```
% Lingling Fan
% 7/16/2021 version. PLL will not be considered.
% 7/3/2021
% examine LC resonance caused overvoltage
% why overvoltage is observed at the inverter PCC bus, not at the
% substation bus with a shunt.
% analysis of 80 Hz oscillations.
% The 44kV capacitor is at station bus, fault level at bus 430MVA,
%capacitor 29.6Mvar, feeder impedance from station to PCC is
%Z1=4.2+j11.65 ohm, Z0=9.3 +j 50.33 ohm, three solar farms at PCC, each 10MW.
clear; clc; close all
flag_C = 1;
flag_FW = 1;

bode_P = bodeoptions;
bode_P.FreqUnits = 'Hz';
bode_P.PhaseWrapping = 'on';
```

feeder, shunt, substation

```
Sb = 30;
Zbase = 44^2/Sb;
R_feeder = 4.2/Zbase;    % 0.0651
X_feeder = 11.65/Zbase;  % 0.1805
X_feeder = 0.30;
Xg = 1/(430/Sb);         % 0.0698
Xg = 0.15;
%Xg = 0.20;
Rg = Xg/8; Bc = 29.6/Sb;
Bc = 0.30;
L_feeder = X_feeder/377; Lg = Xg/377; C_shunt = Bc/377;
```

steady-state analysis

```
I_cur = 1.0+1i*0.3;
Vsub = 1+ (Rg+1i*Xg)*(I_cur);  %
I_conv = I_cur + 1i*Bc*Vsub;  %0.5538, 0.5825
V_pcc = (R_feeder+1i*X_feeder)*I_conv+ Vsub; % 1.0130, 0.2365 angle

[abs(Vsub), abs(V_pcc)]
```

```
ans = 1×2
    0.9861    0.9834
```

converter control and choke filter

```
Kp_PR = 0.2; Kr_PR = 15; tau = 1.0e-4;
Kp_PR =0.5;
%Kp_PR =1; Kr_PR = 10;tau = 1.0e-4;
%Kp_PR =0.2; Kr_PR = 10;tau = 1.0e-4;
```

```
%Kp_PR = 0.4; Kr_PR = 20;
%Kp_PR =0.6; Kr_PR = 30;tau = 2.0e-4;

X = 0.15; L = X/377; R = X/10; w1 = 377;
%X = 0.10; %reducing X leads to higher cap point freuquency in Zpv
```

PR controller gains

```
wc = 2*pi*2;
%wc = 2*pi*2.0;
Kp_PR =0.3; Kr_PR = 15;tau = 1.0e-4;
Kp_PR =0.5; Kr_PR = 30;tau = 1.0e-4;
Kp_PR =0.25; Kr_PR = 10;tau = 1.0e-4;
%Kp_PR =0.3; Kr_PR = 12;tau = 1.0e-4; %if X  = 0.15;
```

PI controller gains

```
Kp_PI = Kp_PR; Ki_PI = Kr_PR*wc; tau = 1.0e-4;
%Kp_PI = 0.05; Ki_PI = 5; tau = 1.0e-4; % if X  = 0.15;
```

construct transfer functions

```
s = tf('s');
s1 = s;
s2 = s-1i*377;

Z_feeder = R_feeder+L_feeder*s; Y_feeder = 1/Z_feeder;
Z_c = 1/(C_shunt*s); Y_c = 1/Z_c;
Zg = Rg+Lg*s1; Yg = 1/Zg;
Z_grid = Z_feeder+ 1/(C_shunt*s+1/Zg);

if(flag_C ==0)
Z_grid = Z_feeder+ Zg;
end

Y_grid = 1/Z_grid;

Td = (1-tau/2*s1)/(1+tau/2*s1);

H_pr = Kp_PR + Kr_PR*2*wc*s1/(s1^2+2*wc*s1+w1^2);
Hs_pi = Kp_PI + Ki_PI/(s2);
H_pi = Kp_PI + Ki_PI/(s1);
```

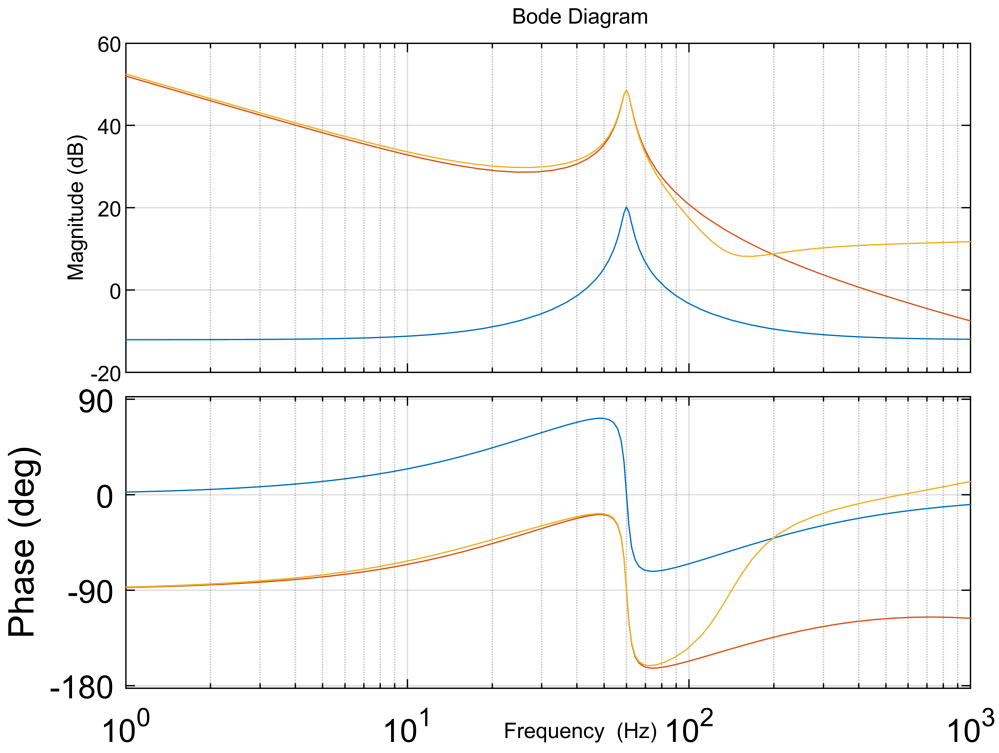
bandwidth calculation

```
G_PR = feedback(H_pr/(R+s*L), 1);
G_PI = feedback(H_pi/(R+s*L), 1);
```

```
[bandwidth(G_PR), bandwidth(G_PI)]/2/pi
```

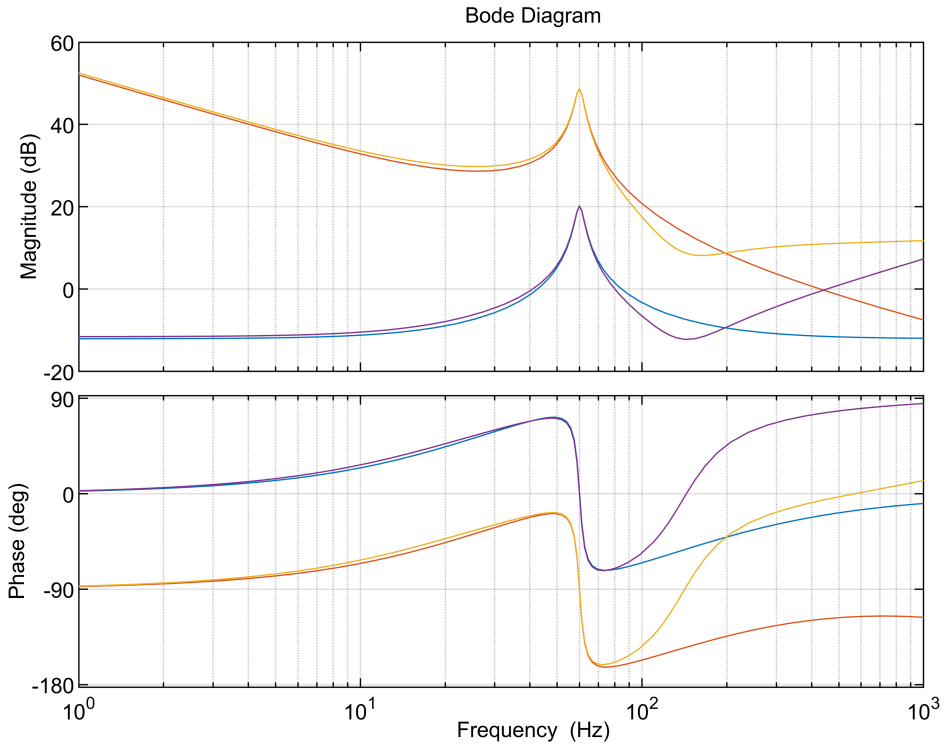
```
ans = 1×2
  229.7394  164.5312
```

```
Td = (1-tau/2*s1)/(1+tau/2*s1);

Z_PV_ref{1} = Td/(1-Td)*H_pr;  % Z_star for PR
Z_PV_ref{2} = Td/(1-Td)*Hs_pi;  % Z_star for PI

%Z_PV_ref{1} = Td*H_pr;  % Z_star for PR
Z_PV{1} = (Td*H_pr + R+s*L)/(1-Td);
%Z_PV{1} = (Td*H_pr + R+s*L);
if(flag_FW==0)
    Z_PV_ref{1} = Td*H_pr;  % Z_star for PR
    Z_PV{1} = (Td*H_pr + R+s*L);
end

Z_PV{2} = (Td*(Hs_pi - 1i*X)+R+s*L)/(1-Td);

figure(666);
set(gca,'FontSize', 12)
```

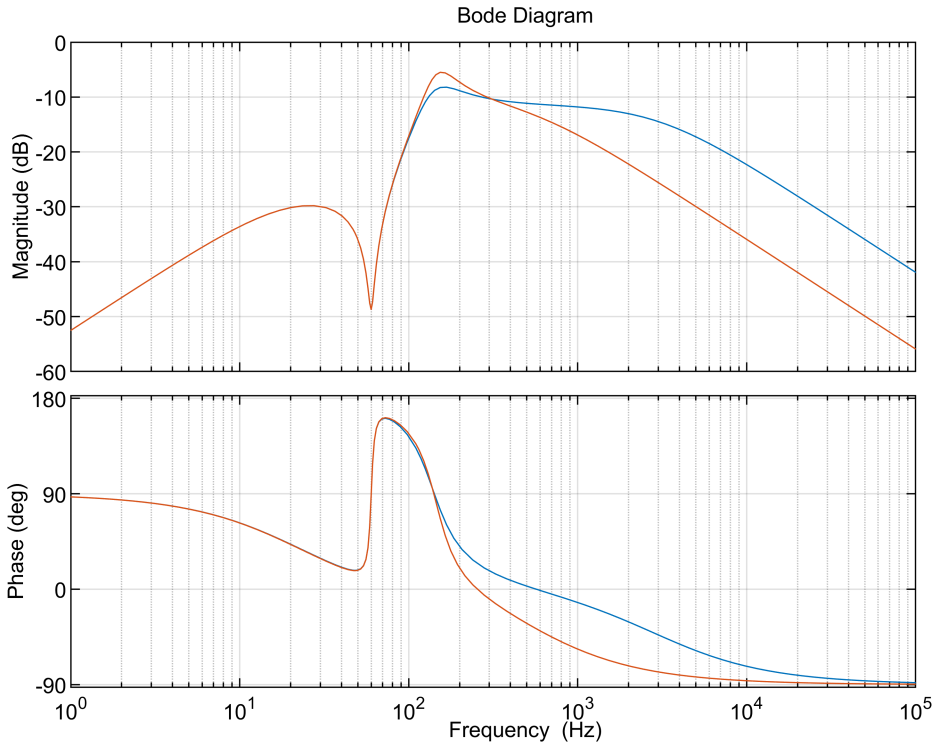


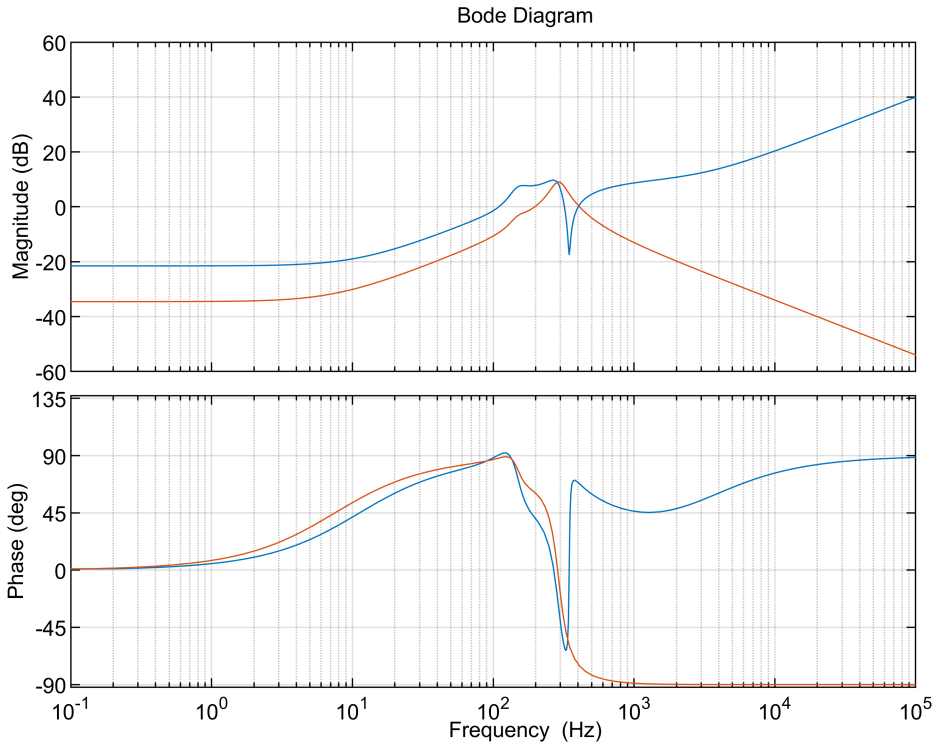

```
bode(H_pr, Td/(1-Td)*H_pr, Z_PV{1}, bode_P); grid on;
xlim([1,1000]);
hold on;
```

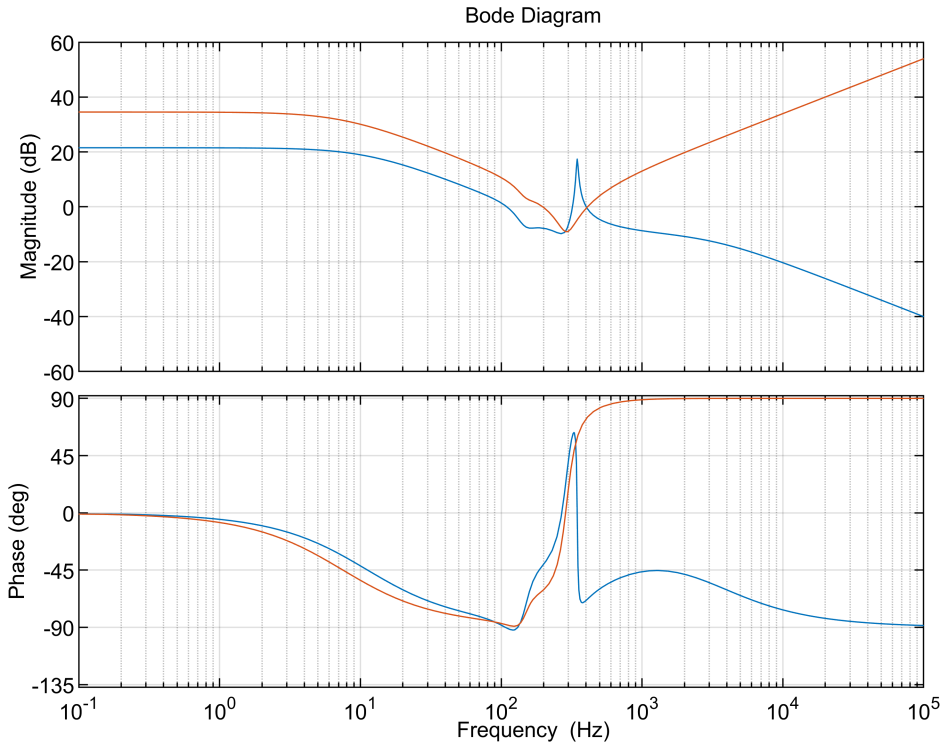
```
bode(Td*H_pr+R+L*s, bode_P);grid on;
xlim([1,1000]);
```

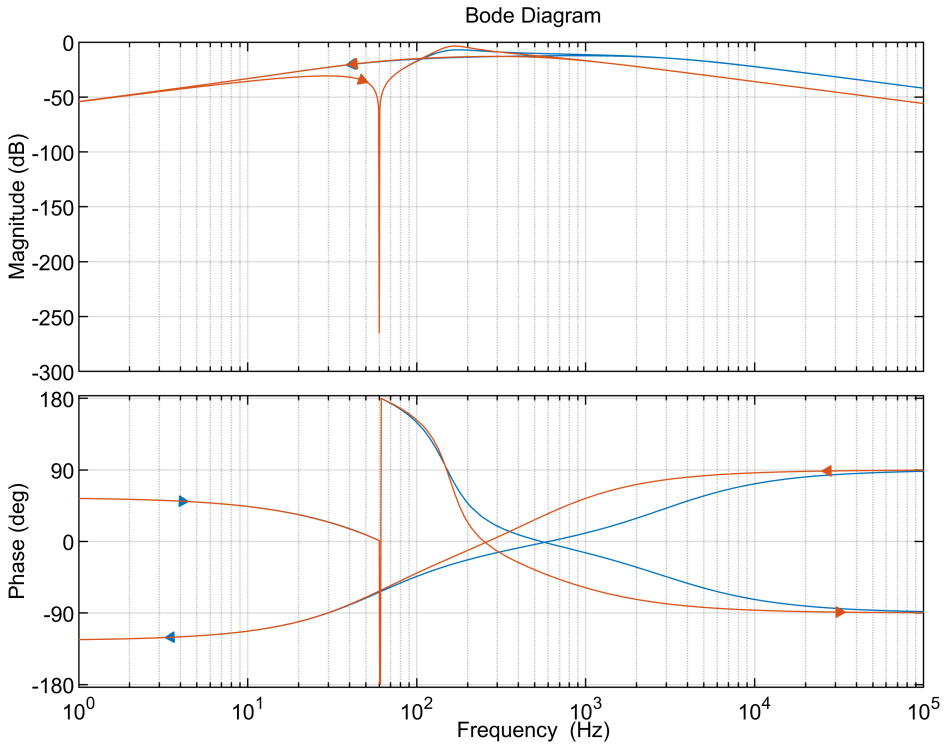


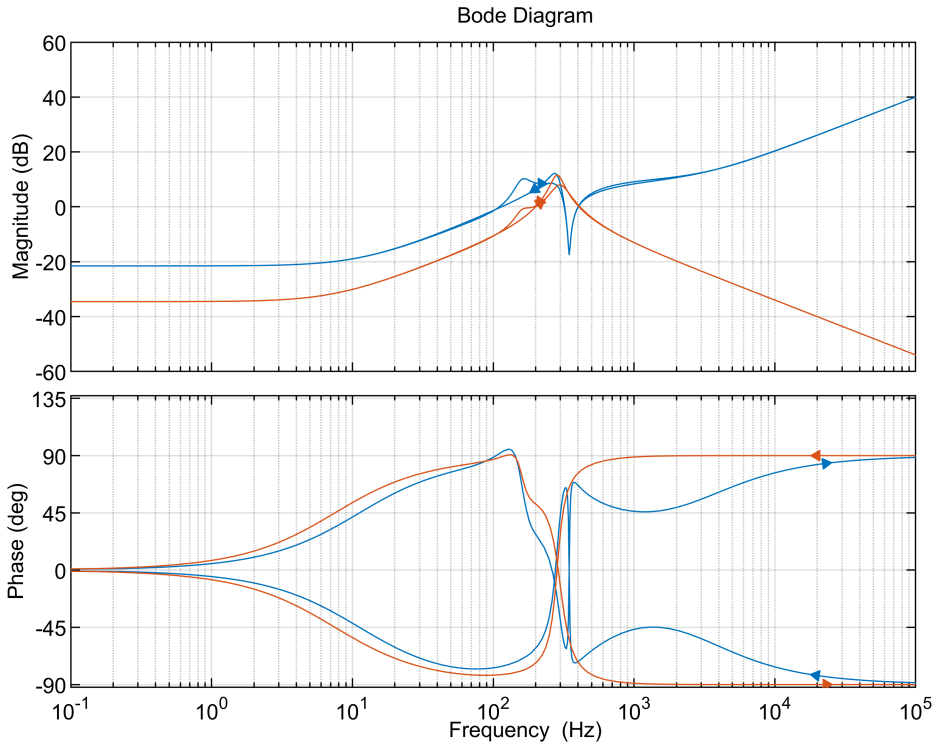

```
%set(findall(gcf,'type','axis'),'FontSize',12)


for k=1:2
    Y_PV{k} = 1/Z_PV{k};
    G_pcc{k} = inv(Y_PV{k}+Y_grid)*Y_PV{k}*Z_PV_ref{k};
    G_sub{k} = inv(1/(Z_PV{k}+Z_feeder)+s*C_shunt +Yg)/(Z_PV{k}+Z_feeder)*Z_PV_ref{k};

    figure(5000+k);
    bode(Y_PV{k}, 1/(Z_PV{k}+Z_feeder), bode_P); grid on;
    figure(6000+k);
    bode(inv(Y_PV{k}+Y_grid), inv(1/(Z_PV{k}+Z_feeder)+s*C_shunt +Yg), bode_P); grid on;
    figure(7000+k);
     bode((Y_PV{k}+Y_grid), (1/(Z_PV{k}+Z_feeder)+s*C_shunt +Yg), bode_P); grid on;
end
```

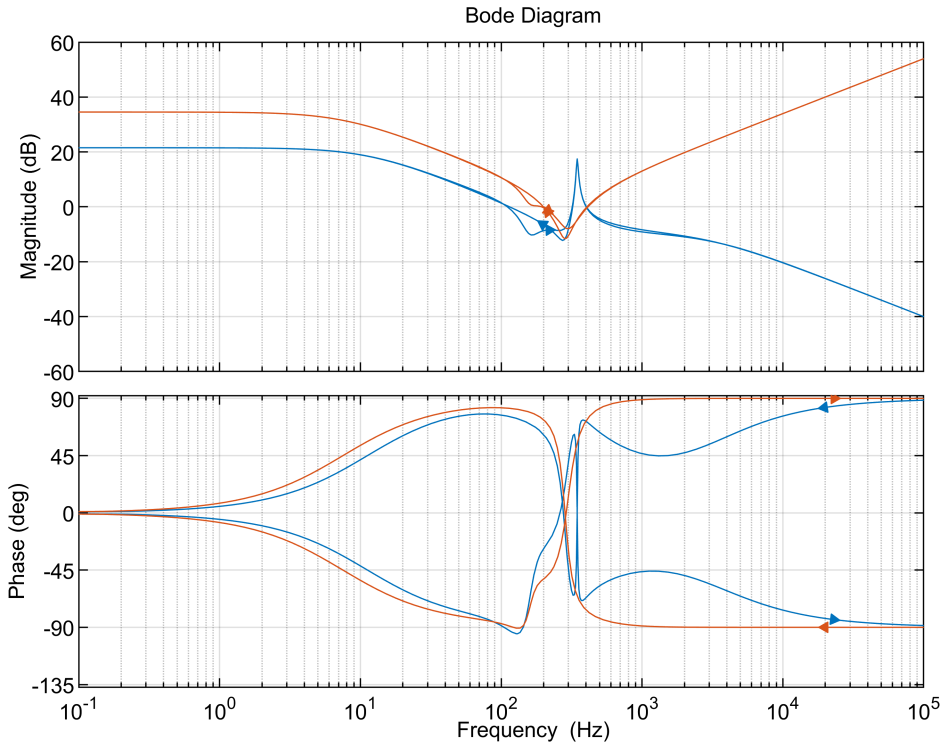

Bode Diagram
Magnitude (dB)
0
-10
-20
-30
-40
-50
-60
Phase (deg)
180
90
0
-90
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)


Bode Diagram
Magnitude (dB)
60
40
20
0
-20
-40
-60
Phase (deg)
135
90
45
0
-45
-90
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)


Bode Diagram
Magnitude (dB)
60
40
20
0
-20
-40
-60
Phase (deg)
90
45
0
-45
-90
-135
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Frequency (Hz)

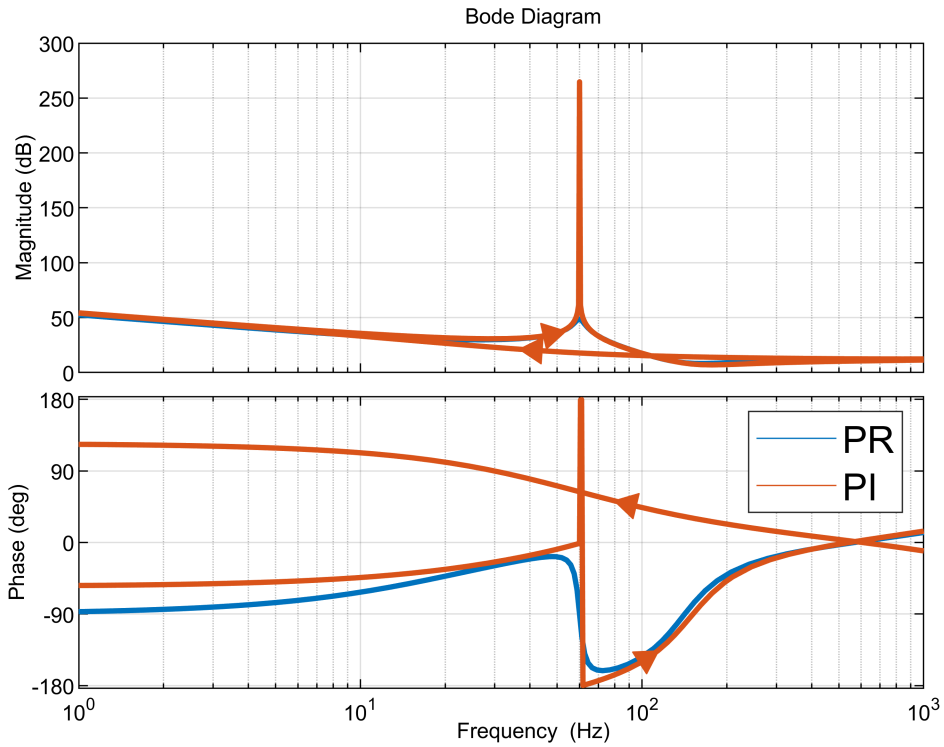

Bode Diagram
Magnitude (dB)
0
-50
-100
-150
-200
-250
-300
Phase (deg)
180
90
0
-90
-180
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Frequency (Hz)



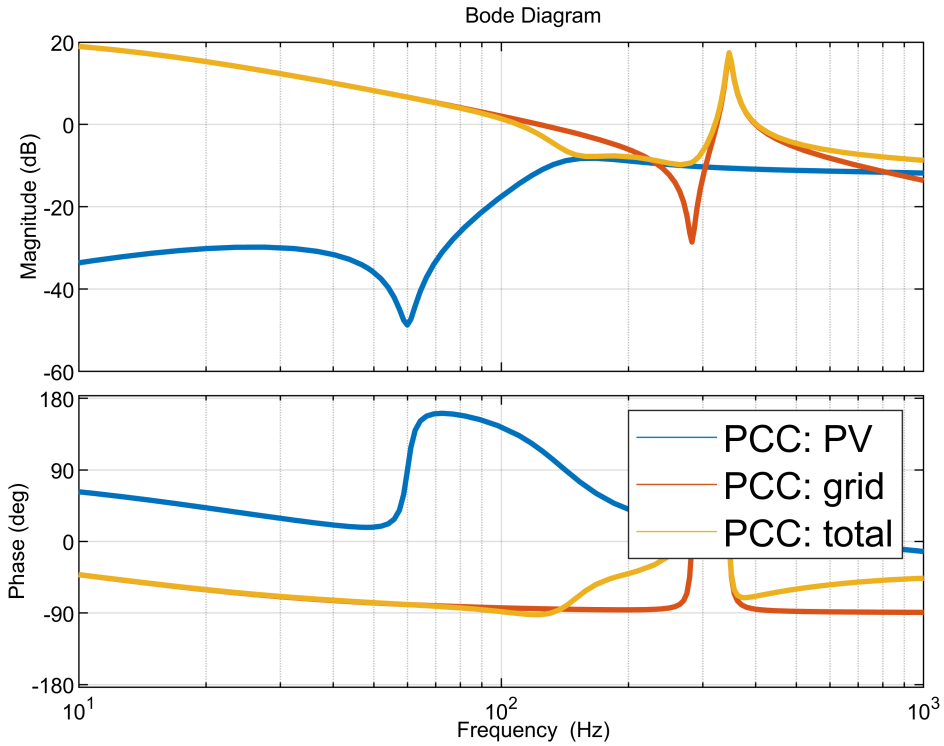



```
figure(101);
hold on;
```

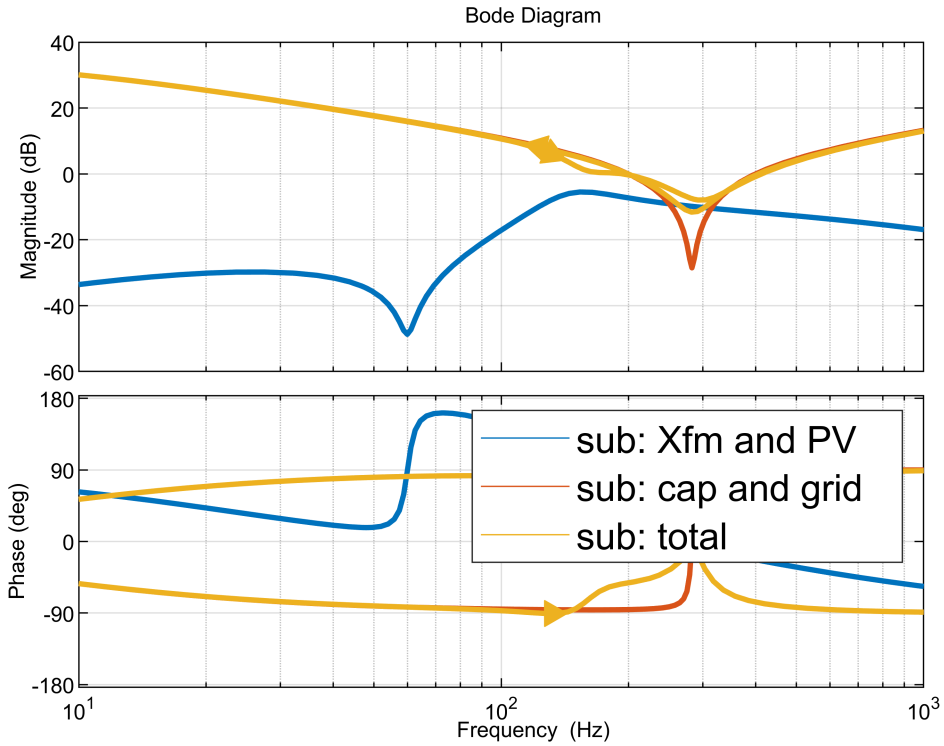
```
bode(Z_PV{1}, Z_PV{2}, bode_P); grid on;
legend({'PR', 'PI'},'FontSize', 14);
set(findall(gcf,'type','line'),'linewidth',2)
xlim([1, 1000])
```



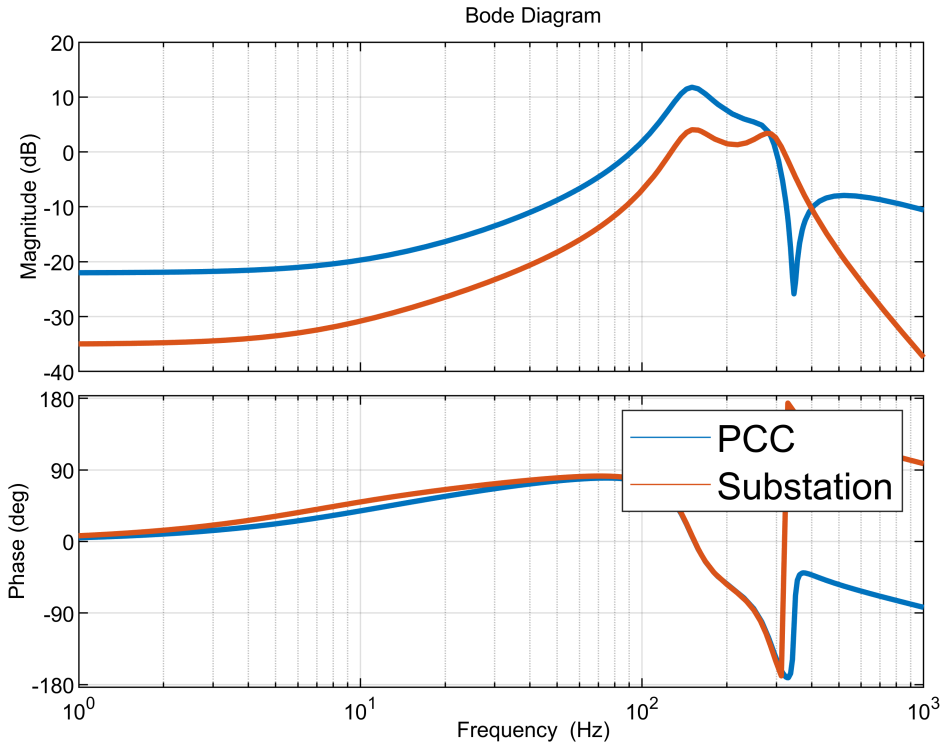

```
figure(111);
bode(Y_PV{1}, Y_grid, Y_PV{1}+Y_grid, bode_P); grid on;
legend({'PCC: PV', 'PCC: grid', 'PCC: total', },'FontSize', 14);
set(findall(gcf,'type','line'),'linewidth',2)
xlim([10, 1000])
```



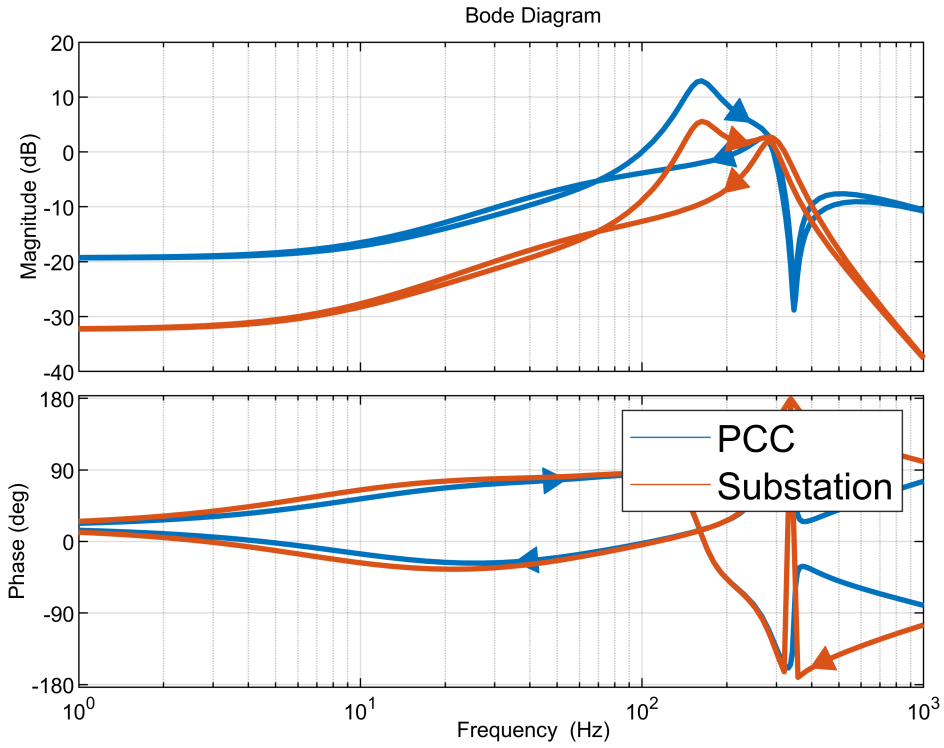

```
%
figure(112);
hold on;
bode(1/(Z_feeder+Z_PV{1}), s*C_shunt+Yg,1/(Z_PV{k}+Z_feeder)+s*C_shunt +Yg, bode_P); grid on;
legend({'sub: {Xfm and PV}', 'sub: {cap and grid}', 'sub: total'},'FontSize', 14);
set(findall(gcf,'type','line'),'linewidth',2)
xlim([10, 1000])
```




```
figure(102);
hold on;
bode(G_pcc{1}, G_sub{1}, bode_P); grid on;
legend({'PCC', 'Substation'},'FontSize', 14);
set(findall(gcf,'type','line'),'linewidth',2)
xlim([1, 1000])
```




```
figure(202);
hold on;
bode(G_pcc{2}, G_sub{2}, bode_P); grid on;
legend({'PCC', 'Substation'},'FontSize', 14);
set(findall(gcf,'type','line'),'linewidth',2)
xlim([1, 1000])
```



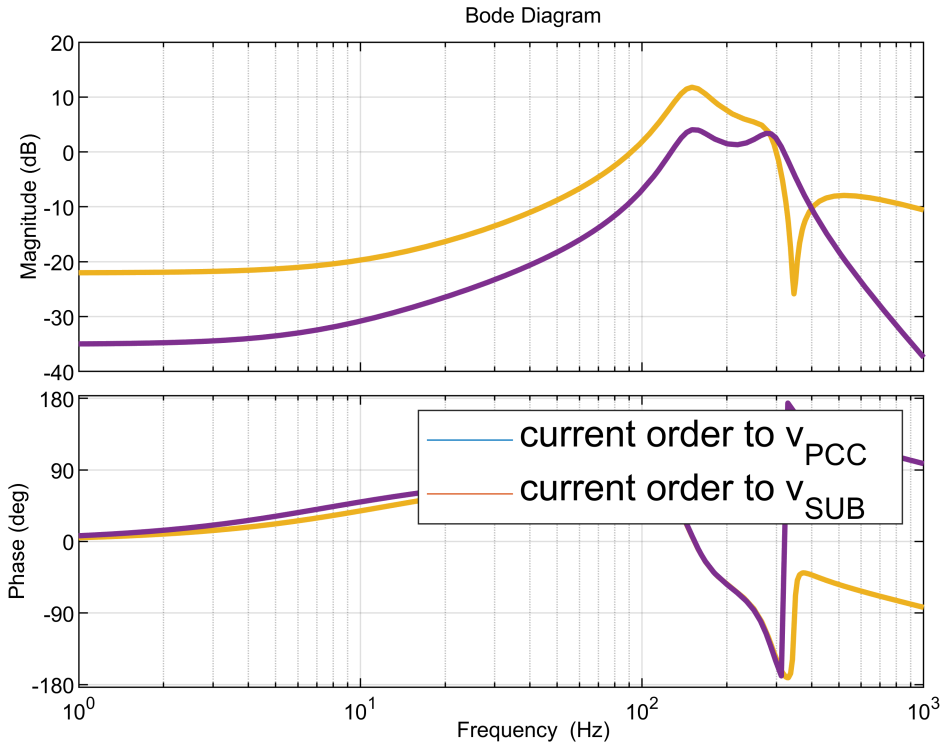

```
% G1 = Kpr*(1-tau/2*s1)/(tau*s1);
% Z_pv = G1+(R+L*s1)*(1+tau/2*s1)/(tau*s1); Y_pv = 1/Z_pv;
% G1 = G1*Y_pv;
%
% figure(101);
% hold on;
% bode(Z_pv, bode_P); grid on;
% %legend({'abc-frame', 'dq-frame'},'FontSize', 14);
% set(findall(gcf,'type','line'),'linewidth',2)
% xlim([1, 1000])
%
%
% Z_feeder = R_feeder+L_feeder*s; Y_feeder = 1/Z_feeder;
% Z_c = 1/(C_shunt*s); Y_c = 1/Z_c;
% Zg = Rg+Lg*s1; Y_g = 1/Zg;
% Zpcc = Z_feeder+ 1/(C_shunt*s+1/Zg);
% Zpcc_noC = Z_feeder + Zg; % no shunt
%
% Ypcc = 1/Zpcc;
% Ypcc_noC = 1/Zpcc_noC;
%
% Z2 = inv(1/(Z_pv + Z_feeder) +C_shunt*s +1/Zg)*Z_pv/(Z_pv+Z_feeder);
%
```

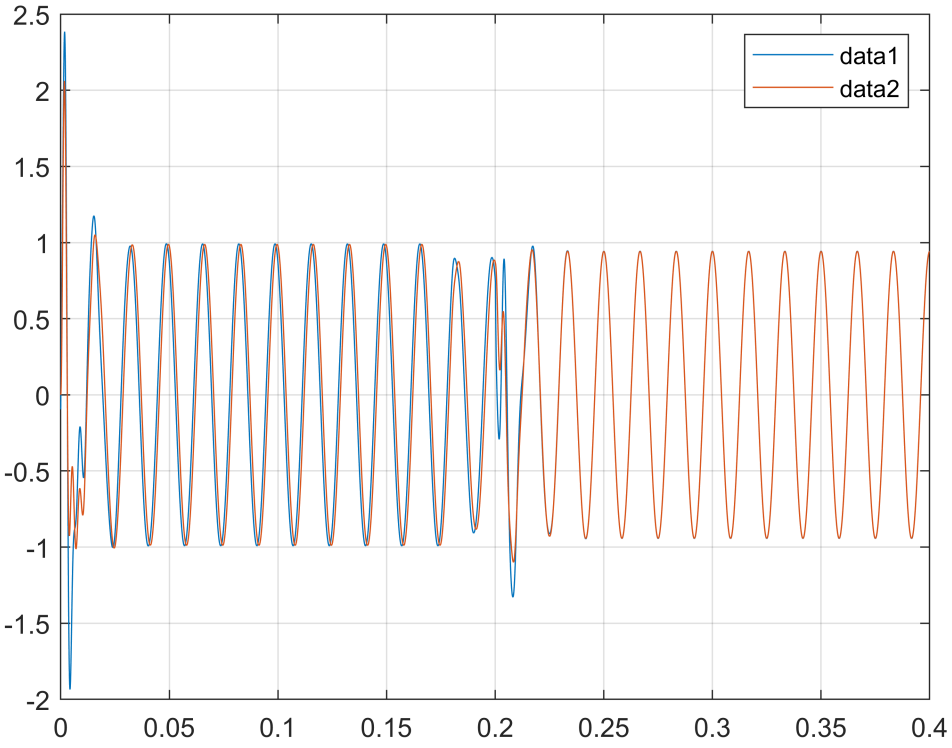
simulation

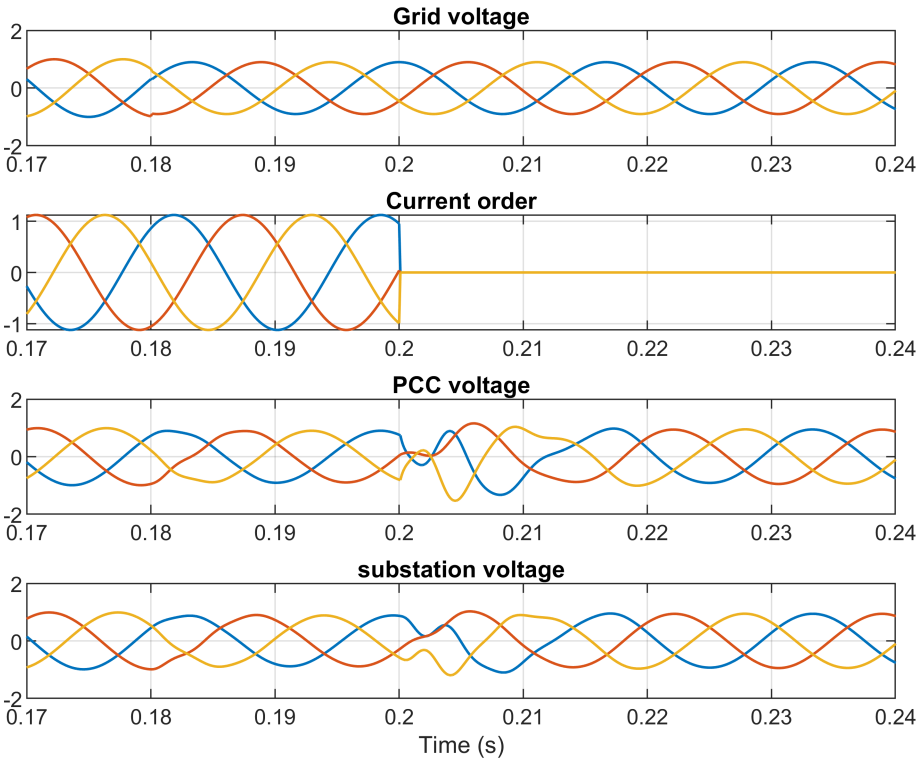
```
for ii=1:1;
Y_net{ii} = [Y_PV{ii}+Y_feeder, -Y_feeder; -Y_feeder, Yg+Y_c+Y_feeder];

if(flag_C ==0)
   Y_net{ii}=[Y_PV{ii}+Y_feeder, -Y_feeder; -Y_feeder, Yg+Y_feeder];
end
% %[data_H, data_f]= freqresp(Y_net);
% w = 2*pi*logspace(-1, 3, 300);
% H = freqresp(Y_net{ii}, w);
% Hh = freqresp(Y_PV{ii}*Z_PV_ref{ii}, w);
% for kk= 1:size(H,3)
%     H1(:,:,kk) = inv(H(:,:,kk));
%  %   H1(:,1,kk) = H1(:,1,kk)*Hh(:,:,kk); % the first column has Y_PV Z_PV_ref
% end
% data_fr = idfrd(H1,w,0);
% G = tfest(data_fr, 10);
% figure(9999);
% hold on;
% bode(G, data_fr);
% %compare(data_fr,Y1_net{ii});

G = inv(Y_net{ii});  % first column is related to the current order.
G_2by2 = G;
G_2by2(:,1) = Y_PV{ii}*Z_PV_ref{ii}*G(:,1);
G_2by2(:,2) = Yg*G(:,2);
%
%
% %G_upper = G1*Ypcc/(1+Ypcc*Z);
% %G_upper_noC = G1*Ypcc_noC/(1+Ypcc_noC*Z);
%
%
% % exact its imaginary part using numerical method
%
% figure(111);
% bode(Ypcc, Ypcc_noC, 1/Z_pv, bode_P); grid on;
% legend({'Y_{grid} with C', 'Y_{grid} without C', 'Y_{pv}'},'FontSize', 14);
% set(findall(gcf,'type','line'),'linewidth',2)
% xlim([1, 1000])
%
% figure(112);
% hold on;
% bode(Ypcc+1/Z_pv, Ypcc_noC+1/Z_pv, bode_P); grid on
% legend('total admittance at the PCC - with Cap', 'total admittance at the PCC - no Cap');
% xlim([1, 1000])
% set(findall(gcf,'type','line'),'linewidth',2)
%
%
```

```
% Y1 = Ypcc+1/Z_pv;
% figure(211);
% hold on;
% bode(1/Y1*G1, Z2*G1, bode_P); grid on
% %bode(1/Y1, G_2by2(1,1), bode_P);
% legend;
% legend({'current order to PCC voltage', 'current order to the substaton voltage'},'FontSize',
% xlim([1, 1000])
% set(findall(gcf,'type','line'),'linewidth',2)
%
 figure(7788);
 hold on;
 bode( G_2by2(1,1), G_2by2(2,1), bode_P); grid on
 %bode( Z2, G_2by2(2,1), bode_P); grid on
 legend;
 legend({'current order to v_{PCC}', 'current order to v_{SUB}'},'FontSize', 14);
 xlim([1, 1000])
 set(findall(gcf,'type','line'),'linewidth',2)


%
%
% %% 1/Y1
% w = 2*pi*logspace(-1, 3, 300);
% H = freqresp(1/Y1, w);
% data_fr = idfrd(H,w,0);
% Z1 = tfest(data_fr, 10);
% figure(555);
% bode(Z1/(1+0.0001*s), 1/Y1, bode_P); grid on;
% xlim([0.1, 1000])
%
t1=[0:0.0001:0.18];
t2 = [0.1801:0.0001:0.20];
t3 = [0.2001:0.0001:0.4];
t = [t1, t2, t3];
alpha = 2*pi/3;
%ang = -1.36;

% pcc bus: 1, current 1+j0,
% substation: 1
Im = abs(I_conv); ang_I= angle(I_conv);
%u1 = ones(length(t),1); %u2 = u1; Ua = [u1.', u2.'];
i1 = Im*cos(377*[t1,t2]+ang_I);       i2 = zeros(1, length(t3));
V1 = 1*cos(377*t1);       V2 = 0.9*cos(377*[t2,t3]);      Ua =[i1 i2; V1, V2];

i1 = Im*cos(377*[t1,t2]-alpha+ang_I);       i2 = zeros(1, length(t3));
V1 = 1*cos(377*t1-alpha);       V2 = 0.9*cos(377*[t2,t3]-alpha);      Ub =[i1 i2; V1, V2];

i1 = Im*cos(377*[t1,t2]+alpha+ang_I);       i2 = zeros(1, length(t3));
V1 = 1*cos(377*t1+alpha);       V2 = 0.9*cos(377*[t2, t3]+alpha);      Uc =[i1 i2; V1, V2];
```

```
%u1 = 1*cos(377*t1-alpha); u2 = zeros(1, length(t2)); Ub =[u1 u2]';
%u1 = 1*cos(377*t1+alpha); u2 = zeros(1, length(t2)); Uc =[u1 u2]';

temp_a = lsim(G_2by2, Ua, t);
temp_b = lsim(G_2by2, Ub, t);
temp_c = lsim(G_2by2, Uc, t);

figure(2233+ii)
plot(t, temp_a);grid on;
legend
%va_pcc = lsim(Z1/(1+0.0001*s), Ua, t);
%vb_pcc = lsim(Z1/(1+0.0001*s), Ub, t);
%vc_pcc = lsim(Z1/(1+0.0001*s), Uc, t);

 figure(2000+ii);
 ax(1)= subplot(4,1,1); hold on; plot(t, [Ua(2,:); Ub(2,:); Uc(2,:)],'LineWidth',1);
grid on; title('Grid voltage'); box on; ylim([-2,2])
 ax(2)= subplot(4,1,2); hold on; plot(t, [Ua(1,:); Ub(1,:); Uc(1,:)],'LineWidth',1);
grid on; title('Current order'); box on;

ax(3)= subplot(4,1,3); hold on; plot(t, [temp_a(:,1), temp_b(:,1), temp_c(:,1)],'LineWidth',1);
grid on; title('PCC voltage');
ylim([-2.0,2.0]); box on;
ax(4) = subplot(4,1,4); hold on; plot(t, [temp_a(:,2), temp_b(:,2), temp_c(:,2)],'LineWidth',1)
grid on; title('substation voltage');
ylim([-2.0, 2.0]); box on;
hold on;
xlabel('Time (s)')
linkaxes(ax, 'x');
xlim([0.17, 0.24])


if(flag_FW==0 | flag_C==0)
    figure(8899);
    ax(1)= subplot(2,1,1); hold on; plot(t, [temp_a(:,1), temp_b(:,1), temp_c(:,1)],'LineWidth
grid on; title('PCC voltage');
ylim([-1.5,1.5]); box on;
ax(2) = subplot(2,1,2); hold on; plot(t, [temp_a(:,2), temp_b(:,2), temp_c(:,2)],'LineWidth',1)
grid on; title('substation voltage');
ylim([-1.5, 1.5]); box on;
hold on;
xlabel('Time (s)')
linkaxes(ax, 'x');
xlim([0.17, 0.24]);
figure_change
end
end
```


Bode Diagram
Magnitude (dB)
Phase (deg)
Frequency (Hz)
current order to v_PCC
current order to v_SUB


data1
data2


Grid voltage
Current order
PCC voltage
substation voltage
Time (s)

```
%end
```