Laboratory setup for teaching DC grid droop control and protection

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***Abstract*—Low voltage DC grids are gaining attention to replace traditional AC grids in home and office. Especially protection and power congestion management is better utilized in a DC grid. The paper discusses the requirements on a hardware laboratory setup, to teach the basic principles as well the applications of DC grids for home and office applications. Using a laboratory setup, a DC grid can be constructed, where the student can learn the basic topology of the power electronics and also the functioning of the control of the power electronics. Improved protection based on rate of change of current is implemented and can be tested as well as inrush current protection of connected external loads. Secondly the student can build a DC grid where he can implement various types of droop control strategies. The learning objectives range from in depth understanding of the power electronic circuit to the design and implementation of various strategies for power congestion management. The laboratory exercises are accompanied with extensive online simulation exercises where all aspects of the power electronics, the protection and the droop control are to be prepared by the student.**

***Index Terms*—dc grid, power electronics, droop control, laboratory setup, simulation**

I. INTRODUCTION

THe Energy Transition is taking place worldwide and is affecting our daily life. Especially the migration from fossil fuels towards renewable energy is an area where electric energy comes into view. We already see the change from combustion engines to electric vehicles in mobility and in Europe, the migration from natural gas towards the use of electricity for heating and cooking is taken into consideration [2]. The energy consumption is increasing yearly and therefore also the electric energy consumption will rise every year. Given the migration from natural gas to be replaced by electricity, there is no doubt that the existing infrastructure for electric energy is by no means large enough to support this increase of energy demand. Blackouts and failures in the electricity grid are seen more often and can have an enormous effect on society and cause economic losses. Although the grid is permanently guarded and measures are taken to prevent failure, still there is a risk on potential disruptive impacts. As the existing AC grids are designed as a top-down distribution structure, where a large power plant is providing the energy to be consumed at large distances from the power plant. However, with the rise of distributed solar power and small wind generators, the energy produced is in the same vicinity as where energy is consumed. This locally produced energy is fed into an existing grid that is top-down controlled. In case of failure, also the local produced solar energy cannot be used. DC grids are considered as a replacement for AC grids to overcome the disadvantages that traditional AC grids have. Most importantly are power congestion and failure. AC grids have a top-down distribution structure. DC grids can have decentralized structure, where production and consumption are local. This means that during failure, the decentralized DC grids can continue. Power congestion is now managed through the application of DCDC power converters. Compared to traditional transformers in AC grids, the DCDC converters are able to control the power flow in a DC grid and can exchange power between connected decentralized DC grids. Since there is no leading ac frequency, island mode of operation is possible, where each producer is allowed to keep the DC grid alive.

Since DC grids are relatively new, also the educational applications need to be developed. Both Simulation [4], [9] and experiments [3] are important and simulation is usually used to prepared the students before conducting experiments. In this paper a laboratory setup is presented that can be used to teach the aspects of DC grids. Typical topics that are covered include control and protection in a DC grid. Since power electronic DCDC converters [3] play an important role in the DC grid, the laboratory exercises are build around methods for power flow control and protection.

Since control and protection in a DC grid is done by the power electronics DCDC converters, the laboratory setup should be able to reassemble the DC grid as close as possible. Instead of having a scaled down version of a DC grid, a more realistic approach is to do the experiments on a low voltage DC grid. The Safety Extra-Low Voltage [SELV] DC grid having a nominal voltage of 48 volts is suitable, as it is an accepted voltage level for home and office DC grids as well as in mobility. The application of SELV voltage levels of 48 volt makes the laboratory setup directly applicable for real experiments without the need for scaling down. In order to

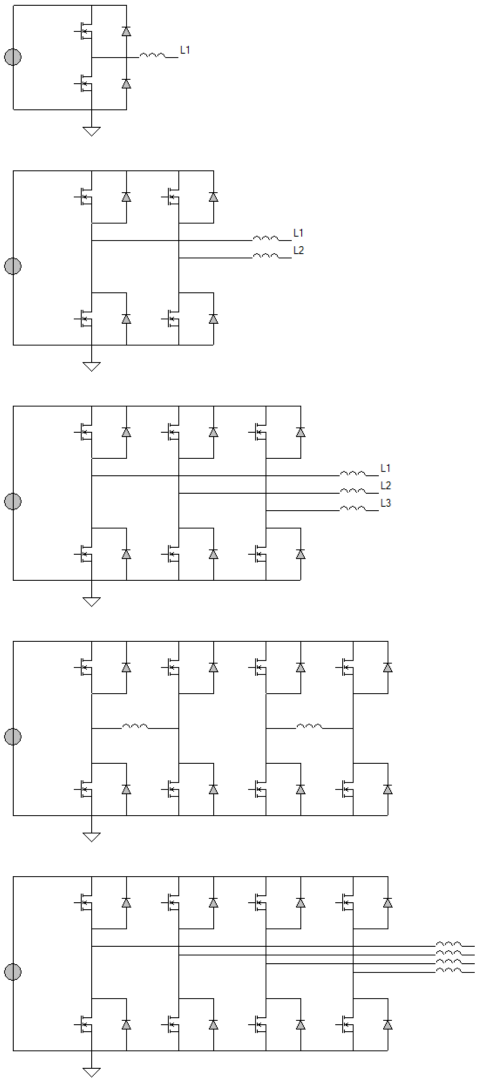

Fig. 1. Basic configurations of parallel inverter legs. From top to bottom: Synchronous buck converter, Single phase full bridge for dc motor control [5] and single phase AC grid connection, Three phase full bridge for AC motor control and AC three phase grid connection, Dual full bridge setup for Dual Active Bridge [DAB] converters and wireless power transfer [WPT] experiments, Grid manager setup with four outputs.

make the experimental setup as general as possible, the setup is organized as a conventional power electronics converter that includes both synchronous bipolar DCDC converters as well as bridge configurations for motor control, maximum power point [MPP] tracking for solar panels and charge control for batteries. The new teaching DCDC converter setup is designed around half bridge inverter legs that can also be configured as synchronous buck converters [1]. The configuration is shown in figure 1. Depending on the number of outputs required, multiple so-called inverter legs are used in parallel connected to the same DC bus. The outputs can either be controlled per leg, or multiple legs can be configured like for example required to produce a three-phase ac motor control output [6].

II. Grid Manager

A Grid Manager is a device that controls multiple loads in a DC grid. The input to the grid manager is the DC grid and it has multiple controllable loads.

The grid manager can be regarded as the controlling and protection device for all external connections to the DC grid. Each output of a grid manager is connected to a single device and as such, the grid manager can control the current to and from that device as well as guard the output current for overcurrent and earth leakage [8].

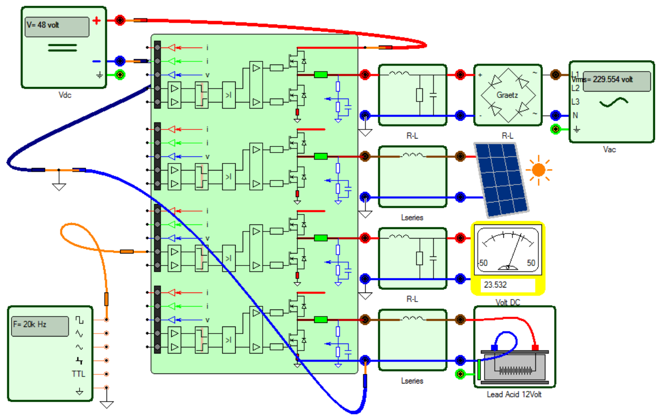

Fig. 2. Grid Manager with four loads; Single phase grid connection, Solar cell; RLC load; rechargeable battery.

The grid manager that is build as a synchronous buck converter possesses the following features:

- Output voltage level is controllable
- Currentflow is controllable
- Overcurrent protection
- Bidirectional powerflow

The most important feature is the ability to control the current level. Since it can limit the current level the grid manager can be used to limit output power, but also to turn it off completely. As there is inherently a current measurement at the output, also the protection can be based on this output current. Overcurrent protection is inherently included because the maximum allowable output current is controllable. However the ability to monitor the output current also makes it possible to detect a sudden rate of change of current that could be due to a short circuit at the output

Typical applications include:

- Battery charging/discharging
- Led current control
- Solar panel MPP

For teaching these applications a single grid manager, can be setup with multiple loads and/or sources. In figure 2, the setup is used to study the behavior of four typical connections. From top to bottom there is a grid connection simplified by using an AC source and rectifier, a solar panel which is current controlled to achieve a maximum power point, a single resistive load with LC filter and a battery connected via an inductor to allow current control.

III. Droop Control

The functioning of the grid manager is to regulate the power flow depending on the voltage level at the DC grid. In this configuration the output of the grid manager is a DC grid. The grid manager regulates current to and from this grid by using sliding mode control [1]. In figure 3 the DC grid voltage is modeled by a constant voltage source of 20 volt. In figure 4 this system is repeated but then the DC grid is modeled by loads and sources only.

A. Current control

The droop control inside the grid manager is build around a current controller. The output current of the grid manager is measured and compared with a reference current from the droop controller. In figure 3 the principle of the current control is displayed. The reference signal is a trapezoidal waveform and a sliding mode control regulates the output current. Scope 1 in figure 3 shows the reference and output current.

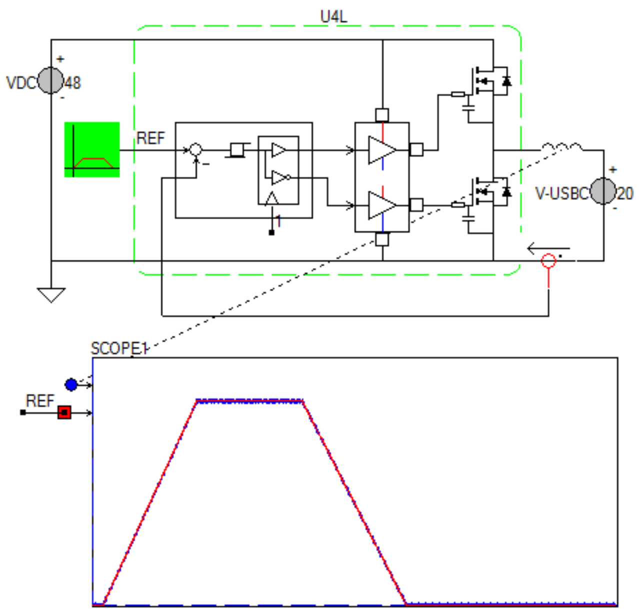

Fig. 3. Current control implementation inside the grid manager. Scope 1 shows the regulation following a reference current profile.

B. Load control

A droop control is added in figure 4 to the grid manager and external loads are modeled by current sources with a typical profile. The output current from the grid manager is displayed in scope 1 in figure 4 together with the two load current profiles. The DC load voltage that has to be regulated, is displayed in scope 2 in figure 4. A reference signal of 20 volt is also displayed in this scope. The droop control in figure 4

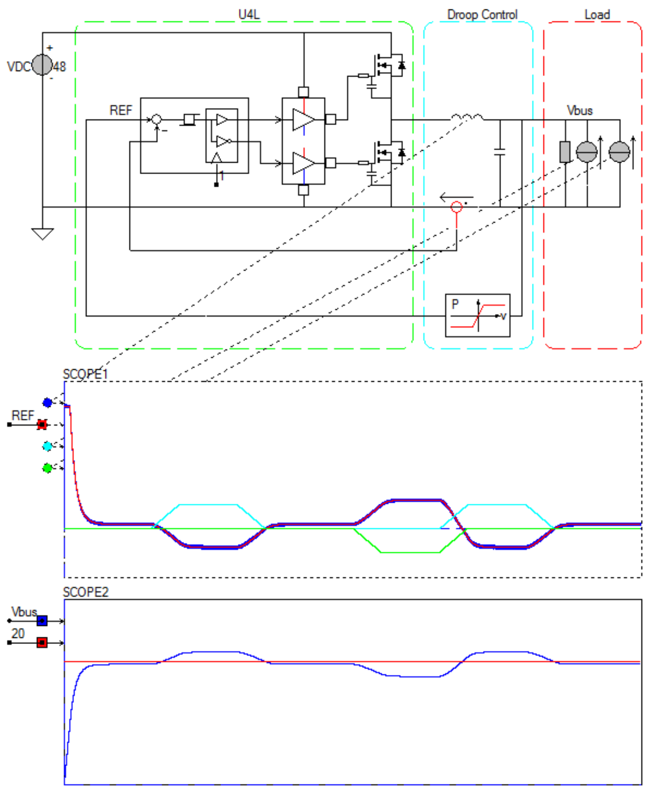

Fig. 4. Droop control using the grid manager. The external load and source/sink current sources model the DC grid are displayed in scope 1. Scope 2 shows the DC grid voltage depending on the sink and source current profiles and the regulation by the grid manager.

measures the output DC voltage and depending on the DC voltage level, it is either sourcing or loading the DC bus.

The droop control in figure 4 controls the current level such as to maintain the voltage level on the DC grid. The output of the droop control is zero for a DC grid voltage equal to the nominal grid voltage. Whenever the DC grid voltage is lower than the nominal voltage, the grid manager starts sourcing current into the DC grid. For a DC grid voltage higher than the nominal DC grid voltage, the grid manager starts sinking current out of the DC grid. The characteristic of the droop control is measured where the DC grid voltage is displayed along the X-axis and the output current from the grid manager is displayed along the Y-axis in figure 5. The nominal voltage is set at 20 volt and the maximum current the grid manager is allowed to sink or source is set to 5 ampere.

The regulation takes place along the characteristic in figure 5 and the slope in the characteristic is known as the droop constant K. For this characteristic the droop constant equals

$$K = \frac{\Delta I}{\Delta V} = \frac{5}{(20-10)} \tag{1}$$

IV. Droop Control Simulation

Teaching droop control is done in two ways. In the first setup the output power levels are dependent on the voltage

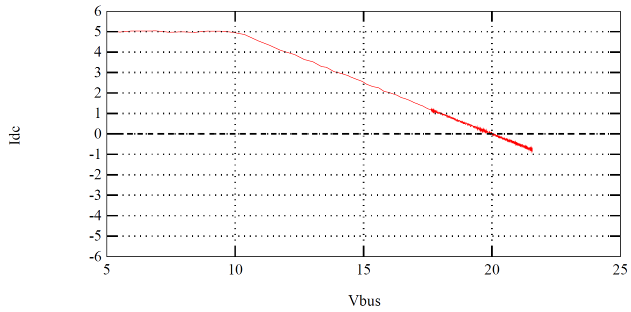

Fig. 5. Simulated droop control characteristic. The maximum source current is 5 ampere and the nominal DC grid voltage equals 20 volts.

level at the input of the grid manager, see figure 6. The grid manager is connected to a variable DC source that mimics the DC grid. Each output is connected to a RLC load and the voltage level at each output depends on the droop control algorithm. This is a straightforward setup and there is no dependency between the outputs.

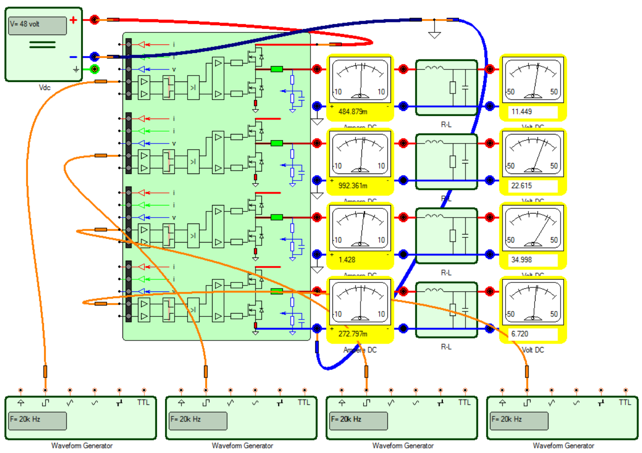

Fig. 6. Configuration Grid Manager, the grid manager in this experimental simulation example controls each application independently.

The second setup mimics the droop control depending on the DC grid voltage, see figure 7. For this the internal control structure in the grid manager is used to control the output current depending on the DC grid voltage at the output. Since all outputs are connected to a single DC grid, this DC grid voltage defines the current level per output. In order to teach different types of loads and users, various droop characteristics are implemented inside the grid manager. An external DC power supply defines the DC grid voltage.

V. Protection

Active protection in a DC grid is preferred against the traditional short circuit protection [8]. In figure 8 a classical short circuit protection is compared with an active protection. The electromechanical circuit breaker has a reaction time of only 100μs but the maximum current rises to the maximum short circuit current within several tens of nanoseconds. This

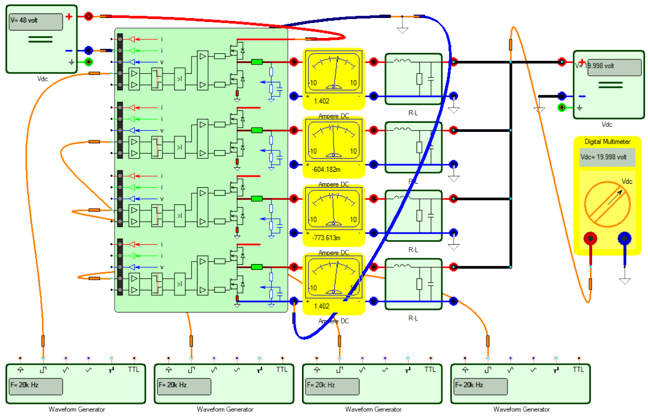

Fig. 7. Configuration Droop Control. The Grid manager in this experimental simulation example emulates four different applications connected to a single DC grid of 20 volt.

current rise depends on the impedance of the cable in between, but is usually much faster than the delay time of the electromechanical breaker.

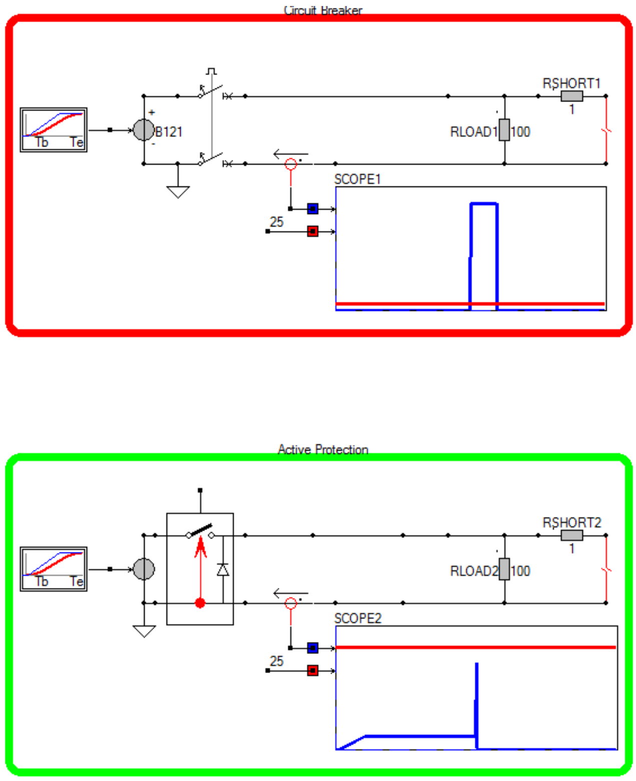

Fig. 8. Short circuit protection by electromechanical circuit breaker(top-red) and active protection(bottom-green). Scope shows short circuit current of 350 amperes, while the current in scope 2 from the active protection remains below the maximum current of 25 amperes.

The active protection measures the rise of the current and detects the short circuit before the output current reaches the short circuit current. Turn off inside the active protection takes place with several tens of nanoseconds and therefore the short circuit current is limited to a much lower level. As can be seen from figure 8, the upper scope shows that the short circuit current is beyond the maximum specified current of 25 amperes, while the lower scope shows the active protection, where the current remains below the maximum of $25A$.

In figure 9 the active protection is compared to a traditional circuit breaker where also the impedance of the cable is considered. Depending on the position of the active protection, before or after the cable, an oscillation is caused due to the cable impedance. Compared to the traditional circuit breaker, the short circuit current is directly turned off and in the case of the active protection, only the energy that was still inside the cable causes oscillations,. However the magnitude of these oscillations are well below the maximum allowed current level.

The influence of the cable impedance on a fault that is turned-off by an active protection requires more detailed attention. There is still energy present inside the cable due to cable capacitance and inductance. Although the amount of stored energy is low, it can lead to oscillations in the DC grid, and therewith trigger other safety equipment and creating unwanted electromagnetic emissions. The influence of the cable impedance is again compared to the traditional system with an electromechanical circuit breaker. The top circuit in figure 9 shows the turn-off within $100\mu s$ After turn-off the short circuit current, having a value of close to 350 Ampere shows a damped oscillation in scope II. This oscillation can cause unwanted EMI, because of the high amplitude of the current.

In case of the active protection, as shown in the simulation middle and bottom simulation in figure 9, the short circuit current never reaches a large value and stays close in the vicinity of the nominal load current. Not only is the maximum current at the fault limited, but also the oscillations after turn-off are very limited in amplitude. As such the EMI is limited too! Depending on the placement of the active protection, before or after the cable, the oscillation takes place at the load side(scope IV) or at the fault side(scope VIII). In either case there is no EMI in the vicinity of the load, as visible by scope VI and scope IX.

Active protection limits the current in case of a short circuit and therefore reduces the risk on fire during short circuit. Secondly, because the overall current in the Dc grid remains below the nominal current, EMI during turn-off is limited.

VI. Laboratory setup

The laboratory setup for demonstrating the droop control is demonstrated in figure 10. This setup demonstrates the experiment as shown in figure 7. The Universal Four Leg [U4L] [6], [7] is enhanced with four droop control experimental boards, that include a droop controller. The reference current is set manually using a potentiometer on the experimental droop control board and the amount of current that is regulated through the output is visualized by the green and red LED's on the board. Green LED's indicate a sink current that is flowing into the grid manager, while the red LED's indicate a sourcing current flowing out of the grid manager.

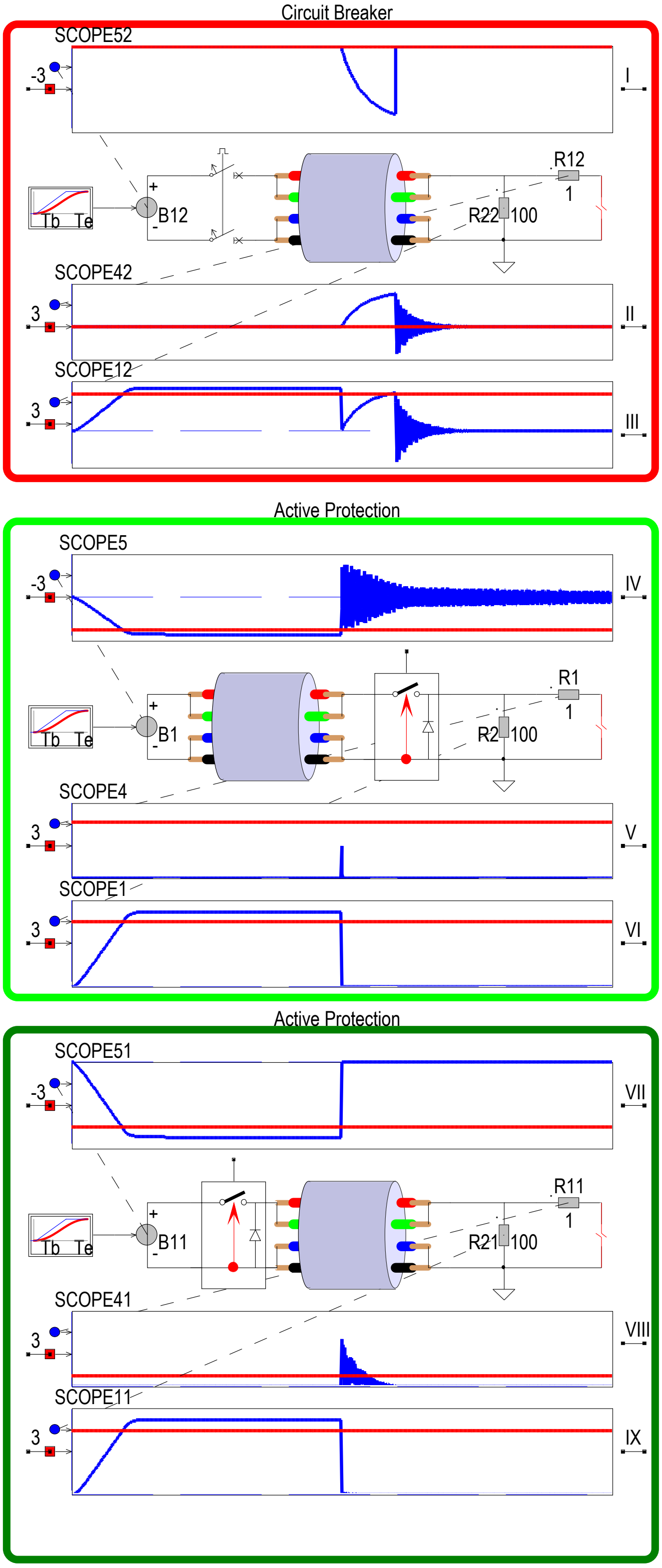

Fig. 9. Influence of the cable impedance on the short circuit current. Scope I:short circuit current before the breaker, Scope II: short circuit current in the fault, Scope III: Fault current at the load. Scope IV: Oscillations before the active protection circuit, Scope V: Fault current, Scope VI: load current, Scope VII: Fault current at supply side, Scope VIII: Damped oscillation due to cable impedance, Scope IX: Load current.

During the assignment the students have to regulate all currents to zero, except for the last leg, which should build a constant output voltage over the resistive load. The current in the last leg is regulated manually such that the desired DC grid voltage is measured by the right placed voltmeter in figure 10. In this experiment the DC grid voltage over the load resister is maintained at 15 volts. The students assign sink and source currents to the other legs and manually have to regulate the fourth leg current in order to maintain a constant 15 volt over the load resistance.

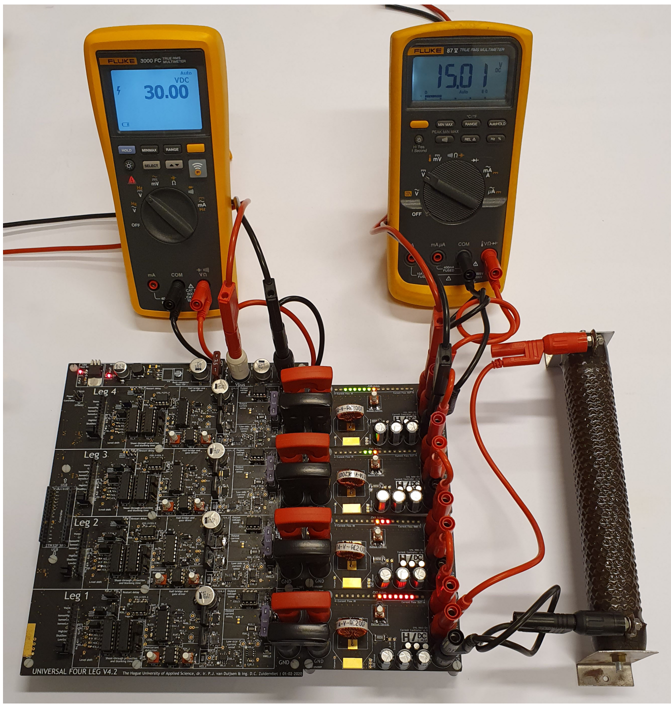

Fig. 10. Experimental setup with the U4L configured as four independent droop controllers emulating various dc grid currents. The load resister emulates the external load on the DC grid. Currents;Leg 1: high sink current, Leg 2:medium sink current, Leg 3:medium sourcing current, Leg 4:high sourcing current

As this assignment is mainly on the operation of the grid manager, the students have to measure and explain the currents as appearing in the four legs, see figure 11. The assignment goes into detail regarding the operation of the current control and the parameters of the external filter components [3].

Conclusions

To teach control and protection in DC grids, a laboratory setup used that can operate at a low voltage level of 48 volts. The setup can be used for teaching both control and protection in DC grids. Since the setup is working at a voltage level of 48 volts, it is directly applicable in Safety Extra Low Voltage DC grids. Experiments include teaching the understanding on how a Grid Manager is operating. Droop control and active protection is first teached using detailed simulations and the droop control experiment is demonstrated in this paper.

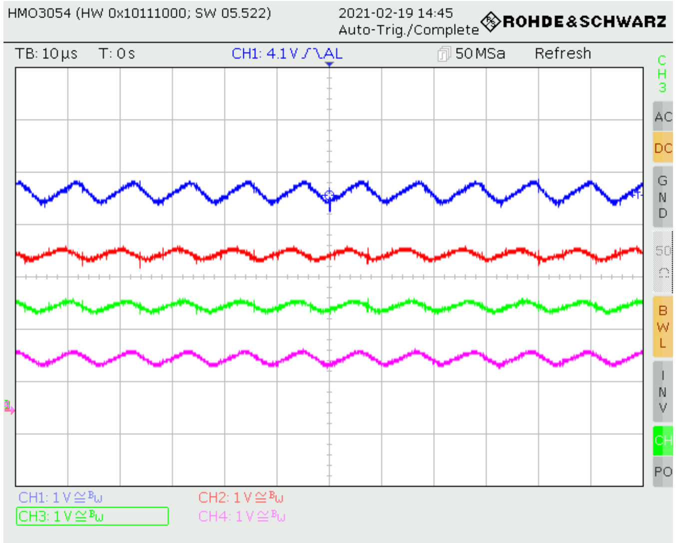

Fig. 11. CH1. Current Leg 1 CH2. Current Leg 2 CH3. Current Leg 3 CH4. Current Leg 4. All currents are measured with an Bidirectional Current Sense Amplifier around the 2.5V reference voltage.

Acknowledgement

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