ZeoN PowerTec
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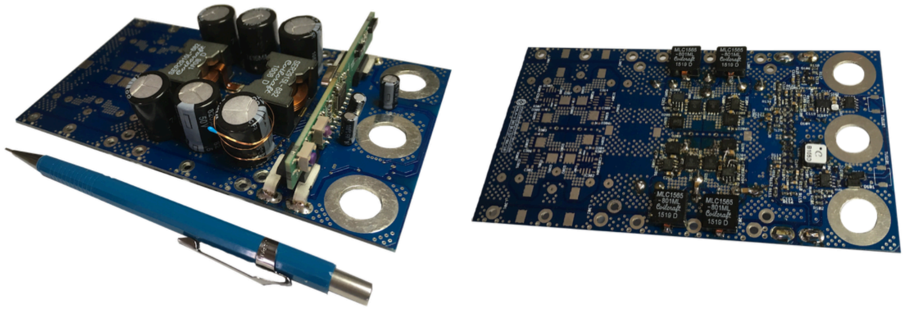
Digital Up-Down DC/DC Converter

Intelligent bidirectional power conversion



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Abstract

Affordable MCU's are opening up new opportunities in the domain of power electronics. This report presents a fully digital, bidirectional and automatic up-down DC/DC converter. After introducing the power architecture, design aspects of the hardware and firmware will be explained. The MCU is programmable on-the-fly via a Python based GUI. Finally an outlook on design status and future developments will be given.

1. Introduction

In the last decades, digital technologies have penetrated many if not most application domains. Power conversion has been lagging for many practical reasons, cost of a digital core being one of them. However, in recent years the situation has changed. Affordable MCU's containing advanced digital cores and crucial mixed signal peripherals have become available in the market. It's time to take advantage.

1.1. Benefits of digital power

In general a digital implementation allows more flexibility during the design phase of the application. While writing robust firmware code should not be underestimated, when available, fast experimental cycles and debugging become feasible. Improvements to the solutions can be made even in the field by means of firmware updates.

The number of external discrete components reduces when functionality moves to the MCU which has a positive effect on robustness and cost. In terms of cost, it's not only the material cost of each individual component, but ordering, stock and mounting cost as well. Also the required PCB area for each component adds to the total bill of material.

Testing shifts from the time consuming functional to the more efficient structural domain. Firmware code testing can be faster with higher coverage. As such, simpler test procedures reduce cost and make the solution more robust.

Programmability is an obvious benefit of a digital implementation. Important settings can be adjusted on-the-fly during development to find optimum solutions or to try alternative algorithms. Besides programming also status information can be queried from the controller to run diagnostics on critical parameters.

Where analog implementations thrive for linear algorithms, digital implementations are far more appropriate when non-linearity is involved. An example could be a parabolic compensation curve instead of a linear gain curve. The situation is even more in favour of digital when discontinuities are to be considered. Switching between voltage and current control can be done instantaneous in digital without disturbance whereas for an analog implementations this becomes difficult to achieve.

In combination with mentioned diagnostics, advanced protection mechanisms can be implemented. "if… then…" and "case… if…" kind of detections are in the nature of a digital implementation. Besides detection also the action to be taken when a protection is triggered can be more advanced. For example, a triggered protection could result in a number of automatic restarts of the converter before shutting down and flagging the error condition to a host.

Digital hardware is less susceptible for EMI. Where information in analog signals depends on very small voltage changes, the information of a digital signal is contained in distinct voltage levels, e.g. 3.3V and 0V.

Finally digital technologies open avenues to new features and functionality not possible with analog hardware. Sophisticated algorithms can improve user experiences and add value to a solution.

1.2. Digital up-down converter

A digitally controlled power converter - shown in Figure 1.1 - has been designed. Power processing is done on the main board and a separate piggyback board is equipped with the microprocessor. The power converter is bidirectional, automatically switches between up or down conversion, regulates either output voltage or current and is scalable in modules of 360W. Interleaving is applied by a split in two separate power phases. All control parameters and settings are I2C programmable via a dedicated GUI. Table 1.1 presents an overview of the most important specifications.

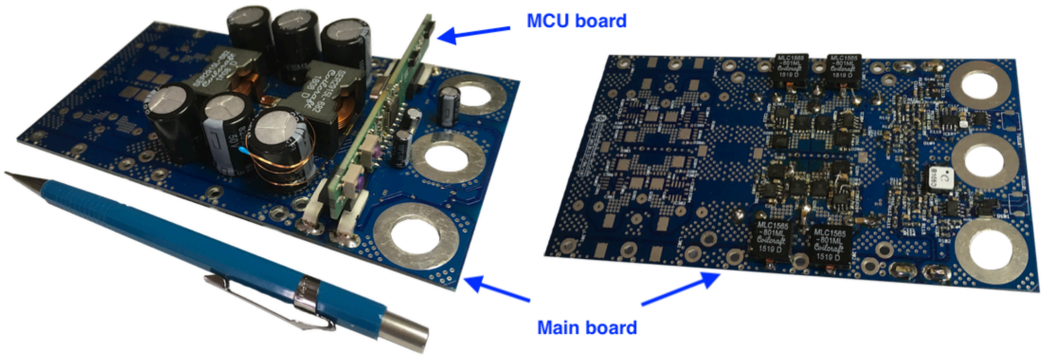

Fig. 1.1 *Digitally controlled 365W bidirectional automatic up/down converter (left: top view, right: bottom view) - board space is reserved to include a second module which is not mounted yet*

Tab. 1.1 *Specification*

Symbol	Description	Min	Typ	Max	Unit
V_i	DC input voltage	7.5		35.0	V
V_{o1}	DC output voltage range 1	7.5	14.4	17.5	V
V_{o2}	DC output voltage range 2	15.0	28.8	35.0	V
ΔV_o	DC output voltage programming resolution		10		mV
I_{o1}	DC output current range 1	0	25.0	27.5	A
I_{o2}	DC output current range 2	0	12.5	13.8	A
ΔI_o	DC output current programming resolution		25		mA
f_{sw}	switching frequency	150	200	250	kHz
T_a	ambient temperature during operation	25		80	°C

2. Power architecture

Central to the power architecture shown in Figure 2.1 is a 32 bit Arm Cortex MCU. Supplied from an auxiliary supply, this MCU drives the four switch fixed frequency up-down interleaved power stage modules. Multiple power stage modules can be connected in parallel to scale the power capability of the converter. Each power stage module is designed to supply a maximum continuous power of 360W. The Python based GUI gives access to the MCU via I2C communication.

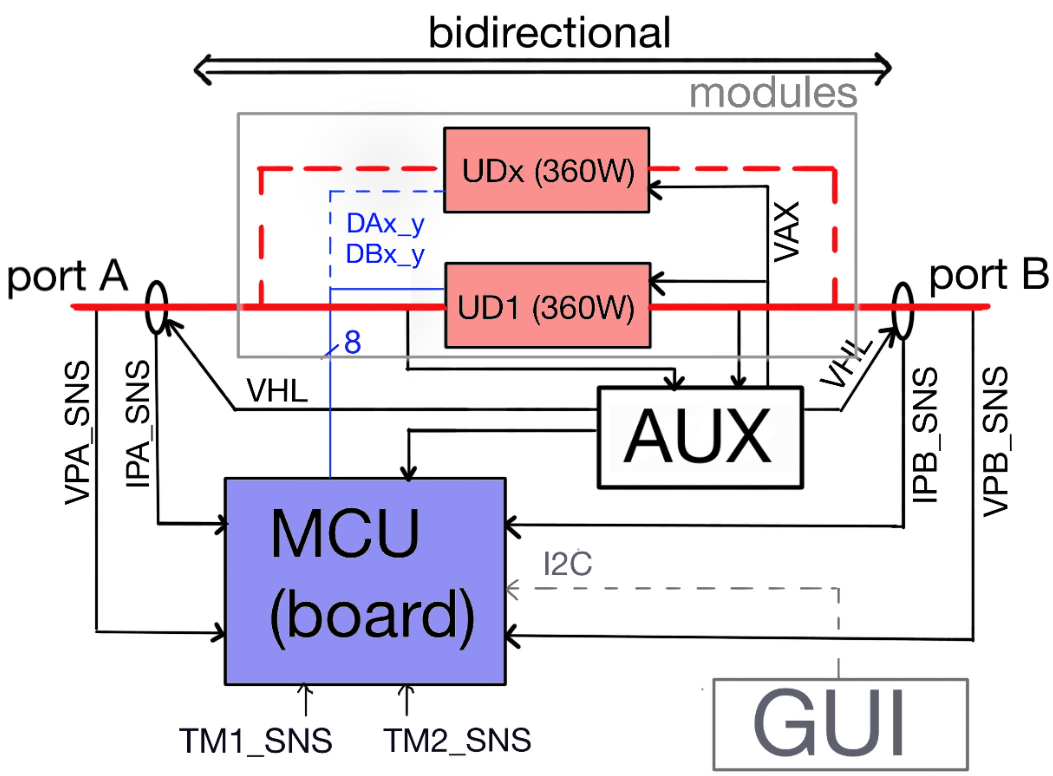

Fig. 2.1 *Microprocessor controlled bidirectional power architecture*

Port A and port B are the power ports of the converter. Due to converter bidirectionality both ports can be configured as either input or output. The voltage and current of each port is sensed and the sense signals are input to the MCU. Current is sensed and amplified via dedicated and power efficient Hall sensors. Based upon the sensed values and by means of voltage mode (duty cycle) control, the processor controls either the output voltage or the output current depending on the programmed settings. The MCU controls the power stage modules by means of 8 logic signals: 4

signals for the first phase of the interleaved power stage and 4 signals for the second phase.

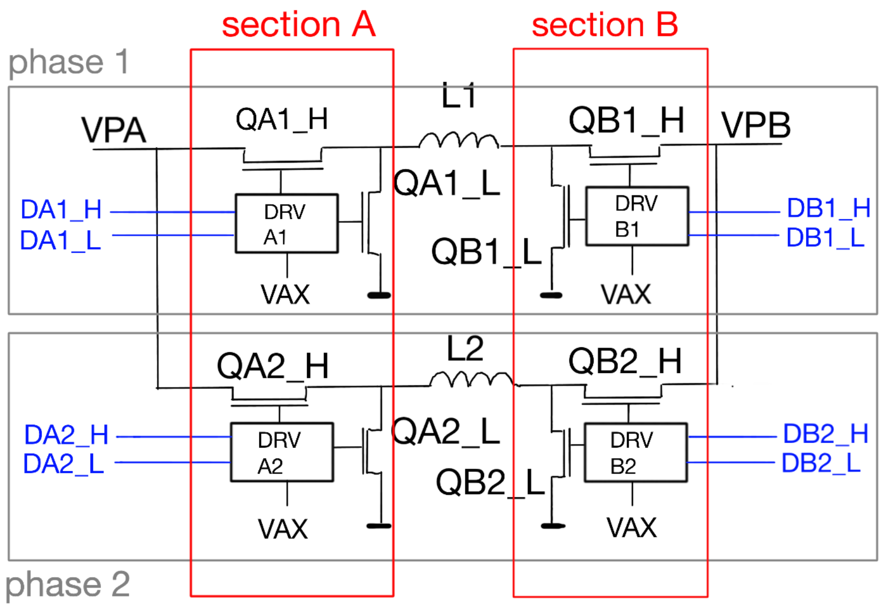

Fig. 2.2 *Dual phase four switch up-down topology per power stage module*

Each power stage module uses a two phase interleaved four switch up-down topology as shown in Figure 2.2. Both up-down topologies are symmetrical and as such facilitate bidirectional operation. Actual power flow direction and up or down mode, determine the switching nature of the individual half-bridges which consist of two stacked NMOS devices. In down mode the A totem pole sections are switching while the high side switches of the B totem pole sections are continuously conducting. Alternatively, in up mode, the B sections are switching while the A sections high side switches are continuously conducting.

Two external temperature sensors are provided that together with the internal MCU temperature sensor can be used for temperature protection.

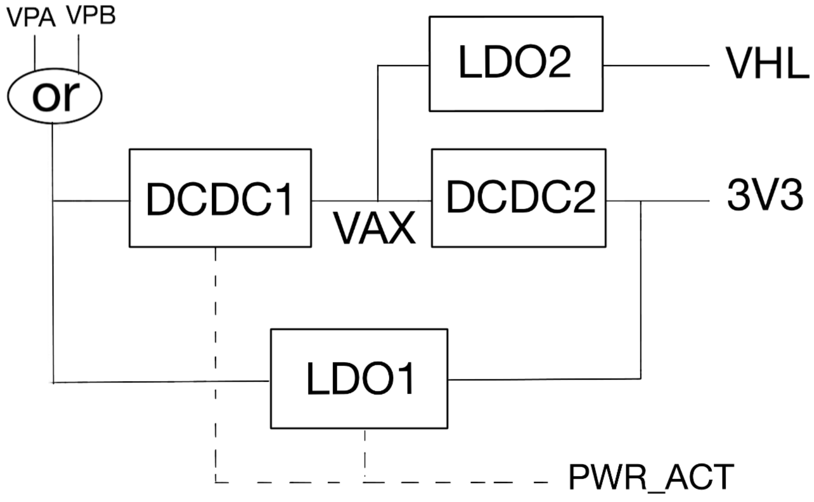

Fig. 2.3 *Auxiliary supply generation*

Two DC/DC converters, an integrated LDO and a discrete series regulator generate the necessary supporting supply voltages, see Figure 2.3. Input to the converters and regulators is the highest voltage derived from port A or port B.

3. Hardware design

A power stage module as depicted in Figure 3.1 is controlled by a smart duty-cycle algorithm that reduces drive power consumption by switching only one of the half-bridge sections at the same time. No additional external error amplifiers are required since the measured voltage and current signals are digitally processed in the MCU. This digital signal processing facilitates on-the-fly compensator coefficient adaptation and intelligent gain compensation for better stability. Dead-time between toggling of the high and low-side MOSFET is achieved by a fixed but programmable time delay. An optional additional external Schottky diode is provided for each driver to improve bootstrap performance of the driver IC.

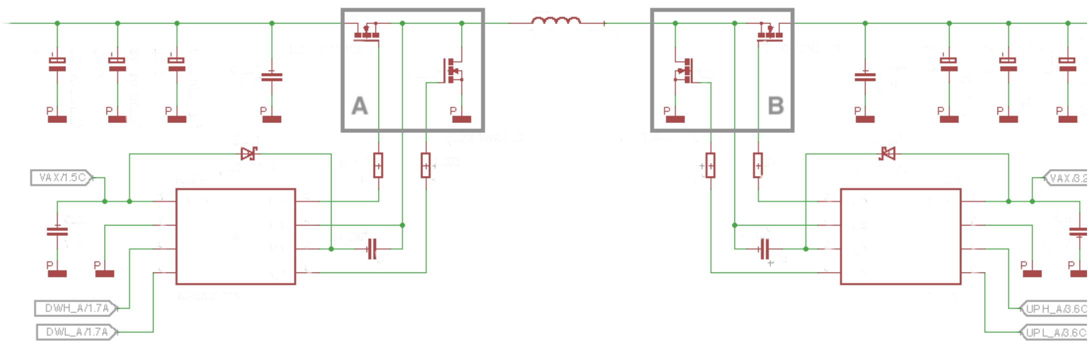

Fig. 3.1 *Single phase of interleaved power stage module*

The MCU as shown in the simplified block diagram in Figure 3.2 digitises the analog sensed input and output voltage and current and compares the digital signals to the programmed digital reference values before processing the error information in a hardware accelerated floating point unit according a second order control law. Dedicated timer peripherals, optimised for high speed and high resolution timing accept the result of the control law an generate a PWM signal for the external hardware driver IC. Direct memory access is implemented to achieve fast signal processing without spurious time delay to avoid interference with the control loop. During operation and on-the-fly, a host can access the MCU via an I2C interface. Settings are stored in registers residing in the flash memory.

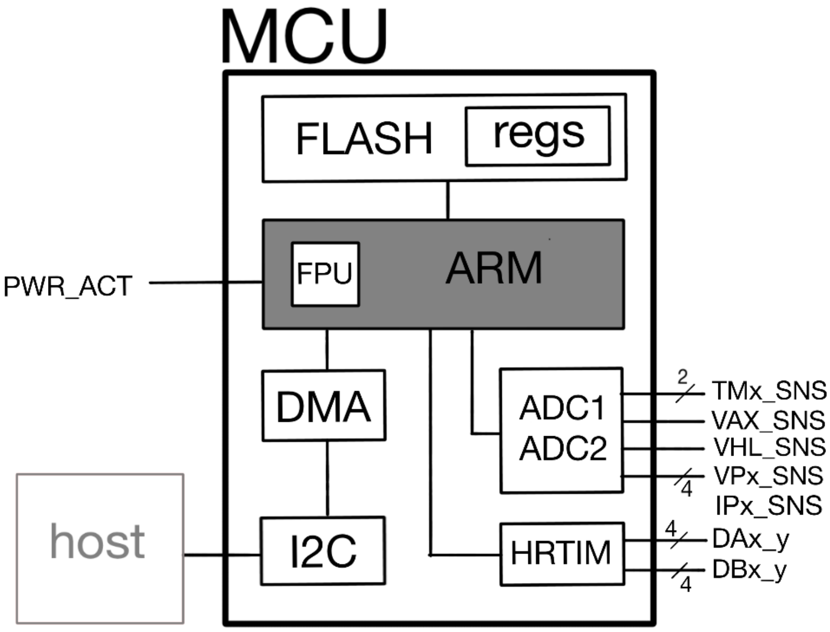

Fig. 3.2 *Micro-Controller Unit with relevant peripherals*

Figure 3.3 presents the implementation of the auxiliary supply architecture. A first switched mode DC/DC converter is supplied from the highest available port voltage. The output voltage of this first converter supplies the half-bridge drivers and is input to a second switched mode DC/DC converter that generates a stable 3.3V supply voltage for the MCU. A discrete series regulator generates a dedicated 5V supply voltage for the Hall sensors in order to have accurate input and output current readings. During low power modes, the MCU can turn-off the first DC/DC converter resulting in reduced power consumption since the Hall sensors are disabled as well as the second DC/DC converter. Turning off both DC/DC converters eliminates switching loss produced in these converters. At the same time the integrated parallel LDO is turned on and keeps the MCU alive.

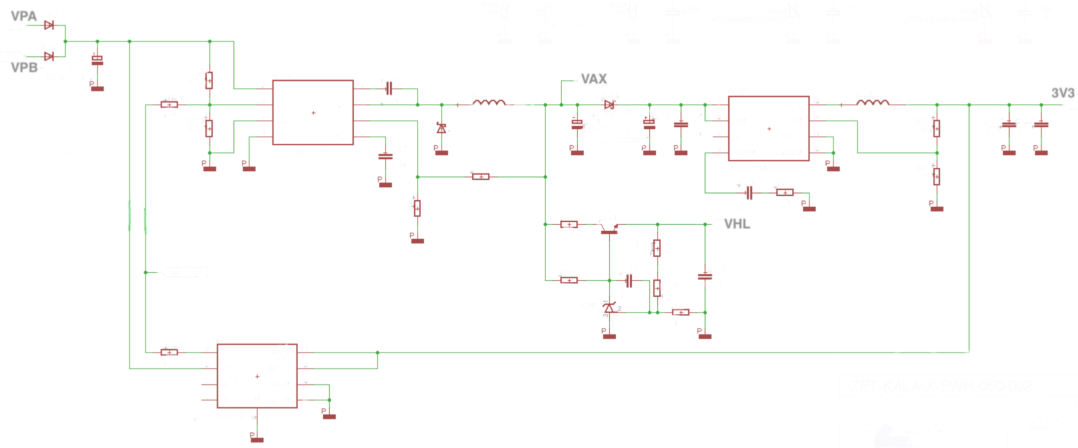

Fig. 3.3 *Auxiliary supply architecture*

4. Firmware design

Basically the firmware is split-up in two parts: the main loop and the interrupt service routines (ISR). All peripherals described earlier - HRTIM, ADC, I2C and DMA - run autonomously and trigger an ISR to handle timing critical functions. A nested vector interrupt controller (NVIC) determines the priorities of the timing critical priorities. Appropriate settings of priorities are crucial for the effectiveness of the power converter. Non-timing critical functions, like for example the external temperature measurements run in the main loop and are handled whenever the MCU is not servicing one of the interrupts.

5. Graphical User Interface

A Python based graphical user interface (GUI) provides host access to the MCU via I2C. The current version of the GUI uses an Aardvark host adapter from the company Total Phase. Next to a general "dashboard" overview, separate tabs in the main window are dedicated to settings and control loop aspects. In the future, the GUI can be extended with new features like spread spectrum control.

5.1. Dashboard

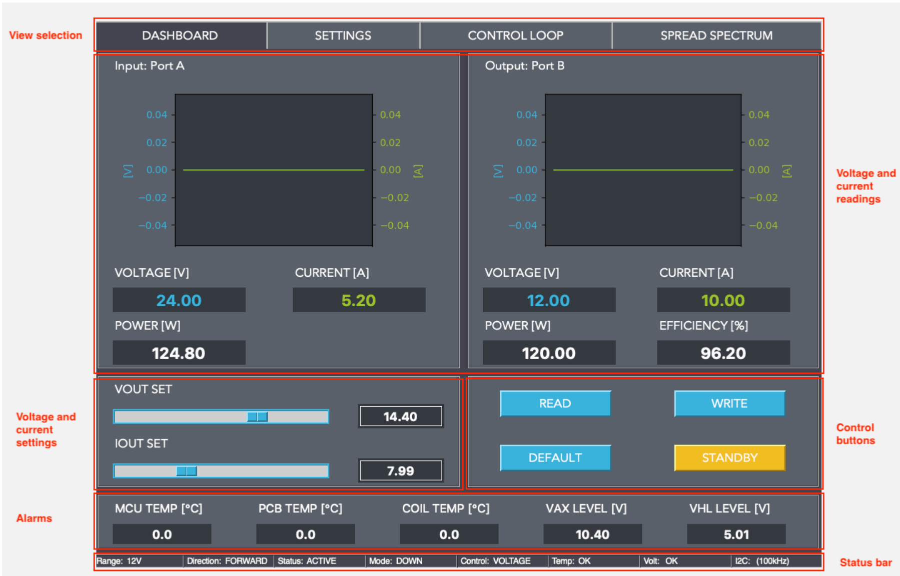

Fig. 5.1 *Graphical user interface: dashboard screen*

The main screen of the GUI, shown in Figure 5.1, is the dashboard. This dashboard is split in multiple areas. The view selection tabs are used to change screens. In the voltage and current readings area, actual port A and port B voltage and current readings are represented numerical and graphically. Based upon these readings, the input power, output power and efficiency are calculated. Output voltage and current setting can be changed on-the-fly by either the sliders or a numerical entry in the voltage and current settings area. All settings can be read from the MCU or written to the MCU by respectively pressing the "READ" or "WRITE" button. Default settings - without writing them to the MCU - can be recovered by pressing the "DEFAULT" button. Toggling the "STANDBY"/"ACTIVE" button controls the actual state of the converter, but only after writing the settings to the MCU. The four buttons are available in the control buttons area. Actual temperatures and auxiliary supply levels are measured and shown in the alarms area. The limits of the alarm ranges can be programmed in the settings screen. Finally, the status bar, which is visible on all screens, shows relevant status information.

5.2. Settings

Fig. 5.2 *Graphical user interface: settings screen*

Specific converter settings can be arranged in the various areas of the settings screen, shown in Figure 5.2. Besides changing the converter operating range between 12V and 24V, which has an impact on the output voltage and current range, also the direction can be changed. The actual direction is represented in the diagram. Underneath this diagram the operating frequency can be set as well as minimum and maximum duty cycle. Protections can be enabled in the protection settings area. Per port the minimum and maximum voltage can be set as well as the maximum current. Finally the ranges of the various alarms in the status bar can be set from the alarm settings area. Mind that all setting changes are effective only after writing the settings to the MCU with the "WRITE" button.

5.3. Control loop

Fig. 5.3 *Graphical user interface: control loop screen*

Two sub-tabs are available in the control loop screen - Figure 5.3 - to select either the voltage control loop or the current control loop. In both cases the coefficients are programmable on-the-fly. Mind that changes to the coefficients only take effect after writing the data to the MCU via the dashboard screen. A graphical representation of the state space averaged converter model ("cnv"), compensation filter ("ctl") and total loop ("loop") is available for reference. The converter model parameters at the top of the screen are used for calculating the converter model. Automatic gain control can be enabled via the AGC button. When turned on and after "WRITE", the MCU compensates converter gain automatically by changing the compensation filter according the actually measured input and output quantities.

note: the current control loop settings programmable via I2C are not yet implemented.

5.4. Spread spectrum

note: the spread spectrum feature is not yet implemented.

6. Outlook

6.1. Status and progress

Hardware (see cover) and firmware for the first prototype are available. Tests and debugging are ongoing and have been carried out up to a level of 10A or 100W. A second version of the hardware with focus on half-bridge driver optimisation and decoupling is under development. The project is in search for a carrier application to better specify the requirements and balance the tradeoff between performance and cost.

6.2. Considered features

Whereas analog circuitry is strong in time critical and accurate power processing, the underlying digital implementation of the automatic up-down DC/DC converter is ideal for implementing intelligent and strongly non-linear features. Advanced "top level" power processing algorithms can be integrated seamlessly.

6.2.1. Phase shedding

Phase shedding allows phases of the power converter to be turned off when power reduces and in doing so, reduce switching loss and thus improve power efficiency. For the dual phase interleaved power stage module this means that one of both phases can be turned off when the power drops below a certain programmable level. One could even consider to increase granularity when multiple power stage modules are put in parallel. E.g. two power stage modules consist of four phases which might be turned off independently.

6.2.2. Power optimiser

Both port A and port B voltage and current is measured. Based upon the measured values, the input and output power and power efficiency can be calculated. An advanced algorithm can change the switching frequency in order to find sweet spot in terms of power efficiency.

6.2.3. Spread spectrum

Electro-magnetic interference (EMI) is a major issue in switched mode power supplies. In order to mitigate the emitted electro-magnetic disturbance, the switching frequency can be modulated with a low frequency signal such that the spectral power density of the EMI is smeared out. This measure compromises between a unique frequency having a high EMI power density and a frequency spectrum having low EMI. The kind of modulation - sine-wave, triangular or alike - can add additional benefits.

Glossary

ADC	Analog to Digital Converter
DMA	Direct Memory Access
EMI	Electro-Magnetic Interference
FPU	Floating Point Unit
GPIO	General Purpose Input Output
GUI	Graphical User Interface
HRTIM	High-Resolution Timer
I2C	Inter-Integrated Circuit
IC	Integrated Circuit
ISR	Interrupt Service Routine
LDO	Low Drop-Out series regulator
MCU	Micro-Controller Unit
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
NMOS	n-channel MOSFET
NVIC	Nested Vector Interrupt Controller
PEC	Packet Error Control
PLL	Phase Locked Loop
PWM	Pulse-Width Modulated

Revision	History	Date
1.0	Initial	09-05-2019