DEE-53117 Solar Power Systems

Practical work: Operation of PV power generators

General instructions

In order to pass the practical work, the student should write a report answering at least to the formulated questions of **the mandatory parts 1–3**. A total of 6 points can be achieved from the mandatory parts and a minimum of 3 point is required for acceptable performance. Scores for the reports will be based on the **analyses and interpretation** of the results and independence while doing the practical work. For 6 points, extensive analysis of the studied phenomena is required. You can revise the mandatory parts of your report once. The maximum score from the mandatory parts that can be achieved by revising the report is 3 points.

Parts 4 and 5 of the practical work are optional by which one can achieve up to 4 extra points to improve the course grade. You cannot revise the optional parts of your report after you have returned it.

The simulations can be done in groups of at most three students but every student has to write a separate report. A group of students may use same figures in their reports but every student should write their own text and present their own analyses of the results. The report can be written **in English or in Finnish**. Please write your **name** and **student number** on your report. The report should be returned as a PDF file named lastname_firstname.pdf to markku.jarvela@tuni.fi. **Deadline is two weeks after the practical work session. Late submissions will be rejected.**

Download the files used in this practical work from POP. Useful help for using Matlab is provided in Matlab_examples.m.

These questions should at least be discussed in the report!

1 Operation of PV modules

Open file **PV_module.mdl**. You can change the values of ideality factor A, series resistance R_s and shunt resistance R_{sh} by double-clicking the PV module block.

1.1 Study how ideality factor A and parasitic resistances R_s and R_{sh} affect the current–voltage characteristics of a PV module. (Initial values: $A = 1.3$, $R_s = 0.33\ \Omega$, $R_{sh} = 188\ \Omega$)

1. Use the initial values for R_s and R_{sh} and modify A (try 3 different values).
2. Use the initial values for A and R_{sh} and modify R_s (try 3 different values).
3. Use the initial values for A and R_s and modify R_{sh} (try 3 different values).

In each case (1–3), plot all three **current–voltage** curves to the same figure and add the figure to your report. Analyse the results.

1.2 Study how operating conditions (irradiance and temperature) affect the current–voltage characteristics. Use the initial parameter values ($A = 1.3$, $R_s = 0.33\ \Omega$, $R_{sh} = 188\ \Omega$).

1. Keep the irradiance constant and modify the operating temperature (try 3 different values).

2. Keep the operating temperature constant and modify the irradiance (try 3 different values within the range of 100–1200 W/m^2).

In each case (1–2), plot all three **current–voltage** curves to the same figure and add the figure to your report. Analyse the results.

2 Operation of series-connected PV modules under partial shading

Open file **Series_connected_PV_modules.mdl**. Operation of series-connected PV modules under different operating conditions can be simulated by using this model.

2.1 Study how power–voltage characteristics change when the number of shaded modules increases. Simulate the following situations:

1. All modules operating at 1000 W/m^2
2. 350 W/m^2 for one module, 1000 W/m^2 for the rest
3. 350 W/m^2 for two modules, 1000 W/m^2 for the rest
4. Etc. until seven modules are shaded (350 W/m^2) and three modules are non-shaded (1000 W/m^2)

Plot all eight **power–voltage** curves to the same figure and add the figure to your report. How many maximum power points (MPPs) are there and what is the voltage of the global MPP (the MPP with the highest power) in each case?

2.2 Next, study situations where there are three values of irradiance affecting the generator. Simulate the following situations:

1. 350 W/m^2 for one module, 700 W/m^2 for one module, 1000 W/m^2 for the rest
2. 350 W/m^2 for five modules, 700 W/m^2 for one module, 1000 W/m^2 for the rest
3. 350 W/m^2 for six modules, 700 W/m^2 for one module, 1000 W/m^2 for the rest
4. 350 W/m^2 for seven modules, 700 W/m^2 for one module, 1000 W/m^2 for the rest

Plot all four **power–voltage** curves to the same figure and add the figure to your report. How many MPPs are there and what is the voltage of the global MPP in each case? What about the number of MPPs if there are more than three values of irradiance affecting the generator?

3 Operation of Perturb and Observe (PO) MPPT algorithm

Perturbation frequency defines how often the MPP tracking algorithm is performed. **Perturbation step size** defines the size of a current step, which the algorithm makes when it perturbs the operating point of the generator when trying to reach the MPP.

Open file **PV_generator_with_MPPT.mdl**. You can change the values of perturbation frequency and step size by double-clicking **Perturb & Observe** -block and operating conditions by double-clicking **Operating conditions** -block. You can change the position of a switch by double-clicking the switch.

3.1 Keep the irradiance of all the modules constant at 1000 W/m^2. What is the effect of perturbation frequency (try 50 and 100 Hz) and perturbation step size (try 0.05 and 0.10 A) on the time to reach the MPP? How does the voltage of the generator behave when the generator is operating at the MPP? What is the effect of the perturbation frequency and step size on that behaviour?

3.2 **Make sure that the perturbation frequency is 50 Hz and the perturbation step size is 0.05 A.** Turn **switch 2** to use 3 second ramp signal builder block to define the irradiance of all the PV modules. First, the irradiance is 1000 W/m^2 for 3 seconds, and then decreases linearly to 350 W/m^2 during the next 3 seconds, and finally remains at 350 W/m^2 for the rest of the simulation time. Plot the operating voltage as a function of time and add the figure to your report. How does the MPP tracking algorithm operate during changing irradiance conditions?

3.3 Turn **switch 3** to define the irradiance of 5 PV modules to be constant at 1000 W/m^2. Use the signal builder blocks to define the irradiance of the other 5 PV modules so that the irradiance is 1000 W/m^2 for the first 3 seconds, decreases linearly to 350 W/m^2 during the next *(a) 3 seconds and (b) 1.5 seconds* and then remains at 350 W/m^2 for the rest of the simulation time. Plot the operating voltages as a function of time for both cases and add the figures to your report. Does the MPP tracking algorithm reach the global MPP? (compare the operating point to power–voltage curve plotted in the second part of the practical work)

3.4 Review the operation of PO MPPT algorithm under varying irradiance conditions based on the simulations. Which are the weaknesses and strengths of the algorithm?

4 Thermal behaviour of PV modules

This part of the practical work is optional.

The temperature of a PV module can be modelled by means of an energy balance analysis:

$$q_{\mathrm{in}} - (P_{\mathrm{out}} + q_{\mathrm{conv}} + q_{\mathrm{lw}}) = C_{\mathrm{mod}} \frac{\mathrm{d}T_{\mathrm{mod}}}{\mathrm{d}t}$$

4.1 Analyse the module temperature response during irradiance transitions caused by overpassing cloud shadows. Compare the measured module temperature with the simulated module temperature and note the error in the prediction of the module temperature.

1. Run file **Script_4.m**
2. Make sure that the variable **G_input** is in the workspace
3. Open file **Thermal_Model.mdl**

In the thermal model, you can modify the operating conditions (irradiance, ambient temperature and wind speed). In addition, you can modify the value of initial module temperature for the simulation and the module heat capacity (C_{mod}) by double-clicking the **Thermal model** -block. You can change the position of the switch by chancing the value of parameter **Switch position**.

4. Modify the **ambient temperature** to **30 °C** and the **wind speed** to **3 m/s**
5. Check the initial module temperature from **Figure 2** and introduce the value in the thermal model.
6. Use the measured irradiance (**G_input**) as input for the model (Switch position 1) and **run the model**.
7. Plot the measured (**T19**) and simulated (**Tmod_sim**) module temperatures in the same figure and add the figure to your report. (Note the time vectors: Time_sim and Time_vector.)

Describe the differences between the measured and simulated module temperatures and try to explain where the error might come from.

4.2 Analyse the effects of ambient temperature, wind speed, heat capacity and irradiance on the temperature response of the module. Keep the rest of the input parameters at their initial values while evaluating the effect of each variable (initial values: $T_{\text{amb}} = 20$ °C, $G = 1000$ W/m^2 (Switch position 2), $v_{\text{wind}} = 2$ m/s, $C_{\text{mod}} = 20700$ J/K). Use 25 °C as the value for the initial module temperature.

1. Ambient temperature: Use 3 different values of ambient temperature and plot the temperature responses in the same graph. Measure the settling times (temperature is within 2.5 °C of steady state temperature) for the 3 values of ambient temperature.
2. Wind speed: Try 3 different values within the range of 1–10 m/s and plot the temperature responses in the same graph. Measure the settling times for the 3 values of wind speed.
3. Heat capacity: Try 3 different values within the range of 1000–30,000 J/K and plot the temperature responses in the same graph. Measure the settling times for the 3 values of heat capacity.
4. Irradiance: Use **Irradiance_Simulator** -block (Switch position 3) to create 3 different changing irradiance conditions within the range of 100–1100 W/m^2. Simulate the created changing conditions and plot the temperature responses in the same graph. Plot also the created irradiance changes. Measure the settling times for the changing conditions.

Include the graphs in your report (make sure that you also include legends in the graphs indicating the values of the analysed variable in each graph) and discuss about the effect of each variable on the temperature and temperature response of the PV module.

Standard Test Conditions (STC) specify an irradiance of 1000 W/m^2 and a cell temperature of 25 °C. How often do you believe that these conditions exist in reality? What is the reason why manufacturers provide the electrical performance characteristics of PV modules under STC?

5 <u>Simulation of the operation of series-connected PV modules with real measurements</u>

This part of the practical work is optional.

In this section, the operation of series-connected PV modules is studied by simulations using the irradiance and module temperature measurements corresponding to four sensor pairs: S9, S10, S11 and S12. These sensors are located so that they measure the operating conditions affecting to a string of 10 PV modules as shown in Figure 1.

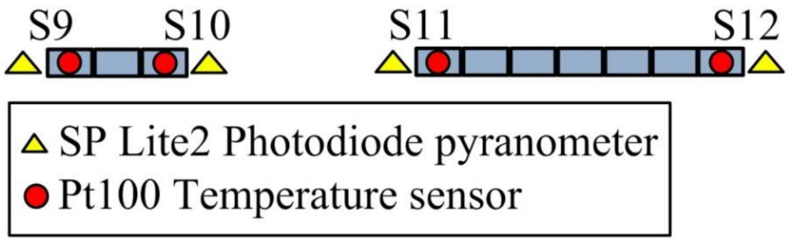

Figure 1. *The representation of the studied string of 10 series-connected PV modules with its four sensors pairs (S9, S10, S11 and S12) of irradiance and module temperature measurements.*

1. Open and run file **Script_5.m**

This file loads the data of a complete day into the workspace and extracts the data corresponding to the increase of irradiance after a shading period caused by a moving cloud between 13:15 and 13:25. After plotting the data in **Figures 1** and **2**, the script interpolates the irradiance and module temperature measurements in order to obtain the operating conditions of each PV module of the string.

Include the graphs of the irradiance measurements (**Figure 1**) and module temperature measurements (**Figure 2**) to your report. Describe the characteristics of the irradiance profile and why it is clear that the irradiance transition is caused by a cloud and not by a building or some other static object.

Simulate the operation of the PV string with real measurements.

2. Open file **PV_string_with_MPPT.mdl**
3. Set the **simulation time** to 600 seconds.
4. Set the **perturbation frequency** of the MPPT algorithm to 1 Hz and the **perturbation step size** to 0.05 A.
5. Make sure that the variables **SimG1** to **SimG10** and **SimT1** to **SimT10** are in the workspace. (These variables are the input variables that the model is going to use.)
6. **Run the model**.

Load file **global_MPP.mat**, which contains the global MPP current and voltage of the studied PV string during the irradiance transition.

7. Plot the current of the string (**I_out_MPPT)** and the current of the global MPP **(I_global_MPP)** with respect to time to the same figure and add the figure to your report.
8. Plot the voltage of the string (**U_out_MPPT)** and the voltage of the global MPP **(U_global_MPP)** with respect to time to the same figure and add the figure to your report.
9. Plot the power of the string and the power of the global MPP with respect to time to the same figure and add the figure to your report.

Discuss about the behaviour of the voltage, current and power produced by the PV string with the changes in the operating conditions (irradiance and temperature). How well does the MPP tracking algorithm follow the global MPP? Calculate the amount of energy lost because of operating in non-ideal operating point instead of the global MPP.

In this practical work, MPPT was implemented by controlling the operating current of the PV generator. Another way is to control the operating voltage of the generator. Which of these ways is more commonly used in real PV systems and why?