Abstract—In this paper, active inductor current balancing method for multi-phase four-switch buck-boost converter is presented. The multi-phase four-switch buck-boost converter is proposed for battery powered applications, such as automotive/truck applications, where high power dc-dc converters capable of stepping up and stepping down voltages are required. Inductor current balancing circuit based on the average current sharing bus approach is used to ensure that the inductor currents are evenly distributed.

A prototype of 4-phase buck-boost converter was implemented to verify the concept. Experimental results are included to show the inductor current balancing during steady state and load transient.

I. INTRODUCTION

In battery powered applications where the output voltage is converted from a wider input voltage range, a dc-dc converter capable of stepping up and stepping down output voltage is often required. In automotive applications, dc-dc converters are often used to regulate 12 V output voltage from batteries. The battery voltage can vary significantly from load-dump to fully-charged conditions. Non-inverting buck-boost converter, Fig. 1(a), is one of the candidates suitable for such applications.

\[\text{Fig. 1. Buck-boost topology circuits: a) non-inverting buck-boost converter, and b) four-switch buck-boost converter.}\]

To reduce conduction loss in the converter, MOSFETs can be used to replace the diodes in the non-inverting buck-boost topology. This topology, as shown in Fig. 1(b), is known as “four-switch buck-boost converter”. It has gained a lot of attention recently due to its flexibility to change modes among buck, boost and buck-boost [1–5].

The multiphase interleaving technique has been intensively studied in buck [6, 7] and boost [8, 9] topologies due to many advantages such as lower switching frequency for each phase, fast transient response, as well as reduced switching ripples in the input/output currents and the output voltage.

In this paper, the four-switch buck-boost topology in multiphase operation with active inductor current balancing is presented. The multiphase operation is proposed to the four-switch buck-boost topology for the applications where high output currents are required. Figure 2 illustrates a simplified circuit of an n-phase four-switch buck-boost converter. Similar to other topologies with multiphase operation, inductor current balancing is critical for achieving optimal performance and distributing thermal stress evenly among phases.

An active inductor current balancing method based on...
The method shows capability to balance inductor currents equally and stably.

This paper is organized as following: the operation of a single-phase four-switch buck-boost converter is reviewed in Section II. Section III discusses the multi-phase operations and the active current balancing mechanism. The experimental results from the prototype are included in Section IV.

II. FOUR-SWITCH BUCK-BOOST CONVERTER

A. The Operation of Four-Switch Buck-Boost Converter

In this section, the operation of a four-switch buck-boost converter is reviewed. The state of the switches, “on” or “off”, is controlled by a pulse width modulation (PWM) signal. Each switching period can be divided into two sub-intervals, \( D \) and \( 1 - D \), where \( D \) is the duty cycle of the PWM signal. Refer to Fig. 1(b), during subinterval \( D \), switches \( Q_1 \) and \( Q_4 \) are on, while switches \( Q_2 \) and \( Q_3 \) are off, the energy is transferred from the input source to the inductor. During subinterval \( 1 - D \), switches \( Q_2 \) and \( Q_3 \) are on, while switches \( Q_1 \) and \( Q_4 \) are off, the stored energy in the inductor is then transferred to the load.

B. Small-Signal Model

The four-switch buck-boost converter with voltage mode control is used for studying in this paper. Using the linearization and perturbation method [10], considering the dc resistance of the inductor (DCR) and equivalent series resistance of the output capacitor (ESR), the circuit equivalent to the small signal model of the four-switch buck-boost converter is illustrated in Fig. 3. The control to output transfer function, \( G_{vd} \), can be expressed as:

\[
G_{vd}(s) = \frac{\hat{v}_o}{\hat{d}} = G_{vd0} \frac{(1 - s/\omega_{RHZ})(1 + s/\omega_{ESR})}{1 + s/Q\omega_0 + s^2/\omega_0^2} \tag{1}
\]

where

\[
G_{vd0} = \frac{V_i + (1 + \frac{DCR}{D'I^2R})V_o}{1 + \frac{DCR}{D'R}}
\]

\[
\omega_{RHZ} = \frac{D'I^2R V_i + (1 - \frac{DCR}{D'I^2R})V_o}{L}
\]

\[
\omega_{ESR} = \frac{1}{C \cdot ESR}
\]

\[
\omega_0 = \sqrt{\frac{D'I^2R + DCR}{LC(R + ESR)}}
\]

\[
Q = \frac{1}{\omega_0 L + C \cdot (DCR(R + ESR) + D'R \cdot ESR)}
\]

\[
D' = 1 - D
\]

The control to inductor current, \( G_{id} \), can also be expressed as:

\[
G_{id}(s) = \frac{i_L}{\hat{d}} = G_{id0} \frac{1 + s/\omega_z}{1 + s/Q\omega_0 + s^2/\omega_0^2} \tag{2}
\]

where

\[
G_{id0} = \frac{(V_i + 2 \cdot V_o)}{D'I^2R(1 + \frac{DCR}{D'I^2R})}
\]

\[
\omega_z = \frac{V_i + V_o}{RV_i + ESR(V_i + V_o)}
\]

For quantitative comparison, Figure 4 shows the frequency responses of \( G_{vd}(s) \) and \( G_{id}(s) \) for a four-switch buck-boost converter with the following parameters: \( V_i = 12 \) V, \( V_o = 12 \) V, \( R_{Load} = 3 \) \( \Omega \), \( L = 6.8 \) \( \mu \)H, \( DCR = 9.4 \) m\( \Omega \), \( C = 300 \) \( \mu \)F, and \( ESR = 10 \) m\( \Omega \).

Note that the zero in the \( G_{id}(s) \) transfer function is proportional to the load current, while the right-half plane zero
in the $G_{vd}(s)$ transfer function is inversely proportional to the load current. At no-load condition, the zero of $G_{id}(s)$ moves to the origin point, on the other hand, the RHZ of $G_{vd}$ moves to high frequency. Audio susceptibility and output impedance transfer functions can also be derived similarly from the small signal model.

III. MULTI-PHASE OPERATIONS

A. Active Current Balancing Circuit

There are several well-established methods focusing on active current balancing [11]. The average current sharing bus architecture is selected for studying in this paper due to:

- the flexibility to scale the number of phases
- the controllable current-sharing loop
- the accurate regulation on the output voltage

In the average current sharing bus method, the current in each phase is regulated to a target value, which is the average of all phase currents. Consequently, the current in each phase can be shared evenly.

Figure 5 illustrates the simplified block diagram of a two-phase buck-boost converter with the average current balancing circuit. On each phase, the inductor current is sensed through a current sensing circuit with a gain of $K_i$. This sensed signal, $I_{\text{sense}1}$, together with the sensed signals from all other phases are used to generate the average current, $I_{\text{AVG}}$. The sensed signal, $I_{\text{sense}1}$, is then compared with $I_{\text{AVG}}$ to generate current-sharing error signal $I_{e1}$ for phase 1. In general, the current-sharing error signal for phase $j$ can be expressed as:

$$I_{ej} = K_i \cdot I_{Lj} - \frac{K_i}{n} \sum_{j=1}^{n} I_{Lj} \quad (3)$$

where $n$ is the number of total phases.

The error signal, $I_{e1}$, is then compensated by current loop compensator with gain of $G_i(s)$ to get the compensated current-error signal, $V_{c1}$.

From the voltage loop perspective, the output voltage is sensed through a voltage sensing circuit with a gain of $K_v$, and is then compared with a reference voltage, $V_{\text{ref}}$, to generate voltage error signal, $V_e$. The voltage error signal, $V_e$, is then compensated by the voltage compensator with a gain of $G_v(s)$ to get the compensated voltage-error signal, $V_{v}$. The signal, $V_v$, is common of all operating phases.

For each phase, the corresponding compensated current-error signal is subtracted from the compensated voltage-error signal $V_v$. The result signals are then fed to the PWM modulators.

B. Loop gain Analysis

To simplify the small signal analysis, one phase of the multiphase buck-boost converter is considered with the current balancing circuit loop included. Figure 6 presents a small signal model which shows that there are two closed loops: the current balancing loop, $T_i(s)$, and the voltage loop, $T_v(s)$. Here, $G_{vd}(s)$ is the control to output transfer function; and
Fig. 6. Small-signal control-loop of the buck-boost converter with current balancing circuit.

$G_{id}(s)$ is the control to inductor current transfer function as derived in Section II.

The current balancing loop, $T_i(s)$, can be expressed as:

$$T_i(s) = K_i G_i(s) \frac{1}{V_M} G_{id}(s)$$  \hspace{1cm} (4)

Typically $K_i/V_M$ is a proportional gain while $G_{id}(s)$ from Eq. (2) has one zero and a double pole. To achieve a stable current balancing loop, $G_i(s)$ can be designed to be either PD or PID compensator.

Similarly, the voltage loop, $T_v$, can be described as:

$$T_v(s) = K_v G_v(s) \frac{1}{V_M} G_{vd}(s)$$  \hspace{1cm} (5)

The overall closed loop, $T(s)$, which includes the current balancing loop, $T_i(s)$, and voltage loop, $T_v(s)$, can be described as [12]:

$$T(s) = \frac{T_v(s)}{1 + T_i(s)}$$  \hspace{1cm} (6)

From Eq. (4) and (5), the Eq. (6) can be rewritten as:

$$T(s) = \frac{K_v G_v(s) G_{vd}(s) / V_M}{1 + K_i G_i(s) G_{id}(s) / V_M}$$  \hspace{1cm} (7)

From the above equation, the right-half plane zero from $G_{vd}(s)$ reflects on the overall closed loop, $T(s)$. As a result, the bandwidth of $T(s)$ is restricted by the right-half plane zero.

IV. EXPERIMENTAL RESULTS

A four-phase interleaving buck-boost converter was implemented and tested. Photographs of the prototype are shown in Fig. 7. The prototype was designed for 8 V to 15 V input voltage range and 12 V output voltage with 18 A rated output current. The converter operated at 250 kHz switching frequency. The output capacitors consist of eight 150 µF; each has the ESR of 20 mΩ. The inductors are 6.8 µH with 9.4 mΩ DCR each. The inductor currents are sensed through MOSFET’s on-resistance.

In the prototype, the loop was designed with following parameters:

$$\frac{K_i G_i}{V_M} = \frac{2.87 \times 10^{-4}}{1 + s/2.5 \times 10^{-6}}$$

$$\frac{K_v G_v}{V_M} = \frac{6.9 \times 10^{-2}(1 + s/5.3 \times 10^3)(1 + s/11.9 \times 10^3)}{s/6.9 \times 10^3(1 + s/3.5 \times 10^5)(1 + s/2.1 \times 10^5)}$$

The measured loop gain, $T(s)$, at 15 V input voltage and 18 A load current indicates 7 kHz bandwidth and 50 degree phase margin approximately, as shown in Fig. 8.

Figure 9 shows inductor currents versus load currents when the input voltage is 15 V and 8 V, respectively. The results indicate the balancing among inductor current is tightly regulated. Figure 10 and 11 show two of the inductor current waveforms during load transient between no-load (0 A) and full-load (18 A) when the input voltage is 15 V. Figure 12 and 13 show two of the inductor current waveforms during load transient between no-load (0 A) and full-load (18 A) when the input voltage is 8 V.

As shown in the experimental results, the inductor currents among all the phases are evenly distributed and stable during steady state and load transient.
Fig. 8. Measured loop gain of four-phase buck-boost converter with current balancing circuit.

Fig. 9. Inductor currents vs. load current: a) at 15 V input voltage, b) at 8 V input voltage.

Fig. 10. Two inductor current waveforms during applying load transient from 0 A to 18 A at 15 V input voltage.

Fig. 11. Two inductor current waveforms during load releasing from 18 A to 0 A at 15 V input voltage.

Fig. 12. Two inductor current waveforms during applying load transient from 0 A to 18 A at 8 V input voltage.

Fig. 13. Two inductor current waveforms during load releasing from 18 A to 0 A at 8 V input voltage.
V. Conclusions

An active inductor current balancing for multiphase buck-boost converters is presented. The multiphase buck-boost converter is proposed for battery-powered applications, where the high-power converters capable of stepping up and down output voltages are required. The active inductor current balancing circuit employed in this paper is based on the average current sharing bus method. Small signal analyses are included to show that both the current balancing and the overall loops can be compensated to achieve a stable system.

A prototype of 4-phase buck-boost converter was build to verify the concept. The experimental results indicate excellent inductor current balancing during steady state and load transient.

References


