Block 5 Micro-inverters

34553 Applied Photovoltaics

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Abstract: This exercise will show how inverters work and you will measure their efficiency.

References and links

Slides from lectures and 34552 photovoltaic systems.

Slides for block 5

Sandia Inverter test protocol draft.

Introduction

An inverter's purpose is to efficiently load the solar panel at its maximum power point, and subsequently efficiently convert the power to match the grid voltage and phase. The first figure of merit (FOM) is called the tracking efficiency, and the last FOM is called the conversion efficiency, and the product of these two is the total efficiency, which is a number stating how much of the energy available on the solar panel is fed into the grid. You will in this exercise investigate the operating range of the inverter and measure the efficiencies at various load inputs.

Theory

This exercise is inspired from the Sandia Inverter test protocol draft. However, the main purpose of this exercise is to provide an understanding of how inverters work and why significant deviations in reported efficiency can occur between different methods.

Inverters have multiple functions including:

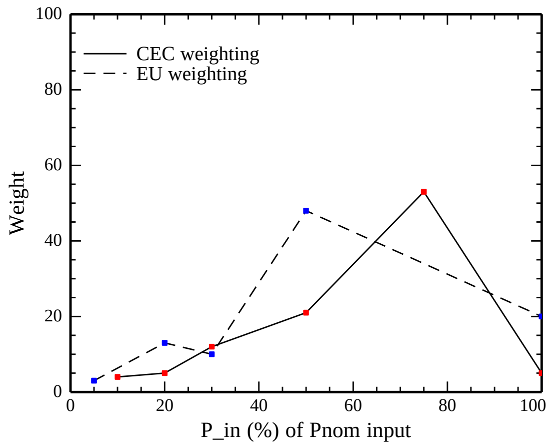
- To operate/load the connected PV array at its maximum power point all the time.
- To convert the array DC power into AC power that can be fed into the grid with high efficiency
- Provide safety and grid support measures

In this exercise you will test the microinverter's ability to load a PV module in its maximum power point (MPP) and measure it's conversion efficiency.

Since it is crucial that the tracker does not only find the MPP but also ensures that the PV-array is operated at the maximum power point as much time as possible, tracking efficiency is measured in static and dynamic conditions. Both measurements are time averaged measurements, so a number of points are recorded during a time period of the order of a few minutes and then averaged. By doing so the measurement includes the tracker's ability to stay at the MPP. In the dynamic mode the solar input is changed as a function of time. Solar array simulators that give an electrical output similar to solar modules are used instead of a real PV-array, since power generated by fielded PV-arrays is difficult to control.

As inverter efficiency is dependent on the load and inverters can operate at a wide range of loads, the industry is using weighted efficiencies namely the California Energy Commission

Weighting (CEC) and the European Weighting (EU-weighting). These weightings are displayed in the below figures.



California Energy Commission (CEC) weighted efficiency

$$\eta_{CEC} = 0.04 . \eta_{10\%} + 0.05 . \eta_{20\%} + 0.12 . \eta_{30\%} + 0.21 \cdot \eta_{50\%} + 0.53 \cdot \eta_{75\%} + 0.05 \cdot \eta_{100\%}$$

European weighted efficiency

$$\eta_{EU} = 0.03 \cdot \eta_{5\%} + 0.06 \cdot \eta_{10\%} + 0.13 \cdot \eta_{20\%} + 0.10 \cdot \eta_{30\%} + 0.48 \cdot \eta_{50\%} + 0.20 \cdot \eta_{100\%}$$

The power generated from the micro inverter will, in this exercise, be fed back into to the grid. Grid connected inverters have to comply with country specific grid codes, where the power and frequency has to be within a range from the nominal values. Inverters can support the grid with frequency; voltage and power factor regulation, and do this according to the needs of the grid. We do not control the power quality of the grid itself.

Lab exercise

In this exercise, a Solar Array Simulator (SAS) is used to emulate the PV panel. The SAS is programmed so when loaded with a current or voltage within a range, the corresponding voltage or current according to an IV curve of a PV-panel will be output. The user programs this IV-curve.

Equipment for this exercise:

- Microinverter i-Energy GT260
- Agilent E4360 + E4361 SAS (Solar Array Simulator)
- Tektronix PA 4000 Power Analyzer
- AC breakout box
- Laboratory computer
- 240 VAC grid (wall socket).

Part 1 – Getting ready

Tasks

a. Familiarize yourself with the Solar Array Simulator
   - Read the datasheet of the Solar Array Simulator to gain a basic understanding of its functionality, determine the maximum ratings of the SAS, and write them in Table 1.
   - Familiarize yourself with the output interface and remote sensing of the SAS (pages 26-33 in the SAS user guide)

Table 1. Solar Array Simulator datasheet specifications

Maximum power [W]	Maximum open circuit voltage (V_{oc}) [V]	Maximum voltage point (V_{mp}) [V]	Maximum short circuit current (I_{sc}) [A]	Maximum circuit point (I_{mp}) [A]

b. Familiarize yourself with the microinverter:
- Read the datasheet to determine the maximum ratings and write them in Table 2.
- Reading the installation guide to familiarize yourself with the interfaces and application of the micro-inverter

Table 2. Micro-inverter i-Energy GT260 datasheet specifications

Maximum input power [W]	
Nominal input power [W]	
Input voltage operating range [V]	
MPPT voltage operating range [V]	
Maximum input current [A]	
Maximum input short circuit current [A]	
CEC efficiency [%]	
Peak efficiency [%]	
Static efficiency [%]	
Max. output power [W]	
Nominal output current [A]	
Power factor	

c. Familiarize yourself with the Tektronix PA 4000 Power Analyzer
- Read the datasheet to understand its capabilities
- Familiarize yourself with the channel measurement interfaces (pages 24-30)
- Familiarize yourself with the Tektronix breakout box

d. Wiring the setup

Do not connect the AC output to the wall socket or power the SAS simulator until your wiring/setup has been approved by the instructor

- You will use 4-wire sensing on Channel 1 of the PA to measure the PV current and voltage at the input of the micro-inverter
  i. Which current input will you need to use to measure PV current?
- You will use 4-wire sensing on Channel 2 of the PA to measure the AC current and voltage at the output of the micro-inverter
  i. Which current input will you need to use to measure AC current?
- The SAS uses a 4-wire connection to regulate the voltage at the input of the inverter
- **Make a simple electrical diagram** of how you will wire the setup, showing all the connections and wires necessary.

- Once you are confident you have an understanding of how the setup should be wired, realize all the connections
- **When you are finished ask the instructor to check it and approve it.**

Safety

- Connect the break out box from the inverter to the wall as the last thing prior to measurements, and when disconnecting as the first. There by the risk of electrical shocks is reduced.
- If you or someone changed the wiring in the setup, ask the instructor to check it before connecting the AC and powering the SAS.

Ensure grounding:

- Make sure all equipment is grounded to the grid including the inverter.

Hints:

- Amp meters are connected in series
- Voltmeters are connected in parallel
- Start the connection by creating the current loops, and subsequently add voltage measurements.
- The SAS requires 4 wire measurement

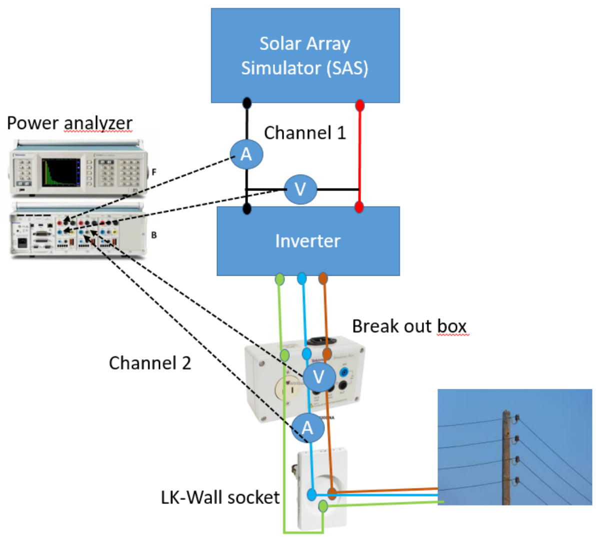


Figure 1: Schematic diagram of the test circuit.

Part 2 – Testing the lower current and voltage operating range

In this part of the exercise you will familiarize yourself with the Labview GUI used to program the SAS, acquire measurements from the PA, monitoring the input and output current and voltages of the micro-inverter, and log the measurements to a data file:

Tasks

a. Familiarize yourself with the Labview interface

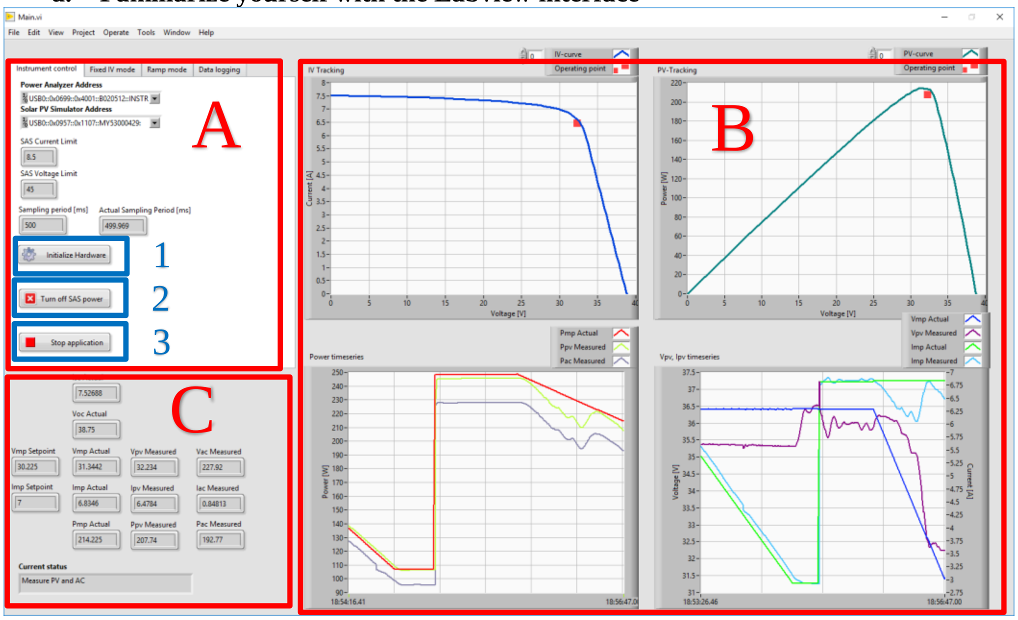


Figure 2. Labview graphical user interface for controlling and monitoring the experiment setup

Panel A

- Is used to control the operation of the SAS
- **Button A.1** – *Initialize hardware* will initialize the SAS and PA instruments to a known state, program a default IV characteristic, start the monitoring and data logging, and turn on the SAS power output.
- **Button A.2** – *Turn off SAS power* will turn off the SAS power output. The monitoring and data logging will keep operating.
- **Button A.3** – *Stop Application* will turn off the SAS power output, stop the monitoring and data logging, and close the application
  Note: the SAS voltage limit has been lowered in software to 45 V – due to safety reasons

Panel B

- Displays and approximation of the I-V and P-V characteristics programmed in the SAS, as well as the current MPP operating point of the inverter
- Displays the timeseries measurements of the real maximum power point (*Pmp actual*, *Vmp actual*, *Imp actual*) programmed in the SAS, and the measured PV operation point (*Ppv*, *Vpv*, *Ipv*) and real AC power output (*Pac*) of the inverter

Panel C

- Displays the current setpoints programmed in the SAS, actual values that the SAS used to generate the IV characteristic, and the measured inputs and outputs of the inverters
- **Note:** the is a small difference between the programmed setpoints from the interface and the actual values of the IV characteristic simulated by the SAS, due to the modelling procedure used in the SAS.
- **The MPP values you should use for calculating MPPT efficiency are the *Pmp actual, Imp actual,* and *Vmp actual***

Datalogging tab

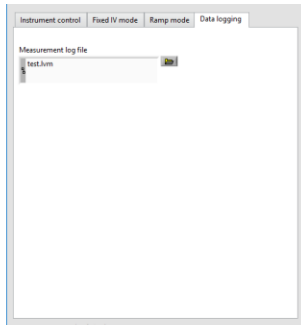


Figure 3. Data logging

All measurements are logged into a file, line by line, which you can configure the path for in the data logging tab. The current date and time will automatically be appended to the file name. If you start, stop and start the application, a new file with the current date and time will be created.

Important: Note down the PC's time when you start and stop a specific measurement, such that you can easily identify which file contains your measurements

Fixed I-V mode tab

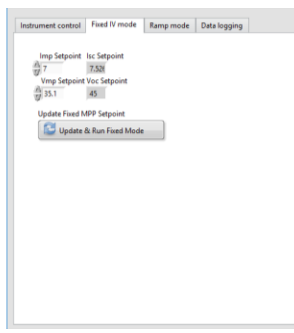


Figure 4. Fixed IV operation mode

- The fixed IV mode is used to program a static IV characteristic in the SAS. Enter the desired *Imp* and *Vmp* point, and press **Update and Run Fixed Mode**.
- The Labview program will calculate the corresponding *Isc* and *Voc* setpoints based on fixed and pre-determined *Imp/Isc* and *Vmp/Voc* ratios, and send these setpoints to the SAS.
- The SAS will use these setpoints to calculate the parameters of an equivalent circuit single diode model of the PV panel, which is then used to simulate the I-V characteristic of the panel.
- The resulting MPP point this I-V characteristic will differ slightly from the setpoints due to inaccuracies in the model. The real MPP point is read back by the Labview software as *Pmp actual*, *Vmp actual*, and *Imp actual*

Ramp mode tab

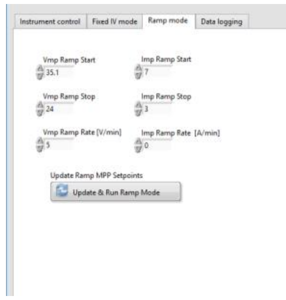


Figure 5. Ramp operation mode

- The ramp mode tab is used to program *Vmp* and/or *Imp* ramps, to test the dynamic tracking efficiency of the inverter.
- You need to specify start and stop values for the MPP current and voltage, as well as the rate of change.
- If you want to keep the current or voltage constant, set the start value equal to the stop value.
- The Labview program will calculate the IV setpoints at each time step and send these to the SAS to simulate a new IV characteristic.

Tasks

b. Test the operation of the GUI

- After you have wired the setup correctly and it has been checked by the instructor
- Turn on the SAS and PA
- Start the GUI
- Configure the data logging file path
- Press **Initialize hardware** - to configure the hardware and start SAS IV simulation, monitoring and datalogging
- Connect the AC output of the setup to the electrical grid
- It takes around 30 seconds or more for the inverter to start operating. Follow the maximum power point tracking, and get a sense of the time scales.
- Use the Fixed mode I-V tab to program a new I-V characteristic
    - Find the ratings for the inverter on the nameplate and enter values corresponding to the mid-range voltage and current.

Questions:

- Describe how the inverter finds the maximum power point?
- How long time approximately does it take for the inverter to find the maximum power point?

c. Identify the minimum input voltages and currents.

- The SAS is has a limit of 8.5 Amps and therefore it's not possible to test the maximum current range.
- Last year the micro-inverter was damaged due to overvoltage/overloading, therefore the *Voc* is limited in software to 45V (*Vmp* limited to 35.1 V)
    - Make sure the MPP setpoint does not exceed 265 W which is the maximum input power of the micro-inverter

Voltage lower limit test:

- This test will consist of observing the operation of the inverter while the value of the MPPT voltage (*Vmp*) is varied.
- Begin the test with the *Vmp* and *Imp* near the center of the operation range. Slowly ramp or step down *Vmp* at a rate of a few V/minute until the inverter

self-limits or reacts according to specifications when the lower limit of the *Vmp* is exceeded. Record the values.

- Repeat this test for the min and the max. possible *Imp* currents

Current limit test:

- This test will consist of observing the operation the inverter while the value of the MPPT Current (*Imp*) is varied.
- Begin the test with the *Vmp* and *Imp* near the center of the operation range. Slowly ramp or step the *Imp* downward at a rate of ≤ 0.02 *Imax*/minute until the inverter self limits or reacts.
- Repeat this test for the min and the maximum possible *Vmp* voltages.

Question:
How does the MPP tracker load the PV-array when it reaches the lower limits of the currents and the voltages?

Part 3 – Measuring static inverter efficiency

In this part of the lab exercise you will need to make measurements of the tracking efficiency, the conversion efficiency and the total efficiency. Perform these measurements at points that enable the determination of the CEC and EU efficiency for a number of different voltages.

Table 3. Micro-inverter operating setpoints for determining the EU and CEC efficiencies

		Pin, nominal 240 W								
	Pin	**5%**	**10%**	**20%**	**30%**	**50%**	**75%**	**100%**	η_{EU}	η_{CEC}
Vin=Vmin	Iin									
Vin=V1	Iin									
Vin=V2	Iin									
Vin=Vmax										

Tasks:

a. Calculate the required input currents at the load-points (Fill out Table 3). Do this test for the minimum input voltage (*Vmin*), the maximum input voltage (Vmax) and two voltages within the range (V1 and V2). Make sure that each point is data averaged over 3-5 minutes.

$$I_{in} = \frac{P_{in,nominal}}{V_{in}}$$

b. Data processing of the static efficiency tests:
   - Make efficiency plots of the tracking, the conversion and the total efficiency for each voltage you measured.
   - For each voltage you measured calculate the CEC and EU weighted efficiency.
   - How do these results compare with the efficiency values specified in the inverter datasheet

Part 4 – Measuring dynamic inverter efficiency

In this part of the exercise you will characterize the capability of the micro-inverter to track the MPP in changing irradiance and temperature conditions, as well as partial shading effects.

Tasks:

a. Slow ramp (Sunrise test)
   - Starting from zero voltage and zero current make a ramp of both voltage and current and adjust the rates in such that the nominal voltage is reached within 7

- minutes and make the current rate slower so the nominal value for the current is reached within 30-40 minutes.
- After a stabilization period of 5 minutes, decrease the current at the same rate to zero and once the current is decreased to 20 % of the max value for this experiment decrease the voltage to zero at the same rate as the one you used when you increased the voltage.

b. Data processing of slow ramp test results:

- Make a graph showing the MPP power, the DC input power to the inverter and the output power to the grid.
- Calculated the MPP utilization factor according to below equation:

$$MPPT\ utilization = \frac{\sum P_{dc}}{\sum P_{mpp}}$$

- Calculate the integral of the 3 power curves and calculate the lost energy due to tracking and due to conversion, (as the difference of the integrals), and find the relative energy loss (in %).

c. Fast ramp (intermittent cloud cover)

- Use the lowest value of the current operating ranges and the mid range voltage and let the inverter feed power to the grid at this setting and let it stabilize for a few minutes.
- Make a rapid increase in current, such that the current increases to 80 % of maximum during 10 seconds. Once this value is reached, decrease the current to the initial value at the same rate. Repeat the test a few times.
- Repeat the test but make a rapid voltage change instead. Increase and decrease the voltage by 30 % starting from the midrange during 10 seconds. Repeat the test a few times.
- As the last test combine the above changes in voltage and current with the 10 seconds ramps.
- Repeat the test a few times:

d. Data processing of fast ramp test results:

- Make a graph showing the MPP power, the DC input power to the inverter and the output power to the grid.
- Calculated the MPP utilization factor.
- Calculate the integral of the 3 power curves and calculate the lost energy due to tracking due to conversion, (as the difference of the integrals), and find the relative energy loss (in %).

5. Presentation

The presentation should include the following:

- Brief description of the experiment setup and measurement procedure
  e. A table with the found limits on the micro-inverter input current and voltage.
- A qualitative description of how the maximum power point tracker works.
  - How long time does it take before the maximum power point is reached
  - Explain what happens when the current is changed.
  - Explain what happens when the voltage is changed.
  - Explain the behavior at the current and voltages limits.
- Plot of the measured efficiency curves, for the conversion efficiency, the tracking efficiency and the total efficiency.
- Comparison of CEC and EU efficiency for all the voltages.
- Plot the measurement and following the data processing requests for the dynamic characterization.
- Comment on the method the results and your own learnings.
- **Summarize the method and main results in 6-7 slides**
- **Add the rest of the results in backup slides at the end of the presentation**