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To cite this article: Daying Sun et al 2018 J. Phys.: Conf. Ser. 1087 042008

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digital controller for single-inductor dual-output A switching converter with low cross regulation

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Abstract. In this paper, motivated by improving the characters of the single-inductor dual-output switching converter (SIDO) at continuous-conduction mode (CCM), a new digital controller for converter is proposed. The digital controller mainly consists of the time-multiplexing control method and the predictive control method. The simulation results demonstrate that the converter with the proposed digital controller can aim high output stability and low cross regulation.

1. Introduction

To meet different application requirements and reduce the power consumption, multiple regulated supply voltages are often needed in electronic devices, so as to supply different voltages for different function modules, which are mainly aimed by many different dc-dc switching converters [1].

Meanwhile, in order to improve the integration level and reduce the cost of the total integrated circuits, the single-inductor multiple-output (SIMO) switching converters have been used more and more popularly [2][3]. Due to the fact that the signal inductor is shared by all output branches during different operating condition, the single branch will inevitably suffer from unwanted voltage disturbance when output voltage or output load changes for some other branches. Many control methods have been proposed to overcome such question [4][5][6][7], although the cross regulation can be reduced, the switch loss and the current peak may increase, or the total circuit enters into unstable condition, and so on.

A new digital controller is proposed in our paper to improve the characters of the SIDO switching converter operating at continuous-conduction mode. The whole SIDO buck converter structure with the proposed digital controller is illustrated in section 2, the operation principle and the detailed control method of digital controller is described in section 3, and simulation results and the conclusion are presented in section 4 and section 5, respectively.

2. The SIDO buck converter structure with the proposed digital controller

The whole SIDO buck converter structure with the proposed digital controller is shown in Fig. 1. The output voltages of two output branches and inductor current of converter are sampled by Analog-to-Digital (ADC) converters, respectively. The proposed digital controller mainly consists of the digital control algorithm and the optimized DPWM module. The desired digital duty cycle value of every switching cycle is calculated by the digital control algorithm, and the final duty cycle signal for the switching tube is converted via the DPWM module.

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IOP Conf. Series: Journal of Physics: Conf. Series 1087 (2018) 042008 doi:10.1088/1742-6596/1087/4/042008



Figure1 The whole SIDO buck converter structure with the proposed digital controller

3. Design of the digital controller

3.1The time-multiplexing control method

The waveforms of output voltages, inductor current and duty cycle signals are shown in Fig.2. During every period time, when one output branch is charged, the other output branch will be discharged.



Figure 2 The waveforms of output voltages, inductor current and duty cycle signals

When the d_i signal is high level, the above output branch will be charged. The inductor current $I_L \ensuremath{\text{can}}$ be expressed as

$$L\frac{dI_{L}}{dt} = V_{in} - V_{i} \quad (\text{when d is 1})$$

$$L\frac{dI_{L}}{dt} = -V_{i} \quad (\text{when d is 0}) \quad (2)$$

Meanwhile the output voltage Vi can be expressed as

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IOP Conf. Series: Journal of Physics: Conf. Series 1087 (2018) 042008 doi:10.1088/1742-6596/1087/4/042008

$$C\frac{dV_i}{dt} = I_L - I_i \tag{3}$$

Hence variation of inductor current I_L and output voltage Vi within one charging period can be expressed as

$$I_{L(t+T)} = I_{L(t)} + \int_{t}^{t+d_{i}T} \frac{V_{in} - V_{i}}{L} dt + \int_{t+d_{i}T}^{t+T} \frac{-V_{i}}{L} dt$$

$$V_{i(t+T)} = V_{i(t)} + \int_{t}^{t+T} \frac{I_{L} - I_{i}}{C} dt$$
(5)

During the discharging period, the relationship of load current I_L and output voltage V_i can be expressed as

$$C_i \frac{dV_i}{dt} = -I_i \tag{6}$$

Hence the variation of the load voltage within one discharging period can be expressed as

$$V_{i(t+2T)} = V_{i(t+T)} + \int_{t+T}^{t+2T} \frac{-I_i}{C} dt$$
(7)

When one branch of the SIDO converter reaches the steady state, the quantity that the output capacitor is charged in must be the same as the output capacitor is discharged out. And some condition can be concluded as

$$V_{i(t+T)} - V_{i(t+2T)} = V_{i(t+T)} - V_{i(t)}$$
(8)

The solution of the above equation is more than one. To meet the condition for the steady state, the initial inductor current at the beginning of each period and the duty cycle can vary in a limited range. The maximum of the initial inductor current corresponds to the zero duty cycle, and the minimum of the initial inductor current corresponds to the full duty cycle. For each output branch, it has a specific range of initial inductor current and duty cycle to satisfy the steady state condition. Meanwhile, the SIDO converter requires that two output branch can both reach the steady state during the steady state condition, and the terminal charging inductor current of one branch is also the initial charging inductor current of the other branch. Fig. 3 shows the steady state of the two output branches for the SIDO converter, which is the intersection of the steady state range of two branches. In Fig. 3, d_{max} is the sum of d_1 and d_2 . It can be estimated by the steady state equation of inductor current.



Figure 3 The steady state of the SIDO buck converter

3.2. The predictive control method

For the SIDO converter, the cross regulation is inevitable when the transient process occurs. When the load condition of one output branch changes, the steady point of the SIDO converter also changes. The

new and old steady points are shown in Fig.4, respectively. During the transition process from the old steady point to the new point, if the inductor current and the duty cycle of the unchanged output branch can always keep the curve relationship as Fig. 4, the cross regulation of the two output branches can be minimized effectively.



Figure 4 The new and old steady points of converter

To reduce the cross regulation, it is essential to determine the new steady point of converter. At the beginning of each switch period, the values of output voltage, inductor current and load current are sampled. So the inductor current can be predicted.

$$I_{L(k+1)} = \begin{cases} I_{L(k)} + \frac{V_{in} - V_{i(k)}}{L} \times T_{step} & d \ge \frac{k}{n} \\ I_{L(k)} - \frac{V_{i(k)}}{L} \times T_{step} & d < \frac{k}{n} \end{cases}$$
(9)

Meanwhile, the output voltage and the output current of the next time step can be concluded as

$$V_{i(k+1)} = V_{i(k)} + \frac{I_{L(k)} - I_{i(k)}}{C} \times T_{step}$$
(10)

$$I_{i(k+1)} = \frac{V_{i(k+1)}I_{i(k)}}{V_{i(k)}}$$
(11)

(16)

Based on the above equations, the proposed predictive control principles are as follows

$$I_{L1(t+T)} = I_{L1(t)} + \int_{t}^{t+d_{1}T} \frac{V_{in} - V_{1}}{L} dt + \int_{t+d_{1}T}^{t+T} \frac{-V_{1}}{L} dt$$

$$V_{1ref_up} = V_{1ref_down} + \int_{t}^{t+T} \frac{I_{L1} - I_{1}}{C} dt$$
(12)
(13)

$$V_{1ref_dowm} = V_{1ref_up} + \int_{t+T}^{t+2T} \frac{-I_1}{C} dt$$
(14)

$$d_2 = d_{\max} - d_1 \tag{15}$$

$$I_{L2(t)} = I_{L1(t+T)}$$

$$I_{L2(t+T)} = I_{L2(t)} + \int_{t}^{t+d_2T} \frac{V_{in} - V_2}{L} dt + \int_{t+d_2T}^{t+T} \frac{-V_2}{L} dt$$
(17)

$$V_{2ref_up} = V_{2ref_down} + \int_{t}^{t+T} \frac{I_{L2} - I_2}{C} dt$$
(18)

$$V_{2ref_down} = V_{2ref_up} + \int_{t+T}^{t+2T} \frac{-I_2}{C} dt$$
(19)

4. Simulation results

The SIDO buck switching converter with the proposed digital controller has been simulated via the

Matlab/Simulink environment. The converter parameters are as follows: $V_{in}=5V$, L=4.7µH, $C_1=C_2=22\mu F$, $f_s=1MHz$, $V_{o1}=1.2V$, $V_{o2}=1.8V$, $R_1=3\Omega$, $R_2=4\Omega$. The sampling frequency is equal to the switching frequency.



Figure 5 The waveforms of the output voltages, the output currents of the two output branches and the inductor current of SIDO converter

Initially the SIDO buck converter is in the steady state mode, and the output load currents i_{o1} and i_{o2} are 400mA and 450mA, respectively. At time 0.027s, the load current i_{02} of the second output branch is stepped down from 450 mA to 400mA while the load current iol of the first output branch is kept constant. Fig.5 shows the output voltages and the output currents of the two output branches and inductor current of SIDO converter, respectively. As shown in Fig.5, when the output load current io2 changes for the second output branch, it can be observed that there is an average drop of 11 mV for the output voltage Vo2 . The cross regulation is 0.02 mV/mA and the transient response time for the second branch is100µs.

5. Conclusion

This paper proposes a new digital controller for the SIDO buck converter at CCM. The digital controller mainly consists of the time-multiplexing control method and the predictive control method. Finally the simulation results confirm satisfactory performance in cross regulation suppression of the output voltages for the SIDO buck converter.

Acknowledgements

The authors should like to thank the National Nature Science Foundation of China (61604075 and 61504065), and the Fundamental Research Funds for the Central Universities (30917012202).

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