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Implementation and Control of Extra High Voltage DC-DC Boost Converter

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Abstract

This research paper article work focussed on the development of an extra high gain boost dc-dc converter for high voltage dc application with simple closed loop control scheme is presented. Classical version of step-up voltage dc-dc conversion configurations are used in high power (voltage/current) applications, but they are limited due to the restricted voltage transfer gain ratio, less efficiency, and moreover require two sensors with complex control algorithm lead to non-economical utilization. Further, the effect of parasitic elements limits both output voltage and power transfer efficiency of dc-dc converters. But with the application of voltage lift techniques pay the way to overcome these limitation, opening reliable way to improve the performance characteristics. Complete model of the proposed high gain dc-dc converter along with simplified closed controller was implemented in numerical simulation software using Matlab/Simulink environment and hardware prototype was realized using DSPTMS320F2812 with resistive loads. The performances are investigated under both line and load perturbation conditions. Numerical simulation results along experimental verifications are provided with complete theoretical developments.

1 Introduction

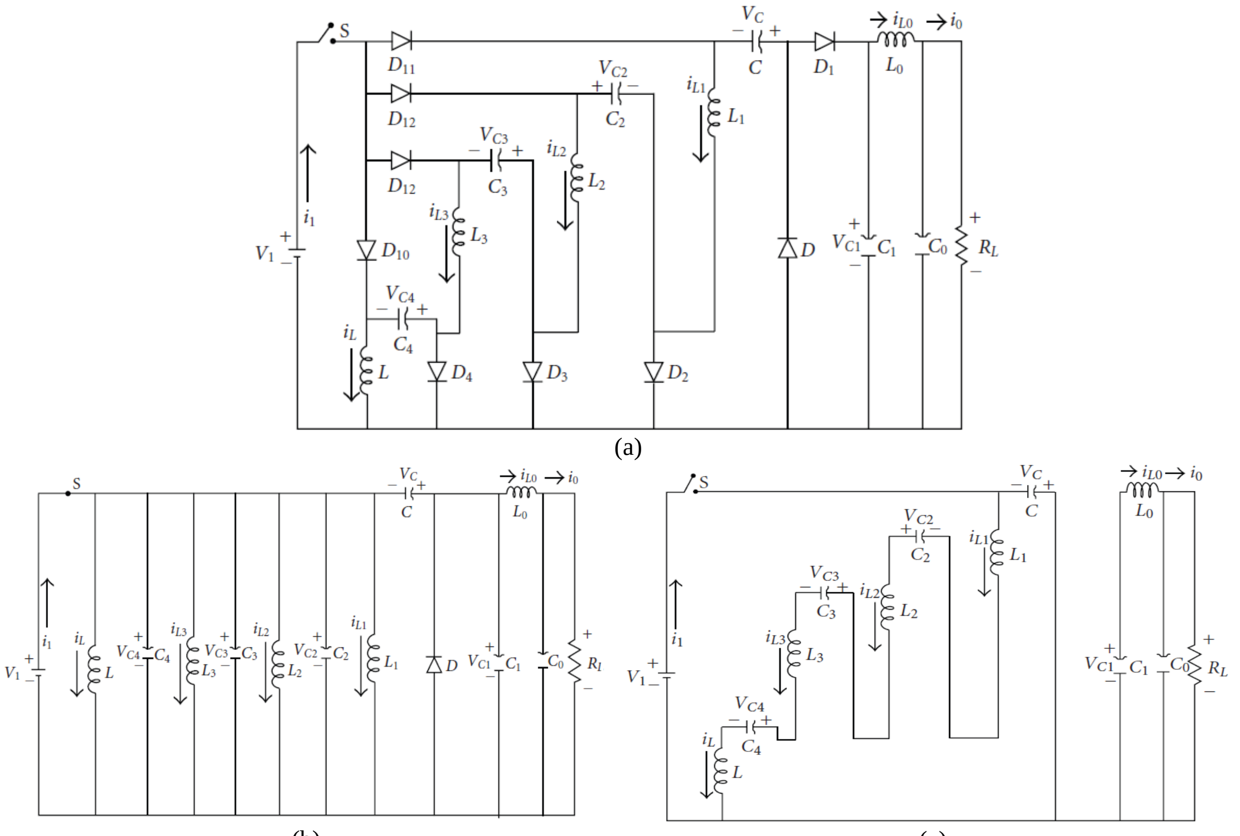
Traditional dc-dc step-up (boost) converters are widely used in HV (high voltage) applications, but they are not perfectly suitable due to the limited output voltage transfer gain, less efficiency and further requires two sensors with complexity in control nature. Moreover, the effects of parasitic elements in converter configuration, the output voltage/transfer efficiency of dc-dc converters are further reduced [1]-[4]. In contrast, voltage lift technique is a popular method widely applied in electronic circuit design and successfully employed in dc-dc converter [1]-[5] applications in recent papers, and provides the open platform to design extra high output voltage gain converters from classical dc-dc step-down (buck) converter configurations. The output voltage increases in geometric progression with stage-by-stage step-up ratio and to overcome the above limitations [6]-[8]. Extra high voltage (HV) dc-dc converter topology [1] which is derived from classical dc-dc step-down (boost) converter, by introducing voltage lift technique using additional passive (inductor/capacitor) components that implement the output voltage increase in a simple geometric progression. Hence, leads to enhance the increased voltage transfer gain as per power-law terms. The performance of this dc-dc extra high voltage converter posse advantageous in comparison to classical dc-dc version [1-2] as follows:

- High voltage transfer ratio gain (k).
- Wide range of control with lower ripple at the output.
- High power density and high efficiency.
- Closed-loop compensator requires only one sensor.

In proceeding to the research article [1], hardware prototype model implementation as been carried out for the extra HV dc-dc converter with simplified control technique using dsp tms320F2812 in this paper. Systematic procedure of operation modes, mathematical analysis as theoretical background of the complete system is presented. Further, a closed-loop control algorithm is developed to generate PWM pulses for the N-channel MOSFET of the proposed converter. Numerical simulation software model of the converter is developed in MATLAB/Simulink toolbox environment and the hardware prototype model was implemented with complete control algorithm developed with DSP-TMS320F2812 processor. Detailed investigation is carried out to study the performance of the whole converter system under both line and load regulations. Simulation results are presented and they are closely matches with the hardware results in perfect agreement with the theoretical developments.

2 Extra High Voltage Boost Converter Configuration

Configuration of the extra HV dc-dc boost converter is derived from classical dc-dc step-down (buck) converter. Circuit essential consist of additional voltage lift components i.e. capacitor/inductors in addition to that classical version and shown in Figure 1(a). Schematic circuit essential consists of a static switch S (N-channel MOSFET), diodes (D, D_1, D_2, D_3, D_4, D_{10}, D_{11}, D_{12} and D_{13}), inductors (L, L_0, L_1, L_2 and L_3), and capacitors (C, C_1, C_2, C_3 and C_4, and the output capacitor C_0). Capacitors (C_1, C_2, C_3 and C_4) perform the characteristics of voltage lift, the capacitor voltage V_c by four times that of input battery source voltage V_S. Correspondingly, the



(a)

(b)

(c)

Figure 1. (a) Investigated extra high voltage (HV) dc-dc converter configuration; (b) Equivalent circuit of converter configuration during ON state mode; (c) Equivalent circuit of converter configuration during OFF state mode.

directions of all voltages/currents are clearly defined and shown in the Fig. 1a. Further, it is assume that all the components are ideal and the capacitors are large enough, and the circuits operate in continuous conduction mode. The output voltage, output current are V_O and I_O and the input voltage, input current are V_I and I_I, power conversion unit performs a positive-to-positive dc-dc step up voltage with high efficiency, high power density and leads to a cheap topology in a simple structure. It is to be noted the output voltage and current of this converter are smooth, four times that of the input source battery voltage. The complete theoretical background analysis are provided in the next session.

3 Analysis of Converter Operating Modes

The equivalent circuit when Switch S is turned ON is shown in Figure 1(b). The source instantaneous current i_1 is equal to $i_{L1}+i_{Lo}+i_{C2}+i_{L2}+i_{C3}+i_L+i_{C4}+i_{L3}$. The load current I_O flows due to the addition of two voltages, i.e. the source battery voltage V_1 and the voltage across the capacitor C during switch-ON period. Also the capacitors, (C_2, C_3 and C_4) are charged to the input voltage under switch-ON condition and all the inductor current rises during switch-ON period. Equivalent circuit of converter when switch S turned OFF, source current i_1 is equal to zero and is shown in Figure 1(c). Now, the stored energy in the inductors (L_1, L_2, L_3 and L), whereas the capacitor (C_2, C_3 and C_4) discharges, lead to charge the capacitor C and charging direction are as shown in the Figure 1(c). Simultaneously, the current i_{L0} flows through the load, which will be sustained by the inductor L_0. Correspondingly, all the inductor currents decrease during the switch-OFF period.

In steady state, the average inductor voltages over a period are zero. Thus described as below:

$$V_{C0} = V_0 \tag{1}$$

Whereas, during switch turned ON period,

$$V_{C2} = V_{C3} = V_{C4} = V_1 \tag{2}$$

Also,

$$V_0 = V_{C1} = V_C + V_1 \tag{3}$$

The load side inductor current I_L, i.e. increases in the switch-ON period and decreases in the switch-OFF period. Simantanously, the voltages across L are V_1 and – $V_{L\text{-OFF.}}$ Therefore,

$$kTV_1 = (1\text{-}k)\ TV_{L\text{-OFF}} \tag{4}$$

$$V_{L\text{-OFF}} = [k/(1\text{-}k)]\ V_1 \tag{5}$$

Similarly for L_1, L_2 & L_3,

$$V_{L1\text{-OFF}} = [k/(1\text{-}k)]\ V_1 \tag{6}$$

$$V_{L2\text{-OFF}} = [k/(1\text{-}k)]\ V_1 \tag{7}$$

$$V_{L3\text{-OFF}} = [k/(1\text{-}k)]\ V_1 \tag{8}$$

From switch-OFF period equivalent circuit, it can be written as follow:

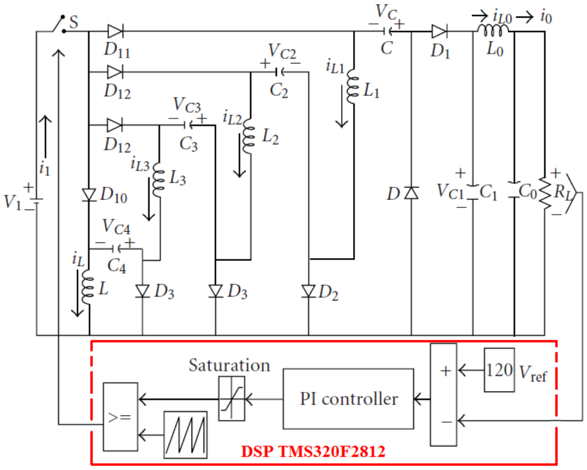


Figure 2. Schematic circuit of simplified closed loop control strategy for converter under line/load regulation.

$$V_C = V_{C\text{-}OFF} = V_{L\text{-}OFF} + V_{L1\text{-}OFF} + V_{L2\text{-}OFF} + V_{L3\text{-}OFF} + V_{C2} + V_{C3} + V_{C4} \quad (9)$$

$$V_C = 4k/(1-k)\, V_1 + 3V_1 \quad (10)$$

$$V_0 = V_C + V_1 \quad (11)$$

$$V_0 = [4/(1-k)]\, V_1 \quad (12)$$

The output current and voltage transfer gain are given as follows:

$$i_0 = [(1-k)/4]\, i_1, \quad (13)$$

$$M_0 = 4/(1-k). \quad (14)$$

Now, the average voltages and currents are given by:

$$V_C = [(3+k)/(1-k)]\, V_1, \quad (15)$$

$$V_{C1} = V_0, \quad (16)$$

$$V_{C2} = V_{C3} = V_{C4} = V_1. \quad (17)$$

$$i_{L0} = i_0, \quad (18)$$

$$i_L = [k/(1-k)]\, i_0, \quad (19)$$

$$i_{L1} = i_{L2} = i_{L3} = i_L + i_{L0} = [1/(1-k)] i_0 \quad (20)$$

The comparison between the proposed extra HV dc-dc step-up converter with the classical step-up (boost) converter was given Table 1, the effectiveness of the proposed converter topologies are shown in Table 2, by comparing the simulation results with classical boost converter. It is seen that the output voltage varies from 44.44 volts to 400 volts for the proposed dc-dc boost converter whereas for the classical ones from 1.11 volts to 90 volts respectively for a set duty ratio of 0.1 to 0.9, for a set input battery voltage of 10 volt. It is clearly verifies that the proposed converter topology produces higher output dc voltage than conventional ones.

Simple closed loop control scheme for the proposed dc-dc boost converter topology is shown in Figure 2. The control scheme consists of only one voltage sensor, when compared with classical dc-dc boost converter which requires both voltage and current sensors. Dc output voltage of the load is fed back and compared with V_{dc} set reference voltage and the error is given to the PI controller to stabilize the error and the signal obtained from the controller is the reference modulating signal (set duty ratio k) for the PWM scheme. Therefore, signal from the PI controller is compared with high frequency ramp signal to produce required pulse for the N-channel MOSFET switch to obtain the reference dc output voltage at the load and PI controller parameters (P-proportional gain, I-Integral gain) are fine tuned to provide effective compensator action [1].

Figure 3. Hardware prototype module of extra HV dc-dc boost converter with DSP TMS320F2812 processor in closed loop operation.

Complete hardware prototype module is developed using dsp TMS320F2812 for generating PWM for N-channel MOSFET (IRFPC60 version). Experimental test are carried under different load/line perturbation condition for the hardware prototype dc-dc converter model and experimental results are compared with numerical simulation results provided in the next session in detail.

Table 1. Performance comparison of the proposed dc-dc Boost Converter with Classical Boost Converter.

DC-DC Boost Converters	**Output Voltage (V_0) (Volts)**	**Output Current (i_0)**
Classical Converter	$V_0 = [k/(1-k)]\, V_1$	$i_0 = [(1-k)/k]\, i_1$
Proposed Converter	$V_0 = [4/(1-k)]\, V_1$	$i_0 = [(1-k)/4]\, i_1$

Table 2. Comparison of simulation result of the proposed converters with classical converter at steady state condition for rated load.

Duty Ratio (k)	**Output Voltage (V_0) Classical Converter**	**Output Voltage (V_0) Proposed Topology**
0.1	1.11	44.44
0.2	2.5	50
0.3	4.28	57.14
0.4	6.66	66.66
0.5	10	80
0.6	15	100
0.7	23.33	133.33

0.8	40	200
0.9	90	400

4. Simulation and Experimental Results

Numerical simulation and corresponding hardware results of the proposed dc-dc boost converter topologies with simplified controller scheme is investigated with parameter taken from Table 3. Design of inductance and capacitance are based on 5% ripple at the output [1], [9] and the values are same for both load and lift part of the circuit.

Table 3. Simulation and Hardware parameter taken for investigations.

Input Voltage V_1	= 10 volts
Inductance	= 100µH
Capacitance	= 5µF
Load Resistance	= 44 ohms
Duty Ratio k	= 0.6666
Switching Frequency	= 50 KHz
Digital Processor	= TMS 320F2812
N-channel MOSFET (IRFPC60)	= V_{dss} = 600V, $R_{ds(on)}$ = 0.40ohm, I_d =16A

Figure 4, depicts the numerical simulation output voltage of the extra HV dc-dc converter at rated condition, maintains 120volts at 44ohms load resistance, keeping duty ratio k = 2/3, it is to be noted controller set reference voltage is V_{ref}=120 volt.

Correspondingly, hardware result of the output voltage was shown in Figure 5, it is to be noted that output slightly lower than reference, settling at 119.8volts, 200 milli-volt lead to loss in power circuits due various parasitic effects and its practically acceptable. Hence, output voltage both simulated and hardware results closely matches and follows the Eq. 12 at k = 2/3.

Output current of the simulated circuit (2.7272) ampere and hardware prototype model (2.722) ampere was shown in Figure 6 and Figure 7. A small deviation is observed in hardware results due to various parasitic effects and follows Eq. 13 and obviously obeys the power-circuit law at 44ohms load resistance.

Figure 8 and Figure 9, illustrates the output voltage of simulated circuit (120volts) and hardware prototype (119.8volts) under both line and load perturbation conditions. To be noted, the output voltage stabilized in 0.005 sec for simulated module, whereas for hardware module at 0.625sec by the closed loop controller, when the input battery dc voltage source subjected to variation from 10 volts to 9 volts.

In the same investigation test, correspondingly load resistance decreases from 48 ohms to 44 ohms, whereas output voltage maintains the reference value of 120volts in simulation and 119.8volts in hardware with settling time of 0.005sec and 0.850sec shown by Figure 8 and Figure 9. Settling time required in hardware result are comparatively more than simulated ones, due to various parasitic nature of

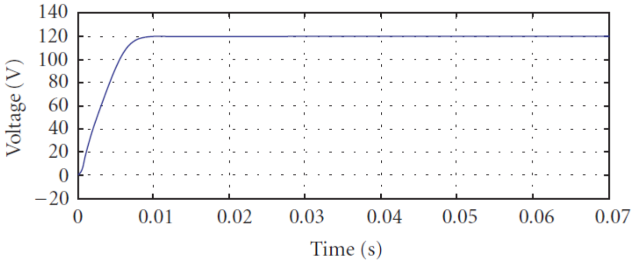


Figure 4. Simulated output voltage of extra HV dc-dc converter along with transient behavior.

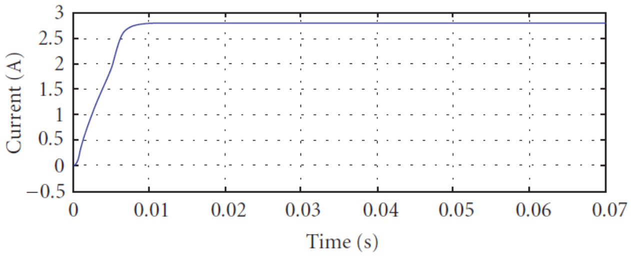


Figure 5. Simulated output current of extra HV dc-dc converter along with transient behavior.

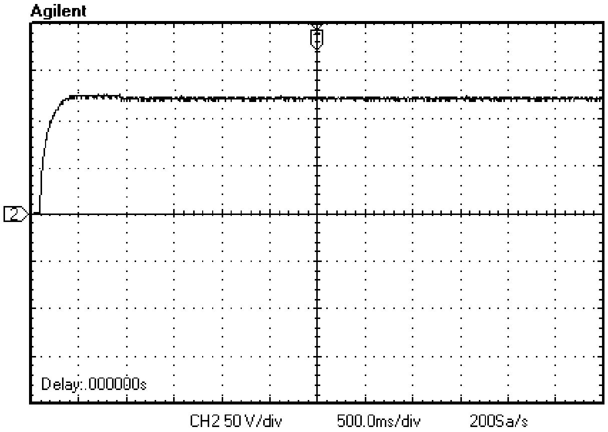


Figure 6. Hardware prototype module output voltage of extra HV dc-dc converter along with transient behavior.

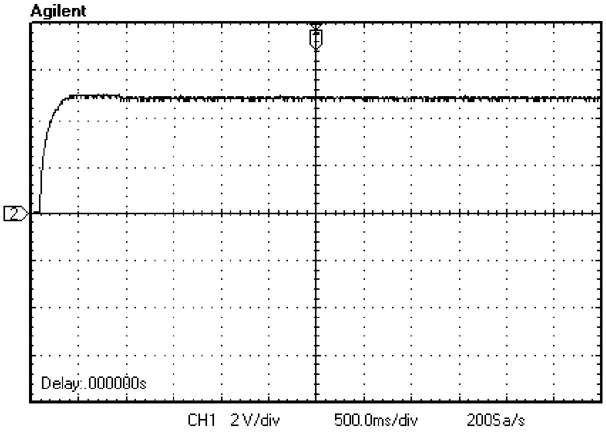


Figure 7. Hardware prototype module output current of extra HV dc-dc converter along with transient behavior.

the entire system. But output voltage both simulated and hardware results closely matches and follows the Eq. 12.

Output current of the simulated and hardware module under line and load perturbation investigation was shown in Figure 10 and Figure 11. It is observed that, during line perturbation, to be noted both simulated (2.5 amperes) and (2.495 ampere) hardware output currents maintains the same values irrespective variation in input dc voltage from 10 volts to 9 volts, with settling time of 0.005 sec and 0.625 sec.

Further when investigation subjected to load variation of resistance decreases from 48 ohms to 44 ohms, load current increases from 2.5 ampere to 2.7272 ampere by the simulated response, whereas from 2.495 amperes to 2.722 amperes for hardware module keeping settling time of 0.005 sec and 0.850 sec.

Settling time required in hardware result are comparatively more than simulated ones, due to various parasitic nature of the entire system. Finally output current both simulated and hardware results closely matches, follows Eq. 13 and obviously obeys power-circuit law.

5 Conclusion

Extra high voltage dc-dc converter hardware prototype was implemented using DSP TMS320F2812 process controller and compared with model developed in numerical simulation software in accordance with theoretical developments. The dc-dc conversion unit use the voltage lift technique to obtain higher output voltage than the classical dc-dc step-up (boost) converter for the same duty ratio and overcomes the effect of parasitic elements with minimized ripple at the output voltage/current.

A simple controller with one sensor was developed to maintain the output voltage at the required level for the load/line perturbation testing environmental conditions. Both simulation and hardware results provided in this paper always perfectly matches with theoretical development and proves the effectives of converter configuration.

Investigated extra HV dc-dc converter find suitable applications in computer peripheral circuits, medical equipments and high voltage regulated power supply for industrial applications where requires high power.

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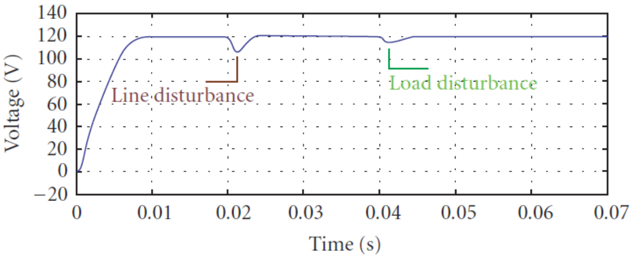

Figure 8. Simulated output voltage of extra HV dc-dc converter along with line/load regulation circumstances.

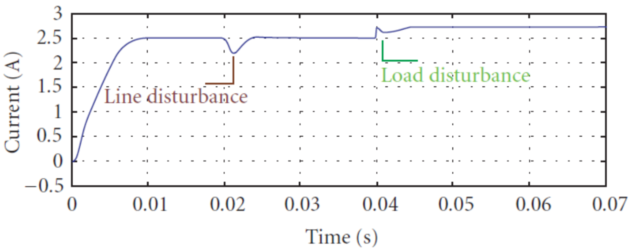

Figure 9. Simulated output current of extra HV dc-dc converter along with line/load regulation circumstances.

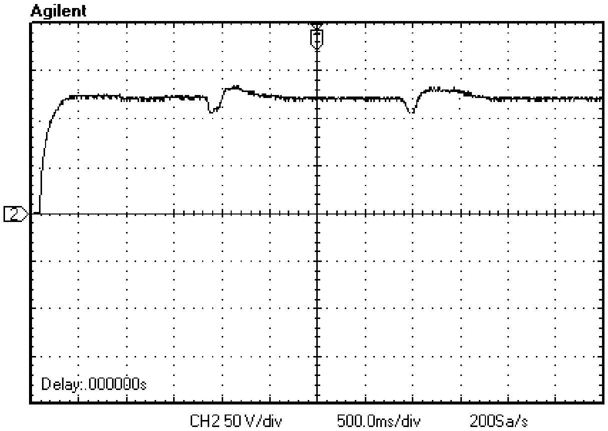

Figure 10. Hardware prototype module output voltage of extra HV dc-dc converter under line/load regulation.

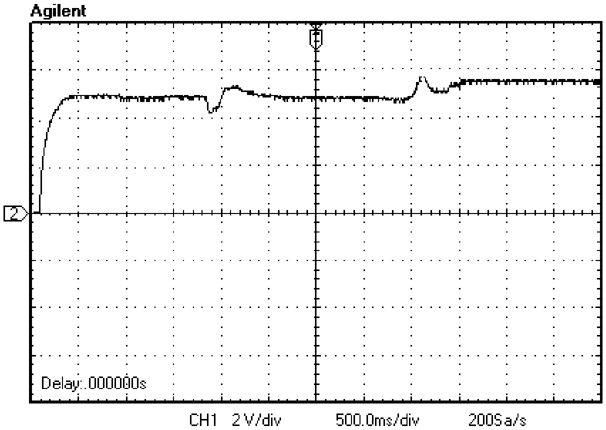

Figure 11. Hardware prototype module output current of extra HV dc-dc converter under line/load regulation.

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Biography

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Dr. Abu-Rub is the recipient of many prestigious international awards, such as the American Fulbright Scholarship (at Texas A&M University), the German Alexander von Humboldt Fellowship (at the University of Wuppertal), he has obtained German DAAD Scholarship (at Bochum University), the British Royal Society Scholarship (at Southampton University), and others. Dr. Abu-Rub has published more than two hundred journal and conference papers. He is on the editor/editorial board of several prestigious journals includes IEEE transaction on energy conversion etc.