Efficiency-based Current Distribution Scheme for Scalable Digital Power Converters

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Abstract—The trend in next-generation switched-mode power supplies will lead to modular, scalable solutions which deliver power efficiently over a wide range of operation. This paper details a new approach to introduce more advanced control features to improve system efficiency into these scalable solutions. While these methods have been incorporated into multi-phase converters in the past, they all require the distribution of information among the individual converters. An advantage of the proposed method is that it does not require such communication signals between the individual power supplies and is therefore fully scalable and cost effective. A system comprising of individual, smart converters is proposed where each converter regulates its respective output power to a level with high efficiency. Converters not required for the delivered output power are shut down. The proposed approach is analysed theoretically. Implementation details for an FPGA experimental prototype system are given. The system performance for a four converter prototype system is analysed and discussed. The efficiency obtained is compared with the efficiency of a multi-phase system with phase-shedding operation and the efficiency of a system with independent power converters without phase shedding support.

I. INTRODUCTION

With the need for today’s power supplies to deliver more output power for less cost, a trend to scalable digital power solutions has emerged. Standardized power supplies are connected in parallel to satisfy application-specific power demands without the need for different converters (Fig. 1). While parallel power converters provide several benefits, such as reduced ripple currents, higher efficiency and faster transient response [1]–[5], they also introduce issues non-existent in single-converter applications, such as current distribution among the converters, frequency synchronization, phase alignment and fault behaviour.

A. Control architectures

In the past, several different control topologies have been presented to control such parallel power converters [5]–[14]. They can be quantified into three different categories: central control architectures, distributed control systems with communication and independently controlled systems.

Central control architectures comprise of one central controller which generates the switching signals for all adjuncted power converters (“phases”). An advantage of this concept is the availability of all information at one central point, i.e. the controller, which allows the implementation of more advanced control schemes or efficiency improving techniques.

A disadvantage is that the central controller restricts the scalability of the system and is a single point of failure.

Consequently, a second architecture has been developed to address this issue. Distributed controllers do not require a central controller as the control architecture is distributed over the individual power converters. Each converter is controlled by its own controller which is connected to the controllers of the other power converters via dedicated communication lines. These enable the distribution of information among the individual converters and allows the use of more advanced control schemes, such as current sharing.

The logical control structure can be categorized into master-slave systems, such as [5]–[7], and masterless configurations such as [8]–[12]. However, both concepts suffer from drawbacks such as restrictions of the PCB layout due to the required communication signals. Hot-plugging of individual converters can brake the communication and hence compromise the system’s operation.

The third system architecture widely used is the parallel connection of multiple independent power supplies where the individual units are not aware of each other and operate individually using passive current sharing techniques. One method to implement such passive current sharing is droop current sharing [13], [14] where the output impedance (natural or artificial) of the power supplies is employed to distribute the current equally among the converters.

However, a high output impedance is undesirable in most of today’s applications, rendering this scheme no longer applicable. Additionally, the scheme does not disable individual
power converters during light-load, which compromises efficiency for this operation mode.

B. Existing current sharing/distribution techniques

While the need for current sharing among parallel power converters is widely acknowledged, several different current distribution patterns and concepts have been investigated in the past. These can be broadly categorized into two groups depending on the availability of the current information. Methods within the first group, such as chain-controlled systems or multi-phase converters, require the sharing of information among the individual converters and therefore require communication signals or a central controller. Methods within the second group, such as passive current sharing, have been developed for parallel power supplies. While they do not require the distribution of the current information, they generally do not accommodate efficiency-improving techniques like phase-shedding.

However, both methods share one common property, i.e. the actual distribution pattern where the current is shared equally among the individual converters. While this is the optimal distribution for identical converters (see section III), there are some limitations in practice. For example, current-sensing elements suffer from tolerances which can lead to a non-uniform distribution or may require calibration [15], [16]. Also, the individual converters are typically not identical, due to effects of component variation, so that an equal distribution is rendered suboptimal in terms of efficiency.

Alternative distribution schemes operate the individual converters with different output currents to improve the overall efficiency of the system. In [4], [17], current distribution schemes for multi-phase converters are detailed where the current is distributed inversely-proportional to the converters' output impedances by equalizing the duty cycle control signals. This distributes the losses equally among the converters (rather than the current) and improves the overall system efficiency. To achieve this, the system in [17] employs a current sharing procedure, while the system in [4] uses a digital filter.

However, none of the reviewed approaches is able to change the number of active converters; a technique referred to as “phase shedding.” Phase shedding improves the overall efficiency [18] and is widely used in today’s applications especially for light-load operation. It is commonly implemented in parallel with the current sharing scheme using information about the total output power as the current control loop is not able to change the number of active converters.

To combine the advantages of independent converters, such as scalability, with the benefits of multi-phase converters without the need for communication lines, a new technique for current distribution is investigated in this paper. Control for smart independent power converters is proposed which introduces methods to improve efficiency, currently only employed in multi-phase converters, into independent parallel converters (Fig. 1). The smart control algorithm is implemented in a digital control core; one for each converter (Fig. 2). Information about the total output current (or the average current), i.e. communication signals between the individual converters, is not required by the individual converters.

The paper is organized as follows: in section II, a current distribution method suitable for independent, parallel power supplies is proposed which allows the introduction of more advanced features such as phase shedding and/or hot-plugging into existing systems. In section III, a theoretical analysis and optimization of the efficiency for parallel power converters is given. This is followed by implementation details and experimental testing on an FPGA prototype system. A final discussion concludes this paper.

II. CURRENT DISTRIBUTION BASED ON OPTIMAL CURRENT LEVELS

Instead of controlling the inductor currents and the number of active converters separately and distributing the output power equally among the converters, the proposed system is based on individual smart converters with optimum current levels. Each converter regulates its output current independently to a target value with optimal efficiency and is also capable of enabling or disabling its operation independently. Therefore it does not require information about the output current from the other converters nor information about the total number of active converters. The concept is based on the principle that the total output current is the sum of the individual currents so that individual converters can change their respective output currents while the remaining converters compensate for this change.

This is enabled by the efficiency curves of the individual power supplies over the output power range. It is shown in section III that for any given number of identical power converters, the optimal current distribution is uniform for identical power supplies. To elaborate, for non-identical power converters, the distribution is inversely proportional to the respective output impedance. A criterion is introduced to determine the number of converters to achieve best efficiency. This is a function of the auxiliary losses of the converter, e.g. drive losses. From these two criteria, the operation range of an individual power converter is derived. It is shown that all these operation ranges rely within a certain current range which is considered the optimal power level. The task of each individual power converter is to either operate within this range or to reduce its output power and disable its switching action.

With no communication signals present, the question is how this can be achieved by independent converters without
causing conflicts of interest. A conflict of interest occurs when different converters try to achieve contradictory goals. For example, if a converter increases its output power level and no other converter in the system is able to reduce its power level, the output voltage will increase undesirably.

To reduce the risks of such conflicts, a prioritization is introduced into the control system which allows the different converters to pursue their respective goals with different precedence. For this reason, the output current is classified into different zones each with a certain priority assigned. These priorities depend on the efficiency of the total system and the converter operation within a certain zone. The different zones are detailed in Fig. 3. The top figure shows the output current levels with the optimal operation zones highlighted and the direction of optimization indicated. In the middle figure, the respective optimization direction is illustrated with the cost-function $J(I_{out})$, where the system will always try to reduce the cost, i.e. move to the lowest possible value. The bottom figure shows the zone’s priorities $Q(I_{out})$, where a larger value corresponds to a higher optimization strength.

The highest priority is given to converters operating with negative output currents, so that they can increase their current to zero first. Note that, negative output current is highly unfavourable in terms of efficiency, but improves the performance during heavy-to-light-load transients. The second highest priority is assigned to converters operating around the optimal operation area which allows these converters to fix their current levels at the optimal point. This is followed by converters operating with output currents higher than the optimal operation area (zone 6). Consequently, they will reduce their output current to operate within the optimal range (zone 5). Converters in zone 4 will follow by increasing their output power to operate also within optimal range (zone 5). Converters operating in zone 3 will start their current transfer process. However, the direction for these transfers is not fixed as it is not known whether more or less output power is more beneficial. Therefore, such converters will choose their desired target levels randomly at the beginning of each transfer. Finally, converters operating with very little output power will reduce their output current and will eventually switch off.

Due to the lack of communication lines, the entire prioritization scheme is implemented via timing. After a load transient, each converter detects steady-state operation at approximately the same time instance and starts its respective transfer process. Shorter wait times within the procedure allow converters with higher priorities to correct their values first.

To ensure stability, the proposed current distribution scheme is embedded into a sequence of conditions, illustrated in the (simplified) flow-chart in Fig. 4. Prior to enabling the current transfer between the individual converters, the converters ensure that the system is in steady-state operation. Therefore output voltage and inductor current are monitored. If both are stable (indicated by the signals $V_{ss}$, $I_{ss}$), the system continues with the current transfer procedure. Within this, each converter waits a time period (depending on priority) prior to enabling the actual current transfer so that it can be ensured that not all converters start their transfer at the same time. During this time, the converters continuously monitor output voltage and inductor current. If any other converter starts its transfer process in the meantime, the wait time is reset and the procedure starts again from the beginning (not shown in the flow chart in Fig. 4).

During the entire process, the stability of the output voltage is monitored closely as it has highest control priority. Note that the output voltage changes marginally during the current transfer process. This is due to the fact that it is the only way to “communicate” with the other converters. When a converter wants to offload current to other converters, it decreases its reference voltage. This causes its loop compensator to decrease the inductor current which leads to a small decrease in output voltage. The other converters sense the voltage drop and increase their respective inductor currents. When the transfer is complete, the output voltage returns to its nominal value. The value of the output voltage deviation during the current transfer process is proportional to the speed of the transfer. Larger deviation from the reference value allows a faster current transfer.

With reference to Fig. 3, the optimal operation zone spans between two thresholds, $I_{opt_{min}}$ and $I_{opt_{max}}$, around an optimal output current, $I_{opt}$. The remaining question is the selection of these levels and the level at which the converters are turned off, $I_{down}$.

III. THEORETICAL ANALYSIS

In Fig. 5, multiple identical converters are connected in parallel and the efficiency is analysed for different numbers of active converters and uniformly distributed current.

The efficiency curve for any given number of active converters, e.g. $n = 1$, is low for small output power due to predominant constant losses, and for high output power due to the increasing contribution of resistive losses. It is highest in the mid-range. Also, it is clearly visible that the optimal number of active converters is a function of the output current.
By changing the number of active converters, the overall efficiency can always track the highest efficiency curve for a given output current. To allow for an efficient implementation and to ensure optimal operation, the system has to actively control the number of active converters. In a multi-phase system, where the total output current information is known, this is implemented with static threshold currents where the system adjusts the number of active phases. The following analysis determines these thresholds and is used in this design to establish common properties.

Note that the efficiency of the individual converters is subject to their current operating conditions such as temperature or input voltage. Therefore the absolute values of the thresholds will change, but not the principle operation. The proposed scheme can be extended so that the threshold values are automatically adjusted with changing operating conditions.

The search for the highest efficiency can be transformed into the search for minimal losses for a given output current. Losses in power converter have been analysed in the past [18]–[22] and can be categorized into three main groups, referred to as current depended losses $P_i$, drive losses $P_{\text{drive}}$ and auxiliary losses $P_{\text{aux}}$. While $P_{\text{drive}}$ and $P_{\text{aux}}$ are constant, the current dependent losses $P_i$ can be approximated with a parabola [22], resulting in

$$P_i(I) = V_L I + R_L I^2 .$$

The parabola parameters $V_L$ and $R_L$ can be determined by measurement and curve-fitting or via a circuit simulation. Consistent with their units, these parameters can be interpreted as voltage and resistance respectively. The drive losses summarize all losses dependent on the number of active converters $n$, while the auxiliary losses include all losses constant during operation.

The losses per converter ($k$) can be expressed as

$$P_{\text{loss},k} = P_{\text{aux},k} + P_{\text{drive},k}(n) + P_{i,k}(I_{\text{out}}) ,$$

so that the total losses of $N$ parallel converters are

$$P_{\text{loss}} = \sum_{k=0}^{N-1} (P_{\text{aux},k} + P_{\text{drive},k} + P_i(I_{L,k})) .$$

This function is now recast as an optimization problem with the objective of determining the optimal number of active converters $n$ and the respective inductor currents $I_L$ for a given output current $I_{\text{out}}$.

In order to do so, (3) is separated as follows

$$P_{\text{loss}} = P_{\text{aux}} + \sum_{k=0}^{N-1} P_{\text{drive},k} + \sum_{k=0}^{N-1} P_i(I_{\text{out},k}) ,$$

where the three parts represent the constant losses, the losses dependent on the number of active converters and losses dependent on the inductor current. As the sum of the individual output currents equals the total output current, (4) is subject to the following constraint:

$$I_{\text{out}} = \sum_{k=0}^{N-1} I_{\text{out},k} .$$

To verify these equations, they are now optimized considering $N$ identical converters, i.e. converters with identical loss functions. However, the equation is independent of the actual loss functions and therefore can also be applied to systems with different converters. Such differences can be caused by system tolerances as analysed in [4] or by design as described in [2], [23].

Equation (4) can be optimized for a given $(n, I_{\text{out}})$ in order to determine the optimal current distribution using well-known optimization methods, e.g. Lagrange multipliers. As a result, the lowest losses can be achieved for an equal current distribution with

$$I_{L,n} = \frac{1}{n} I_{\text{out}} .$$

This is the expected result which states that for a given number of active converters $n$, the losses are minimal when the current is distributed equally. However, this does not explicitly state the optimal number of converters for a given output.
current. This is now determined by substituting (6) into (4) resulting in

$$P_{\text{loss}}(I_{\text{out}}; n) = P_{\text{aux}} + \sum_{k=0}^{n-1} P_{\text{drive},k} + \sum_{k=0}^{n-1} P_{\text{I}} \left( \frac{1}{n} I_{\text{out}} \right),$$

which would be minimal for

$$n \approx \sqrt{\frac{R_L I_{\text{opt}}}{P_{\text{drive}}}} = I_{\text{out}} \sqrt{\frac{R_L}{P_{\text{drive}}}},$$

if $n$ is a rational number. However, $n$ is an integer value, so that the standard minimization, i.e. the first-order derivative set to zero, does not apply. While (8) reveals the optimal number of active converters $n$ as a function of the output current, it is more favourable for an efficient hardware implementation to know the actual threshold values. This results in one optimal current interval for each number of active converters and can be implemented via a small look-up table. To calculate the width of each interval, the problem is reformulated into the search for the threshold currents where it is beneficial to increase/decrease the number of active converters. This is equivalent to the computation of the discrete derivative and can be mathematically expressed as

$$P_{\text{loss}}(n + 1, I_{\text{out}}) - P_{\text{loss}}(n, I_{\text{out}}) < 0,$$

which can be solved as

$$I_{\text{out}} > \sqrt{n(n+1)} \sqrt{P_{\text{drive}}/R_L}.$$

(10)

For example, the current threshold for a change from two to three converters is

$$I_{\text{out}} = \sqrt{2(2+1)} \sqrt{P_{\text{drive}}/R_L} \approx 2.45 I_{\text{thres}},$$

where

$$I_{\text{thres}} = \sqrt{P_{\text{drive}}/R_L}$$

(12)

is constant for a given power converter. If this total threshold value is scaled back into the current per converter, the operation intervals for each of the individual converters can be calculated as

$$\sqrt{\frac{n-1}{n}} \sqrt{P_{\text{drive}}/R_L} < I_{\text{L}}(n) < \sqrt{\frac{n+1}{n}} \sqrt{P_{\text{drive}}/R_L}.$$  

(13)

The resulting scaling factors are listed in Table I. All individual converters operate in an interval around the optimal output current which shrinks with increasing output current. This can be explained with the reduction of the resistive losses, due to smaller inductor currents compared to the drive losses of an additional turned-on converter.

While the detailed optimization defines clear threshold currents in a typical multi-phase application (where the total output current is known at a central point), it cannot be directly applied to the system detailed as the defined threshold currents are only valid if the output current is distributed equally among all active converters after an additional converter is turned on. If the enabled converter only takes the additional current and the other converters maintain their output currents, the proposed equations are not valid. However, they provide good insight to the optimal operation interval required for the current sharing scheme presented in this paper.

The acquired results are now applied to the proposed scheme in order to select the required power levels. With $I_{\text{opt}}$ selected according to (12), the levels spanning the optimal zone have to be selected. While this could be performed using (13), more considerations should be taken into account. Namely, it has to be ensured that the spanned zone is not too wide.

Consider the following scenario: a certain number of converters are off, a certain number operate in the optimal operation zone and a single converter operates between zero and the optimal operation zone. The question is if the converter should transfer its output current into the optimal zone or if it should be turned off, noting that there exists an optimal number of active converters for a given output current. Also it should be ensured that the converter does not remain on when it is actually not required; nor should it be turned off when it is required.

To elaborate, consider $n$ converters operating at a load current within the optimal operation zone. Each current is subject to a stochastic process and its actual value within this optimal operation zone is unknown. As a result, the current uncertainty per converter equals the width of the optimal zone. With $n$ converters active in the optimal range, a total current uncertainty of

$$\Delta I = n \Delta I_{\text{span}} = n(I_{\text{opt,max}} - I_{\text{opt,min}})$$

is expected. The sum of the total uncertainty and the threshold current should not exceed the lower threshold of the optimal operation range

$$\Delta I + I_{\text{down}} < I_{\text{opt,min}},$$

(15)

to ensure that the optimal number of converters is active.

With all design parameters derived, a review of the resulting efficiency can be performed. Analysing the resulting efficiency of the overall system is difficult, due to the statistical distribution of the individual load currents in the optimal operation region. Fig. 6 shows the expected efficiency for the worst-case scenario with all but one converter operating at the maximum current in the optimal range. The efficiency is less than the efficiency of a multi-phase converter with ideal current sharing. However compared to existing systems without active current sharing or phase shedding, the efficiency is significantly improved for light-load operation, as these systems will operate always with all converters active. Also it should be noted that the proposed system can also be used

<table>
<thead>
<tr>
<th>Table I</th>
<th>NORMALIZED CURRENT THRESHOLDS FOR VARYING NUMBER OF CONVERTERS.</th>
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<tbody>
<tr>
<td>$n$</td>
<td>1</td>
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<tr>
<td>$I_{\text{out}}$</td>
<td>$\sqrt{n(n+1)}$</td>
</tr>
<tr>
<td>$I_{\text{L, min}}$</td>
<td>$\sqrt{\frac{n-1}{n}}$</td>
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<tr>
<td>$I_{\text{L, max}}$</td>
<td>$\sqrt{\frac{n+1}{n}}$</td>
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IV. IMPLEMENTATION

A. Current sharing scheme

A block diagram of the proposed current distribution scheme for an implementation in discrete logic, feasible for FPGAs, is detailed in Fig. 7. The system consists of four units: The zone-decoder determines the current operation zone of the converter (Fig. 3). The supervisor logic assesses the converter’s operation state and signalizes steady-state conditions to the control logic. The control logic acts as overall control unit for the algorithm. An additional auxiliary block implements a timing- and random-generator.

The current distribution procedure, together with the required prioritization, is implemented using a small finite-state-machine (FSM). With reference to Fig. 8, the current sharing system can be in one of four states. The system remains in the unsteady state until output voltage and output current have settled. As soon as the outputs have stabilized, i.e. when output voltage and inductor current have remained within a given window for a predefined time, the target current is determined using the current output current and the optimization diagram in Fig. 3. The system transfers into a wait state where it remains until the desired wait time has expired. At this stage the state is changed to the active state where the current distribution scheme is enabled and the output current is transferred into the optimal operation zone. The converter remains in the active state until output voltage or current are disturbed by external events, e.g. load transients. When disturbed, the system goes back into the initial state and the procedure is restarted. An additional lock state is used to disable the current control procedure in case the converter cannot reach its optimal current value. For example, this is required if the optimal currents have not been selected properly and one converter has to deliver non-optimal current. Without a lock state, this converter will try to reach an optimal current indefinitely and consequently create perturbation on the output voltage.

Note that prioritization and current transfer are not active for all types of load transients. Small load transients do not trigger the unstable condition of the current sharing FSM and therefore do not require the current transfer to be reset. Rather the currently active converters share the increase across each other and then distribute the current afterwards. Also, if the load changes slowly, the currently active converters take action and share the current across them. There is no need to restart the entire scheme.

B. Loop compensation

The current distribution FSM is integrated into an existing digital control loop; in this case a predictive digital current programmed control architecture (Fig. 9). Such schemes have been presented in the past [24], [25] and provide direct control of the inductor current via a dedicated current reference value. An inner current loop regulates the inductor current on a cycle-by-cycle basis, while an output voltage control loop (VMC) provides the current reference value. The control loop is augmented with an additional input to control the inductor current.
The compensation of the voltage loop is a trade off between system resources and performance requirements as the number of active converters can change during operation. Two options can be considered: an adaptive loop compensation can be used which adapts the compensator to handle the number of currently active converters and to ensure good performance. Such auto-tuning compensator designs have been investigated in the literature, e.g., [26]. Alternatively, a compensator can be designed which is able to accommodate the different number of currently active converters without causing any problems. However, such a compensator is not optimal as it needs to be able to handle every possible case without causing instabilities. On the other hand, such a design is relatively simple and efficient in implementation. Therefore, the latter option has been chosen for the prototype system.

C. Prioritization

When implementing the proposed control scheme, special attention must be given to the prioritization in order to avoid potential control conflicts between converters, as detailed in section II. Therefore, the individual controllers are subject to two types of prioritization. The different zones are prioritized so that the converter operating in the “most undesirable” zone changes its operation state first. Additionally, the converters are prioritized so that two converters do not start their current control operation at the same time when they operate within the same zone. This priority can either be hard-coded, so that particular converters are always favoured, or alternatively random. For the latter, all converters have equal priority and a random factor decides about the actual priority. This balances the usage of the individual converters over time and hence increases the life-time of the system compared to a hard-coded (static) prioritization scheme. Note that if the randomness is not induced effectively, different converters can in fact create control conflicts. For example, in a case of two active converters, both converters may decide to change their output currents to higher values. This leads to an increase in output voltage until the converters detect a conflict of interest and resume voltage mode control. Hence, one of the converters has to deliver non-optional current until it can achieve a more optimal level. In this case, the converter restarts the current distribution procedure after a load transient which can be either indicated by a large voltage error (for a fast transient) or a change in operation zone (for a slow load transient). For the implementation detailed, a randomization scheme has been chosen. The random contribution is selected so that the probability for a conflict of interest is small (< $\frac{1}{64}$) when two converters are in the same operation zone. To introduce the randomness into the FPGA prototype system, a combination of a linear feedback shift register with the LSBs of the ADC has been used. In an ASIC implementation other alternatives may be chosen.

V. EXPERIMENTAL TESTING

The proposed system has been implemented and assessed in practice using a total of four parallel converters (technical specification in Table II.) Each converter features output voltage and inductor current sensing via a dedicated ADC. Attention has been given to the DCR current sensing circuit as this must be able to sense negative inductor currents. The system is controlled by an Altera DE2 evaluation board employing a Cyclone 2 FPGA where four identical digital cores have been implemented. Note that for a real system these cores would be implemented on separate ICs.

Fig. 10 shows a typical current transfer process where the current is transferred from one converter to another after a load transient. For illustration purposes, two active converters have been chosen. When a load step (12 A) is applied to the system, the two converters regulate the output voltage back to the reference value. This is followed by the prioritization phase until one of the converters initializes its transfer process. Converter 1 decreases its output current while converter 2 compensates for this change, i.e., it increases its output current. After the transfer converter 1 is switched off (not shown in the figure). The output voltage deviates slightly during this process as it is the only method of communication between the converters. The speed of the transfer is dependent on the output voltage tolerance where a larger tolerance accommodates a faster transfer.

The efficiency curve for a four-converter prototype system is shown in Fig. 11. The measured profile includes power

| Table II |
| TECHNICAL DETAILS FOR THE EXPERIMENTAL CONVERTERS. |
| --- | --- |
| Input voltage | 12 V |
| Output voltage | 1.5 V |
| Inductance | 680 nH |
| Switching frequency | 500 kHz |
| Output power | 25 W |
drain loss and drive loss, but does not include the power consumed by the measurement circuits or the FPGA. The operation of the system with different numbers of active converters is clearly visible. The number of active converters over the output current range matches the expected value and therefore validates the functionality of the current distribution scheme. Small discrepancies in the efficiency are due to mismatch between the simulation models and the hardware implementation, and measurement tolerances. Note that the random influence of the current behaviour in the optimal zone cannot be modelled. The system efficiency is compared with a standard current distribution scheme which distributes the current equally among the converters using. This has been implemented using the same prototype system, where the individual converters are now controlled from one central point. The efficiency of the proposed approach is marginally less than the efficiency of a multi-phase solution with equal current sharing and external phase shedding control.

Note that the efficiency shown is for an “optimal current” in the range of 9 to 11 A. This value has been chosen to illustrate the operation principle and does not relate to the optimal current value for the prototype system which is approximately 6 A. This leads to an apparently wrong number of phases for the operation between approximately 15 and 22 A.

The current distribution over the individual converters and the respective number of active converters over the load range is shown in Table III. The current is distributed so that the converters operate within the most efficient range, i.e. 9 to 11 A. The random distribution of the load current over the different converters shown is due to the equal prioritization of the individual converter which results in a first-come-first-serve basis, i.e. the converter, which decides to take the load current first, will get it. Note, the resulting current distribution also depends on the load transient. If the current increases slowly within one operation zone, the active converters share the increase equally. If the current increases more rapidly, additional converters are enabled to improve the transient performance. Once the current has settled, they are turned off again if not required by the load. To elaborate, the two different cases can be observed in Table III: For the 10 A case, the load current has been increased from 5 A to 10 A, hence converter 1, already active during the 5 A case, takes the additional load current. In contrast, the output current of 15 A has been applied in one single step leading to a different distribution of the output currents.

To highlight stability, applicability and influence of the randomization, Fig. 12 shows the efficiency pattern for multiple repetitive measurements. The efficiency shows a small spread for each current value caused by the influence of the randomization, discrepancies between the active phases and measurement tolerances. It is envisaged that this efficiency spread is not of practical relevance for most applications. However if maximum efficiency is essential, systems with standard current distribution patterns, and therefore higher overall efficiency, may be preferred.

VI. CONCLUSIONS

An approach for digital control of independent, parallel power supplies suitable for today’s independent, scalable power converters has been presented. With the introduction of control methods only present in existing multi-phase converters, it has been shown that the system performance can be improved over existing parallel solutions without requiring digital communication signals, i.e. additional wiring between the individual converters. A method to perform current sharing based on individual, smart power converters performing an optimization based on optimal current levels has been proposed, analysed and tested. The resulting stochastic system results in an efficiency comparable to existing multi-phase converters.
which has not been achieved with independent, parallel power supplies to date.

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[16] S. Saggini, D. Zambotti, E. Bertelli, and M. Ghioni, “Digital autotuning digital control theory to companies in Ireland and training courses in signals and systems theory and lectured at the university and has given professional applications, which he completed in 2004. He has Ph.D. research focused on developing safety-critical robustness analysis tools for x-by-wire automotive applications, which he completed in 2004. He has lectured at the university and has given professional training courses in signals and systems theory and digital control theory to companies in Ireland and abroad. His main area of research interest is designing and developing advanced control law solutions from simulation through to implementation and test for a variety of commercial applications. His current research work focuses on developing suitable digital control algorithms to improve the efficiency and transient performance of multi-rail/multi-phase converters.


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