University of Nottingham
UK | CHINA | MALAYSIA Department of Electrical and Electronic Engineering

# Power Electronic Application and Control – Coursework Description

## "Design and simulation of a grid connected single-phase full-bridge inverter"

### Introduction:

This document describes the coursework you will have to complete as part of the module "Power Electronic Application and Control". Let's start summarising some important points – please read them carefully:

- The coursework is an individual exercise where you will have to design and simulate power electronics and control of a single phase grid connected inverter.
- The application is also covered in the lectures. You will be expected to use the lectures as guidance to progress with your coursework. On the other hand, the coursework will be very important to strengthen the understanding of the taught topic – don't think about the coursework as something disconnected from the lectures!
- Learning how to design and simulate a state-of-art converter is an essential skill for a future power electronic engineer, as they are the standard steps before construction of a laboratory prototype.
- We will use Matlab for the control design part and Plecs for the power electronics and for the simulation of the full system.
- The coursework is worth 25% of the module, or equivalently 5 credits. This means that you are expected to spend 25 hours on the coursework.
- Assessment will be based on a written report, submitted electronically on Moodle. The most important learning outcome of the coursework will be the application of the correct design and validation methodology. You are not expected to write a long essay but rather to be as clear as possible about how you designed the system and about how you validated your design. Any additional critical comment/discussion of the results is obviously welcome!
    - The way you have to think about the report is as a technical document you might be asked to submit to the management of the company you work for, and that would be used to decide whether to put the converter into production or not – and if something goes wrong, for example because you designed it wrong or because you didn't explain it clearly, somebody might come and knock at your door ☺

## System under study:

The power conversion system you have to design and simulate is a grid-connected single-phase full-bridge converter, typically used to interface photovoltaic and/or energy storage systems with the AC grid or to power DC loads.

Referring to photovoltaic/energy storage we can represent the system as:

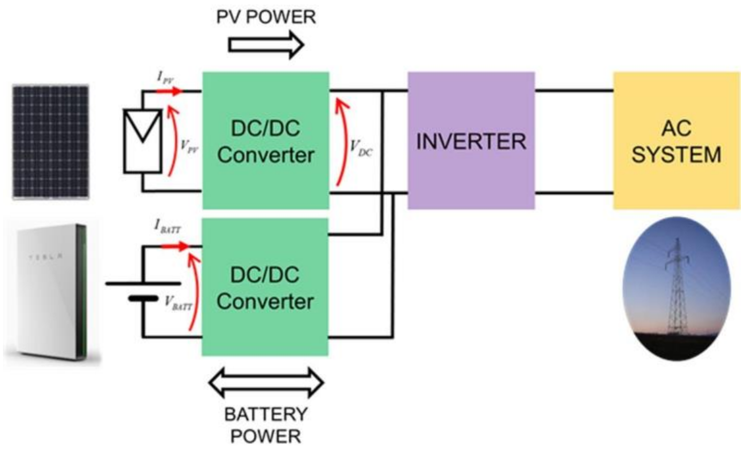


Figure 1: Photovoltaic and energy storage system

The system looks pretty complex – and it actually is complex if we want to design and build everything we see in the figure. However, our focus will be only on the inverter part, and we will use simplified circuits to represent the DC side. In particular, the design of the converter and of its control will be split in 2 parts:

### Part 1: Inverter with constant DC source and AC current control

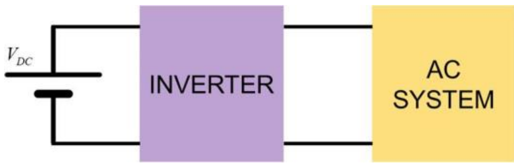


Figure 2: Simplified circuit for AC current control

### Part 2: Inverter with DC link capacitor, DC voltage control and AC current control

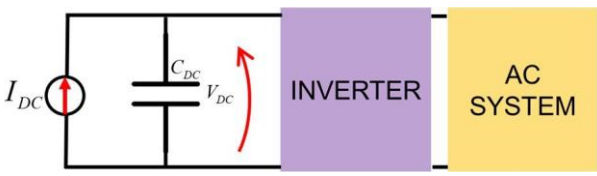


Figure 3: Simplified system for DC voltage control

**System Specifications:**

- DC voltage $V_{DC}$=600V
- DC voltage ripple peak to peak ΔV=1V
- AC RMS voltage $V_{AC}$=240V
- AC current ripple peak to peak ΔI=0.5A
- Rated power P=2.4kW
- Inverter switching frequency $f_{SW}$=10kHz
- Loss in the inductor at rated power: $P_{LOSS}$=0.5%P

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## Project deliverables:

**Note: the tasks are not necessarily sequential**

### Part 1: Inverter with constant DC source and AC current control

1. Design the inductor L required in order to connect the converter with the grid respecting the maximum ripple $\Delta I$ and calculate the resistor R that models the inductor loss

2. Calculate the inverter voltage needed to inject the rated power into the grid (rated active power and zero reactive power)

3. Build an average time Plecs model of the system, representing the inverter as a controllable voltage source. Demonstrate that the calculations done in 2 are correct, showing the average power exchanged with the AC grid

4. Build a switching Plecs model of the system, including the PWM modulator and the full-bridge converter. Feed the PWM modulator with the voltage demand calculated in 2 and demonstrate that the correct average power is exchanged with the AC grid. This should match with the one from 2 and 3

   Hint: Make sure the full-bridge is built as the combination of two half-bridges with independent PWM modulators, as discussed during the lectures. Also, leave the average time model built in 3 in the same file as the one in 4, so that you can check if they match

5. In 4, show that the average over a switching period of the voltage generated by the full-bridge matches the voltage demand provided to the PWM modulator. In addition, show the Fourier spectrum of the generated voltage and discuss it

6. From the same switching simulation, demonstrate that the design of L is correct, showing that the current ripple is always below the maximum value

7. Calculate the transfer function of the plant represented by the converter. The input is the voltage demand to the PWM and the output is the grid current. Implement the equivalent block diagram in Plecs, and compare the result with the simulation in 3. Show the current control block diagram.

8. Design, using Matlab "sisotool", the current control based on a continuous implementation in the s-domain with the following specifications: Damping factor $\zeta$=0.7, Natural Frequency $f_o$=500Hz ($\omega_o$=2*π*500 rad/s)

9. Implement the controller in the average time Plecs model first, and then in the switching Plecs model. For both models, provide an AC current reference that enables the exchange of a desired active power and zero reactive power. Show that the close loop control can follow the current reference in steady state, commenting

on any discrepancies you find. In addition, show the response of the system to the following transients: case A) power step from 0 to P/2 and from P/2 to P and case B) power step from 0 to –P/2 and from -P/2 to –P and discuss how it relates with the expected closed loop performances.

Hint: make sure you design a simple block the receives the desired AC power reference and generates the required AC current reference

10. Repeat 8 and 9 using a digital implementation in the z-domain with the following specifications: Damping Factor $\zeta$=0.7, Natural Frequency $f_o$=500Hz ($\omega_o$=2*π*500 rad/s), Sampling Rate fs= $f_{SW}$ ($\omega_S$=2*π*$f_{SW}$ rad/s).

## Part 2: Inverter with DC link capacitor, DC voltage control and AC current control

1. Design the DC link capacitor in order to achieve the desired voltage ripple at rated power P

2. Calculate the transfer function of the plant represented by the converter. The input is AC power reference and the output is the square of the DC voltage. Show the voltage control diagram and the overall voltage plus current control diagram.

3. Design, using Matlab "sisotool", the DC voltage control based on a continuous implementation in the s-domain with the following specifications: Damping factor $\zeta$=0.7, Natural Frequency $f_o$=5Hz ($\omega_o$=2*π*5 rad/s). Discretise the controller for a z-domain implementation, assuming sampling rate fs= $f_{SW}$ ($\omega_S$=2*π*$f_{SW}$ rad/s).

4. Keeping everything you have done in the simulation model for Part 1.10, replace the DC source with the calculated capacitor with a controllable current source in parallel, representing the current coming from the photovoltaic / energy storage system. Set the value of the DC current to zero and implement the DC voltage controller in the discrete time domain. Make sure you set the initial value of the capacitor voltage to the peak grid voltage. Also, add a saturation block at the output of the controller, which limits the power demand in the range ±1.5P. Saturate also the integral part of the controller (very important!). Run the simulation and verify that the DC voltage reaches steady state at the desired value.

5. Run again the simulation in 4 but during the simulation increase the DC current from 0 to half the rated current first and then from half the rated current to the full rated current. Show the transient response of the DC voltage and compare it with the transient you expected from control design.

6. When operating at full DC current, the system is injecting rated power in the AC grid. Demonstrate that in these conditions the DC voltage ripple respects the system specifications.

## Marking scheme:

Each of the deliverables will be marked out of 10, according to the rubric in Table I below. Marks for each deliverable will then be multiplied by the weight of the task (proportional to the complexity of the task itself) shown in Table II and everything will be added together. The weights of the different parts have been designed so that if you get 10 marks in all the tasks you will get 100/100 marks for the coursework.

Make sure you understand the marking scheme, if not please come and talk to us.

Remember that showing a result (hopefully correct!) is only part of the work. Explaining it clearly and convincing the reader that the result proves what you wanted to prove is as important as the result itself. Remember the initial comment about the objective of this work: you will be successful if you convince the reader that your design is good and ready for construction with minimum technical risk.

Table I Marking rubric for each deliverable

| Mark awarded | Description |
|---|---|
| 10/10 | The task has been completed to an outstanding standard. Results are correct and there is clear demonstration that the design achieves the expected performance. Graphs are clear and compare actual performances with the expected ones. Critical comments are provided. All the information needed for repeatability of the results is included. |
| 9/10 | The task has been completed to an excellent standard. Results are correct and there is clear demonstration that the design achieves the expected performance. Graphs are clear and compare actual performances with the expected ones. Critical comments are provided. |
| 8/10 | The task has been completed to a very good standard. Results are correct and there is clear demonstration that the design achieves the expected performance. Results are shown with clear graphs that compare actual performances with the expected ones. Critical comments are provided. Some minor flaws can be present in the way results are shown and/or discussed. |
| 7/10 | The task has been completed to a good standard. This includes mostly correct results and demonstration that the design achieves the expected performance. Results are shown with mostly clear graphs that compare actual performances with the expected ones. An attempt to comment results is made but discussion is not always clear and/or too long and/or not completely correct. Some minor technical and/or presentation flaws are present. |
| 6/10 | The task has been completed to a satisfactory standard. Some of the results are correct and attempts are made to demonstrate that the expected performances are achieved. Results and graphs are presented in a sufficiently clear way. Some discussion is included but limited to basic observations. Some technical and/or presentation flaws are present but they do not affect the overall design. |
| 5/10 | The task has been completed to a sufficient standard. There is evidence of application of the correct methodology but the results are not fully consistent and/or not clearly presented. Some technical flaws are present but overall the design is functional, even though not fully meeting the expected performances. Clarity of the results and graphs is acceptable. An attempt to discuss the design is made. |
| 4/10 | Some major flaws are evident in the design, which is mostly not functional and/or is presented in a way that does not enable to understand if the design specifications have been met. Low confidence about the practical feasibility of the design. Marginal attempts to discuss results. |
| 3/10 | |
| 2/10 | None to very little evidence of work, without clear results |
| 1/10 | |
| 0/10 | |

Table II Weight of the deliverables

| Deliverable | Weight |
|---|---|
| **Part 1.1** | **2.5%** |
| **Part 1.2** | **2.5%** |
| **Part 1.3** | **5%** |
| **Part 1.4** | **15%** |
| **Part 1.5** | **5%** |
| **Part 1.6** | **2.5%** |
| **Part 1.7** | **5%** |
| **Part 1.8** | **10%** |
| **Part 1.9** | **15%** |
| **Part 1.10** | **5%** |
| **Part 2.1** | **2.5%** |
| **Part 2.2** | **2.5%** |
| **Part 2.3** | **5%** |
| **Part 2.4** | **15%** |
| **Part 2.5** | **5%** |
| **Part 2.6** | **2.5%** |
| TOTAL | **100%** |