Energy-Efficient Electrical Power Distribution with Multi-Agent Control at Parallel DC/DC Converters

Janos Hamar, Peter Bartal and Daniel T. Sepsi

***Abstract*—**Consumer electronics are pervasive. It is impossible to imagine a household or office without DVD players, digital cameras, printers, mobile phones, shavers, electrical toothbrushes, etc. All these devices operate at different voltage levels ranging from 1.8 to 20 VDC, in the absence of universal standards. The voltages available are however usually 120/230 VAC at 50/60 Hz. This situation makes an individual electrical energy conversion system necessary for each device. Such converters usually involve several conversion stages and often operate with excessive losses and poor reliability. The aim of the project presented in this paper is to design and implement a multi-channel DC/DC converter system, customizing the output voltage and current ratings according to the requirements of the load. Distributed, multi-agent techniques will be applied for the control of the DC/DC converters.

***Keywords*—**DC/DC converter, energy efficiency, multi-agent control, parallel converters.

I. INTRODUCTION

TODAY still, the energy distribution system suffers from its lack of flexibility, which seriously hinders optimization efforts or the large-scale introduction of home power plants connected to the grid. In the past, this scheme was not problematic because electrical energy was almost exclusively used for lighting and fixed-speed rotary motors. Today most loads do not directly use 120/230 VAC (50/60 Hz), but need other (often low DC voltages) for proper operation. The inflexibility of the system forcibly moves the problem of conversion to the consumers, which have to handle it on an individual basis. Neither the efficiency nor the costs of this approach are sustainable. The situation is similar in the case of renewable energy sources connected to the power distribution network. Normally several conversion stages are required to interconnect these systems with the grid (DC-to-AC or AC-to-DC-to-AC).

This research paper focuses on future intelligent, low-power residential electrical distribution systems with multi-channel dc-dc converters as shown in Fig. 1. The single input/multiple output converters, investigated in this paper, are supplied with DC power and the output voltage of each converter channel is controlled by the intelligent agent associated with the load. The agent-based control determines also which converters are to be turned on or off in order to ensure optimized power transfer. The aim of the optimization of the research was the maximization of the efficiency of the power conversion stage.

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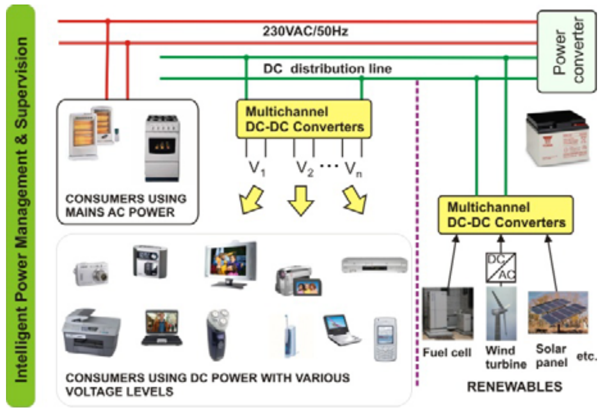


Fig. 2 Multichannel DC/DC converters in local power distribution

II. TOPOLOGY

For this project the buck (step-down) converter was chosen both because of its simple topology and for the wide range of control algorithms that can be implemented.

Digital control, which sports extreme flexibility and (re)configurability, was chosen over analog control. The parallel converters are controlled by a microcontroller, which runs the multi-agent software.

The basic configuration of the proposed agent-based control is shown in Fig. 2. The converters are assigned to control agents, while the output load is assigned to consumer agents. The consumer agents have the same basic tasks: measuring the output voltage and calculating the global current reference $I_{ref,total}$ from the reference output voltage $V_{out,ref}$ and the measured output voltage V_{out}. A negotiation between the consumer agents is initiated after turning on the system, which results in the selection of the only active agent, while the other ones become passive, that is, they do not initiate any communication or make decisions, only accept incoming messages. Thus, a simple hierarchy is established. During normal operation the same consumer agent will stay active until the next start-up, however in the event of malfunction or failure the agents can pass on its role to another properly working agent (if sufficient redundancy is provided for), increasing the failure safety of the overall system. The implementation presented in Fig. 3 takes advantage of the flexibility provided by the variable structure. Fully distributed control of the paralleled conversion units can be achieved with quasi-optimal operation and increased error tolerance. In the proposed implementation the control agents are assigned to microcontrollers, while a consumer agent is also implemented in each microcontroller as shown in Fig. 3.

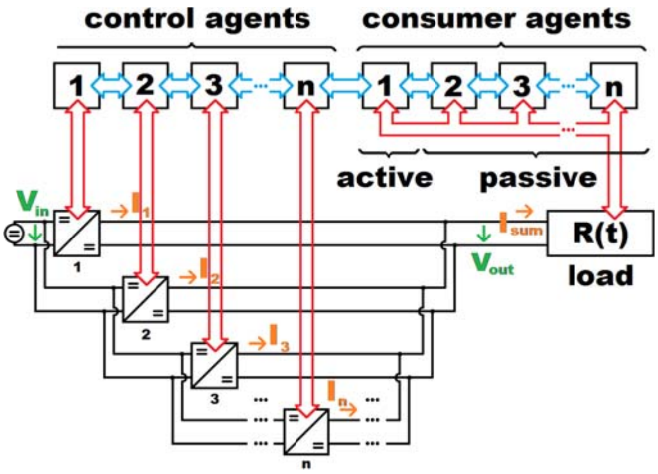


Fig. 2 Parallel energy conversion system with agent-based control

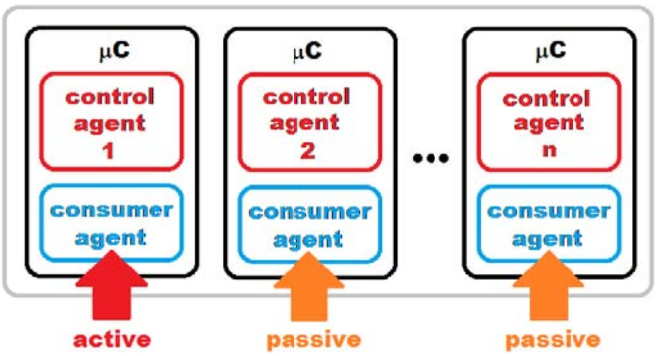


Fig. 3 Implementation of control and consumer agents

Control agents have basically two important roles. First, every single agent makes decisions (locally) to optimally fulfill the overall (global) control strategy. Second, the control agent is responsible for the low-level control of the converter as shown in **Error! Reference source not found.**4.

An external control loop keeps the output voltage level (V_{out}) constant, while an internal control loop, which takes into account the decision of the agents, controls the current of each converter. The control agents negotiate with each other to optimally share the current among the parallel converter units:

$$I_{ref,total} = I_{ref,1} + I_{ref,2} + ... + I_{ref,n} \quad (1)$$

where $I_{ref,i}$ is the reference current value of the i-th control agent (converter), and n is the number of the control agents. For this purpose a current sensor monitors the inductor current ($I_{L,i}$) from each converter.

The main advantage of this approach is that adding consumer agents requires only modification of the software running in the embedded microcontrollers, without further hardware need, thus reducing the overall system costs.

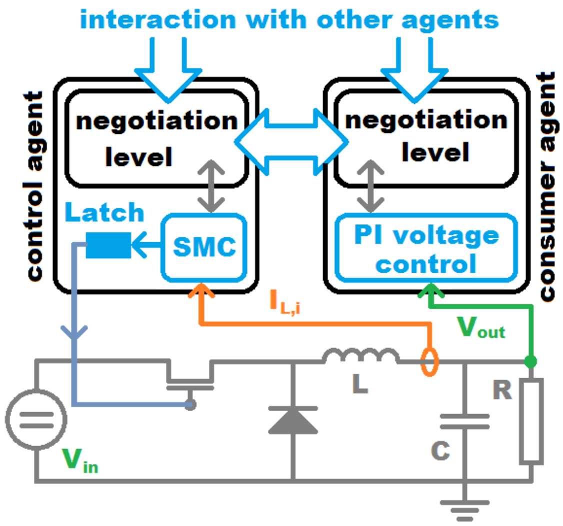


Fig. 4 Interaction between the agents and the buck converter

III. Control

In order to make the system operate smoothly, the following conditions and criteria are drawn up. The control strategy will be defined, taking into consideration these aspects:

1. To avoid any damage in the semiconductor switches (MOSFETs), an upper limit for the inductor currents is prescribed: $I_{L,i} < I_{L,max}$.

2. The power loss of each switching converter P_{loss} changes with load current (I_L). Power loss consists of two components: $P_{loss} = P_{switch} + P_{conduction}$. P_{switch} is the switching loss associated with the MOSFET switching transition, and $P_{conduction}$ is the conduction loss from the MOSFET on-resistance. The efficiency comes from the following equation:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + P_{loss}} \quad (2)$$

The typical efficiency curve of a buck converter has a peak associated to a certain current. Any alteration in the current value results in decreased converter efficiency. On the basis of the efficiency curves, every single converter has an optimal load current $I_{L,OPT}$, where efficiency η is maximal. From (2):

$$\frac{P_{loss}}{P_{out}} = \frac{1}{\eta} - 1 \qquad (3)$$

According to the efficiency curve (Fig. 5), this equation has a minimum at $I_{L,OPT}$ (and conversely, efficiency reaches its maximum). When the converter is turned off, its power loss is nearly zero. A cost function, penalizing the power losses, is assigned every single converter:

$$\mu(I_{L,i}) = \begin{cases} \frac{1}{\eta(I_{L,i})} - 1 \leftarrow if : I_{L,i} \neq 0 \\ 0 \leftarrow if : I_{L,i} = 0 \end{cases} \qquad (4)$$

To define optimization strategies a cost function was created, which is minimized by the control agents. To demonstrate the viability of the control scheme the following simple function was selected:

$$f_{\cos t} = \min_{i_{L,1} \ldots i_{L,n}} [W_1 \sum_{i=1}^{n} \mu(I_{L,i})] \qquad (5)$$

where W_1 is a weighting factor.

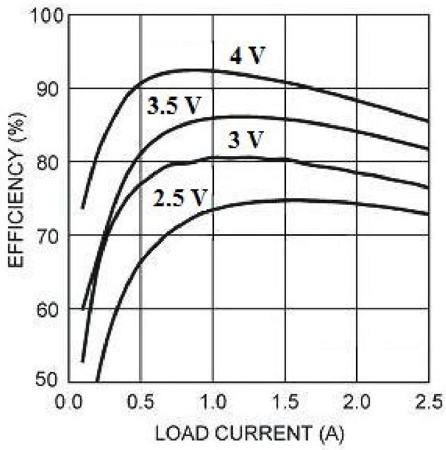


Fig. 5 Typical efficiency vs. load current curves of the buck converter for different output voltages

Control agents share their currents to minimize this cost function and, in addition, two conditions must be satisfied:

1. $I_{L,i} < I_{L,max}$ for all converters that are on;
2. $I_{ref,total} = I_{ref,1} + I_{ref,2} + \ldots + I_{ref,n}$.

It is worth noting here that various other cost functions can be defined, e.g. output power maximization, voltage ripple minimization, etc. Several such criteria can be incorporated into a cost function, with different weighting factors W_i, to prioritize one or the other criterion, depending on the needs of a specific application.

Identical DC/DC converters are used to reduce costs, implying that the efficiency curves of the converters are also the same. To minimize the cost function, a possible solution for load current distribution can be that m-1 DC/DC converters are operated in their optimal point (with maximum efficiency), while the m^{th} converter provides the remaining current, resulting in: $I_{sum} = (m-1)\, I_{opt} + I_m$, the total current required by the consumer. This is also in line with the “selfishness” principle of intelligent agents. This principle states that every intelligent agent seeks to minimize its own costs.

Each of the control agents decides about turning on or turning off their respective converter. At any load current value, an optimal number of turned on converters always exist, which assures the minimum value of the cost function. Increasing or decreasing the number of the converters, which are turned on, that is, having a different number of converters working than the optimal number, the cost function is monotonically increasing.

Let us assume that m is the number of the turned on converters at a certain moment, and n is the total number of the paralleled converters. The process to find the optimal number of turned on converters is presented in Fig. 6.

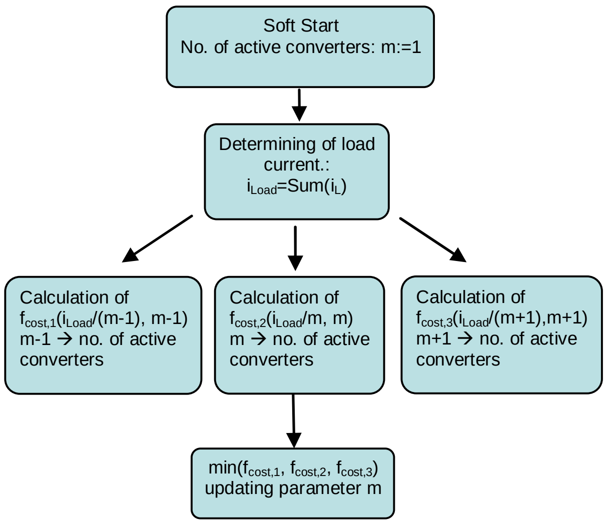


Fig. 6 Process leading to determine the optimal converter number

This method guarantees that the control agents find the minimum of the cost function for every value of the load current. When more than one converter should be turned on or off due to a sudden significant change of the load current, the control agents will perform it in several consecutive steps. It means that the transients will appear consecutively in the load current, and in the output voltage.

IV. Simulation Results

Four paralleled step-down converters were simulated using the Matlab/Simulink program package. The block diagram of the control can be seen in Fig. 7. The converters have the following parameters: $L = 39\ \mu H$, $C = 680\ \mu F$, $r_c = 20\ m\Omega$, $f_s = 400$ kHz, where r_c is the series resistance of the capacitance, and f_s is the switching frequency. The input voltage is $V_{in} = 9$ V, and the reference output voltage is $V_{ref} = 5$ V. The load resistance can be changed in steps.

During the simulation process, $I_{ref,total}$ is calculated by the active consumer agent from V_{out} and V_{ref} through a PI (proportional–integral) control algorithm. Next, a sliding mode control algorithm is applied for the subordinated current control by each of the control agents.

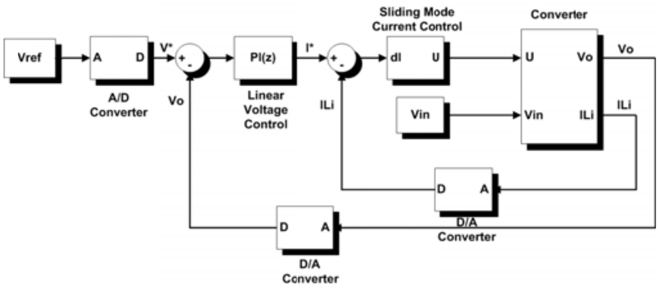


Fig. 7 Simulation block diagram of the control loops

The aim of the optimization here was the minimization of the power losses in the parallel converters. $W_1 = 1$ was selected. The load resistance R_{load} was changed according to the time function shown in Fig. 8. Initially the load current is 1 A; only one converter is turned on. In order to maintain 5V at the output, the control has to increase the output current from 1 A to 5 A (region II. in Fig. 8). It means that now all converters must be turned on. This can be followed also in the current graphs of each converter. The simulated inductor currents ($I_{L,i}$) of each converter i are shown in Fig. 10 (a) to (d).

Fig. 9 (a) shows the simulated output voltage V_{out}. The transients from switching on an additional converter can be seen a small ripples. They are much better visible in the voltage error graph (Fig. 9 (b)).

This value never exceeds 0.5 % in the simulation. It is to be noted that a higher number converters in operation yields a smaller disturbance in the control and in the output voltage. The reason is that the ratio between the total current of the already turned on converters and the current provided by the additional converter is getting smaller if the total number of the converters is increased.

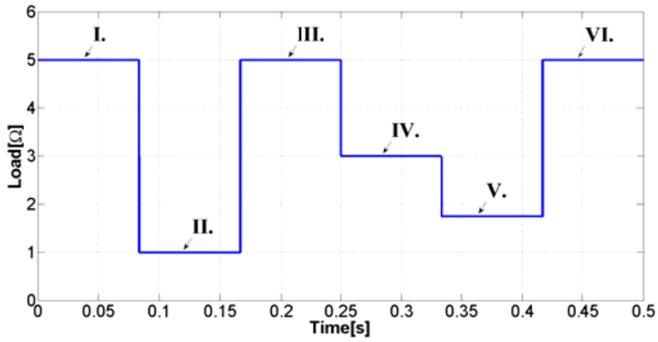
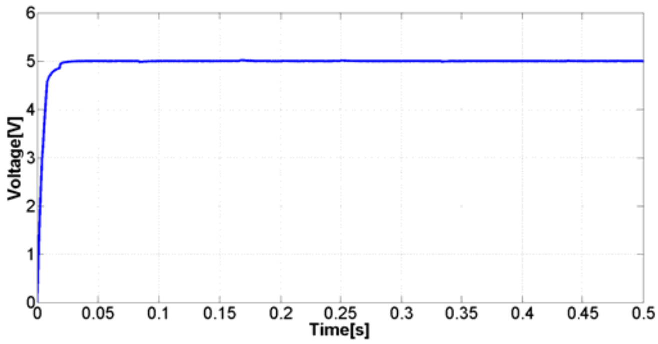
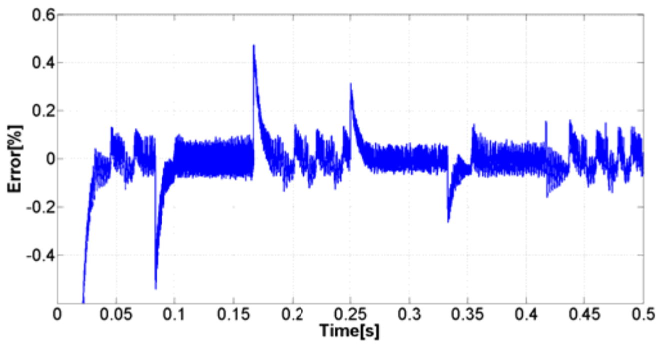


Fig. 8 Load profile

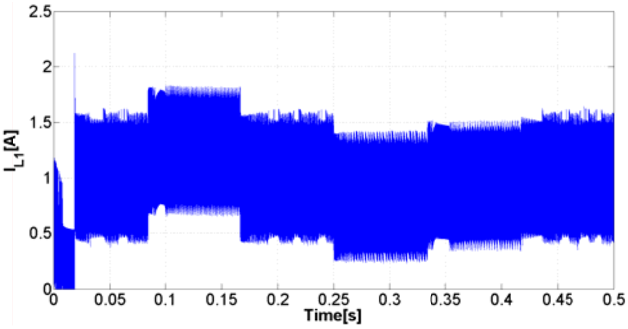


(a)



(b)

Fig. 9 (a) output voltage V_{out}, (b) output voltage error [%]



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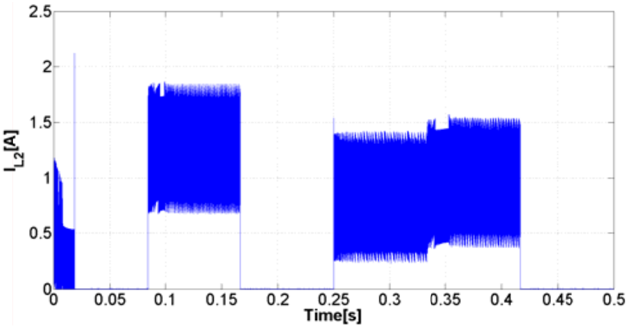

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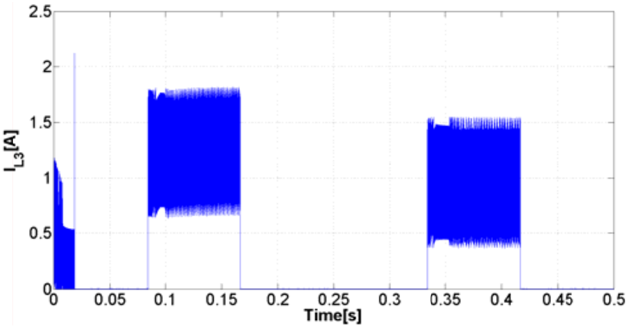
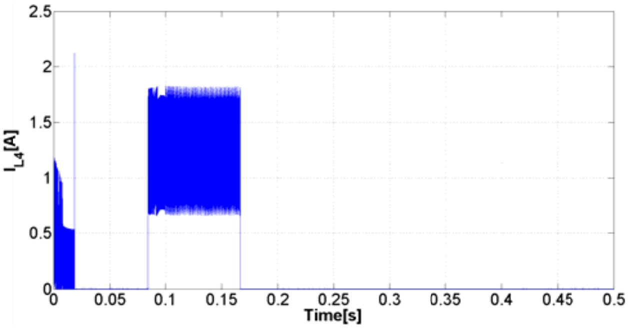


(c)

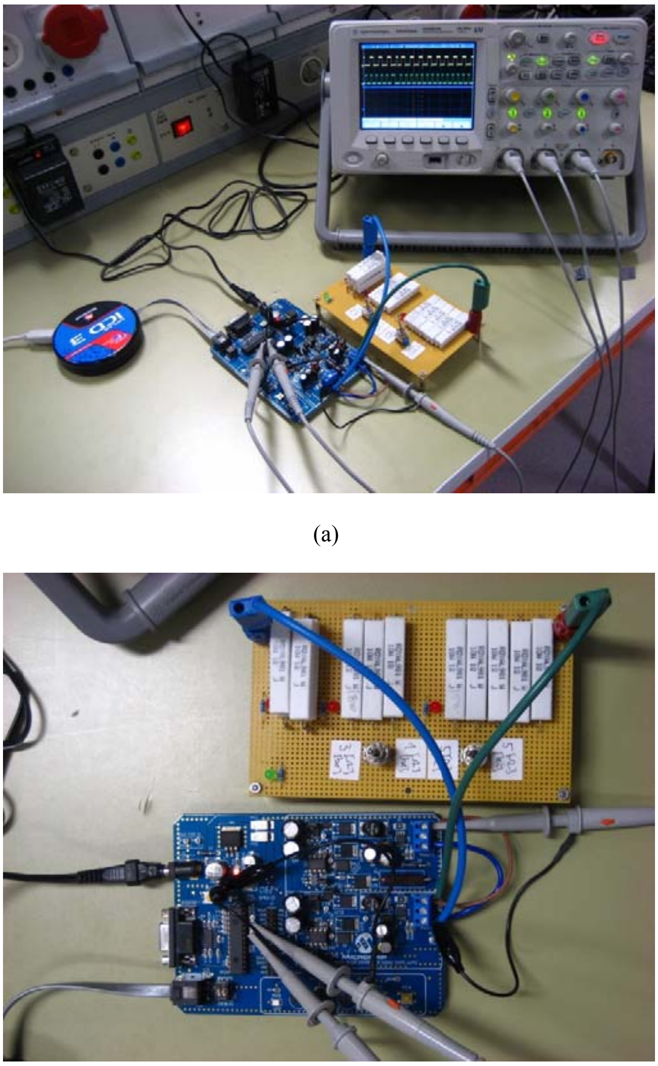


(d)

Fig. 10 Inductor currents of each buck converter: (a) $I_{L,1}$, (b) $I_{L,2}$, (c) $I_{L,3}$, (d) $I_{L,4}$

V. Laboratory Measurements

A Microchip dsPICDEM™ SMPS Buck Development Board was used for the laboratory measurements. A dsPIC30F2020 digital signal controller (DSC) controls two independent DC/DC synchronous buck converters. The experimental setup can be seen in Fig. 11.



(a)

(b)

Fig. 11 Experimental setup: (a) setup with oscilloscope and Microchip ICD3 debugger, (b) SMPS development board and switchable load

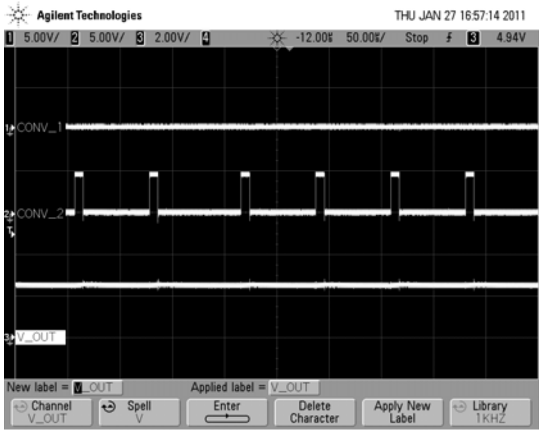
The software of the microcontroller provides a closed-loop Proportional, Integral (PI) control, cascaded with a sliding mode control (SMC) current loop to maintain desired output voltage and current levels. The dsPIC DSC device incorporates all the necessary memory and peripherals for A/D conversion and general purpose I/O, precluding the need to perform these functions in external circuitry. The used development board facilitates the agent-based control and investigation of parallel DC/DC converter units. In the laboratory measurement, two parallel converters on a board have been used. The parameters of the converters are the same as the simulated ones. The PI voltage control algorithm and the inner SMC current control algorithms are also implemented with the same parameters. The load resistance at the output of the converters is selectable; it can be switched between 5 Ω, 3 Ω and 1 Ω. Another 5 Ω load is attached to the output through a MOSFET that can be switched on or off by the microcontroller. Turning on this auxiliary MOSFET, the additional load resistance is connected in paralleled to the load at the converter output terminals. The cost function is defined so that the control agent turns on the 2nd converter when the load current exceeds the prescribed maximum value for efficient operation for the 1st converter, and turns off the 2nd converter when the load current drops below the aforementioned level. For this reason, during the laboratory measurement one of the converters was always on, establishing a sort of hierarchy between the converters.

The experimental results confirmed the theoretic considerations laid out in the previous sections. The results of the measurement are explained below.

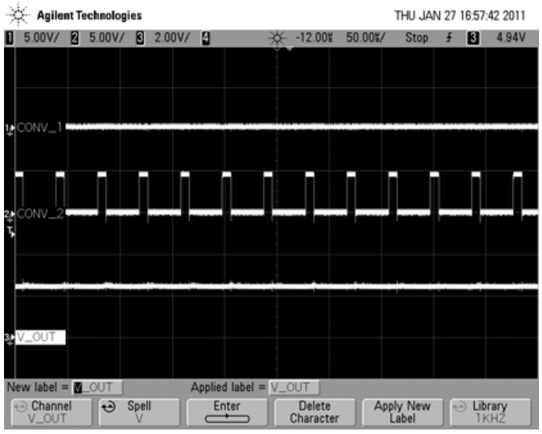
As can be seen in Fig. 12, the first signal (CONV_1) is the switching signal of one of the converters, the second (CONV_2) is that of the other buck converter (which stays always on) and the last signal is the output voltage (V_OUT). In Fig. 12 (a), (b) and (c) the output voltage is $V_{out} = 2.5$ V. The load is set to 5 Ω, 3 Ω and 1 Ω, respectively. It can be seen that as long as the load draws a current, which is below 1 A, only one converter will operate (resistance of 5 Ω and 3 Ω). When the load exceeds the prescribed limit, the second converter kicks in, supplying the rest of the required current (Fig. 12 (c)).

As a consequence of using the SMC algorithm for current control, the switching frequency of the converters is not constant, despite the constant sampling frequency, which is 400 kHz in this case (Fig. 13).

The transients in the output voltage V_{out}, resulting from the converters switching on and off can be seen in Fig. 14.



(a)



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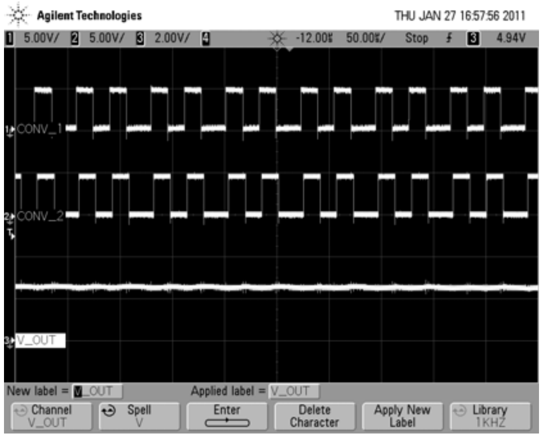


(c)

Fig. 12 Experimental readings: (a) $V_{out} = 2.5$ V, $R_{load} = 5$ Ω, (b) $V_{out} = 2.5$ V, $R_{load} = 3$ Ω, (c) $V_{out} = 2.5$ V, $R_{load} = 1$ Ω

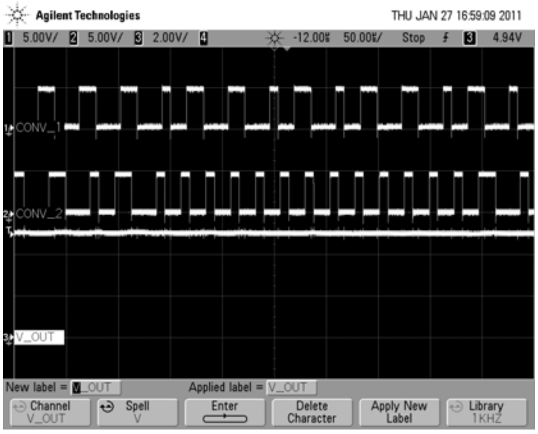
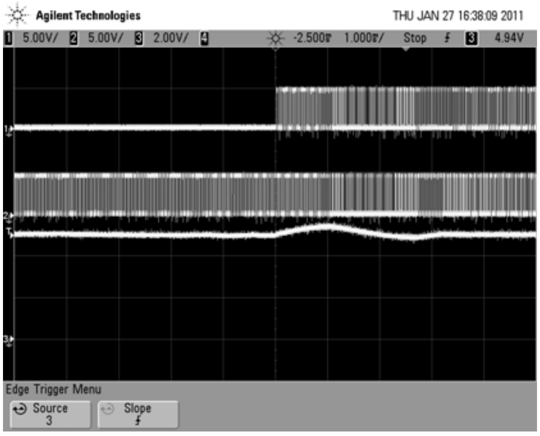
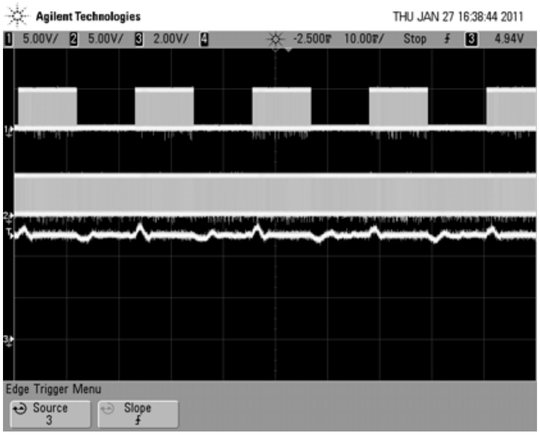


Fig. 13 Variation of switching frequency due to SMC (V_{out} = 5 V, R_{load} = 5 Ω)



(a)



(b)

Fig. 14 Transients resulting from a converter switching on or off (V_{out} = 5 V, R_{load} = 5 Ω)

VI. CONCLUSION

A multi-agent controlled energy conversion system consisting of parallel buck converters was presented as well as experimental results.

Future work will include demonstrations with more converters in parallel. Also, new cost functions will be implemented, to accommodate more optimization criteria (output voltage ripple, transferred power, etc.), which can be weighed against each other and thus prioritized.

ACKNOWLEDGMENT

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