Current Ripple Cancellation of Multiple Paralleled Boost Converters for PV/Battery Charging System with MPPT

Boyang Hu, *Student Member, IEEE* and Swamidoss Sathiakumar, *Senior Member, IEEE*

Abstract**-- For conventional paralleled PV sources, the current ripple at the load side increases when the ripples are added up from each converter, which also reduces the life time of the battery storage. Even though the ripple is able to be reduced by increasing switching frequency, the extra switching losses must be taken into account. In this paper, a switching technique is proposed based on paralleled multiple-input sources with boost converters. Since the current ripple of the battery charging current can be minimized without the restrictions of source voltages, currents and duty cycles, the Maximum Power Point Tracking (MPPT) algorithm is also able to be implemented with the proposed technique for integrating renewables into the smart grid. The proposed technique is validated through detailed numerical analysis, simulation and experiment results.**

Index Terms**-- PV/battery system, parallel boost converters, current ripple cancellation, MPPT.**

I. INTRODUCTION

PARALLEL converter configuration is widely used in telecommunication power supplies, renewable sources and so on. For the most of the renewable sources, for example photovoltaic, wind and fuel cells, they have relatively low voltage output compared with the voltage of dc bus or battery/ultra-capacitor storage. Even though the series connection is able to provide the high output voltage, it has the power limit because of the limited number of series connections in order to increase the nominal power [1]. The parallel connection [2]-[3] is realized as a more reliable and flexible configuration for multiple-input source applications. Boost converters are popularly employed in different applications to step up the line input voltage to the higher dc bus voltage, which will be considered in this paper. Based on the basic circuit theories, for parallel connection, the current at the load side is the sum of the current from each input branch. Hence, the current ripple is also added up at the load side to form a larger current ripple than that of each input.

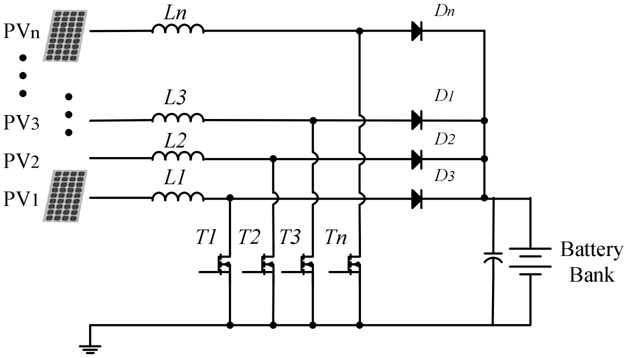

Fig. 1. Parallel PV sources with boost converters for battery charging.

Interleaving based paralleled boost converter techniques with the features of high output power and low current ripple are proposed in [4]-[6]. Even though performance can be improved for parallel systems by using the interleaving technique, it is conventionally used for only one input source. For one input source, the output current ripple is reduced by paralleling boost converters with switching phase shift. The shift angle is determined by $2\pi/N$, where N is the number of converters. However, none of them takes the multiple inputs into consideration for the interleaving analysis. The main problem is that the conventional interleaved converters are implemented for only one input with the fixed phase shift offset (angles) between individual stages [7]. As the development of the renewable energy in the current decade, the MPPT algorithms applied to each PV sources come to be a new challenge to the interleaving techniques, which requires the variable duty cycle operation of each converter for different source voltages.

In this paper, a novel multi-input boost-converter based interleaving technique is proposed, analyzed and verified by simulation and experiments. The proposed interleaving technique is also validated through the well known P & O MPPT algorithm to each boost converter with different voltages of input PV sources. The organization of this paper is listed as follows: Section II presents the operation principle interleaved boost converters for multiple input sources, Then, the proposed current ripple cancellation technique for parallel boost converters is proved by the simulation results shown in Section III and the experimental results in Section IV. Section V concludes the most favorable advantages.

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II. PRINCIPLE OF OPERATION

The proposed switching technique for paralleled boost converters is presented in this section. The analysis starts from the two paralleled boost converters and then it is extended to *n* parallel boost converters.

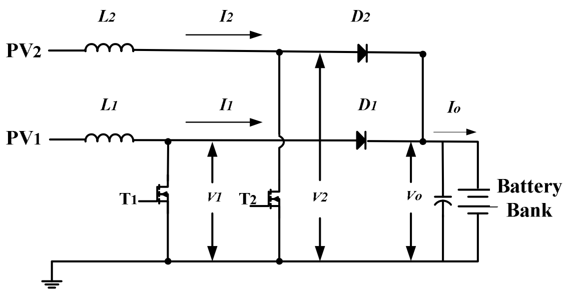

Fig. 2. Two paralleled boost converters for battery charging system.

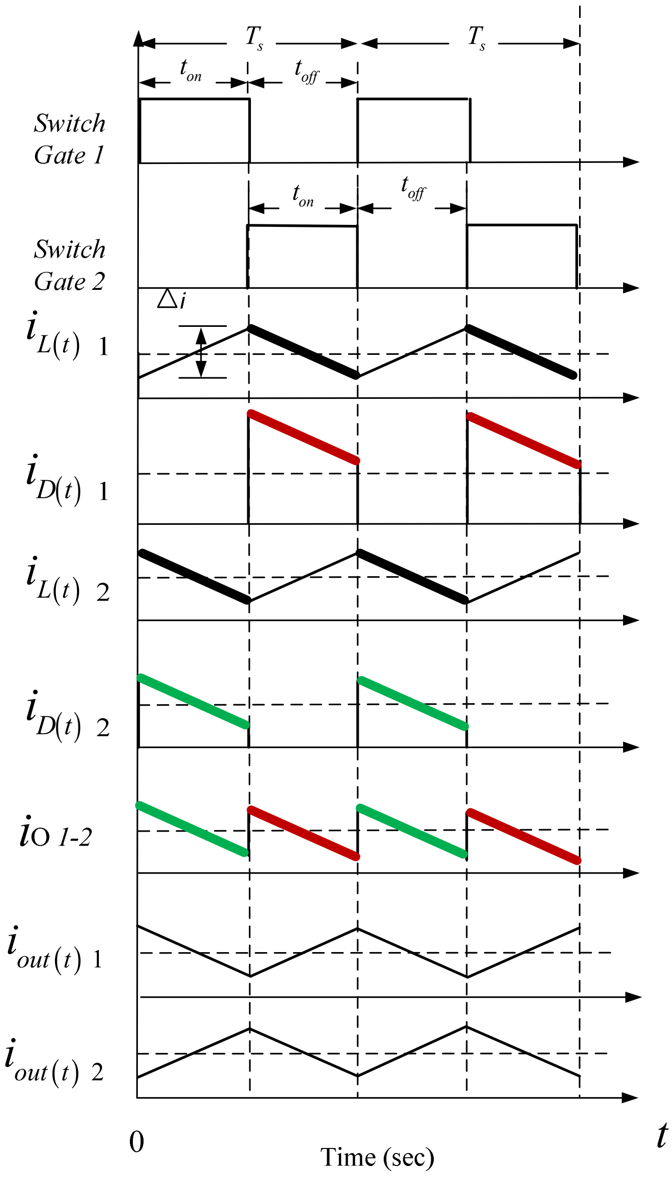

Fig. 3. Key waveforms of the proposed switching technique (d1=d2=0.5).

As can be seen from the Fig.2, two PV sources *PV1* and *PV2* are connected in parallel to charge a battery bank. The current *I1* and *I2* flow into the battery simultaneously. Hence, the battery charging current *Io* is obtained from the sum of the two average components and two ripple components of the currents *I1* and *I2*. Then, the concept of the phase shift is employed for the proposed switching technique for boost converters, which is shown in Fig.3. As shown in Fig.3, the diode current *iD* is always the falling edge of the inductor current *iL*. By controlling the falling edges of the inductor currents through shifted switch gate signals, the ripple of output current *io* can be minimized.

For the uncontrolled parallel converters, the diode currents *iD1* and *iD2* are added together, which forms a larger ripple component to the output current *Io*. Unlike the conventional interleaving technique with equally shifted phases, the ideal phase shift to minimize the output ripple is letting the diode current *iD2* always start rising at the same instants when the diode current *iD1* drops to zero, hence, the output current ripple is able to avoid the sum of the ripple components. The control unit of the proposed switching technique is described as shown in Fig.4.

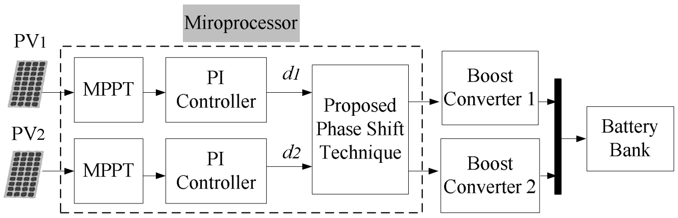

Fig. 4. Control of the proposed switching technique.

The operation of a boost converter consists of two modes [8], as shown in Fig.5 and Fig.6 respectively. As shown in Fig.5, *Model 1* is the "ON" time interval when $0 < t \le t_{on}$. *Model 2* shown in Fig.6 is the "OFF" time interval when $t_{on} < t \le T_s$. The switch voltage V_S of the time interval t_{on} is expressed as

$$V_s = L\frac{\Delta I}{t_{on}} \tag{1}$$

hence, the duration of the time interval t_{on} is given by

$$t_{on} = \frac{L\Delta I}{V_s} \tag{2}$$

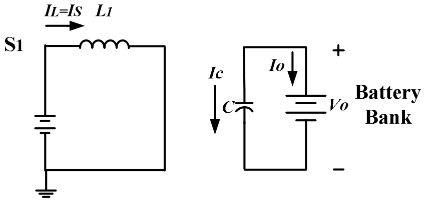

Fig. 5. Model 1 of boost converter when $0 < t \le t_{on}$.

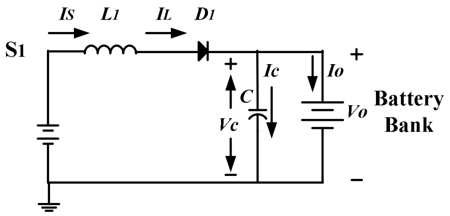

Fig. 6. Model 2 of boost converter when $t_{on} < t \le T_s$.

For the time interval $t_{on} < t \le T_s$, the voltage across inductor is expressed as

$$V_s - V_o = L\frac{\Delta I}{t_{off}} \tag{3}$$

then, the time duration of the interval $t_{on} < t \le T_s$ can be written as

$$t_{off} = \frac{L\Delta I}{V_a - V_s} \tag{4}$$

In addition, the average output voltage equation of *Vo* for a boost converter is shown in Equ. (5) as follow:

$$V_o = \frac{V_s}{1-D} \tag{5}$$

For the entire switching period, the following expression is given as

$$T = 1/f = t_{on} + t_{off} = \frac{L\Delta I}{V_s} + \frac{L\Delta I}{V_o - V_s} = \frac{L\Delta I}{V_s(V_o - V_s)} \tag{6}$$

The current ripple of the boost converter can be simplified by Equ. (1) - (6) into

$$\Delta I = \frac{V_s D}{f_s L} = K \bullet D \tag{7}$$

where,

$$K = \frac{1}{L} V_s T_s \tag{8}$$

For the comparison of the current ripple versus duty cycle between buck and boost converters is described in the Fig.7 for the same constant *K*.

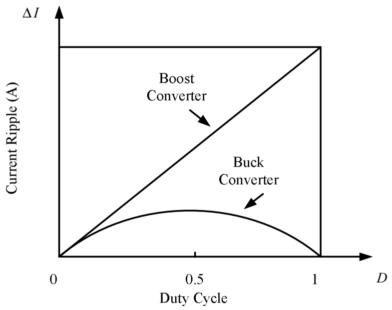

Fig.7. Current ripple versus duty cycle of buck and boost converters (same K).

Based on the peak ripple expression in Equ.(7), the ripple components of the currents *I1* and *I2* are given by Equ. (9) and (10) respectively.

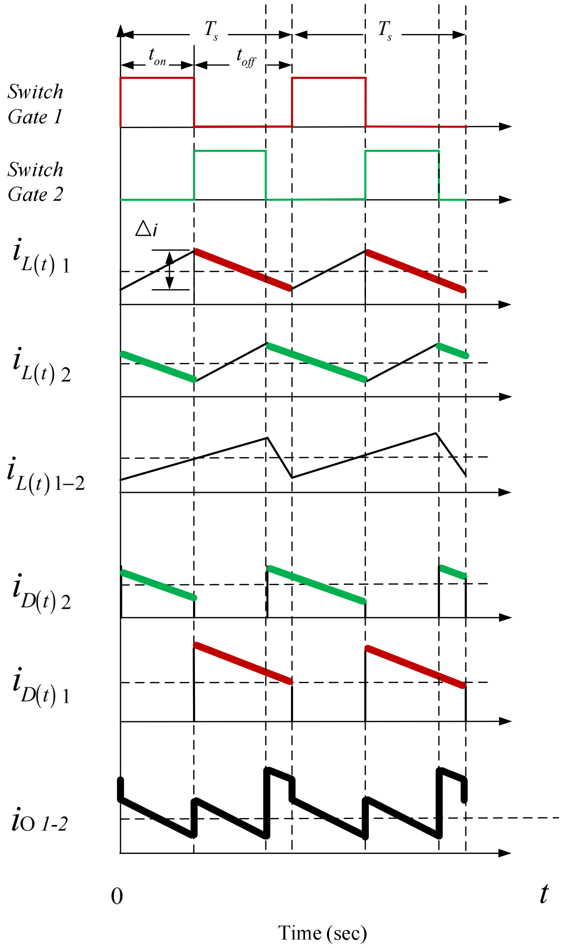

Fig. 8. Key waveforms of the proposed switching technique ($d_1 \neq d_2$).

$$\tilde{I}_{1\_peak} = K_1 \bullet d_1 \tag{9}$$

$$\tilde{I}_{2\_peak} = K_2 \bullet d_2 \tag{10}$$

As described in Fig. 8, inductor currents i_{L1} and i_{L2} are shifted by shifting two gate signals G_1 and G_2 . As the rising edge of G_2 always occurs at the same instant of the falling edge of G_1 , the inductor current i_{L2} continues the current when i_{L1} starts falling, which forms the new duty cycle d_{1_2} of the second generation as

$$d_{1\_2} = d_1 + d_2 \tag{11}$$

where the duty cycle d_{1-2} must be limited into the range $0 \le d \le 1$. It is well known that boost converters will not deliver power to the load when the duty cycle is 1. In addition, boost converters will not step up voltages when the duty cycle is 0. However, if the duty cycle is 1 or 0 for the first generation, it is taken into account for the calculation of the next generation duty cycle. Then, to develop the proposed switching technique to the n generation, the new duty cycle is given by $d_{new} = d_1 + d_2 - 1$, whenever the new duty cycle exceeds 1.

$$\tilde{I}_{new\_peak} = K \bullet (d_1 + d_2) \qquad (12)$$

For the two parallel boost converters, the output charging current is controlled by the falling edges of inductor currents. As described in Fig.8, as long as the switch gate signal *G2* starts at the same instant when *G1* is "OFF", the overlap of the two current ripples can be avoided for the output current. In the following sections, the proposed switching technique for paralleled boost converters is validated through simulation and experiment results with detailed discussion.

III. SIMULATION ANALYSIS

The simulation is carried out by Simulink/Matlab®. The case of two parallel boost converters is firstly tested with equal duty cycles *d1=d2*=0.5. Then, two different sources with P&O MPPT algorithm (different duty cycles) are analyzed, which is in different irradiations for the whole daytime from morning to evening, to each converters. Finally the proposed switching technique of multiple inputs is validated though the two boost converters plus one more boost converter with MPPT algorithm. The circuit parameters are listed in TABLEI.

A. Equal duty cycle test: d1=d2=0.5

TABLE I
THE CIRCUIT PARAMETERS

Parameters	Value	Unit
Battery Voltage	12	V
Switching Frequency	30	kHz
Maximum Current Ripple	10	%
Inductor	150	µH
Capacitor	220	µF

The two input voltages are 7 V to charge the output batteries with the same duty cycles are 0.5. Both the inductor currents are shown in Fig.9 and the sum of the inductor currents IL1-2 is with nearly zero ripple in this test. The enlarged waveforms are described in Fig.10.

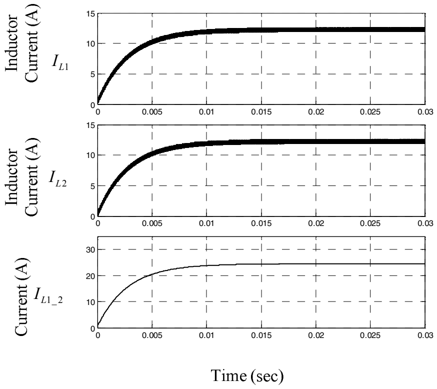

Fig. 9. Inductor currents of the two boost converters.

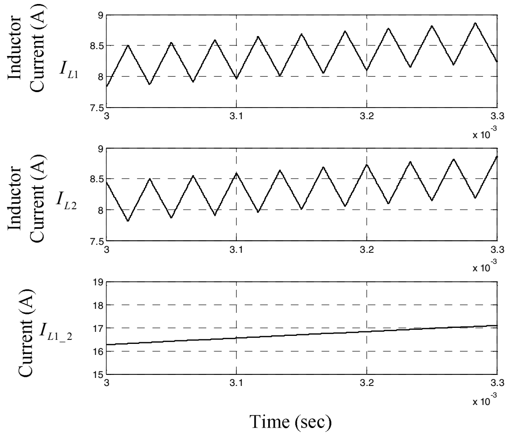

Fig. 10. Enlarged inductor currents shown in Fig.9.

As can be seen in Fig.11, the two converters are controlled by the proposed switching technique to cancel the two diode currents, which is to minimize the output current at the load side.

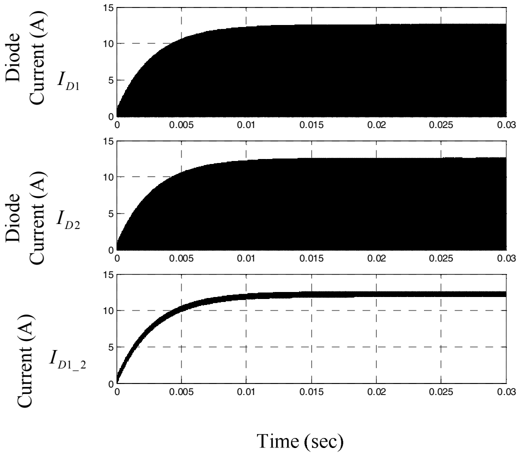

Fig. 11. Diode currents of the two boost converters.

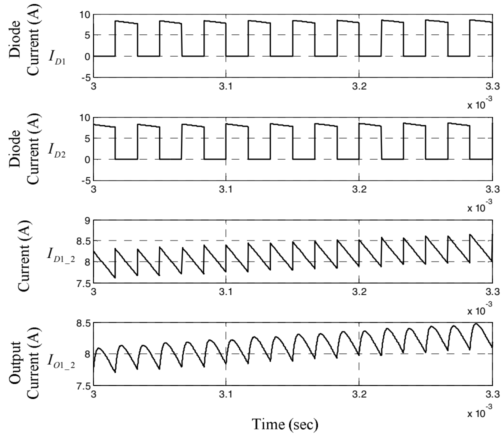

Fig. 12. Enlarged diode and output current of the two boost converters.

The enlarged current waveforms are presented in the Fig.12, which is perfectly matched the theoretical analysis shown in Fig.3. Thus the ripples of the output current are cancelled at the load side by using the proposed technique.

B. Two converters with MPPT algorithm.

Two paralleled boost converters for the MPPT implementation is tested in simulation. The simulation of two PV panels with the whole day irradiation is shown in Fig.13. The sunlight is simulated from the morning to evening for a typical 12 hours.

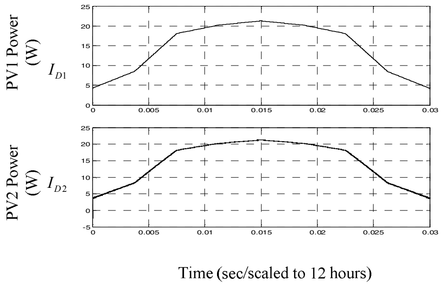

Fig. 13. Power of PV1 and PV2 for different irradiation of the daytime.

The currents flow through diodes of the two converters are shown in Fig.14 and the sum of the two diodes currents forms the current to the capacitor and load.

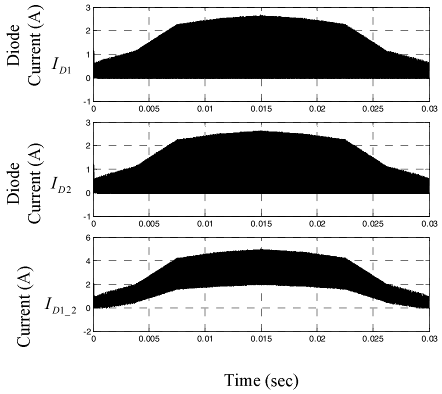

Fig. 14. Diode currents and of tracking maximum power point.

The enlarged waveforms of the Fig.14 are presented in Fig.15. As can be seen in Fig.15, the diode currents are shifted by the proposed switching technique to avoid the overlap. Ripples of the two diode currents are reduced to minimize the possibility of the overlap. Hence, the diode currents flow into the load side via the filtering of the load capacitor. The simulation results shown in Fig.15 match the analysis described in Fig.8.

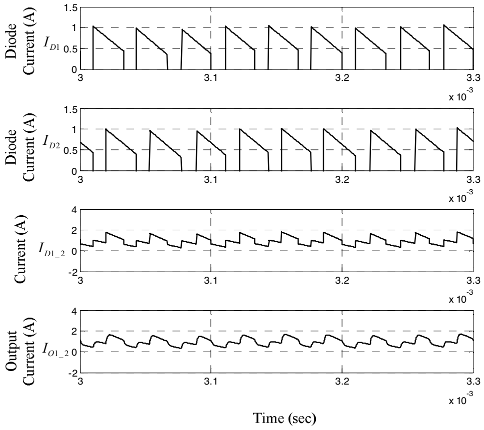

Fig. 15. Diode currents I_{D1}, I_{D2}, I_{D1_2} and output current I_{o1_2}.

C. Two plus one converters with MPPT algorithm.

Three paralleled boost converters are tested. Based on the operation principle mentioned in the previous section, inductor currents $I2$ cancels the peak ripple of $I1$, which results in the current $I1\_2$ with the new duty cycle. Thus, the ripple of the third boost converter is adopted to cancel the peak ripple of $I1\_2$ as shown in Fig.16. Since the inductor currents of paralleled boost converters are not summed together to the load side, however, by controlling the inductor currents, diode currents are adjusted for proper phase shift to minimize ripple of the load current. Thus, as shown in Fig.17, the output current at the load side is obtained with the minimized current ripple on it.

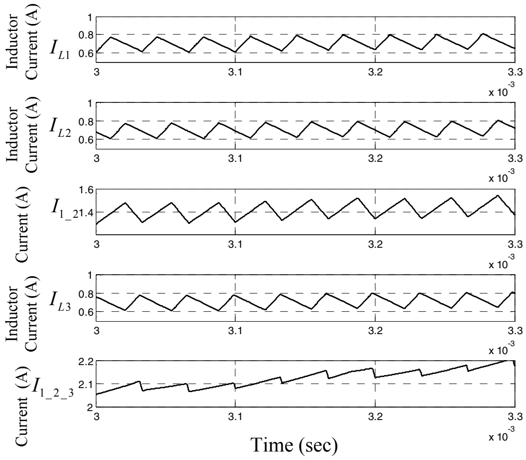

Fig. 16. Inductor currents of the three boost converters.

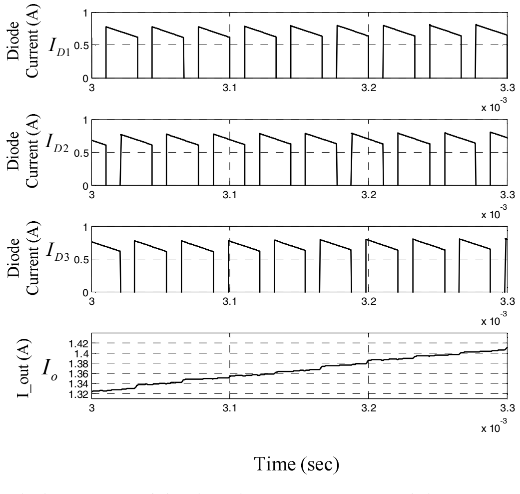

Fig. 17. Diode currents of the three boost converters and the output current.

IV. EXPERIMENT RESULTS

The proposed switching technique for parallel boost converters is verified through both steady-state and transient conditions with PI current controller employed. The steady-state operation is implemented with two different input voltages and different duty cycles. The input voltages are $V1=3.21V$, and $V2=6.18V$ and the battery voltage is $12V$. The reference currents are $I1\_ref=0.2A$ and $I2\_ref=0.15A$ respectively. The results presented in Fig.18 shows good cancellation results between the peaks of the two boost converters at the load side. For the proposed boost switching cancellation technique, transient and step responses are also tested with satisfied performances. For the transient test, the command reference current of both converters are same from *0.3A* to *0.2A.* As can be seen in Fig.19, the current at the load from each converter can both track the command current in transient condition. The ripples of both currents are able to cancel each other during transient conditions. When both currents *Iout1* and *Iout2* increase to *0.3A*, a step change occurs from *0.3A* to *0.2A*. Both currents can track the command currents satisfactorily from *0.3A* to *0.2A* with ripples cancelled at the same time.

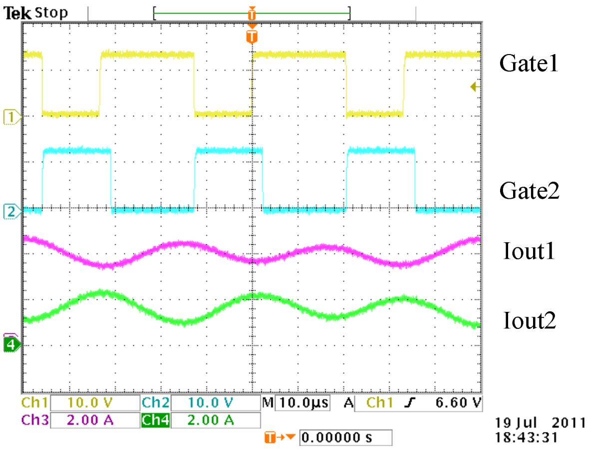

Fig. 18. Steady-state implementation of two different sources with current control.

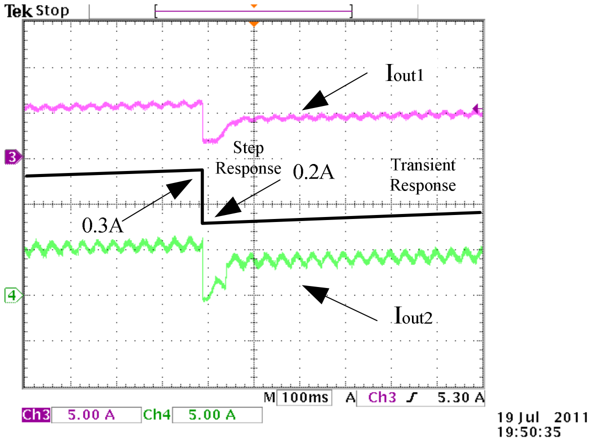

Fig. 19. Transient and step reponses implementations of two boost converters with current control.

V. CONCLUSION

In this paper, a boost-converter based switching technique is proposed for parallel configuration. Detailed analysis is presented with the verification through simulation and experiment results. The most favorable advantages are 1) the input sources can be many, 2) the voltages and duty cycles can be different from each other for the proposed technique, 3) the proposed technique can be applied to different control for the multiple input configuration. The proposed switching technique for boost converters will be extended to other types of converters in parallel configurations with different current and voltage controllers in the future papers.

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VII. BIOGRAPHIES

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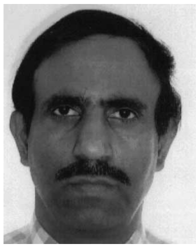

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