DC/DC-Converters in Parallel Operation with Digital Load Distribution Control

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Abstract - **The parallel operation of power supply circuits, especially in applications with higher power demand, has several advantages. One of the most important aspects is to improve the system reliability and the operational redundancy by it. There is also a trend in producing standard converter modules which can be connected in parallel to cover a wide power range. This significantly reduces the costs of development and existing systems can be extended easily.**

A main problem of the parallel operating converters is to attain an accurate equalization of the modules output currents. There are different solutions of this problem arising in literature. All these approaches try to reach this goal with a minimum of technical complexity in order to keep the costs at a low level.

In recent years the implementation of digital control concepts in switching power supply systems seems to be of growing interest. Digital control offers several possibilities: Functions of communication can be embedded quite easily, control structures and parameters can be changed by modifying only the software, adaptive control systems are realizable and complex control strategies become possible.

In this paper parallel operating DC/DC-converters are combined with a digital control unit. So a complex control strategy called Load Distribution Control (LDC) becomes possible. This new method of LDC will be described in detail by the paper. Simulation results are presented as well as experimental verifications.

I. INTRODUCTION

In power supply systems for higher power demand the parallel operation of standard converter modules is taken more and more into consideration. This parallel connection offers several advantages:

- The design with these standard converter modules influences the costs of development in a positive manner.
- System reliability and operational redundancy are improved.
- The supply system can be extended quite easily by adding another converter module instead of replacing the converter by a stronger one.
- If the trigger equipments are synchronized and phase-shifted the ripple contents of output voltage and inductor current are reduced significantly.
- Lower conducted EMI, because the input current becomes more continuous.
- Reduction of the size of the magnetic devices. This leads to lower stray inductances and therefore to lower switching losses [5].

The main problem occurring with the parallel operation is the accurate distribution of the total power to each module to avoid stress of a single module. In recent papers different approaches to equalize the modules inductor currents are described [1],[2],[3],[4]. All these papers try to reach this goal with very simple control strategies to keep the costs low. None of these publications take a more complex control strategy into account. Instead of an equal current sharing a current distribution would be advisable where a number of converters which are not necessary to deliver the demanded power are out of operation. This kind of discontinuous distribution control can hardly be realized by analog control methods.

As the costs of microprocessors decreasing rapidly in the last few years digital control of switching power supplies seems to be acceptable under economic aspects. So the constraint of producing very simple load share concepts is no longer valid. Furthermore a microprocessor based control unit might be recommendable for other reasons. Advantages of digital implementations are:

- Functions of communication can be realised quite easily.
- Control structures and parameters can be changed by modifying only the software
- Adaptive control systems are realizable
- Complex control strategies become possible.

The aspects mentioned above suggest to combine parallel connection of converter modules with a digital control unit (see figure 1). The following investigations were made with a power supply system (4 x 250 W) consisting of four paralleled forward converters (see figure 2) each with an analog current control loop (average current mode). The pulse-width-modulators are synchronized by

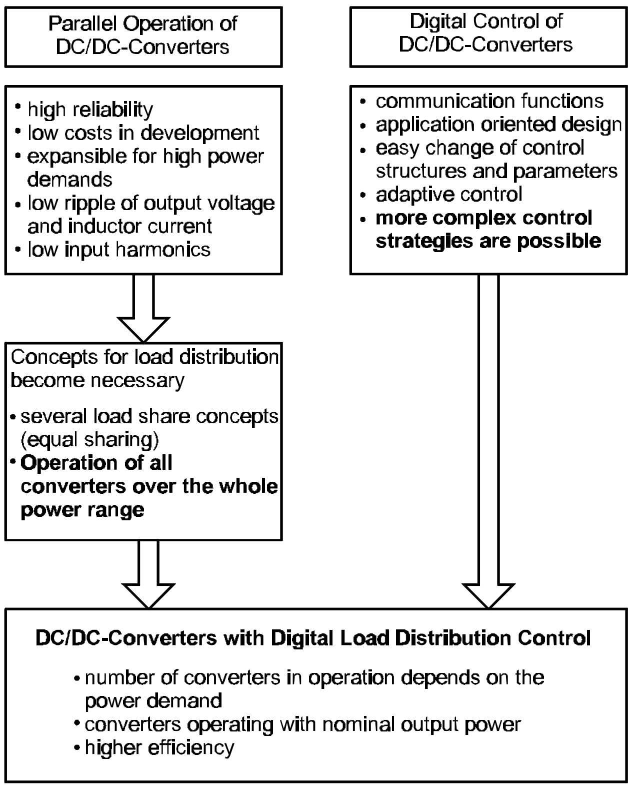


Fig. 1 Motivation for Digital Load Distribution Control

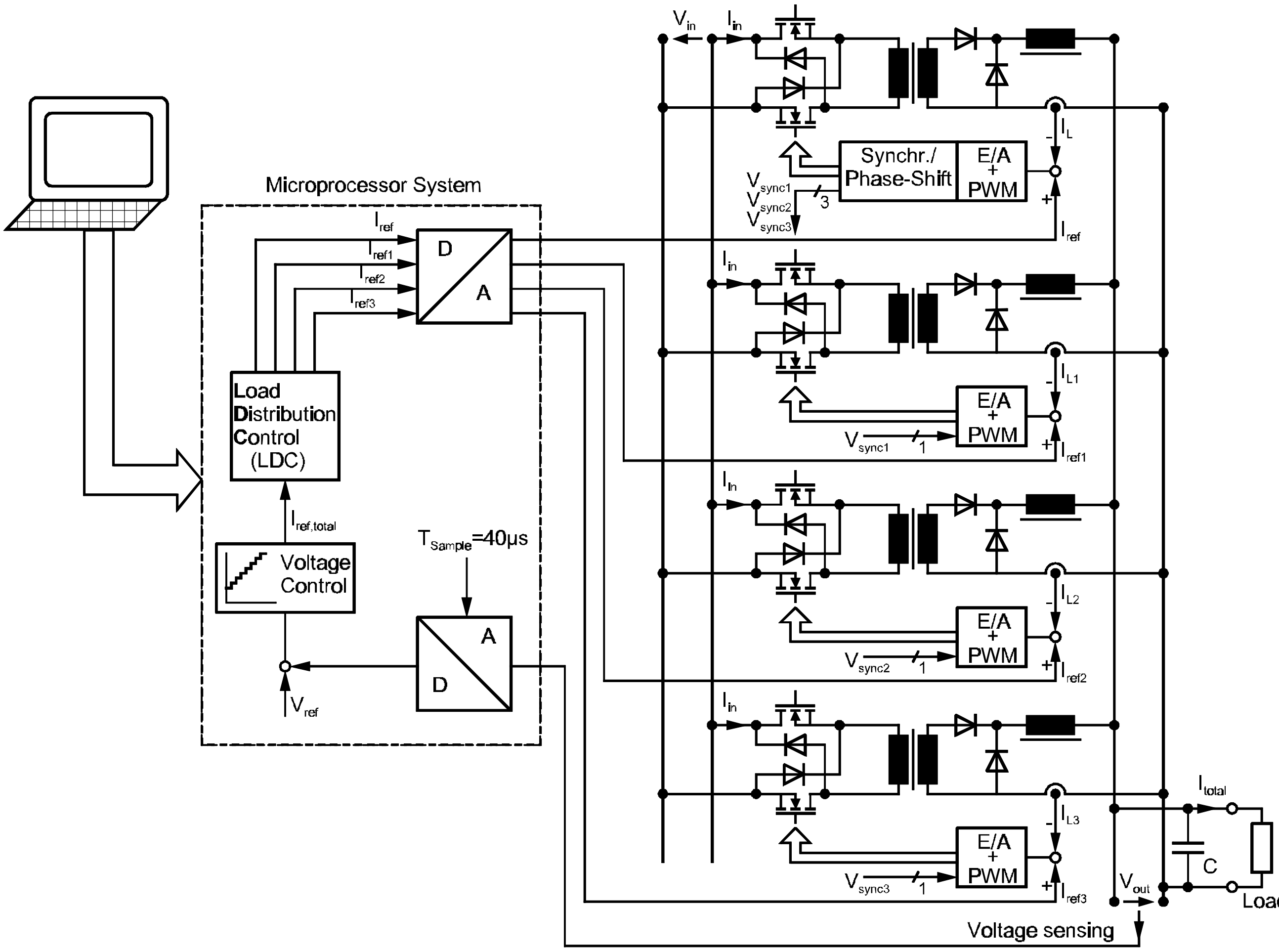


Fig. 2 System Overview

an external clock with the ability to provide a phase shift between the PWM-waveforms. The outer voltage control loop is digitally realized by a signal processor. The voltage controller generates a global current reference which is the input for the **L**oad **D**istribution **C**ontrol (LDC). The output of this LDC-unit which will be described in detail by the next chapter are four reference values for the inductor current control loops of each converter. This equipment allows a more complex **load distribution** compared to the **load share** concepts basing without exception on an equal current sharing [1],[2],[3],[4]. The LDC-method discussed here keeps only that number of converter modules in operation which are necessary to supply the power demanded actually from the load. This improves efficiency because nearly all (except one) of the converters being in operation are working with nominal power.

II. LOAD DISTRIBUTION CONTROL

As mentioned above the output of the digital voltage controller is the input of the **L**oad **D**istribution **C**ontrol (LDC). It represents the reference value $I_{ref,total}$ of the total output current I_{total} the load demands from the converter modules. The total output current I_{total} is the sum of the inductor currents of each converter module:

$$I_L + I_{L1} + I_{L2} + I_{L3} = I_{total} \qquad (1)$$

Hence, the calculation of the reference values $I_{ref\ i}$ of each inductor current by the LDC bases on equation (2). This is the fundamental equation of the LDC.

$$I_{ref} + I_{ref\,1} + I_{ref\,2} + I_{ref\,3} = I_{ref\,,total} \qquad (2)$$

The first possibility to calculate the reference values $I_{ref\ i}$ is averaging the demanded total current over the number n of operating converter modules (equ. 3).

$$I_{ref} = I_{ref\,,1} = \ldots = I_{ref\,,n-1} = \frac{1}{n} \cdot I_{ref\,,total} \qquad (3)$$

The dependence of the number n on $I_{ref,total}$ is given by equation (4), where $I_{total,max}$ is the maximum load current of the whole converter.

$$n = \operatorname{int}\left(n_{\max} \cdot \frac{I_{ref\,,total}}{I_{total\,,\max}}\right) + 1 \qquad (4)$$

Additionally a change of n must not depend only on the value of $I_{ref,total}$,but also on the last calculated number n. The value of $I_{ref,total}$ where n changes from n* to n*+1 must be higher than that value where n changes from n*+1 to n*. Such a hysteresis characteristic is necessary to avoid instabilities when

$$I_{ref\,,total} \approx k \cdot {I_{total\,,\max}}/{n_{\max}} \ ; k = 1..n_{\max}$$

This method of computing the reference values $I_{ref\ i}$ causes step changes of each reference value $I_{ref\ k}$ with k<n whenever n changes. That means a sudden load variation leads to sudden variations of each modules inductor current. To prevent this the load distribution procedure has been modified. Figure 3 shows the state graph of this improved version.

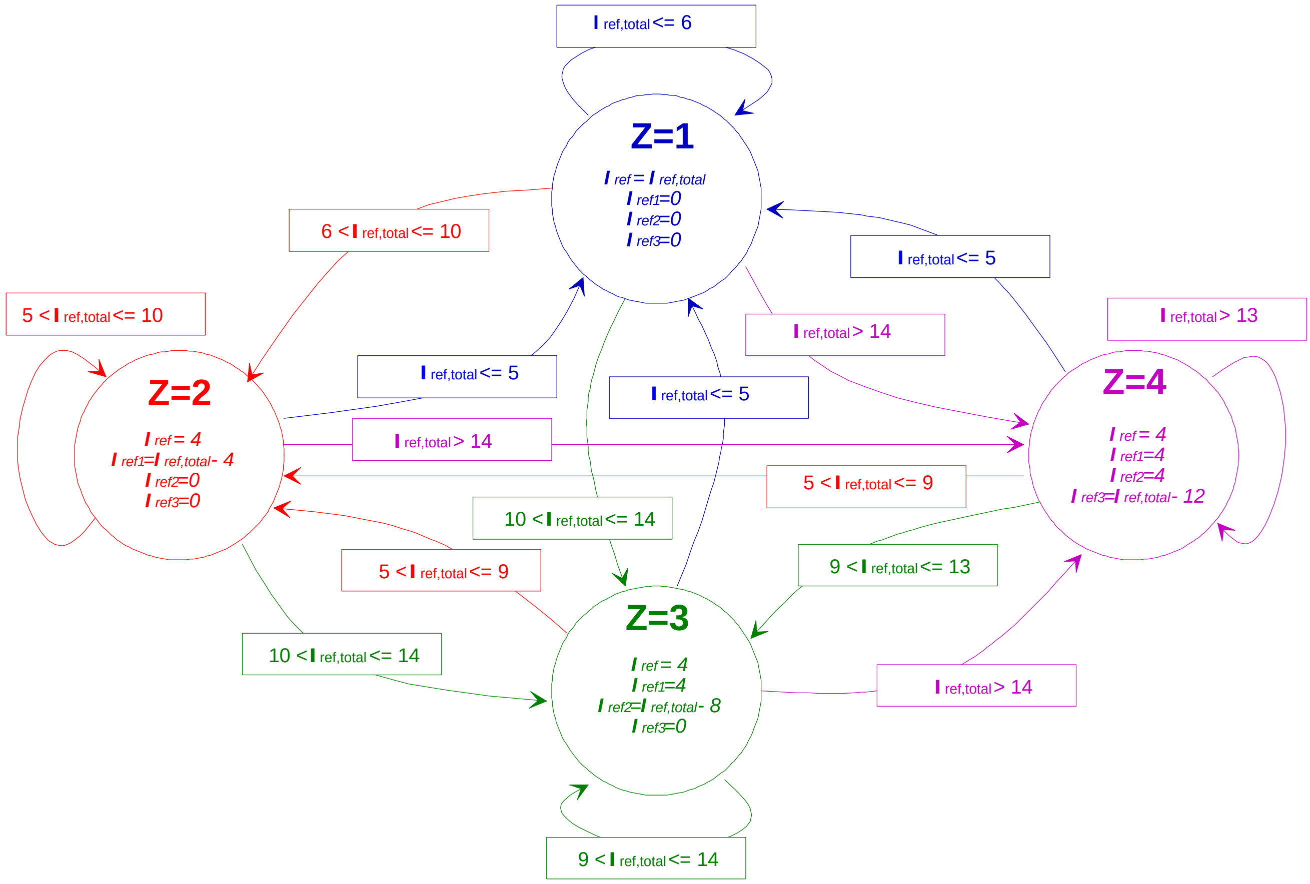


Fig. 3 State graph of the modified Load Distribution Control method

The variable Z indicates the state of the LDC. Its value is equivalent to the number of converters being in operation in this state. Additionally the current references of the modules are given for each state. Turning over from one state to the other depends on conditions determined in the boxes.

Basic terms of the load distribution method described by the state graph shown above were:

- The maximum current in a single module should not exceed 6A.
- The minimum current in a single module should not be lower than 1A to avoid discontinuous operation.
- The turn over thresholds between the states should have hysteresis characteristic to prevent instabilities.
- The change from Z = n* to Z = n*+1 or reverse should not affect the current references $I_{ref,n}$ with n < n*-1.

In the following the function principle will be described guided by some examples. If one module is operating (that means Z = 1) and the total current reference $I_{ref,total}$ is less than 6A the LDC is held in that state. If $I_{ref,total}$ increases to values higher than 6A the LDC leaves the state 1 and enters state 2, 3 or 4 depending on the value of $I_{ref,total}$. In any case the reference value of the first module I_{ref} is set back to 4 A. This is necessary to prevent discontinuous operation, if $I_{ref,total}$ increases to just over 6A. In states of higher order Z than 1, i.e. more than one converter module is running, Z-1 modules get a current reference of 4A and the last converter carries the residual current. On the way back to a lower current the thresholds where the LDC exits the several states have lower values (hysteresis characteristics) to ensure that the residual current is greater than 1A.

III. SYNCHRONIZATION AND PHASE-SHIFT OF THE PWM-DRIVERS

A. *Synchronization*

The additional expenditure of providing a synchronization of all (in this case four) PWM-drivers is absolutely necessary. Only a small difference in the switching frequencies of the converter modules causes subharmonic oscillations in the input and output characteristics. To find the reason for these oscillations the waveforms of the inductor currents are analysed. If the frequencies of the triangle alternating components are exactly the same, the sum of these currents feeding the output capacitor contents an alternating component with constant amplitude. It is obvious that in a case of differing frequencies in certain switching periods all inductor currents are in phase. That leads to a maximum ripple of the total current, whereas a minimum ripple occurs when the currents are in phase opposition. If the converter modules operate asynchronously the state of operation of the whole converter system changes continuously between these two extreme states. This leads to the above mentioned subharmonic oscillations.

B. *Phase-Shift of the synchronised PWM-Drivers*

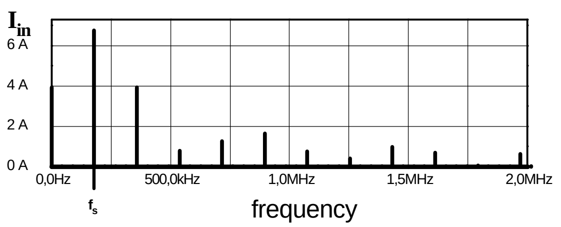
If a phase-shift is provided to the synchronized PWM-drivers the energy flow from the input to the output becomes more continuous, because the power switches of the converter stages are not in a conducting state at the same time intervals. So the harmonic content of the input current is reduced significantly and input filters can be designed smaller. Obviously the superimposition of the phase-shifted, triangle inductor current waveforms leads to reduced output current ripples and, hence, to a suppression of output voltage ripple. To optimize the phase-shift angle in order to attain low input and output harmonics the following basic constraints must be fulfilled:

- The number of converters whose power switches are in a conducting state at the same time must kept as low as possible.
- The time interval where the switches of more than one converter are conducting should be short as possible.

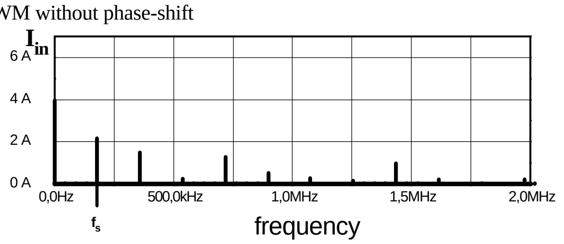
The compliance with these constraints depends on the number of converter modules and the duty cycle of each module and therefore it depends on the state of operation. If the topology of the modules are given and the nominal duty cycle is identical for all modules, it would be advisable to choose the phase-shift of the PWM-drivers in dependence on the number n of converters connected in parallel. If the phase-shift time t_{ph} between each PWM-driver is

$$t_{ph} = \frac{1}{n} \cdot \frac{1}{f_s} \quad (f_s : \text{switching frequency}) \qquad (5)$$

the conducting intervals of the converters are distributed continuously over the switching period.
To obtain the optimum distribution the nominal duty cycle d_n is to be less than $d_n = 1/(n \cdot f_s)$. Then there is no overlap of the conducting intervals of each power stage. In power supply systems with four or more converters working in parallel this constraint can hardly be realized and overlapping conducting intervals are unavoidable.
The effect of the phase shift described above is to be seen in figure 4. The spectrum of the input current in a certain point of operation (I_{total} = 13A; three converters in operation) is compared with and without phase shift. A significant reduction of the peak amplitude to about 30% is obvious, although this point of operation is not optimal in this connection, because the converter system is designed with four single modules and the phase-shift time is fixed to $T_s/4$. Hence, with the nominal duty cycle d_n=0.3 there are overlapping conducting intervals. If the phase shift time would be $t_{ph} = T_s/3$ a higher reduction rate would be possible in this certain case. This example was pointed out to show that even in non optimal points of operation the rate of harmonic reduction obtained by phase-shifted PWM-drivers is significant.

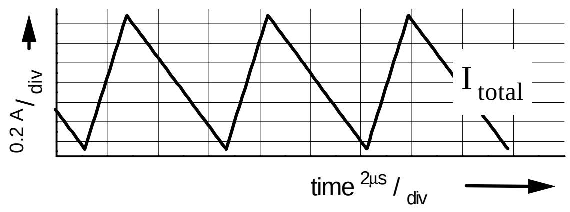


a) PWM without phase-shift

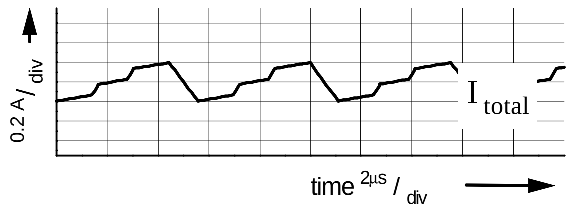


b) PWM with phase-shift

Fig. 4 Effect of the phase-shifted PWM on the input current spectrum



a) PWM without phase-shift



b) PWM with phase-shift

Fig. 5 Effect of the phase-shifted PWM on the output current ripple

In figure 5 the influence of the phase-shift on the total output current ripple at this point of operation is shown. The ripple of the current feeding the output capacitor is reduced by the phase-shift from about 1.5 A to less than 0.5 A. The short intervals of higher transition are caused by positive voltages across the inductors of two modules at the same time, i.e. overlapping conducting intervals of power switches of two modules as described above.

C. Hardware realization

The PWM-section of each converter module is realized by commercial control ICs designed for switch-mode power supplies. As usual this IC (UC3825) provides an on-chip oscillator which charges and discharges the external ramp capacitor with a current programmed by an external resistor. At the instant the maximum or minimum value of the voltage across the capacitor is reached, the oscillator toggles between charging and discharging. If the oscillator frequency is fixed a few Kilohertz below the desired synchronization frequency the change from charging to discharging can be triggered by a synchronization signal which is added to the capacitor voltage. As synchronization signal a clock pulse with a pulse width of about 150 ns and a frequency of exactly 186 kHz is used. The four phase-shifted synchronization signals are produced with a PLD clocked by a 12 MHz quarz oscillator. Frequency and phase-shift time t_{ph} are programmable quite easy in a wide range. The resolution of the programmable phase-shift interval t_{ph} depends on the frequency of the PLD-clock.

IV. SIMULATION RESULTS

In the following an example is pointed out to describe the behaviour of the LDC and its reliability performance. Figure 6 shows the simulated results of a sudden load variation from 5A to 13A which is critical point of operation for the LDC, because 13A is the threshold were the fourth converter is shut down. In the first row the waveforms of the output voltage V_{out} (left hand side), total current reference $I_{ref,total}$ and the total current I_{total} are delineated. Below the characteristics of the inductor currents and their references which are the output of the LDC are

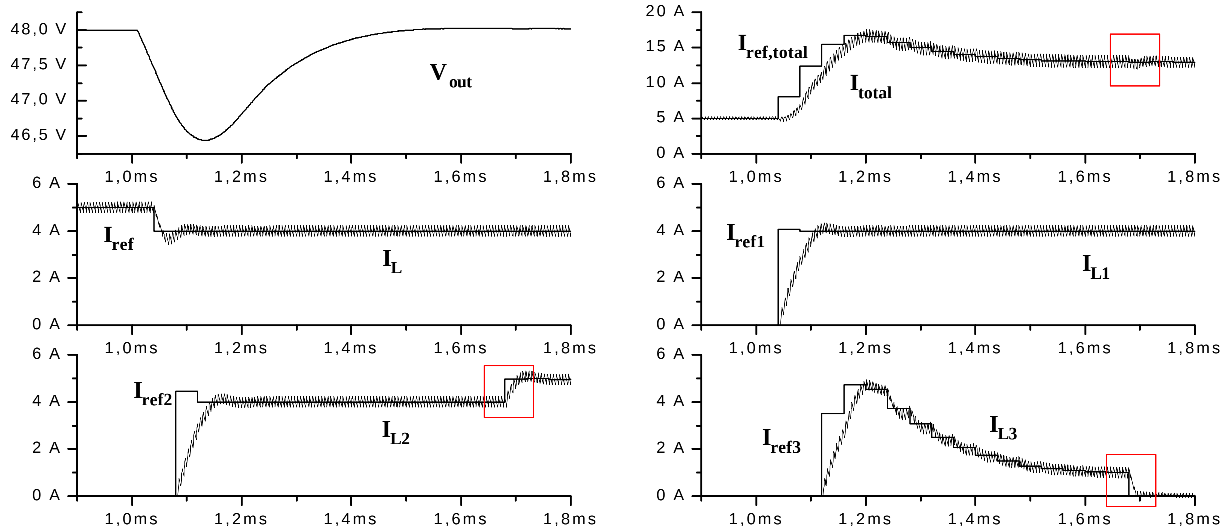


Fig. 6 Transient behaviour of the LDC after a sudden load variation at t = 1 ms

figured. When the load current steps up, the output of the discontinuous voltage controller rises in three steps to a value higher than 13 A. After the first sampling I_{ref} is set to 4A and the second module is turned on with about 4A. One respectively two sampling times later the third and fourth converter are going to operate. For steady-state-operation with 13A the fourth converter is not necessary, but the voltage controller provides an over-current to obtain a good dynamic response and a low transient error of the output voltage. This over-current is carried by the fourth converter. The voltage control loop has to be designed carefully, because such an over current may cause an over current lockout of the fourth module, if the load steps to the maximum load of the whole converter system. After the recovery time of the voltage control loop the fourth module is turned off and the third module takes over its current of 1A. To avoid this effect of transient operation the gain of the voltage controller has to be reduced. The consequence will be a higher transient voltage error.

At this instant a transient decrease of the total current is to be seen. This effect bases on properties of the converter topology. The duty-cycle of the two-transistor-forward-converter used here is limited to 0.5. So the transition of I_{L2} from 4A to 5A is slower than the negative transition of I_{L3} from 1A to zero.

V. EXPERIMENTAL VERIFICATION

The experimental verification has been done with modified parameters of the Load Distribution Control. So the maximum inductor current of a single module is limited to 5 A instead of 6 A in the simulated system. A certain state Z=n is left, if the reference value $I_{ref,n}$ exceeds 5 A. $I_{ref,n}$ is then set back to 3 A (instead of 4 A). All other parameters and the basic structure of the LDC are the same as in the simulation model.

Additional to the simulation results in the last chapter in the following experimental results are presented to verify the correct function of the Load Distribution Control. As a comparison to the simulated behaviour of a sudden load change figure 7 shows the measured time characteristics of the output voltage V_{out} and the inductor currents I_L-I_{L3} after a load change from 3A to 12A (stationary four converters in operation). In difference to the simulation results in figure 6 the gain of the voltage controller is set to a lower value to demonstrate the behaviour of the LDC when the Voltage controller demands no over current. So large load steps to the maximum load of the whole converter system are possible without activating the over-current lock-out of the last converter module. The lower cross-over frequency of the voltage loop results in a higher transient voltage error. After the load variation the current I_L of the first converter rises up to 5 A. The LDC turns on the second converter with I_{L2} = 2 A while I_{L1} is reduced to 3 A. With the increasing total current the modules three and four are turned on in the same manner. As no current overshoot is produced by the voltage controller the fourth converter could stand load steps up to its maximum current without transient or steady state over-current lockout. A very interesting experiment to demonstrate the function of the LDC is delineated in figure 8. The voltage control-loop is kept open and a triangular total current reference is given to the LDC-unit. Each 40 µs $I_{ref,total}$ is increased by 10 mA. This results in a frequency of about 12 Hz as $I_{ref,total}$ varies from 1A to 12A.

The basic terms of the LDC mentioned in chapter III are demonstrated by this experiment. These are:

- Limitation of the maximum current to 5 A,
- Limitation of the minimum current to 1 A in order to avoid discontinuous operation,
- Hysteresis characteristic of the turn over thresholds from one state to the other, (Each module is turned on with $I_{ref,i}$ = 2 A and turned off at $I_{ref,i}$ = 1 A.)
- State changes of a single module does not influence the current of others. (For example I_L is constant during all state changes of the other modules.)

The transient decreases of the total current at instants of state changes described in the last chapter can be seen, too. Summing up this experiment shows that the requirements on the LDC defined above are fulfilled.

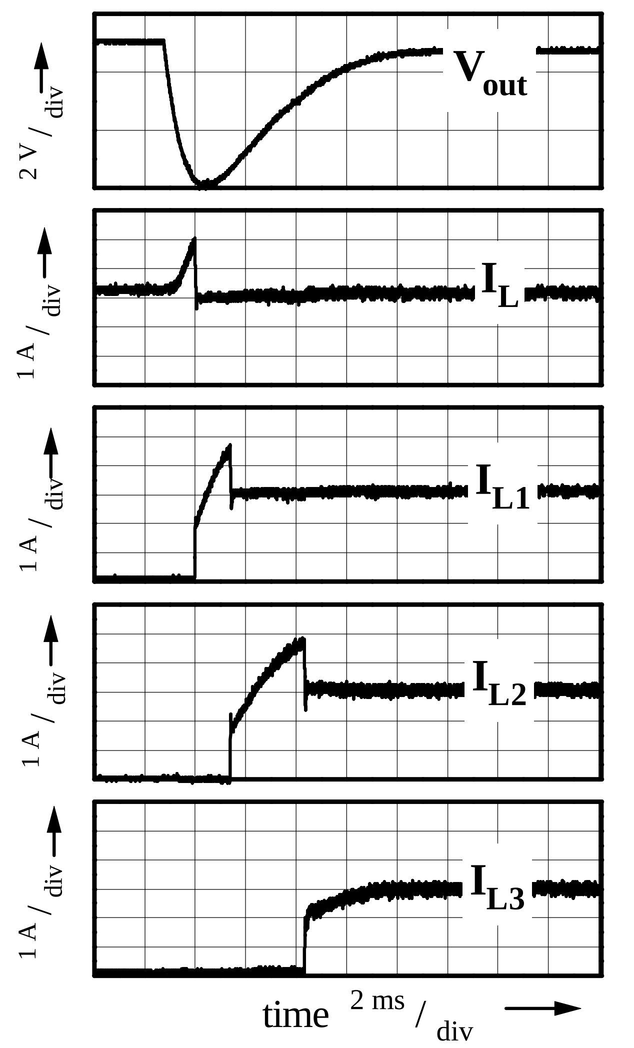


Fig. 7 Experimental measurement of sudden load variation from 3A to 12A

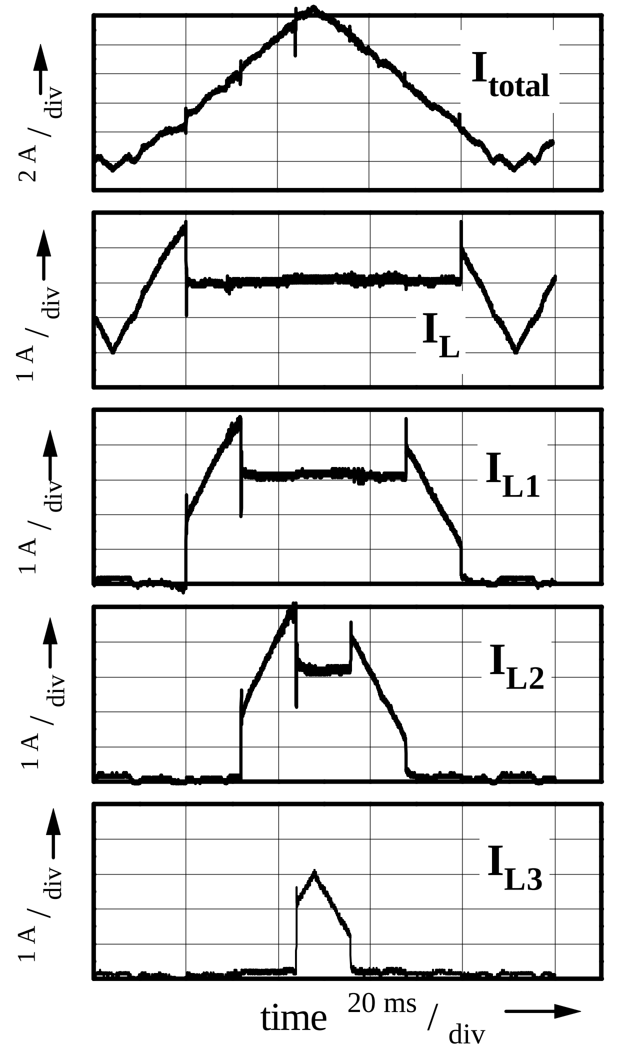


Fig. 8 Triangular current reference (LDC demonstration experiment)

VI. CONCLUSIONS

*Conclusions:*This paper presented the combination of paralleled DC/DC-converters with a microprocessor based control unit. This allows to implement more complex control strategies compared to analog concepts. Especially a improved method of load distribution is possible.

A new discontinuous distribution control, where only the number of converters are in operation which are necessary to supply the power demanded actually from the load, is described and analysed. Its performance reliability is demonstrated by simulations and experimental measurements. Further its dynamic behaviour is investigated and the positive effects on harmonic contents of input and output waveforms are outlined.

*Further Investigations:*As the Load Distribution Control exists exclusively of software routines a multitude of LDC-strategies are possible. A very interesting application is for example the parallel connection of different converter topologies, where resonant converters supply the base load and hard switching converters operate only if short-time peak loads are required. Such a solution can improve efficiency without unacceptable increases in costs. Another important field of application are power supplies with solar cells. Than a special LDC would be able to manage the additional connecting of battery or line driven converters if the solar cells get to weak.

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