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Transient Current Suppression Scheme for Bi-Directional DC/DC Converters in 42V Automotive Power Systems

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ABSTRACT

42V electrical power systems are on their way to replacing the present l4V systems in automobiles and 42V/14V dual voltage systems have been proposed to provide backward compatibility with the existing components for the 14V systems. A synchronous buck/boost converter is an attractive topology for 42V/14V dual voltage systems since it offers the possibility of bi-directional operation without additional components. In this paper, transient currents generated during converter startup or changes in operation modes between buck and boost are analyzed and a cost effective solution to remove the transient currents is proposed. The validity of the proposed control strategy is investigated through simulation and experiment with bi-directional converters.

Keywords: Dual voltage system, Bi-directional operation, Buck/Boost converter

1. Introduction

The use of electrical/electronic loads to improve performance, fuel economy, passenger comfort, convenience and safety in automobiles has been growing exponentially. A typical luxury class vehicle today draws between 1200W to 1500W of steady state power from the electrical system and has about 2.5 km of wiring in the harness[1]. 42V electrical power systems are on their way to replacing the present l4V systems in automobiles and 42V/14V dual voltage systems have been proposed to provide backward compatibility with the existing components in 14V system[2][3]. Fig. 1 shows one of the popular architectures for implementing the 42V/14V dual voltage system. A bi-directional DC/DC converter is equipped with 42V and 14V buses and batteries are connected to each bus, respectively[4].

In implementing a DC/DC converter, a non-isolation buck or boost is a good topology because the isolation between 42V and 14V buses is not required in automobiles and the voltage conversion ratio of input and output is only about 1/3 or 3. The voltage conversion ratio is not exactly 1/3 or 3 because of power losses, efficiency and control methodology.

A synchronous buck/boost topology using active switches instead of diodes is considered to be more attractive because bi-directional operation is possible without additional components and the efficiency is a little higher than that of

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ordinary diode buck and boost topologies[5][6].

Fig. 2 shows the synchronous buck/boost converter where switches Q1 and Q2 are operated as the main switch or as the freewheeling diode according to the operating direction. Unlike typical converters for power supplies, this synchronous buck/boost converter has voltage sources on both sides of its input and output. Therefore, whenever the controller is started up and the operation mode is changed between buck and boost, abnormal transient currents can flow because the transient switching duty is not the same as the regular duty related with the converter input voltage and the output load voltage.

The topology for a bi-directional converter in this paper is not a special one, and there are several papers written on the use of this topology. However, they dealt with control method, improvement of efficiency, and noise problems in the converter. They did not deal with converter startup[7-12].

Compared with previously discussed approaches, the converter in this paper has the following characteristics and advantages:

1) The bi-directional converter has voltage sources on both input and output.

2) When the controller is implemented by a conventional PWM IC, the transient currents during the startup and mode changing between buck and boost are analyzed.

3) A cost effective solution to remove the transient current is proposed.

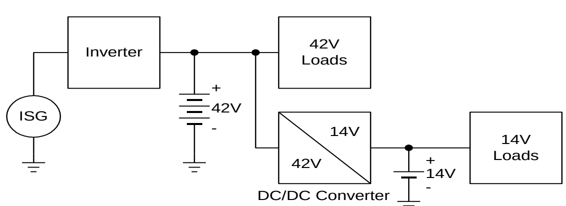


Fig. 1. Dual battery 42V/14V system.

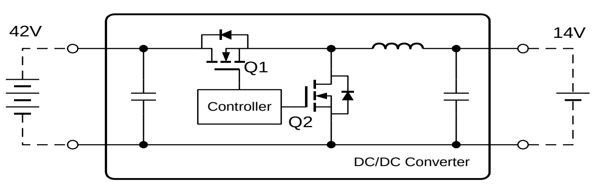


Fig. 2. Synchronous buck/boost converter with voltage sources in input and output.

The validity of the proposed control strategy is investigated through simulation and also through experiments with bi-directional converters.

2. Transient Current during Startup

The voltage conversion ratio of the synchronous buck/boost converter is given by:

$$\frac{V_{14V}}{V_{42V}} = \frac{T_{Q1\_ON}}{T_{Q1\_ON} + T_{Q1\_OFF}} \tag{1}$$
$$where \quad T_{Q1\_OFF} = T_{Q2\_ON}, \quad T_{Q2\_OFF} = T_{Q1\_ON}$$

If the bus voltages, V42V and V14V are 36V and 12V, which are the nominal voltages of the batteries, the switching duty for Q1 and Q2 should be about 1/3 and 2/3, respectively. If the bus voltages are changed according to the battery charge and discharge conditions during the converter operation, the switching duty has to be changed as much as the changed in the bus voltage ratio. Since the DC/DC converter has a voltage source load on both sides of the input and output, there are some points to consider for smooth operation when the controller is started up or when the operation mode is changed between buck and boost.

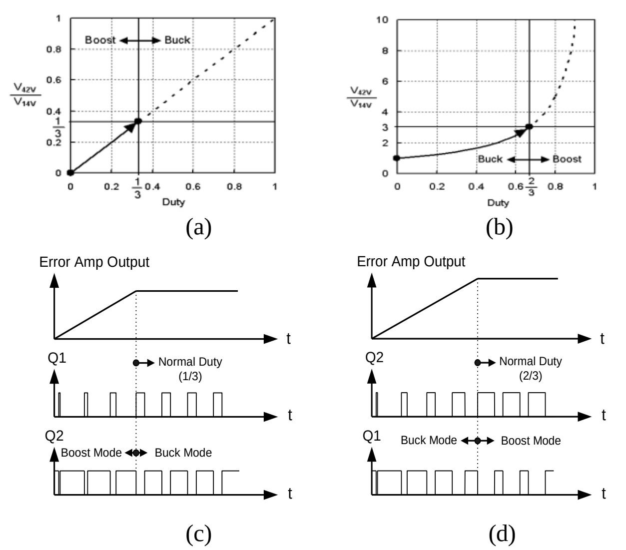


Fig. 3. Relationships between voltage transfer ratio and duty-ratio of main switch. (a) Buck mode (b) Boost mode (c) Duty ratio of main (Q1), auxiliary switch (Q2) at Buck mode (d) Duty ratio of main (Q2), auxiliary switch (Q1) at Boost mode.

When most converters are turned on, the switching duty and output voltage are designed to increase slowly because of a soft-start function. However, the soft-start in this DC/DC converter will show an abnormal transient current. As shown in Fig 3(a), if the input and output voltages are 42V and 14V, and the bi-directional converter is operating as a buck converter, the duty ratio will start from 0, and it will be operated in boost mode until the duty ratio reaches 0.33. If there is no voltage source at the output, output voltage will increase from 0V to 14V. However, as shown in Fig. 3(c), if there is a voltage source at the output and the duty ratio is less than 0.33, the output voltage can not increase according to the duty ratio, because the output voltage is already 14V. When this happens, Q2 becomes the main switch, and it is operated in boost mode. Therefore, the direction of the inductor's current flows in reverse.

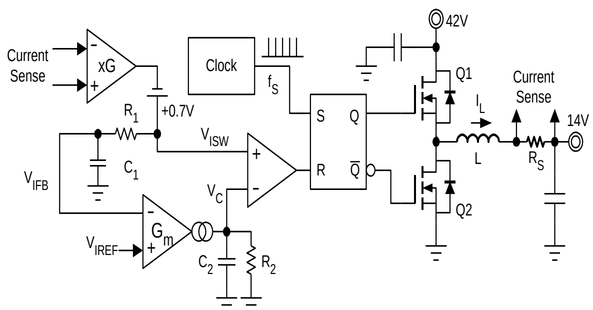


Fig. 4. Current mode synchronous buck converter circuit.

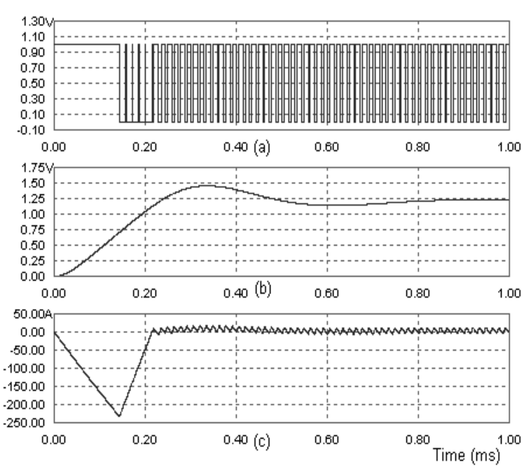


Fig. 5. Transient current simulation results during startup.
(a) Q2 PWM signal (b) Error amp output voltage Vc
(c) Inductor current I_L.

As shown in Fig. 3(b) and Fig. 3(d) similar results are shown during boost mode. To prevent this situation, the switching duty of the converter should instantaneously become value related to the input and output voltage ratio without soft-start. However, due to several capacitive components including the error amp compensator, the soft-start feature cannot be suppressed perfectly.

Fig. 4 shows the current mode PWM circuit diagram for a synchronous buck converter without additional soft start elements. This circuit is based on the internal block diagram of a Linear Technology LT1339 PWM controller for use as a prototype. This control IC is suitable for high power synchronous buck/boost converter applications up to 60V and it has a differential amplifier with high common mode input voltage for current sensing.

As shown in Fig. 5, the simulation results through PSIM show the transient state during buck startup. The important parameters for the simulation are listed below:

- V_{IREF} : 0.95V, G:15, G_m:0.9mS
- L : 7μH, Rs : 0.003Ω, f_S : 70kHz

Due to the capacitor (C_2) of the error amp compensator, the error amp output, V_C, is slowly increased. Since the current feedback loop has an offset voltage (0.7V), Q2 is turned on and the output source voltage becomes short until V_C reaches the offset value. Most of the PWM ICs have the voltage offset in the feedback loop or on the error amp output to get the noise margin. Even though there is no offset, an abnormal negative transient current flows during startup and an abnormal negative current cannot be detected protected against because the PWM IC including op amp, comparator and differential amp for current sensing operates with only a single voltage supply.

3. Proposed Method

Fig. 6 shows the inductor current waveform according to the amplitude of the load current.

The synchronous buck/boost converter with voltage sources at the input and output terminals is always operated in a Continuous Conduction Mode (CCM) and the current can flow in the reverse direction as the output current decreases. This is due to a path which allows reverse current flow[13]. Therefore, when the load is large, as shown in Fig. 6(a), the inductor current always flows from input to output. However, when the load is small, the inductor current can flow in reverse from output to input as shown in the shaded region of Fig. 6(b). This happens because the current from the output can flow through the Q2 switch with the role of a diode.

However, the control IC which is fed by a positive single power supply cannot detect the negative feedback current as shown in the shaded region of Fig. 6(b). As a result, the controller operates the converter in a Discontinuous Conduction Mode (DCM) according to the output current level[14][15]. Therefore, this converter should be analyzed separately for each mode. The peak current that flows through the inductor can be defined with bus voltages, inductance L and the switching period, T_S, by the following equations:

$$I_{L(PK)}\Big|_{DCM} = \frac{2\cdot T_S\cdot I_{L(AVG)}}{D\cdot T_S + D'\cdot T_S} = \sqrt{\frac{2\cdot T_S\cdot I_{L(AVG)}\cdot V_{14V}\cdot (V_{42V}-V_{14V})}{L\cdot V_{42V}}} \quad (2)$$

$$I_{L(PK)}\Big|_{CCM} = I_{L(AVG)} + \frac{V_{42V}-V_{14V}}{2\cdot L}\cdot D\cdot T_S = I_{L(AVG)} + \frac{V_{14V}\cdot (V_{42V}-V_{14V})\cdot T_S}{2\cdot L\cdot V_{42V}}$$

Detected current flowing through a shunt resistor (Rs) is converted to voltage signal, and the feedback currents, V_{ISW} and V_{IFB} in Fig. 4 are as follows.

$$V_{ISW(PK)} = I_{L(PK)}\cdot Rs\cdot G + 0.7$$
$$V_{IFB} = I_{L(AVG)}\cdot Rs\cdot G + 0.7 \cong V_{IREF} \quad (3)$$

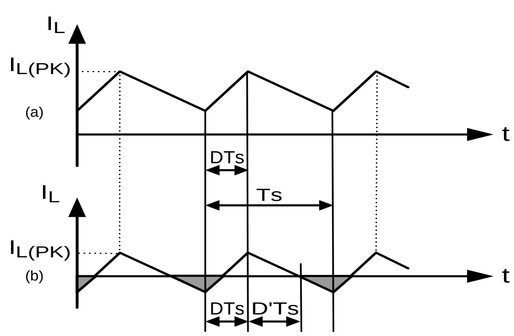


Fig. 6. Inductor current waveforms according to the amplitude of the load current. (a) Inductor current when the load is big (b) Inductor current when the load is small.

$I_{L(AVG)}$ is the same as the output current in the buck mode and the input current of the boost mode. If the control target of the controller is the average inductor current and the switching off time is decided by comparing the switch current, V_{ISW}, and the error amp output, V_C, equations (2) and (3) can be applicable for both buck and boost mode. Therefore, as shown in Fig. **7** if the current reference, $V_{IREF,}$ during startup is fixed and the switching is stopped until V_C reaches the value, $V_{ISW(PK)}$, determined by (2) and (3) and then started, the transient current can be removed.

The error amp configuration in the switching blocked condition is shown in Fig. 8. While the gate signal is blocked, the inductor current(I_L) can not flow and the feedback voltage(V_{IL}) will be zero.

Fig. 9(a) shows a blocking time at a fixed load current ($I_{L(AVG)}$=6A) and different input and output voltages. Fig. 9(b) shows a blocking time at different load current with the fixed input and output voltages.

$$T_B = \frac{C_2}{G_m\cdot (V_{IREF}-0.7)}\cdot V_{ISW(PK)},\quad if\ R_2 >> 1/\omega C_2 \quad (4)$$

Until now, switching blocking time, T_B, has been done by using a transconductance amp as an error amp. As shown in Fig. 10, when using a conventional PWM IC with op amp of voltage type, equation (5) can be applicable.

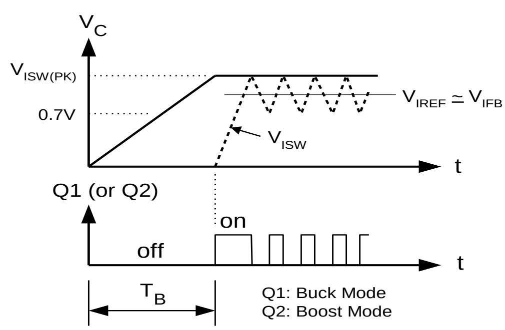


Fig. 7. Method to remove the transient current during startup.

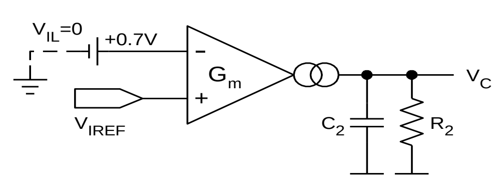
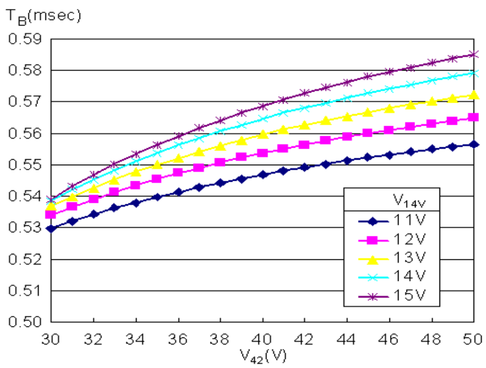
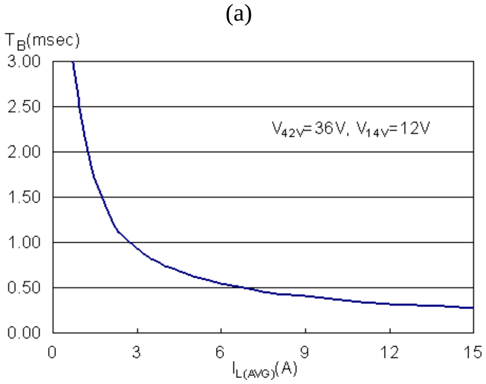


Fig. 8. Error Amp during gate block.



(a)



(b)

Fig. 9. Blocking time calculation results. (a) T_B at fixed $I_{L(AVG)}$(=6A) and different input and output Voltages (b) T_B at different $I_{L(AVG)}$ and fixed input and output voltage.

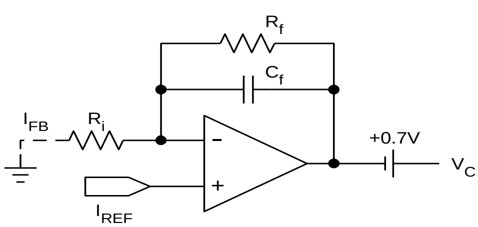


Fig. 10. Voltage mode error amplifier during blocking.

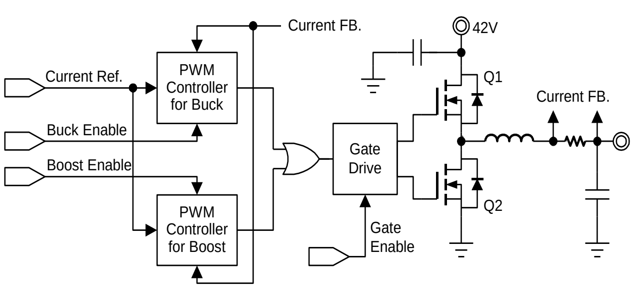


Fig. 11. Controller block diagram for bi-directional operation.

The block diagram of the proposed controller is shown in Fig. 11. Two PWM controllers are used to implement the bi-directional operation. Only one PWM controller should be in operation at a time. When changes in operation modes are required, the controller in operation has to be turned off before the other controller can be turned on.

$$T_B=\frac{\left(V_{ISW(PK)}-V_{IREF}-0.7\right)\cdot R_i\cdot C_f}{V_{IREF}},\quad if\ R_i>>1/\omega C_f \qquad (5)$$

The switching signal outputs from the controllers are combined with OR gates and are sent to the gate drive circuit. The gate enable circuit is designed to block the gate signal with a microprocessor (MCU) until the error amp output reaches the correct level to reduce the transient current. Whenever changing the operation mode, the same situation with the startup happens and the microprocessor should enable and disable the switching signal with this circuit.

The microprocessor can get 42V and 14V through the AD converter. It also searches for the adequate TB according to the input, output voltage and initial inductor current. However, the initial inductor current can be treated as a constant if it is fixed at the value that we want during startup. Therefore, only the input and output voltage are necessary to search T_B. After startup, the microprocessor has to output current reference as the output voltage controller.

An analog circuit operates as a current controller that limits the maximum current. A microprocessor which is a digital circuit operates as a voltage controller for controlling the output voltage, and outputs the current reference to the analog current controller. Therefore, when the output voltage is lower than the reference voltage, the converter outputs the maximum current. If the output voltage reaches the reference voltage, it controls the current to maintain the desired voltage, which is the same process used by battery chargers, so there is no possibility for the control signals of the two controllers to collide.

4. Simulation and Experimental Results

The system parameters for the simulation are shown in Table 1.

Table 1. System parameters for simulation.

Parameters	Value
Input/Output Voltage (V_1, V_2)	42V, 14V
Inductor (L)	7μH
Capacitor(C_{in}, C_{out})	20μF, 20μF
Switching Frequency	70KHz
Current Detecting Resistor(Rs)	3mΩ

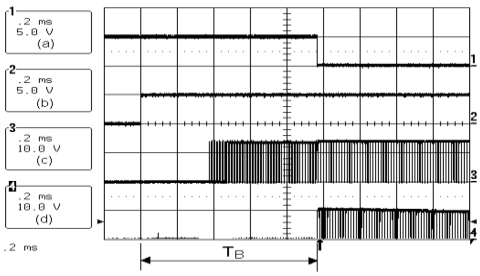


Fig. 12. Timing during buck mode start up (1) gate blocking enable/disable signal (2) controller enable signal (3) controller PWM output for Q1 (4) actual switching signal for Q2.

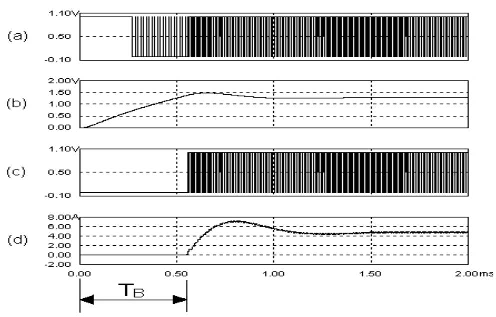


Fig. 13. Simulation results for the proposed method during buck mode start up. (a) PWM controller output for Q2 (b) error amp output Vc (c) switching signal for Q2 (d) output current.

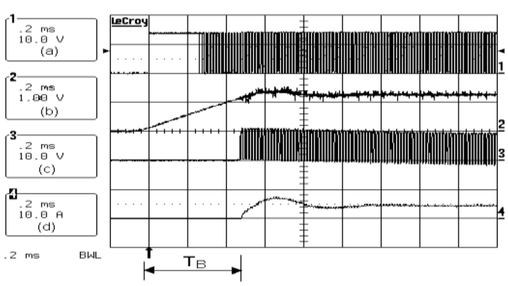


Fig. 14. Experimental results of the proposed method during buck mode start up. (1) PWM controller output for Q2 (2) error amp output Vc (3) switching signal for Q2 (4) output current.

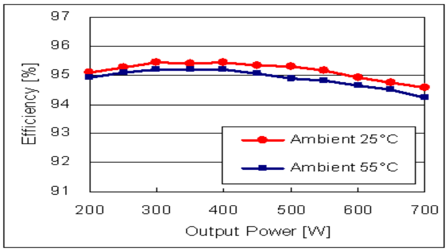
Fig. 12 shows the sequence timing during startup. When the buck controller is enabled with the buck enable signal, the controller outputs the PWM switching signals for Q1 and Q2. However, the actual switching is delayed until the microprocessor enables the switching. The switching enable time is determined by the microprocessor using a blocking time table.

Fig. 13 and 14 show the proposed method in simulations as well as the experimental results. Fig. 13 (1) shows the Q2 switching waveform before gate block. Although the Q2 turn on signal appears during start up, it is blocked by the gate block signal. Fig. 13 (2) shows the error amp output V_C. Fig. 13 (3) shows the actual switching waveform applied to the switching component. The switching starts only after the error amp output Vc reaches a certain level calculated according to the input and output voltage. Fig. 13 (4) shows the output current. Fig. 14 shows the experimental results which are identical to the results of Fig. 13.

To verify the proposed strategy, a control system was implemented using a 700W prototype. MOS-FET's TO-220 packages developed for 42V applications were used as switches, and the system was they were designed with two modules because the maximum efficiency of one module was achieved at around 300W and the interleaved synchronization scheme was used to reduce the size of the filters[16][17]. The PIC18F2480 made by Microchip was used.

Fig. 15(a) shows a photograph of the 700W prototype with a heat sink for natural convection. Fig. 15(b) shows the total efficiency of the converter when the ambient temperature was 25℃ and 55℃, respectively. It is about 95% throughout the entire output range.

(a) 700W prototype with heat sink



(b) Total efficiency of the converter

Fig. 15. Proto type and efficiency.

Fig. 16 shows the switching signals and inductor currents under interleaved operation in which the two main switches work alternatively with an 180° phase shift[18][19].

Fig. 17 shows the experimental results when the blocking time is not suitable. Fig.17(a) shows the transient current without the blocking time during startup, which is almost the same result as the result shown in Fig. 5. Fig. 17(b) shows the transient current when the blocking time is shorter than the nominal value, and the output current flows in reverse until the error amp output reaches the nominal value. Fig. 17(c) shows the transient current when the blocking time is longer than the nominal value and the output current flows much more than the nominal load current.

Fig. 18 is the current waveform during operation mode change with 0.5 sec stop duration. There is no significant current transient during operation mode changes and the current is varied according to the battery condition due to partially loaded conditions.

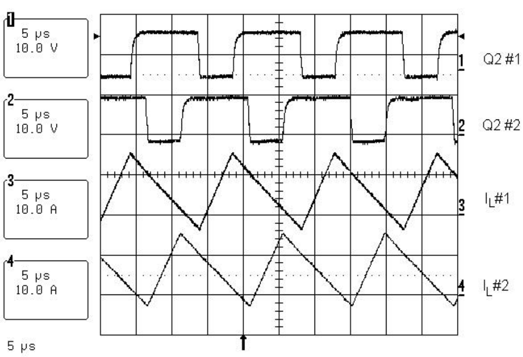
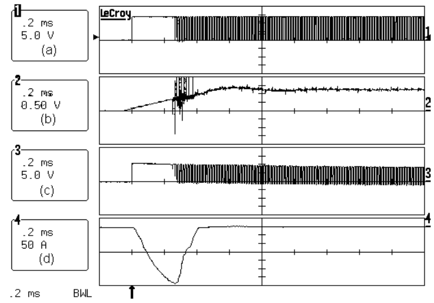
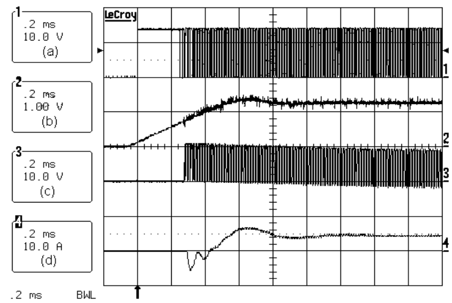


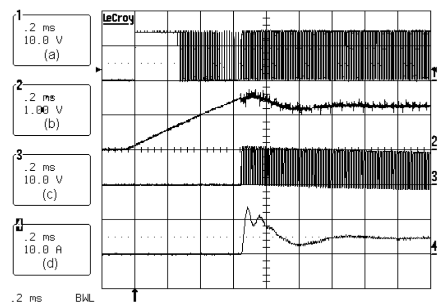
Fig. 16. Gate signal & inductor currents in interleaving mode (1) PWM signal for module #1 (2) PWM signal for module #2 (3) inductor current of module #1 (4) inductor current of module #2.



(a) Transient current without blocking time during startup



(b) Start up with an abnormal short blocking time



(c) Start up with an abnormal long blocking time

Fig. 17. Experimental results when the blocking time is not suitable. (1) PWM controller output for Q2 (2) error amp output Vc (3) actual switching signal (4) output current.

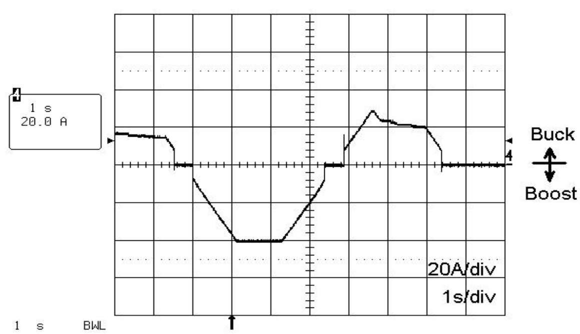


Fig. 18. Current waveform of a 14V terminal during operation mode change.

5. Conclusions

This paper presents the transient current during startup of the synchronous buck/boost converter with voltage sources on both input and output terminals and proposes a cost effective solution to remove the transient state.

This scheme can be easily implemented with simple additional circuits and a low cost microprocessor. As the microprocessor is only used to read the table and set the timer, large computational resources are not required for this method. Therefore, the program can be ported in the microprocessor to be used for other function such as CAN communication. A prototype with 700W of output power was designed and the effectiveness was verified through experimental results.

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