INTERLEAVED DC-DC CONVERTER WITH DISCRETE DUTY
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The authors present the control principle of the multiphase interleaved DC-DC converter that can be used to vastly reduce output current ripple of the converter. The control algorithm can be easily implemented by using microcontroller without current loop in each phase. The converter works in discontinuous conduction mode (DCM) but close to boundary conduction mode (BCM). The DC-DC converter with such a control algorithm is useful in applications that do not require precise current adjustment. The prototype of the converter has been built. The experimental results of the current ripple are presented in the paper.

Keywords: DC-DC power converters, discontinuous conduction mode multiphase switching converters.

1. INTRODUCTION

Interleaving control schemes of the DC-DC converters are more often used in the converter applications, especially in the converters that require high power capability and high performance. Benefits of such control methods include reduction of size, losses and cost of the input and output filters, reduction of current stress of the dc bus capacitor, improved dynamic performance and increase in the power capacity of the converters. Interleaved DC-DC converters are used in various applications: as voltage regulation modules [1]–[2], renewable applications [3]–[5], traction applications [6]–[8] and in other areas.

The current of the interleaved DC-DC converter can be controlled in the two modes: continuous conduction mode (CCM) or DCM. When the converter operates in the DCM, zero current switching can be implemented without additional control or components; smaller inductance than in the CCM is necessary. In the discontinuous conduction mode (DCM), the reverse-recovery losses of the diode are eliminated

and switching losses can be reduced. On the other hand, input current and output voltage ripple are increased in the DCM. Due to this reason, it is important to find a way how to reduce this ripple. Moreover, most of the published papers require a current control loop in each phase to achieve balanced phase currents and to improve transients [9]–[12]. The cost, weight and control complexity grow when the number of phases increases due to the control loop into each phase; therefore, open-loop control allows solving this problem.

The particular control method of the DC-DC converter can not provide accurate regulation of the current but in many applications it is not necessary. One of the examples is the boost or buck-boost converter in a DC drive (Fig. 1.). As a DC motor has a very high starting current that has the potential of damaging the internal circuit of the armature winding, current must be restricted to some limited value. Therefore, all DC motors must be provided with a means to limit the starting current to reasonable values. Thus, during transition processes and when high torque is required the proposed control method is applicable, but when low current is required then the DC-DC converter can work in deeper DCM mode or a number of the active phases can be reduced.

Fig. 1. Six-phase boost converter for DC drive.

The proposed control method uses variable frequency mode. Compared to DCM with constant switching frequency [12], [13], [14], [15] variable frequency mode yields to lower total harmonic distortion of the current and smaller peak inductor currents and results in lower switching and conduction losses. As the MOSFETs (metal–oxide–semiconductor field-effect transistors) have parasitic capacitance and the converter works close to boundary conduction mode, it is possible to achieve zero voltage switching conditions similar as in [16], [17], [18].

2. THE CONTROL METHOD

The operation into the DCM requires a phase ripple current larger than twice the average phase current. Therefore, the use of a large output capacitance is necessary to hold a constant output voltage. But as in a multiphase converter, the phases share current equally and the phase ripple is proportional to the current that flows in each phase, the phase ripple decreases if the number of phases increases. Even more depending on the duty cycle, the actual output ripple can be lower due to ripple cancelation between the phases:

$$\Delta i_o = \frac{V_{IN}}{f_{sw} L N^2} \left[(Nm - \text{floor}(Nm)) - (Nm - \text{floor}(Nm))^2 \right] \quad [19], \quad (1)$$

where V_{IN} – input voltage; f_{sw} – switching frequency; L – inductance; N – number of phases; m – modulation index.

By using (1), it is possible to draw curves shown in Fig. 2. As can be seen from Fig. 2, the current ripple reaches zero when the modulation index is equal to multiple of $1/N$. In a particular six-phase case, the zero current ripple takes place by duty cycle equal to 0.17, 0.33, 0.50, 0.67 and 0.83. Of course, in real design exactly zero current ripple is hard to reach due parasitic resistance, capacitance, inductance and transients into circuit. The six-phase converter has less than 0.8 percent output ripple by any duty cycle.

Fig. 2. Normalized output current ripple of boost converter.

One of the problems that must be considered in the design of the interleaved converter is current sharing. One of the solutions is to include an additional current loop. This leads to higher cost, increased size and decreased reliability of the converter. The goal of the paper is to use a large number of phases but without any current loop in each phase. In continuous conduction mode (CCM), a 1% difference in one duty cycle causes a 47% unbalance in the current of the unbalanced phase [15]. Misbalance of the currents is also caused by unequal inductance and parasitic resistance. In the discontinuous conduction mode (DCM), equalization of the currents is much better. In the DCM, the differences in phase current are caused by duty cycle, inductance and not parasitic resistance. Since each phase current starts from zero every switching cycle, the average values are quite similar even if the duty cycles are relatively different.

In the DCM mode, per-phase current is determined in each period and it does not depend on the previous periods. This greatly improves the converter dynamics and simplifies control system of the converter as if any converter is stable in the CCM, then it will be stable in the DCM as well.

In the boundary conduction mode (BCM), the peak current in the inductor (Fig. 3.) is twice the average current. Therefore, this mode is the most economical and control will be designed to ensure work of the converter in the DCM mode as

close as possible to the BCM. The summary output current I_{out} of n phase converter is the sum of all choke currents. In the BCM, the peak current in the choke (I_m) can be expressed as shown below:

$$I_m = \frac{2 \cdot I_{IN}}{N}. \quad (2)$$

Using the inductance (L) as well as the input (V_{in}) and output (V_{out}) voltage, the required on-time (t_{on}) and off-time (t_{off}) for boost mode can be calculated as shown in (4) and (5) and similarly for boost mode to ensure operation in boundary conduction mode:

$$t_{ON} = I_m \frac{L}{V_{out}}, \quad (3)$$

$$t_{OFF} = I_m \frac{L}{V_{in} - V_{out}}. \quad (4)$$

As the DC-DC converter works at a constant duty cycle (D), the switching period (T) can be calculated as follows:

$$T = \frac{t_{ON}}{D}. \quad (5)$$

Fig. 3. Inductor current in boundary conduction mode within boost mode.

The selection of the duty cycle D may be carried out in several ways. The simplest method is to control output voltage by discrete values. If the converter has a large number of phases, then in such a way output voltage with normal resolution can be formed.

Figure 4 shows the method of controlling current during starting of the motor with the boost converter. The method is a bit similar to the use of starting resistors only without energy losses. The main principle is to control input current (I in Fig. 4), and if current decreases to some minimum value then transition to the next duty

cycle takes place. The variable I_m can be calculated by (2), if input current I_{IN} is measured by current sensor. By using (3) and (5) time and period values can be calculated. The converter works in variable frequency mode close to the BCM.

If no current regulation is necessary after the starting process, the converter can work at a constant duty cycle to ensure nominal output voltage. If current control is required, then the converter can work at any duty cycle. Although current ripple will be relatively larger, it will not be so important because the nominal current is much smaller than starting current; therefore, current ripple will be lower anyway.

Fig. 4. Duty cycle changing algorithm of boost converter during starting of the motor.

One of the methods of current control is that the variable I_m can be used not only to maintain the desirable current, and t_{on} and t_{off} are calculated by equations (3) and (4). This can be done if I_m is output of the proportional-integral (PI) regulator. This method is described in [4]. Another method is working with constant switching frequency in the DCM. Some control algorithms in this mode are discussed in [12], [14], [15]. Also work in the CCM is possible. It can be done if some phases work in parallel mode and additional current sensors are placed in these branches. Many other control methods can be implemented, too.

3. RESULTS AND DISCUSSION

Figure 5 shows the prototype of the six-phase boost converter. In the figure, 1 denotes power supply for driver circuits, 2 is the digital signal processor that provides control of the converter, 3 – inductors, 4 – MOSFET transistors. The inductors used in this interleaved converter have a low inductance value as the converter works in the DCM. The inductance of the inductor is equal to 50 μH ; it consists of 5 windings of Litz wire on the RM8 core, the ceramic capacitors are placed near the transistors to reduce the impact of parasitic inductance. PSMN6R5-80BS MOSFET transistors and STM32F407 digital signal processor are used in the prototype.

Fig. 5. The prototype of the boost converter.

Figure 6 shows per-phase current of DC-DC converter in the DCM. As can be seen, current goes a little into the negative, it means that zero voltage switching can be achieved in the BCM because the inductor current declines under zero and a subsequent oscillation between inductor and parasitic MOSFET capacitors starts in which the voltage over MOSFET drops to zero (or near zero).

Fig. 6. Per-phase current in the DCM.

Fig. 7. Per-phase current and input current of the interleaved DC-DC boost converter.

Figure 7 shows per-phase and output current of the boost converter in the BCM. The switching frequency of the converter in the experiment was close to 170 kHz. As current probe with the bandwidth of 200 kHz is not available, current has a bit filtered shape. The algorithm described above allows correctly calculating the period to ensure work in the BCM.

4. CONCLUSIONS

In this paper, the control algorithm of interleaved multiphase DC-DC converter has been described. The converter with such an algorithm can be designed avoiding the use of current loops that would not be feasible with a very large number of phases. The algorithm can be used in many applications. In the paper, the application example has been shown for motor starting with the boost converter. The converter works at discrete duty cycles that allow reducing output and input current ripples and size of capacitors. Operation in the BCM allows implementing zero voltage and zero current switching without additional elements. The algorithm can be implemented using digital control. The experimental prototype has been developed, and experimental results have been shown. The further research is needed to investigate the change of active number of phases to increase operating points with tiny current ripple.

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VAIRĀKFĀŽU LĪDZSTRĀVAS PĀRVEIDOTĀJS AR DISKRĒTU AIZPILDĪJUMU UN BEZ ATGRIEZENISKĀS SAITES

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K o p s a v i l k u m s

Rakstā piedāvāts izmantot līdzstrāvas pārveidotāju, mainot aizpildījumu diskrēti - tas ir, izvēloties tādas vērtības, pie kurām strāvas pulsācijas ir minimālas. Šāds risinājums ļauj samazināt pārveidotāja izmērus un izmaksas, kā arī ir iespējams realizēt bezsprieguma un bezstrāvas komutāciju. Pārveidotājs var tikt izmantots risinājumos, kur ir pieļaujama diskrētas formas sprieguma izmantošana vai arī neprecīzai strāvas regulēšanai. Kā piemērs apskatīts paaugstinošā līdzstrāvas impulsregulatora izmantošana motora startēšanai. Piedāvātā metode var tikt realizēta, izmantojot mikrokontroleri. Rakstā aprakstīts prototips, kura darbības pamatā ir pielietotā metode.

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