Intelligent Home DC Power Network

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1 Introduction

The dependence of today's society from electric energy is undeniable. Yet, the power distribution infrastructure and the technology behind it have changed little, although in the last decades several advanced solutions have emerged, such as FACTS (Flexible AC Transmission Systems) or HVDC (High Voltage DC) lines. With the advent of distributed power generation and smart metering and consumers, new possibilities and new challenges have surfaced.

Smart homes are part of a new paradigm which encompasses also efficient energy distribution. With the focus on the efficiency of energy usage, it is not enough to have highly efficient end-users, the power distribution has also got to be efficient.
In a home, traditionally the wall sockets provide a fixed AC voltage (230 V or 120 V, depending on the location), which is then converted into the appropriate voltage (usually DC) for the end-user. This is not a very efficient approach. The paper proposes an alternative, using a DC power network built into a smart home with converters that are able to optimize the efficiency of the system by a method called phase-dropping, assuring high efficiency over a wide range of loads.

The next section presents the digitally controlled converters that work cooperatively and communicate with the "smart" load to set the appropriate voltage level. Section 0 details the phase-dropping concept, then in section 0 the results of an experimental prototype will be presented and finally the Conclusions section sums up the paper and offers an outlook on future research.

2 Cooperative Converters with Digital Control

Digital control has extended the possibilities of converter control greatly. The added flexibility and the possibility to use advanced algorithms have pushed the limits farther. Several microcontrollers have integrated ADC and DAC circuitry and PWM modules, such as the dsPIC family by Microchip, specially designed for power conversion and motion control applications. This allows to add functionality that was unthinkable with analog control.

Along this line, the power can be supplied by converters that communicate with each other and thus work in a cooperative manner. The converters would then be able to meet common goals and reach a global optimimum for certain system parameters.
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Along this line, the power can be supplied by converters that work in a cooperative manner, communicating with each other to reach an optimal working point in terms of efficiency and other criteria, too, such as output voltage ripple.
It is possible to define a function that gives a preceived value of the current share each converter carries. The natural choice for such a function is the efficiency curve of the converter. Unfortunately, it is very difficult to find a universal analytical formula for the efficiency of a step-down converter, let alone for converters in general. However, it is possible to measure the efficiency curve using various methods, including calorimetric[1] and electric[2] ones, the former being more accurate, albeit very slow and absolutely unsuitable for real-time efficiency measurement, while the latter is a fast, but less precise method.

Several converters in parllel will have a total efficiency:

$$\eta = \frac{\sum_{i=1}^{n} P_{out_i}}{\sum_{i=1}^{n} P_{in_i}}$$

where η is the efficiency, P_{out} is the output power, P_{in} the input power and i is an index denoting the current converter, while n is the total number of converters in parallel.
Given the fact that the converters are in parallel, the input and the output voltage are the same across converters, so these can be factored out and the formula reduces to:

$$\eta = \frac{\sum_{i=1}^{n} I_{out_i}}{\sum_{i=1}^{n} I_{in_i}}$$

with I_{out} the output current and I_{in} the input current. If the individual efficiencies (η_i) are known, the formula can be rewritten as:

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1 Wolfs, P. & Li, Q., "Precision calorimetry for power loss measurement of a very low power maximum power point tracker", *in the Proceedings of the Power Engineering Conference, 2007. AUPEC 2007. Australasian Universities,* **2007**, 1-5

2 Yu, W.; Qian, H. & Lai, J.-S. "Design of high-efficiency bidirectional DC-DC converter and high-precision efficiency measurement", *in Industrial Electronics, 2008. IECON 2008. 34th Annual Conference of IEEE,* **2008**, 685-690

$$\eta = \frac{1}{\sum_{i=1}^{n}\left(\frac{I_{out_i}}{\eta_i I_{out}}\right)} = \sum_{i=1}^{n}\left(\eta_i \frac{I_{in_i}}{I_{in}}\right)$$

Since the formula obtained is a function of the current, the valuation function used to determine how well a converter parforms can also be written as a function of current and will be easier to track.
In addition, if the aim is to have a low output voltage ripple, the ripple can be also incorporated into the valuation function and will yield a cost function of the form:

$$c_{total} = \min\left(w_1 \sum_{i=1}^{n} f_1(\eta_i) + w_2 \sum_{i=1}^{n} f_2(\Delta u_i)\right)$$

where w_1 and w_2 are weighting factors. Optionally a number of other weighted functions can be added, for various other optimization criteria.

3 Parallel Converters with Phase-Dropping

The majority of consumers in a home require a very different voltage from what is supplied by the AC network. Only very simple or obsolete devices still use directly the fixed AC voltage from the outlets, like small heaters, toasters or light bulbs, the latter condemned to be phased out very soon. Usually the AC voltage is converted into DC voltage or some high frequency AC signal, which does not even need to be sinusoidal.
In view of the above, it would be a “greener” approach to have a local DC network which recognizes the load it serves and sets the output voltage to meet its requirements. Needless to say, such low voltage DC networks would also mean a serious improvement in safety.

To illustrate the concept, consider Figure 2, where a distributed power supply is shown.
The voltage supplied by the AC line undergoes several conversion steps. It would be beneficial from efficiency point of view to have less power conversion stages in cascade and also from system complexity point of view.

The approach chosen by the author is to integrate the step-down and the point-of-load (PoL) converters or voltage regulator modules (VRM) into a single unit, with variable output voltage. Instead of a having two different converters, one to step down the voltage and another one to adjust it to the needs of the load, a single step-down converter would be sufficient to produce the voltage required by the load. This in turn requires the load to be “smart” and to be able to communicate with the converters to set the appropriate voltage level.

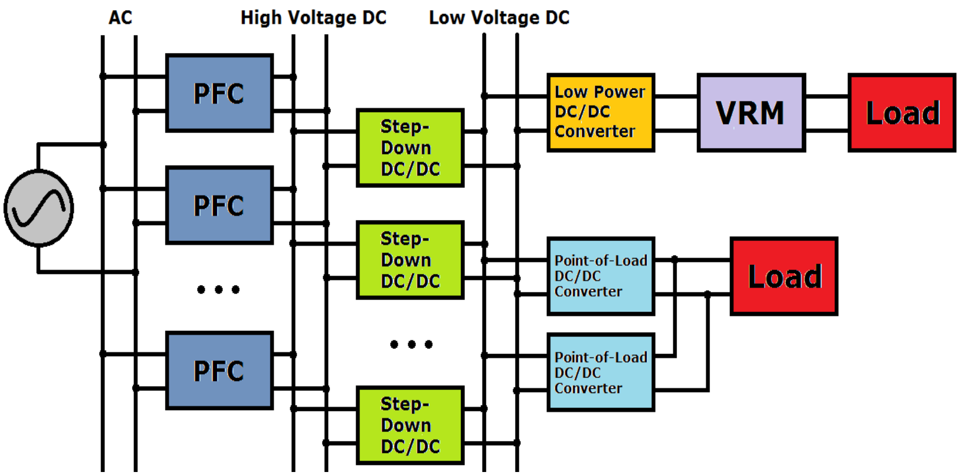

Figure 2: Distributed power system

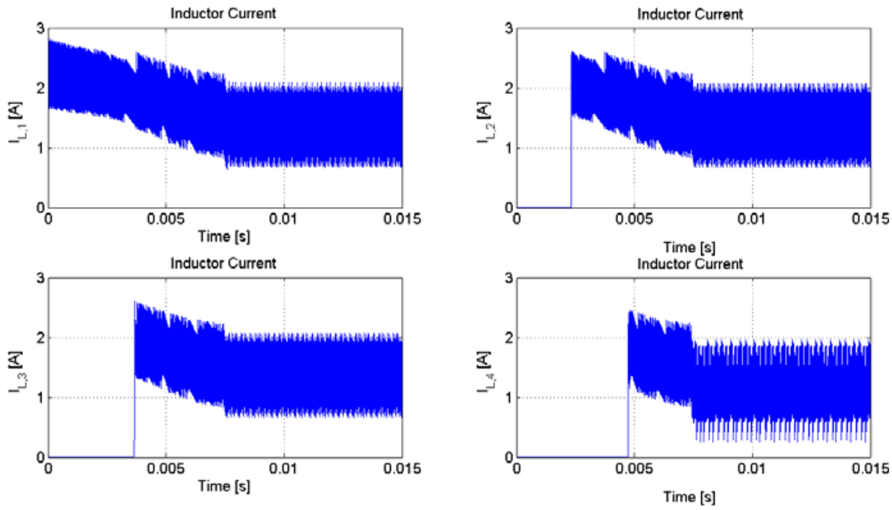

Figure 1: Simulated inductor currents of the converters in parallel at 5 V output voltage and with a load of 1 Ω

Phase-dropping refers to shutting down the converters that are not necessary to carry the load, letting the system work with the minimum number of converters (phases) necessary to deliver the required power. By doing so, the efficiency can be improved, especially

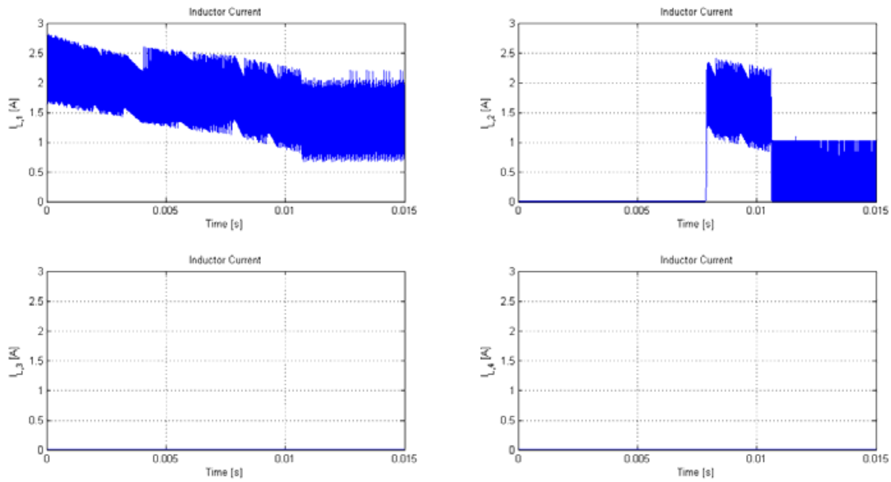

Figure 3: Simulated inductor currents of the converters in parallel at 5 V output voltage and with a load of 3 Ω

when the load is light. It is especially advantageous either in the case of loads that spend a lot of time idling or in stand-by (e.g. TV sets or hi-fi towers) or highly dynamical loads (such as PCs, game consoles or routers and switches).
A simplified version of this technique is used in the LTC3732 DC/DC regulator chip by Linear Technologies[3], but researchers at Intel have also experimented with phase-dropping.
The technique can be adapted to a DC network built into a smart home as will be described in the following paragraph.

If a smart load is connected to the DC power, the converters on the low voltage DC rail will communicate with the load determining the voltage level and current it requires and other parameters. With this information, the converters will decide how many of them are required to serve the load and only that number of converters will go online, while the others will not be turned on. If the load varies, the number of converters in operation can be changed dynamically, making sure that the efficiency of the system is maximized. Since in the setting presented here, the voltage ripple needs to be reduced, too, in fact a compromise will be reached, because reducing the output ripple is achieved by increasing the switching frequency, which in turn reduces efficiency. The compromise reached is affected by the weighting factors of the valuation functions.

[3] Linear Technologies, LTC3732 datasheet, available at: http://www.linear.com/product/LTC3732

4 Experimental Setup and Results

The concept has been tested on a SMPS (Switch-Mode Power Supply) development board by Microchip, which has two converters in parallel, controlled by a microcontroller. Two such boards were used, thus a total of four converters in parallel were available (shown in Figure 4).

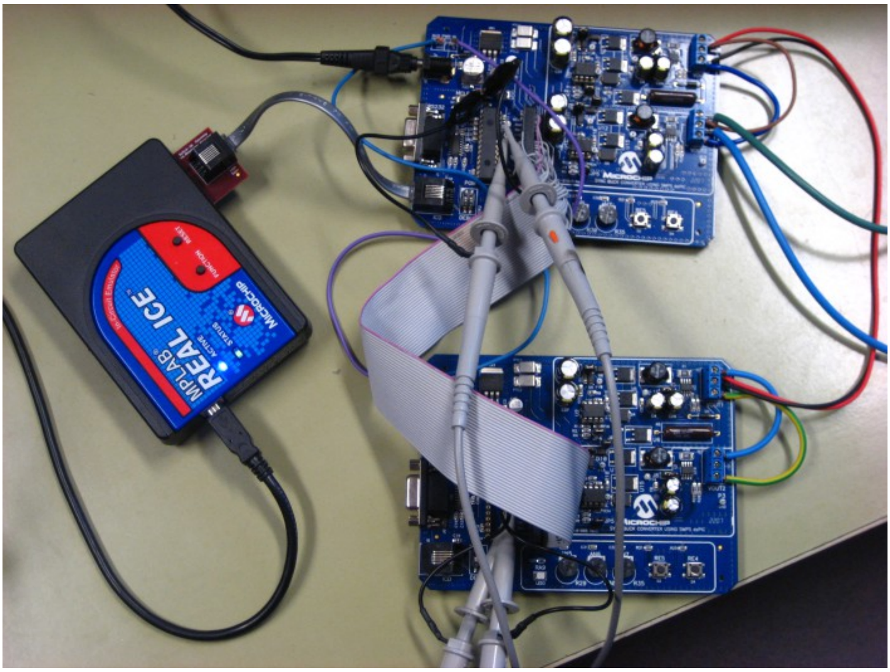

Figure 4: Experimental setup

Figure 1 and Figure show the currents simulated for each converter, in case various loads are connected to them. As can be seen, in the case of a heavier load all converters go online, while at lighter loads, only the required number to carry the load (in this case 2) will be operating.

The same is confirmed during operation, as resulted from monitoring the PWM signals of the converters (Figures 5 and 6).

Also, the reduced output voltage ripple, achieved through increasing the switching frequency is demonstrated for two different settings of the weighting functions in Figures 7 and 8.

4 Conclusions

In this paper a concept has been presented for an intelligent DC power network fed through step-down converters able to communicate with the load and to adapt their output to its needs.
Further research is necessary to assess the dynamic properties and the stability of the system. Also, another direction of research is to make the converters automatically form groups delivering different voltages to different loads. Of course, for this, the converters need to have access to switches connecting or disconnecting portions of the DC rail.

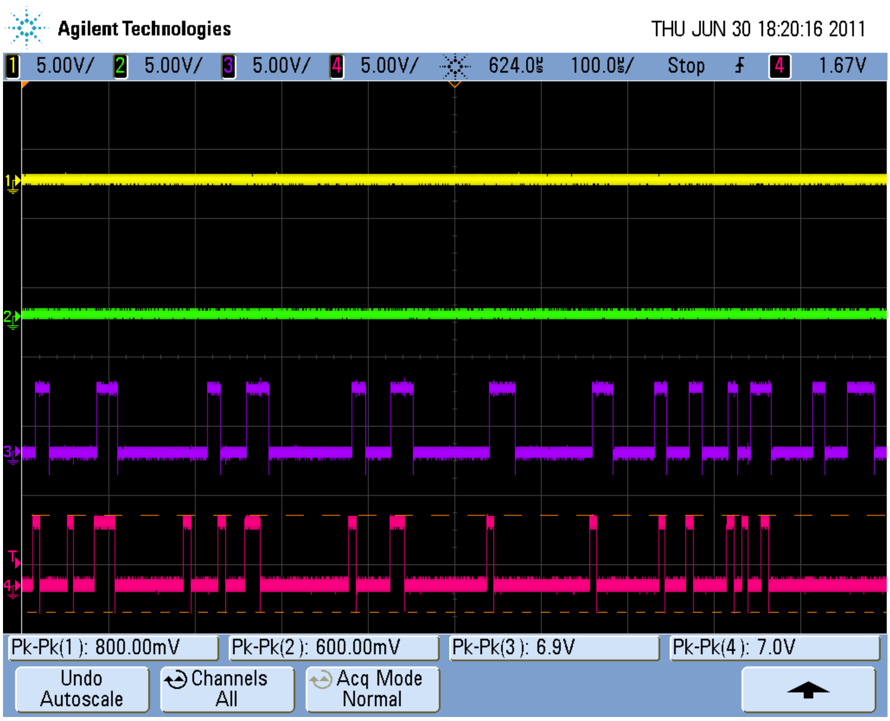

Figure 5: PWM signals of the converters, when loaded with 5.5 Ω at 5 V.

Series, 2002

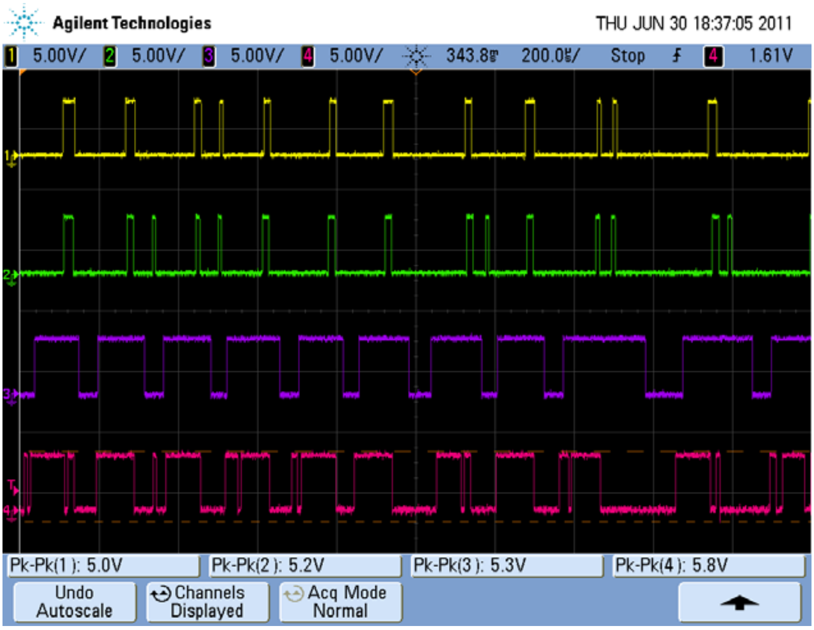

Figure 6: PWM signals of the converters, when loaded with 2 Ω at 5 V.

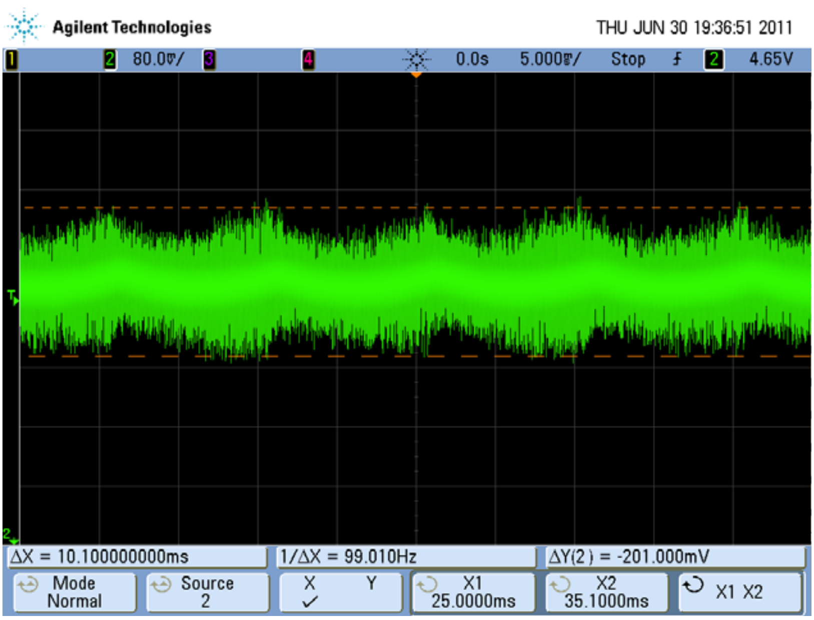

Figure 7: Output voltage ripple of 200 mV at 5 V output voltage, with weighting factors w_1=10 and w_2=1

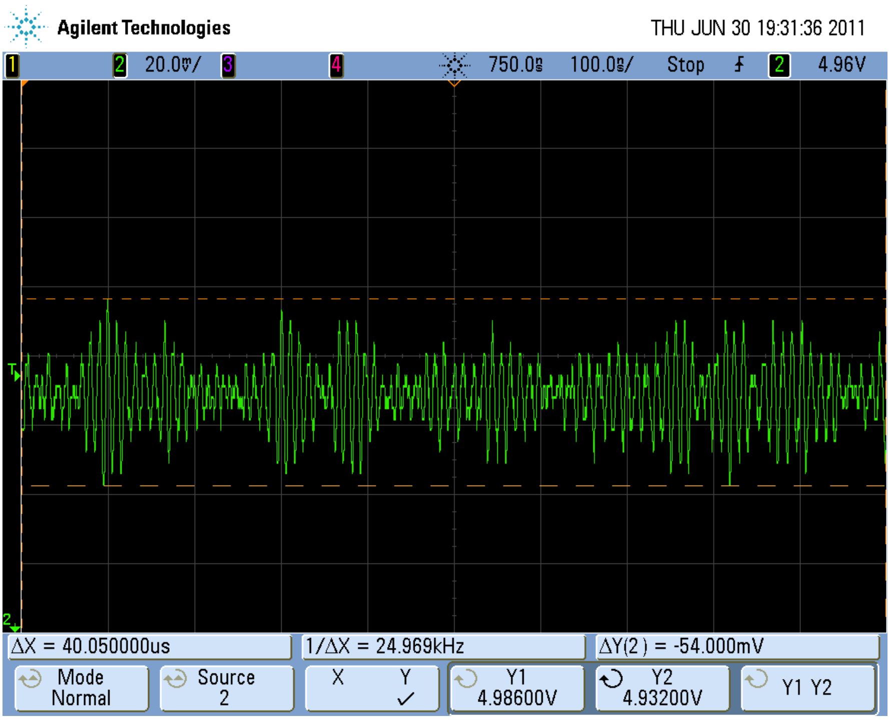

Figure 8: Output voltage ripple of 55 mV at 5 V output voltage, with weighting factors w_1=1 and w_2=10

5 References

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