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Power Electronics for Energy Systems

Project Part 1: Boost Converter for PV Applications

1 Introduction

1.1 Motivation

In this part of the project you will design a boost converter to interface strings of PV panels to a dc bus. This comprises the part of a three-phase solar inverter responsible for voltage level adaptation and for seeking the maximum power point of the solar panels.

The file `PV_characterization.plecs` contains a simulation model of two parallel PV strings composed of 22 photovoltaic modules KC200GT from Kyocera each connected in series. The next section deals with the characterization of the PV strings, and the aforementioned file should be used to answer the questions.

Section 3 deals with the design of a converter to step-up the voltage from the PV strings, as shown in Figure 1.1. The design includes: dimensioning of the filter components, design of the modulator, design of the current and voltage controllers, and maximum power point tracker algorithm. The output of the voltage converter will be connected to a dc-ac converter in a following part of the project. For this part, we can assume the dc bus voltage is constant. Two MOSFETs are used as switches. Use the file `PV_boost_MPPT.plecs` as a base for this section and the next one.

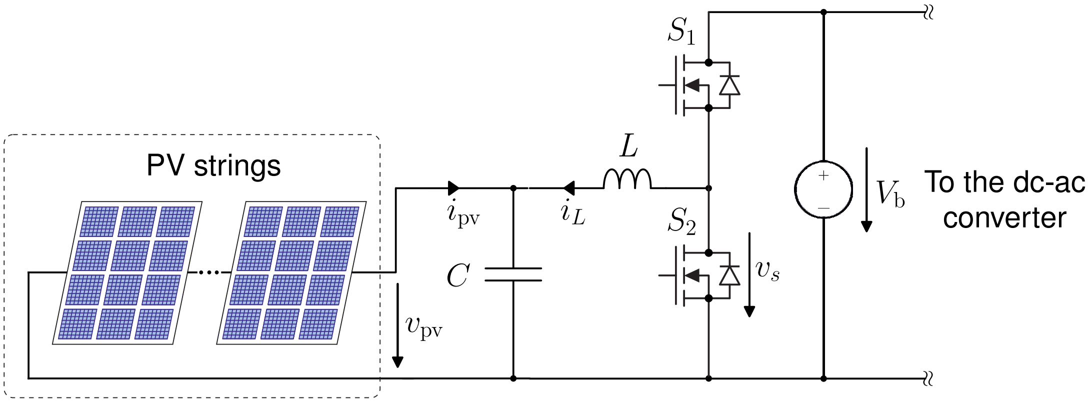


Figure 1.1: Boost converter used to interface PV strings to a dc bus.

In Section 4 you will develop an algorithm that seeks maximum power point of the PV strings. The algorithm generates a reference for the input voltage (v_{pv}), and the control loops should follow it.

1.2 Instructions

You should deliver a written report that contains the answers to the questions in this document. This is not an exam. Explain what you are doing. Add plots and/or waveforms to better illustrate your methodology or show that the results you got are consistent. For example, if the question asks to calculate the inductance based on current ripple, you could add a plot of the inductor current from the simulation.

Some questions deal with manipulation of transfer functions. You can use MATLAB control toolbox to help you calculate and check your transfer functions, plot Bode diagrams, calculate margins, etc. Functions such as `ss()`, `tf()`, `ss2tf()`, `bode()`, `margin()`, and others might come in handy. Of course, you can also use any other software you may prefer.

2 PV characterization

The Figure 2.1 shows the electrical characteristics of the PV module used in the simulation model. The first curve shows how the generated current changes with the voltage applied to the module. If a voltage close to zero is applied, the current is maximum, but since $P = VI$, the power is also close to zero. If $V = 32$ V is used (assume $T = 25°C$), the current is zero and so is the power. Thus, maximum power is extracted when a intermediate value around 26 V is used. Solar inverters employ a MPPT algorithm (Maximum Power Point Tracker) that seeks this optimum point. Note that the electrical characteristics of the module changes with irradiance and temperature, causing the optimum voltage to shift accordingly to the environmental conditions.

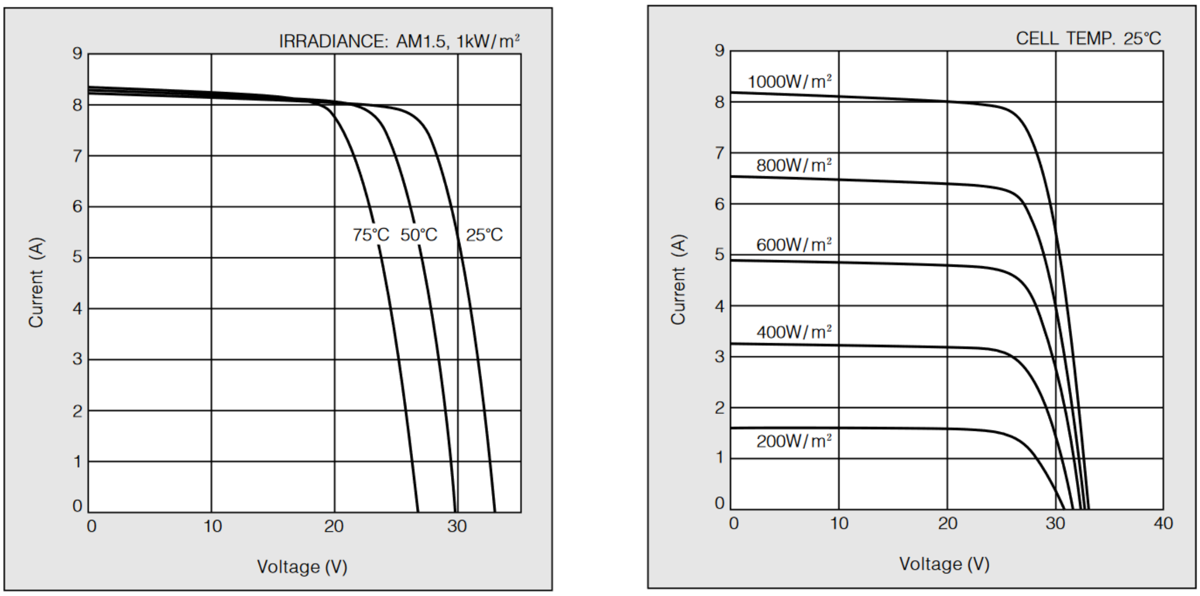


Figure 2.1: KC200GT module electrical characteristics (copied from the datasheet).

Q1. (PV characterization) Check how the maximum power and the optimum voltage changes with temperature and irradiance.

(a) In the simulation model `PV_characterization.plecs`, the voltage applied to the PV strings is swept in a triangular manner. The diode $D1$ prevents that the current flows back into the PV module. The scopes in the "PV Measurements" region record the $P \times V$ and the $I \times V$ curves. The irradiance applied to the module is normalized with respect to the nominal value. Try to understand how the characterization works. The block "Normalized irradiance" can generate a step like waveform. Configure its "Time step" and "Final output" so that the system traces two $P \times V$ curves, one for irradiance $I' = 1$ and other for $I' = 0.25$. Note that one voltage sweep cycle takes 0.5 s to complete (check the "Voltage sweep" block parameters). Configure the block "Normalized irradiance" so that $I' = 1$ during the first cycle and $I' = 0.25$ during the second. Use $T = 60°C$. Plot the curves $P \times V$ and the $I \times V$ and indicate which case is each. How do the optimum voltage and output power change with irradiance?

(b) Similarly, plot the $P \times V$ and the $I \times V$ curve for $T = 60°C$ and $T = 5°C$. Assume nominal irradiance. What are the maximum power and the optimum voltage for the different conditions?

(c) What would be the loss of power (percentage, with respect to the maximum possible) if we keep the optimum voltage for the operation $I' = 1$ also for operation with $I' = 0.2$?

3 Boost converter

Q2. **(Filter and modulation)** Design an appropriate filter for the dc-dc converter and finish the modulator in the simulation model. The maximum normalized irradiance is 1, and the minimum cell temperature is 25°C. Follow the questions and aim for efficiency.

(a) Choose an appropriate dc bus voltage. Leave a margin of at least 10% above the minimum possible voltage, and 25% below the rated voltage of the semiconductors (1200 V). Switching losses in the MOSFETs are higher for higher voltages.

(b) Build the PWM modulator. D should be duty cycle of s_1, and the switching frequency 70 kHz.

(c) Specify a relative current ripple (with respect to average current) and calculate the necessary inductance for the worst case condition (maximum power point).

(d) The inductor L has an equivalent series resistance R_L that dissipates 0.1% of the input power when the system operates at the maximum power point ($I' = 1$, 25°C). Please calculate it and adjust your simulation model accordingly.

(e) The fictitious standard your converter has to comply with states that the maximum amplitude of the input voltage components above 150 kHz should be smaller than 5 mV. Calculate the necessary input capacitance for the worst case. The PV strings can be modelled as current sources.

(f) The block "Vs_ref to D" is used when the system operates in open loop. v_s is the average value of the switched voltage (voltage across S_2). You need a block to calculate the duty cycle from the v_s reference. Although in the real application a capacitor is used instead of the voltage source V_b (meaning that the voltage may vary), you can design your block assuming a constant dc bus voltage equal to the nominal value.

(g) The system is operating in open-loop. Check the response of the system for a step-like variation in the v_s reference. What is the overshoot in v_pv (in percentage) when the reference changes from 400 V to 410 V?. What is the settling time (when the error is less than 2%)? Both are calculated with respect to the amplitude of the step.

Q3. **(Controller design)** The control system of the boost converter is shown in Figure 3.1. There are two control loops, connected in a cascaded manner. The outer loop (around $C_v(s)$) controls the capacitor voltage by generating a reference for the inductor current, which, in turn, is controlled by $C_i(s)$. The matrices $\mathbf{A}$ and $\mathbf{B}$ represent the dynamics of the boost converter. The states and the inputs are respectively represented by

$$\mathbf{x} = \begin{bmatrix} i_L \\ v_\mathrm{pv} \end{bmatrix}, \quad \mathbf{u} = \begin{bmatrix} \tilde{d} \\ \tilde{v}_\mathrm{b} \end{bmatrix}. \tag{3.1}$$

Where $\tilde{d}$ is a small variation in the duty cycle, and $\tilde{v}_\mathrm{b}$ is a small variation in the dc bus voltage. There is another input in the system: the current from the PV strings. But since it varies slowly, it has been neglected in the model. The disturbance in the dc bus voltage has been included because in the real application it is likely that some low frequency ripple (100 Hz) will be present in the dc bus voltage, and its effects should be analysed. The main goal of the control system is to force the input voltage of the boost converter to follow the reference v_pv^*. A single loop structure could also have been used, but the controller would be more complex. Besides, directly controlling the current, as in the cascaded structure, has the advantage of easily limiting it by limiting its reference. The block "Vs_ref to D" is not used in closed loop operation.

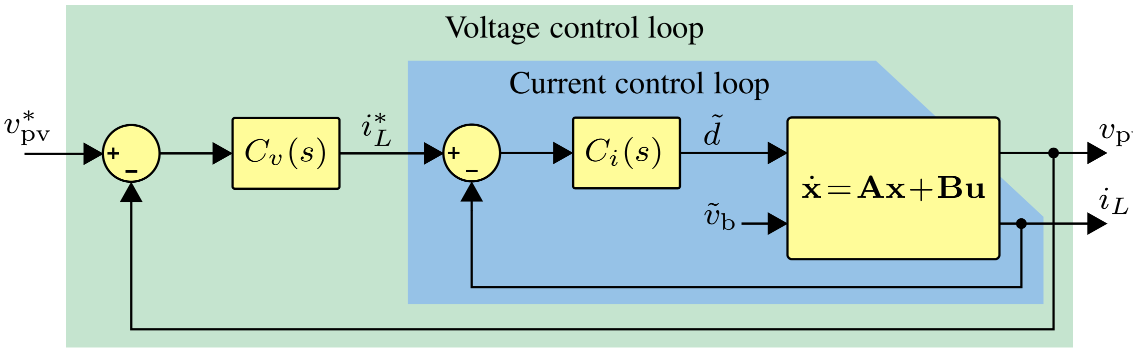


Figure 3.1: Control system of the boost converter.

(a) If you assume that the dc bus voltage is an input, the system is non-linear. Find the non-linear model, linearize it, and calculate the matrices $\mathbf{A}$ and $\mathbf{B}$.

(b) Find the four transfer functions that can be derived from the state space model,

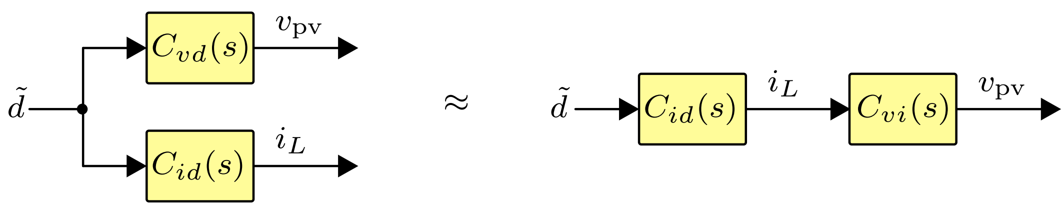
$$G_{vd}(s) = \frac{v_{\mathrm{pv}}(s)}{\tilde{d}(s)},\ G_{id}(s) = \frac{i_L(s)}{\tilde{d}(s)},\ G_{v\mathrm{b}}(s) = \frac{v_{\mathrm{pv}}(s)}{\tilde{v}_{\mathrm{b}}(s)},\ G_{i\mathrm{b}}(s) = \frac{i_L(s)}{\tilde{v}_{\mathrm{b}}(s)}, \tag{3.2}$$

and redraw the control loop from Figure 3.1 using the transfer functions instead of the state space model.

(c) Which transfer function should you use to design your current controller? Compare its frequency response with the simplified transfer function $V_{\mathrm{dc}}/(sL + R_L)$. For which range of crossing frequencies should the simplified transfer function result in a very similar controller when compared to the full transfer function? Why does the simplified transfer function work in this range? Explain from the point of view of circuit analysis.

(d) Design two PI controllers that result in a phase margin of 50° and crossing frequencies of 1/5 and 1/10 of the switching frequency. Check your designs by applying a step in the reference signal with appropriate values. You can substitute the capacitor with a voltage source of appropriate value. What are differences in the modulating signal when you compare the two designs? Why?

(e) Slightly redrawing the control loop allows some simplification when designing the voltage controller. Redraw the control loop diagram taking the following equivalence into consideration.



Where $G_{vi}(s) = v_{\mathrm{pv}}(s)/i_L(s)$. You can neglect the disturbance $\tilde{v}_{\mathrm{b}}$ in this step. What is the transfer function $G_{vi}(s)$? You can find it from the previous transfer functions or by just inspecting the circuit.

(f) A simplified way of designing the voltage controller is neglecting the dynamics of the whole current control loop, meaning that $i_L = i_L^*$. This is possible when the response of the inner loop is much faster than the outer loop. Draw the simplified control loop from the previous one. Design the controller $C_v(s)$ for a phase margin of 60° and crossing frequencies of 1/10 and 1/4 of the crossing frequency of the current control loop. Show the responses of the two designs for step like variation in the voltage reference of 10 V around the maximum power point. Assume the use of the slower current controller.

(g) (**Bonus**) Redesign the voltage controller for the same specifications now taking into account the dynamics of the current control loop. What transfer function should you use to design the controller? Compare the responses of the faster and slower designs with the responses obtained in the previous part.

(h) (**Bonus**) A short circuit happens in the connection between the PV strings and the input of the boost converter when the system is operating at maximum power. The short ciruit has a duration of 100 ms and has a resistance of 0.05 Ω. What happens to the inductor current during the short circuit? How could this be prevented?

(i) (**Bonus**) Find the transfer function that relates small variations in the dc bus voltage to the input voltage. Plot the Bode diagram. Assume the use of the slower voltage controller. What the expected gain for a frequency of 100 Hz?

(j) (**Bonus**) Change you simulation model so that the dc bus voltage contains a 100 Hz, 10 V amplitude sinusoid on top of the dc value. Check if the ripple at the input matches the theoretical value. You can use the FFT tool to measure the amplitude more easily.

(k) (**Bonus**) How can you compensate the duty cycle signal calculated by the current controller to improve the rejection of the disturbance in the dc bus voltage? Test again the response of the system.

4 Maximum Power Point Tracker

Q4. **(MPPT)** MPPT stands for Maximum Power Point Tracker. The MPPT should generate the reference for the input voltage of the boost converter v_{pv} and seeks the optimum voltage that results in maximum power being extracted. One common algorithm is the so called "Perturb and Observe". The main idea behind the algorithm is changing the input voltage by a small value and checking whether the power has increased or decreased. If it has increased, keep changing the voltage in the same direction. If not, try the other direction.

(a) Based on the idea explained above, draw the flowchart of the "Perturb and Observe" algorithm. Assume you have access to the voltage and current at the input of the boost converter.

(b) Code a MPPT based on the "Perturb and Observe" technique. You can insert your code on the the tab Code → Output function code (inside the C-Script block). Use the C language.

(c) Based on the time response of the voltage control loop, what should be one appropriate sample time for the MPPT algorithm? You can change it in the panel Setup of the C-Script block. How does it impact the response of the whole system?

(d) Try different values for the input voltage increment/decrement. How does the response of the system during transients and steady-state changes?

(e) Apply different steps of irradiation and check the response of the system.