

THE DEVELOPMENT OF A PROOF OF CONCEPT FOR A SMART DC/DC POWER PLUG BASED ON USB POWER DELIVERY

Hendrik Reydam²; Vincent Lauwereys², Dries Haeseldonckx^{1,2}; Pepijn van Willigenburg³; Johan Woudstra³, Stijn De Jonge^{1,2}

¹CORE cvba-so – Kapeldreef 75 – 3001 Heverlee – Belgium

ABSTRACT

Instead of using a passive AC power grid for low power applications, this paper describes a smart plug for DC networks that is capable of providing the correct power to a device (up to 100W) and that allows for communication between different plugs and monitoring of energy consumption across the DC network using the Ethernet protocol in conjunction with a signal modulator to adapt the signals to the DC network. The ability to monitor consumption on a device-per-device basis allows for closer monitoring of in-house energy use and provides an easily scalable platform to monitor consumption at a macro level.

In order to make this paper attractive for the consumer market and easily integrable with existing consumer devices, a generally compatible solution is needed. To meet these demands and to take advantage of the trend of charging consumer devices through USB, we opted for the recently adapted USB Power Delivery standard. This standard allows devices to communicate with the plug and demand a specific voltage and current needed for the device to operate.

The purpose of this paper is to give the reader insight in the development of a proof of concept of the smart DC/DC power plug.

1. INTRODUCTION

The development of a proof of concept USB Power Delivery plug is promoted by CORE [1], a Leuven based student cooperative aimed at providing an active contribution towards the sustainable development of the local community. Core is partnered with The Hague University of Applied Sciences in the project ‘DC- the road to its full potential’ [2], which aims to study the economic feasibility of broad scale implementations of Micro-DC and Mini-DC grids. It is within the development of a Micro-DC grid that this paper is situated. An issue that arises with the proposal of a 350V Micro-DC grid is the fact many consumer devices cannot handle such a high voltage. This would require each device to be fitted with its own converter to meet its power demands. In 2010, the average American household was estimated to have an average of 25 consumer electronic devices [3].

Of the devices considered in the study (figure 1), virtually none require AC power.

Analyzed in Highest Detail	Analyzed in Lesser Detail
Audio-Video Receiver	Camcorder
Blu-ray Player	Compact Audio
Computer Speaker	Copy Machine - Stand-alone
Computer - Desktop	Cordless Phone
Computer - Portable	Digital Camera
DVD Player	Digital Picture Frame
DVD Player & Recorder	Fax Machine - Stand-alone
Modem	External Storage Device
Monitor	Home Theater in a Box
Printer - Multi-function Device	Mobile Phone
Printer - Stand-alone	Personal Video Recorder - Stand-alone
Router	Portable Audio
Set-top Box – Cable	Projector
Set-top Box – Telco	Radio
Set-top Box – Satellite	Scanner - Stand-alone
Set-top Box - Stand-alone	Telephone Answering Device
Television	Video Cassette Recorder
Video Game Console	

Figure 1: List of consumer devices included in study [3].

With global sales of USB 3.0 devices expected to exceed 1 billion worldwide in 2014 [4] and with the development of the USB Power Delivery standard [5], the USB standard provides a solution that is compatible with an extensive assortment of consumer products and provides new possibilities for further development ideas. As of writing, there are no commercially available USB Power Delivery controllers. This has led to the development of an emulation of the USB Power Delivery standard rather than a concrete implementation of a USB Power Delivery controller.

The proof of concept can be divided into three objectives:

1. The development of a power solution able to convert 350V DC to a variable output voltage ranging between 5V-20V at a max of 5A while maintaining as high efficiency as possible.
2. The emulation of the USB PD protocol between two devices to request a certain power profile.
3. The emulation of USB communication between power plugs over the DC grid.

2. USB POWER DELIVERY

USB Power Delivery is a standard released by the USB Implementers Forum in 2012. Initially it allowed for an increased power level up to 100W, but manufacturers are free to specify even higher levels. Devices are able to negotiate for a manufacturer defined power profile, in which voltage and maximum current are specified. The power exchange does not have a fixed direction. Previously, power was always provided by the host to the device. This allows for both data communication and high power transfer over the same cable, eliminating the need for a separate power adapter.

2.1 POWER SOLUTION

The goal while designing the power supply was to provide all the voltages specified by the initial five power profiles (figure 2) stated by the standard with the highest efficiency possible.

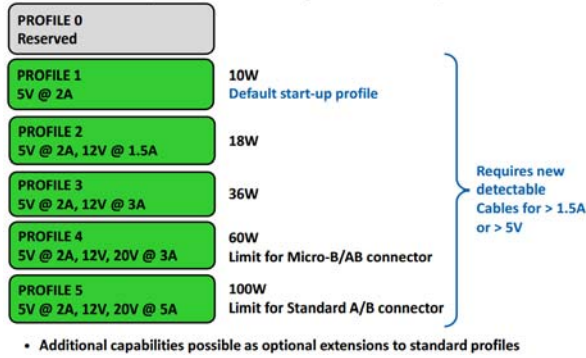


Figure 2: Initial profiles defined by USB PD [5]

To meet both these requirements we opted for a two tiered solution (figure 3). The first step is from 350V to 20V DC using a flyback converter followed by a synchronous buck converter from 20V to the specified voltage. In the case where 20V is requested, the 20V from the flyback is directly applied to the load.

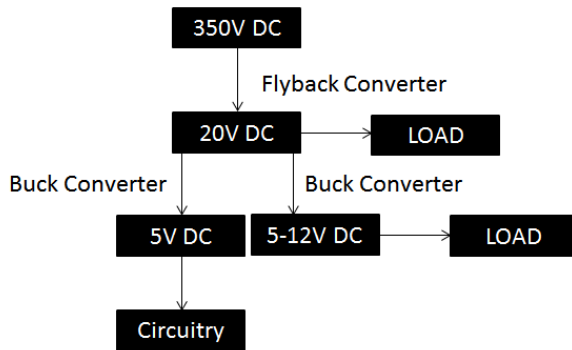


Figure 3: Schematic overview of power supply

An additional smaller buck converter was implemented to provide internal circuitry with 5V DC regardless of what the load demand is.

2.1.1 Flyback converter

The flyback converter is driven unipolar by a switch (N-channel MOSFET) controlled by the LM5023 [6], a quasi-resonant pulse width modulated controller ideal for the design of a highly efficient off-line power supply. The LM5023 drives the MOSFET so that energy can be stored in the core and can be transferred to the output after a certain peak storing current is sensed.

Quasi-resonant switching minimizes switching losses compared to traditional continuous and discontinuous modes of operation, which is possible when the switching is not synchronized with a certain frequency, but with the drain voltage of the MOSFET. When the current on the

secondary reduces to zero, the transformer is demagnetized, which results in the formation of a resonant circuit between the transformers primary inductance and the output capacitance specified by a resonant frequency. The demagnetization of the transformer is detected by an auxiliary sensing winding, which follows the drain voltage when demagnetization occurs.

The drain voltage which will ring down towards the ground after the switch is turned off and current is decreased towards zero. When the sensed voltage drops below 0,35V, the controller turns on the switch again which results in minimal switching losses (see figure 4). Quasi resonant switching reduces switching losses by switching the MOSFET when a minimum drain voltage occurs. The speed of switching is then defined by a resonant frequency.

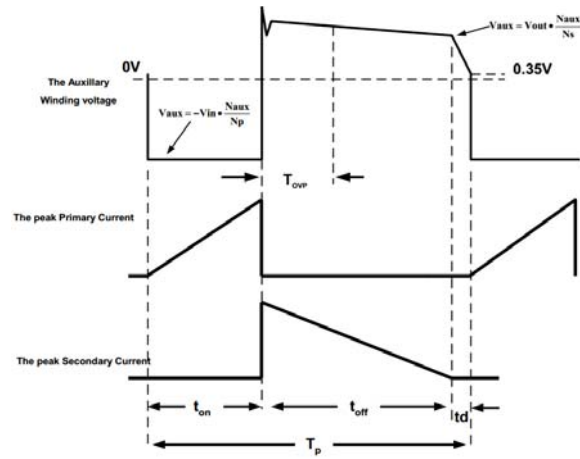


Figure 4: Resonant switching behaviour [6]

2.1.2 Efficiency at light IOAD

The quasi-resonant switching gives high efficiencies for higher loads, but when lower loads are considered, less current is transferred to the load resulting in a shorter on- and off-time, increasing the frequency. Combining the lower need for power and the higher switching frequency results in a converter in which a significant percentage of power is needed for switching. To improve the light load efficiency, the controller enters a skip cycle mode in which no output is generated to turn on the switch.

2.1.3 Switching mosfet

The FCD4N60 [7] is an N-channel MOSFET driving the transformer. In order to maintain high efficiency, this power MOSFET is characterized by a very low $R_{ds,on}$ (1Ω) and a lower gate charge performance. Besides a high efficiency, superior switching performance is guaranteed with a high dv/dt rate and high avalanche energy.

2.1.4 Synchronous buck converter

In the second stage of the DC/DC conversion the 20V DC is converted to one of the output voltages stated by the USB PD standard. Because isolation between load and source is already implemented in the first stage and the focus on high efficiencies, a synchronous buck converter is used. A synchronous solution uses a MOSFET instead of a diode (used in basic buck converters) to reduce power dissipation.

The switcher used to drive the synchronous design is the LM3150 [8], a step-down switcher with constant on-time architecture, which implies a fixed on-time to regulate the output. Regulation of the output is made possible by using a digital potentiometer in the feedback path, adjusting the resistance changes the feedback voltage sensed by the controller which leads to a change in the switching frequency and thus output voltage. The potentiometer is controlled by the central microprocessor through an SPI interface.

The switches used for the bipolar drive of the converter are the CSD16412Q5A [9]. Conducting losses are reduced to a minimum by a low $R_{ds,on}$ (13 m Ω) and due to the low gate drive needed to trigger the switch, switching losses are minimized.

2.2 USB PD EMULATION

Since there are no consumer products brought on the market that support USB PD or commercially available USB PD controllers, it is not possible to test the implementation with an existing product. To be able to demonstrate the plug, an emulation of the USB PD is made using two LPC 1830 Xplorer microcontrollers [10], with host and device being assigned arbitrarily and having the two microcontrollers then negotiate for power transfer.

The power supplies were designed to be compatible with a commercially developed USB PD controller that would generate the necessary control signals to the power supplies to properly regulate the power. Bearing this in mind, the USB PD emulation implementation restricts itself to generating the control signals to the power supply after negotiation between devices.

The USB PD emulation allows for the five initial profiles mentioned in the USB PD standard, manufacturers are free to implement additional profiles that may exceed 100W. However, seeing as the microcontroller boards do not actually implement USB PD, it is impossible to have data transfer take place over the same line as the power transfer. Therefore the power transfer line is connected directly to a load.

2.3 COMMUNICATION OVER DC GRID

The addition of a USB controller to a power supply offers new opportunities on a number of levels. The USB – power line interface offers an already present data communication line, be it for the exchange of information between devices connected to the plugs, or between the plugs themselves. In the context of sustainable development and conscious energy use, the ability to monitor the plugs for their current active power consumption, the device type that is drawing power, possible error messages or warnings, etc. offer new and useful information that is easily extractable and easily scalable to mine data at a micro or macro level.

Seeing as the LPC 1830 Xplorer microcontrollers have on-board Ethernet capability, and the ease-of-use the Ethernet protocol offers in conjunction with a monitoring server, the Ethernet protocol was chosen as the protocol over the DC line. The microcontrollers encapsulate the USB data in Ethernet packets which are placed on the DC line using an ASK modulator, NXP TDA5051A [11].

3. RESULTS AND DISCUSSION

The efficiencies of the power supplies (figure 5) discussed in section two are shown in figure 6.

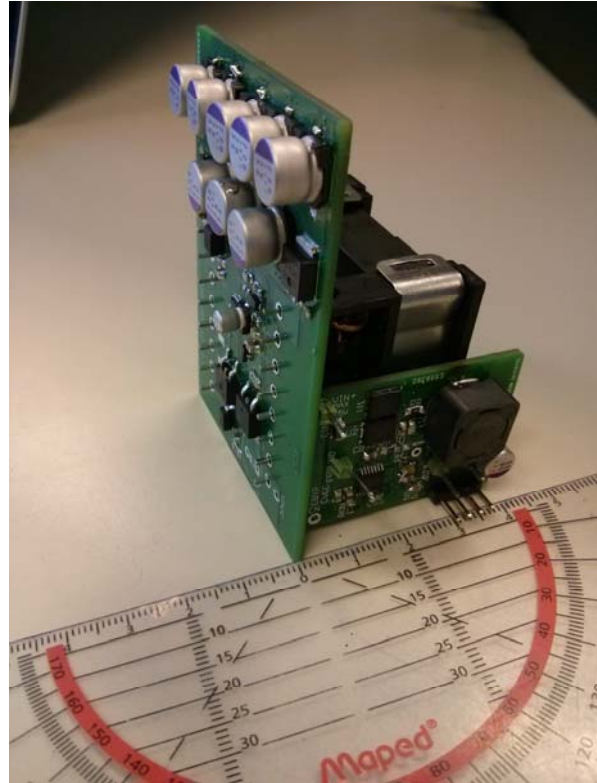


Figure 5: Power supplies

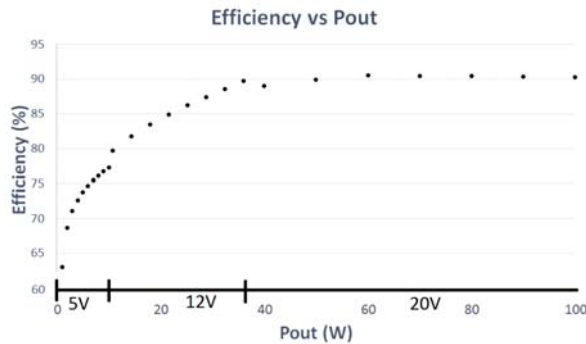


Figure 6: Plot of Efficiency vs Pout

The efficiencies shown in figure 6 are the theoretical efficiencies of the cascaded converters as the 350 – 20 VDC converter is currently non-operational. The efficiency of the 20 – 5/12 VDC converter is shown in figure 7. The efficiency at high loads can be greatly increased (~6 %) by replacing the diode on the secondary side with a synchronously driven MOSFET, and is something that will be explored further.

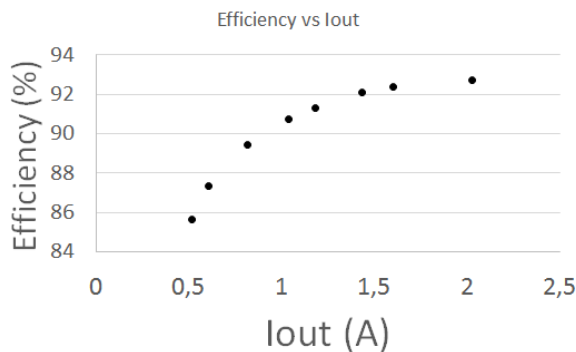


Figure 7: Efficiency 20-5 VDC

Future work consists of getting the 350 – 20 VDC converter operational, writing software to emulate USB PD power negotiations on the microcontrollers, implementing Ethernet emulation on the microcontrollers to enable communication between devices and the development of a power line communication modem.

3. REFERENCES

- [1] <http://www.thinkcore.be/website/index.php>
[February 2014]
- [2] <http://www.thehagueuniversity.com/research/overview-research-groups/energy-and-the-built-environment/project-direct-current/general>
[February 2014]
- [3] Urban, B., Tiefenbeck, V., Roth K., 'Energy Consumption of Consumer Electronics in U.S.Homes in 2010', Fraunhofer, Massachusetts, 2010, pp 117.
<https://www.ce.org/CorporateSite/media/Government-Media/Green/Energy-Consumption-of-CE-in-U-S-Homes-in-2010.pdf>
- [4] 'USB by Device, Q1'12 Forecast', In-Stat/MDR, Global, January 2012

- [5] <http://www.usb.org/developers/powerdelivery/>
[February 2014]
- [6] <http://www.ti.com/product/lm5023>
[Accessed September 2013-February 2014]
- [7] <https://www.fairchildsemi.com/ds/FC/FCD4N60.pdf>
[Accessed September 2013-February 2014]
- [8] <http://www.ti.com/product/lm3150>
[Accessed September 2013-February 2014]
- [9] <http://www.ti.com/product/csd16412q5a>
[Accessed September 2013-February 2014]
- [10] <http://www.nxp.com/demoboard/OM13028.html>
[Accessed September 2013-February 2014]
- [11] <http://www.nxp.com/applications/lighting/lighting-controls/power-line-modem.html#overview>
[Accessed September 2013-February 2014]

4. AUTHORS

Principal Author: Hendrik Reydam is a master student intelligent electronics engineering at KU Leuven – Campus GROUP T in Belgium.



Principal Author: Vincent Lauwereys is a master student intelligent electronics engineering at KU Leuven – Campus GROUP T in Belgium.



Co-author: Dries Haeseldonckx

Co-author: Pepijn van Willigenbrug

Co-author: Johan Woudstra

Co-author: Stijn De Jonge

Presenter: The paper is presented by Hendrik Reydam.