Photovoltaic Power Systems Laboratory Handbook

-2015-

Index

Lab 1 - E1D1 - PV Modelling (SIM – Matlab GUI)

Introduction

The present session has as objective to simulate the electrical characteristics of a PV panel in various environmental conditions.

The effects of irradiance, temperature, series resistance and different types of partial shadow on a PV system will be evaluated using the provided Matlab GUI presented in Fig. 1-1.

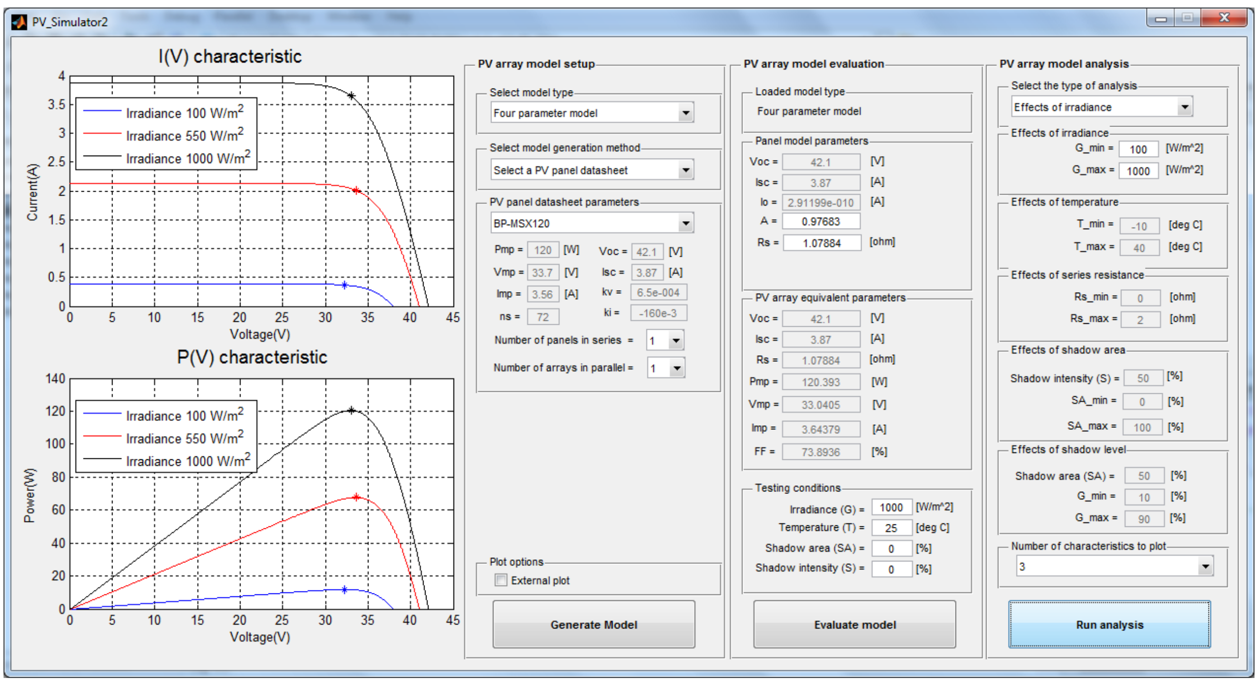


Fig. 1-1 Graphical User Interface of the PV array simulator

As can be seen in the above figure, there are four main sections of the graphical user interface: one section with the I-V and P-V curves, and three sections for the PV model setup, parameter evaluation, and model analysis in various conditions.

Please note: in every section, the set parameters become active only after the button in the bottom of the section pressed (Generate model, Evaluate model, or Run analysis)

In order to perform the simulation tests, the next steps need to be followed:

1. Setup a PV array model
    - the electrical model used for modelling a PV array in this exercise is the "single diode simple model", also known as the "four parameter model", and is selected by default
    - in order to generate the model, a PV panel datasheet has to be provided, this can be done in two ways:
        - by selecting one of the predefined datasheet for the two panel types available: BPMSX 120 or KC 125
        - or by entering the panel datasheet parameters manually (Pmp, Vmp, Imp, ns, Voc, Isc, kv, ki)
        - once the panel datasheet parameters are chosen, the PV array configuration has to be specified by setting the "Number of panels in series" and "Number of arrays in parallel" parameters
    - by pressing the "Generate model" button, the specified PV array model will be created in the background, and the characteristic I(V) and P(V) curves corresponding to the model will be displayed in the plot area
2. Evaluate the PV array model
    - once a PV array model has been generated the model parameters for **one** PV panel will be displayed in the "Panel model parameters" area (Voc-open circuit voltage, Isc-short circuit current, Io-diode dark saturation current, A-diode ideality factor, Rs-series resistance)
    - furthermore the model parameters scaled for the **entire** PV array will be displayed in the "PV array equivalent parameters" area (Voc, Isc, Pmp, Imp, Vmp, FF)
    - the loaded PV array model can be evaluated at different testing conditions, by setting the desired irradiation (in W/m^2), temperature (in ^oC) or partial shadowing (shadow area in % and shadow intensity in %), and/or with different panel model parameters by setting the diode ideality factor A and the series resistance Rs
    - by pressing the "Evaluate model" button, the PV array model will be evaluated at the specified model parameters and testing conditions, and the

characteristic I(V) and P(V) curves corresponding to these conditions will be displayed in the plot area

3. Analyse the PV array model
    - for in-depth analysis of the generated PV array model the effects of: irradiance, temperature, series resistance, partial shadow intensity or partial shadow area can be studied by selecting one of these options in the "Select type of analysis" combo-box
    - once the analysis type has been selected, the minimum and maximum values of the parameter to be analysed (irradiance, temperature, series resistance, partial shadow intensity or partial shadow area) can be set
    - also the number of I(V) and P(V) characteristics to be plotted for the current analysis can be selected in the "Number of characteristics to plot" area
    - by pressing the "Run analysis" button, the loaded PV array model will be evaluated at different points between the minimum and maximum values of the parameter to be analysed, and a family of I(V) and P(V) characteristics will be plotted
    - to be noted that if the effects of one parameter is analysed (for example the effects irradiance between 100W/m^2 and 1000W/m^2), the rest of the parameters will be set to "Standard Testing Conditions" values (temperature=25°C, series resistance=original model value, shadow area = 0%, shadow intensity=0%)

Laboratory tasks

- Using the provided GUI, analyse the effects of irradiance, temperature, series resistance and partial shading on the characteristics of a BP-MSX 120 panel, for the conditions given in the tables below, where the parameters which are not specified have default values from the GUI;

A. Effects of irradiance:

Temperature [ºC]	25
Irradiance [W/m^2]	50 → 1000 in 5 steps
Plot:	Voc(G), Vmp(G), Pmp(G)

B. Effects of temperature:

Irradiance [W/m^2]	1000
Temperature [ºC]	-20→100 in 5 steps
Plot:	Voc(T), Pmp(T), Isc(T)

C. Effects of series resistance:

The rated series resistance is $R_{s,rated} \cong 1.05\Omega$.

Irradiance [W/m^2]	1000		
Temperature [ºC]	25		
Series resistance [Ω]	1	2	3
Vmp			
Pmp			

D. Effects of shadow area:

Irradiance [W/m^2]	1000				
Temperature [^{o}C]	25				
Irradiance level at partial shadow [%]	50				
Shadow area [%]	20	40	60	80	100
Vmp					
Pmp					

E. Effects of shadow level:

Irradiance [W/m^2]	1000				
Temperature [^{o}C]	25				
Shadow area [%]	50				
Irradiance reduction at partial shadow [%]	20	40	60	80	100
Vmp					
Pmp					

- Plot: $V_{mp} = f(R_s)$, $P_{mp} = f(R_s)$, $V_{mp} = f(G)$;

- Write a short report containing the plotted characteristics, the filled tables and brief conclusions regarding the effects of irradiation, temperature, series resistance and partial shading on the characteristics of a BP-MSX 120 panel.

Upload your result to Moodle: https://phd.moodle.aau.dk/course/view.php?id=498

Lab 2 - E1D2 - Spire Demo (EXP – Spi-Sun 5600SLP)

Introduction

The goal of this laboratory exercise is to get familiar with the I-V curve measurement using the solar flash simulator, and to perform simple diagnostic tasks on a PV module, using the measured I-V curves. The main purpose is to observe the effect of the main types of failures (series resistance increase and partial shadow) on the electrical characteristic of the PV panel, and, based on the measured *I-V* curve be able to have an idea about the type of failure that affected the panel.

Setup description

The block diagram of the setup that is going to be used in this laboratory exercise is presented in Fig. 2-1.

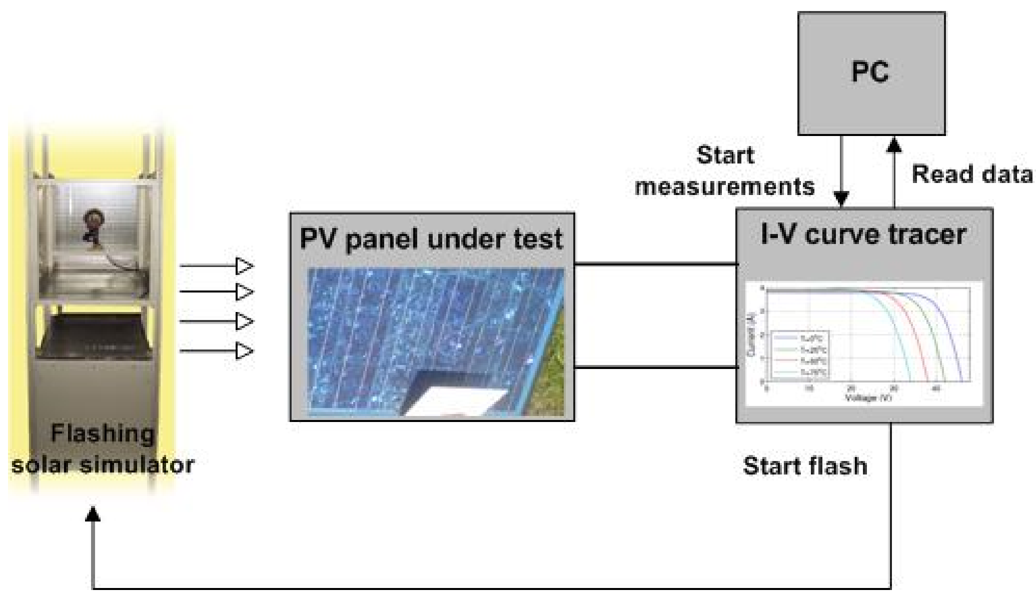


Fig. 2-1 Block diagram of the laboratory test setup

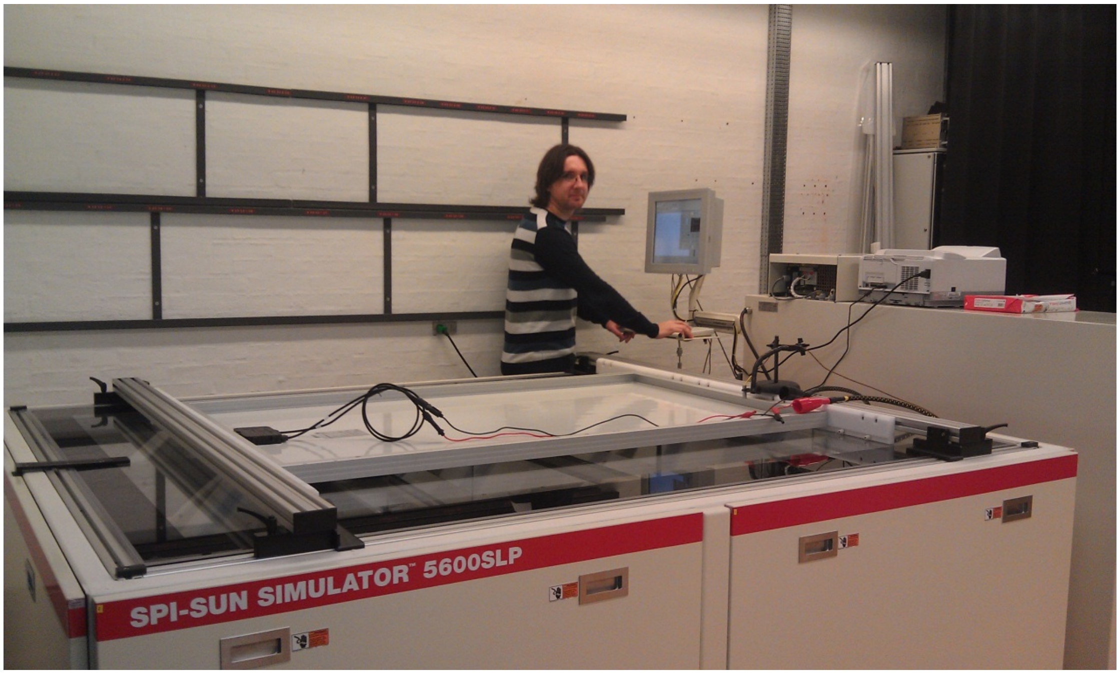


Fig. 2-2 Photo of the Spi-Sun 5600 SLP with a PV module under test

The main components of the test setup are:

- **PV panel under test**

The datasheet of the BP-MSX120 solar panel used in the tests is given in Table 2-1.

Table 2-1 BP-MSX 120 solar datasheet parameters

Maximum power	P_{mp}	120 W
Voltage at P_{mp}	V_{mp}	33.7 V
Current at P_{mp}	I_{mp}	3.56 A
Short circuit current	I_{sc}	3.87 A
Open circuit voltage	V_{oc}	42.1 V
Temperature coefficient of I_{sc}	k_i	(0.065 ±0.015) %/ºC
Temperature coefficient of V_{oc}	k_v	-(80±10) mV/ ºC

- **Flashing solar simulator**

The A+A+A+ class flashing sun simulator provides the irradiation for the panel under test. Upon a command, the Xenon lamp flashes the PV panel, providing high irradiance for a short period of time. During this time, the characteristic of the panel is measured by the I-V curve tracer.

Some key parameters of the flashing solar simulator are given in Table 2-2:

Table 2-2 Spire Spi-Sun 5600SLP flashing light system technical data

Flashing tube	Xenon flash 4800Ws
Irradiated area	2 x 1.370 m
Irradiance levels	200-1100W/m^2
Inhomogeneity	<1% (class A+)
Spectrum	AM 1.5 (class A+)
Repeatability at module measurement	≤0.25 %
Pulse duration:	20-140 ms @ 1000W/m^2

• **I-V curve analyser software**

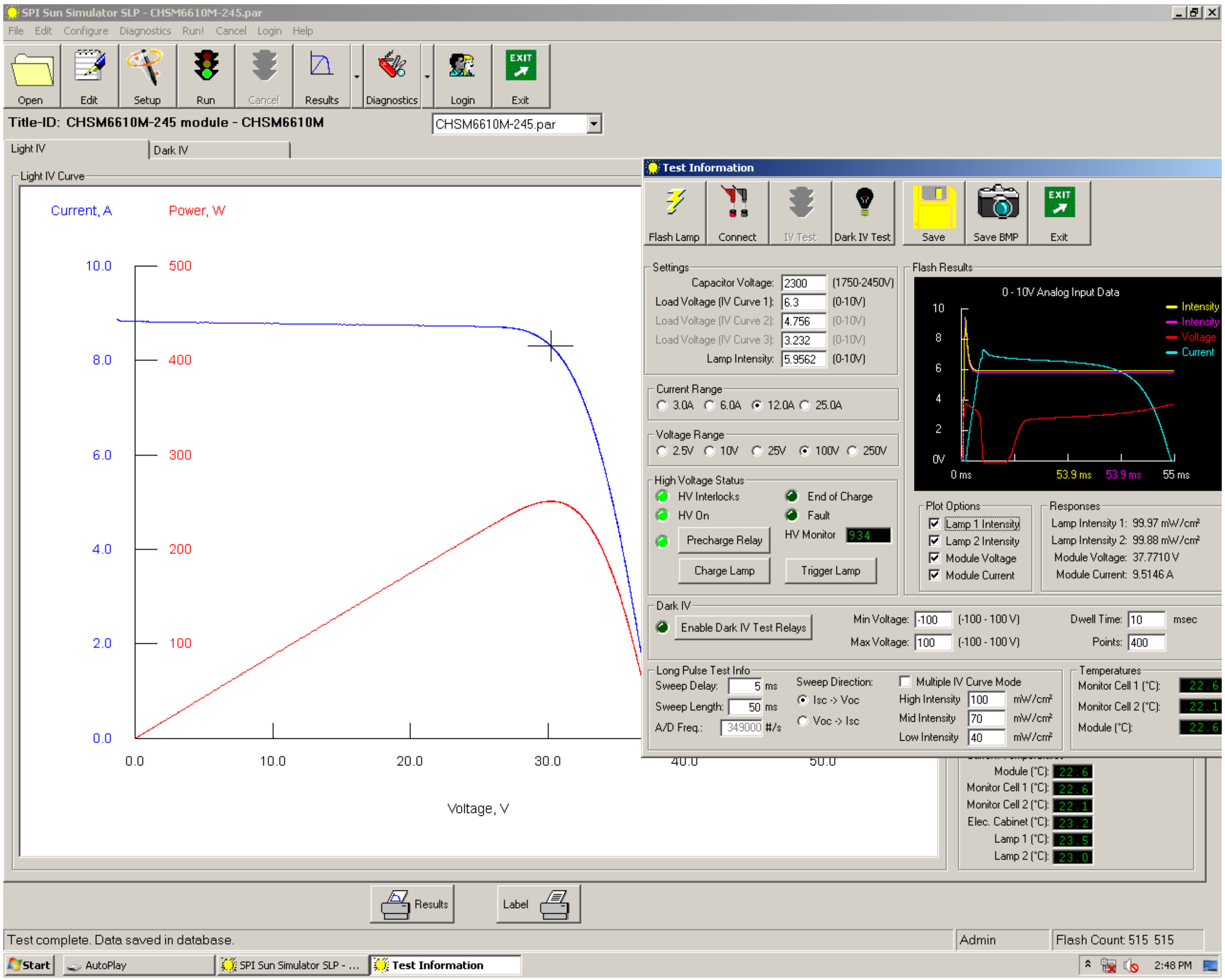


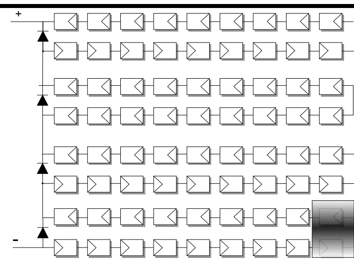
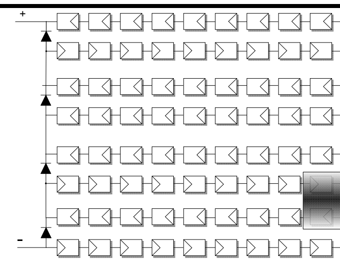
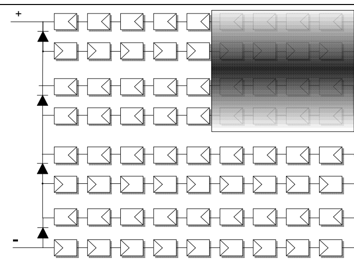
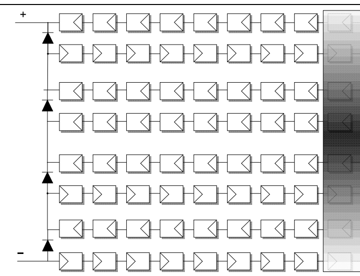
Fig. 2-3 Screenshot of the Spi-Sun Simulator SLP graphical user interface

The IV curve analyser measures the current-voltage characteristic of the panel under test during the length of the light pulse. The variable load on the panel terminals is emulated by power MOSFETs controlled in their linear region.

A. Various irradiance levels at standard temperature

Temperature [°C]	25			
Irradiance [W/m^2]	200	400	600	1000

B. Partial shadows:

Irradiance [W/m^2]	1000	
Temperature [^{o}C]	25	
Shadow type	 (a)	 (b)
	 (c)	 (d)

D. Increased series resistance

Irradiance [W/m^2]	1000	
Temperature [^{o}C]	25	
Added resistance	R_1	R_2

The laboratory tasks for this exercise involve an analysis of several *I-V* curve measurements. The main goal is to detect changes in the *I-V* curves, compared to a reference curve. The reference curve is an *I-V* curve measured at high irradiance conditions when the module was in perfect operating conditions, no partial shadow or increased series resistance was present. Therefore, in order to detect partial shadow or increased R_s, the estimation results are compared to those using the reference measurement.

Laboratory tasks

• Effects of PS and increased R_s on the measured *I-V* curve

The GUI below can be used to analyse the effects of partial shadow and increased series resistance on the *IV* curve of the panel.

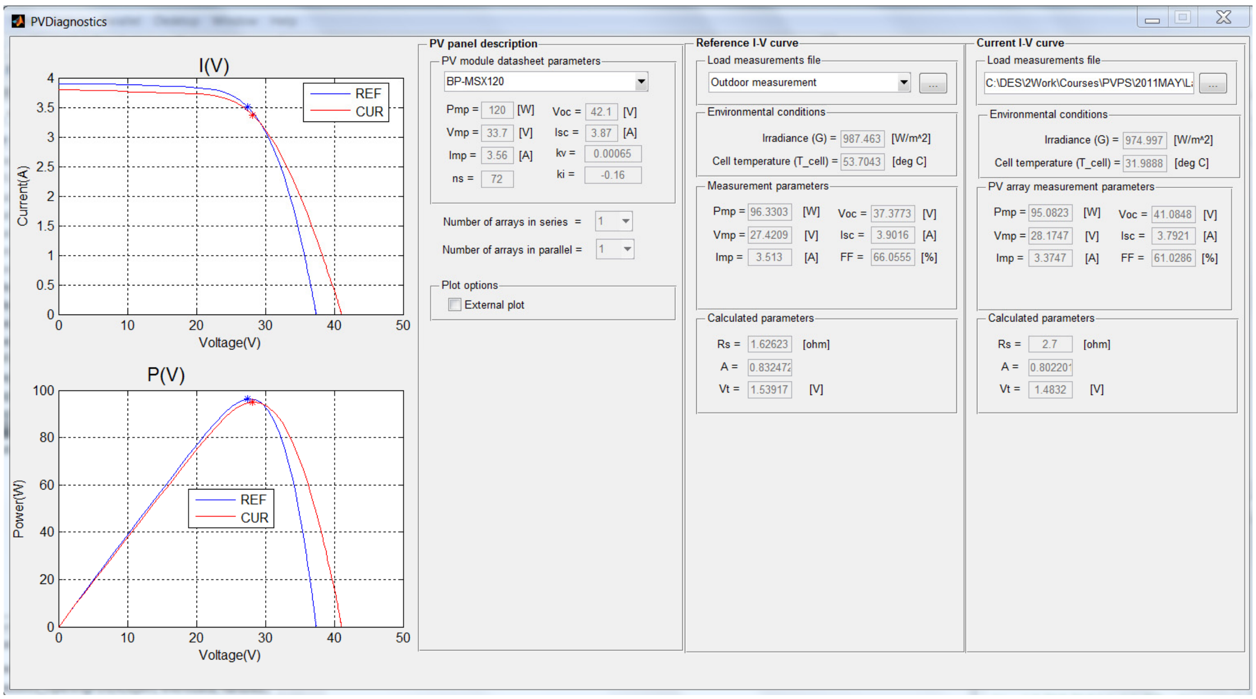


Fig. 2-4 Graphical user interface for analysing measured *IV* curves

• Observe the effects of the environmental conditions on the measured I-V curves, and compare with the reference, by using the provided Matlab program with the GUI on the above figure. The reference *IV* curve (based on outdoor measurement or solar simulator) can be loaded by clicking on the button on the right hand side in the 'Load reference measurement' field.

• Observe the effect of various partial shadows on the *I-V* curve of the panel. Compare the maximum output power of the panel for partial shadow type (a) (in the table above) with partial shadow type (b). Repeat this comparison for the cases (c) and (d). The measurement files can be loaded by clicking on the button in the right hand side of the 'Load measurement file' field, and selecting the desired measurement file in the 'Open File' window. The folder is automatically loaded according to the reference *IV* curve (whether is outdoor or indoor).

- **Diagnostic functions**

- Observe the key parameters of the tested BP-MSX 120 panel, on the GUI.

The method to calculate the equivalent series resistance and thermal voltage is based on the equations below. The FF can give indication regarding overall performance loss. These parameters can be determined as:

$$R_{se} = \left(\frac{V_{te}}{I_{sc}} + R_{sm} \right) = -\left. \frac{dV}{dI} \right|_{OC}$$

$$V_{te} = \frac{\left(2V_{mp} - V_{oc}\right)\left(I_{sc} - I_{mp}\right)}{I_{mp} - \left(I_{sc} - I_{mp}\right) \cdot \ln\left(\frac{I_{sc} - I_{mp}}{I_{sc}}\right)}$$

$$FF[\%] = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} \cdot 100$$

- Compare the *FF*, R_{se}, and V_{te} for the rest of the test measurements found in the folder for outdoor measurements

Write a short report including data plotting, values of FF, R_{se}, and V_{te}, as well as main conclusions regarding effect of increased R_s and partial shadow on the *I-V* curve.

Upload your result to Moodle: https://phd.moodle.aau.dk/course/view.php?id=498

Lab 3 - E2C1 - Converter Topologies (SIM - PLECS)

Introduction

The objectives of this exercise are:

- Study the performance of several transformerless PV inverter topologies, by evaluating their DC to earth voltage (V_{PE}) and efficiency (η);

The simulations are going to be performed in Matlab/Simulink, using the PLECS blockset. All the simulation models are going to be provided.

Description of inverter topologies

In this exercise, the performance of the following PV inverter topologies is going to be tested:

• Half-Bridge

The HB inverter topology is presented in Fig. 3-1.

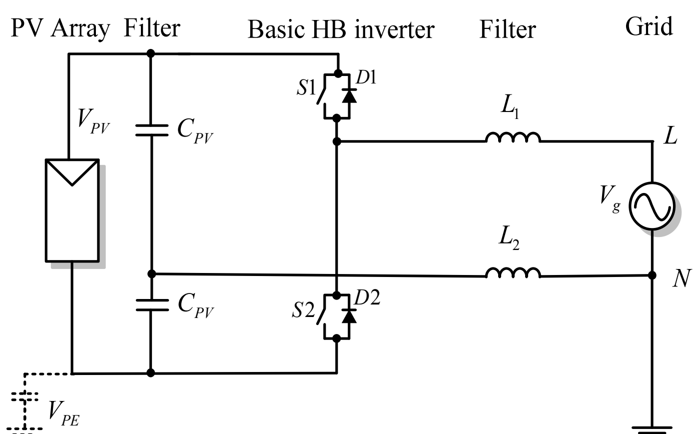


Fig. 3-1 Half-Bridge inverter topology

This topology uses only two switches to connect either the upper or the lower half of the dc-link to the phase connection of the grid, while the neutral wire is always connected to the middle of the dc-link capacitors.

• Full-Bridge

The FB inverter topology is presented in Fig. 3-2.

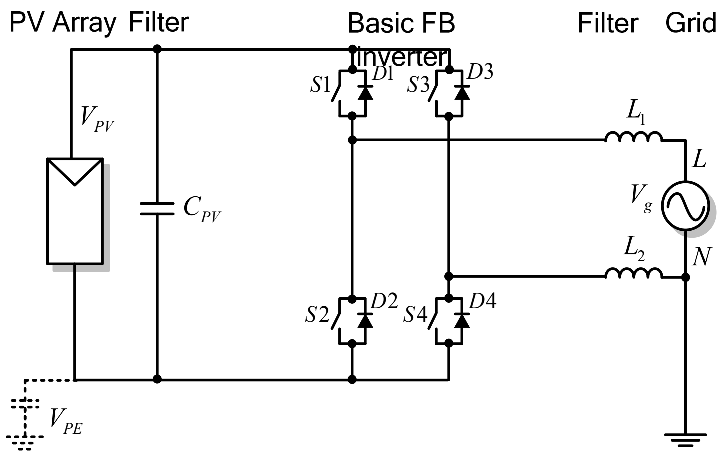


Fig. 3-2 Full-Bridge inverter topology

Three main modulation strategies can be used:

1. Unipolar modulation

- leg A and leg B are switched with high frequency, with mirrored sinusoidal reference

- two zero output voltage states possible: $S1$, $S3$ = ON and $S2$, $S4$ = ON

2. Bipolar modulation

- leg A and leg B are switched synchronously in diagonal (S1=S4 and S2=S3) with high frequency, and the same sinusoidal reference

- no zero output voltage state is possible

3. Hybrid modulation

- leg A is switched with grid frequency and leg B is switched with PWM frequency

- two zero output voltage states possible: S1,S3 = ON and S2,S4= ON.

• H5

The H5 (SMA) inverter topology is presented in Fig. 3-3. This topology, as its name indicates, it is a classical H-bridge with an extra fifth switch in the positive bus of the dc-link high frequency content of V_{PE} .

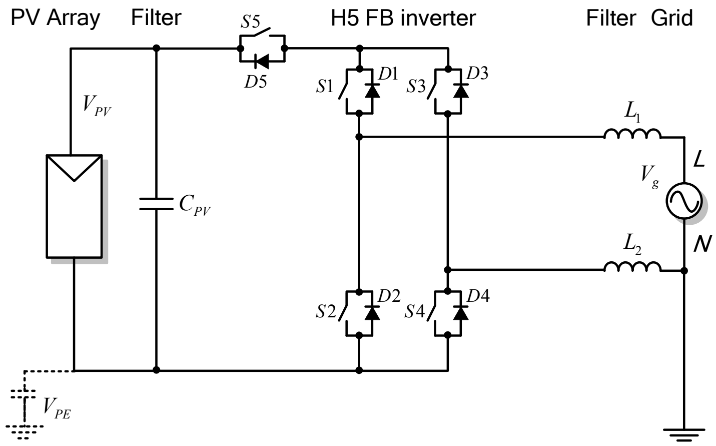


Fig. 3-3 H5 inverter topology

The main features of this topology are:

- $S5$ and $S4$ ($S2$) are switched at high frequency and $S1$ ($S3$) at grid frequency,

- two zero output voltage states possible: $S5$ = OFF and $S1$ ($S2$) = ON.

• HERIC

The HERIC (Sunways) inverter topology is presented in Fig. 3-4.

The High Efficiency Reliable Inverter Concept topology is also derived from the classical H-bridge, by adding a bypass leg in the ac side, using two back-to-back IGBTs .

The main features of this topology are:

- $S5$ and $S4$ ($S2$) are switched at high frequency and $S1$ ($S3$) at grid frequency,

- two zero output voltage states possible: $S+$ = ON and $S-$ = ON (providing the bridge is switched off).

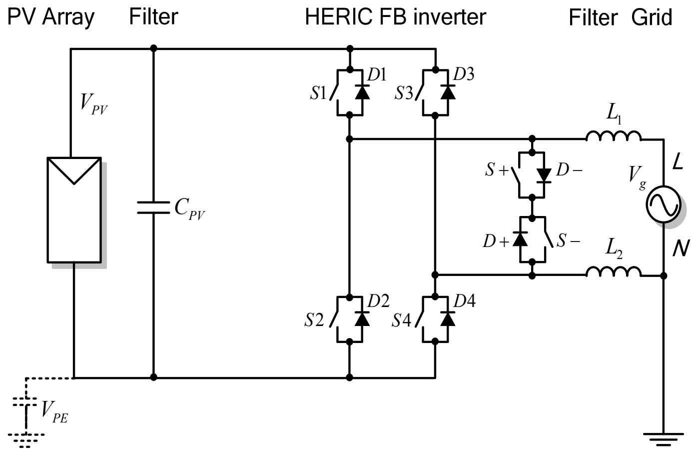


Fig. 3-4 HERIC inverter topology

• H6

The H6 (Gonzales) inverter topology is presented in Fig. 3-5. This topology is also a modified H-bridge topology, having two extra switches and two diodes.

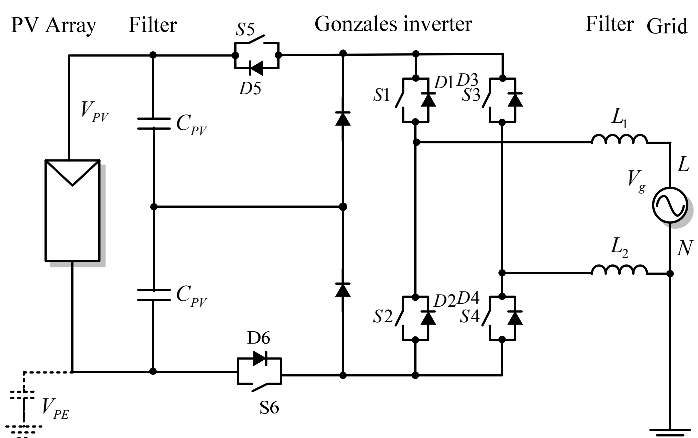


Fig. 3-5 H6 inverter topology

• Full-Bridge Zero Voltage Rectifier

The FB-ZVR inverter topology is presented in Fig. 3-6. This topology is a classical H-bridge with an additional bidirectional switch, made of one IGBT and one diode rectifier bridge, clamped to the midpoint of the dc-link capacitors. An extra diode is used to protect the lower dc-link capacitor from short-circuiting.

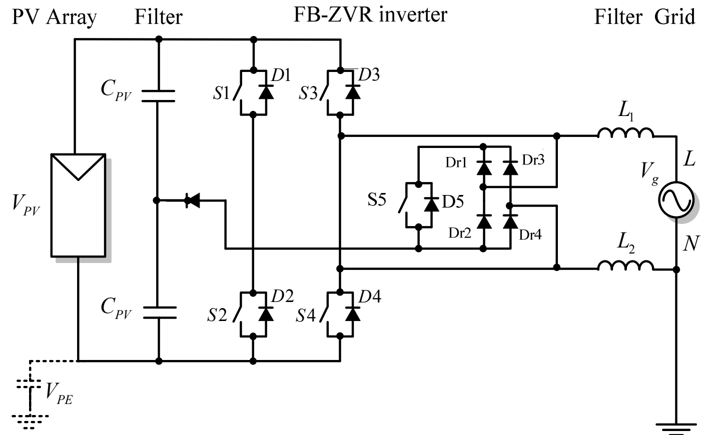


Fig. 3-6 Full-Bridge Zero Voltage Rectifier inverter topology

Laboratory tasks

The parameters used in the simulations of the PV inverters are given in Table 3-1.

Table 3-1 Simulation parameters

Simulation step size	**Ts**	**250 ns**
Switching frequency	f_{sw}	**5 kHz** **10kHz**
Single phase DC voltage	V_{dc}	**400 V**
DC-link capacitance	C_{dc}	**1 mF**
Output filter inductance	L_f	**1.8 mH**
Output filter capacitance	C_f	**2 µF**
Grid voltage (peak of phase to neutral voltage)	V_g	**325 V**
Grid frequency	f_g	**50 Hz**
Grid inductance	L_g	**50 µH**

Note! The output filters used in the simulation models have been selected as the optimal solution for each of the topologies.

• Evaluation of DC to ground voltage for DC-AC topologies

Task1: Run the provided simulations for two chosen topologies, save the shapes of the DC to ground voltage (V_{PE}), and paste them into Table 3-2.

Table 3-2: Simulation results for the DC to earth voltage

PV inverter topology	DC to ground voltages: V_{PE}
Half-Bridge	
Full-Bridge - unipolar modulation	
Full-Bridge - bipolar modulation	
Full-Bridge - hybrid modulation	
H5	
HERIC	
H6	
Full-Bridge Zero Voltage Rectifier	

• Efficiency evaluation for DC-AC topologies

Task2: Select 2 topologies from Table 3-3, run the provided simulations for them and fill out the corresponding fields in the table.

- The formula for calculating the European efficiency is given by :

$$\eta_{EU} = 0.03 \cdot \eta_{5\%} + 0.06 \cdot \eta_{10\%} + 0.13 \cdot \eta_{20\%} + 0.1 \cdot \eta + 0.48 \cdot \eta_{50\%} + 0.2 \cdot \eta_{100\%}$$

Upload your result to Moodle: https://phd.moodle.aau.dk/course/view.php?id=498

Table 3-3: Simulation results for the efficiency

Pdc [%] / **PV inverter topology**	$\eta_{5\%}$	$\eta_{10\%}$	$\eta_{20\%}$	$\eta_{30\%}$	$\eta_{50\%}$	$\eta_{100\%}$	η_{EU}
Half-Bridge							
Full-Bridge unipolar modulation							
Full-Bridge bipolar modulation							
Full-Bridge							

hybrid modulation							
H5							
HERIC							
H6							
Full-Bridge Zero Voltage Rectifier							

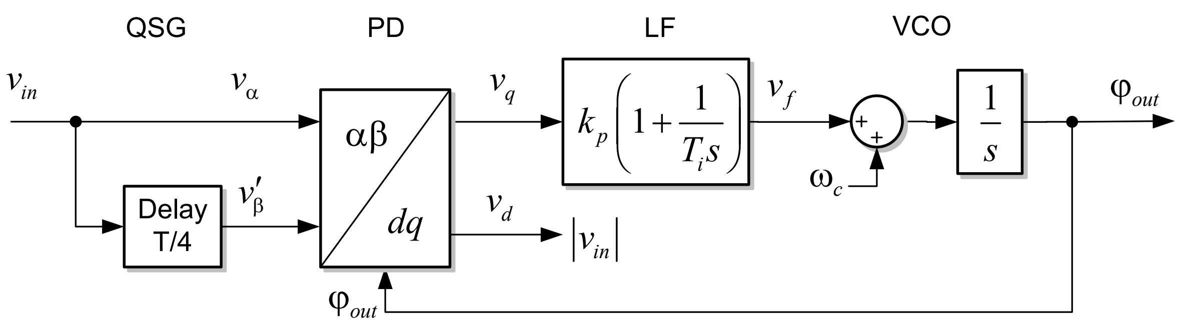
Lab 4 - E2C2 - PLL (SIM - dSpace)

Introduction

The objective of this laboratory exercise is to experimentally test the designed T/4 Delay-PLL, Derivative-PLL, Inverse Park-PLL and SOGI-PLL structures in real time, and evaluate their performances in presence of grid disturbances. The grid model will be provided.

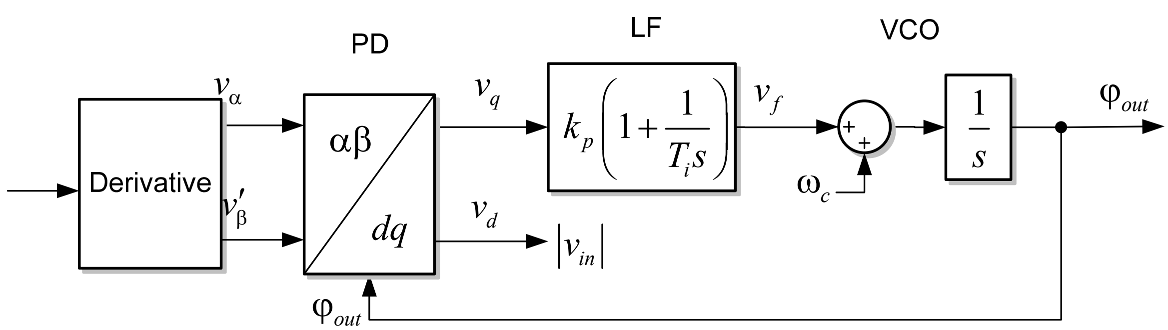
PLL structures used in this exercise

T/4 Delay – PLL



T/4 Delay – PLL structure

Derivative – PLL



Derivative – PLL structure

The quadrature signal of the system input can be obtained by using the following expressions:

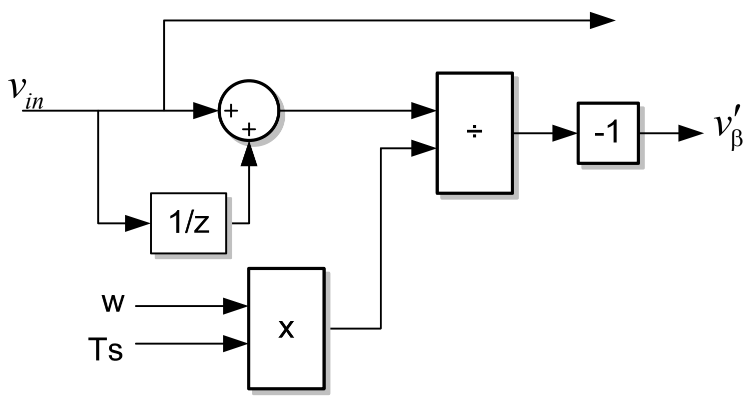
$$\frac{d}{d\theta} sin(\theta) = cos(\theta)$$

If the sine wave is considered as the input then:

$$\frac{d}{d\theta}x(t) = \frac{x(t) - x(t-1)}{\Delta\theta}$$

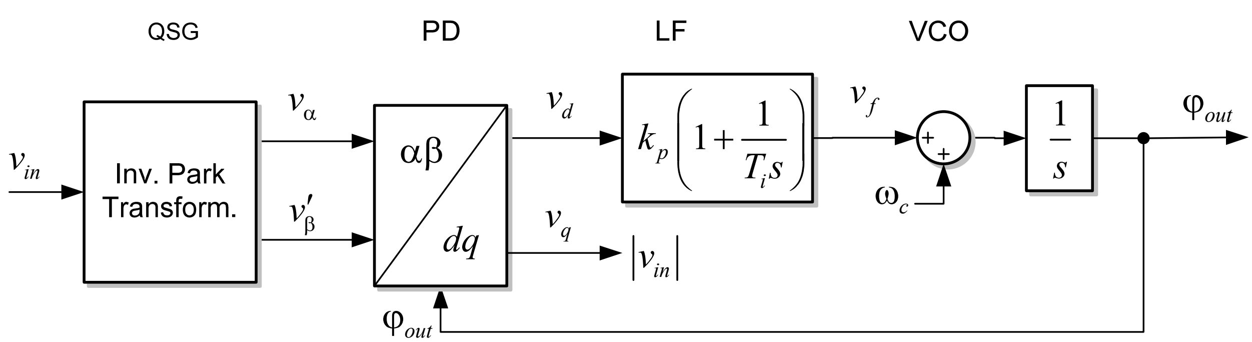
Where

$$\Delta\theta = w\Delta t = wT_S$$



Block diagram of the Derivative QSG

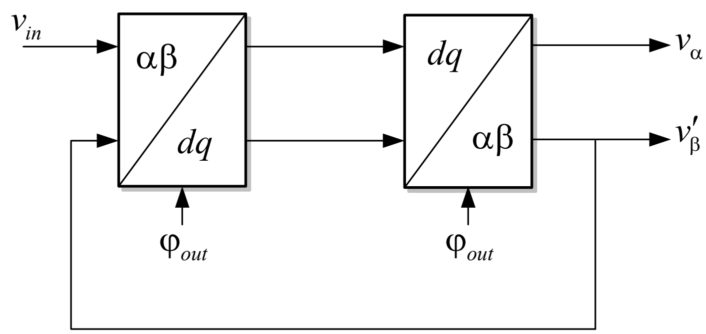
Inverse Park – PLL



Inverse Park – PLL structure

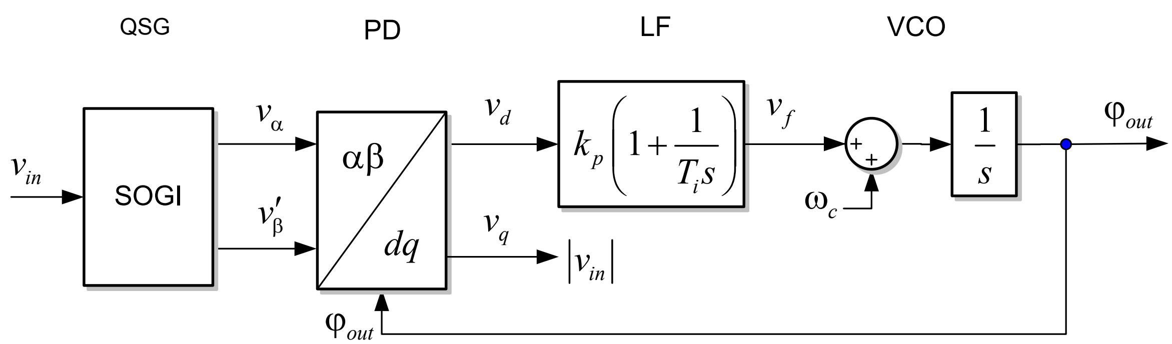
This technique is based on the feedback of the beta component in the stationary frame. Both of park transformations need the use of the PLL output angle, and for this reason if there is any error between the voltage angle and the PLL angle, this QSG will not provide the right signals in alpha/beta.

The orthogonal system is created according to the block diagram shown below:



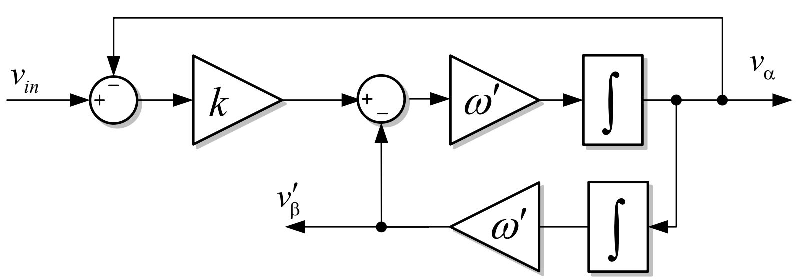
Block diagram of the Inverse Park QSG

SOGI – PLL



SOGI – PLL structure

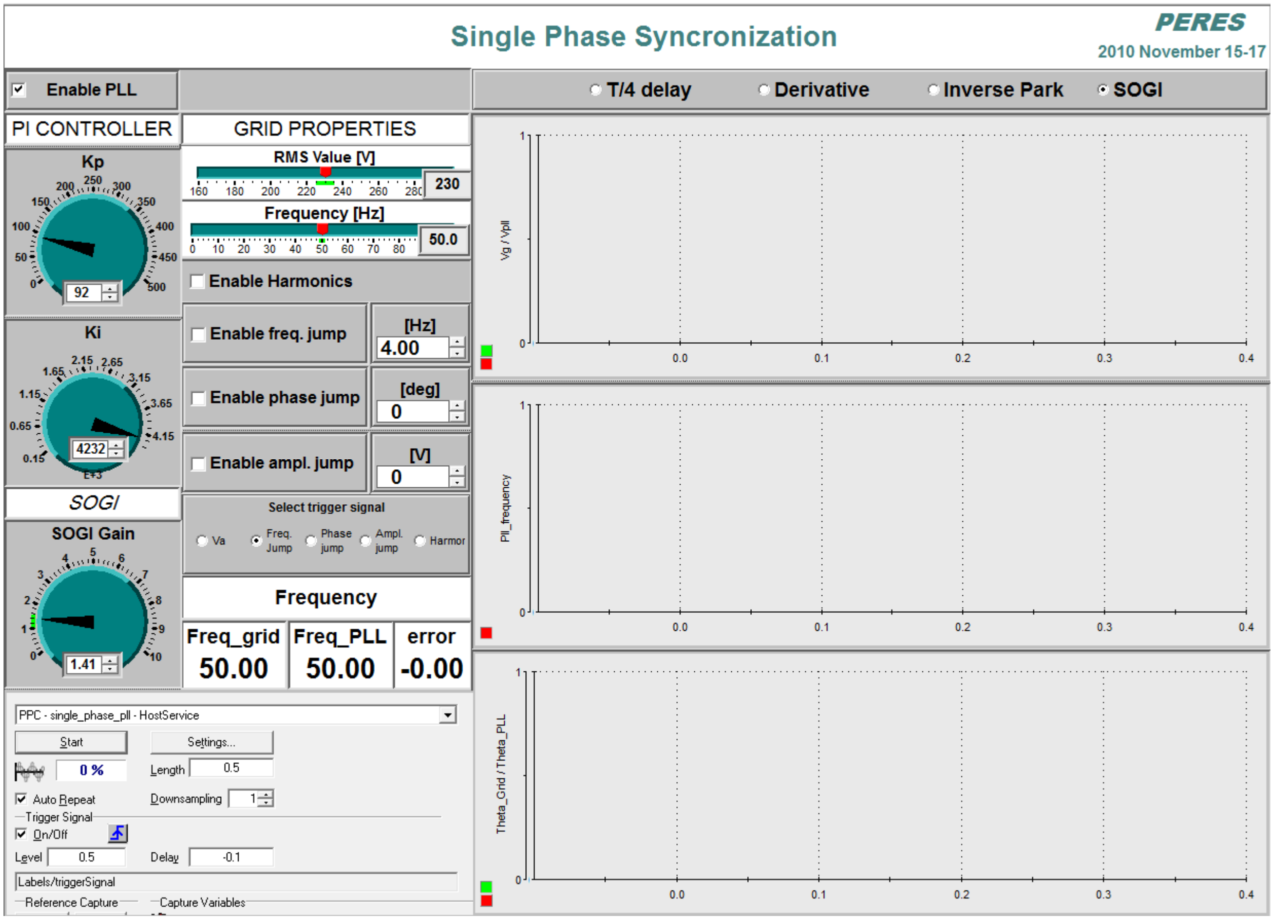
The orthogonal system is created by using a Second Order Generalized Integrator (SOGI), according to the block diagram shown below:



Block diagram of SOGI – QSG

Description of the front panel

The hardware setup for this experiment consists only of the dSPACE system. The Control Desk interface of this experiment is shown below:



Screenshot of the Control Desk interface for Single Phase Synchronization

The Control Desk layout is divided in three parts:

The first column is used for the PI controller parameters, which will be used to describe the dynamic of the system.

In the second column shows the grid parameters and grid disturbances.

Finally, in the last part shows the QSG selection (top) and the plots of the grid voltage / PLL voltage, PLL frequency and, PLL and grid phase.

Laboratory tasks

Task 1: Set the PI parameters of the PLL in order to obtain a settling time of 100ms with a damping factor of 1/sqrt(2) according to the following formula:

$$ts = \frac{4.6}{\xi \omega_n}$$

$$K_p = 2\xi\omega_n$$

$$T_i = \frac{2\xi}{\omega_n}$$

$$K_i = \frac{K_p}{T_i}$$

- The PI parameters can be changed in Control Desk

Task 2: Evaluate the performance of the T/4 delay, Derivative, Inverse Park and SOGI-PLL quadrature signal generators under a reduction in the input voltage amplitude.

- Attach and comment the experimental plots in order to compare the different QSGs.

Task 3: Evaluate the performance of the T/4 delay, Derivative, Inverse Park and SOGI-PLL quadrature signal generators under a 90° jump in the phase-angle of the input voltage.

- Attach and comment the experimental plots in order to compare the different QSG.

Task 4: Evaluate the performance of the T/4 delay, Derivative, Inverse Park and SOGI-PLL quadrature signal generators under a frequency jump of 4Hz of the input voltage.

- Attach and comment the experimental plots between the different QSG

Task 5: Evaluate the performance of the T/4 delay, Derivative, Inverse Park and SOGI-PLL quadrature signal generator under harmonic distortion in the input voltage. The harmonic contents are preset in the experiments.

- Attach and comment the obtained plots between the different QSG

Task 6: Fill the following table with your evaluation from 1 to 4 (best to worst) for the QSG previously evaluated under different grid disturbances:

	Amplitude Jump	Phase Jump	Frequency Variation	Harmonics
Delay-QSG				
Derivative-QSG				
Inverse Park-QSG				
SOGI-QSG				

Upload your result to Moodle: https://phd.moodle.aau.dk/course/view.php?id=498

Lab 5 - E2D1 – Current Control Design (SIM - Matlab)

Current Control

• Introduction

The present session has as objective to design two control structures for grid connected inverters based on PI and P+Resonant current controllers. The stability in case of LCL-filter will be tested too.

The parameters of the plant can be set according to the used experimental setup to validate the simulation results.

The present laboratory session will be performed using Matlab and the Sisotool or the bode, rlocus and lsim functions depending on the background of the students.

• Control structure

The control structure of the three phase grid connected inverter using PI current controllers in dq frame is in the next figure.

The inputs of the current controllers are the errors between the measured and reference grid current, in d-q. After transforming the grid voltages from α-β to d-q coordinates, they are applied to the PLL block. The PLL block together with the *α-β→d-q* block returns the grid phase, which is used to generate the d-q current components from *α-β*, and to transform the voltage references from d-q to *α-β*.

The outputs from the current controllers are the reference grid voltages in d-q form, which transformed back to the stationary three phase coordinates, and divided by the DC source voltage gives the duty cycles for the inverter.

The structures of the current controllers are identical for d and q axes.

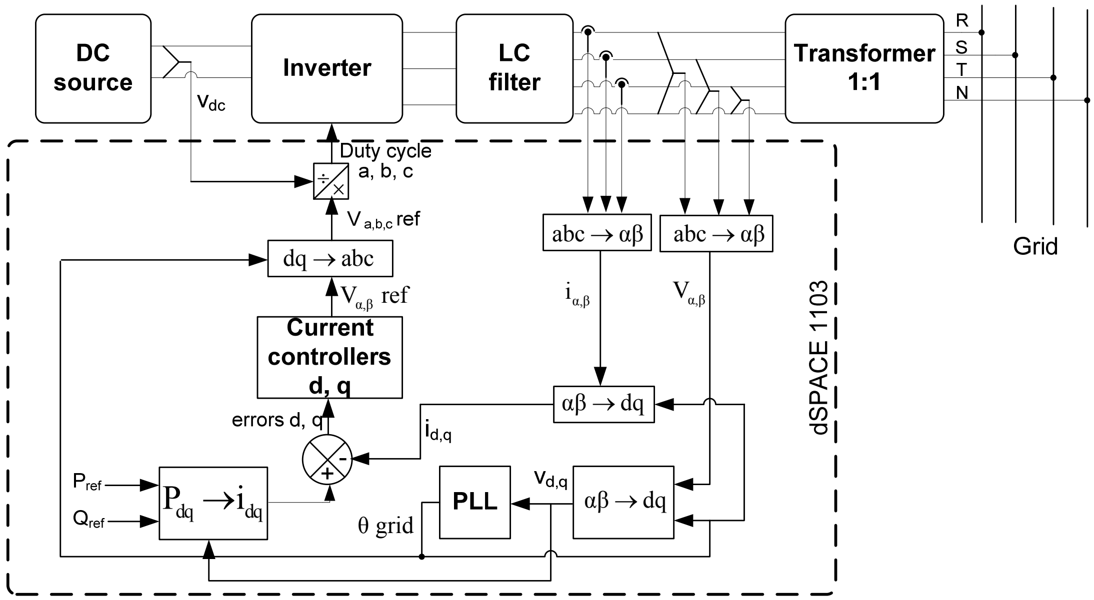


Fig. 5-1: The dq current control based on PI controllers

The control scheme of the three-phase grid connected converter based on PQ control and the use of resonant integrators is in the next figure.

The input of the current controller is the error between the measured and reference grid current. In order to synchronize the injected grid current with the grid voltage, the phase of the reference current is taken from the grid voltage, calculated by the PLL block.

The current controller output is the reference grid voltage, which divided by the DC source voltage gives the duty cycle for the inverter.

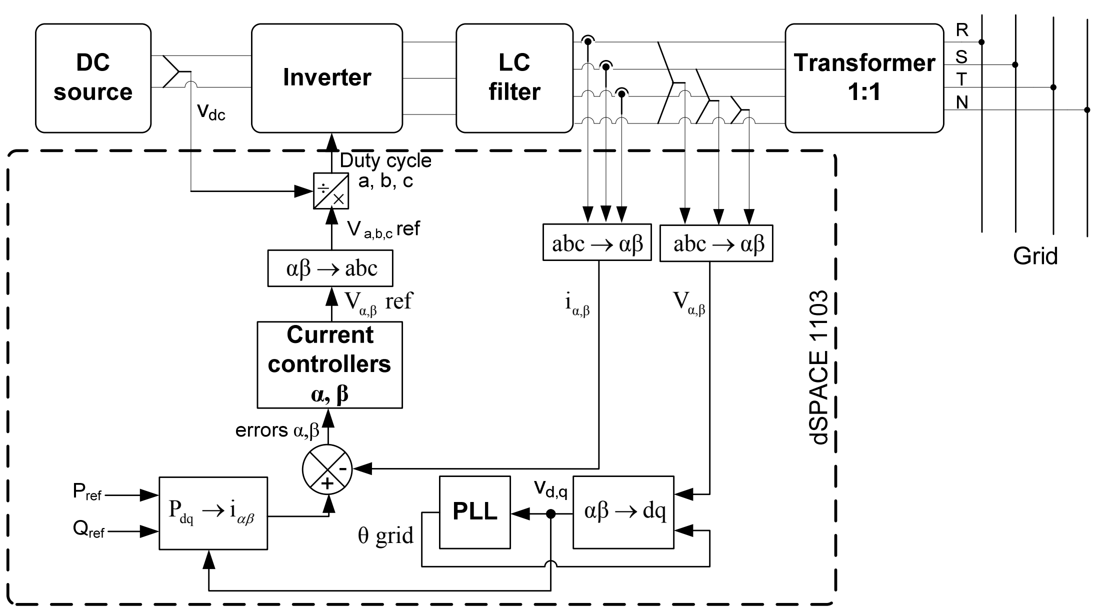


Fig. 5-2 The PQ current control for three-phase inverters based on resonant controllers

In this laboratory exercise the PI (for three-phase system) and PR (for three-phase system) are designed neglecting the shunt capacitor of the LCL-filter (the second L is provided by the transformer) and considering the following two schemes

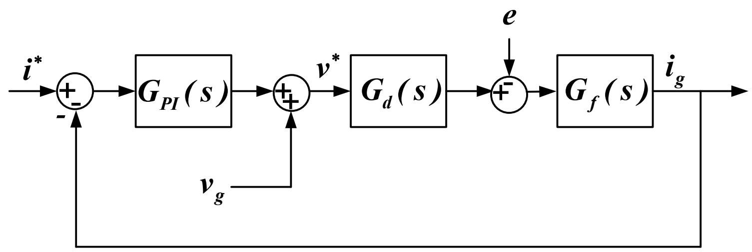


Fig. 5-3: Block diagram of the current loop (PI, three-phase system).

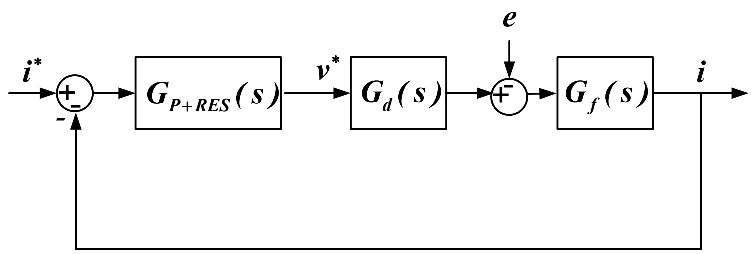


Fig. 5-4: Block diagram of the current loop (PR, single-phase system).

Then the stability of the current loop is verified reintroducing the neglected shunt capacitor in the analysis.

The parameters of the three-phase system are reported in the following table. In the three-phase set-up the shunt capacitors are star connected.

Table 5-1: The parameters of the LCL filter

	Three-phase
Inductor of LC filter on the inverter side	**L_I=1.8 mH;**
LCL filter shunt capacitance	**C_F=4.7 µF;**
Damping resistance of filter (no damping resistor)	**R_D=0 Ω;**
Transformer inductance (grid side inductance)	**L_G=2 mH;**
Sampling frequency	**fs=10kHz**

Laboratory tasks

Task 1 Design of PI current controller

The PI controller has the following transfer function:

$$G_{PI} = K_P\left(1 + \frac{1}{T_I s}\right)$$

$G_d(s)$ is the 1.5Ts delay due to the elaboration of the computation device (Ts) and to the PWM (0.5T_s), indicating with T_s the sampling period

$$G_d(s) = \frac{1}{1 + 1.5T_s s}$$

and $G_f(s)$ is the transfer function of the filter (i.e. the plant of the control loop)

$$G_f(s) = \frac{1}{R + Ls}$$

where L is the overall inductance of the filter and R is the overall filter resistance equal approximately to 0.1 pu of the filter reactance.

Using the above transfer functions, design the current controller with the following requirements and considering the sampling period T_s used in the laboratory.

Requirements:

- The current loop should be stable, (closed loop) with a phase margin larger than 45˚. Hint: use *margin* Matlab function.
- The bandwidth of the system should be minimum equal to 500 Hz. Hint: use *bandwidth* Matlab function.

Task 2: Design of the PR current controller

The P+Resonant controller has the following transfer function:

$$G_{\mathrm{P+Res}} = K_P + K_I \frac{s}{s^2 + \omega_0^2}$$

Using the above transfer functions $G_d(s)$ and $G_f(s)$ design the current controller with the following requirements and considering the sampling period T_s used in the laboratory.

Requirements:

- The current loop should be stable, (closed loop) with a phase margin larger than 45˚. Hint: use *margin* Matlab function.
- The bandwidth of the system should be minimum equal to 500 Hz. Hint: use *bandwidth* Matlab function.
- The gain of the resonant integrator K_I will be calculated by examining the system response at a sinusoidal input with 90 degrees initial phase and have the stationary error to be reduced to less than 5 % after 10 ms. Hint: use *lsim* Matlab function.

Task 3: Stability of the current loop considering the shunt capacitor

The overall transfer function of the LCL-filter is considered and the stability is investigated looking at the damping of the resonant poles:

$$G_f(s) = \frac{R_D C_F \cdot s + 1}{L_I L_G C_F \cdot s^3 + R_D C_F (L_I + L_G) \cdot s^2 + (L_I + L_G) \cdot s}$$

The stability is investigated for the three-phase system with 8kHz sampling frequency. The goal is to find for which gain the system tends to be unstable.

Requirements:

- The current control loop should be stable with resonant poles properly damped. Hint: discretize the system and use the Z-locus unity to verify the stability, use *c2d, rlocus* and *bode* Matlab functions.

Upload your result to Moodle: https://phd.moodle.aau.dk/course/view.php?id=498

Harmonic Compensation

• Introduction

The present session has as objective to design and simulate the harmonic compensation strategy for grid connected inverters. In particular the design of harmonic compensators based on generalized integrators to be used for single-phase converter PQ implementation and based on PI controllers in rotating frames to be used for three-phase converter dq implementation will be considered in respect to non-ideal grid conditions.

• Control structure

In the following the two current controllers in stationary frame (with resonant harmonic compensators) and in multiple frequencies rotating frame (with standard integrators) are shown.

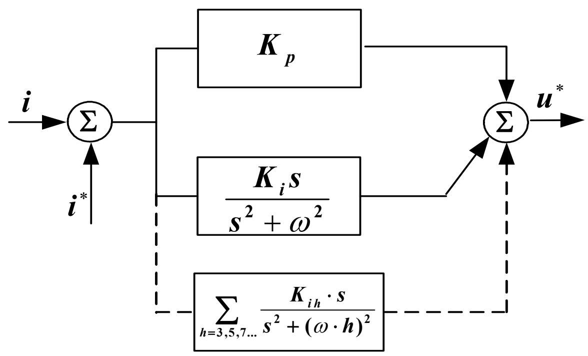


Fig. 5-5: Current control structure of the three-phase grid inverter with 5th and 7th harmonic compensation using 5th and 7th resonant controllers.

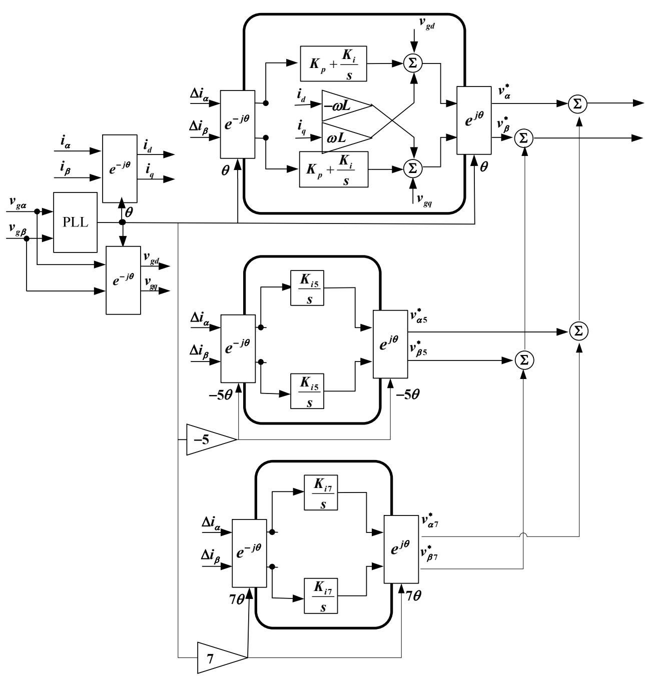


Fig. 5-6: Current control structure of the 3-phase grid inverter with 5th and 7th harmonic compensation using 5th and 7th d-q reference frames without filters.

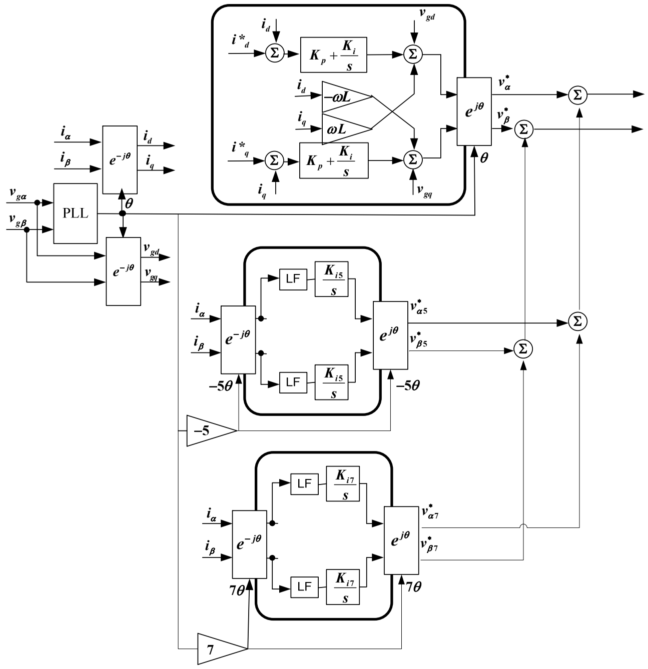


Fig. 5-7: Current control structure of the 3-phase grid inverter with 5th and 7th harmonic compensation using 5th and 7th d-q reference frames with filters.

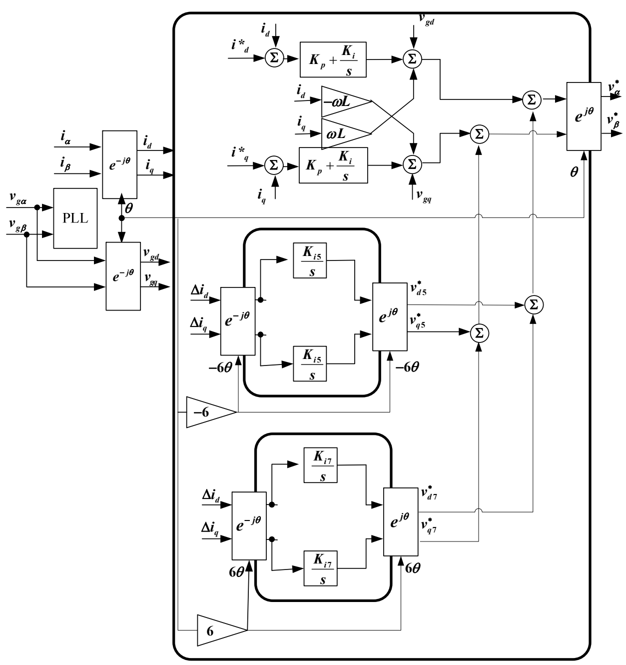


Fig. 5-8: Current control structure of the 3-phase grid inverter with 5th and 7th harmonic compensation using 6th and -6th d-q reference frames nested in the main.

In this laboratory these controllers will be tuned using simple Simulink schemes where $G_d(s)$ is the 1.5Ts delay due to the elaboration of the computation device (Ts) and to the PWM (0.5Ts), indicating with Ts the sampling period

$$G_d(s) = \frac{1}{1 + 1.5T_s s}$$

and $G_f(s)$ is the transfer function of the filter (i.e. the plant of the control loop)

$$G_f(s) = \frac{i(s)}{v(s)} = \frac{1}{R + Ls}$$

Laboratory tasks

Task 1: Design harmonic compensation of the current control in stationary frame

- Add selective harmonic compensation to the current control for the, 5th, and 7th harmonics
- Examine the grid current harmonic content with and without harmonic compensation in presence of a distorted grid voltage.
- Each group should write a short report with current controller design (Bode plot) and dynamic test (step response)

Task 2: Design harmonic compensation of the current control in multiple frequencies rotating frames

- Find the gains of the integrators using the first configuration (no filters), such that each compensated harmonic will be reduced below 1%. Ki=1/0.0158
- Find the gains of the integrators using the second configuration (with filters), such that each compensated harmonic will be reduced below 1%.
- Find the gains of the integrators using the third configuration (nested frames), such that each compensated harmonic will be reduced below 1%.
- Compare the previous three solutions can you find differences ?
- Examine the grid current harmonic content with and without harmonic compensation in presence of a distorted grid voltage.

	5th harmonic	7th harmonic	THD
MSRF without filter			
MSRF with filters			
Nested frames			

In both tasks the current harmonics will be compared with the limits from the standard IEEE929:

ODD HARMONICS	***DISTORTION LIMIT***
3rd through 9th	***less than 4.0%***
11th through 15th	***less than 2.0%***
17th through 21st	***less than 1.5%***
23rd through 33rd	***less than 0.6%***

The THD of the grid current should not be higher than 5%

Upload your result to Moodle: https://phd.moodle.aau.dk/course/view.php?id=498

Lab 6 - E2D2 - Current Control (EXP)

Introduction

The objective of this lab is to enable the student to test experimentally the designed PLL and current control strategy for three-phase grid inverter.

Hardware setup

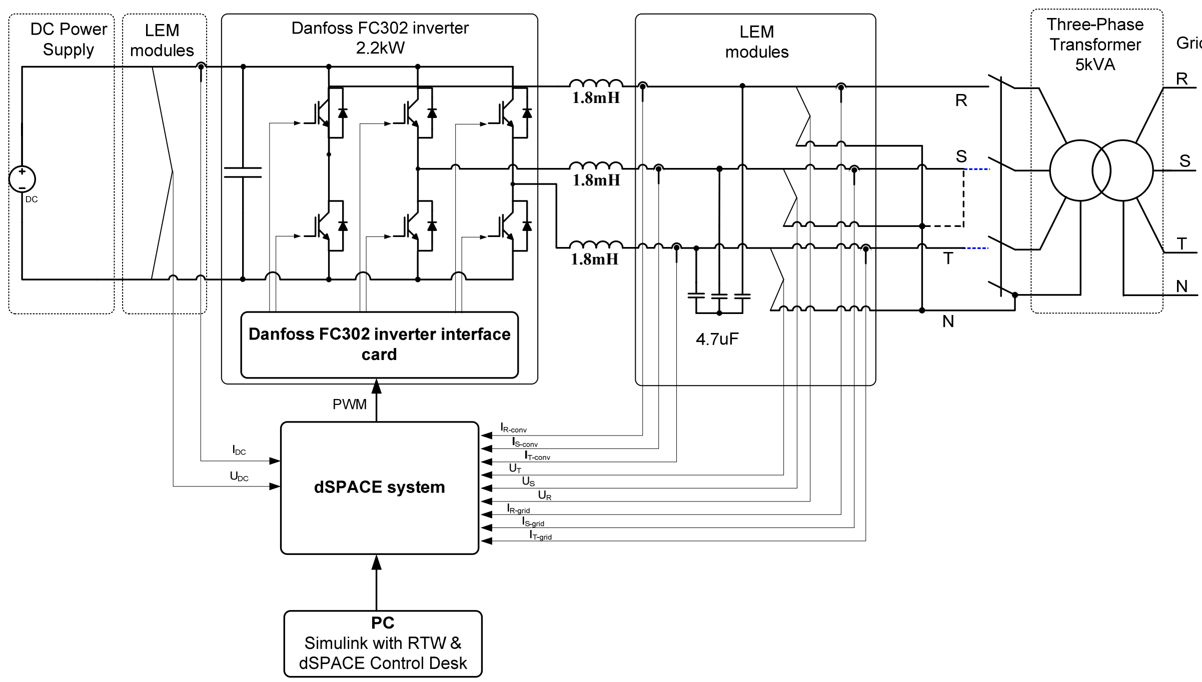
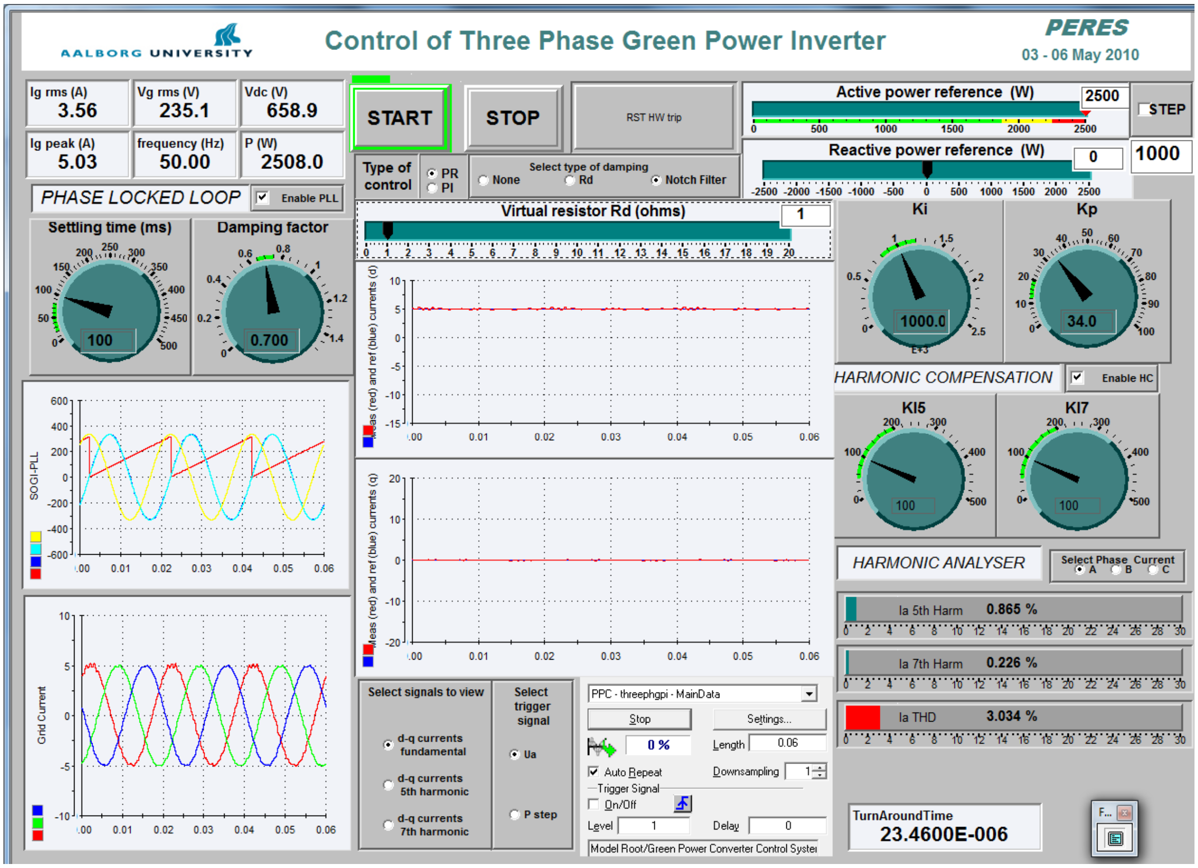


Fig. 6-1: The Green Power Inverter hardware setup

Laboratory tasks



Control Desk interface for Experimental Testing of three-phase Inverter

Task1: Test the d and q (PI) control and harm compensation

- Set the gains for the current controller according to the design using Control Desk.
- Start the inverter and test the current controller for different power references (P=2kW and Q = ±1kVAR)
- Make a step change in the reference from zero to full load (from 1 to 2kW active power). The "Active power reference" and the "Step" values will be added (Pact=1kW and Pstep=1kW). The grid current waveform during the step should be captured on the Control Desk graph and optionally on the scope. Select "P step" as trigger source
- Make a table of the grid current harmonic content and THD with and without harmonic compensation. Compare the results with the IEEE 929 standard.

Task 2: Test the alfa-beta (PR) control and harm compensation

- Set the gains for the current controller according to the design using Control Desk.
- Start the inverter and test the current controller for different power references (P=2kW and Q = ±1kVAR)
- Make a step change in the reference from zero to full load (from 1 to 2kW active power). The grid current waveform during the step should be captured on the Control Desk graph and optionally on the scope.
- Make a table of the grid current harmonic content and THD with and without harmonic compensation. Compare the results with the IEEE 929 standard.

Task 3: Compare the performance of PI and PR controller in stationary and dynamic condition

Upload your result to Moodle: https://phd.moodle.aau.dk/course/view.php?id=498

Lab 7 - E3C - Voltage Support

Introduction

The present session has as objective to experimentally test voltage control strategies for low voltage grids.

Control structure

The control scheme of the single-phase grid-connected PV inverter is depicted in Fig. 7-1.

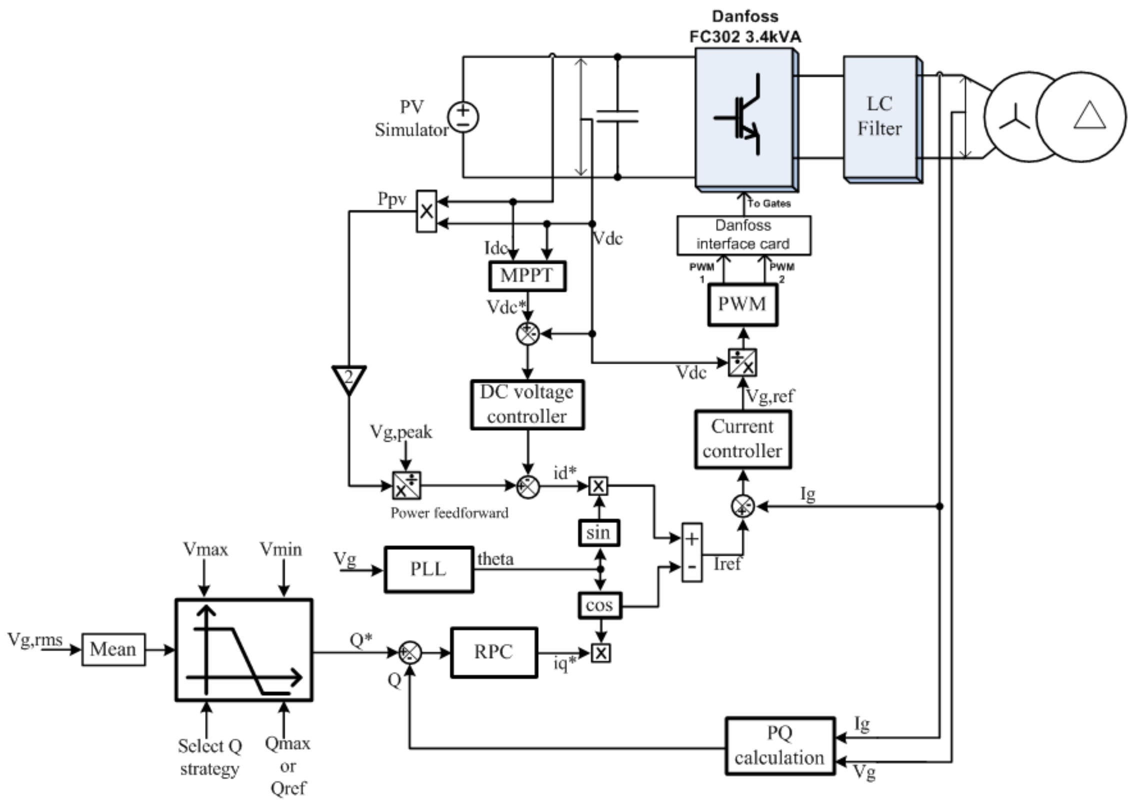
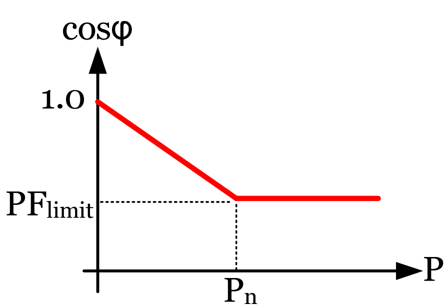
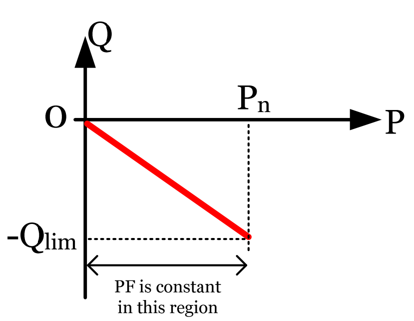


Fig. 7-1 Single phase current control of Green Power Converter

Electrical grids have limited distributed generation absorption capacity due to reverse power flow. Hence, voltage rise problem is the most important barrier to extend PV penetration level more. As one of the solutions, voltage drop is fulfilled by means of drawing reactive power from network by each PV inverter. Reactive power set value generation strategies based on injected active power (P) and terminal voltage deviation (Δu) (see Fig. 7-2) can be selected depending on voltage rise severity and reactive power losses in the network (Fig. 7-2):

- P-dependent strategies:
  - cosφ – P
  - Q – P
- Δu-dependent strategies:
  - cosφ – Δu
  - Q – Δu
  - tanφ – Δu

(a)  	$\cos\phi = 1 - C_{CP}.P$ if $\cos\phi < PF_{\lim}$ then $\cos\phi = PF_{\lim}$ By projection into Q $Q_{CP} = -P.\sqrt{\frac{1}{(1 - C_{CP}.P)^2} - 1}$ if $(Q_{CP} < -Q_{\lim it})$ then $Q_{CP} = -Q_{\lim it}$ where $Q_{\lim it} = P.\sqrt{\left(\frac{1}{PF_{\lim it}}\right)^2 - 1}$
(b)  	$Q_{QP} = -C_{QP}.P$ Slope coefficient is limited by: $\lvert C_{QP} \rvert \leq \tan(\arccos(PF_{\lim}))$

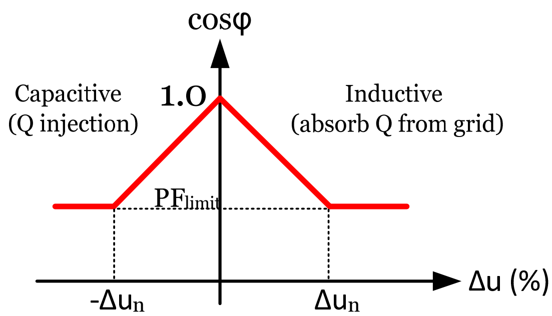
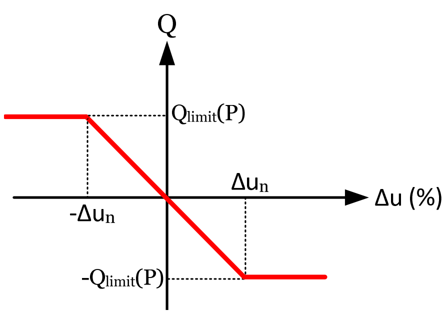
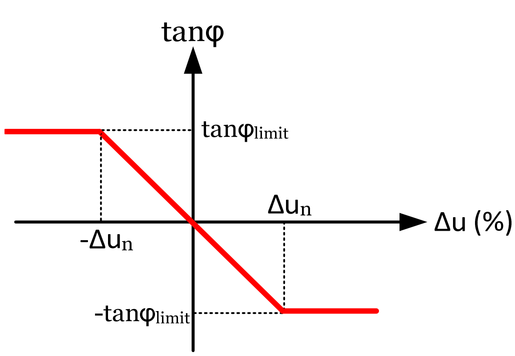
(c) 	$\cos\phi(\Delta u) = 1 - C_{CU}.\lvert\Delta u\rvert$ if $\cos\phi < PF_{\lim}$ then $\cos\phi = PF_{\lim}$ Q ↓ $Q_{CU} = -sign(\Delta u).P.\sqrt{\frac{1}{\left[1 - C_{CU}.\lvert\Delta u\rvert\right]^2} - 1}$ if $((Q_{CU} > Q_{\lim}) \parallel (Q_{CU} < -Q_{\lim}))$ then $Q_{CU} = -sign(\Delta u).Q_{\lim}$ where $Q_{\lim} = P.\sqrt{\left(\frac{1}{PF_{\lim}}\right)^2 - 1}$
(d) $(Q_{TU} > Q_{\lim})$ 	$Q_{QU} = -C_{QU}.\Delta u$ if $((Q_{QU} > Q_{\lim}) \parallel (Q_{QU} < -Q_{\lim}))$ then $Q_{QU} = -sign(\Delta u).Q_{\lim}$ where $Q_{\lim} = \tan(\arccos(PF_{\lim})).P$.
(e) 	$\tan\phi = -C_{TU}.\Delta u$ if $((\tan\phi > \tan\phi_{\lim}) \parallel (\tan\phi < -\tan\phi_{\lim}))$ then $\tan\phi = -sign(\Delta u).\tan\phi_{\lim}$ where $\tan\phi_{\lim} = \tan(\arccos(PF_{\lim}))$ By projection into Q ↓ $Q_{TU} = -C_{TU}.\Delta u.P$ if $(\parallel (Q_{TU} < -Q_{\lim}))$ then $Q_{TU} = -sign(\Delta u).Q_{\lim}$ where $Q_{\lim} = \tan(\arccos(PF_{\lim})).P$

Fig. 7-2 Reactive power generation strategies

To evaluate strategies, each generated reference values ($\cos\phi$, $\tan\phi$) must be written in terms of reactive power (Q). As an example, $\cos\phi = 1 - C_{CP}.P$ can be projected into Q as follows:

$$P = S.\cos\phi = \sqrt{P^2 + Q^2}.\cos\phi \;\rightarrow Q^2 = \left(\frac{P}{\cos\phi}\right)^2 - P^2 \;\rightarrow\; Q = |P|.\sqrt{\left(\frac{1}{\cos\phi}\right)^2 - 1}$$

$$Q = |P|.\sqrt{\left(\frac{1}{1 - C_{CP}.P}\right)^2 - 1}$$

The slope parameters of voltage support strategies are key factors to minimize reactive power losses and maximize voltage support depending on short-circuit power at the connection point and regarding of inverter power conversion efficiency, power factor is also limited here between 0.85 lagging and 0.85 leading.

As depicted in Fig. 7-2, depending on user set values, Q strategy block generates reactive power reference which is input to either the reactive power controller (RPC) block or current controller. Both RPC and DC voltage controllers include discrete PI compensators whose bandwidths are lower than the bandwidth of current controller.

The Control Desk interface for the voltage support is presented in Fig. 7-3.

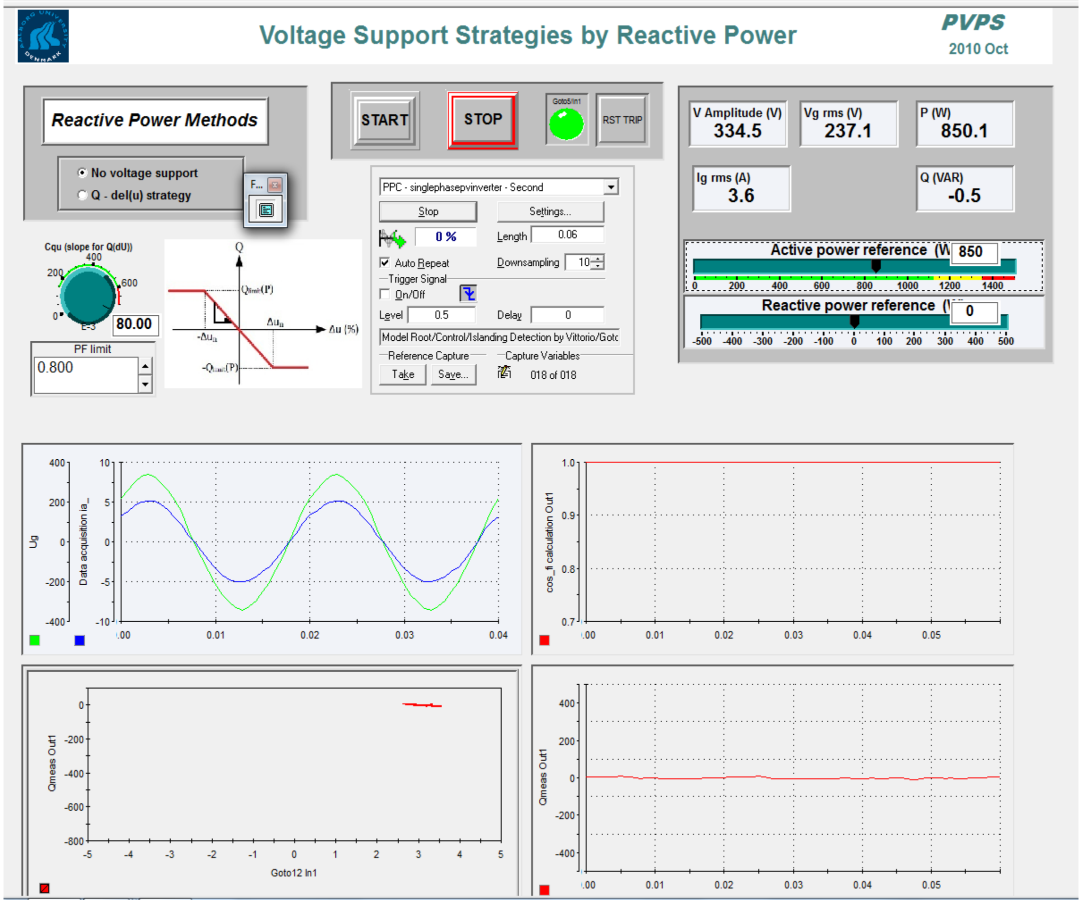


Fig. 7-3 The Control Desk interface for voltage support

Laboratory tasks

• Test of the voltage support strategies

- Without reactive power support, increase the active power reference. As the injected power increases, the voltage at PCC should also increase. Set the active power to 1.5 kW and note the resulting PCC voltage (U_{pcc}).
- Turn on the Q - Δu voltage support strategy in Control Desk interface with slope value of 150. Slope (C_{qu}) is defined as VAr increment value per every voltage rise in percent:

$$C_{qu} = \frac{\Delta Q[VAr]}{\Delta u[\%]} \quad \text{where} \quad \Delta u = \frac{U_{rms} - U_{nom}}{U_{nom}} \times 100$$

- The voltage at PCC should have dropped by means of Q-Δu method. Further increase active power until the previous voltage level is reached again. Note the active power level in this case.
- Repeat the previous two steps using a slope value of 300.

- Fill in Table 9-1, below.

Table 7-1 Experimental results

Strategy	P [W]	Q [VAR]	Voltage [U]
No voltage support			U_{pcc}=
Q-Δu with slope of 150			U_{pcc}=
Q-Δu with slope of 300			U_{pcc}=

- Make sure that the x-axis of the graphs are set to Δu (-5<Δu<5) in the Control Desk interface to see Q-Δu curve. And make sure that apparent power is not higher than the nominal VA rating of inverters during experiment (current will be limited).
- After filling in Table 9-1 without any voltage support and with Q-Δu strategy, observe the voltage support functionality if it helps on increasing penetration level (in the sense of maximum active power injection) regarding highly resistive laboratory grid. Observe if other setups affect the voltage at your PCC.

Upload your result to Moodle: https://phd.moodle.aau.dk/course/view.php?id=498

Lab 8 - E3D – MPPT (SIM - dSpace)

Introduction

The objective of the present session is to design and simulate an MPPT control structure for a single-phase grid-connected photovoltaic inverter, based on Perturb & Observe (P&O), Incremental Conductance (INC), Constant Voltage (CV) and improved Perturb & Observe (dP-P&O) MPPT algorithms.

Main MPPT methods

• Perturb & Observe (P&O)

Perturb & Observe (P&O) is one of the so called 'hill-climbing' MPPT methods, which are based on the fact that, on the voltage-power characteristic, on the left of the MPP, the variation of the power against voltage, $dp/dv > 0$, while on the right, $dp/dv < 0$. If the operating voltage of the PV array is perturbed in a given direction and $dp/dv > 0$ it is known that the perturbation moved the array's operating point toward the MPP. The P&O algorithm would then continue to perturb the PV array voltage in the same direction. If $dp/dv < 0$, then the change in operating point moved the PV array away from the MPP, and the P&O algorithm reverses the direction of the perturbation.

The P&O is perhaps the most-often used MPPT method due to its ease of implementation and low computational demand. However, it has some drawbacks, due to oscillations around the MPP in steady state conditions, and poor tracking (possibly in the wrong direction, away from MPP) under rapidly-changing irradiations.

The flowchart of the P&O method is depicted in Fig.8-1.

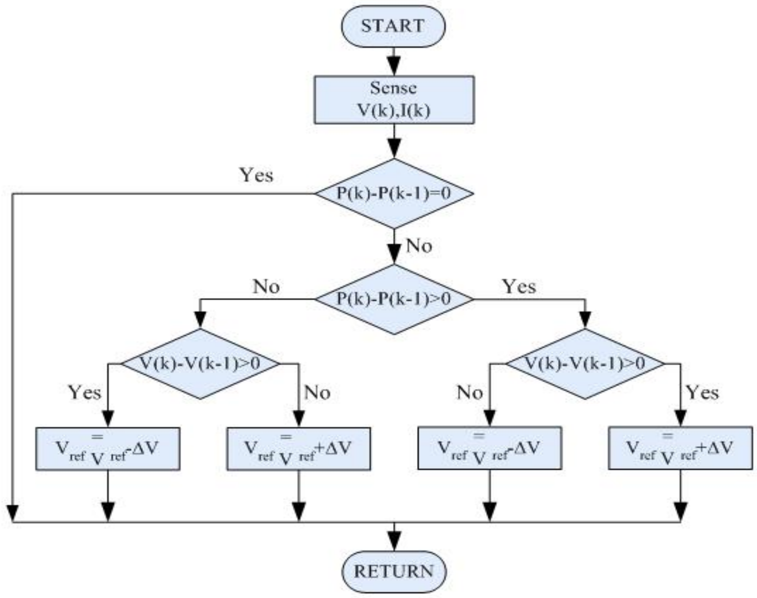


Fig.8-1 The flowchart of the P&O method

• Incremental Conductance (INC)

Incremental Conductance (INC) is another "hill-climbing" MPPT method, which replaces the derivative of the power versus voltage dp/dv , with the PV array's incremental conductance $di/dv > 0$.

Although the INC method is generally considered to be more efficient that P&O, it is essentially equivalent to P&O, therefore it has the same disadvantage that it can track in the wrong direction during fast changing irradiations, as well as it presents oscillations around the MPP in steady state operation.

The flowchart of the INC MPPT method can be seen in Fig.8-2.

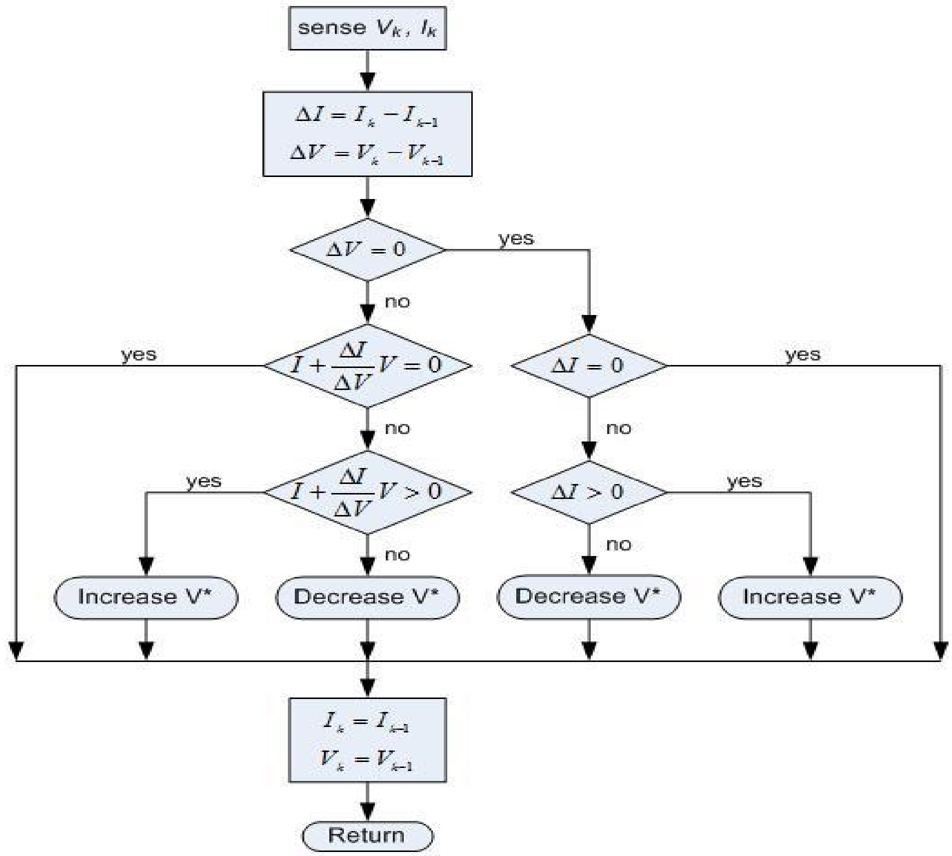


Fig.8-2 The flowchart of the INC method

• Constant Voltage (CV) method

The Constant Voltage (CV) method uses the fact that the PV array MPP voltage changes only slightly with irradiation. In this algorithm, the PV array current is periodically set to zero, to allow the measurement of the open circuit voltage, V_{oc}. The operating voltage is then set to a fixed percentage of V_{oc}. Although the ratio between the open circuit voltage and the voltage at MPP (V_{oc}/V_{mp}) depends on the solar array parameters, a commonly used value for crystalline silicone panels is 76%. This operating point is maintained for a set amount of time, after which the cycle is repeated.

The main problem with this algorithm is that energy is wasted while the open circuit voltage is measured, and the V_{mp} is not always at the fixed 76% of the V_{oc}.

The flowchart of the CV MPPT method can be seen in Fig. 8-3.

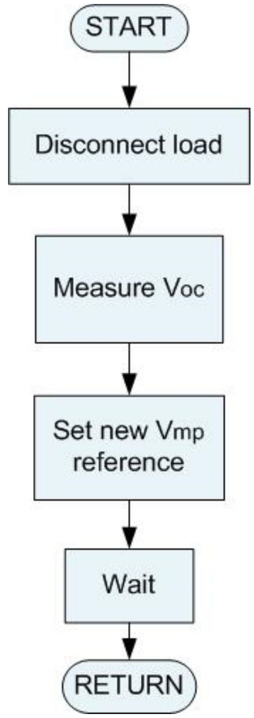


Fig. 8-3 The flowchart of the CV method

• Improved Perturb & Observe method (dp-P&O)

The dP-P&O method determines the correct tracking direction by performing an additional measurement in the middle of the MPPT sampling period. This way, the classical P&O method is improved, in the sense that it can prevent misdirected tracking under rapidly changing irradiance.

The flowchart of the dp-P&O MPPT method can be seen in Fig. 8-4.

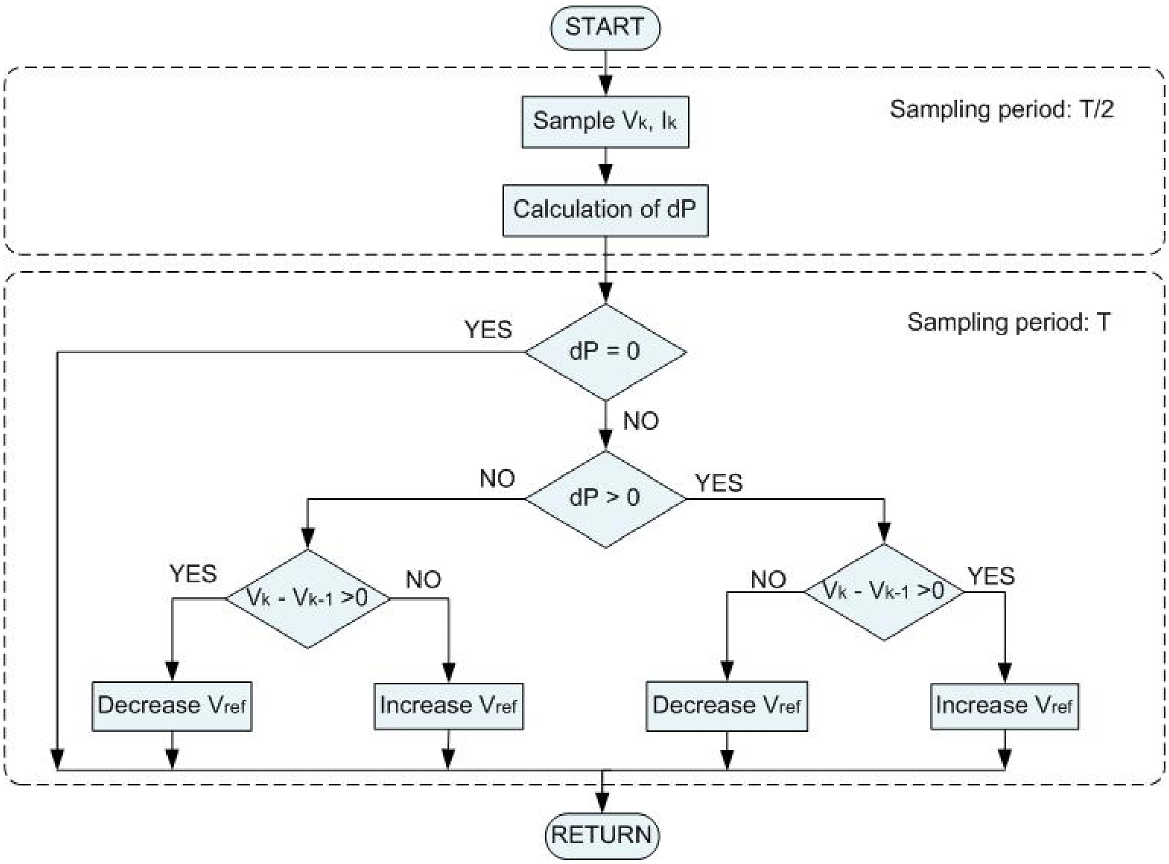


Fig. 8-4 The flowchart of the dp-P&O method

Laboratory tasks

Task1: Effect of the MPPT sampling rate and voltage increment

The aim of this task is to evaluate the effect of the sampling rate and increment size on the performance and precision of hill-climbing MPPT methods. A PV simulator with GUI and an average model for the PV inverter is provided for the study of the MPPT. The experiment has been implemented on the dSpace platform and a Control Desk graphical user interface is provided, as can be seen in Fig. 8-5.

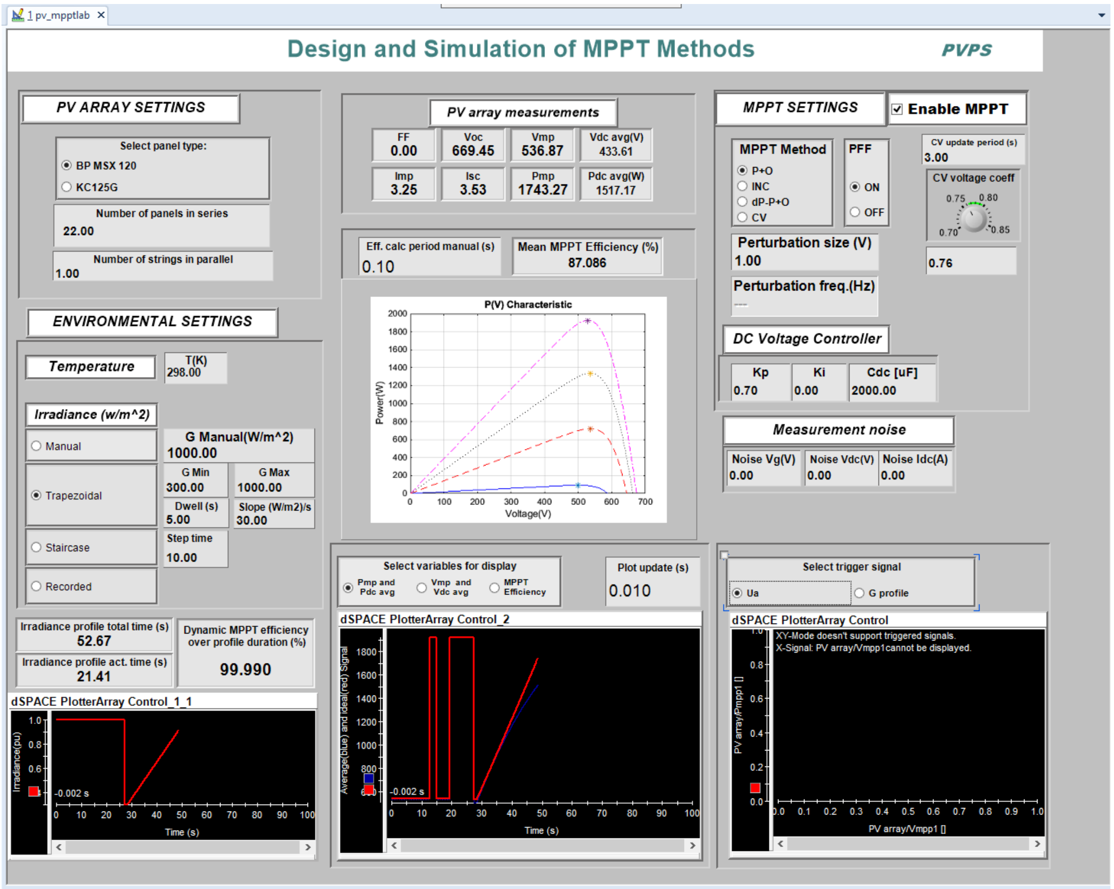


Fig. 8-5 Screenshot of the Control Desk interface

In order to perform the experiment, the steps given below need to be followed:

- Select how the characteristics of the PV array will be defined: using the datasheet of the PV panel (V_{oc}, I_{sc}, V_{mp}, I_{mp}) or by the parameters of the PV array (P_{mp}, V_{mp}, FF);
- If the PV array characteristics are defined based on the datasheet, select the type of the solar panel (BP MSX 120 or Kyocera KC125G), then the number of panels in series and the number of strings in parallel;
- When the PV array is defined using the parameters of the array, set these parameters (P_{mp}, V_{mp}, FF – determined by the type of the PV array and the array type);
- Set the temperature;
- Set the profile of the irradiation:

a. manual – a constant irradiance is applied (default);

b. trapezoidal – the irradiation profile is presented in Fig. 8-6, where G_{min}, G_{max} and the rate of change (RoC) are introduced by the user;

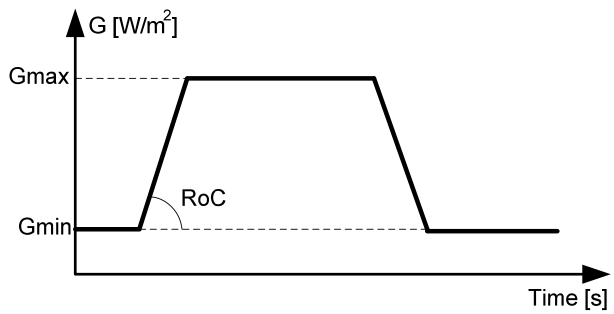


Fig. 8-6 Trapezoidal irradiance profile

c. staircase – the irradiation profile is presented in Fig.8-7;

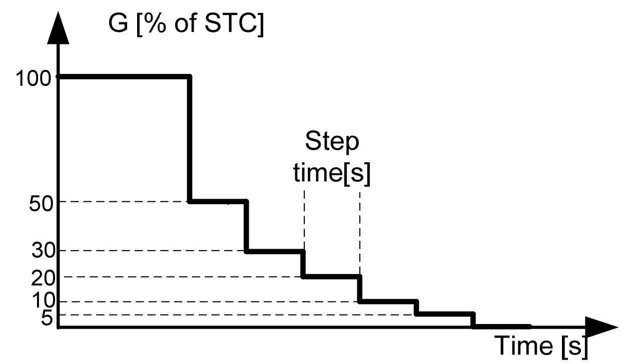


Fig.8-7 Staircase irradiance profile, with percentage values relative to STC irradiance

d. recorded – a previously measured profile of the irradiance is considered (see Fig. 8-8);

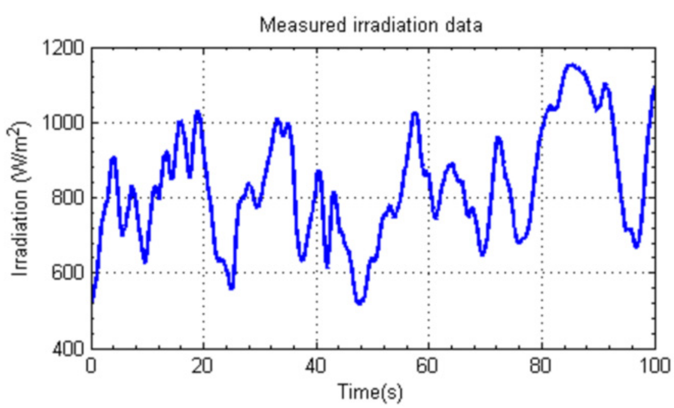
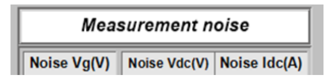


Fig. 8-8 Irradiation profile measured during weather with fast moving clouds

- Set the MPPT method to be applied: P&O, INC, CV or dP-P&O, the voltage increment, the perturbation frequency. In case of the CV method, the frequency for measuring the open circuit voltage and calculating the output voltage, and the voltage coefficient (the percentage of the open circuit voltage which will be the output voltage) needs to be set;

Task2: MPPT static efficiency calculation

- Set the irradiance profile to 'manual'
- Check that the measurement noise levels are set to default values (approximately 0.5% of peak values for Voc and Isc in STC for the selected system (Vdc and Isc)). AC side noise (Vg) can be left as zero as it has little effect on MPPT).



- After setting an irradiation value from the table below, wait until steady state conditions
- Select 'MPPT efficiency' for the main plot (middle) in Control Desk.
- Fill in Table. 8-1 with the results obtained from the simulation (reading steady-state MPPT efficiencies from the plot or the display):

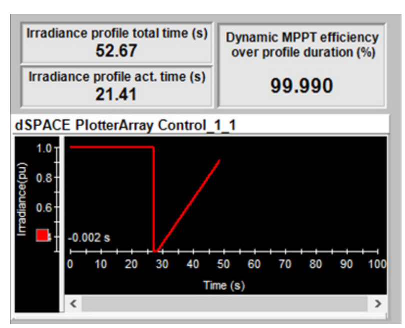
Table. 8-1 Simulation results

G [W/m^2]	P_{mp} [W]	P&O		INC		CV		dp-P&O	
		P_{dc} [W]	η_{MPPT} [%]	P_{dc} [W]	η_{MPPT} [%]	P_{dc} [W]	η_{MPPT} [%]	P_{dc} [W]	η_{MPPT} [%]
300									
1000									

- Choose the best MPPT method for static efficiency based on the obtained results.

Task3: MPPT dynamic efficiency evaluation

- Set the minimum and maximum irradiation limits (100W/m^2, and 500W/m^2)
- Set the rate of change 30W/m^2/s
- Select the 'trapezoidal' irradiation profile in Control Desk; The displays over the irradiance plot (left hand side) will show the total time required for completing the selected profile ('*Irradiance profile total time (s)*'), the time spent since starting the profile ('*Irradiance profile act. time(s)*'), and the dynamic efficiency calculated for the entire profile ('*Dynamic MPPT efficiency over profile duration (%)*'). Please note that this value only updates after the profile is executed, and make sure to write it down, as the calculations won't stop with the finishing of the profile.



- Read the dynamic efficiency of the MPPT for the period;
- Repeat the above steps for all four considered MPPT strategies;
- Choose the best MPPT for dynamic efficiency based on the obtained results.

Upload your result to Moodle: https://phd.moodle.aau.dk/course/view.php?id=498

Lab 9 - E4C2 - Design of PV Plants (SIM)

Introduction

The objective of this laboratory exercise is to design a large PV plant connected to the grid, using the Matlab GUI with the AAU designed algorithm.

Initial assumptions for the PV Plant	
Country and Location	Greece, Kythira
Latitude	35.53^{o}
Longitude	24.06^{o}
Azimuth	0^{o}
Rated Power	96kWp

Use the initial assumptions and create a large PV Plant for each of the following cases:

- Try various PV panel technologies (maintain Rated Power constant)
- Try various Inverters (use different nominal Power)
- Modify the tilt angle and determine the optimum (regarding the AEP)
- Slightly oversize the inverter (How AEP varies?)
- Determine the arrangement of the installation (modules in series, number of strings for the above cases)
- What is the requested area (m^2) for each of the above cases?
- What is the Performance Ratio for each of the above cases?

*AEP – Annual Energy Production

Upload your result to Moodle: https://phd.moodle.aau.dk/course/view.php?id=498

Lab 10 - E4C1 – Control of PV Inverters under Grid faults

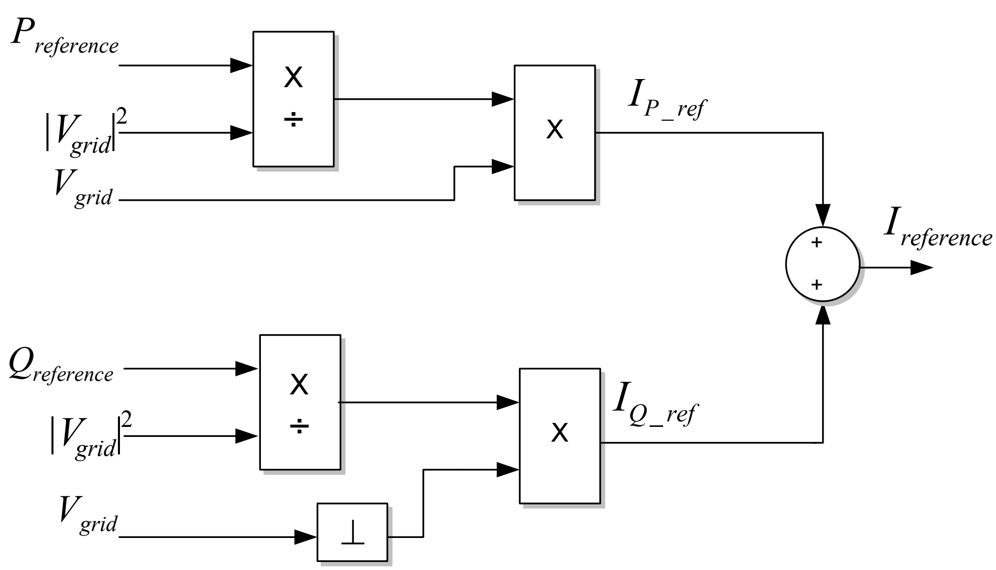
Introduction

The objective of this laboartory exercise is to enable the student to test experimentally several current reference strategies able to control the P and Q powers under grid faults.

In this exercise, the grid synchronization technique and the current controller will be provided as a DSOGI – FLL and a stationary current controller. The distorted grid is also provided in this exercise.

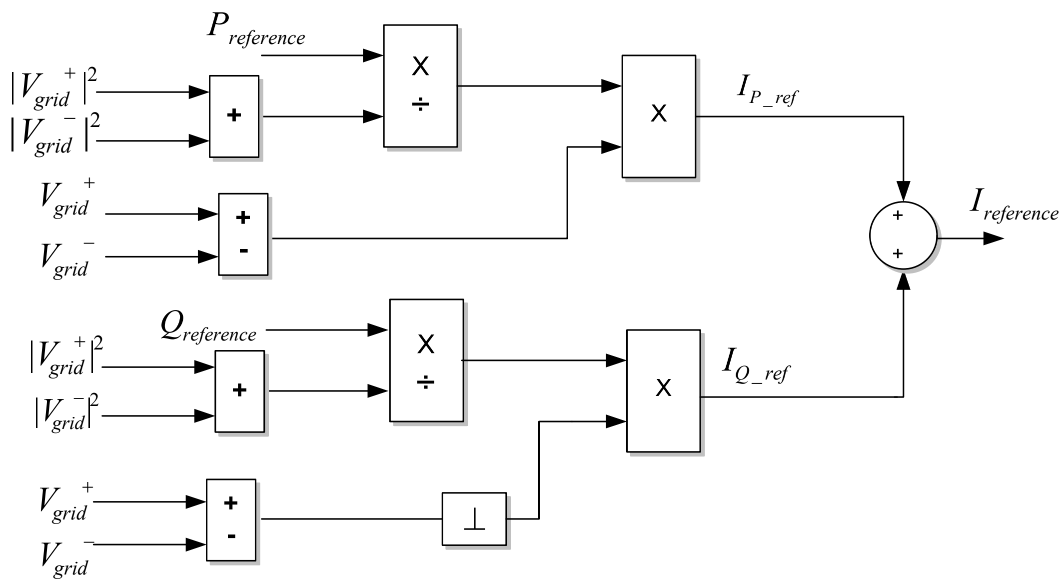
Structures of reference current strategies

Instantaneous active and reactive control



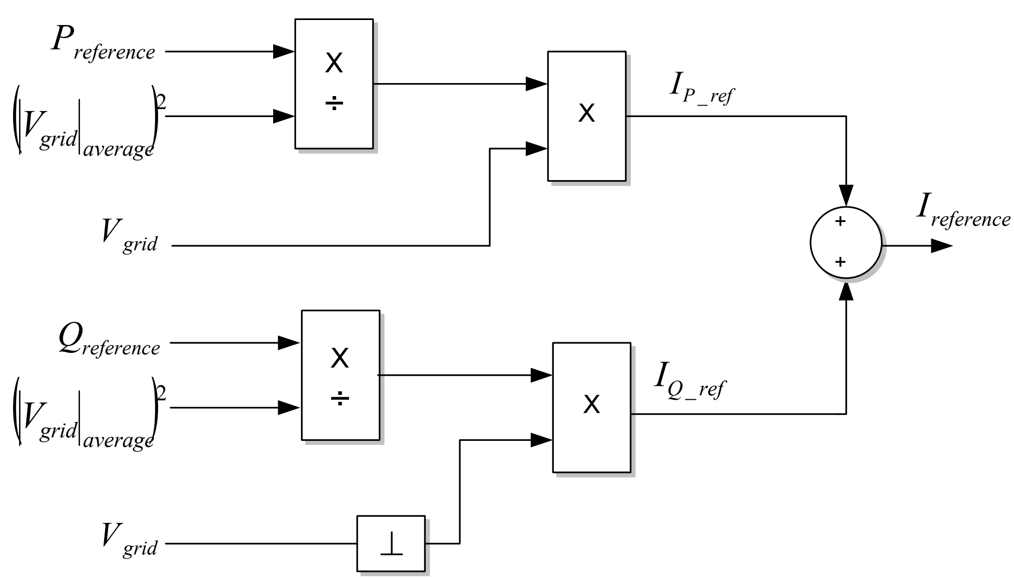
IARC structure

Positive and negative sequence compensation



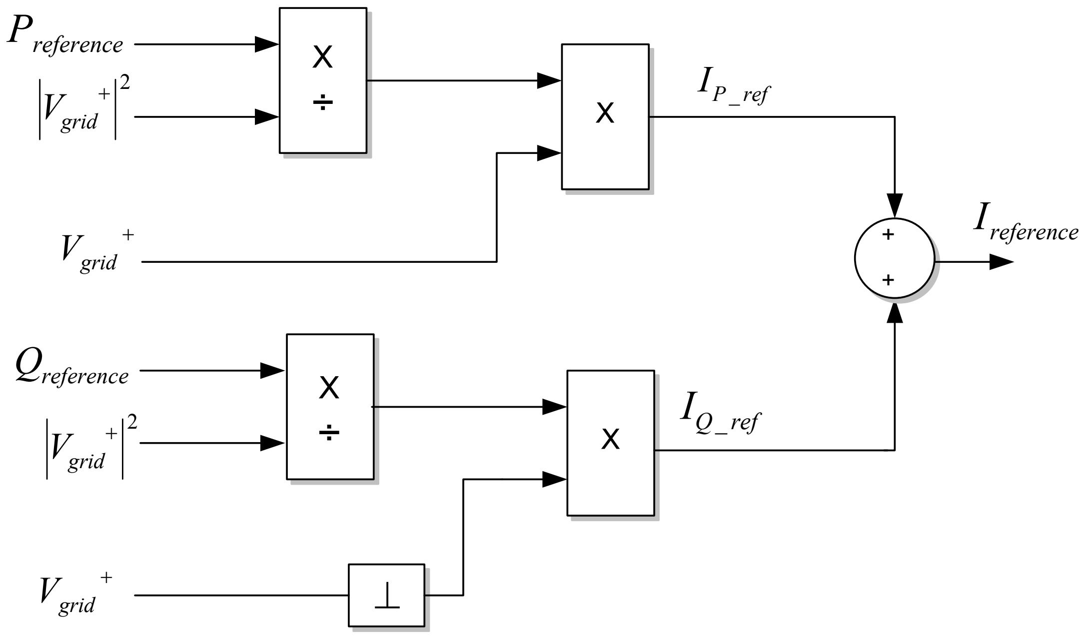
PNSC structure

Average active and reactive control



AARC structure

Balanced positive sequence



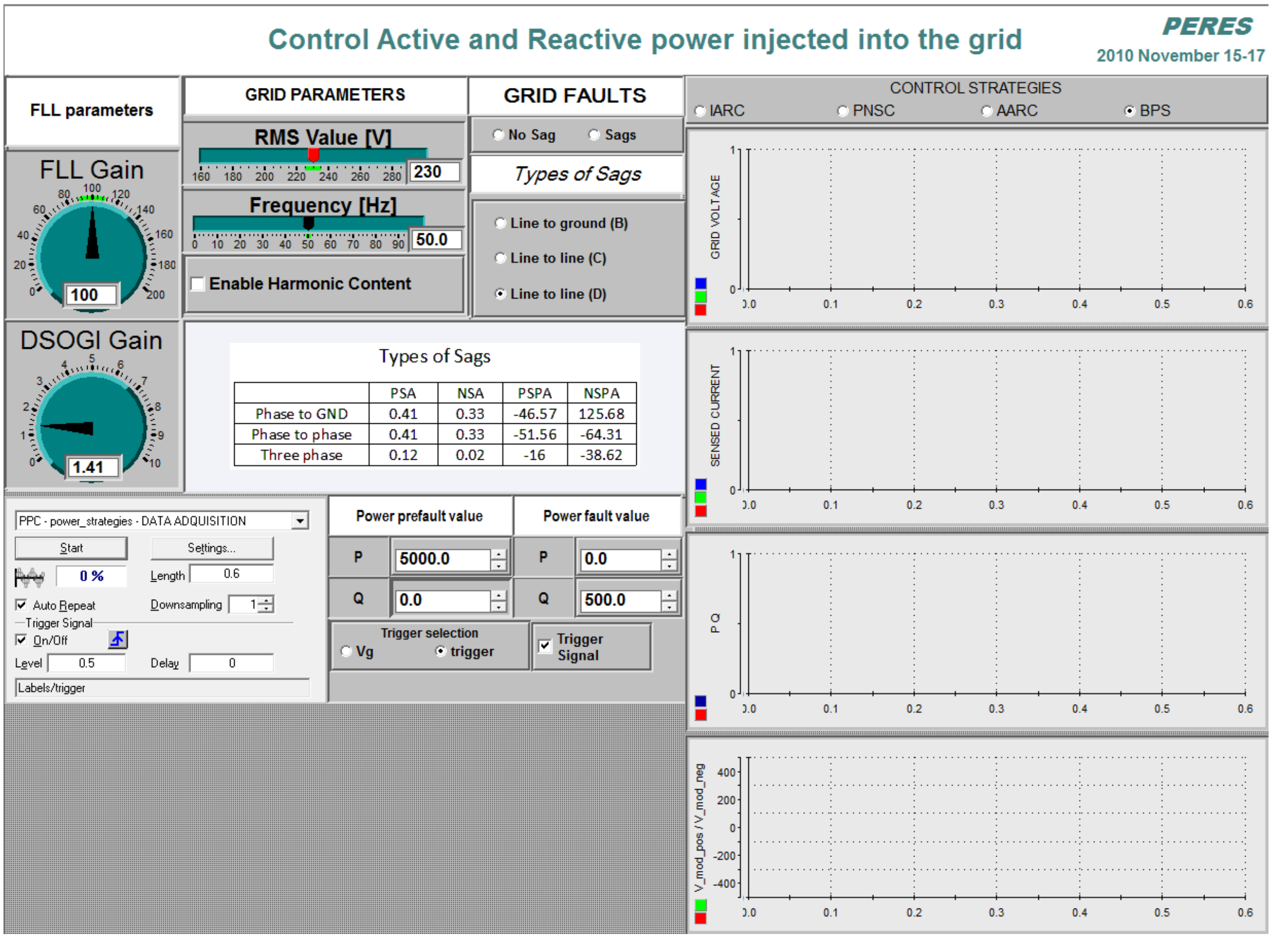
BPS structure

Description of the front panel

A real-time simulation model including faults capabilities, the DSOGI-FLL and the PR controllers on the stationary reference frame is implemented in dSPACE real-time simulator and the Control Desk interface to be used is shown below:

As it can be observed in the front panel there are three differentiated parts:

- In the left side, the control parameters of the DSOGI – FLL are shown
- The grid parameters and the grid fault control are situated in the central part of the panel. In this central part it can be also found the reference values of P and Q which will be injected during the grid fault.
- In the right side, grid voltage, sensed current, P and Q, and modules of positive and negative voltage sequences are plotted.



Control Desk interface for Experimental Testing of Current Reference Strategies for Control under Fault

Laboratory tasks

Task 1: Set the active and reactive references according to the following set-point and evaluate the response of the different current reference strategies (IARC, PNSC, AARC and BPS) when the grid voltage is not affected by any fault.

- Set the reference for the pre-fault active power to 5 kW.
- Set the reference for the pre-fault reactive power to 0 kvar.

Task 2: Set experimentally the maximum reactive power that can be injected to the grid by each current control strategy (IARC, PNSC, AARC BPS) during a sag type B in order to do not overpass a threshold value of 10A in the injected current. The following plots should be attached for each reference current control strategy:

- Injected current
- Active and reactive powers delivered to the grid

- Module of the positive- and negative-sequence voltage at the PCC. ($|V^+|, |V^-|$)

Task 3: Set experimentally the maximum reactive power that can be injected to the grid by each current control strategy (IARC, PNSC, AARC BPS) during a sag type C in order to do not overpass a threshold value of 10A in the injected current. The following plots should be attached for each reference current control strategy:

- Injected current
- Active and reactive powers delivered to the grid
- Module of the positive- and negative-sequence voltage at the PCC. ($|V^+|, |V^-|$)

Task 4: Set experimentally the maximum reactive power that can be injected to the grid by each current control strategy (IARC, PNSC, AARC BPS) during a sag type D in order to do not overpass a threshold value of 10A in the injected current. The following plots should be attached for each reference current control strategy:

- Injected current
- Active and reactive powers delivered to the grid
- Module of the positive- and negative-sequence voltage at the PCC. ($|V^+|, |V^-|$)

Task 5: According to the experimental results, evaluate which is the most suitable reference current control strategy to be applied during an unbalanced rid fault.

Upload your result to Moodle: https://phd.moodle.aau.dk/course/view.php?id=498