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Dc Grid Power Congestion Management Laboratory Experiments

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In the process of the electrical energy transition, a new curriculum for bachelor electrical engineering is developed. A new development is DC grids, as they are shown to be promising in solving the power congestion management problem. Particularly when adding solar power, battery storage, and load appliances including power electronics, DC grids are replacing AC grids, especially in micro-grids.

The development of new laboratory experiments using three educational methods is described in this paper. First, theory combined with online calculation tools is used to prepare the students for the subject. Second, the experiment has to be prepared using simulation tools, and third, the experiment is conducted using a hardware trainer, specially developed for DC grid education.

The purpose of laboratory experiments is to learn how power congestion management is regulated in a DC grid. For this, students have access to a Grid Manager, with a current control add-on. This so-called Droop Controller enables the control of a bidirectional current flow.

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There are four learning objectives. 1-Control voltage level, 2-Control current level, 3-Regulate output power from a Grid Manager, 4-Regulate bidirectional power flow using emulated appliances. These learning objectives are spread over four weeks.

Students will first learn the basics of the grid manager. They will learn how to control the voltage in a DC grid in week 1. In the second lecture, they will use a current controller and notice a difference in controlling the output power while maintaining a stable output voltage. In Lectures 3 and 4, the grid manager and droop control with bidirectional power flow is explored.

The outline of the lectures and experiments is presented in this paper as well as the minimum requirements that students must meet.

1 INTRODUCTION

Since DC power [1] is independent of frequency and phase, it can therefore be utilized easily for a single reason. There is no need for complicated AC synchronizing techniques to make full use of renewable energy sources. Another reason is that most appliances are already DC-powered. Since power congestion management is easier to implement in a DC grid [2, 3], it can be favored over AC grids. For controlling the power flow in a DC grid [4], new techniques such as droop control [5], are being developed. Power consumption can be made dependent on the variation of the voltage in the main power grid. This dynamically assists in keeping the power grid in good health and prevents critical applications from failing. The application of droop control in DC grids is discussed in [6, 7, 8]. An experimental setup was created [9, 10], for doing experimental work in low voltage DC grids [11]. It includes power electronics educational training laboratory exercises [12, 13]. A DC grid manager with training software [14] is presented in [15].

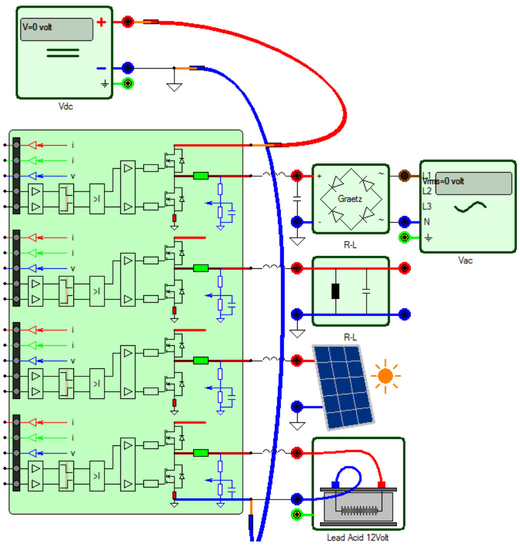

Fig. 1. Grid Manager Hardware

In section 2, an introduction in the methods and tools is given, which is used to achieve the four learning objectives. The four learning objectives are explored in section 3, 4, 5 and 6. An optional assignment on power congestion management in DC grids, is discussed in section 7. The results and minimum requirements are discussed in section 8.

2 OBJECTIVES

The aim of the laboratory experiments is to learn how power congestion management is regulated in a DC grid. For this, the students have access to a Grid Manager, see figure 1, with current control add-on. This so-called Droop Controller enables the control of a bidirectional current flow.

There are four learning objectives.

1. Control voltage level
2. Control current level
3. Regulate output power from a Grid Manager
4. Regulate bidirectional power flow using emulated appliances

The basics of the grid manager, see figure 1 is the first subject, the students encounter. First voltage control in a DC grid is explored in the first week. In the next week, current control is applied and the students should observe the difference in controlling the output power, compared to voltage control.

Using simulation and tooling, see figure 2, the basics of using switched mode power supplies in the DC grid is explained. Using the tool, the basics of the wave forms that will be measured are explained.

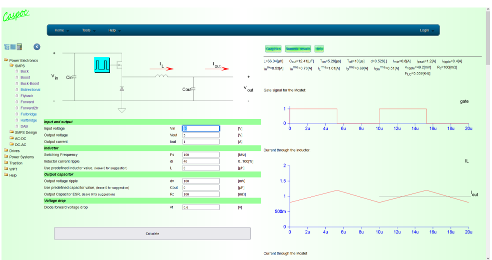

Fig. 2. Tool [14] to study the basics wave forms of switched mode power supplies.

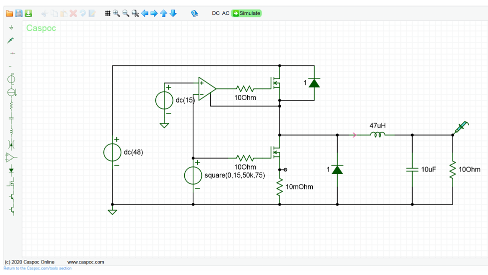

Fig. 3. Online simulation [14] of the synchronous Buck converter..

To understand the operation of the semiconductors inside the switched mode power supply, the students have to study the internal working of the applied synchronous buck converter. For this the online simulation is used, see figure 3, as it give insight into the influence of the switching frequency, duty cycle and blanking time in the applied gate controlling signals.

To prepare the students for the experiment, the laboratory set up is simulated as a digital twin, see figure 4. All connections and external devices that are connected to the Universal Four Leg [2, 3] are available in the simulation [14]. Students can practice the connections they have to make in the experiment.

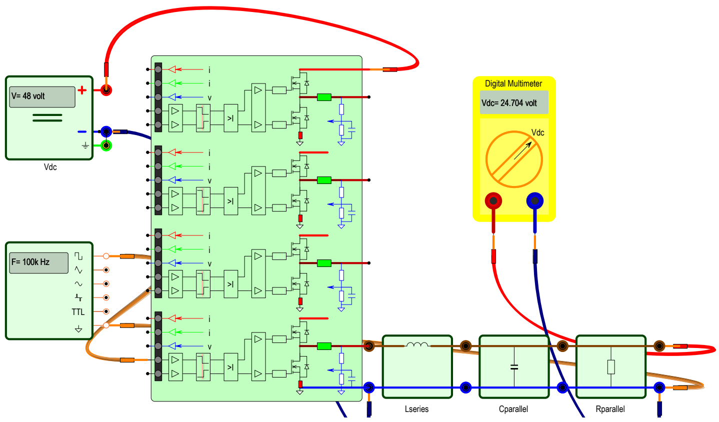

Fig. 4. Simulation of the Universal Four Leg configured as a synchronous Buck.

Students have to measure the relation between the duty cycle and the averaged output voltage. Adding inductance at the output reduces the output voltage ripple. Adding a capacitor at the output, reduced the output ripple even further.

In the first lecture, the students will learn about the basics of the DC grid. Using an online simulation tool, they will learn how power electronics is used. A basic switched-mode power supply is studied using simulation. The differences between the most basic configuration of a buck converter compared to the synchronous buck converters, are explained using the software.

In the next lecture, current control is added and students will see the improvement over voltage control. After practicing voltage and current control, in week three, the students are given the typical example of a Grid Manager. The DC Grid voltage is used to control the amount of power that is regulated into each load of the grid manager. During this laboratory, the student will practice voltage, current and power measurements. The principle of droop control is introduced this week. The parameters of the droop characteristics are programmed, and by varying the DC grid voltage, the loads are regulated according to the programmed droop characteristics.

The last laboratory emulates four appliances connected to the DC grid. Each appliance has a typical droop characteristic programmed and all appliances are connected to the same DC grid. The Universal Four Leg emulates four appliances. Since the appliances are either consumer or producer, the Universal Four Leg is operated in bidirectional current control mode.

3 WEEK 1: INTRODUCTION HARDWARE, VOLTAGE CONTROL

In this laboratory, the students are going to explore the functioning of the DC grid. A very basic first introduction in power electronics switched mode power supplies is given using simulation. Using the simulation, see figure 5, the basics of controlling voltage in a DC grid is explored.

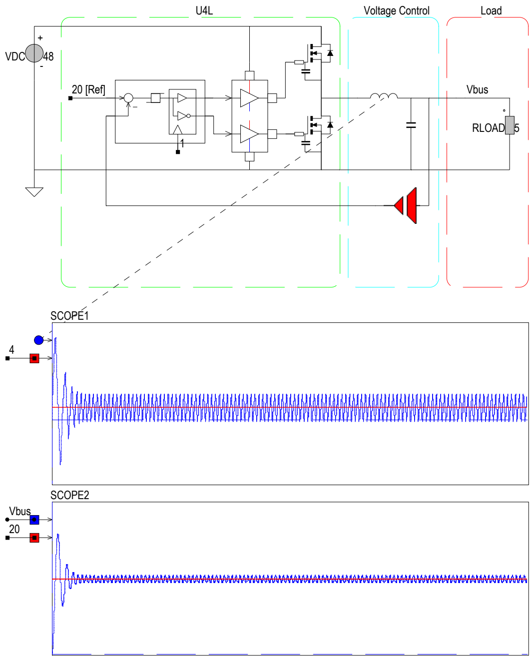

Fig. 5. Voltage control.

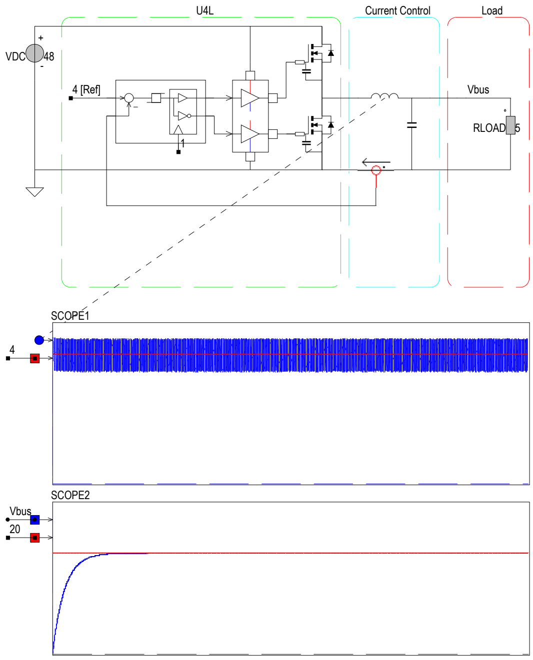

Fig. 6. Current control.

4 WEEK 2: INTRODUCTION HARDWARE, CURRENT CONTROL

In the second laboratory, the students have to practice the use of current control to regulate the flow of power, see figure 6. Again using online tooling and inline simulation and finally the simulation using the digital twin prepares the students for the experiments.

5 WEEK 3: GRID MANAGER DROOP CONTROLLED OUTPUTS

The previous two laboratories were mainly teaching students the basics of the applied hardware. In this laboratory the students will meet the first use of the Universal Four Leg as a Grid Manager, see figure 7. The input DC Grid voltage to the Grid Manager can be varied using the power supply bench. The droop characteristics are programmed inside the universal four leg. There are four passive loads, that will be powered from the grid manager according to the droop characteristics.

The main part of the laboratory experiment will be programming the droop characteristics and confirming them by measurements.

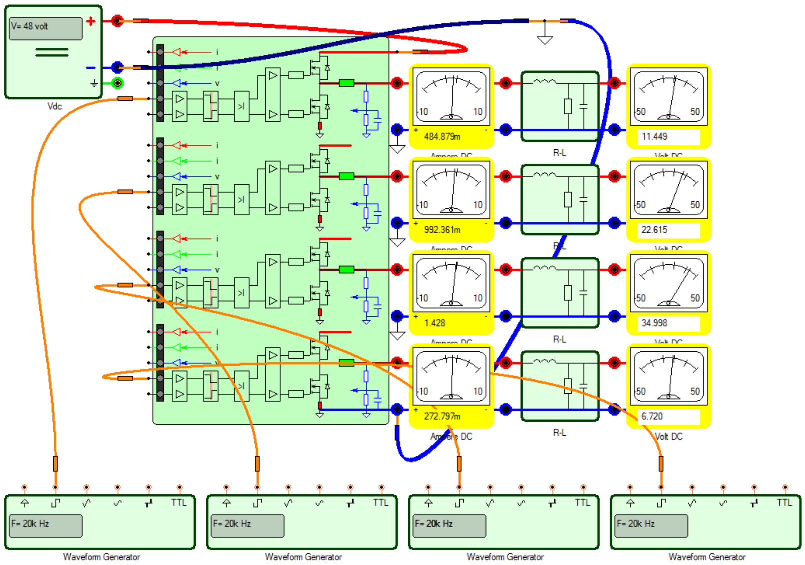

Fig. 7. Universal-Four-Leg configured as Grid Manager

6 WEEK 4: EMULATING DROOP CONTROLLED APPLIANCES

All the ingredients for power congestion management in a DC Grid, are explored in the previous laboratories. In this laboratory, the students have to create a DC Grid with four emulated appliances, see figure 8. This configuration enables bidirectional power flow which allows students to see the behavior of a dynamic system. The Universal Four Leg is used to emulate the four different appliances:

Battery (Storage)	Solar (Producer)
Load (Consumer)	External Grid (Power Exchange)

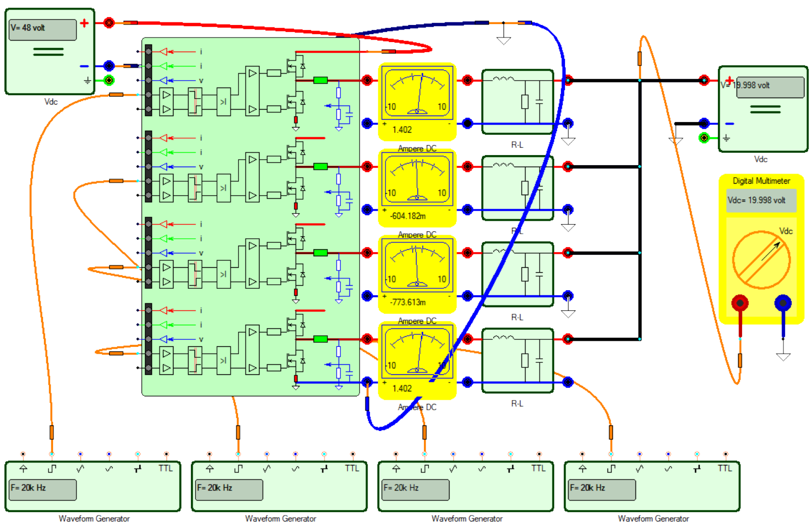

Fig. 8. Universal-Four-Leg configured as appliance emulator

7 OPTIONAL ASSIGNMENTS: POWER CONGESTION MANAGEMENT

With the U4L per group, and a long main cable through the lab, we can connect a number of students with their U4L with droop control. They can send the power control signal either manually or via the Arduino.

The assignments include different subjects, like manually adjust a set point, and then view the power balance between the various connected groups. The different groups are then subdivided into solar panel, battery and consumer, each with its own function.

In the first assignments, the students adjust the droop controller manually. In the following assignments, the students program the droop characteristic, see Figure 9, into the Arduino. In this assignment, the maximum source current is 5 ampere and the nominal DC grid voltage equals 20 volts. Using the programmed droop characteristic, the power congestion management should correct automatically.

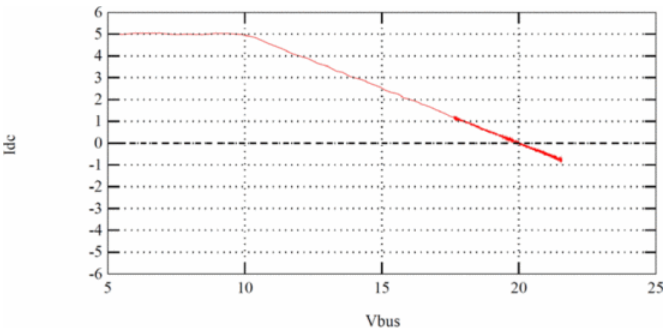

Fig. 9. Droop control characteristic.

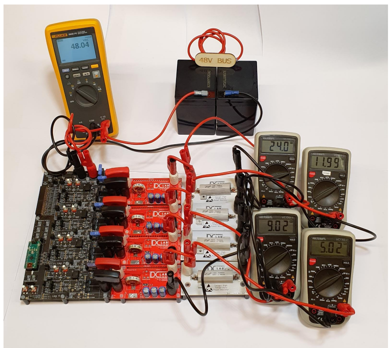

Fig. 10. Gridmanager.

By setting the voltage on the main cable with an external power supply (performed by the laboratory supervisor), different scenarios can be tested.

Using this approach, the laboratory exercises vary from simple entry-level assignments to more advanced assignments. There is also room for going into detail for the advanced students, by explaining the functioning and operating principle of the used power converters.

The experimental setup is working at a low voltage, so everything is safe and the students can measure everything using a probe and safely touch all terminals.

Students can adjust the set points themselves, and immediately measure the response of such a setting. Using a multimeter and because of the low voltage, students can immediately safely measure voltage and current. The 10 red and 10 green LEDs (VU-meter) immediately display the influence of the setting, as these LEDs indicate the size and direction of the current. Figure 10 shows the Universal Four Leg as gridmanager and configured as a droop controller.

8 RESULTS AND REQUIREMENTS

For each objective, theory, simulation and experimental results have to meet the minimum requirements. For this, the students have to complete questionnaires on several subjects within each objective. For the questionnaire on the theoretical part in lecture 1, it is required to calculate a set of parameters, to be applied in the following lectures, in the simulation of the digital twin and the experimental setup. These parameters are checked by the lab instructor, and only after approval can the student continue with the simulation of the digital twin.

The simulation results have to be reported as wave-forms in a graphical plot. After a visual check by the lab instructor, the student is allowed to perform the laboratory experiment. The constant numerical results, like output voltage or load current, have to be presented in a table in the report. The wave-forms as measured on the oscilloscope in the experimental setup, have to be included in the report as screenshots.

The results from the simulation of the digital twin and the results from the experimental set-up, should be comparable within a certain region. A deviation of up to 5 to 10% is allowable, and the experimental results will show much more high-frequency effects. If the results are comparable, the student will get a mark that they finished that typical objective. The student needs to finish each objective, before continuing to the next objective. These short moments of checking values achieve more students to understand every step in the process and help students not to continue with wrong values. This allows students not to deviate too far from realistic numbers and help them to get a better feeling for the subject. This translates to overall better grades for their exams in these topics and a higher success rate in finishing the lab courses.

9 CONCLUSION

To teach the subject of power congestion management in DC grids, requires a specific approach. Learning by doing is the first that comes into mind, but hands-on practical training is required to give the students the look and feel of the real appliances. The fact that the students are using real appliances, gives them the confidence that the approach contributes to an understanding of the subject in detail.

To get to this understanding, the students first have to pass the theoretical part, and via simulation studies, they are prepared for the real experimental set-up. The fact that a digital twin is used in the simulation, gives them better insight on what is possible with the real experimental set-up.

Using three methods, theoretical evaluation using calculation tools, simulation of the digital twin and finally the experimental set-up, the students are working on four learning objectives. These learning objectives are to be carried out in the proposed order.

An optional assignment combines the learning objectives from the third and fourth week. For this students have to work in groups and connect their laboratory setups.

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