A Practical Application of DC Droop Control with IoT capabilities

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Abstract. The application of DC grids is gaining more attention in office applications. Especially since powering an office desk would not require a high power connection to the main AC grid but could be made sustainable using solar power and battery storage. This would result in fewer converters and further advanced grid utilization. In this paper, a sustainable desk power application is described that can be used for powering typical office appliances such as computers, lighting, and telephones. The desk will be powered by a solar panel and has a battery for energy storage.

The applied DC grid includes droop control for power management and can either operate stand-alone or connected to other DC-desks to create a meshed-grid system.

A dynamic DC nano-grid is made using multiple self-developed half-bridge circuit boards controlled by microcontrollers. This grid is monitored and controlled using a lightweight network protocol, allowing for online integration. Droop control is used to create dynamic power management, allowing automated control for power consumption and production. Digital control is used to regulate the power flow, and drive other applications, including batteries and solar panels. The practical demonstrative setup is a small-sized desktop with applications built into it, such as a lamp, wireless charging pad, and laptop charge point for devices up to 45W. User control is added in the form of an interactive remote wireless touch panel and power consumption is monitored and stored in the cloud. The paper includes a description of technical implementation as well as power consumption measurements.

Keywords. *DC grid, power management, sustainable, solar, battery, office desk, droop control, digital control, IoT.*
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1. Introduction

Power consumption in an office was until recently not problematic, as consumption was low compared to energy use for cooling or heating. However, reducing the carbon footprint in the office is becoming a trend for companies to increase their sustainability. Reducing power consumption by optimizing the lighting at the office is discussed in [1]. If the lighting in an office is optimized in the areas where light is required, less power is consumed. In [2] the trend in consumption is analyzed. To optimize the use of energy, an algorithm is used to control all components. This requires extra communication with all components. Using the DC droop control as is done in this work, the same goal can be reached without the extra external control. And in [3] the power consumption at an office is discussed. To know where the power consumption can be optimized, the consumption profiles need to be known. Based on these profiles, the droop control can be specified.

DC power [4] is independent of frequency and phase, and could therefore be utilized to make full use of renewable energy sources without needing complicated AC synchronizing mechanisms. Furthermore, most appliances in offices are already DC-powered, so there is no need for an AC grid. Secondly, power congestion management is easier to implement in a DC grid[5][6]. For controlling power in a DC nano-grid[7] new techniques are being developed, one such technique being droop control [8]. This requires measuring the voltage on the main power grid, and changing power consumption accordingly, which dynamically assists in keeping the power grid in good health and keeping critical applications from failing. In [9][10][11] the method and application of droop control in DC grids is discussed. From the experimental work done on low voltage DC grids at [12], an experimental setup was created [13][14], including power electronics educational training laboratory exercises [15][16]. In [17] a DC grid manager with training software [18] is presented. In this paper, a DC nano-grid specific for an office desk is proposed. The main idea is to have a sustainable DC nano-grid inside each office desk. Not to increase efficiency, but to have full control of the

self-regulating system. If a solar panel and battery are connected to the office desk, the office desk can operate independently from the national grid. And additionally, It can also share electric power with neighboring DC desks, creating a larger nano-grid. The choice for DC is made as there is no need for AC, since all sources, e.g. the battery and solar cell, as well as the loads, LED, laptop, and phone chargers are DC. As well that DC has more capability to regulate the power flow by using DC droop control compared to AC.
The sections in this paper contain the following information. In section 2 an overview of the implementation methods is presented. The developed converter to build the DC-powered desk is presented in section 3. The benefit of a DC-powered desk, DC droop control, is outlined by an example in section 4. In section 5 the system control is further elaborated, along with measured response times of the system. In section 6 the monitoring method along with network features are discussed and in section 7 the safety regulations and protection aspects of a DC installation. In section 8 the demonstrative setup is presented followed by the conclusion in section 9. Ending with the references in section 10.

2. Implementation methods

The DC-powered desk is subdivide into three distinct parts: the DC nano-grid, a demonstrative setup, and IoT capabilities. Each elaborated below:

2.1 DC nano-grid

This part includes the used circuits, and the software driving them. It's responsible for regulating the grid and managing the applications connected to the grid. The power electronic circuits in the DC grid enable the following functions:

- Voltage control for a specific voltage;
- Current control for a specific current;
- Implement a dynamic droop curve;
- Charging a battery with charge algorithm;
- Maximize generated PV power using MPPT.

With these functions, it's possible to create a DC nano-grid structure and drive a large variety of different applications. If the DC bus is connected to another DC nano-grid, power can be exchanged. The appliances in the external connected DC nano-grid can be either a consuming load or a producing source. As the power flow can be bidirectional, these appliances are called prosumers, being the combination of either producing or consuming electric power.

The maximum power the office desk can deliver is limited by the State of Charge [SoC] of its battery. However, two connected office desks can deliver twice the amount of power to a third DC nano-grid. The maximum current that can be supplied to the loads is limited by the rating of the DC cable and connectors, which in the case of the office desk is calculated on 10 Ampere.

2.2 Demonstrative Setup

A demonstrative DC nano grid setup is built. A desk is modified to contain all kinds of office appliances, such as phone and laptop chargers, a desk lamp, and USB charge sockets. The desk will function as an off-grid DC platform, able to function on solar and battery energy. Figure 1, gives an overview of the desk. The desk will be able to connect along with other desks, creating one larger meshed grid [19]. This meshed grid can manage electricity among each connected smart-desk and autonomously keep the grid healthy on a local scale. This means that each desk has a battery and a solar source. when insufficient energy is available in one prosumer, the energy sources of other grids can manage the miss-match. This becomes possible by using DC droop control, where the power flow is regulated, to maintain a stable grid.

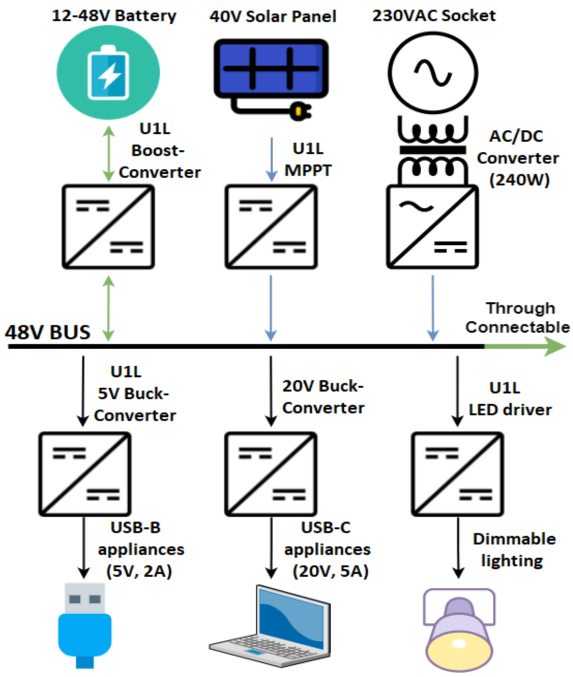

Fig. 1 – Overview of the DC-powered desk.

2.3 IoT capabilities

Internet of Things [IoT] capabilities to measure and exchange data are added to this system. The network protocol MQTT *(Message Queuing Telemetry Transport)* is used, due to its simple structure to send and receive telemetry data through different interfaces. A Raspberry Pi is used as a server and logs all received data. This data can be plotted in time graphs to get a visual understanding of produced and consumed energy. Each driver in the DC desk has an integrated Arduino Nano 33 IoT. The Arduino sends all measured data to the server. The Arduino can also receive data from the server which is easily accessible through the user-friendly interface. The server-UI is realized with Home Assistant, which any smart device can connect to. The UI allows the user to easily control the system with features like On/Off toggles and changing the voltage/current parameters. Figure 2 shows an overview of the implementation of the IoT system.

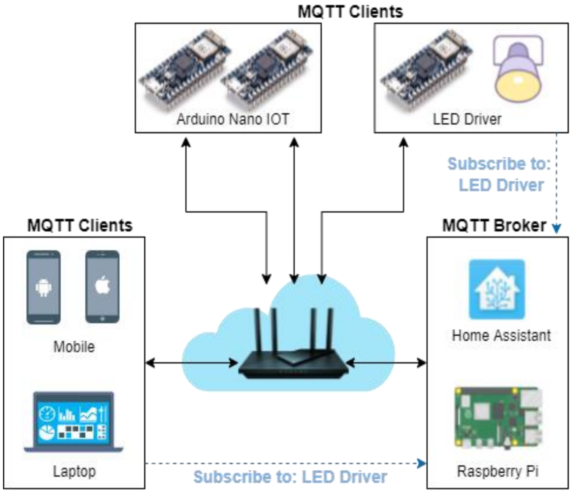

Fig. 2 – MQTT overview of the IoT DC-powered desk.

3. Powering the DC nano-grid

To power this DC nano-grid, a Universal One Leg[16] (U1L) is used. This circuit is based on a half-bridge topology[20], developed by The DC-LAB[12]. The U1L functions as educational hardware to help students better understand power electronics. An Arduino Nano socket is available on each of the U1L. As seen in Figure 3, the Arduino Nano can be programmed to measure voltage and current signals and adjust the output accordingly by changing its PWM. The input ranges from 15V up to 60Vdc and the output ranges from 0 to Vin. The U1L can function as both voltage or current controller by adjusting the halve bridge PWM ratios to keep a reliable output. This way it becomes possible to regulate the amount of consumed energy, based on the available energy.

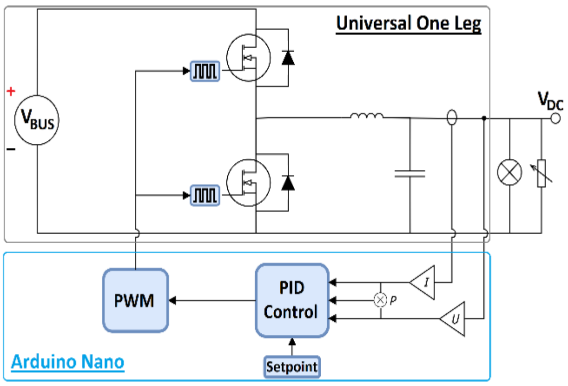

Fig. 3 – Schematic interaction U1L and Arduino Nano.

The U1L can switch as a buck- or boost-converter depending on which terminal is used as input or output. The Vbus (in) terminal and Vdc (out) terminal can be changed, depending on connecting a source or a load to these terminals. The half-bridge topology enables these possibilities.

4. DC Droop Control

In AC systems, switches can be used to regulate energy consumption. This is done by looking at the grid frequency and adding or removing loads based on the available energy. The disadvantage is that AC regulation is limited to passively enabling or disabling systems to adjust the energy consumption. In a DC grid, regulation using power electronics is possible, which allows power congestion management via droop control. This is because DC droop control is not only available to add or remove loads, but also to adjust the amount of energy that is used in loads. This is important for power management. With the increase of daily electricity consumption to compensate for electric cars and electric heating, more advanced technology will be required to manage the grid[19]. To demonstrate the difference between using an AC grid with a constant voltage level, and a DC grid where droop control is implemented, an illustrative simulation is made. In this scenario, an electricity grid typical for an office environment is pictured with three active components, Figure 4.

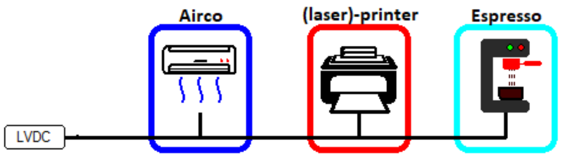

Fig. 4 – CASPOC Simulation model of an LVDC branch with three common components as active loads.

Figures 5 and 6 display the power consumption, of the active loads with corresponding colors, in an electricity branch. The purple line indicates a maximum allowed power of 3.5 kW and the green line indicates the total consumed power. The first figure demonstrates the scenario with a constant voltage AC grid supply. The amount of current used by the appliances is simply the sum of each appliance at full power. Therefore it is a simple addition of all currents. When all components are turned on at the same time, the electrical branch will exceed its maximum power and a fuse will blow, shutting down the entire branch. Since all components consume maximum power, the total power is simply the summation of all individual powers, exceeding the 3,5kW branch fuse, as indicated in figure 5.

When the components are implemented in a DC grid, the amount of power available is indicated by the voltage level in the DC grid. If the voltage level is high, there is enough energy in the DC grid and the components can consume maximum power. If the voltage level is reduced, the power consumption has to be lowered. If the total power consumption is increasing, the voltage level is decreasing accordingly. Due to the lower voltage level, each component is then reducing the power consumption until the final total power consumption is below the maximum power level of 3.5kW. The air conditioning is programmed to reduce its power consumption accordingly, allowing the espresso and printer to fully operate. Once the espresso completed its task, the air conditioning continues with its nominal power, and the branch is never shut down. This way components in a branch can each be tasked with different priorities. This way important components, such as lighting, will maintain full functionality while lower priority components can reduce the power they consume.

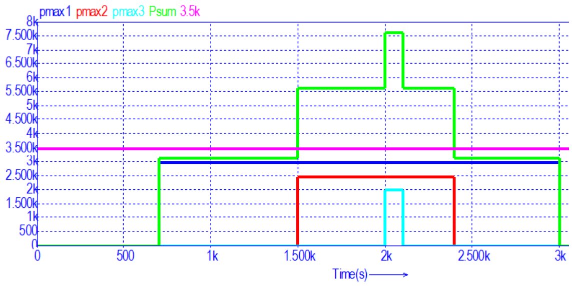

Fig. 5 – AC system, the maximum power (pink) is exceeded as the total power (Green) increases. Fuse breaks.

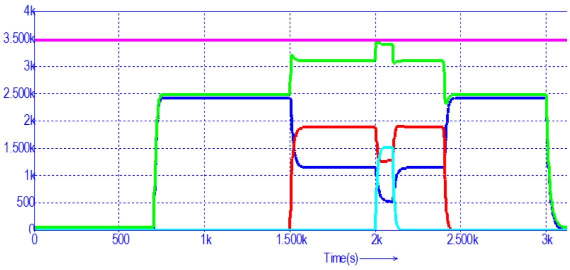

Fig. 6 – DC system, total energy consumption is regulated automatically. No fuse is broken

5. Controlling The System

To actively drive the halve bridge for a stable output voltage, a feedback loop is used. This feedback loop acts as a PI controller, taking the measurement from the output and comparing it to the input, altering the output PWM accordingly. This core system is used for every application that the software can do, along with minor adjustments. For example, the code regulating a normal output voltage is identical to the code charging a battery, the only difference being the parameters of the feedback loop and a few physical header changes.

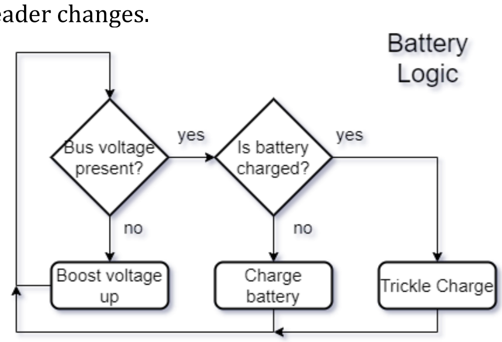

Fig. 7 – Flowchart Battery management.

Software is not only designed for the PI feedback loop. It also includes being able to switch between different operation modes, perform calibrated measurements, and understand the state of other parts of the system. For example, as shown in figure 7, the battery is only allowed to charge itself if a steady external voltage is present on the Vbus. If this voltage is not present, the battery is in charge of creating it. Likewise in figure 8, the U1L which generates the Vbus voltage from an external 24 V DC source needs to keep its feedback cycle in check whenever the battery is delivering power.

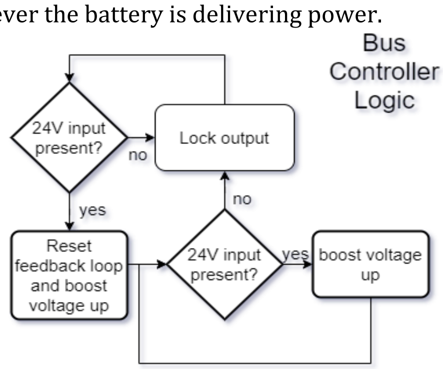

Fig. 8 - Flowchart Vbus management.

To stabilize the system further, extra functions are included to aid the current controller add-on. The function is built to detect whether the current controller is functioning correctly, and use the start-up function if it is not. This ensures that it does not lose control of its output during unforeseen events, locking up the feedback loop.

5.1 Feedback Loop

The feedback loop programmed in the Arduino for this system contains the following equation(1). It is needed to ensure reaching the desired value.

$$PWM[n] += \qquad (1)$$

$$\frac{V_{out}[n] - V_{goal} * 0{,}2}{V_{Bus}} + \frac{\sum(V_{out}[n] - V_{out}) * 0{,}02}{V_{Bus}}$$

It continually takes the previous PWM value, adding an error to bring it closer to the desired value. The amount of error that's added is based on the difference between where the output is and where it needs to be, scaled appropriately in perspective to the bus voltage (since the amount of change in the output due to change in PWM is scaled by the strength of the bus voltage). It also includes a small integral value, to add a marginal amount of extra aggression for large-error cases, ensuring that the voltage rise is as fast as possible in all parts of the curve.

This technology is used in the demonstrative setup to actively adjust the flow of energy. As the source voltage level exceeds or drops below certain critical points, the system will adjust its output behavior accordingly. This way the consumer can use the desk unhindered. Figure 9 visualizes this in the practical setting. As the source voltage (red) changes, the power output (blue) will differ accordingly. With this feature, the available electricity can be used optimally. Charging the battery only when the source is healthy and disabling low-priority components when the available energy is lower.

Fig. 9 – A droop curve measured with an oscilloscope. As Vbus (red) changes, Voltage out (blue) dynamically changes along.

5.2 Response time

The feedback loops in this system were calibrated and have acceptable performance. The rise-time of 305 ms, from 0 V to 10 V at the output, can be considered acceptable. Figure 10 demonstrates this rise-time. If looked closely, the individual correction cycles of the Arduino are visible. Completing a cycle of code takes about 30 ms and increases the output according to equation*(1)*.

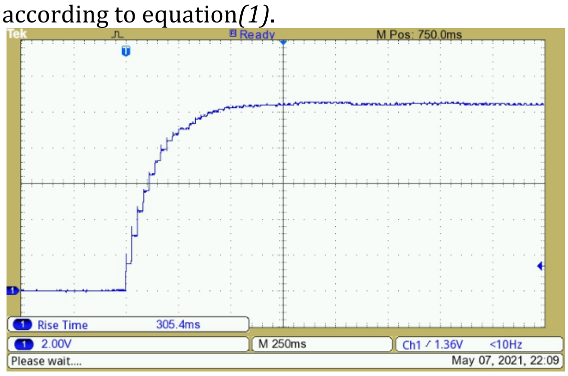

Fig. 10 – Rise-time and Feedback-cycle time to reach 10 V SteadyState output.

5.3 SteadyState accuracy

Once the SteadyState is reached on the output, a noise of 50 mV is experienced on the output line. This is an acceptable error compared to a general laptop charger. Typical usb 5volt chargers are known to experience a 200 mV deviation from the mean voltage and in the USB-PD specification, transients are allowed up to 5% from the mean plus/minus an extra 0.5 volt. Figure 11, demonstrates the SteadyState noise.

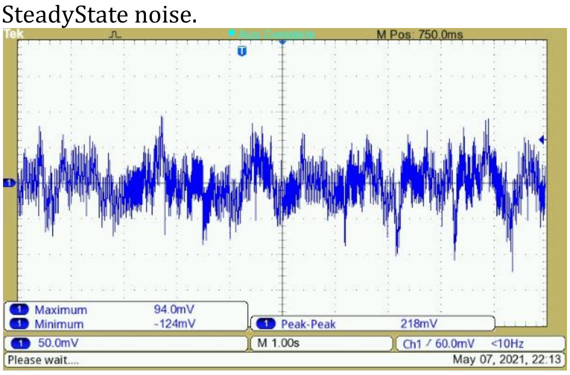

Fig. 11 – AC measurement of the SteadyState performance during active feedback loop. Common deviation of 50 mV with occasional peaks up to 100mV.

6. IoT and grid monitoring

To monitor and control the nano-grid, Home-Assistant is used for the online User Interface [21]. Home Assistant has the capabilities to display and monitor all kinds of data. The collected data is visualized in a simple overview making it ideal to read the grid status from any smart device. The accessibility can be made as simple as needed, depending on the end-user.

6.1 MQTT Protocol

The MQTT allows devices to publish and subscribe to self-made channels, allowing simple to set up telemetry communication. The central broker, the Raspberry Pi, receives published messages, forwarding them to any subscribed client. This allows many clients to log data, and allows any client to access the data that is considered relevant to them. This makes MQTT ideal for sharing information within this particular network. This helps to get all communication to one location in the network and add multiple U1L converters to the Office environment.

6.2 Communicating with the U1L

The communication with the U1L boards can be split into two groups: telemetry and control. The telemetry part sends all measured data to Home-Assistant for display purposes. Each U1L sends two voltage and two current measurements, for the bus and output3 terminal. For the control part, bi-directional communication can be possible. The user can change parameters on the U1L from Home-Assistant, as shown in Figure 12. This includes the operation mode of the U1L, the output voltage, the droop control curves, battery characteristics, and a toggle switch, allowing the system to be shut down remotely.

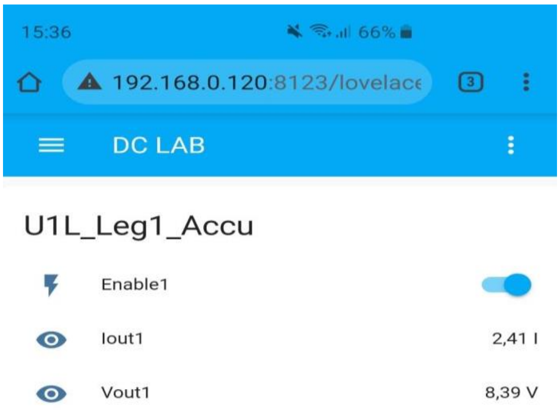

Fig. 12 – Simple Home Assistant User Interface (PC).

6.3 Data Visualization

Once logged into the Home Assistant server the visuals can be extended according to preference, as shown in Figure 12. This enables the data to be observed in a visually pleasing way. All data is also stored on the internal SD card of the Raspberry Pi, also allowing a historical view of all measured data.

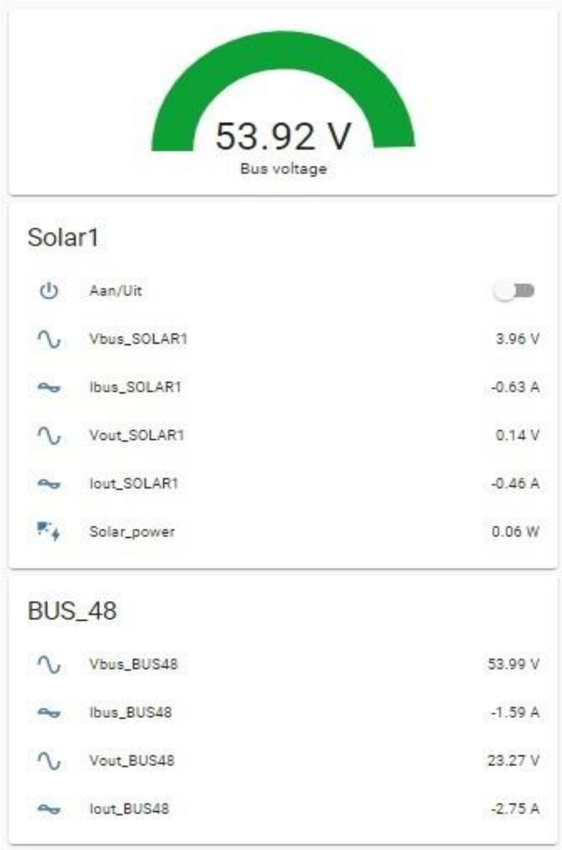

Fig. 12 – More advanced layout for Home Assist User Interface (Smartphone).

Additionally, it is possible to run custom scripts inside Home assistant. This enables endless possibilities for the user to manage its system. One of these scripts is seen in figure 13. Multiple sources of data such as the bus voltage, outputs, and battery levels are plotted on a single time graph. This visualization creates a better understanding of the energy flows within the demonstrative setup.

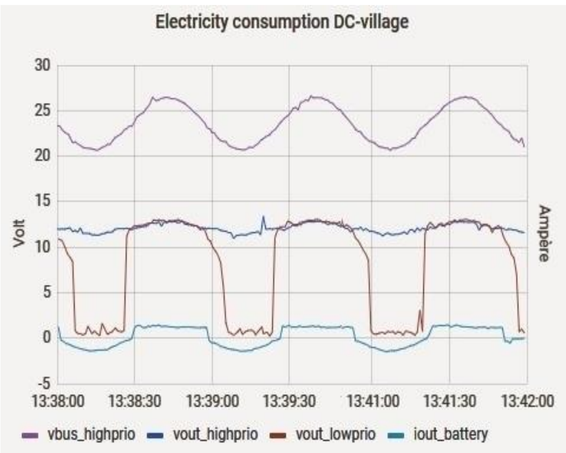

Fig. 13 – Plotting multiple sources on a time graph for an easy understanding of the energy flow in this setup.

As shown in figure 13, the purple line indicates a grid voltage, which swings between 20~26 V. When the grid voltage gets below a certain point, the low priority loads(red) are disabled, while the high priority loads(blue) stay operational for a healthy grid.

7. Protection

The demonstrative setup is designed to be placed in the office environment as a single-person work desk. The goal is to practically experience the pros and cons when using a DC-grid instead of the usual AC-grid. The NPR9090[22] for Dutch practical guidelines explains how DC power sources need to be safely protected. This document divides all kinds of LVDC-installations into 5 separate zones, each indicating how they should be protected to keep the environment safe, Figure 14. In this list, the most dangerous zone is in zone-0. This zone categorizes Solar parks, Battery plants, and the public grid. The important properties of these components are that they are capable to deliver huge currents on demand, acting as an infinite current source. The safest zone is in zone-4. This zone contains all connectable devices below 60 V, the Low Voltage Direct Current (LVDC) level, and below 1000 W. The short-circuit current for devices in zone-4 is very limited as these devices are unidirectional and below the human hazard voltage. The U1L-hardware powering the applications is protected against electrical surges and other hazards. Fuses and RVS diodes are used to shut down the system directly once a malfunction is detected. Devices connected to this side of the source are safe for touch and are not able to harm people.

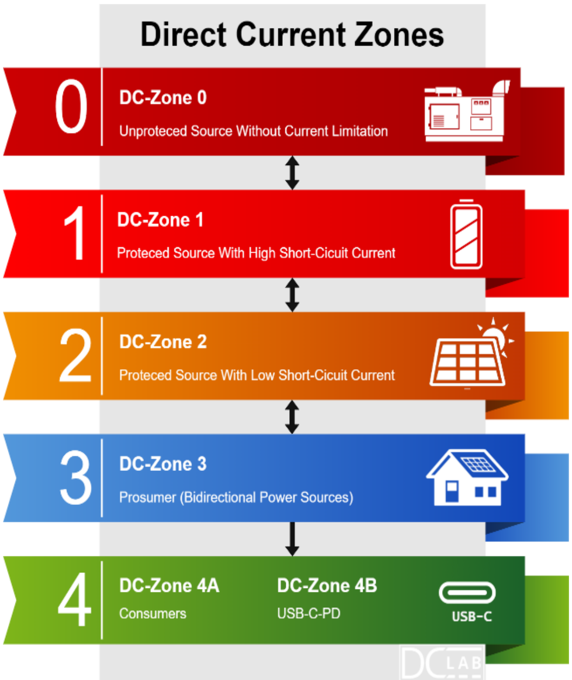

Fig. 14 – DC-zones stated by the NPR9090[22]. Each zone is defined with criteria to connect the devices.

In the demonstrative setup, two zones are represented. As the product will contain a lot of human interaction, the entire desk itself is only equipped with a zone-4 installation, for the lighting and charge sockets. The energy sources powering the system are identified as a zone-3 installation. These sources are applied to the table in a concealed way. Those who use the table as an office desk will be out of direct reach of these components.

8. Demonstration setup

The demonstration setup contains a 74x74 cm Scandinavian homemade table redesigned with multiple appliances connected to all the U1L converters, Figure 15. There are four U1L converters able to power four types of appliances. The bus voltage is realized by connecting a 48Vdc lead acid battery to the Vbus.

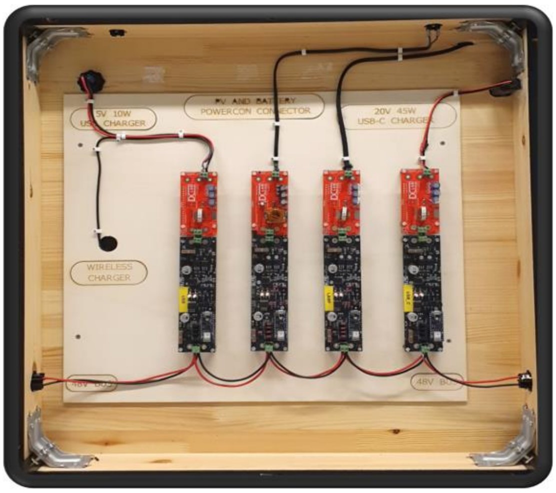

Fig. 15 – Bottom-view demonstrative setup. All devices powered by U1L circuits are mounted underneath the table.

To power this system, three different methods are available:

- A 48V is applied on the Vbus line;
- A 24-48V battery is applied on the battery line;
- A 24-48V Solar panel is applied on the PV line;
- A mixture of these sources is applied.

With sufficient power, each of these options can operate the table. Once powered, the devices will automatically boot up within 10 seconds.
During this time each U1L will upload their operation mode and create each of their desired voltages. Each U1L connected to a load will function as a buck converter and those connected to a power source will function as a boost converter. As the devices in the table turn on, all measured data is published through Wi-Fi. The broker will gather this information once connected in the same network space as the table.

The four U1L's installed in the table are specified as:

1. The 5Vdc line for all portable appliances that need USB power through a typical USB-B port. In this office table, it is a 10W wireless charger and 10W USB-B charge port.
2. A 12Vdc line as a LED-Driver, this line can go in current-control mode to drive LED lights, up to 100W.
3. A 20Vdc USB-C socket with power delivery, capabilities to charge laptops with 45W.
4. A ranged input for PV with a maximum power point algorithm, up to 100W. Or a ranged input for external batteries to boost the bus voltage. This battery acts as a backup for the 48Vdc line.

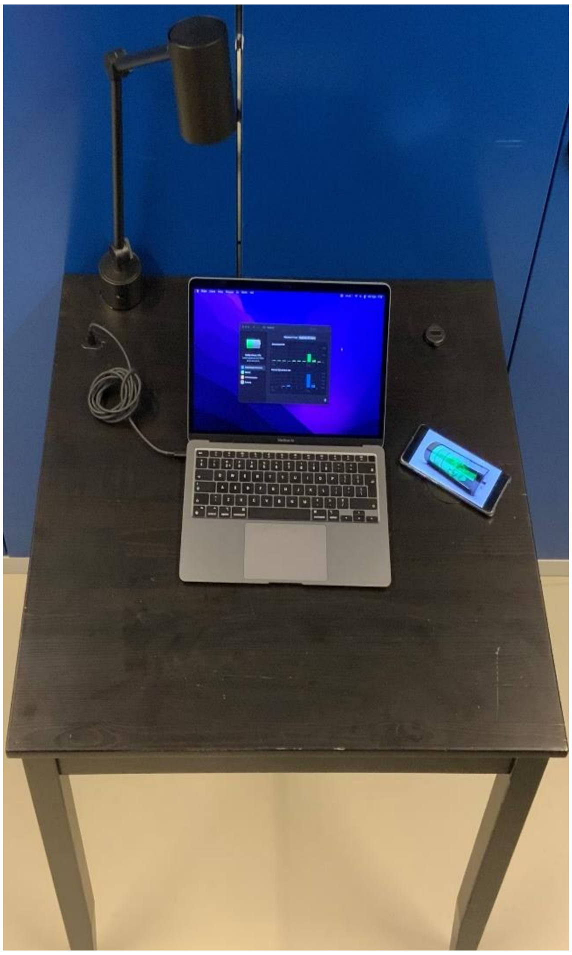

Fig. 16 – DC-powered table placed in the living lab in the auditorium of THUAS, fed by a 48V battery. While charging the laptop and Phone with LEDs [23]

Figure 16, shows the final result. The table can fully function as an off-grid system. By connecting multiple tables on the same Vbus line, a meshed grid can be created. This meshed grid can communicate grid statuses among each consumer and act accordingly if certain events occur. For example, each table can be connected with a PV panel and battery. If half of the tables are barely used, excessive solar energy can be used to power neighboring batteries. This way each table becomes a prosumer, using dynamic droop control curves to contribute to a healthy state of the grid.

9. Conclusion

In a DC grid, power management can be performed using droop control. To demonstrate the use of power management by droop control, in an office environment, a demonstration desk including a DC nano grid is developed. The DC nano grid includes energy storage, has a photovoltaic connection with a maximum power point tracker, and is remotely configurable and monitored. The desk can be connected to other desks to form a larger DC grid for the exchange of energy.
Since the desk can be configured and monitored remotely it is flexible in use, especially in an office building.

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