The design of isolated multiphase interleaved converter for battery charging of military applications

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Abstract

In this paper, an isolated four-phase interleaved boost converter (I4PIBC) is presented for battery charging of military applications that overcomes the problem of high input current and output voltage ripples. Also, these kinds of converters are used in order to decrease the input current through each element. However, the current will be equal in all inductors. Moreover, the switching frequency is high to minimize the components. This converter is controlled by the proportional–integral–controller with high frequency. The input and output are isolated using high-frequency switch mode power supply transformer. And there will be also experimental comparison on our next study. The simulation results will be presented for closed-loop I4PIBC using MATLAB/Simulink Program.

Keywords Four-phase interleaved converter · Voltage control · MATLAB · PI controller · DC–DC converter

1 Introduction

Recently, in several sectors of manufacture, the interleaved topologies are vastly utilized, ranging from low output power to many hundred kilowatts due to their charming features. They are much utilized for many applications, such as improved power factor PF. The other advantage is existent in the voltage-regulated model application in the motherboard of the computer, where the output voltage is very low, while the ampere is high [1–3]. Therefore, several paths of the multiphase interleaved converter can be used to reduce the high input current so it will be divided through several paths of the multiphase converter without using power devices with greater current ratings, which leads to reduced power losses. To achieve the same current ripple, smaller inductors can be used compared to conventional boost converter; however, the transient response of the interleaved is faster, and thus, we get better performance [1, 4].

In designing DC–DC converters, some parameters as the inductors and capacitors have great importance. To decrease the storage capacitor, switching frequency should be increased; nevertheless, this method is not possible for some cases. In the boost converter during the on state of the switch, the capacitor supplies the load with current, which causes a discontinuity in the capacitor current and this discontinuity raises the RMS value of both the capacitor and the current which is necessary for perfect working for the converter. It is unfamiliar to design capacitors one or two orders of size bigger than the ideally desired capacitance in standard designs. This problem can be overcome by using multiphase operation with a suitable phase shift and this phase shift can be designed in the control system for main switches of the converter. That can be done in a way that the current at any time will be supplied by one of the inductors. By using this method (multiphase converter), the output capacitor ripple current's frequency is n times compared with the single-stage, and thus, the capacitor demanded value can be decreased [5].

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The isolated DC–DC converters become so common and used in many applications. Such converters have several advantages comparing to the non-isolated ones, like low manufacturing cost, high efficiency, electrical isolation using transformer [6, 7]. It is necessary to have isolation between input and output in several applications. High-frequency transformer can be used as isolation between input and output. Moreover, when we need a high step-down or step-up conversion ratio, the isolation improves the performance of the converter [8].

2 Circuit description and operation

Many topologies are used in DC–DC converters. In this study, the topology utilized is an isolated multiphase interleaved converter that includes four conventional boost converters which connected parallel. These converters are controlled with the interleaving mode and operated with 90° shift. Due to the input inductors are connected in parallel, the ripple in the input current is reduced and each inductor has the same current [7, 9].

Figure 1 illustrates the schematic diagram for the proposed converter, and the circuit is divided into two parts: The first part consists of a multiphase interleaved converter. The circuit diagram for the first part which is four-phase interleaved boost converter is illustrated in Fig. 2. Simply it is four boost converters that have been connected parallel, each one is operating phase shift. It consists of four inductors, switches and diodes operating in parallel.

Fig. 2 Four-phase interleaved converter diagram

The load and the output capacitor are supplied by at least one of the phases. The summation of four inductor currents L_1, L_2, L_3 and L_4 is the input current. The inductor ripple currents tend to be cancelled, as they are out of phase. Therefore, the input ripple caused by the boost inductors will be reduced [10].

The second stage consists of the isolation which is four switches (S_5, S_6, S_7 and S_8) and high-frequency transformer to maintain a desired DC output voltage. Moreover, this isolation is used as a step-down transformer to drop the voltage on the capacitor C_d from 80 V to 28. The primary switches S_5 – S_8 are operated in pairs S_5 – S_8 , and S_6 – S_7 , respectively. The pulse signals are driven with phase-shifted; moreover, the duty cycle for the isolation D is 50 percent.

Fig. 1 Schematic of an isolated multiphase interleaved converter

Table 1 The designed values of the proposed converter

p_{out}	v_i	v_{cd}	v_o	Δv_o	Δi	η	f_s	L_1	c_d	c_o	$N_1 : N_2$
1 kW	9–36 v_{dc}	80 V	28 V	1%	1%	98%	20 kHz	500 μ H	100 μ F	150 μ F	2.85

Fig. 3 The implementation of isolation

The interleaved converter has been designed for a voltage on the capacitor of 80 V. The input inductors work in continuous conduction mode CCM; therefore, the input current is continuous for the entire switching period. The boost inductors are calculated based on parameters such as switching frequency, input and output voltages, and the inductor current ripple [10].

$$L_1 = L_2 = L_3 = L_4 = \frac{V_s(V_s - V_{cd})}{\Delta i_{l1} * f_s * V_{cd}}$$

Figure 4 illustrates the waveforms of the inductor currents for the interleaved converter $i_{l1}, i_{l2}, i_{l3}, i_{l4}$.

The I4PIBC Converter design values are given in Table 1. As we see from Figs. 1, 2 and 3, the input of the isolated transformer is the output of the four-phase interleaved converter which is the voltage on the capacitor v_{cd} where the isolated transformer is operating at a high switching frequency of 50,000 with 0.5 duty ratio and the relation between input and output for the isolated transformer can be obtained as the following equation:

$$\frac{V_{cd}}{V_o} = \frac{N_1}{N_2}$$

$$V_{cd} = 80 \text{ V}, \quad V_o = 28 \text{ V}$$

$$\text{Then, } \frac{N_1}{N_2} = \frac{80}{28} = 2.85.$$

Fig. 4 **a** Inductor current ripple waveforms (L_1, L_2, L_3, L_4), **b** input current ripple waveform

3 PI controller for proposed converter

In this study, the proposed converter operates in CCM and the control system is connected with the middle of the converter or the output of four-phase interleaved converter so, at any T instant, the control system is sensing DC-link voltage, v_{cd} and then comparing it with the reference voltage, v_{ref} . The error v_{0e} is obtained as following equation.

$$v_{0e} = v_{ref} - v_{cd}$$

That means the voltage on the capacitor in each cycle follows up the reference voltage and attempts to get zero steady-state error between the capacitor voltage and the reference voltage.

To generate an output v_{ce} , a proportional–integral (PI) controller is used to process the voltage error signal as the following equation.

$$v_{ce} = v_{0e} \left(k_p + k_i \frac{1}{s} \right)$$

where k_p denotes the proportional gain and k_i denotes the integral gain of the PI controller. Lastly, to create the PWM pulses for the four-phase interleaved converter, a saw-tooth waveform with high-frequency is compared with the voltage controller output.

Fig. 5 The implementation of simulation using MATLAB/Simulink

Fig. 6 Waveforms of input voltage, input current and output voltage

Fig. 7 The waveform of output voltage ripple

Fig. 8 The waveform of input current ripple

If $m_{I1} < v_{ce}$ then $s = 1$

If $m_{I1} > v_{ce}$ then $s = 0$

where 0 is the off state and 1 refers to the on case for switching pulses.

To ensure that the interleaved converter operates in a correct operation, each PWM signal is needed to have 90° phase shift respect to the previous one. Therefore, it is necessary to have a synchronization circuit to get those pulses with a phase shift. Nevertheless practicable, the analogue realization causes definite limitations.

4 Simulation studies

The proposed converter's performance has been simulated in closed-loop configurations using MATLAB/Simulink, and

Table 2 Comparison between the designed and obtained values of input current and output voltage ripples

Ripples	Designed value	obtained value
Input current ripple Δi	1.144	0.9
Output voltage ripple Δv_0	0.28	0.01

Fig. 9 Input and output power for different cases

Fig. 5 illustrates the implementation of the simulation.

Figure 6 illustrates the simulation results for the input voltage, current and the output voltage while the input voltage is changed between 9 and 36 V. Figure 7 shows the output voltage ripple at rated input voltage.

Figure 8 illustrates the ripple of the input current while the input voltage of 9 V is applied, and Table 2 illustrates the comparison between the designed and obtained values of input current and output voltage ripples. The output power and the input power at full load are shown in Fig. 9 while the input voltage is changed.

5 Conclusions

In this paper, the four-phase interleaved boost converter with isolation performs in continuous conduction mode CCM has been simulated with the closed-loop controller. It is found that the ripple values for the input current and output voltage are low which is needed for battery charging applications. Furthermore, the DC-link voltage throughout the operating range is adjusted to a constant value. Furthermore, the closed-loop operating scheme tends to be an added advantage for the four-phase interleaved boost converter to operate with fewer ripples and almost constant output voltage. It has been considered that the RMS current in the capacitor, output ripple

voltage and input ripple current are small and the size of the tank capacitor is small as well, which is considered as a significant point.

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