Educational Droop Control Laboratory Setup

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***Abstract*—Power congestion management problems can be solved with droop control in DC microgrids. This requires a grid controller capable of controlling current. An extension has been made for a universal half-bridge educational power electronics trainer called the Universal Four Leg, for application as a grid manager in 48V DC micro-grids. This extension is intended to be used for educational and demonstration purposes, so manual interfacing and a clear visual indication of the resulting current are required. The main objective is to teach droop control in DC grids, both using manual interaction and via programmed droop characteristics. The learning objective is to understand the principle of power congestion management via droop control in DC grids.**

***Index Terms*—DC grid, Droop Control, Caspoc, Half bridge, Education, Grid Manager, U4L, Current Limiter.**

I. INTRODUCTION

Right now there's a gradual switch in the usage of steady power generators like coal power plants towards less consistent sources like wind turbines and solar panels. This is difficult to work within our current system because the modern power grid uses a frequency and phase-dependent system, which has to be delicately balanced. A switch to dynamic DC microgrids could be a solution to this. DC power [1] does not depend on frequency, nor a steady phase, and could therefore be utilized to make full use of renewable energy sources without needing complicated AC synchronizing mechanisms.

The role of education in teaching smart grids and future electricity distribution grids is typically the domain of electrical engineering educational institutes. Starting with education on smart grids and AC grids [2] and multi-disciplinary approaches [3], it gradually started to include also DC grids [4] and [5]. Also, the application of DC grids in development countries is of importance [6] and [7]. In [8] the emerging topics in smart grids are summarized that should be included in a Master level course, being the DC grids as one of the main topics.

To control power in DC microgrids new techniques are being developed, one such technique being droop control. This involves measuring the voltage on the main power grid, and changing power consumption and production accordingly, which dynamically assists in keeping the power grid in good health and keeping critical applications from failing because of power loss. In [9]–[11] droop control in DC grids is discussed. To include this in the educational process, hardware trainers and software are required. In [12] a DC grid manager with training software [17] are presented.

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This paper describes a setup that can apply droop control on a DC microgrid through a DC/DC converter. The system is comprised of the Universal Four Leg, [U4L] as detailed in [13], [14], which is a system using multiple DC/DC converters and a current controller add-on circuit that creates a feedback loop that can control the Universal Four Leg. This can be used to control the current flowing in and out of specific legs of the U4L with great stability and ease. A microcontroller is further utilized to apply droop control using these current controllers, enforcing the currents dictated by the droop control curves.

The requirements of this system are:

- The bidirectional ability to control current between -2.5A and 2.5A
- Manual control over the current
- Automated control over the current through an input PWM
- Visual indication of the current flow
- Maximum ratings of 60V, 2.5A

In section II an overview of the system and its subsystems is given. Section III explains the basics of droop control. Sections IV describe the power flow indication circuit, section V the droop control programming, and the resulting PCB in section VI. In section VII the experimental setups used to verify the system are explained. The overall system verification is explained in section VIII and in section IX the results of the tests are shown.

II. SYSTEM OVERVIEW

This section will describe the general structure of the current controller setup, including the general function of each subsystem. Included in figure 1 is a block diagram showing a rough look at the used setup, including a few examples of possible functions. In this system, a microcontroller on the U4L contains the decision-making to apply droop control. It measures data from the U4L, like the grid voltage and the voltage and current going to individual legs of the U4L. This data is used to apply a droop control curve to the applications attached to the setup, which is enabled by the current controller add-on which can accurately control currents.

In the following sections these core ideas will be expanded, before diving in-depth into individual components and methods.

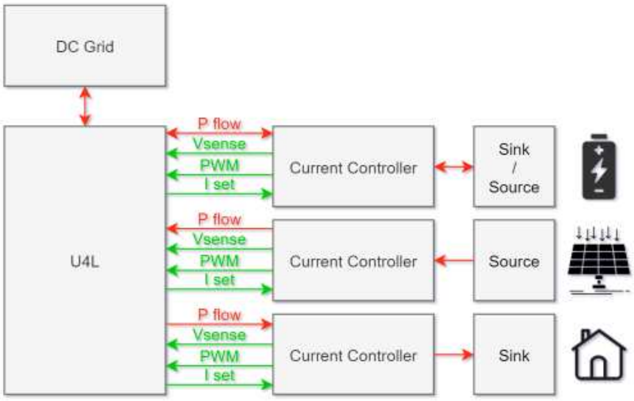


Fig. 1. Block diagram of the current controller system, displaying various possible applications. The red lines indicate possible power flows, and green lines indicate information signals

A. The Universal Four Leg

A synchronous bidirectional Buck converter [15], is the core of the design and contains the half-bridges used to convert voltages to the necessary levels. The U4L is fed by the grid voltage and can convert that voltage into other values separately for each leg. The U4L additionally contains circuits that are capable of measuring voltage and current at the individual legs and can pass on this information to an onboard microcontroller. The U4L also provides power to add-on boards connected through a 15V bus. A simplified diagram of the U4L is shown in figure 2 as simulation model in Caspoc [17].

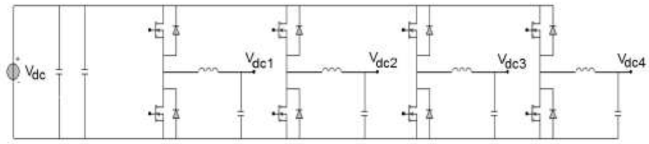


Fig. 2. Simplified topology of the U4L [14], containing four half bridges.

B. The Current Controller Add-on

To control the half-bridges of the U4L a PWM signal is required, which is supplied by the hysteresis controller [15]. It does this by measuring the current flowing out of the U4L and comparing that flow to a reference value. Based on whether the flow exceeds the reference or not, the flow is toggled. Because the LC filter stabilizes the voltage and current, the result is a triangle-wave shape in the power flowing from or towards an application, with active control based on the amount of current flowing. The average current flowing will follow the reference value, which allows a system to control the current flow by controlling that reference value. This value can be generated on-board by using a potentiometer or can be added externally through an I/O pin. Additionally, this board contains LED's that indicate the amount of current flowing, and in which direction. A block diagram of the current controller add-on is shown in figure 3.

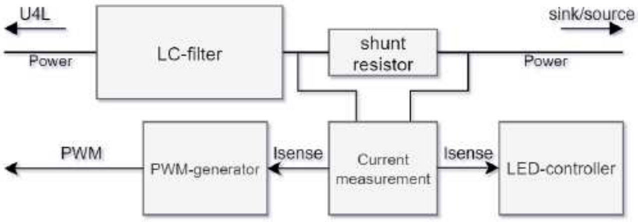


Fig. 3. Block diagram of the current controller add-on

III. DROOP CONTROL TECHNIQUE

Since this system allows controlling the current flowing bidirectionally with relative ease, this system has been configured to use droop control. This style of control is based on the adjustment of power consumption and production to fit the state of the DC power grid. The "health" of a DC power grid is measurable in the level of its voltage, with a higher voltage corresponding to more energy being available for consumption, and a lower voltage level corresponding to less energy being available for consumption. The droop control system can use this principle to adjust energy consumption to fit the current state of the power grid [16]. To achieve this, it utilizes so-called "droop control characteristics", which describe how much power should be used in specific conditions. A few examples of such characteristics as simulated in Caspoc [17] are shown in figure 4.

These characteristics describe various applications that can be used in a grid. The blue line, for example, describes behavior that something like a battery might have: discharging when energy is scarce, and charging back up when energy is readily available. Having systems with this kind of behavior connected to the power grid act in a stabilizing way, attempting to bring the power grid to an equilibrium. In figure 4 this equilibrium is found at $V_{dc} = 367.5V$.

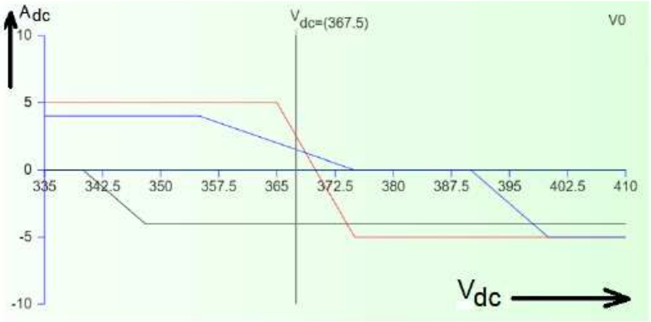


Fig. 4. Various droop control characteristics in one graph simulated in Caspoc [17]. The X-axis shows the DC grid voltage V_{dc}, while the Y-axis shows the maximum allowable current A_{dc}.

An additional way that droop control can control the grid is through loads. A droop control system can mirror the voltage droop that happens on the grid onto the voltage it provides to applications. Systems within those applications can measure those changes and react accordingly, altering their power-consumption to fit the power available. [19]

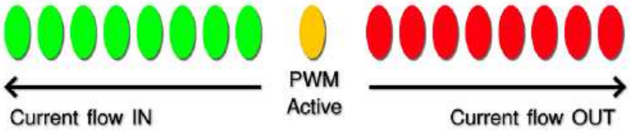


Fig. 5. The layout of the indication LED's, red LED's indicate sourcing current, the green LED's indicate sinking current and the orange LED in the middle indicates if the current controller is active,

IV. LED Current Indication

Since this circuit is intended to be used in demonstrations, some form of visual feedback is required. The choice has been made for a series of LED's that indicate how much current is flowing, and in which direction. Additionally, there is an orange LED that indicates whether the PWM signal is being generated or not. The positions and colors of the LED's are shown in figure 5.

V. Droop Control Software

The digital control loop is implemented based on a droop characteristic as shown in 4. Figure 6 shows the general flow of the program, including the main control loop.

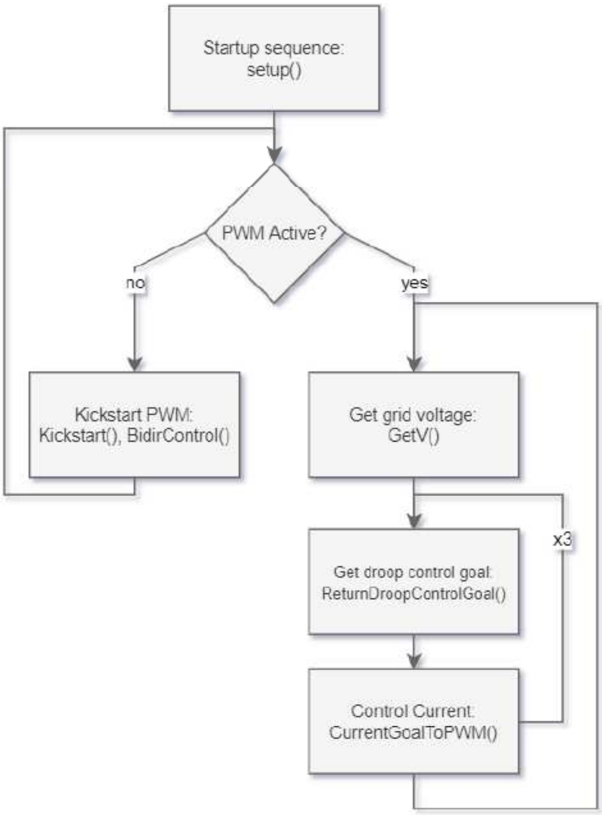


Fig. 6. Flowchart describing the droop control software

A. *Main Control Loop*

The main control loop in the droop controller is an endless loop, where depending on the measured voltage, via the droop characteristic, the amount of current to be regulated is determined. The main program contains three subroutines:

- Reading Grid Voltage.
- Lookup in the Droop characteristic.
- Output of the to be regulated current.

This cycle is the core of controlling the current controller, obtaining information and reacting accordingly.

1) Getting Grid Voltage: To get the required current goal it is necessary to know the grid voltage since this is the input of the droop control curve. To achieve this the function `GetV();` is called. This function samples the voltage on the specified leg 32 times and averages it. Since the U4L can be configured so that V_{Grid} can be measured on leg 4, leg 4 is passed on as an argument for this function. The resulting measurement is stored as `VBus` for later use.

2) Lookup and Output: This is the part of the control loop that actively controls the individual legs, so this section of code is executed a total of 4 times, one for each leg on the U4L.

The aforementioned `VBus` is used to look up the required output value in each leg's droop control curve, and said value is then converted to a PWM signal. This PWM signal is passed on to the current controller add-on, which in turn filters it and uses it as a reference value for the control.

B. *Data Storage*

The aforementioned droop control curves need to be stored in some way, in addition to the other data that is required to properly control the current controller. This section will describe these storage methods.

1) Droop Control Curve: To store a curve as described in section III, it is easiest to work with points, and use linear interpolation to make those points describe a continuous line. Each point has 2 values, V_{Grid} and I_{out}, so the decision has been made to combine those in a struct named `DroopCurvePoint`. Following that, a droop control curve consists of a few of those points. 4 points are enough to describe the vast majority of possible curves, so an array is constructed containing 4 `DroopCurvePoint` structs. And because there are 4 legs total, there are 4 curves needed, which means that another array is constructed, containing 4 droop control curves.

2) Miscellaneous Data: Considering the repeating nature of controlling 4 legs, most leg-specific variables are needed in four separate times. Instead of opting to create an array for every variable, the decision has been made to create an array of a struct that contains all necessary data. The struct `LegInternalData` contains data about each leg, including things like `StateMachine` and `CurrentPWM`, describing the current state of control and the current goal being written to the current controller add-on.

VI. Current Controller PCB

The current control PCB is an add-on to the U4L and is placed between the U4l and its load.

A. PCB Design

The designed PCB for the current controller add-on is 100mm wide and 50mm tall. These dimensions are specified to give the add-on the same height as a leg on the U4L, which allows 4 add-ons to sit next to each other to connect properly to the legs. The width was not defined to fit anything, so it has been optimized to be as short as possible. An overview of an assembled version of the PCB is visible in figure 7.

Fig. 7. Fully assembled current controller [18]. The connectors on the left side match the connectors on the U4L. The application is connected to the connectors on the right side.

B. I/O

The current controller add-on has multiple pins dedicated to transferring signals between circuits. These are subdivided into 4 categories, those being power, signals to and from the U4L, signals to potential applications connected to this setup, and test points.

1) Power: As expected, the power I/O includes a ground pin and a +15V pin. These are also used on-board to create +5V for the ICs that need it.

2) Signals U4L: To control the half-bridges aboard the U4L there is a PWM pin, which should be connected to the low-side pin of the leg the add-on board is connected to. And in much the same way, to control the controller itself there is an input pin for the reference voltage, which should be connected to the microcontroller on the U4L.

3) Signals External: To accommodate possible future boards to be connected in series with these current controller add-on boards, some pins are provided for those to connect to, providing +15V, ground, and the measured current signal. This is because it is expected that that signal can be used to create larger, more dynamic demonstration setups in the future.

4) Test Points: There are multiple testing points available on the current controller add-on, including the following signals: V_{ref}, $V_{I_{sense}}$, $V_{compare}$, V_{enable} and $+2.5V$.

C. Modes of Operation

This system allows for both automated and manual control. The PWM generator uses a reference voltage as a goal, and this value can be changed through external hardware, or through a small voltage selector circuit using a potentiometer. To select between these two signal sources, there is a jumper-header which can connect in two ways to select the two methods.

VII. EXPERIMENTAL SETUP

The setup used to test this system can be seen in figure 8. It uses $12V, 5Ah$ batteries to simulate the power-grid and the bidirectional-source. For the power grid, two batteries are connected in series to create a 24V source. For this setup, only one leg is being tested. This leg is connected to a load, which is simulated by a 5Ω resistor in parallel with a light bulb, to draw current and emit light to show proper function. All of this is hidden inside a model house, to create a more understandable view for demonstration purposes. The 2_{nd} battery is connected in parallel to the load, to provide a stable voltage and the ability to send power back to the U4L. If the current controller add-on is configured to be in manual-control mode, this setup will allow for the user to freely control how much current flows between the U4L and the load-battery pair by rotating the potentiometer. If the controller is configured to be in automatic-control mode, it will control the current based on predetermined droop control curves instead.

Various parts of this setup are interchangeable with other components, to simulate and test different things. For example, the batteries can be interchanged with power supplies to give more freedom in testing automated-control modes, since with that setup it is possible to vary V_{Grid}.

Do note that if a power supply is used, a load has to be connected in parallel to ensure that it has a way to consume power. Both resistors need to be selected to be able to consume as much current as can be sent using the selected shunt resistor on the current controller add-on. For example, to ensure a leg that has a 12V power supply doesn't get overwhelmed by a 2.5A current, this requires a $\frac{12}{2.5} = 4.8\Omega$ resistor or less. Since this value is close enough to 5Ω, a 5Ω resistor has been used instead.

A schematic view of this setup is shown in figure 9.

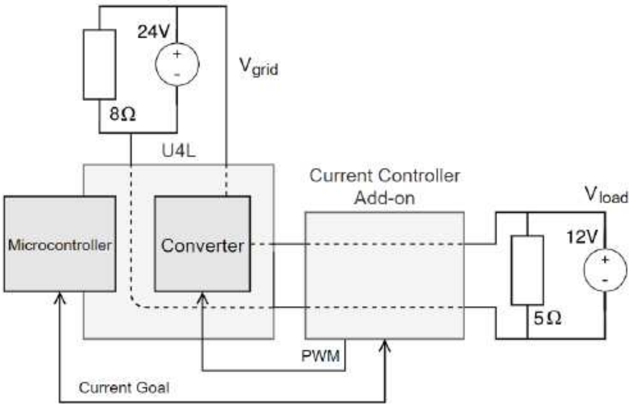


Fig. 9. Schematic view of the experimental setup used, the resistors are emulating the power consumption.

VIII. SYSTEM VERIFICATION

To verify that this design works as intended, multiple things need to be tested. Since this system is a control system, the following functions have to be tested: measuring, controlling, and the link between measuring and controlling.

Fig. 8. Experimental setup used to test an active DC-grid system. From left to right: the U4L with a $24V$ DC-link battery and current measurement, a current controller PCB with current measurement, a resistor load and fixed $12V$ DC voltage battery with current measurement.

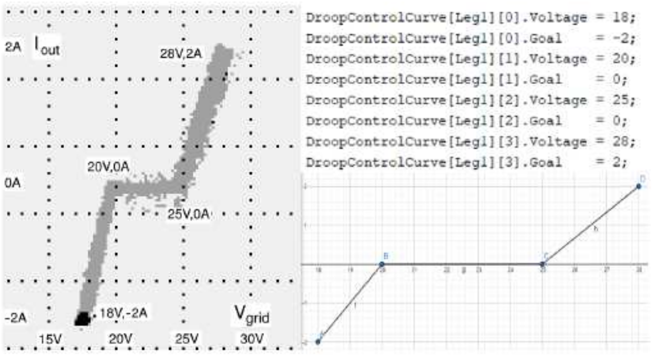
1) Measuring: To test this, a DC voltage was supplied to the U4L, and the measurements of the onboard microcontroller were monitored. Altering the supply voltage and taking measurements each time provides data on the accuracy of voltage measurements. The results show great accuracy in scaling, but with a small offset (largest measured being 300mV) being possible on some legs.

The current measuring system was measured in a similarly, but with the current controller being used to create stable currents. Results are again very accurate while scaling, but with small offsets being possible on individual legs.

2) Controlling: To measure whether the current controller could control current, the following test was run: The current controller was configured in manual-control mode and a multimeter was used to measure the resulting current flow. A multimeter was also used to measure the reference value that dictates how much current should flow. A comparison of those two measurements showed that the current controller is accurate, and controls current as intended.

3) Complete Test: This test is aimed at testing the entire system, to see if individual sub-systems can work together properly. A droop control curve was programmed into the microcontroller, and the current controller add-on was configured to be on automatic-control mode. So in this setup, the expected result is to be able to measure this droop control curve if you measure the current flowing from the U4L, and compare it to the voltage on the grid.

A variable power supply was used to alter the grid voltage smoothly, and a Fluke 190-204 Scopemeter was used to measure and record the values of both the current and the voltage in an XY plot. This plot is shown in figure 10, along with the curve programmed into the microcontroller. These curves are mirrored vertically compared to figure 4 because the perspective on current flow is switched. Instead of measuring current flow towards the grid, this measures current flow away from the grid.



```
DroopControlCurve[Leg1][0].Voltage = 18;
DroopControlCurve[Leg1][0].Goal    = -2;
DroopControlCurve[Leg1][1].Voltage = 20;
DroopControlCurve[Leg1][1].Goal    = 0;
DroopControlCurve[Leg1][2].Voltage = 25;
DroopControlCurve[Leg1][2].Goal    = 0;
DroopControlCurve[Leg1][3].Voltage = 28;
DroopControlCurve[Leg1][3].Goal    = 2;
```

Fig. 10. XY plot of the measured automated droop control curve. X is V_{Grid}, Y is I_{out}. X: 5V/div, Y: 1A/div

The plot clearly shows the same points that were programmed into the microcontroller. One thing to note is that there is a lot of noise visible in the plot. This noise is the result of the current being pulse width modulated, meaning that any individual measurement might deviate from the requested value, but on average they are correct.

IX. RESULTS

The current controller add-on can accurately control current in a bidirectional situation, as described in section III and verified in section VIII. The PWM that the circuit generates to control the half-bridges on the U4L has a frequency in the range of $30kHz$ - $90kHz$. A measurement showing the resulting current flow is shown in figure 11. Here the grid voltage of $24V$ is visible, in addition to the $12V$ output voltage on the connected bidirectional source. Additionally, the measured current is shown, having a ripple of approximately $300mA$.

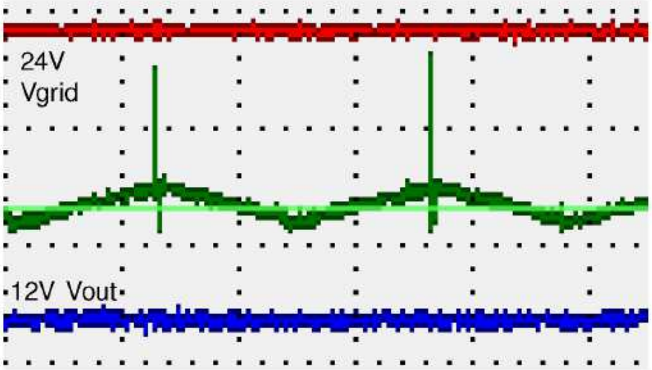


Fig. 11. Measurement showing stable voltages (Red: $24V$ DC, Blue: $12V$ DC, $5V/div$) and a triangle-wave current flow (Green: $1A/div$, $10\mu s/div$)

If the current controller is configured in manual-control mode, the user has full control over the current flow, demonstrated in figure 12 where a user controls the current through the potentiometer over the course of 10 seconds.

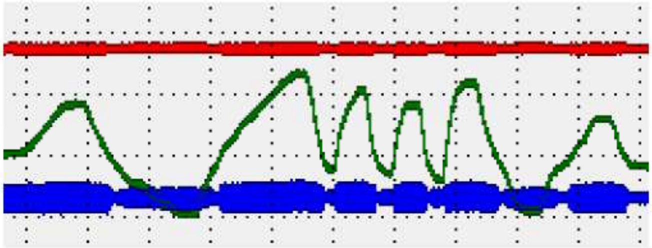


Fig. 12. Measurement showcasing manual control over the current (Red: 24V DC, 5V/div, Blue: 12V DC, 5V/div, Green: 2A/div, 1s/div)

X. CONCLUSION

Education for future electricity distribution grids is nowadays including DC grids and its control. Next to the smart AC grids the role of DC grids with droop control is increasing and this is reflected in education. For the purpose of of teaching droop control, a current limiter add-on is created for educational hardware power electronics trainer. Using this add-on, the principles of droop control can be demonstrated.

The current control add-on is capable of accurately controlling current to and from sources and loads, like batteries, PV panels and passive loads. Next to manual operation for teaching, this control can be fully automated using a microcontroller. Droop control characteristics can be specified in the microcontroller. By either using manual control or a programmed droop characteristic, the principle of droop control for power congestion management can be taught.

Experimental results prove the ability to control the power flow using the current controller according to the droop control characteristics. This enables the application of the current controller for power congestion management in DC grids.

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