Article

Decentralized Phase-Shedding with Low Power Mode for Multiphase Converter

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Abstract: This article presents a decentralized phase-shedding technique for multiphase converters. The usual central digital controller is replaced by identical local controllers forming a daisy-chain structure. Phase-shedding decisions are taken locally based on a local inductor current monitoring and threshold crossing management. This control strategy allows to implement as many phases as desired in a modular manner. In order to handle specific events such as load current inrush or a start-up sequence and to guarantee optimal transient responses, additional functions are included into each local controllers. The inter-cell communication protocol is described, along with necessary design considerations of threshold and timing values. Finally, functional simulations are carried out on a 5-leg 12V/1.2V 60W multiphase converter, which validate the proposed decentralized phase-shedding strategy for a microcontroller power supply implementation.

Keywords: Multiphase converter, Phase-Shedding, Decentralized Control

1. Introduction

The popularity of multiphase converters for high load applications such as microprocessor power sup-ply has brought forward the need to improve the efficiency of the converter across a wide range of load current, from high level in normal operating mode towards very light level during standby/sleep mode for instance. The most popular technique used to reach good performances is the phase add/drop technique, also known as phase-shedding, consisting in adapting the number of active phases to always operate close to the maximum efficiency point of each phase for any load current.

At first applied through systems based on centralized control units, the benefits of phase-shedding regarding efficiency at light load have been highlighted in [1] where a fundamental study of the method is described. Further improvements towards an optimal implementation of phase-shedding have been achieved with digital time-optimal control in [2], average current compensation across phases during phase-shedding for fast transient in [3], as well as binary-weighted current sharing for precise coverage of the load range in [4].

Beyond the efficiency matter, various other interests of phase-shedding have been developed, with advantages for power stage lifespan by using a rotating phase-shedding method in [5] and system lifespan with current threshold adaptation to input current and frequency variation in [6]. Power losses are also taken into account as temperature variations are involved in the computation of current thresholds in [7].

In parallel with the development of these specific control techniques dedicated to optimize the efficiency of the multiphase converter, other studies focusing on the decentralized/modular control have emerged to address the other control aspects of the multicellular converters such as the carrier interleaving [8-12], the current-sharing [13] and also the voltage regulation [14-18]. Now, a similar decentralized approach can be applied to

the phase-shedding in order to achieve full modularity for the multiphase converter control part, leading to more flexibility, robustness and also fault tolerant capability.

Fig. 1 describes the decentralized / modular implementation of the phase-shedding technique for multiphase converters proposed in this article. It is based on a daisy-chain configuration of local phase controllers, each communicating only with its close neighbors. Each local controller monitors its own phase current, compares it with minimum and maxi-mum current thresholds and take locally the decision to remain active or not depending on the state of its close neighbors. This control strategy effectively achieves the output efficiency optimization across the full load range as presented in [1], but in a decentralized manner.
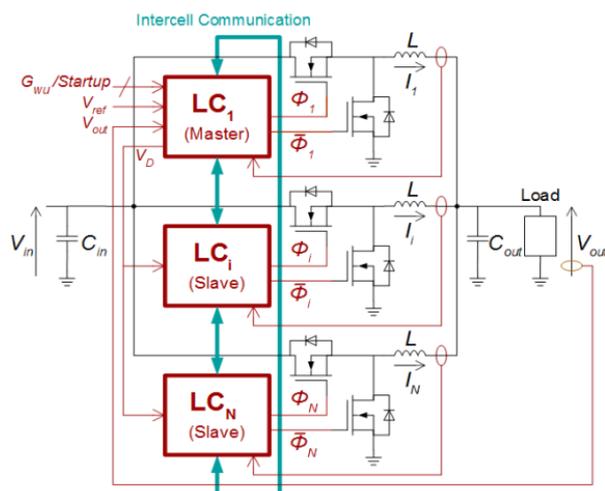
Figure 1. Decentralized phase-shedding principle using daisy-chain local communications (V_{ref} : the reference voltage, V_D : the error-amplifier output, V_{out} : the load voltage to regulate and $G_{wu}/Startup$: two bits to handle heavy-load events).

In order to operate, the local controllers require several external signals provided either by a supervisor (startup/ wakeup orders, the voltage reference V_{ref}) or sensors (phase currents I_i and the load voltage V_{out}). A Master/Slave bit determining their roles in the chain is also required. It should be noted that, in order to correctly operate during heavy-load events like startup and wake-up of the load as well as in reaction to a current inrush, the phase-shedding function has to be disabled automatically. Moreover, for very low load conditions, only one phase among the N will remain active and a so-called "low power" regulation mode will be used.

In chapter II, the principle and architecture of the local controller are detailed. Its internal logic functions are described, as along with threshold and timing considerations necessary to configure the system and ensure optimal operation.

In III, transient simulations show the appropriate phase-shedding behavior across the full load current range. Slow and fast load transients are considered and analyzed.

2. Principle

The principle of the presented control method is based on the usage of N identical local controllers, each associated to one phase of the multiphase converter. Each controller manages its own state (active or not) depending on the current level of its phase and the state of its close neighbors. Then, inter-controller communications are proposed using a daisy-chain topology, current thresholds are set and timing consideration for the phase activation or deactivation delays are analyzed.

Moreover, it should be noted, in order to handle some specific cases of operation (start-up, high load current, low power control mode), one of the local controllers has to be set as the master, the others being the slaves. The roles can be permuted if necessary, to address fault tolerance purpose for instance.
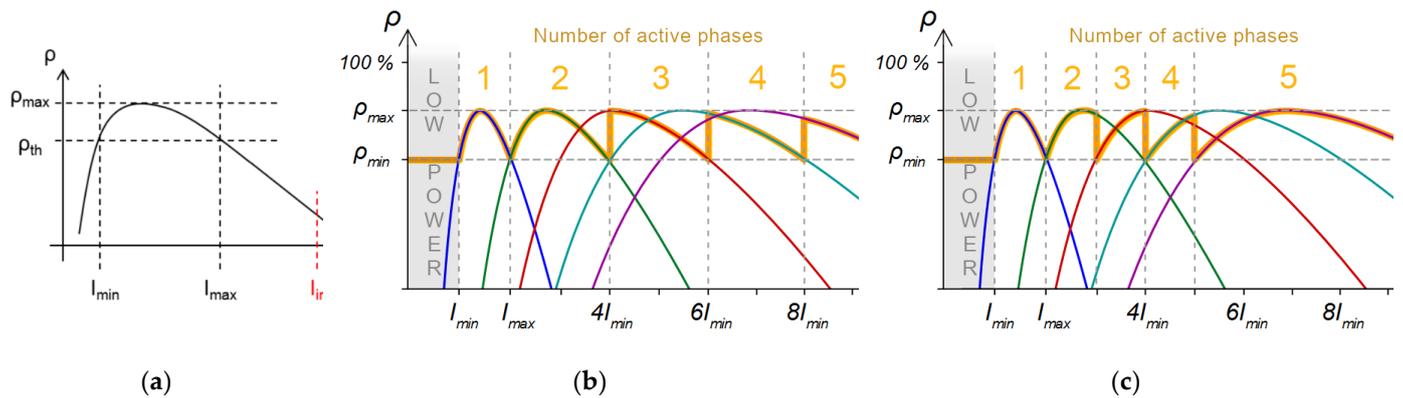
Figure 2. Decentralized Phase-Shedding strategy: (a) Min, max and inrush current thresholds considering the local phase efficiency; (b) The global efficiency during a load current increase; (c) The global efficiency during a load current decrease ($I_{max} = 2I_{min}$).

2.1. Daisy-chain architecture

First, each controller is assigned a status, either by an external supervisor or by hardware: one is the Master (M) and the others are the Slaves (S). While M always remains ON regardless of the load current, Slaves turn-on or turn-off in a chaser sequence accordingly to the load current.

In order to achieve decentralization of the phase-shedding, each S observe its own phase current and uses current thresholds to decide to stay ON or not. The goal is to maintain each active phase within its maximum local efficiency range, as shown in Fig. 2.a). If the local phase inductor current increases and crosses I_{max}, the number of active phases should in-crease as shown in Fig. 2.b); if it decreases and reaches I_{min}, the number should decrease as shown in Fig. 2.c). This threshold crossing is monitored within each active local controller.
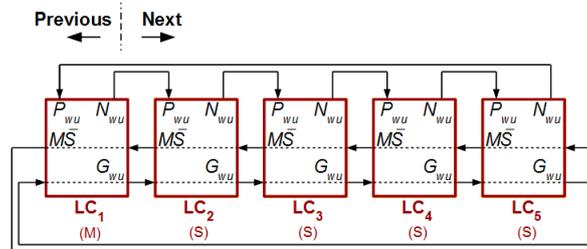
Figure 3. Daisy-chain topology with inter-controller communications.

In case of current threshold crossing and because all phase currents are supposed to be equal in steady-state, a sequencing of the local controllers is required to prevent the phases from turning-on or off altogether simultaneously. This is achieved for the incremental turn-on sequencing by using a Master/NotSlave signal chain ($M\overline{S}$) received by the local controllers and sent in the opposite direction to their neighbors, as shown in Fig. 3. The master M sends $M\overline{S}$ =1 and this signal flows through every inactive phase, each one also sending $M\overline{S}$ =1 to their previous neighbor in the chain (they are called "bypassed"). The first active slave encountered by this signal can therefore acknowledge that it is leading the chain. It is allowed to use the current threshold crossings either to turn-off itself (I_{min} crossing) or turn-on its next neighbor (I_{max} crossing). From there, an active slave sends $M\overline{S}$ =0, indicating to active slaves not leading the chain that they cannot change their states. The signal scheme sets local controllers in an orderly manner within the chain, with only the leading one allowed to take action.

Phase activation and deactivation sequences are presented in Fig. 4. It is shown that if the low current threshold I_{min} is crossed, the leading active Slave turns off and bypasses itself to indicate to the previous one it becomes the leading slave. On the other hand, if the high current threshold I_{max} is crossed, the leading active Slave sends a Next Wake-up (N_{wu}) signal to activate its next close neighbor.
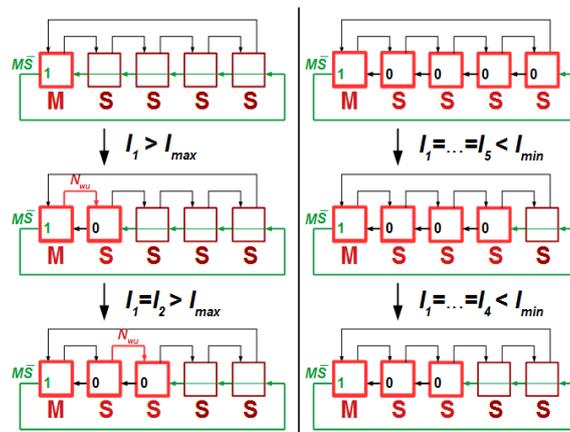
Figure 4. Activation and deactivation sequences depending on current threshold crossings.

Two extreme cases can be highlighted: if all phases are already active, the number of active phases can only change by decreasing once I_{min} is crossed; if the Master is the only remaining active local controller and I_{min} is crossed, Master goes in a Low-Power mode (LP), i.e. a voltage regulation mode based on a hysteretic control such as Pulse Frequency Modulation (PFM) or Auto Pulse Skip Mode (APS), to maintain high efficiency at even lighter loads.

In addition to the standard operation of the system which is based on the I_{min} and I_{max} current thresholds, specific events require all phases to become active at once: during system startup where a high output current is required to charge the output capacitor, during a heavy load activity almost planned by the microprocessor, or during a heavy load current inrush. Two input bits, respectively Startup and Global Wake-up (G_{wu}), allow to disable the phase-shedding function while activating all the Slaves, with Master transmitting the G_{wu} signal to every Slaves in a daisy-chain manner.

To implement this decentralized method, two state-machines are encoded in each local controllers. Depending on the role played by the local controller, Master or Slave, the state-machine of Fig. 5.a) or Fig. 5.b) is used. It should be noted in the Master state-machine, the parameter *PS* indicates whether the phase-shedding is enabled or not.
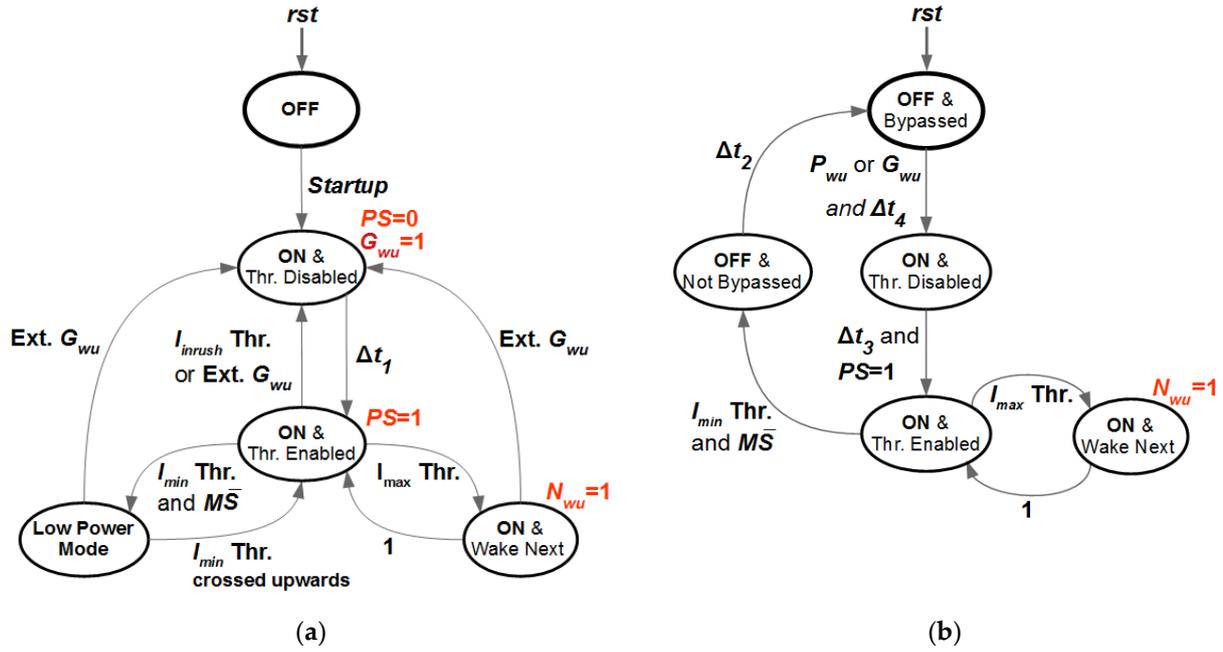
Figure 5. Local Controller state-machines: (a) Master; (b) Slave.

However, in order to avoid instabilities during phase-shedding, the principle of operation proposed requires additional considerations regarding the current threshold values and also the timing delays that are required during the activation/deactivation transitions.

2.2. Current threshold considerations

The system previously described based on phase current monitoring and control logic units does not guarantee the stability of phase-shedding by itself. It is relevant to consider stability matter during a deactivation sequence.

Indeed, a possible event consists in the decrease of the well-balanced phase currents of k active phases reaching the I_{min} threshold all at the same time (with $k \leq N$). Then the leading Slave turns-off and the inductor current of its phase discharges toward 0A through the low-side power switch body-diode. If load conditions do not change after this deactivation event, i.e. the load current I_{out} remains equal to kI_{min}, a new steady-state is reached where the k-1 remaining phases share the same portion of the load current. The ith phase currents I_i become:

$$I_i(\infty) = \frac{k}{k-1} I_{min} \qquad (1)$$

where k is the number of active phases among the N phases of the converter.

Now, if the value of this local current exceeds the I_{max} threshold, the upper threshold is crossed, and an order to reactivate the previously turned-off phase is sent by the leading Slave. Then, the currents of the now k active phases will decrease again since no load event has occurred. This configuration is unstable. Hence, the condition to fulfill is the following:

$$I_{max} > I_{min} + \frac{I_{min}}{k-1} \qquad (2)$$

The values of the steady-state phase currents depend on the number k of active phases. A worst case for Eq. (2) is obtained with $k = 2$, i.e. the last remaining Slave turns-off and twice I_{min} is handled by the Master, resulting in the stability condition:

$$I_{max} > 2I_{min} \qquad (3)$$

A second threshold consideration concerns the dynamic response of the phase-shedding system during an unexpected fast load current surge. As presented in the previous section, phases turn-on sequentially during a current increase sequence, therefore limiting the transient response speed to a high inrush current event. The solution designed consists in implementing a third threshold higher than I_{max}, called I_{inrush} (see Fig. 2a).

This threshold is only considered by the Master and, as it is crossed, the Master issues a G_{wu} signal across the daisy-chain, temporarily turning-on all phases and canceling the phase-shedding activity. The I_{inrush} threshold ensures the operational safety of the converter and leads to optimal efficiency during unforeseen strong load events.

2.3. Timing considerations

Fig. 5 shows transitions towards the "Wait for event" state, mainly current threshold crossing, which include delays Δt_1, Δt_2, Δt_3 and Δt_4. These delays must be implemented in order to create appropriate time shifts and to avoid instabilities.

Δt_1: basic timing considerations concern the previously implemented Startup, Global Wake Up and Inrush events.

On the one hand, the duration of the Startup event, during which phase-shedding remains deactivated, depends on the application and has to be estimated considering the time required to charge the output capacitor.

The duration of both G_{wu} and I_{inrush} events, which are induced by external actions, have to be also designed according to load specifications and worst-case current surge transients.

Δt_2: on the other hand, the increase and decrease rate of the local inductor current has an impact on the duration of transients during phase-shedding transitions.

Upon deactivation of a phase, local inductor current decreases over time from I_{min} to 0A. During this transient, the remaining active phases see their local currents increase while still potentially remaining below I_{min}. If the deactivated phase is bypassed too quickly and sets its previous neighbor the leader of the chain, the latter would potentially deactivate itself as well. A chain reaction occurs leading to a fast deactivation of all Slave phases.

To prevent this chain reaction, a delay between the phase deactivation and its bypassing is implemented. Its value corresponds to a full inductor discharge transient, and can be computed using simple design and application considerations:

$$\Delta t_{2\min} = \tau \ln\left(1 + \frac{I_{\min}R_{ph}}{V_{out}}\right) \tag{4}$$

where R_{ph} is the ohmic resistive path of each phase (R_{ON} switches + inductor DCR + copper wires), τ is the time constant L/R_{ph}.

Unless the load current decreases further, which would create a valid sequential deactivation of phases, such a delay ensures that all remaining phases have time to cross the I_{min} threshold upwards before the leading one is allowed to deactivate itself.

Δt_3: the activation of a phase is another potential source of instability. During the inductor charge transient of an activated phase from 0A to I_{out}/k, as the local controller see its local current below the I_{min} threshold, it will try to turn itself OFF.

A delay implemented between the phase activation moment and the one the phase is allowed to deactivate itself solves this instability issue. The worst case to consider is a phase current after charge in steady-state right above the I_{min} threshold, i.e. the load current slightly higher than kI_{min}. Hence full charge has to be reached before deactivation is allowed:

$$\Delta t_{3\min} = 5\tau = 5\frac{L}{R_{ph}} \tag{5}$$

This delay allows 99% of the steady-state current value to be reached before any further transition.

Δt_4: the last delay consideration corresponds to the prevention of a re-wake event due to the large bandwidth voltage regulation loop. After a phase is deactivated, during a short transient, the voltage regulation loop might cause a temporary increase of the duty-cycle, inducing a local current overshoot across the remaining active phases. The phase current of the new leading Slave may in turn potentially cross the I_{max} threshold and cause it to send a N_{wu} signal to wake up the phase which has just been deactivated. To prevent this behavior a delay has to be added between the deactivation of a phase and its ability to be reactivated as shown in Fig. 5b).

3. Simulation results

This section presents the simulation results of the multiphase converter controlled by the proposed decentralized phase-shedding technique. Table I shows the parameters of the application that requires a five-phase multiphase buck converter, along with phase's local controllers implementing a logic control unit as well as a current-mode voltage regulator, as shown in Fig. 6.
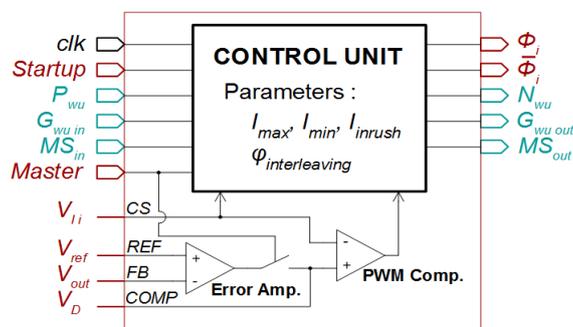
Figure 6. Implementation of the Local Controller cell (V_{Ii}: the local current sensor output signal, V_D: the output of the voltage regulation loop error opamp).

Table 1. Simulation parameters.

Parameter	Value
N (phase number)	5
V_{in}	12 V
V_{out}	1.2 V
I_{out}	$0 - 60$ A
f_{sw}	1 MHz
L	1 μH
C_{out}	500 μF
I_{min}	3 A
I_{max}	6.5 A
I_{inrush}	15 A

The voltage loop error amplifier is only active in the Master. Its output is connected to node COMP in order to send to all remaining Slave Local Controllers the signal allowing to compute the local PWM signals [19].

The simulated load scenarios feature output current transients covering the entire converter's current range, thus showing phase-shedding during both a turn-on and a turn-off sequence (Fig. 7).

Appropriate phase-shedding scheme is obtained in both cases with a smooth sequence set by I_{max} and I_{min}, as well as delays Δt_3 and Δt_4. Fig. 7a) shows the system response to a slow increase of the load current. Each time a phase's local current reaches $I_{max} = 6.5$

A, a local wake-up signal is sent to the next phase by the leading Slave, thus increasing the number of active phases. The opposite behavior is observed on Fig. 7b) where phases are successively deactivated each time I_{min} = 3A is reached.
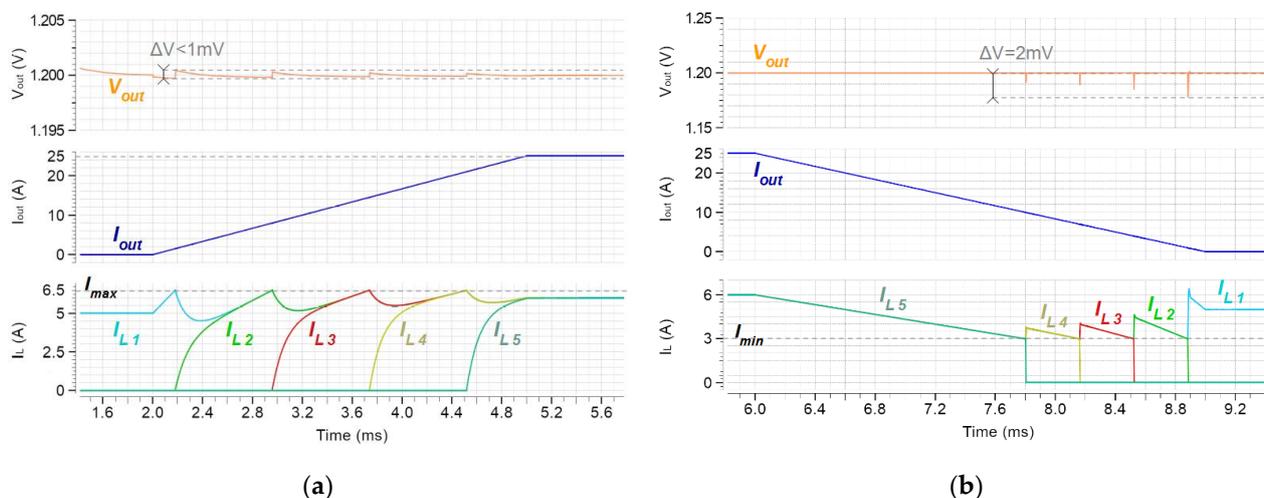
Figure 7. Simulation of load transient response: (a) from 0 to 25 A with turn-on sequence (I_{max}=6.5A); (b) from 25 to 0 A with turn-off sequence (I_{min}=3A).

A secondary simulated scenario, shown in Fig. 8, is the fast decrease of the load current. Delay Δt_2 prevents a deactivation runaway during a fast decreasing load transient. Each phase sees its local current bellow I_{min}, but this delay ensures a smooth transition from five phases to one phase by time shifting the ability of a phase to turn itself OFF when it leads the chain.
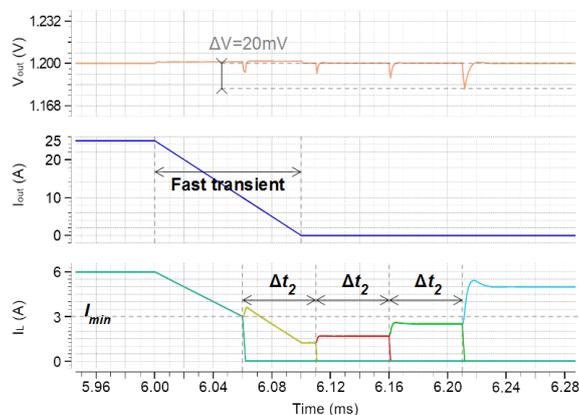
Figure 8. Fast load transient 25 to 0 A with shutdown prevent delay (Δt_2=50µs).

Finally, the effect of the third threshold I_{nrush} used to handle fast inrush current transient is illustrated in 0. Natural incremental phase-shedding response to strong inrush current, i.e. without threshold I_{nrush}, is presented in 0.a). Potentially destructive 13 A overcurrent is observed in one phase and system time response is 6 ms. In 0.b), the threshold I_{nrush} is used. It generates a global wake-up signal G_{wu} that activates all phases instantaneously, overriding the phase-shedding function. System transient is improved with only 2 ms time response and lower safe overcurrent is reached with only 8A for the Master.
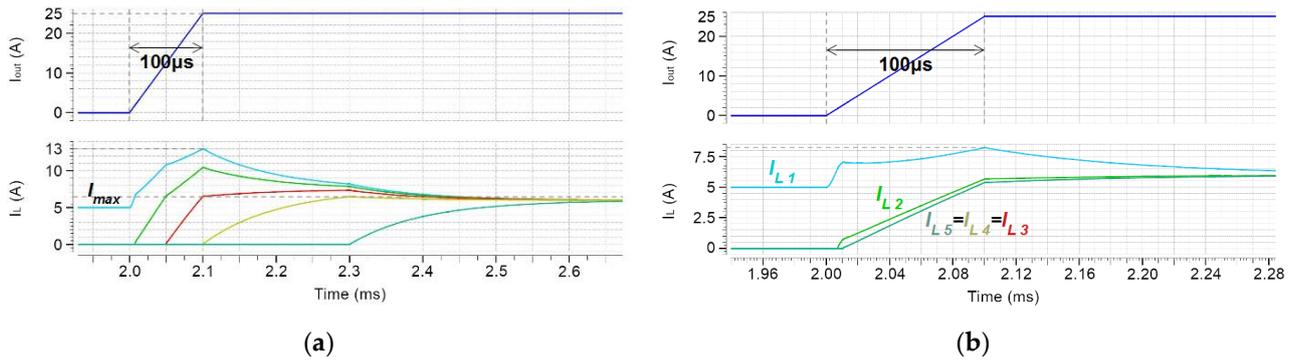
Figure 9. Simulation of current inrush transient: (a) with I_{inrush} threshold deactivated; (b) with I_{inrush} threshold activated.

5. Conclusion

A decentralized phase-shedding technique has been presented. It consists of taking local decision to turn-on or turn-off each phase of the multiphase converter in order to maximize its power efficiency depending on the load current level. Each phase monitors its own local current and compares it with min and max thresholds. Using local communications, depending on its own position in the chain and the state of the others, each phase disables or enables its local power stage consequently. For very low load current, the remaining active phase enters a low power mode to maximize the converter efficiency. In order to handle specific events such as start-up sequence or inrush current requiring the fast activation of all the phases, additional functionalities are included into the local controllers. The inter-cell communication protocol used is described, along with necessary design considerations of threshold and time shifting values. Finally, functional simulations are carried out on a 5-phase converter, which validate the proposed control strategy.

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