c==1
parametri_cella = [iph1, is1, m1, Rsh1/ns, Rs1/ns,
Voc/ns, Isc, Vmpp/ns, Impp];
curve=[Vm(sample1:samplemax),Im(sample1:samplemax),
transpose(vk), transpose(ik)];
curve2=[transpose(Videal), transpose(Iideal)];
dlmwrite('modulo_ombrato_EXPC.txt', parametri_cella,
'delimiter','\t')
dlmwrite('modulo_ombrato_EXPC.txt', curve,
'delimiter','\t','-append')
dlmwrite('modulo_ombrato_EXPC.txt', curve2,
'delimiter','\t','-append')
end
```

Mismatched I-V characteristic of a PV module

Computing of the I-V characteristic of a PV module, mismatched due to a shaded solar cell. Two different sets of solar cell parameters are used to reconstruct the I-V curves of the irradiated and shaded 20-cells blocks (one block for each by-

pass diode). Each set is evaluated with the procedure reported in the section 7 considering the right zone (totally irradiated or shade) of the I-V characteristic of the experimental curve, where the current is almost constant.
When the two I-V characteristics are computed, they can be combined to simulate the I-V curve of the total PV panel with partial shading. If only one by-pass diode intervenes, the combination requires two irradiated elements and only a shaded one, as in the code reported below.

```
clear all

close all


% PV generator composition: ns: cells in serie;

% np, cell in parallel.

ns=20;

np=1;


% PV panel datasheet

K = 0.002;

alpha = 0.005028;

beta = -0.12784 *ns/60;

NOCT=47;


c=4; % measurement number to be considered


% Environment data during the experimental measurement

% on the shaded PV module
```

```
Ta=28.4

sonda1=63.76;

G=(sonda1/73.7)*1000

% Cell Temperature in K

Tc_ill=Ta+G*(NOCT-20)/800 + 273.15


% Other constant

k=1.3806503*10^-23;

q=1.60217646*10^-19;

Eg=1.124;


% Cell model Parameters

iph=[];

is = [];

m = [];

Rsh = [];

Rs = [];

Voc = [];

Isc =[];

Vmpp = [];

Impp = [];


%  file to be opened for the parameters


fname = 'parametri_EXPC.txt';
```

```
fid = fopen(fname, 'r');
dati = textscan(fid,'%f%f%f%f%f%f%f%f%f');
fclose(fid);

iph(1) = dati{1,1}
is(1)= dati{1,2}
m(1)= dati{1,3}
Rsh(1)= dati{1,4}
Rs(1)= dati{1,5}
Voc(1)= dati{1,6}
Isc(1)= dati{1,7}
Vmpp(1)= dati{1,8}
Impp(1)= dati{1,9}

fname = 'parametri_EXPC2.txt';

fid = fopen(fname, 'r');
dati = textscan(fid,'%f%f%f%f%f%f%f%f%f');
fclose(fid);

iph(2)= dati{1,1}
is(2)= dati{1,2}
m(2)= dati{1,3}
Rsh(2)= dati{1,4}
```

```
Rs(2)= dati{1,5}

%is(2)= is(1)

%m(2)= m(1)

%Rsh(2)= Rsh(1)

%Rs(2)= Rs(1)


Voc(2)= dati{1,6}

Isc(2)= dati{1,7}

Vmpp(2)= dati{1,8}

Impp(2)= dati{1,9}


%fname = 'rapporto.txt';


%fid = fopen(fname, 'r');

%dati = textscan(fid,'%f');

%fclose(fid);


%ratio=dati{1,1};

%iph(2)=ratio*iph(1)

%Isc_shaded=ratio*Isc


%  file to be opened for the experimental measurement


fname = sprintf('misura%d.txt', c);
```

```
fid = fopen(fname, 'r');
dati = textscan(fid,'%f%f%f');
fclose(fid);

% Data saving
tempo = dati{1,1};
V = dati{1,2};  % segnale da canale 1, tensione
I = dati{1,3};  % segnale da canale 2, corrente

offset_cur=mean(I(2:502));

I=I-offset_cur;
P=V .* I;

% first sample to process the experimental data
Voc2=mean(V(2:102));
sample1=find(V<(Voc2/2),1)+100;
samplemax=length(V);
if isinteger((samplemax-sample1+1)/2)==false
    sample1=sample1+1;
end

% By-pass diode data
%vt2 = 1.25*vtstc
isdby = 1e-09;
```

```
vtdby=1.2*k*Tc_ill/q

% Reconstruction of the I-V characteristics of
%the irradiated and shaded 20-cell blocks

no=400;
Tc_shaded=1*Tc_ill;
T=[Tc_ill, Tc_shaded];

vd(1)=0;

for n=1:2
 n

vt=k*T(n)/q

dvd=0.8*Vmpp(n)/no;

for j=1:no
 % computing cicle for the almost constant current tract
Ij = iph(n) -is(n)*(exp(vd(j)/(m(n)*vt))-1);
im(n,j)= Ij - vd(j)/Rsh(n);
vm(n,j) = (vd(j)-Rs(n)*im(n,j))*ns;
idby = isdby * (exp((-1* vm(n,j)) / vtdby) - 1);
im(n,j)=im(n,j)+idby;
```

```
vd(j+1) = vd(j)+dvd;


end

dim=iph(n)/no; %passo sulla corrente


% computing cicle for the almost constant voltage tract

for i=no+1:2*no

    Ij=Ij-dim;

    if i==2*no

    Ij=0;

    end

    vd(i)=(m(n)*vt)*log((iph(n)-Ij)/is(n)+1);

    im(n,i)=Ij-vd(i)/Rsh(n);

    vm(n,i) = (vd(i)-Rs(n)*im(n,i))*ns;

    idby = isdby * (exp((-1* vm(n,i)) / vtdby) - 1);

    im(n,i)=im(n,i)+idby;


end


end


figure (1)


plot(vm(1,:),im(1,:),'g', vm(2,:),im(2,:),'magenta',
'Linewidth', 2);
```

```
title('I-V characteristic at experimental conditions');

set(gca,'YAxisLocation','left', 'Layer','top', 'YLim',[0 12],
'XLim',[-4 20],'XTick',-4:4:20,'YTick', 0:1.5:12)
ylabel('Current (A)');
grid on
hold on

h1 = gca;
h2 = axes('Position',get(h1,'Position'));

pm = vm .* im;
plot(vm(1,:), pm(1,:),'g', vm(2,:), pm(2,:),'magenta',
'Linewidth', 2);
set(h2,'Color','none', 'YAxisLocation','right', 'YLim',[0 80],
'XLim',[-4 20],'XTick',-4:4:20, 'YTick', 0:10:80)
xlabel('Voltage (V)');
ylabel('Power (W)')
legend('Illuminated elements','Shaded elements');

hold off

% Building of the I-V characteristic of the mismatched
% string/module
caratteristiche = 2;
```

```
no=(samplemax-sample1);
%Istring = 0:0.005:12;
Istring = 0:12/no:12;

lstring = length(Istring);

Vstring = zeros(1,lstring);

n_ill = 2; % irradiated block number

n_shaded = 1; % shaded block number

 Vstring(1) = 0;

    for jj=1:lstring,

        for kk=1:caratteristiche,

            if kk ==1,
                n = n_ill;
            else
                n = n_shaded;
            end
```

```
            istr = Istring(jj);
            % searching for the index in vk,ik corresponding
% to Istring(m)
            ii = min(find(im(kk,:) <= istr));

            if ii == 1,
                Vstring(jj) = Vstring(jj) + n*vm(kk,ii);
            else
                Vstring(jj) = Vstring(jj) + n*(vm(kk,ii) +
(istr - im(kk,ii))*(vm(kk,ii-1)-vm(kk,ii))/
(im(kk,ii-1)-im(kk,ii)));
            end
        end
    end
    Pstring = Vstring .* Istring;

figure (2)

plot(Vstring,Istring,'r',V(sample1:samplemax),I(sample1:samplemax),'k',
'LineWidth', 2);
title('String characteristic at experimental conditions');
set(gca,'YAxisLocation','left', 'Layer','top', 'YLim',[0 12],
'XLim',[0 40],'XTick', 0:4:40, 'YTick', 0:1.5:12)
ylabel('Current (A)');
xlabel('Voltage (V)');
```

```
grid on
legend('Model curve','Experimental curve');
hold off

parametri_cella = [iph(1), is(1), m(1), Rsh(1), Rs(1),
Voc(1), Isc(1),
Vmpp(1), Impp(1);iph(2), is(2), m(2), Rsh(2), Rs(2),
Voc(2), Isc(2),
Vmpp(2), Impp(2) ];
curve=[V(sample1:samplemax),I(sample1:samplemax),
transpose(Vstring),transpose(Istring)];
curve2=[transpose(vm), transpose(im)];

dlmwrite('modulo_ombrato_EXPC.txt', parametri_cella,
'delimiter','\t')
dlmwrite('modulo_ombrato_EXPC.txt', curve,
'delimiter','\t','-append')
dlmwrite('modulo_ombrato_EXPC.txt', curve2,
'delimiter','\t','-append')
```

Appendix B

In the following, the MATLAB® code for computing the PQ indicators of chapter 6 from a tree-phase current system (in particular the case for "structured unbalance" is considered) is reported.

```
clear all

close all


for c=1:6


%c=1; % number of the measurement considered


%  file to be open with the data of time and of the four signals,

%  one for each channel, in column


fname = sprintf('vi_rete_totale_%d.txt', c);


fid = fopen(fname, 'r');

dati = textscan(fid,'%f%f%f%f%f%f%f');

fclose(fid);


% Three-phase measurement on the total system

% saving of the data of time and signals to be processed
```

```
tempo = dati{1,1};
V1 = dati{1,2};  % segnale da canale 1
I1 = dati{1,3};  % segnale da canale 2
V2 = dati{1,4};  % segnale da canale 3
I2 = dati{1,5};  % segnale da canale 4
V3 = dati{1,6};  % segnale da canale 5
I3 = dati{1,7};  % segnale da canale 6

T = 0.2;        % time window
Fs = 102400;     % sampling frequency
N = Fs*T;       % samples' number
Ts = 1/Fs;      % time-step between samples
f1 = 1/T;       % reference frequency
omega1=2*pi*f1/N; % reference pulse

f = transpose(f1*(0:N-1));  % frequency vector

% Mean values of the six signals
V1mean=mean(V1)
I1mean=mean(I1)
V2mean=mean(V2)
I2mean=mean(I2)
V3mean=mean(V3)
I3mean=mean(I3)
```

```
% Elimination of the mean values

V1=V1-V1mean;
V2=V2-V2mean;
V3=V3-V3mean;
I1=I1-I1mean;
I2=I2-I2mean;
I3=I3-I3mean;

% RMS values
V1RMS=sqrt(sum(transpose(V1)*V1)/N)
V2RMS=sqrt(sum(transpose(V2)*V2)/N)
V3RMS=sqrt(sum(transpose(V3)*V3)/N)
I1RMS=sqrt(sum(transpose(I1)*I1)/N)
I2RMS=sqrt(sum(transpose(I2)*I2)/N)
I3RMS=sqrt(sum(transpose(I3)*I3)/N)

% Eventual neutral current evaluation

In=I1+I2+I3;
InRMS=sqrt(sum(transpose(In)*In)/N)

ISRMS=[I1RMS; I2RMS; I3RMS;];
figure(1)
```

```
plot(tempo,I1,'k',tempo,I2,'b',tempo,I3,'r');
title('Segnali delle correnti');
xlabel('tempo (sec)');
ylabel('Corrente (A)');

% three currents' FFT

% ampiezze
Y1 = fft(I1,N);
amplY1=(2*abs(Y1)/N)/sqrt(2);
Y2 = fft(I2,N);
amplY2=(2*abs(Y2)/N)/sqrt(2);
Y3 = fft(I3,N);
amplY3=(2*abs(Y3)/N)/sqrt(2);

% fasi
faseY1=(angle(Y1)+pi/2)*180/pi;
faseY2=(angle(Y2)+pi/2)*180/pi;
faseY3=(angle(Y3)+pi/2)*180/pi;

% analysis is limited to the harmonic order hordermax
% massimo ordine armonico che interessa
hordermax = 50;
% numero di periodi nella finestra temporale scelta
Ncicli = T/0.02;
```

```
% massimo numero di punti che interessano
nmax = Ncicli*hordermax+1;

% THD
harms1(1)=0;
harms2(1)=0;
harms3(1)=0;
harms4(1)=0;
phase1(1)=0;
phase2(1)=0;
phase3(1)=0;
phase4(1)=0;

% harms e phase vector are constructed for each signal
% to isolate the harmonic orders

% the fundamental frequency component is at the moment escluded
% to make the THD computing easy

j=0;
for k=(1+2*Ncicli):Ncicli:nmax
    j=j+1;
    harms1(j) = amplY1(k);
    phase1(j) = faseY1(k);
     harms2(j) = amplY2(k);
```

```
     phase2(j) = faseY2(k);
      harms3(j) = amplY3(k);
      phase3(j) = faseY3(k);

end

% THDs

THDi1 = sqrt(harms1*transpose(harms1))/amplY1(1+Ncicli)
THDi2 = sqrt(harms2*transpose(harms2))/amplY2(1+Ncicli)
THDi3 = sqrt(harms3*transpose(harms3))/amplY3(1+Ncicli)

% saving of the signals' spectrum and harmonics in spettro.txt
spettro = [f, amplY1, amplY2, amplY3];
armoniche = [amplY1(1+Ncicli), harms1; amplY2(1+Ncicli), harms2;
amplY3(1+Ncicli), harms3;];
angoliarmoniche = [faseY1(1+Ncicli), phase1; faseY2(1+Ncicli),
phase2; faseY3(1+Ncicli), phase3;];

dlmwrite('spettro-structured-unbalance.txt',spettro,'delimiter','\t')
dlmwrite('spettro-structured-unbalance.txt', armoniche,
'delimiter','\t','-append')
dlmwrite('spettro-structured-unbalance.txt', angoliarmoniche,
'delimiter','\t','-append')
```

```
% saving of the signals vs. time in segnali.txt

    segnali = [tempo, I1, I2, I3, V1, V2, V3];
    dlmwrite('segnali-structured-unbalance.txt', segnali,'delimiter','\t')
    parametri = [I1mean, I1RMS, I2mean, I2RMS, I3mean, I3RMS,
THDi1, THDi2, THDi3];
    dlmwrite('segnali-structured-unbalance.txt', parametri,
'delimiter','\t','-append')

% Plot single-sided amplitude spectrum.

figure(2)

hn = transpose((1:hordermax));

bar(hn,transpose(armoniche), 'grouped');
axis([2 15 0 5])
colormap summer;
title('Single-Sided Amplitude Spectrum of signals');
xlabel('Frequency (Hz)');
ylabel('|Y(f)|');

% Current phasors construction with positive, negative
% and zero sequence components (of the first phase)
```

```
phasors = zeros(3,hordermax);

preale = zeros(3,hordermax);

pimmaginaria = zeros(3,hordermax);


    alpha=exp(i*2/3*pi);

    alpha2=exp(-i*2/3*pi);

    S = [1 alpha alpha2; 1 alpha2 alpha; 1 1 1];

    simm_comp = zeros(3,hordermax);


% if the analysis regards the currents, the rows from

% the second to the fourth % of the harmonics amplitude

% and phase matrix are to be considered


        for k=1:3

          for j=1:hordermax

          phasors(k,j)= (armoniche(k,j)*

  *exp(i*angoliarmoniche(k,j)*pi/180));

          end

        end


    % Symmetrical components (SC) computing for the first

% phase and each harmonic order


    for k=1:hordermax

    simm_comp(:,k) = 1/3*S*phasors(:,k);
```

```
end

% Plot of the current phasors, positive, negative
% and zero sequence components
figure(3)
for k=1:3
    xPlot=[0 real(phasors(k,1))];
    yPlot=[0 imag(phasors(k,1))];

% in blue the current phasors at fundamental frequency

plot(xPlot,yPlot,'b')
hold on

    xPlot=[0 real(simm_comp(k,1))];
    yPlot=[0 imag(simm_comp(k,1))];

switch (k)
    case 1
        r=1.0;g=0.0;b=0.0;
    case 2
        r=0.0;g=1.0;b=0.0;
    case 3
        r=0.0;g=0.0;b=1.0;
end
```

```
    % in red the positive, in green the negative and in
% black the zero sequence component

    plot(xPlot,yPlot,'Color',[r,g,b])
    hold on
    end

    % Saving of the phasors and SC, with real and immaginary
% parts, for other processing
    preale=real(phasors);
    pimmaginaria=imag(phasors);
    fasori = [preale; pimmaginaria];
    dlmwrite('fasori-structured-unbalance.txt', fasori,
'delimiter','\t')
    preale=real(simm_comp);
    pimmaginaria=imag(simm_comp);
    fasori = [preale; pimmaginaria];
    dlmwrite('fasori-structured-unbalance.txt', fasori,
'delimiter','\t','-append')

    % Power Quality Indicators

    % Phase Current
```

```
    % Balanced phase current component
    Ipb=0;
    for k= 1:hordermax

        if (((k-1)/3 - round((k-1)/3)) == 0)

        Ipb = Ipb + abs(simm_comp(1,k))^2;

            else if (((k-2)/3 - round((k-2)/3)) == 0)

                Ipb = Ipb + abs(simm_comp(2,k))^2;

                  else if ((k/3 - round(k/3)) == 0)

                          Ipb = Ipb + abs(simm_comp(3,k))^2;

                  end
            end
        end

        %Ipb = Ipb + abs(simm_comp(1,3*k+1))^2 +
+ abs(simm_comp(2,3*k+2))^2 + abs(simm_comp(3,3*k+3))^2;

    end
    Ipb = sqrt(Ipb)
```

```
% Unbalanced phase current component
Ipu=0;
 for k= 1:hordermax

     if (((k-1)/3 - round((k-1)/3)) == 0)

        Ipu = Ipu + abs(simm_comp(2,k))^2 +
+ abs(simm_comp(3,k))^2;

        else if (((k-2)/3 - round((k-2)/3)) == 0)

            Ipu = Ipu + abs(simm_comp(1,k))^2 +
+ abs(simm_comp(3,k))^2;

              else if ((k/3 - round(k/3)) == 0)

                      Ipu = Ipu + abs(simm_comp(1,k))^2 +
  + abs(simm_comp(2,k))^2;

              end
        end
    end

     %Ipu = Ipu + abs(simm_comp(2,3*k+1))^2 + abs(simm_comp(3,3*k+1))^2
```

```
 + abs(simm_comp(1,3*k+2))^2 + abs(simm_comp(3,3*k+2))^2 +
 + abs(simm_comp(1,3*k+3))^2 + abs(simm_comp(2,3*k+3))^2;

    end
    Ipu = sqrt(Ipu)

     %  phase current Distortion component
    Ipd=0;
    for k= 2:hordermax
        Ipd = Ipd + abs(simm_comp(1,k))^2 + abs(simm_comp(2,k))^2 +
+ abs(simm_comp(3,k))^2;
    end
    Ipd = sqrt(Ipd)

   % Balance fundamental phase current component

   Ipb1 = abs(simm_comp(1,1))

   % Unbalance fundamental phase current component

   Ipu1 = sqrt(abs(simm_comp(2,1))^2 + abs(simm_comp(3,1))^2)

   % Balanced phase current distorsion component

   Ipbd = sqrt(Ipb^2 - Ipb1^2)
```

```
 % Unbalance phase current distorsion component

Ipud = sqrt(Ipu^2 - Ipu1^2)

 %  Alternative phase current Distortion component

 Ipd2 = sqrt(Ipud^2 + Ipbd^2)

 %Balance distortion factor

 phi_pI_bd = Ipbd / Ipb1

 %Unbalance distortion factor

 phi_pI_ud = Ipud / Ipb1

%Unbalance distortion factor at fundamental frequency

 phi_pI_u1 = Ipu1 / Ipb1

 % Total Phase Distortion referred to the non distorded phase current
 % components at fundamental frequency

 TPDi = Ipd / sqrt(Ipb1^2+Ipu1^2)
```

```
 % Overall Unbalance factor

 phi_pI_u = Ipu / Ipb1

% Total Phase Unbalance factor

TPUi = Ipu / Ipb

% Negative to positive ratio, current unbalance factor, CUF

CUF = abs(simm_comp(2,1))/abs(simm_comp(1,1))

%  complex current unbalance factor, CCUF

CCUF = (real(simm_comp(2,1))+i*imag(simm_comp(2,1)))/(real(simm_comp(1,1))+
+ i*imag(simm_comp(1,1)))

modCCUF = abs(CCUF)
if (real(CCUF)>0)
phaseCCUF = atan(imag(CCUF)/real(CCUF))
else phaseCCUF = atan(imag(CCUF)/real(CCUF)) + pi
end

% Ui
```

```
    Ieff = ISRMS(1:3,1);
    Imin = min (Ieff);
    Imax = max (Ieff);
    Iaverage = mean (Ieff);
    Ui = max(abs(Iaverage - Imin),abs(Imax-Iaverage))/Iaverage

% Current Unbalance Index, CUI

 Ieq = sqrt(transpose([Ieff;InRMS])*[Ieff;InRMS] /3)

 dI = sqrt(abs(power(Ieff,2)-Ieq^2))/Ieq;

 CUI = sqrt(transpose(dI)*dI /3)

% Current Unbalance Indicator, CUNB

Ie1 = sqrt(transpose(abs(simm_comp(:,1)))*abs(simm_comp(:,1)));

CUNB = sqrt(Ie1^2 - abs(simm_comp(1,1))^2)/Ie1

% Absolute Current deviations
```

```
deltaI = abs((Ieff-Iaverage)/Iaverage)

% ITUD computing

Itr = zeros(3,hordermax);

 for k=1:hordermax

     if (((k-1)/3 - round((k-1)/3)) == 0)

     T = S;

         else if (((k-2)/3 - round((k-2)/3)) == 0)

             T = [1 alpha2 alpha; 1 alpha alpha2; 1 1 1];

               else if ((k/3 - round(k/3)) == 0)

                       T = [1 1 1;1 (-1-sqrt(3))/2 (-1+sqrt(3))/2;
1 (-1+sqrt(3))/2 (-1-sqrt(3))/2];

               end
         end
     end
```

```
        Itr(:,k) = 1/3*T*phasors(:,k);

    end

    Ibn = Itr(1,:);
    Ifu = Itr(2,:);
    Isu = Itr(3,:);

   Iu1pow2 = abs(Ifu(1))^2 + abs(Isu(1))^2;
   Ibkpow2 = Ibn(2:hordermax)*transpose(conj(Ibn(2:hordermax)));
   Iukpow2 = 0;
   for k =2:hordermax
       Iukpow2 = Iukpow2 + abs(Ifu(k))^2 + abs(Isu(k))^2;
   end

   ITUD = sqrt((Iu1pow2+Iukpow2)/(abs(Ibn(1))^2+Ibkpow2))

   % Saving of the indicators' values in indicatori.txt

   if (c == 1)

       indicatori = [THDi1, THDi2, THDi3, CUF, phi_pI_bd,
   phi_pI_ud, phi_pI_u1, TPDi, phi_pI_u, TPUi, CCUF, modCCUF,
   phaseCCUF, Ui, CUI, CUNB, deltaI(1), deltaI(2), deltaI(3),
   ITUD, Ipb,Ipb1,Ipbd,Ipu,Ipu1,Ipud,Ipd,Ieq,dI(1),dI(2),dI(3),
```

```
   Ieff(1),Ieff(2),Ieff(3),Iaverage];
         dlmwrite('indicatori-structured-unbalance.txt',
 indicatori,'delimiter','\t')

   else
          indicatori = [THDi1, THDi2, THDi3, CUF, phi_pI_bd,
  phi_pI_ud, phi_pI_u1, TPDi, phi_pI_u, TPUi, CCUF,  modCCUF,
  phaseCCUF, Ui, CUI, CUNB, deltaI(1), deltaI(2), deltaI(3),
  ITUD, Ipb,Ipb1,Ipbd,Ipu,Ipu1,Ipud,Ipd,Ieq,dI(1),dI(2),dI(3),
  Ieff(1),Ieff(2),Ieff(3),Iaverage];
          dlmwrite('indicatori-structured-unbalance.txt', indicatori,
  'delimiter','\t','-append')

   end

end  % close the cicle for the multiple file opening
```

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